National Aeronautics and
Space Administration

TOWARD A GLOBAL PLANETARY BOUNDARY LAYER OBSERVING SYSTEM

THE NASA PBL INCUBATION STUDY TEAM REPORT

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CONTENTS

1. EXECUTIVE SUMMARY

A global Planetary Boundary Layer (PBL) observing system is urgently needed to address fundamental PBL science questions and societal applications related to weather, climate and air quality. This PBL observing system should optimally combine new space-based observations of the PBL thermodynamic structure with complementary surface-based and suborbital assets, while taking advantage of, and helping improve, modeling and data assimilation systems.

The Earth science community has expressed great interest in improving the characterization of the atmospheric PBL in the recent National Academies of Sciences, Engineering and Medicine (NASEM) 2017-2027 decadal survey for Earth Science and Applications from Space (ESAS 2017), see NASEM (2018a). Better observations of PBL temperature and water vapor profiles, and of PBL height were selected as priorities by ESAS 2017, which recommended the PBL as an Incubation Targeted Observable (TO). In response to the ESAS 2017, NASA established the decadal survey incubation program focused on priority PBL science and technology components that require advancement and development prior to implementation. This program established a competed NASA PBL Study Team.

The PBL Study Team identified (i) the most critical PBL science questions and applications topics in the context of Earth System science; (ii) specific PBL needs from a data assimilation, modeling (large-eddy simulation, regional, global) and prediction perspectives; (iii) the critical geophysical observables and their associated spatial and temporal measurement requirements so as to address the key PBL science questions and applications topics; (iv) the observational gaps from the current program of record; and (v) practical yet effective emerging measurement approaches and technologies to address measurement requirements from space using a range of system architectures.

The following critical aspects require a global space-based PBL observing system:

- Several of the key PBL science questions are about the interactions between PBL thermodynamics and global processes (e.g., the relation between PBL thermodynamic structure and clouds from a **global perspective**) that can only be properly observed from space.
- The interactions between the **mesoscale and PBL thermodynamic structure** are a key PBL science topic, and it is clear that to properly observe these interactions, a global perspective such as the one provided by space-based platforms is needed.
- Although we can often categorize the PBL in specific types and regimes, the interactions between mesoscale (and large-scale) atmospheric systems and the PBL thermodynamic structure, as well as the constraints of extreme physical environments on Earth and varying surface conditions, lead to a **wide variety of PBL structures** all around the globe. A space-based PBL observing system will likely lead to the discovery of new types of PBL thermodynamic structures (and their interactions with the overall Earth System) particularly over sparsely observed regions of the world such as the oceans and the polar regions. In this context, a space-based PBL mission will be a **mission of discovery**.

Table 1-1 briefly summarizes the four key PBL science goals and the topics associated with each of the PBL science questions. A much more detailed preliminary Science and Applications Traceability Matrix (SATM) is presented and discussed in chapter 4.

Table 1-1. Summarized SATM highlighting the key PBL science goals and topics.

Overarching PBL Vision	Science Goal	Science Topics (summarized questions)
Globally characterize the thermodynamic structure of the PBL	**G1. PBL, Convection and Extreme Weather**	**Q1.1**: PBL, Convection and Mesoscale **Q1.2**: Shallow and Deep Convection **Q1.3**: PBL, Surface processes and Precipitation
	G2. Cloudy PBL	**Q2.1**: PBL Thermodynamics and Clouds **Q2.2**: PBL Clouds, Surface Fluxes and Free Troposphere **Q2.3**: PBL, Clouds and Mesoscale
	G3. PBL and Surface Interaction	**Q3.1**: PBL Thermodynamics and Surface Fluxes **Q3.2**: Water Vapor Near the Surface **Q3.3**: Surface Heterogeneity, PBL and Convection **Q3.4**: PBL Thermodynamics and Extremes
	G4. PBL Modeling, Mixing and Air Quality	**Q4.1**: PBL Mixing and Transport **Q4.2**: PBL Parameterizations and Models

Essential components of a future global PBL observing system illustrated in Figure 1-1 include:

1. **Differential Absorption Lidar (DIAL) and Differential Absorption Radar (DAR) in low Earth orbit (LEO)** to provide high vertical resolution (approximately 200 m) water vapor profiles and high horizontal resolution (1 km) total precipitable water in clear and cloudy conditions, estimates of temperature profiles in liquid phase clouds (DAR), profiles of aerosols and clouds, and high horizontal resolution (1 km) estimates of PBL height (DIAL).
2. **High horizontal resolution hyperspectral infrared (IR) (1 km) and microwave (MW) (5 km) sounders in LEO** to provide 3D temperature and water vapor structure context to DIAL+DAR observations, potentially on SmallSat or CubeSat constellations (to provide higher temporal sampling).
3. **Radio Occultation (RO)** using larger constellations of Global Navigation Satellite System (GNSS-RO) receivers and/or novel orbital configurations and signal frequencies to provide additional high-vertical resolution and temporal sampling of temperature and/or water vapor profiles, and reliable estimates of PBL height.
4. **Geostationary hyperspectral IR sounding**, taking advantage of international (e.g., EUMETSAT) and national inter-agency (NOAA) collaborations, to dramatically increase temporal sampling of temperature and water vapor profiles.
5. **Modeling and data assimilation** capabilities to optimally assimilate these PBL observations to produce the best state estimate of PBL thermodynamics globally (with a potential focus over the continental United States) every day.

<u>Additional key components include:</u>

- Program of Record (POR) observations from a variety of platforms (space, suborbital, and surface-based).
- Suborbital campaigns focused on technology demonstrations, data fusion, and process studies in different regions.

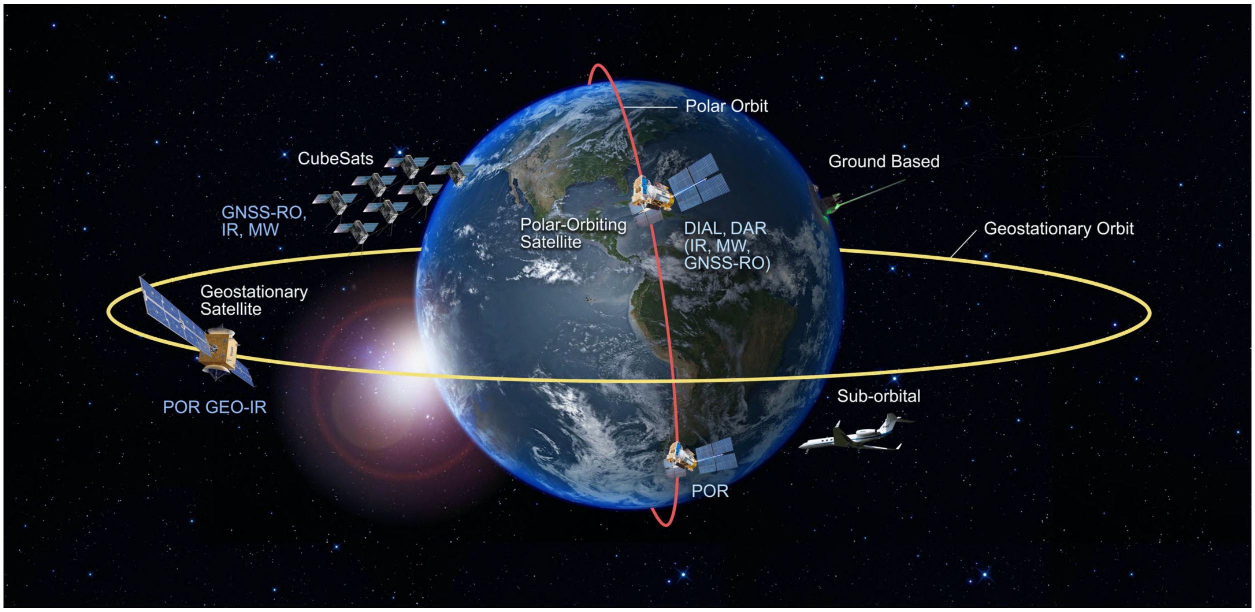

Figure 1-1. Overarching architecture for a future integrated global PBL observing system.

The PBL Study Team developed a technology roadmap to enable a future orbital observing system (in combination with suborbital and surface-based observations, models and data assimilation) based on these technologies. Simulator methodologies – involving high-resolution LES models, global weather and climate models, instrument forward models, joint retrievals and data assimilation – were identified to explore optimal combinations of potential measurement approaches and technologies; and approaches were identified to field emerging airborne instruments in science campaigns to evaluate the information content of joint retrievals and their relevant impact. The present PBL Study Team report summarizes several of these findings in a preliminary PBL SATM. This PBL report emphasizes the critical need to organize a PBL working group or science team in the coming decade and articulates several findings regarding how NASA could leverage a new PBL program with existing programs to bring together the diverse community of researchers working on PBL science, technology and applications.

To conclude this chapter, we present a figure that summarizes in a schematic manner the findings of the Study Team regarding a PBL Incubation roadmap for science and technology activities.

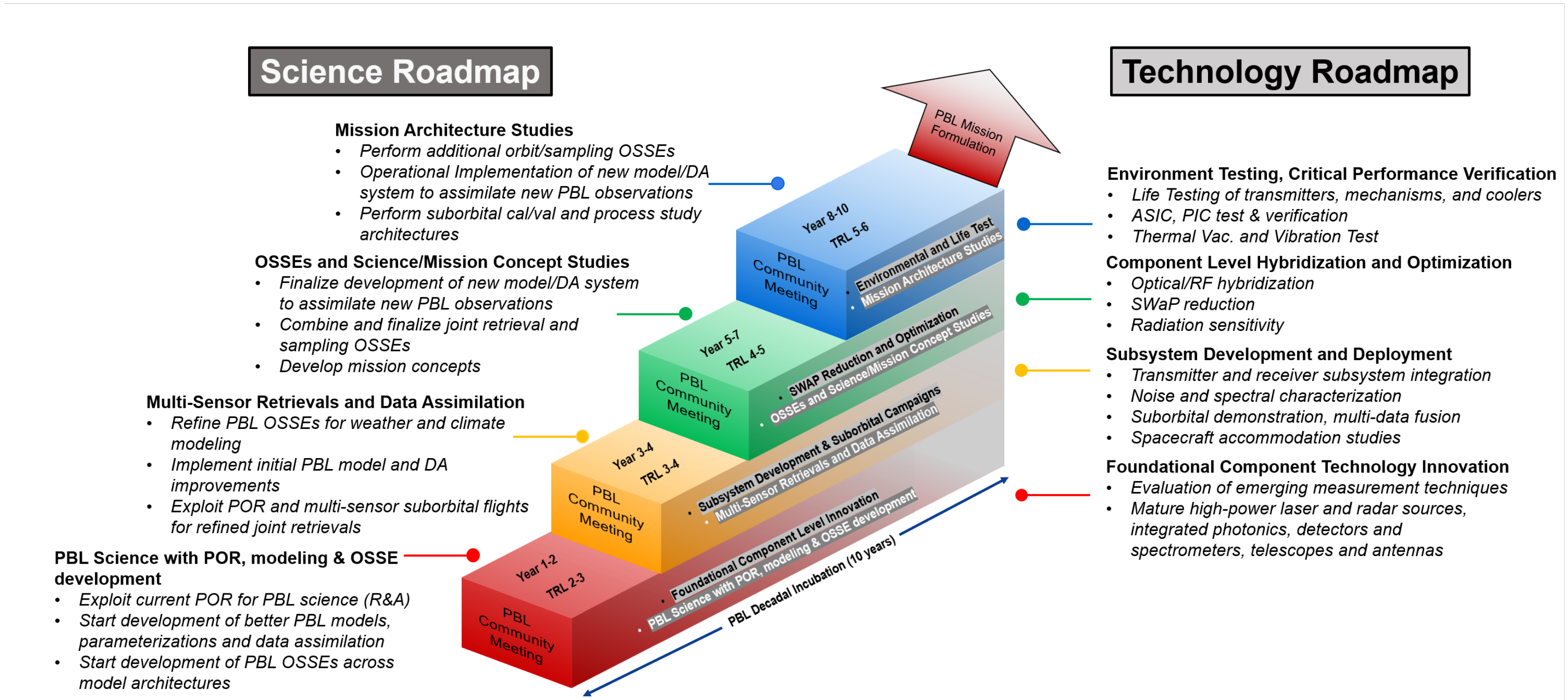

Figure 1-2. Schematic summarizing the PBL Incubation science and technology roadmap.

2. INTRODUCTION AND MOTIVATION

The planetary boundary layer (PBL) can be generally defined as the turbulent layer of the atmosphere adjacent to the Earth's surface, which mediates the interactions between the surface and the atmosphere. The PBL height varies depending on the intensity and nature of turbulence from a few tens of meters (e.g., over cold surfaces during night or winter) up to values of the order of 5 km (e.g., over deserts during daytime) – although it is typically of the order of 1 km. The PBL fundamentally connects the surface and atmosphere components of the Earth system and varies systematically both geographically and temporally, spanning diurnal to seasonal and climate scales that bridge global weather and climate. The recent work of LeMone et al. (2019) provides an excellent review of PBL science over the last 100 years.

