The Importance of Routine Planetary Boundary Layer Measurements over Land from Space

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1 Introduction

The planetary boundary layer (PBL) is the lower part of the atmosphere in which we live, and which is coupled to the land surface where plants perform photosynthesis and most pollutants are emitted. The PBL controls surface fluxes as well as the temperature range and concentration of gases (water vapor, CO_2, pollutants), aerosols, and chemical constituents that humans and ecosystems experience. In addition, the turbulence in the PBL and its coupling with free-tropospheric conditions controls convective initiation, cloud coverage as well as pattern and intensity of precipitation. The PBL is thus a critical layer in the atmosphere, but is still not optimally represented both in current weather and climate models as well as in observations.

As a result, there is an established and growing need for PBL observations over land for research in hydrology, ecology, land-atmosphere interaction, turbulence, cloud and convection processes, turbulence (e.g. large eddy simulations (LES)), and aerosol/chemistry studies as well as associated weather and climate model evaluation and development (Workshop Report on Scientific Challenges and Opportunities in the NASA Weather Focus Area, 2015). Modulated strongly by PBL structure, evolution, and feedback processes (e.g. entrainment and atmospheric circulation at the meso- to macro-scale), an improved PBL representation will have profound impacts on society, surface hydrology (namely soil moisture and runoff), its connection to clouds and precipitation, and anthropogenic influences (e.g., CO_2 and pollution gases), and extreme weather in a changing climate.

1.1 Need for Space-based Observations

The last ten years have seen considerable attention and mission support dedicated to individual components of Earth's water and energy cycles as a result of the 2007 Decadal Survey. This includes land surface states and fluxes (e.g. soil moisture, snow, surface temperature, groundwater, evapotranspiration) and atmospheric quantities and profile information above the PBL (e.g. temperature, humidity, clouds, precipitation). The PBL, however, remains a major gap in our observational suite and is therefore currently the limiting factor in observational process studies. Ground-based remote sensing and in-situ (i.e. radiosonde) measurements of the thermodynamic and kinematic structure and evolution of the PBL will continue to be limited to short-term field campaigns and spatially restricted networks for the foreseeable future. Spaceborne instruments, on the other hand, would afford the ability to monitor and improve understanding of these processes on global and multi-year scales. Even so, there is very little attention or planning (short or long-term) in place for improving lower tropospheric thermodynamic sounding from space and, as a result, PBL research and observations have been identified as a 'terra incognita' in current agency programmatic focal areas.

1.2 Timeliness

The impacts of the PBL on water and energy cycles are typically felt at sub-daily timescales (e.g. 1-3 hourly) and at ~100m vertical and ~100m-10km spatial scales. To this end, the current suite of spaceborne instruments has seen only limited advances in instrument technology and algorithms as they relate to PBL (height and structure) retrieval. Hyperspectral sounders such as AIRS and IASI are the most capable in terms of spectral (and hence, vertical) resolution, but retrievals have not been tailored for the PBL and are strongly limited by cloud cover and surface emissivity effects. Standard lidar (e.g. CALIPSO) can obtain high vertical resolution of backscatter, but is limited in return time and spatial sampling and does not provide thermodynamic state information. Geostationary satellites (e.g. GOES) have the required temporal (i.e., 15-min to 1-hr) coverage, but are limited by having only a few IR channels capable of resolving the PBL. GPS-RO shows some promise for PBL retrieval, but is limited by irregular sampling, multipath effects, and confounding issues related to humidity and topography, as well as the inability to capture variations horizontally in the thermodynamic field. Thus, while each of these sensors have some lower tropospheric monitoring capabilities, there are even more limitations that make them impractical for routine PBL observations. It is therefore timely to assess how available technologies, including CubeSats, can be leveraged, combined, or evolved in order to form a dedicated mission or sub-mission to routinely monitor the PBL on diurnal timescales.