Figure 2-1. A schematic depiction of key aspects of the PBL.

The PBL is of critical importance as it connects the atmosphere to the other components of the Earth system (oceans, land, and ice) and is essential to a number of Earth science priorities as stated clearly in ESAS 2017 (NASEM 2018a). Characterizing the complex three-dimensional (3D) thermodynamic structure of the PBL from a global perspective is an unmet grand challenge, as the PBL not only influences weather and air quality forecasts and climate prediction but is also inherent to many other high-priority objectives connected to Earth system science as a whole. In the proceedings of a recent NASEM workshop on *"The Future of Atmospheric Boundary Layer Observing, Understanding, and Modeling"* (NASEM 2018b), an overarching question is posed to the PBL community: What observations are needed (over land, ocean, and ice) to make meaningful progress in our understanding and modeling of the global PBL?

Humans live in the PBL and the weather and climate 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, and the PBL plays a critical role in high-impact weather events. Acting as a buffer between the surface and the free atmosphere above, the PBL regulates the mixing of energy, water, carbon, and other atmospheric constituents. In this context, the PBL thermodynamic structure influences the surface sensible and latent heat fluxes, the PBL-top entrainment of free tropospheric air, and deep convective processes that mix PBL air with the free atmosphere. Improved estimates from space of PBL thermodynamic profiles and PBL height are essential to improve weather and climate forecasts. The mixing that occurs across the PBL-top interface is central to understanding the transport of key atmospheric constituents involved in problems of air quality and the carbon cycle.

Reports from the Intergovernmental Panel on Climate Change (IPCC) have reiterated over the years that clouds are at the heart of the most significant source of uncertainty in current climate projections. PBL clouds play a key role in projections via their response to a changing climate system, thus altering its transient evolution through cloud-climate feedbacks. Clouds are closely coupled with the PBL temperature and water vapor structure, and more accurate knowledge of the PBL thermodynamic structure, and of the key physical processes associated with it, is critical to resolving fundamental climate uncertainties.

The PBL plays a central role in all four guiding questions of the World Climate Research Programme (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?

As will be discussed in detail in this report, there are several reasons related to weather, climate, and applications why it is timely to improve the quality of observations of the PBL thermodynamic structure, including:

- Climate model projections remain highly uncertain and it is essential, for decision makers, to reduce these uncertainties. Much of the uncertainty regarding these projections is anchored in PBL-modulated cloud feedbacks. In order to systematically improve climate model PBL parameterizations, more detailed observations of the global PBL thermodynamic structure are absolutely crucial. Space-borne observations provide the only means of obtaining the global coverage required over key regions that are remote and vast.
- Numerical weather prediction and data assimilation (including reanalysis) systems have improved over time, but there remains potential for significant improvement associated with more accurate PBL observations and models. Assimilation of space-based global PBL observations of the thermodynamic structure would lead to better initial conditions for forecast models and more accurate global reanalyses. More detailed observations of global PBL structure will also lead to improved PBL parameterizations for weather prediction and reanalysis.
- Air quality significantly impacts human health, particularly in and around our growing cities. PBL height in particular strongly modulates the impacts of surface pollutant emissions via dilution (lower air quality is associated with a shallower PBL). Improved observations of PBL height and thermodynamic structure will lead to improved air quality characterization and forecasts.
- Solar and wind power are critical players in energy production. In order to optimize energy production using wind and solar power, there is a crucial need for better PBL observations, which will lead to improved wind and solar power planning and more accurate production forecasts.

A long-term goal for weather and climate models is the development of accurate parameterizations to represent the processes associated with PBL turbulence, moist convection and clouds – in particular, unified PBL mixing parameterizations. In spite of much recent progress, current weather and climate models are still a long way from representing realistically the PBL thermodynamic structure and its evolution, and several problems remain. Addressing the key parameterization issues would benefit tremendously from better global satellite observations of the PBL thermodynamic structure. Critical requirements are increased global coverage, and enhanced horizontal and vertical resolution.

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

Existing space-based methods for remote sensing of temperature and water vapor profiles include passive infrared (IR) sounding, passive microwave (MW) sounding, and GNSS 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, by themselves, from profiling PBL temperature and water vapor with the resolution and quality required by key PBL science questions and applications. Current MW sounding provides little information on the PBL. Existing IR sounders have some sensitivity to PBL structure but are hindered by coarse vertical (around 1 km) and horizontal resolution (around 10 km). Additionally, clouds are frequent in the PBL, which strongly influences IR radiances and is only partially addressed by combined IR+MW retrievals. RO is sensitive to PBL water vapor with high vertical resolution (around 100 m) at low to middle latitudes. However, the utility of RO is reduced by an additional dependence on pressure and temperature, sampling issues, and an even coarser horizontal resolution (around 100 km). Improving space-based observations of the PBL thermodynamics will require incremental advancements in the current sounding techniques (i.e., increase spectral and spatial resolution for sounders), in addition to new types of observations including active observations from lidar, radar, and perhaps new approaches to RO.

Numerical weather prediction relies heavily on assimilation of existing water vapor and temperature measurements. Given the recent history of the remarkable impact of MW, IR and RO sounding in improving NWP forecasts, there is little doubt that more detailed information on the PBL structure would have an additionally significant impact on weather forecasts, including severe weather and convection. The PBL is frequently cloudy, which complicates existing IR+MW remote sensing with the present coarse horizontal resolution. IR sounding with higher horizontal resolutions would allow the capture of additional clear regions between clouds. In addition, new radar-based methods are being developed to profile water vapor (and indirectly temperature) within clouds. It was recognized in a recent statement of guidance for NWP to the World Meteorological Organization (WMO) that 'critical atmospheric variables that are not adequately measured by current or planned systems are temperature and humidity profiles of adequate vertical resolution in cloudy areas' (Andersson 2014). In fact, few PBL observations are currently assimilated in NWP. This implies that much of the PBL structure produced by these modeling and analysis systems, which are also the source of global reanalyses, derive directly from the overall model physics and dynamics, and in particular from PBL parameterizations, with their associated biases.

A recent NASA Weather Focus Area community workshop report (Zeng et al. 2015) highlights the importance of the PBL for weather and identifies some key unanswered questions: How does moist convection interact with the PBL and the surface? What are the fundamental mechanisms controlling PBL clouds? The report states that in particular better measurements of PBL temperature and water vapor are needed. The report recommends continuous investment in temperature and water vapor profile measurements from space, focusing on higher spatial and temporal resolution, and synergistic measurements involving multiple instruments, and different platforms.

The Earth science community has expressed great interest in improving the characterization of the PBL in the ESAS 2017 decadal survey (NASEM 2018a). Measurements of the PBL were rated *Most Important* or *Very Important* by three of the five ESAS 2017 decadal survey panels. Better observations of PBL temperature and water vapor profiles and of PBL height are recommended as priorities. However, the technology needed to make these measurements of PBL properties from space was deemed too immature for implementation. The ESAS 2017 decadal survey therefore recommended that the PBL Targeted Observable be placed in the Incubation class. In response to the decadal survey, NASA established the Incubation Program for high-priority capabilities that need advancement and development prior to implementation. This program established a PBL Study Team which was competed through a NASA Research Announcement.

The PBL Study Team started its work in January 2020 and completed the following tasks:

- Identified **critical PBL science and applications questions** in the context of Earth System science considering the diverse spatial and temporal scales of the atmosphere, ocean, land and ice.
- Identified specific **PBL needs from a data assimilation, modeling and prediction** perspective (climate, weather, regional, LES);
- Identified the **critical geophysical observables** and their associated spatial and temporal requirements (resolution, sampling) to address the key PBL science questions and applications;
- Identified **observational gaps** from the current program of record;
- Identified **emerging measurement approaches and enabling technologies** to address measurement goals from space using a range of system architectures;
- Developed a **roadmap** to enable a future orbital observing system based on these technologies (in synergy with suborbital and surface-based observations, models and data assimilation);
- Identified **simulator methodologies** to explore optimal combinations of potential measurement approaches and technologies (including high-resolution LES models, instrument forward models, joint retrievals and data assimilation systems);
- Identified approaches to **combine emerging airborne instruments** in science campaigns to evaluate the information content of joint retrievals and their relevant impact;
- Synthesized these findings in a preliminary PBL Science and Applications Traceability Matrix (**SATM**);
- Produced this **report**.

Although two 'PBL from Space' workshops were convened since the publication of the ESAS 2017 decadal survey focusing on both science (May 2018) and technology (October 2018), one of the key objectives of the PBL Study Team was the organization of a NASA PBL Incubation workshop. The purpose of the PBL Incubation workshop was to summarize the work and charter of the PBL Study Team, and to collect input from the PBL science, technology and applications communities. The workshop was organized in a virtual environment and took place on May 19, 20, 26 and 27, 2020. After introductory presentations describing the NASA PBL Incubation program and summarizing the PBL Study Team's goals and activities, the workshop consisted of the following science, applications and technology sessions: 1) High-latitude PBL; 2) PBL and deep convection; 3) PBL over land and surface interaction; 4) PBL over the ocean and air-sea interaction; 5) PBL applications; 6) Weather and climate models, and data assimilation; 7) PBL passive remote sensing; 8) PBL active remote sensing; and 9) In-situ and suborbital opportunities. Most sessions were a mixture of presentations and discussion, starting with invited presentations (to set the stage for the discussion) followed by short contributed presentations and a detailed discussion. Over two hundred virtual participants per day attended the workshop. A PBL technology survey, to further engage the technology community, was released in early October 2020. The inputs provided by the PBL science, applications and technology communities during the workshop and to the survey were essential for informing the study and are reflected in a variety of aspects throughout this report.

3. SUMMARY OF DECADAL SURVEY RECOMMENDATIONS

At the behest of NASA, NOAA, and the USGS, the National Academies began the first roadmap for Earth science from space in 2005 (ESAS 2007) with a request for information (RFI) that solicited satellite mission proposals in three cost classes. The roughly 100 responses received served as the foundation for the recommendation of 15 missions for funding by NASA and 3 by NOAA, each based on specific or notional instruments and an associated mission life cycle cost estimate. In preparing a second roadmap, the National Academies' charge was broadened to first establishing earth science and applications priorities and then identifying “targeted observables” (TOs) rather than specific missions. In keeping with that charge, two sequential RFIs focused first on leading questions and then on proposed solutions. Responses provided input to the 35 key science and application priorities identified in the ESAS 2017, as well as the 14 TOs allocated to one of three new mission flight program elements (Tables S.1-2). Although the 14 TOs identified as a primary outcome of the ESAS 2017 effort are considered relevant to all three commissioning agencies (NASA, NOAA, and USGS), all missions were anticipated to be implemented under NASA’s leadership (see Chapter 4 of the ESAS 2017 report for discussion of NOAA and USGS participation).

The ESAS 2017 process led to identification of the PBL as a TO in the new “Incubation” class, generally indicating a high-priority observable not yet considered feasible for cost-effective flight implementation but warranting acceleration of factors that could lead to a higher readiness level. The emergence of the PBL as a very high science priority without a currently mature and affordable mission concept can be seen as an outcome of the process to explicitly begin with the scientific priorities in the ESAS 2017. It is important to note that the ESAS 2017 PBL TO is identified as “diurnal 3D PBL thermodynamic properties and 2D PBL structure”, whereas the “Atmospheric Winds” TO is defined as “3D winds in troposphere/planetary boundary layer”, thus introducing some degree of overlap that is discussed briefly below. The Incubation Program element is intended to support maturation that would be required to define and enable cost-effective implementation, including developing associated prospective user communities to mature both measurement requirements and potential implementation concepts.

In the case of the PBL Incubation TO, the following specific goals were outlined in ESAS 2017 (Chapter 3):

- Improve understanding of measurement needs through modeling and mission concept studies.
- Identify needs that can be addressed through surface-based or airborne technologies rather than requiring a space-based component, including required technology developments.
- Identify any mission elements that are suited to lower cost Venture-class or competed Earth System Explorer opportunities.
- Identify suborbital observations of temperature and water vapor and the modeling needs to complement atmospheric winds and PBL height measurements.
- Determine optimal augmentations to the POR (both space- and surface-based) that would address identified measurement needs.
- Assess state-of-the-art passive and active technology capabilities to profile water vapor and temperature in the clear and cloudy PBL.
- Assess strategies to resolve the diurnal cycle, including via combination of GEO, LEO, suborbital, constellation or other novel concepts.
- Identify where additional investment in existing or emerging technologies may be required to achieve target capabilities.

Taken together, meeting these objectives can be seen as providing an appropriately broad foundation and context for potential advancements.

In an effort to comprehensively address Earth system science and applications, ESAS 2017 uses integrating themes – extreme events, carbon, water and energy cycles, as well as sea-level rise to ensure that disciplinary (panels) and cross-disciplinary (integrating themes) are considered together to address societal grand challenges in the coming decades. These integrating themes made it possible to view Earth system science in the context of thematic areas spanning multiple panels. The PBL plays a central role as described in ESAS 2017: "*The Weather and Air Quality Panel also identified important linkages between the PBL to other panels and Integrating Themes: (1) the PBL interacts with surface processes, which are important to the objectives of the Hydrology Panel, the Ecosystems Panel, and the Climate Panel (through near-surface atmospheric quantities such as wind speed, precipitation, aerosol and trace gases, and air-sea-land surface fluxes) and (2) subseasonal-to-seasonal prediction will bridge the weather and climate continuum and relate to hazardous event preparedness and mitigation via long-lead forecast information (e.g., floods, droughts, wildfire potential). The strategy requires a combination of space-based observations, and expansion of aircraft and surface-based observations, in conjunction with data assimilation and numerical modeling representing the 3D structure of the PBL.*"

In the first step of the ESAS 2017 process, five interdisciplinary panels identified a total of 35 leading science questions that spanned the full range of inquiry, including basic knowledge gaps, and monitoring change. Three of the five panels identified geophysical observables related to PBL properties, associated with weather and air quality (panel W), climate variability and change (panel C), and global hydrological cycles and water resources (panel H). The ten questions associated with PBL-related geophysical observables can be briefly summarized as follows:

- What PBL processes are important to surface-atmosphere exchanges, weather forecasts, and air quality projections? (W-1)
- How can weather and air quality predictions be seamlessly extended for lead times of a week to two months? (W-2)
- How do spatial variations in surface characteristics modify weather and air quality? (W-3)
- Why do storms, heavy precipitation and clouds occur where and when they do? (W-4)
- How do clouds affect surface radiative forcing and predictability on minute to subseasonal time scales? (W-10)
- How can we reduce uncertainty in global climate sensitivity, and local and regional climate responses to anthropogenic forcings? (C-2)
- How are decadal-scale atmospheric and ocean circulation patterns changing, and what will be the effects of such changes? (C-7)
- What will be the consequences of polar amplification on global sea-level rise, atmospheric and oceanic circulation, extreme weather, and carbon fluxes? (C-8)
- How is the water cycle changing? (H-1)
- What are anthropogenic effects on water and energy cycles? (H-2)

Associated with the above questions, each panel identified one or more specific earth science and applications objectives, and further ranked each objective as important (I), very important (VI), or most important (MI) based on considerations such as applications and policy benefit, breadth of interdisciplinary benefit, likely future importance, readiness, and timeliness. Overall, the ESAS 2017 report recommended PBL thermodynamic profiles and/or PBL height as priority geophysical observables for five objectives in the MI class, seven in the VI class, and one in the I class (Table 3-1). In addition, there are other objectives that require quantities within the PBL, such as near-surface vapor pressure deficit, which is determined by near-surface temperature and water vapor.

Table 3-1. Range of ESAS 2017 measurement requirements for PBL variables: temperature (T), water vapor (q), and PBL height (PBLH). Importance identified as I=Important, VI=Very Important, and MI=Most Important, as re-mapped from each panel discussion of objectives and SATMs to resolve inconsistencies in Appendix C of ESAS 2017. Italics indicate objectives common to the Atmospheric Winds TO.

Objective (Importance)	Variable	Horizontal Resolution	Vertical Resolution	Temporal Resolution
W-1a (MI)	**T, q profiles**	20km	200m	3h
W-1a (MI)	**PBLH**	20km	100m	3h
W-2a (MI)	**T, q profiles**	3-5km	1km	1-3h
W-3a (VI)	**PBLH**	5-10km	10m	1-2/day
W-4a (MI)	**q profiles**	1km	500m	15m
W-10a (I)	**cloud fraction**	200m	--	--
C-2b (VI)	**T, q profiles**	100km	2km	decadal trends
C-2h (MI)	**T, q profiles**	25km	2km	decadal trends
C-8a (VI)	**T, q profiles**	25km	200m	daily
C-7a-e (VI)	**T, q profiles**	50km	1km	daily
H-1a & *H-2a* (VI)	**near-surface T and q**	1-10km	--	6h

The requirements in Table 3-1 are notably broad, reflecting the diverse scientific objectives both within and across the interdisciplinary panels. The resolutions cover roughly 1-25 km horizontal resolution, 0.2-2 km vertical resolution, and 1-24 h temporal scales or longer (climatological statistics) for temperature and water vapor profiling, depending on the science or application question. It is also important to note that while temperature and water vapor profiles comprise the majority of the recommendations and PBL height is specifically cited for only two of these, it is understood that PBL height can generally be estimated given finely enough resolved temperature and/or water vapor profiles (e.g., 100-200m). That said, PBL height is a TO that can be derived in a number of ways, including from temperature and water vapor profiles/gradients, as well as from vertical gradients in aerosol backscatter, and GNSS-RO refractivity profiles.

The proposed measurement approaches to meet these requirements in ESAS 2017 range from hyperspectral IR and MW (some at high spatial resolution, also GEO and SmallSat concepts), GNSS-RO, lidar (backscatter), DIAL, temperature lidar (Raman), airborne, sonde, and ground observations. These represent a subset of the technologies considered and proposed in this white paper for PBL Incubation. In addition, there are new developments in technology, which were not identified in ESAS 2017, that are also discussed below in Chapter 8.

It should be noted that more broadly, ESAS 2017 cites the full suite of 'PBL-related' measurements to include three-dimensional (3D) temperature, water vapor, aerosol and trace gas (e.g., ozone) concentrations, as well as two-dimensional (2D; in the horizontal direction) PBL height, cloud liquid water path, cloud base, precipitation, and surface fluxes of water and energy. 3D horizontal wind vector measurements, which are part of the Atmospheric Winds TO, are also essential to understanding PBL processes. Whereas the Atmospheric Winds TO addresses 3D winds throughout the depth of the troposphere, the winds that are of greatest relevance to PBL processes can be considered more narrowly as 2D (horizontal) winds that increase in strength from those within the PBL surface layer (roughly the bottom tenth of the PBL; near surface) to those at PBL top. It is possible that observing one of these more limited classes of PBL-related winds at some places and some of the time (e.g., surface winds over oceans or PBL top winds) could be achieved at modest expense or even with technologies already under consideration.

Lastly, the objectives and PBL TO measurements recommended by ESAS 2017 above are used to derive respective SATMs in ESAS 2017. As mentioned, these are largely based upon the expertise and outreach of the respective interdisciplinary panels, as well as RFI input from the community. The present report, and the preliminary SATM presented in the science chapter, represent a superset of the ESAS 2017 recommendations insofar as they are based on the refinement of the ESAS 2017 recommendations based on the PBL Study Team expertise and outreach, including input from a workshop and a technology survey. The technology considered in the present report, to meet the proposed requirements, therefore maps directly to this report's science questions and measurement requirements summarized in the preliminary SATM included below.

4. PBL SCIENCE

4.1 PBL PHYSICS AND PBL REGIMES

At the heart of PBL physics are the critical interactions between PBL turbulence and mean thermodynamic (temperature and water vapor) vertical structure: the mean thermodynamic structure helps shape the PBL turbulence structure, while in turn PBL turbulence sets the mean thermodynamic structure. PBL turbulence is driven by two critical mechanisms: buoyancy production or consumption, and wind shear (which are source/sink terms in the turbulent kinetic energy equation). Buoyancy is a function of temperature, water vapor and cloud water, and from a thermodynamic perspective, the PBL manifests itself in the following essential and fairly distinct PBL types: convective (dry and cloudy) and stable (dry and cloudy).

The convective PBL is often well-mixed, which means that (moist conserved) thermodynamic properties such as water vapor and potential temperature (in the dry case) or liquid water potential temperature and total water (in the non-precipitating cloudy case) are fairly constant from near surface to the top of the PBL. Examples of well-mixed convective PBLs include the dry convective PBL and the stratocumulus-topped cloudy PBL. The dry convective PBL often occurs over land when and where the atmosphere is sufficiently dry (low values of water vapor) not to produce clouds, and can be quite deep (depending on the surface heat fluxes) – values of PBL height around 2 km or more are fairly common during the local afternoon over warm land surfaces. Figure 4-1 shows the potential temperature and water vapor profiles of a well-mixed dry convective PBL over land observed over flat terrain during summer. Figure 4-1 illustrates (i) the well-mixed nature of the potential temperature vertical profile within the PBL, (ii) the sharp inversion of potential temperature and water vapor at the top of the PBL, and (iii) the complex water vapor structures above the PBL highlighting the need to also observe the thermodynamic structure of the free atmosphere above the PBL.

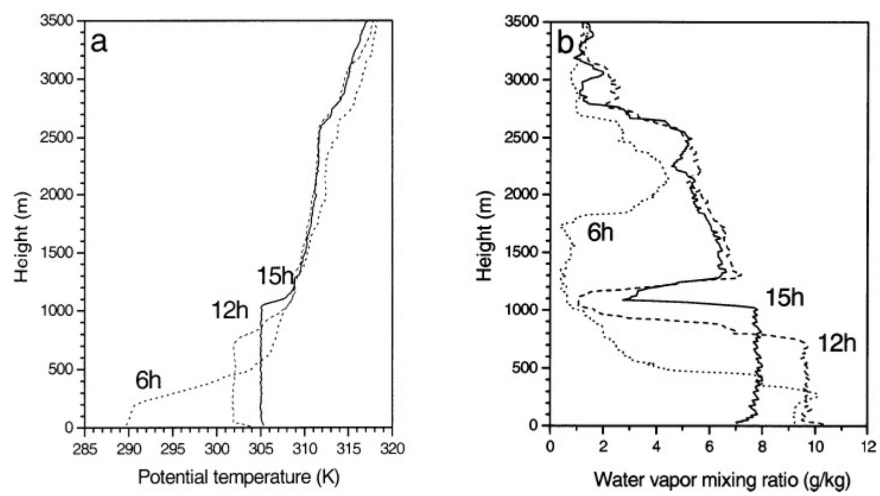

Figure 4-1. Example of dry convective PBL thermodynamic structures: Observed (a) potential temperature (K) and (b) water vapor mixing ratio (g kg-1) profiles from a field experiment in Southern Portugal during Northern Hemisphere (NH) summer at 6, 12 and 15 UTC. From Teixeira et al. (2004).

The convective cloudy PBL can take different forms but essentially can be divided into stratiform (e.g., stratus or stratocumulus) and shallow moist convective (e.g., cumulus) cloudy PBLs, and variants (combinations) of these types. Stratiform PBL clouds are often associated with large values of cloud cover which imply a stronger link with longwave and shortwave radiation. Moist convective PBL clouds are usually associated with smaller values of cloud cover (weaker radiation interactions) but often with stronger surface heat fluxes that lead to the plume-like structures characteristic of moist convection.

Figure 4-2 illustrates the evolution of observed potential temperature profiles along a transect from Los Angeles to Hawaii from sondes launched from a container ship during the MAGIC field experiment (Lewis and Teixeira 2015). As the PBL flows along the trade winds from California to Hawaii it experiences a fundamental change in its nature from well-mixed stratocumulus PBLs to moist convective cumulus PBLs.

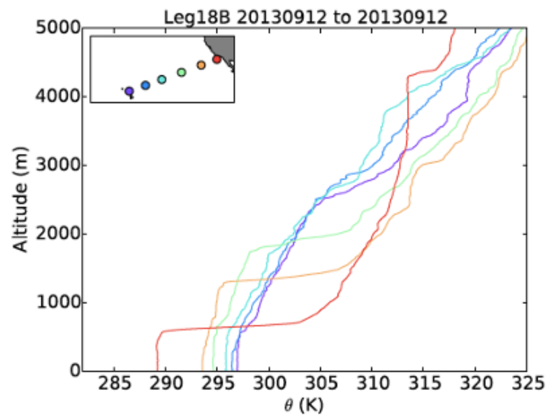

Figure 4-2. Example of potential temperature (K) structures during a (spatial) transition from a well-mixed stratocumulus-topped PBL close to California, through cumulus under stratocumulus, and finally to a cumulus PBL close to Hawaii. Observations from the DOE ARM MAGIC field experiment, leg 18B, September 2013 (Kalmus, personal communication).

Critical challenges in measuring the thermodynamic structure of the convective PBL (dry or cloudy) include resolving the often fairly sharp temperature and water vapor gradients (i.e., the PBL inversion) at the top of the PBL, and estimating PBL-top entrainment (which drives the mixing between the convective PBL and the free atmosphere above) and lateral entrainment (which controls the mixing between convective plumes and the surrounding environment within the PBL).

The stable PBL often occurs over land and ice/snow surfaces, such as during the night and winter, and over the ocean when warm air advects over colder water, often in oceanic coastal regions, in locations of strong ocean temperature gradients such as the western boundary currents, and in wind and pressure induced ocean upwelling areas in tropical cyclones. The stable PBL is typically much shallower (of order 100 m) than the convective PBL (of order 1000 m) with often strong temperature gradients close to the surface, and interacts much more strongly with the wind, in part due to the strong wind shear close to the surface. In this context, remotely measuring such structures, which are shallow (i.e., requiring particularly high vertical resolution) and so close to the surface, from a satellite is extremely challenging.