2 Key Challenges and Science Questions

- How can we quantify and improve the process-level and diurnal cycle representation of the water (including precipitation), carbon and energy cycles in weather and climate models?
    - PBL monitoring is required to address unresolved issues related such as those to surface heterogeneity, entrainment, stable and transitional PBLs, urban PBLs, aerosol, and land use change impacts.
    - PBL is a regulator of the highly uncertain soil moisture-precipitation feedback and the role of surface land cover gradients and change.
- When and where, globally, are the mechanisms that support hydrological and climatic extremes (such as drought) amplified or suppressed by PBL processes and feedbacks?

    - Feedbacks of soil moisture on temperature and precipitation are PBL-dependent and are strongly connected with the evolution of extreme events.
    - The diurnal cycle of the PBL is dependent on climatic regime and surface soil moisture and vegetation states.
- How can the PBL be used to integrate and improve estimation of other water, energy, and carbon cycle components that are difficult to monitor from space (e.g. surface fluxes (ET), winds speed, pollutants)?

3 Space-based Observations and Synergies with other Data

To fully retrieve the structure and evolution of the PBL, the community will need to bridge the gap between current disparate attempts across missions (mentioned above) to characterize the PBL over land and determine the challenges for improving retrieval of PBL height and lower tropospheric thermodynamic profiles via next-generation satellite technology. This will require a) an evaluation of the current methods and products related to PBL remote sensing from satellite, b) identification of the most likely approaches that will meet weather/climate modeling, process-level understanding and human health needs, and c) determination of the instrument and mission strategy that can achieve these goals.

One potential approach is to synergistically use both space-borne (active and passive) and ground-based remote sensing to simultaneously retrieve the thermodynamic structure of the PBL. The high vertical resolution and PBL height detection from active sensors compliments the true thermodynamic sounding capability of passive sensors. The majority of the information content in ground-based spectral observations is in the PBL, and using these observations will aid in the separation of the emission from the surface vs. the lowest atmospheric levels from the space-borne point-of-view. A small number of ground-based spectrally resolved remote sensors are operational; these instruments can be used to improve and evaluate methods to retrieve PBL structure at high temporal resolution from satellite sensors, which can then be applied globally. [These sites include the ARM instruments at the Southern Great Plains (SGP) supersite (1 Raman lidar, 5 AERIs and Doppler lidars over a 100 km diameter region), at the North Slope of Alaska (NSA) sites at Barrow and Oliktok Point, and at Graciosa Island in the Azores, and at the Lindenberg, Cabauw, Payerne, and Chilbolton observatories in Western Europe.]

3.1 Calibration/Validation

Remote sensing studies of the PBL will require calibration and validation support, much of which is already in place or being planned at extensive field campaigns using new advances in ground-based remote sensing platforms. One such example is the ARM-SGP supersite that includes numerous ground-based profilers as well as routine radiosonde launches, and a number of proposed L-A campaigns with new instrumentation focused on diurnal PBL monitoring. One significant challenge is to characterize the surface contribution (in both temperature and emissivity) to the satellite observation, and to develop methods to separate this contribution from the emission from the lower troposphere. A complete error analysis should be included so that uncertainties in the quantification of the surface contribution can be propagated to provide uncertainties in the retrieved boundary layer profiles.

3.2 Synthesis with Other Platforms

The PBL is a key integrator and transport layer that links the water, energy and carbon cycles and pollutants (gas and particulates) at the L-A interface. As a result, routine observations will enable closure of the PBL budgets of heat, moisture, and CO_2 and at the same time enable coupling of current satellite-based retrievals of individual variables of the L-A system, such as soil moisture (e.g. SMAP/SMOS), land cover states such as vegetation properties and types (MODIS, Quicksat), evapotranspiration and surface temperature (MODIS, Landsat), clouds and aerosols (CloudSat/CALIPSO), precipitation (GPM), dust and smoke emissions (Terra/MISR), and free atmosphere thermodynamic profiles (AIRS/IASI).