The PBL response to, and modulation of, the diurnal cycle of insolation is a particularly important manifestation of the key role of the PBL in interacting with the surface below and the atmosphere above. Figure 4-3 shows a schematic of the PBL diurnal cycle over dry land where the temporal evolution from a stable PBL during night to a growing convective PBL during the day and back to a stable PBL is depicted. This PBL diurnal cycle is critical for the vertical transport of atmospheric constituents that originate at the surface: during the night the vertical transport is hindered by the low PBL inversion and any atmospheric constituents originating at the surface will remain or increase close to the surface, while during day-time the growing convective PBL will lead to a stronger and more effective vertical transport of constituents not only through the PBL (as it is growing) but also across the PBL inversion through PBL-top entrainment.

When intense vertical transport covers the full troposphere, the PBL actively interacts with deep convection, mesoscale dynamics, and frontal systems, and can often be difficult to distinguish from the lower troposphere above the PBL. Under such conditions, the PBL thermodynamic structure is heavily influenced by the deeper convective flow associated with the complex interactions between mesoscale dynamics, turbulence and cloud microphysics. These phenomena associated with storm, mesoscale and larger-scale dynamics can interact quite strongly with the PBL thermodynamic structure in a variety of important ways and the PBL structure can often deviate from the more canonical PBL regimes discussed above.

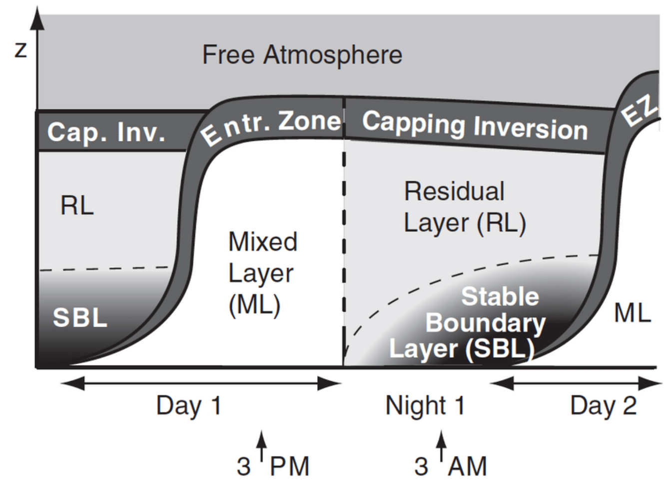

Figure 4-3. Schematic of the diurnal cycle of the dry PBL over land. From Stull (2000).

Over high-latitude regions, because of unique insolation and surface conditions (e.g., lack of a diurnal cycle during polar night over widespread sea ice), the PBL often manifests properties that are quite distinct from the prototypical PBL regimes of the tropical and mid-latitude regions. Over ice surfaces during polar night, for instance, the PBL is often extremely stable, such that cloud layers may fail to turbulently couple with the ultra-stable near-surface air despite robust cloud top radiative cooling.

Complex topography, in general, presents a further challenge at all latitudes, including the role of drainage flows, differential insolation, and relevance for PBL-modulated phenomena such as wildfire dynamics. For example, the Antarctic plateau is subject to well-known katabatic winds. The diversity that we already know exists in terms of PBL thermodynamic structure associated with more complex large-scale and mesoscale atmospheric three-dimensional flow and with extreme thermodynamic conditions highlights the fact that much more is still to be discovered about the PBL thermodynamic structure in the under-explored regions of the Earth.

Besides the PBL's tight coupling with the free atmosphere above, its tight coupling with the (land, ocean, ice) surfaces also suggests that space-borne surface or near-surface measurements (e.g., land and ocean surface temperatures, ocean surface wind stress) can be very helpful to constrain spaceborne measurements of PBL temperature and water vapor structure.

As discussed before, the PBL Study Team organized a NASA PBL Incubation Workshop to communicate and summarize the work and the charter of the Study Team, and to collect input from the PBL science, technology and applications communities. The science presentations and discussion during the Workshop provide a more detailed depiction of PBL physics pertaining to specific regimes and emerging science challenges. The remainder of this section 4.1 provides a summary of the PBL science sessions.

PBL and Deep Convection

The overall guiding question of the PBL and deep convection session was about how the PBL and deep convection interact over land, coastal regions, and open oceans, including phenomena as diverse as cold pools, the diurnal cycle, land and sea breezes, mesoscale synoptic phenomena such as tropical cyclones and winter storms, and sub-seasonal variability such as equatorial waves and the Madden-Julian Oscillation (MJO). The presentations and discussion focused on key theoretical questions, observational gaps (e.g., surface-based, airborne, satellite) and model deficiencies. In the context of observations, topics of discussion included how to characterize the PBL structure, simultaneous observations of convective and PBL processes and the limitations of existing data sets (ground based, airborne, satellite).

To improve the representation of moist convection in weather and climate models there is a need to increase the emphasis on PBL physics and its coupling with deep convection. In this context, there is a critical need to understand if, and in what circumstances, cold pools promote or inhibit new convection. What observations are required to better understand the physics of cold pools is still an open question, but what is well-accepted is the notion that the community needs to move beyond the case study stage and accumulate useful statistics on cold pool physics and the interaction between the PBL and deep convection.

<u>*PBL over the Ocean and Air-Sea Interaction*</u>

The marine PBL covers roughly 70% of the Earth's surface and its interaction with the air-sea interface affects momentum, temperature, water vapor, other gases and particle exchanges, all of which have direct impact on the global weather and climate. Unfortunately, a critical problem is that the marine PBL is data sparse. Cloud-climate feedback was highlighted as a fundamental motivation for additional observations of the cloudy PBL over the ocean. In this context, the stratocumulus to cumulus transition is key to better understand cloud-climate feedback. Critical physical processes were discussed and in particular (i) the coupling of clouds to the ocean surface and (ii) the potential key role of the mesoscale (e.g., cold pools) were highlighted as essential to understand. Recent discoveries of the existence and prevalence of multi-layered cloudy PBLs over the ocean - due to a variety of processes including the influence of land (even fairly far away from the coast) and mesoscale circulations - reiterates the need for global PBL observations to better characterize the mesoscale and potentially for additional discoveries regarding PBL structure and regime diversity all over the globe.

There are many challenges in observing and modeling the marine PBL. The moving water surface makes it difficult to define the roughness sublayer, especially in high wind conditions. The surface layer, PBL, and the cloud layer are determined by multi-scale atmosphere and ocean circulations. The current observing capability is not able to capture the variability of the marine PBL.

In the context of current PBL observations from space, even integral cloudy PBL properties such as PBL height and liquid water path (LWP) are presently not measured from space with the necessary accuracy. In this context, GNSS RO, in spite of its sampling and horizontal resolution issues, is a current satellite data set with the potential to provide PBL thermodynamic profile measurements from space with the necessary vertical resolution, and more studies should be performed to better use GNSS RO PBL data. The scientific potential of the wealth of current field campaign data and the well-known fact that weather and climate models are not able to represent realistically the cloudy PBL thermodynamic structure are important to highlight. Key science questions include: (i) How do PBL clouds relate to the vertical PBL thermodynamic structure? and (ii) what aspects of thermodynamic structure and turbulent dynamics are necessary for driving mesoscale circulations and shallow convective cloud organization in the marine PBL?

Regarding air-sea interaction, a critical issue is the fact that the coupling between the PBL and the ocean boundary is fundamentally different at different scales, and that we are only now starting to explore air-sea interaction at smaller scales from a global perspective. In this context, being able to measure air-sea interaction at horizontal scales that could sample the horizontal heterogeneity due to ocean mesoscale phenomena is perceived as critical. Since current observations show that different types of PBL thermodynamic vertical structure are associated with different regions (different SSTs) within these ocean mesoscale structures, measurements of the horizontal variability of the ocean surface need to be associated with measurements of the PBL vertical structure with sufficiently high vertical resolution. Crucial aspects of air-sea interaction related to the PBL include the SST diurnal cycle and ocean surface waves. A key but often neglected fact is that stable PBLs are at places quite prevalent over the ocean, particularly near the coast and are often associated with fog. Atmospheric mesoscale phenomena at a variety of scales, such as cold pools or hurricanes, have been shown to play critical roles in air-sea interaction. The severe lack of surface-based PBL observations over the ocean is a critical impediment for the development of better understanding and parameterization of air-sea interaction in the context of the PBL. Although new ideas about locally observing supersites, and of exploring links with offshore wind energy sites are promising, the global nature of space-based observations of both air-sea properties and of PBL thermodynamic structure is perceived as critical.

PBL over Land and Surface Interaction

Critical science questions are related to the structure of the PBL over land, the coupling between the carbon cycle and meteorological processes, the nature of land-atmosphere (L-A) coupling and L-A feedbacks. The measurements needed to address these science questions, the role and impact of land surface heterogeneity, and how these evolve with a changing climate are additional key topics.

The structure of the PBL over land was characterized as very heterogeneous in space and time, with transitions that are not well understood. To properly observe this structure and improve model capabilities, it is necessary to have measurements of PBL height (PBLH), co-located profiles of temperature and water vapor, and winds, surface roughness and cloud properties. Since PBLs are seldom stationary and homogeneous, temporal and spatial information is important. Ideally, PBL height should be derived from direct observations of vertical profiles of turbulent quantities, as these would provide estimates of the turbulent layers present, but these are only available at a few locations. In practice, a multitude of methods are applied on vertical profiles of temperature, water vapor, refractivity, cloud or aerosol properties, to estimate PBL height from observations.

Diurnal L-A interactions are considered in the context of the Amazonian rainforest-cloud system with a focus on understanding the energy, water/cloud and carbon cycles at the sub-daily and sub-km scales. The importance of the coupling between biochemical and physical processes has been addressed using LES, observations and other modeling approaches. It has been shown that the diurnal cycle of carbon fluxes is asymmetric, and that this asymmetry is not well captured by the models, in large part due to lack of observations. In this regard, LES results were comparable to results from a global model. Another important process related to the exchange of carbon between the PBL and the free atmosphere, is the transition from shallow to deep convection. Observations at cloud base are critical for process understanding and comparisons to LES and global models results. These processes are well simulated by LES but not by global models, allowing LES results to be used in lieu of missing observations.

The tight coupling of the land-atmosphere on monthly and diurnal scales is demonstrated with results from long-term observational records in the Canadian Prairies. Relationships among surface and meteorological variables such as relative humidity, temperature, cloud cover, radiation, snow cover, wind, and precipitation have been established (Betts et al. 2018). The representation of these relationships in coupled models could all be significantly improved with additional, diurnally resolved, global observations of L-A variables. Some of these observations can be obtained from satellite and reanalysis datasets, such as precipitation (GPM), advection (reanalysis), soil moisture (SMAP), and terrestrial water storage (GRACE), but distinctly lacking are observations of the PBL thermodynamic structure.

Of particular value to understanding L-A feedbacks, the application of metrics to assess them, and the development of accurate models to describe them, are observations of the diurnal cycle of the PBL, as well as surface skin temperature. What is distinctly lacking from the existing suite of observations is information on the PBL and its evolution that links the land surface and the atmosphere together. For example, improved profiles of temperature and water vapor in the PBL would enable improved estimates of surface evaporation (which is currently a challenge to obtain from space). Surface roughness (momentum, heat) and surface drag are also critical elements driving surface fluxes and the connection of the land and PBL. Near-surface wind observations are therefore needed across a range of scales to improve these components in coupled models. Overall, improvements in the understanding of PBL processes and in forecast models will come from multi-variate relationships, which require co-located (space and time) measurements of key variables driving the coupled system.

High-latitude PBL

This session emphasized unique aspects of polar PBLs, with a stronger emphasis on Arctic conditions owing to orders of magnitude greater availability of observations than over the Antarctic. The vertical structure and thermodynamics of polar PBLs are generally shaped by two leading factors: unique surface conditions (often frozen water, snow, ice, or both) and an absent or muted diurnal cycle of solar radiation (no guarantee of daily mixing) within the context of a strong annual cycle. Owing to commonly weak insolation and surface forcing over ice surfaces, longwave radiative fluxes often dominate the surface energy budget. Although the polar atmosphere is dry in absolute terms, cooling leads to commonly high relative humidity. Barriers to efficient ice nucleation also contribute to the commonality of persistent supercooled cloud layers and strong top-down cloud forcing. Once initiated, a supercooled cloud generally begets more supercooled cloud water via efficient radiative cooling, in a positive feedback loop that weak ice nucleation generally fails to deter. Persistent supercooled clouds commonly replace efficient surface longwave cooling (of a very dry atmosphere in absolute terms) with surface longwave heating, leading to rapid surface warming, followed by equally rapid surface cooling once cloud layers are advected or otherwise dissipated (e.g., via large-scale descent). If the surface cannot be sufficiently warmed, a decoupled state may persist wherein an actively turbulent cloud-topped layer overlies a highly stable near-surface cloud-free layer. Ice clouds are less important radiatively owing primarily to lesser opacity associated ultimately with microphysical characteristics.

Where open water is present, Arctic cold air outbreaks (CAOs) are characterized by frigid air advecting over relatively warm ocean water in patterns that commonly persist for several days. CAOs exhibit combined latent and sensible heat fluxes reaching the highest values on Earth owing to huge air-sea differentials in both temperature and water vapor, along with high wind speeds. Cold-air outbreak PBLs are initially well mixed owing to strong buoyancy and shear driven turbulence. PBL height increases rapidly with fetch from the originating ice surfaces, leading to closed-cell stratocumulus with high liquid water paths and resulting supercooled drizzle, as well as active ice precipitation. Despite contributions to mixing from efficient cloud top cooling, the continuous deepening of the PBL and the stabilizing role of precipitation processes may give way to open cell or cumulus conditions at great fetch. Like mid-latitude cold-air outbreaks, horizontal wind shear leads to pronounced PBL roll structures with embedded cloud streets that tend to broaden with increasing fetch. Polar lows are commonly found under CAO-adjacent conditions, associated with poorly understood coupling of dynamical and microphysical processes under persistently mixed-phase conditions over (relatively) warm water.

The session closed with attention to regional challenges in defining the polar "PBL". Is it only the turbulent layer nearest the surface, or should it include near-surface overlying layers that are also turbulent (driven by cloud top cooling) and are also commonly much deeper but are not dynamically coupled to a shallow ultra-stable surface layer? By extension, a pronounced capping (temperature) inversion would certainly be associated with such a decoupled and near-surface cloud layer, but a water vapor inversion would also be expected (moister rather than drier overlying air), in stark contrast to subtropical stratocumulus conditions. Furthermore, multiple such layers one atop the other are common over both poles, and a sizable fraction of such layers exist in a non-turbulent state at any one time. Such contrasts to lower latitude PBL structure can be expected to have important implications for assumptions in retrieval algorithms or observational strategies that relate relatively coarsely resolved thermodynamic profiles with relatively better observed shallow cloud top heights, for instance.

Since the Arctic is among the fastest changing regions on Earth in a manner that is closely related to PBL processes, and the Antarctic is among the least observed, such regional characteristics merit dedicated consideration in PBL mission planning and motivation. Perhaps a key question is how well are models performing over polar regions, given a general paucity of observations? How well do models represent the particular physics of air mass transformations between polar and lower latitudes, which appear uniquely related to transitions in surface properties and the evolution of lower tropospheric thermodynamic structure? How can we effectively cast the unique physics of the mid-to-lower polar troposphere and its coupling to the surface, which deviates in these fundamental ways from lower latitude canonical PBL concepts and often in a manner that is dominated more by clouds than strictly by surface processes?

The following four sections of this chapter discuss in detail the PBL science goals (as stated in the preliminary SATM) and the science questions associated with each goal. These detailed discussions are summarized in the preliminary SATM in section 4.6.

4.2 PBL, CONVECTION AND EXTREME WEATHER

The interaction between the PBL and deep convection is one of the key open topics of research in PBL and moist convection physics in the atmosphere. The strong interactions between the PBL and deep convection manifest themselves, and play a key role, in phenomena as diverse as cold pools, the diurnal cycle of precipitation, thunderstorms, squall lines, land and sea breezes, and synoptic scale storms such as tropical cyclones and winter storms. A notable aspect of the convective environment is the fact that during intense deep convection and storm conditions, the PBL thermodynamic structure is often complex and, in many cases, the PBL itself does not actually have a well-defined identity. This fact does not imply that the PBL is unimportant to convection. On the contrary, the PBL plays a fundamental role in determining updraft buoyancy, regulating surface fluxes, and modulating the organization of storms. Recent observations have shown that the complex interactions between deep convection, surface fluxes, and the PBL vary on time scales from hours to sub-seasonal and beyond (e.g., Chen et al. 2016).

The PBL and deep convection interact in several critical ways. On the one hand, deep convective plumes usually grow out of the PBL carrying with them PBL thermodynamic properties. On the other hand, downdrafts from deep convection can significantly alter the PBL and surface fluxes. In this context, a key question is what changes in the PBL precede the onset of deep convection? Once deep convection is active, understanding the mechanisms, particularly PBL processes, that modulate the duration of convective systems is critical to understand and to be able to represent the PBL and deep convection in a more realistic manner in weather and climate prediction models.

An important aspect is to understand how and when the PBL "forces" deep convection. Specifically, deep convection converts Convective Available Potential Energy (CAPE) into convective kinetic energy and continuing convection is dependent on an ongoing re-supply of CAPE. This line of thought gave rise to what can be referred to as the "forcing and response" paradigm, which in its simplest form means that forcing and response just balance each other. This is often referred to as the "Quasi-Equilibrium" hypothesis (Arakawa and Schubert, 1974). A particular perspective in this context is that the PBL forcing exerts a powerful influence on CAPE since what happens in the PBL affects an updraft's buoyancy at all levels.

The parameterization of PBL heterogeneity, and its interaction with deep convection, along with mesoscale organization are major challenges to the traditional assumptions upon which parameterizations are based. Issues associated with the coupling between PBL, shallow and deep convection parameterizations may be best solved by the unification of the PBL and convection parameterizations. The fact that over the last few years LES models are now being used to simulate deep convection has dramatically changed the ability to investigate in detail the interactions between the PBL and deep convection. However, LES studies of deep convection suffer from the fundamental issue that microphysics, which significantly affects simulations, is highly parameterized. LES studies can only cover a few regimes and because of computational limitations LES domains are not yet large enough to resolve mesoscale phenomena in a reliable manner. These limitations point to the need for global-scale PBL observations that are likely only possible from satellites.

The mesoscale plays a central role in many aspects of PBL-convection interaction. Mesoscale variability of water vapor within the PBL and surface flux variability appear to be an important control on the timing of deep convection organization. Such variability is modulated by variable surface fluxes and plays an important role in land-atmosphere interactions. Within an active storm environment, the organization of the PBL on the mesoscale can take many forms depending on the storm type (e.g., from ordinary convection to supercells to squall lines to tropical cyclones). As a result, there is a large diversity of spatial and temporal scales that need to be simultaneously observed to quantify the interactions between PBL mesoscale variability and deep convection. In addition, the strong non-linear feedbacks between physical processes and scales make all these interactions difficult to deconvolve.

At least three major observational gaps must be addressed to advance our knowledge of the interactions between the PBL and deep convection from a global perspective: (1) the convective environment is often heavily clouded necessitating advances in remote sensing techniques that leverage the microwave spectrum; (2) Measurements with high horizontal resolution (~1 km) are necessary to characterize thermodynamic variability that occurs on the mesoscale; (3) high vertical resolution is necessary to resolve the signatures of mixing between the PBL and the free troposphere above.

While there is a large set of in-situ (surface-based, airborne) observations of the PBL thermodynamic structure and its close interactions with deep convection that has been, and should continue to be, explored in more detail, there is a clear lack of a global observational perspective that is only achievable from space.

Q1.1: What is the role of mesoscale variability (e.g., cold pools, aggregation) in the interactions between PBL and convection?

It is well-known that convection tends to aggregate into organized clusters on the mesoscale. This tendency to aggregate may play a key role in the upscale growth of shallow to deep convection (Kuang and Bretherton, 2006). One form of aggregated convection, Mesoscale Convective Systems (MCSs) are responsible for a large percentage of precipitation in the tropics (Roca et al. 2014) and the summertime midlatitude continents (Haberlie and Ashley 2019). They are additionally responsible for a great deal of extreme weather including lightning, hail, tornadoes, and damaging winds. It has recently been suggested that convection will increase its tendency towards aggregation in a warming climate (Wing and Emanuel 2014), which may act as a negative climate feedback (Mauritsen et al. 2015). While the existence and importance of convective aggregation is well established, the precise physical mechanisms responsible for organization and in particular the role of the PBL is not well established. An obvious reason that these connections have remained elusive is that the PBL thermodynamic structure is poorly observed, particularly in the presence of storms. The observational challenge is highlighted by cold pools which result from evaporation of precipitation within the PBL, an environment that is particularly challenging for many remote sensing methodologies.

It has been known for several decades that cold pools are intrinsically related to strong deep convection events (Weaver and Nelson 1982). Cold pools play an important role in organizing intense convective storms such as mesoscale convective storms (Johnson and Hamilton 1988) and squall lines (Rottuno et al. 1988). Recently it has become apparent that cold pools are also associated with a variety of other types of precipitating convection, including drizzling stratocumulus (Terai and Wood 2013), shallow convection (Zuidema et al. 2012), and the shallow to deep convection transition (Tompkins 2001). Cold pools in drizzling stratocumulus can affect cloud break up and the formation of pockets of open cells, while for deep convection they can significantly enhance its organization, vertical development, wind gustiness and precipitation. Despite the important role in the development of deep convection, and in spite of some recent studies, the physics of cold pools has often been neglected in convection parameterizations of weather and climate models (e.g., Suselj et al. 2019).

Addressing the question of mesoscale PBL variability and convection necessitates both (i) improved horizontal resolution, compared to that offered by the program of record, and (ii) improved sampling within cloudy and precipitating conditions.

Q1.2: How does the thermodynamic structure of the PBL and lower troposphere foster a transition to deep convection?

Deep convection often has its roots in the PBL, and the PBL interacts with deep convection on various time-scales from the diurnal cycle to regime changes spanning days to months where shallow convective regimes evolve into deep convection. The transition from shallow-to-deep convection is tied to changes in the thermodynamic structure of the PBL and lower free-troposphere that promote instability within the atmospheric column. Several processes play a role in modulating the lower tropospheric thermodynamics including low-level convergence, surface fluxes, convective and turbulent mixing, and cloud radiative effects. The potential for deep convection is also related to the vertical wind structure of the PBL, local topography, and transient dynamical disturbances. Understanding the relative roles and interactions of various processes in the PBL in the initiation of deep convection is required for progress on this critical unresolved science question. For example, it has been suggested that shallow cumulus act to gradually moisten the lower free-troposphere thereby preconditioning the atmosphere for the success of subsequent convective plumes to become deep (Waite and Khouider 2010). While there is no question that a moister lower troposphere is more conducive to convection, there is active debate on the relative magnitude of local moistening and low-level convergence in the moistening process in real world convection (Hohenegger and Stevens 2013; Bellenger et al. 2015). Each process influencing deep convective transition has different time scales and the relative roles of each process varies by region and regime. Failure to make progress on this topic manifests itself in important ways in model biases such as the common inability to produce the correct diurnal cycle of precipitation (Collier and Bowman 2004) and the transitions to deep convection-dominated weather states over the diversity of global regimes. The key measurement requirements for addressing these science questions are the ability to measure vertically resolved temperature and water vapor perturbations within the PBL and lower free-troposphere, and mesoscale variability in bulk PBL thermodynamic properties.

Q1.3: What is the role of PBL and surface processes in the diurnal cycle of precipitation?

Many land areas show a peak of precipitation in the afternoon, while some areas, such as the Southern Great Plains, show a nocturnal peak. The timing of precipitation is important to the net radiation available to drive evaporation and so to the overall water cycle. The response to surface turbulent fluxes has been shown to have large influence on the timing of precipitation, particularly in convective regimes and transitional moisture regimes such as over the U.S. Southern Great Plains. The PBL thermodynamic structure also affects the timing and amount of precipitation because it modulates the convective stability (e.g., CAPE, Convective Inhibition (CIN)), and its interactions with the surface and feedbacks that govern whether the PBL height is high enough for a surface parcel of air to reach the critical level required for condensation and convection (i.e., Lifting Condensation Level (LCL), Level of Free Convection (LFC)). In addition, for nocturnal precipitation, the nighttime residual layer of the (much deeper) daytime PBL is important. The inability to accurately represent the diurnal cycle of precipitation over land is a well-documented weakness in weather and climate models, and reanalysis products (Collier and Bowman 2004). The aggregation of PBL water vapor in the pre-convective environment is seen as a critical component of the timing of deep convection (Stirling and Petch 2004; Wulfmeyer et al. 2006). These variations in water vapor over convective continental environments are primarily driven by variability below 2 km on the mesoscale (Couvreux et al. 2009). Oceanic precipitation also shows diurnal variability associated with both cloud top cooling processes and diurnal sea surface temperature impacts on surface fluxes (Demott et al. 2015). Over the ocean the dominant mode occurs in the early morning hours, related to cloud top radiation processes, but under low-wind conditions when diurnal warming of the sea surface temperature can be strong, the surface fluxes can drive a response closer to the precipitation timing over land with higher values in the early afternoon. The impact on clouds and precipitation over the ocean is also quite dependent on surface inhomogeneities in sea surface temperature and roughness. As with the land precipitation, the causes and impacts of the ocean precipitation diurnal cycle remain poorly understood. Thus, advances in monitoring PBL profiles, PBL height, and the land surface are required on these diurnal (sub-daily) timescales in order to provide process-level understanding and predictive improvement.

4.3 CLOUDY PBL

The cloudy PBL is notoriously difficult to model by weather and climate prediction systems and, as discussed above, plays a fundamental role in cloud-climate feedbacks and as such is critical to improve climate projections. There are several different key types of cloudy PBL, including (i) over land, ocean and ice surfaces, (ii) associated with stable PBLs (e.g., fog and low stratus clouds), (iii) convectively well-mixed or decoupled cloudy PBLs with stratiform clouds (e.g., stratocumulus), and (iv) conditionally unstable (shallow moist convective) cloudy PBLs (e.g., cumulus).