3.3 Synthesis with Models

PBL parameterizations used in weather, climate and Earth System models generally vary widely in terms of complexity and physical assumptions (as evidenced by the large number of PBL schemes available in the community WRF model). Single-column models (SCMs) have not evolved significantly in the last 15-20 years, while LES and cloud resolving models (CRMs) are being more widely developed but still lack extensive observations needed for validation across a range of conditions and representation of spatial heterogeneity. Overall, these modeling assets would benefit from the process understanding gleaned from observations of PBL structure and evolution over a wide range of climatic regimes, including those of feedback processes such as cloud-surface radiative effects and entrainment. For example, the GEWEX local land-atmosphere coupling ('LoCo') community has developed a suite of diagnostics to quantify the connection of soil moisture to precipitation in models and observations, most of which require or would benefit from information on the structure (e.g. PBL height) and/or composition of the PBL.

4 Anticipated Scientific and Societal Benefits

The need to understand the direct and indirect (feedback) effects of natural and anthropogenic activities over land at meso- (e.g., mountain, low-level jet, sea breezes, and monsoon), synoptic- (e.g., frontal systems) and global- (e.g., El Nino Southern Oscillation) spatial scales and seasonal-to-decadal time scales is of critical relevance to commerce (esp. food, energy, and transport) and public and environmental health. The PBL is the region in the atmosphere where the influence of local terrain and terrestrial processes and anomalies on large-scale atmospheric processes is felt, and the majority of atmospheric water vapor, heat, momentum and carbon are transported within the PBL. Observational evidence shows that the structure of the PBL can either suppress or support the following: extreme weather phenomena including, heat waves, severe thunderstorms, and tornadoes; dispersion of environmental (e.g., dust and smoke) and anthropogenic (e.g., pollution) emissions, and prolonged wetness or drought. As such, an improved representation of the PBL is a prerequisite for next-generation model simulations of clouds and precipitation as well as extreme events in weather forecast and climate models.

The diurnal evolution of the PBL is also strongly modulated by adiabatic heating by absorbing aerosols such as soot and black carbon, while the dispersion of aerosol into the free atmosphere is governed by the timing and strength of PBL lifting. This feedback is a key factor in dictating air quality near the surface, which has a direct impact on human health, particularly in developing regions. Improved PBL representation will directly aid in pollution and air quality forecasts, which will extend the benefit of this effort to human health and well-being. Thus, Earth system models and end-to-end user models benefitting from these advances will enable improved information for decision makers, hydrologists, and water management agencies. This will also have a positive impact in disaster management for the benefits of society and economy.

5 Key Science Community Involvement

Identified research communities: atmospheric sciences, atmospheric chemistry, climate sciences, environmental sciences, forestry, hydrometeorology, biology, physics, renewable energy (wind and solar), water resources engineering, hydrology, environmental health, geospatial information sciences.

Community contributions: This proposal is responding to the new WCRP/GEWEX Grand Challenges (see www.wcrp-climate.org/grand-challenges), which have been developed by the WCRP Joint Scientific Committee and based on a series of consultation with WCRP sponsors, stakeholders, and affiliate network of scientists during past several years. Particularly, new PBL observations will make key contributions to the challenges on "Clouds, Circulation, and Climate Sensitivity", "Climate Extremes", and "Water Availability". Furthermore, this project will making unique contributions to several projects of WWRP (www.wmo.int/pages/prog/arep/wwrp/new/wwrp_new_en.html) such as "Data Assimilation and Observing Strategies", "Nowcasting and Mesoscale Forecasting", "Predictability, Dynamics, and Ensemble Forecasting", "High Impact Weather", and to the "Subseasonal and Seasonal Prediction Research Project". The new thermodynamic profiles will provide key data sets for the major forecast centers such as NCEP, FSL, ECWMF, Meteo-France, UKMO, etc., particularly for data assimilation, model verification and model improvement.

6 References

Zeng, X., Ackerman, S., Ferraro, R. D., Murray, J. J., Pawson, S., Reynolds, C., and Teixeira, J., 2015: Workshop Report on Scientific Challenges and Opportunities in the NASA Weather Focus Area. NASA Aeronautics and Space Administration, 7-9 April 2015.