Although these partitions are important and useful from theoretical and modeling perspectives, the incredible variability of the Earth's atmosphere as a whole, leads to numerous variants of these types of cloudy PBL and even significantly different types (such as over the high-latitudes). Much of the knowledge that has been accumulated over the recent decades about the detailed thermodynamic structure of the PBL has been obtained from (i) local surface stations (e.g., DOE ARM and others essentially over land); (ii) spatially localized field experiments, and (iii) spatially localized Large Eddy Simulation (LES) numerical experiments. Although numerous, these information sources can only provide a relatively modest depiction of the Earth's PBL in terms of its large diversity (e.g., over the largely unexplored regions of the Earth like the oceans). In fact, none of these data sources is able to provide a global perspective that is only possible with satellite observations.

A significant underestimation of PBL clouds off the west coast of continents (i.e., stratocumulus upwelling regions) has been a long-standing problem in climate models (e.g., Siebesma et al. 2004; Teixeira et al. 2011) that has an enormous impact on the simulation of the Earth's climate. These PBL cloud biases have critical consequences in terms of SST and radiative fluxes at the ocean surface and top of the atmosphere (TOA) with critical impacts on cloud-climate feedbacks. Figure 4-4 shows the differences in TOA shortwave (SW) cloud forcing (annual long-term mean) between the latest NCAR atmospheric model version (CAM6) and the CERES satellite observations (Neale et al. 2021). This figure is an illustrative example from a state-of-the-art climate model - that recently has undergone substantial modifications in order to improve its simulation of the PBL in general and of the cloudy PBL in particular - that clearly shows significant biases off the west coast of continents, in particular off California, North Africa and Angola/Namibia. These radiative flux biases are due to insufficient cloud cover and water in these stratocumulus regions. These cloud biases are common in weather and climate models and often extend deep into the subtropics (sometimes reversing sign) illustrating well the connection between stratocumulus and the overall physics of the subtropical PBL, namely the transition from stratocumulus to cumulus PBLs (e.g., Siebesma et al. 2004; Teixeira et al. 2011).

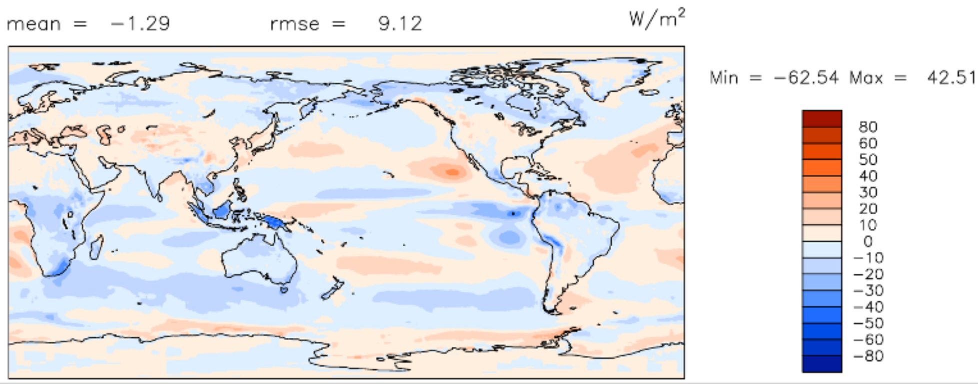

Figure 4-4. Differences in TOA shortwave (SW) cloud forcing (Wm^{-2}), annual long-term mean, between the latest NCAR atmospheric model (CAM6) and the CERES observations. From Neale et al. (2021).

To first order, PBL clouds are essentially determined by the PBL temperature and water vapor vertical structure – clouds form where and when the water vapor barely exceeds its saturation value (which is a function of temperature and pressure), meaning that small errors in temperature and water vapor can easily lead to large errors in cloud cover and liquid/ice water. In this context, it is well known that the stratocumulus biases discussed above are often related to biases in PBL temperature and water vapor vertical structure – a clear example is when a particular model significantly underestimates the PBL height leading to unrealistically thin clouds or no cloud at all. Significant biases in PBL height are common in weather and climate models and even in reanalyses (e.g., Kalmus et al. 2015). Making the problem more challenging is the fact that the clouds themselves significantly impact the PBL thermodynamic structure through their interactions with both shortwave and longwave radiation. A canonical example of this coupling is the important role that longwave cooling, at stratocumulus cloud tops, plays in maintaining the turbulent structure of the PBL. This two-way coupling of clouds with the temperature and water vapor profiles is an essential feature of all cloudy PBLs.

Improvements in the simulation of the cloudy PBL clearly require improved simulation of the PBL temperature and water vapor vertical structures, and for that, improved observations of the PBL thermodynamic structure are necessary from a global perspective. As mentioned, the temperature and water vapor vertical structure of the cloudy PBL is often characterized by sharp vertical gradients of temperature and water vapor at the top of the PBL, that require vertical resolutions of the order of 100 m.

Figure 4-2 in section 4.1 shows the evolution of observed potential temperature profiles along a transect from Los Angeles to Hawaii as the PBL transitions from well-mixed stratocumulus to conditionally unstable cumulus. This is a prototypical cloud transition (from large values of cloud cover to low values) that encapsulates several of the key mechanisms that are responsible for PBL cloud transitions in other regions of the globe. Cloud transitions such as these from stratocumulus to cumulus are likely to play a fundamental role in the overall issue of cloud-climate feedbacks. In this context, it is absolutely essential to answer the question: what are the key mechanisms behind the cloud transition from stratocumulus to cumulus?

It is critical however, to understand that this question can be approached from two very different spatial-temporal scales: (i) the small turbulent scales (order 1-100 m) associated with cloud-top entrainment and with the mixing mechanisms that ultimately lead to the demise of a specific cloud, and (ii) the large (meso) scales (order 10-1000 km) that determine the cloud transition from a climatological perspective. The 'small-scale' question has been addressed essentially using LES models and some field experiments since it requires high-resolution data (e.g., Wyant et al. 1997, Bretherton et al. 1999, Chung et al. 2012). The 'large-scale' question has been addressed using climatological data from a global perspective (e.g., Klein and Hartman 1993, Wood and Bretherton 2006). However, since there really are no reliable observations of PBL vertical temperature and water vapor structure from a global perspective (i.e., with sufficient vertical resolution and accuracy), the 'large-scale' question has never been properly addressed from an observational perspective. New space-based PBL observations that would be able to provide a large-scale view of fields such as cloud cover and LWP while also measuring the temperature and water vapor vertical structure with sufficiently high vertical resolution (required for theories such as Cloud Top Entrainment instability CTEI and others) would help address the 'large-scale' question of what mechanisms are behind cloud transitions in a definitive manner.

Much of the cloudy PBL research (and observations) over the last couple of decades has been focused (with some recent important exceptions) on specific regions of the Earth like the subtropics where stratocumulus and cumulus are prevalent and play a fundamental role in cloud-climate feedbacks. In addition, much of the theoretical and parameterization development has been rather local in its focus (e.g., simulations with LES models of only a fairly limited number of cases). Although these have been fruitful, there is a need for more concerted research on cloudy PBLs outside the subtropics (e.g., shallow convection over land, polar clouds, clouds over the Southern Ocean, fog). A global coverage of cloudy PBL thermodynamic profiles is required to undertake this endeavor in a consistent manner.

Investigating the potentially critical influence of mesoscale circulations - associated with dynamics, cloud microphysics, and aerosols – on the cloudy PBL would also require a large-scale observational perspective. For all the reasons mentioned above, a global PBL observational system that would optimally combine simultaneous high vertical resolution measurements of temperature and water vapor structure with measurements of the large-scale fields of cloud related properties would be able to address key science questions in a manner never attempted before. In addition, this new global PBL observational system would allow to explore and potentially discover new types, or variants, of cloudy PBLs in the unexplored regions of the Earth.

Key science questions regarding the cloudy PBL that naturally follow from the workshop and from this discussion are the following:

Q2.1: How do the PBL thermodynamic structure and cloud properties covary and interact with each other, and how does it depend on cloud type?

As mentioned, it has long been apparent that global weather and climate models do not represent the physics governing PBL clouds appropriately. However, it remains unclear exactly why models are failing in this regard. Our knowledge comes largely from LES models and localized field experiments.

It is clear that temperature and water vapor structure determine cloud structure. In turn, cloud properties also determine temperature and water vapor structure through their effect on radiative fluxes, condensation, evaporation and microphysics. A clear example of this interaction is the transition from largely cloud-covered stratocumulus PBLs to the scattered cloud cover of cumulus PBLs. While the change in cloud cover between these regimes can be rather dramatic visually, the transitions themselves are often manifested in rather subtle changes to the temperature and water vapor profiles. Further complicating these interactions is the role of cloud microphysics which can influence both the radiative heating of the PBL and influence thermodynamics by modulating the formation of precipitation and associated cold pools.

To properly diagnose the causes of model biases and to establish physical relations between PBL thermodynamic structure and cloud properties, coincident measurements of PBL temperature and water vapor profiles, and cloud properties over a diversity of real-world meteorological regimes are required.

In this context, temperature and water vapor profiles with high vertical resolution of 100-200 m in clear and cloudy conditions are required. These high vertical resolution observations should be complemented with PBL temperature and water vapor information at lower vertical resolutions but at high horizontal resolutions of order 1 km to provide three-dimensional context to the high vertical resolution observations. These observations should be coincident with observations of large and meso-scale cloud properties and radiative fluxes from synergistic measurements from the program of record (POR).

Q2.2: How are these PBL-cloud interactions mediated by turbulent surface fluxes and overlying free tropospheric thermodynamic conditions?

It is crucial to perform measurements of the PBL thermodynamic structure as well as of the surface properties and of the free troposphere that are as simultaneous as possible. The PBL vertical structure is determined by the forcing at its boundaries: the surface interface and the PBL top interface. Important examples in the context of the cloudy PBL include the role of tropospheric temperature and water vapor in PBL-top entrainment and relations similar to lower tropospheric stability LTS-cloud relations, and the role of surface heat fluxes in determining the thermodynamic structure of stratocumulus, cumulus and the transition between them.

Most of the required PBL observations that currently exist are from field campaigns or single surface stations. Given the sparsity of these observations from a global perspective, a critical sampling question regarding PBL observations is: how representative are these particular observations of the PBL over the rest of the world? In addition, all of these observations have temporal and spatial scale limitations. A global perspective from space that would provide observations of the cloudy PBL thermodynamic structure together with observations of the surface and free troposphere is critical.

To achieve these objectives, temperature and water vapor profiles (within the PBL and in the free troposphere) in clear and cloudy conditions, with measurement requirements similar to the ones for Q2.1 are necessary. In addition to the requirements for Q2.1, these observations should be coincident with observations of surface properties, in particular surface energy and water fluxes, from synergistic measurements from the program of record (POR).

Q2.3: What is the role of mesoscale variability in modulating the vertical structure of the cloudy PBL temperature and water vapor?

From current satellite observations it is quite clear that PBL clouds show a strong mesoscale morphology. A critical question in the context of the cloudy PBL is: how does the mesoscale modulate the vertical thermodynamic structure of the cloudy PBL? There are several clues from observations and models that the mesoscale can play particularly important roles in the stratocumulus and cumulus cloudy PBL structure. For example, stratocumulus is typically organized in clusters of closed or open mesoscale convective cells. Field experiments and LES models suggest that the open cellular structure is associated with narrow bands of precipitation which further produce cold pools that help organize and sustain the open cellular structure. In a similar manner, clusters of shallow cumulus convection can form over both ocean and land surfaces, and satellite imagery clearly suggest that lines of cumulus form at outflow boundaries associated with cold pools, over orography, or over perturbed land where surface fluxes differ from the surrounding natural environment. Despite the fact that mesoscale organization is ubiquitous in the PBL and that it can be associated with internal processes such as precipitation or external forcing such as variable surface or large-scale forcing, it is unclear to what extent this variability interacts with the PBL thermodynamic structure. Assessing these relationships requires widespread observations from space of temperature and water vapor with the appropriate vertical resolution. Atmospheric scales associated with variability in land surface conditions including vegetation and orography also play a key role in PBL structure but clearly require large (global) observational scales only possible from space. Similarly, PBL variability associated with oceanic mesoscales and the associated surface flux variability is an active area of research that remains extremely data limited, also requiring both high resolution and large observational scales.

Temperature and water vapor profiles (within the PBL and in the free troposphere) in clear and cloudy conditions with measurement requirements similar to Q2.1 are necessary. In particular, temperature and water vapor information at high horizontal resolutions of order 1 km covering large domains (of order 100 km or larger) are necessary to judiciously investigate the role of the mesoscale. Coincident observations of cloud and surface properties at these scales, from synergistic measurements from the program of record (POR), are critical.

4.4 PBL AND SURFACE INTERACTION

4.4.1 OCEAN SURFACE

Over the last couple of decades there has been significant progress in terms of the parameterization of surface turbulent fluxes based on expanded surface-based observations (e.g., Edson et al. 2013). Although there has been progress in satellite-based observations of the atmosphere-ocean turbulent exchanges of heat, water, and momentum, much remains to done in this respect (Tomita et al. 2019; Liman et al. 2018; Roberts et al. 2019; Robertson et al. 2020). In this context, the fact that the coupling between the PBL and the ocean boundary is fundamentally different at different scales is a critical science topic that urgently requires further investigation from a global perspective.

Unlike the PBL over land that is dominated by a strong diurnal forcing, the marine PBL is highly variable over a wide range of temporal and spatial scales, including the diurnal. The physical processes at the air-sea interface in various wind regimes and processes driving clouds at the top of the PBL are not well understood and are difficult to observe. Over the years, many field campaigns (e.g., CBLAST 2003-04, RAINEX 2005, ITOP 2010, DYNAMO 2011, GLAD 2012, LASER 2016, CPEX 2017) have observed diverse conditions over the tropical ocean and the coastal marine environment that modulate and drive weather systems including the Madden-Julian Oscillation (MJO), tropical cyclones, and winter storms. Both in situ and remote sensing airborne data in the context of coupled atmosphere-wave-ocean modeling are used to document the complex PBL structure, e.g., the asymmetry induced by sea state/waves (Lee and Chen 2012) and the stable PBL over the cold wake in tropical cyclones (Lee and Chen 2014). For example, observations from the ITOP field campaign show that all three types of PBL, from near neutral to stable and unstable, can co-exist in Typhoon Fanapi (2010). This is a common feature in most tropical cyclones, which is important for tropical cyclone intensity and dynamics.

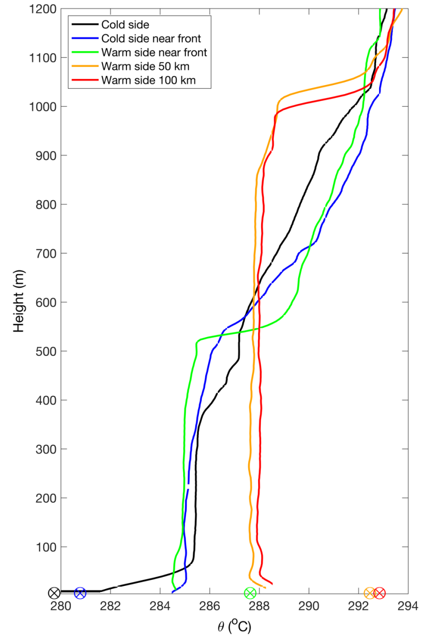

Figure 4-5. Profiles of potential temperature from a cruise across the Gulf Stream, displaying the differences in the stable PBL on the cold side through the growing convective PBL on the warm side of the Gulf Stream. Sea surface temperatures are also shown. Potential temperature data is from the CLIMODE cruise 16 March 2007, available from the NCAR ISS data server.

On intraseasonal time scales, interactions of convective cold pools and the marine PBL and upper ocean may hold the key to better understand and predict the MJO (e.g., Chen et al. 2016). The variability of the marine PBL is invariably coupled directly to the sea surface and upper ocean processes. One of the most important and unique properties of the marine PBL is its coupling to temporally and spatially variable sea state (e.g., surface waves) and/or sea surface temperature, which affects the PBL thermodynamic properties, as in the example in Figure 4-5.

Air-sea interaction has been shown to have differing characteristics as a function of the spatial scale. Variability of the ocean over time scales of decades or less has traditionally been viewed as a passive response to stochastic atmospheric forcing (Xie 2004). However, improvements in the resolution of satellite observations of the ocean surface and near-surface winds, as well as improvements in coupled model resolutions, have demonstrated that at smaller scales, oceanic mesoscale variability may be key to the variability in surface fluxes and thus the overlying PBL (e.g., Chelton and Xie 2010). At these scales, the coupling between the ocean and atmosphere is tighter and more dependent on the ocean surface characteristics, including temperature, waves, and currents. At even smaller scales, the ocean submesoscale regime below ~50 km, recent work suggests that ocean heat transport may become up-gradient, influencing the sea surface temperature and air-sea fluxes, which may affect air-sea interaction in ways that have not yet been explored (Su et al. 2018).

Differing currents and waves across ocean mesoscale eddies create a mechanical damping between the ocean and atmosphere, reducing the transfer of momentum from the PBL into the ocean. Sea surface temperature anomalies associated with these eddies also impact the surface layer, with warm eddies increasing heat fluxes, which leads to a destabilization of the PBL and increased momentum mixing from above into the PBL, reducing the surface winds (Seo 2017). The PBL responses can also be seen in increases in cloud liquid water, water vapor content, and rain rate. Cold eddies produce a stabilization of the PBL, and opposite effects to warm eddies in decreasing of the PBL height, cloud liquid water, rain rate, and surface winds. Other mesoscale structures associated with narrow sea surface temperature fronts in regions like the western boundary currents and across tropical instability waves have shown to produce even more dramatic PBL responses (e.g., Figure 4-5 above). As air flows from cold to warm water across the fronts, internal boundary layers form, with increased air temperature and water vapor and increased turbulent mixing; opposite flow induces a stable internal boundary layer that is colder and dryer. Changes lead to increased (decreased) PBL heights, thus extending past the PBL into the troposphere and perhaps modulating storm tracks and downstream weather patterns (Ma et al. 2015).

In addition, important aspects of air-sea interaction related to the PBL include sea spray, breaking waves, gustiness at low wind speeds, oceanic fog, the diurnal cycle of Sea Surface Temperature (SST) and the coupling between the surface and clouds.

A more integrated observational approach that couples the ocean, the PBL thermodynamic structure and clouds is required to properly address the critical science questions below. Being able to measure air-sea interaction at horizontal scales that could sample the horizontal heterogeneity due to ocean mesoscale phenomena while able to measure the PBL vertical thermodynamic structure with enough vertical resolution is essential.

Q3.1-O: What is the impact of surface heat fluxes on the PBL thermodynamic structure (and vice-versa)?

Over the ocean, there is a complex and multilayered feedback between the surface and the PBL through surface fluxes, which are coupled through multiscale air-sea interaction processes. Modeling studies have demonstrated the importance of coupling at the ocean meso- and sub-mesoscales, but differ in the response of the PBL. A component of this uncertainty is the lack of data regarding how the PBL over ocean often differs significantly from the PBL over land. Components of certain parameterizations of the PBL over ocean are still based on measurements over land with much drier conditions among other critical differences. For instance, fairly modest changes to the surface latent heat flux seem to be important to maintaining column moist static energy anomalies in the tropics (Demott et al. 2015), which then affect convection and may indirectly affect cloud feedbacks associated with longwave heating and moistening. Monin-Obukhov similarity theory which supports the bulk of existing surface flux parameterizations is currently in question, and violated under conditions driven by wave-induced flow near the ocean surface (e.g., Grare et al. 2018) and the PBL-top entrainment (Fodor et al. 2019).

Aerosols of varying compounds can be ejected from the ocean into the atmospheric surface layer and the PBL, where they can act as cloud condensation nuclei and affect the global albedo through the formation of haze and cloud layers (Mulcahy et al. 2008). The strength of PBL winds is a key factor in the production of marine aerosols, through the wave field. The PBL thermodynamic structure is affected by aerosols through changes in precipitation, which impacts the turbulent kinetic energy and water budget of the PBL (Wood et al. 2015).

In addition, the surface underneath the marine PBL is also a turbulent flow, and the interface between the two fluids changes over very short time and space scales. Many coupled models do not have all the components of the ocean surface needed to accurately describe this coupling, including waves and surface currents, and the horizontal resolution of many models is inadequate to represent the mesoscale structures in the ocean. In addition, basic questions about the impacts of seasonality and interannual variability on the atmospheric response to gradients in the surface fluxes from ocean eddies and fronts require more attention. Comparisons of the atmospheric response to these ocean features from diverse regions demonstrate distinct differences, most likely related to the differences in the scale and structure of the heat fluxes, in possible combination with regional background atmospheric conditions, and requires exploration. The atmospheric response to the surface conditions is better understood than the coupled effect: for instance, it is unknown whether changes in the precipitation fields induced by the mesoscale surface flux conditions could perhaps induce eddy intensification, and to what extent this may be mitigated through the changes in wind speed and cloud fraction. Untangling the connections between the atmospheric PBL and the ocean will require global high-resolution PBL profiles of temperature and water vapor with 100-200 m vertical resolution as well as global observations of surface fluxes and surface characteristics (including waves and currents).

Q3.2-O: Which processes control water vapor near (~ 100 m above) the surface?

Water vapor near (approximately 100 m above) the surface, particularly over the ocean, is a key variable to better understand the overall physics of how climate is changing and will change. At the heart of our understanding of the physics of climate change from a thermodynamic perspective is the fact that relative humidity in the troposphere remains fairly constant as the planet warms (e.g., Held and Soden 2006). This fundamental concept allows to understand and predict the water cycle response to global warming. Although models and some observations seem to confirm its validity to first order, it is clear that there is some variability of relative humidity in different regions of the globe and levels of the atmosphere. In addition, it is not completely clear why the relative humidity should stay fairly constant as the planet warms.

In this context, water vapor near the surface over the oceans (particularly over the tropics and sub-tropics) is a key variable that needs to be better observed and monitored from a global perspective since it provides important clues about the physical processes controlling the thermodynamics of the PBL. This is because water vapor near the surface is influenced by (and impacts) surface fluxes, PBL turbulent dynamics, cloud physics, deep convection dynamics, and large-scale dynamics, and as such plays a critical role in the coupling of all these processes. Better understanding of the behavior of water vapor near the surface will help understand the delicate balance between all these processes that leads to a fairly constant relative humidity as climate changes. In addition, it is still unclear what processes control relative humidity near the surface and what explains its observed values over vast regions of the global oceans.

Water vapor near (approximately 100 m above) the surface over the ocean is difficult to estimate from a global and climate perspective as clear differences between datasets illustrate. Satellite observations offer a, much needed, global perspective, but currently have extreme difficulties in measuring both temperature and water vapor so close to the surface. However, as described in detail in chapter 8, there are novel technologies that could be developed in the near future that would provide a vertical resolution in terms of thermodynamic structure close to the surface that could potentially allow for much more reliable global estimates of water vapor near the surface. In addition, in convective PBLs over the tropical and sub-tropical oceans, water vapor and potential temperature are close to a constant value from the top of the surface layer to cloud base (the sub-cloud layer) or the PBL height (if there are no clouds). This is a key factor related to PBL physics over the ocean (particularly over the tropics and sub-tropics) that would contribute to more accurate estimates of water vapor near the surface from space. Given the technologies described in chapter 8, including GNSS RO, DIAL and DAR, this is clearly within reach in the next decade.

In summary, the key measurement requirements are for PBL water vapor profiles with vertical resolutions of 100-200 m down to the surface, with additional estimates of surface variables such as SST and near-surface wind from synergistic datasets such as satellite observations or reanalysis.

Q3.3-O: What is the impact of surface heterogeneity on the PBL thermodynamic structure and convection initiation?

Changes in locations of strong SST fronts, particularly in the midlatitudes, drive local PBL responses which are dependent on model resolution. Higher resolution models in these regions result in weaker surface circulation, stronger and deeper vertical motion, and higher transient eddy heat flux, as well as increased impacts on the development of extratropical cyclones. Understanding the PBL response and its impact on the troposphere appears to provide a mechanism for understanding changes in atmospheric front and storm evolution, downstream storm tracks, and resulting rainfall variability, across the seasonal to decadal time scales. However, whether this small-scale variability does rectify into interannual variability is still an open but pressing question. Other small-scale ocean features, such as fresh lenses, may also play a role in affecting the PBL, but the net effect of these small-scale phenomena on air-sea interaction and PBL variability is still a gap in our knowledge.

Understanding of the coupling of the atmosphere and ocean at mesoscales and smaller is coming through modeling studies, given the paucity of concurrent measurements of the fluxes and the PBL. Observations from limited field campaigns such as DYNAMO have shown that the PBL and air-sea fluxes vary from hours to intraseasonal time scales. They are affected by atmospheric convection (e.g., convective cold pools), upper ocean features and large-scale circulation. In return, the air-sea fluxes and the PBL can control the convective initiation and life cycle (Chen et al. 2016). Other observations demonstrate a close connection between structures such as warm eddies, which can drive a dynamic response and cause local increases in marine PBL height and increased stratocumulus (Wang et al. 2019). Satellite analysis of this coupling is mainly through the winds and sea surface temperature, as current satellite flux analyses rely on multiple satellite inputs with varying temporal and spatial resolutions, some of which are not optimized for evaluating the appropriate surface layer processes (e.g., Small et al. 2008). Future observations to address these questions will require improved and simultaneous surface flux measurements as well as PBL thermodynamic structure. Coincident estimates of surface fluxes at higher spatial resolution and accuracy than currently available from satellite, below 25 km, with high-resolution PBL profiles of temperature and water vapor with vertical resolutions of order 100 m would provide crucial improvements needed to address the understanding of the impacts of the ocean mesoscale. Studying sub-mesoscale variability effects on the PBL would require surface fluxes and coincident PBL profiles at much higher horizontal resolution (order 1 to 10 km).

Q3.4-O: How does PBL thermodynamic structure and evolution modulate local and remote processes and feedbacks that govern hydrological and climatic extremes?

Improving our estimates of air-sea coupling and impacts on the PBL will have a direct impact on predictions on both local synoptic scale extreme events such as tropical and extratropical storms, as well as downstream events including flooding. Air-sea interactions are critical to tropical cyclone development, with exchanges of heat and moisture providing “fuel” to the storm, and momentum loss through the resulting wave surface providing “brakes” – thus the evolution of the storm is quite dependent on the relative ratio of these processes, and on the local ocean changes as a result of these fluxes (Emanuel 1995). Recent research indicates that variations in the PBL associated with storms passing over the strong SST gradients of the western boundary currents induce PBL changes that can propagate through the troposphere and affect the downstream flow, as the mesoscale SST variability enhances moist baroclinic instability, leading to strong storm growth in the local region and altered downstream storm development (Ma et al. 2017). Most, if not all, of these investigations have been based on modeling studies, and would require observational data resolving the surface forcing at horizontal resolutions of 25 km or less, and coincident PBL thermodynamic profiles to allow for a more observationally based analysis of thermodynamic effects.

4.4.2 LAND SURFACE

The predictability of the Earth System at scales beyond synoptic depends critically on the memory that resides in the land surface (as well as in the oceans) and on the time scales of the interactions between the land surface and the atmosphere (e.g., Shukla 1998; Dirmeyer et al. 2015). The PBL over land acts as the mediator between the land surface and the atmosphere, and therefore plays a crucial role in modulating the impact of surface states and associated anomalies and extremes on the global water and energy cycles.

In contrast to the marine PBL, the PBL over land is characterized by a strong diurnal cycle and the existence of moisture-limited regimes, and is strongly influenced by surface type and surface heterogeneity. Over land the diurnal cycle of the sun's radiation induces a diurnal cycle in the surface temperature due to the low heat capacity of the layer that absorbs the radiation. This in turn induces a strong diurnal cycle in the surface sensible heat flux and in the PBL height itself.

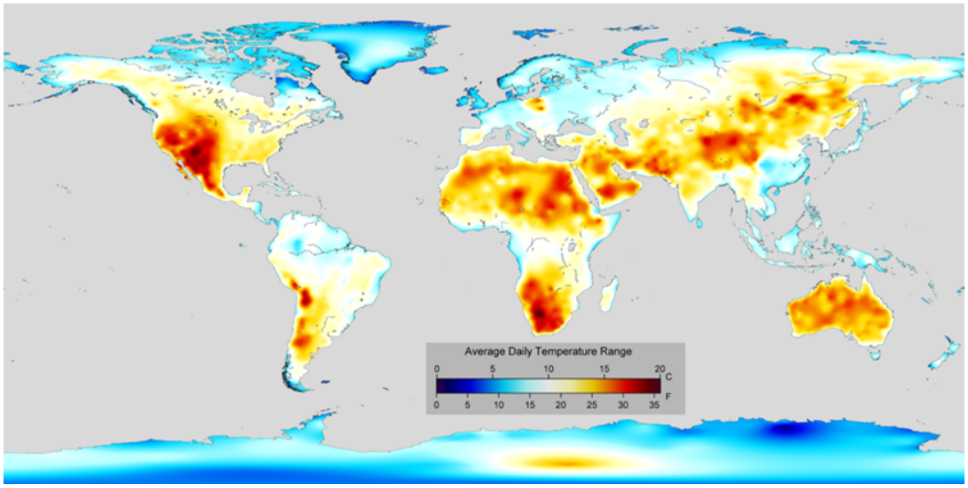

Figure 4-6. Estimated diurnal temperature range over land from 1951 to 1980, based on the interpolation of ground level weather station data (source: berkeleyearth.org).

The diurnal temperature range over land is illustrated in Figure 4-6, which depicts that the range can be as large as 20ºC in a long-term mean. Comparable values over the ocean have been shown to be closer to 0.5ºC.

Another aspect of PBL over land is the existence of moisture-limited regimes that impact the strength and the character of the L-A feedbacks. For example, a high precipitation anomaly results in a moistening of the soil, which can increase the evaporation and provide an added source of moisture for rainfall. The correlation between precipitation, evaporation and surface moisture is unique to land surfaces. Koster et al. (2004) showed that the regions of strongest L-A coupling are the semi-arid areas where these feedbacks are most active. In these areas, soil moisture modulates L-A feedbacks through the exchanges of latent and sensible heat fluxes.

Heterogeneities in the land surface also influence the structure of the PBL over land, in particular where sharp horizontal gradients in the character of the surface exist over small scales. Because of surface heterogeneities, differential heating of the PBL gives rise to atmospheric circulations over a wide range of spatial and temporal scales. At the mesoscale, examples of this type of circulation are sea and lake breezes produced by the thermal gradient between adjacent land and water bodies. Studies, mostly using numerical models, have shown that these circulations significantly affect the structure of the PBL, fluxes of heat, water and scalars, and organization of clouds and precipitation (e. g., Weaver and Avissar 2001). Although some of these studies have used limited data from field and surface-based observations, satellite-based data that can provide evidence of systematic organization of convection at preferred scales over land (e. g., at the 10–20 km scale range) is expected to be critical for these types of studies.

As described in Section 4.3 and Q2.3 above, land has a large impact on clouds. The role of soil moisture on PBL cloud development has been studied using analytical approaches and coupled land surface-PBL models with observational verification using data from specific regions (e.g., Ek and Holtslag 2004). For example, the potential for PBL cloud formation has been found to be strongly influenced by the effect of soil moisture in increasing or decreasing the PBL-top relative humidity tendency and that, depending on atmospheric stability above the PBL, an increase in soil moisture could result in a decrease in cloud cover.

Over the last three decades there has been significant progress in terms of the development and application of land surface and hydrological models. This includes advances in the maturity and complexity of parameterizations that capture water and energy cycle, carbon, bio-geophysical, and anthropogenic processes (such as irrigation and groundwater withdrawal). This progress has been aided in large part by satellite-based observations of surface properties (e.g., land cover, albedo, vegetation structure and amount) and states (soil moisture, land surface temperature, snow water equivalent) that are critical to driving accurate prediction in land surface models and data assimilation. Progress in terms of advancing model description of L-A coupling, however, is difficult without routine observations of the PBL. Implementation of quantitative, integrative metrics such as those developed under GEWEX in the Local land-atmosphere Coupling (LoCo) (Santanello et al. 2018) and Global Land Atmospheric Coupling Experiment (GLACE) (Koster et al. 2006) communities has been severely limited by the lack of routine PBL thermodynamic profile and PBL height observations. As a result, L-A coupling studies have often relied on proxies for information on the PBL due to lack of routine observations. Global observations of the diurnal cycle of PBL thermodynamic profiles and PBL height would therefore enable a more complete characterization of the coupled system.

In summary, because the PBL is the mediator of the land surface states, fluxes, and heterogeneity influences on convection, new PBL observations will offer insight and quantifiable information on how land surface information influences turbulence, clouds, convection and how those feed back onto the land surface itself. As a result of the limited observations available to increase understanding across the L-A interface, there are a number of high priority and high impact science questions and issues that remain unanswered, as discussed below.

Q3.1-L: What is the impact of surface heat fluxes on the PBL thermodynamic structure (and vice-versa)?

Surface sensible and latent heat fluxes are the principal drivers of convective PBL growth over land during the daytime. Their partition (Bowen ratio, evaporative fraction) results in a series of L-A interaction and feedback processes, and ultimately determines the equilibrium and PBL characteristics and growth of each day. The PBL growth and entrainment of dry, warm air from the free troposphere depend on the surface fluxes, their partitioning, and the stability of the PBL at the beginning of the day (which can be influenced by the prior day residual layer). Understanding these interactions requires synergistic observations and fully coupled model assessment using integrative, process-level metrics such as those developed by the L-A community under GEWEX. The relationship of evaporative fraction to PBL height is a well-known metric (Betts 2009; Santanello et al. 2009); others are the RH-Tendency, and Buoyancy Condensation Framework (Tawfik and Dirmeyer 2014), each focusing specifically on the relationship of fluxes to PBL structure, growth, and evolution. Accurate assessment of these relationships in coupled models therefore requires advances in global observations of PBL structure and evolution, at resolutions that include estimates of mixed-layer mean temperature and water vapor and PBL height at diurnal time scales (4 times per day or more). In addition, due to the interdisciplinary nature of L-A interactions, synergistic observations of surface properties such as soil moisture, surface fluxes (e. g., Abolafia-Rosenzweig et al. 2020), and screen-level meteorology are required to address these science goals.

Q3.2-L: Which processes control water vapor near (~ 100 m above) the surface?

PBL water vapor is one of the most important new observations that will contribute to improved forecasting of convective events. At a given location, PBL water vapor is controlled by a variety of physical processes including large-scale advection of water vapor, surface evaporation, PBL mixing, condensation/evaporation within the PBL, and entrainment of dry air into the growing PBL (e.g., Ek and Holtslag 2004). In addition, as already mentioned, water vapor modulates surface fluxes, and controls stomatal conductance and plant stress (which under extreme conditions can lead to droughts and heatwaves), as well as the likelihood of convective initiation. Different hydrological and meteorological drought indices have been developed that rely on estimates of water vapor near the surface (e.g., AghaKouchak et al. 2015). Likewise, the convective triggering potential-low-level humidity index (CTP-HI) metric of Findell and Eltahir (2003) used to diagnose soil moisture-precipitation coupling relies on the PBL stability and on a humidity index, which is essentially a measure of the lower tropospheric relative humidity. To date, the use of metrics like these for process understanding and model assessment is limited to locations where PBL thermodynamic profiles and low-level relative humidity data are available, and often limited to reanalyses. Therefore, estimates of water vapor near the surface from space would enable global model assessment of surface-PBL coupling and carry implications for the diurnal cycle of precipitation, extremes such as drought, heatwaves and floods. Such observations would also enable characterizing complex surface-PBL positive and negative feedback regimes.

PBL water vapor profile observations with vertical resolutions of 100-200 m down to the surface are a key requirement. Improved observations of PBL mixed-layer mean temperature and water vapor and PBL height at diurnal time scales (4 times per day or more) would enable improvements in all of these scientific and societal applications. In addition, due to the interdisciplinary nature of L-A interactions, synergistic observations of surface properties such as soil moisture, surface temperature and surface fluxes are required to address these science goals.

Q3.3-L: What is the impact of surface heterogeneity on the PBL thermodynamic structure and convection initiation?

The influence of surface heterogeneities extends vertically in the atmosphere up to a level, referred to as the “blending height”, generally above the surface layer and within the PBL. The blending height is variable, depends mostly on the nature of the surface roughness elements, the buoyancy, and the horizontal scale of heterogeneity, and can be as high as the height of the PBL or even higher for an unstable atmosphere under the influence of strong surface heating. Studies have shown that the blending height has an impact on the bulk PBL response, and on clouds and convection, but this impact depends on factors such as the synoptic conditions, wind speed/direction, length scales of the heterogeneity, and type of heterogeneity itself (e.g., Molod et al. 2004).

The impacts of land surface heterogeneities can be characterized as ‘‘aggregation’’ effects and ‘‘dynamical’’ effects, the first arising directly from spatial heterogeneity in the land surface and the second associated with the small-scale (micro- and mesoscale) circulations induced by heterogeneous surfaces (Giorgi and Avissar 1997). Aggregation effects arise, for instance, over a terrain that is partially covered by vegetation, or partially irrigated, resulting in a patch with higher latent heat fluxes and higher overlying equivalent potential temperature than the surrounding terrain. The occurrence of deep convection over the wetter areas of the domain is considered an aggregation effect of spatial heterogeneity. In addition, positive and negative land-atmosphere feedbacks can set up over dry and wet patches, impacting soil moisture-precipitation relationships and mesoscale convective processes (Taylor et al. 2007; Lee et al. 2019). Dynamical effects arise under certain synoptic conditions, when the patches in the terrain are larger than about 5–10 km in size, and the surface fluxes are organized into mesoscale patterns. These organized mesoscale circulations are induced by mesoscale-sized contrasts, due to heterogeneities in vegetation, soil, terrain elevation, or irrigation practices, for example. These circulations can affect the vertical structure of the PBL, the turbulent fluxes, and may induce localized areas of moist convection.

Models have attempted to deal with surface heterogeneity by using tiling approaches, where sub-grid heterogeneity at the surface is explicitly retained throughout the surface layer but then averaged before merging with the overlying atmosphere. These modeling efforts are hampered by the lack of knowledge of which scales of heterogeneity need to be resolved in order to properly capture the interaction between the heterogeneous surface and the PBL and convection. Satellite-based estimates of surface properties have improved dramatically over recent decades (e.g., 250 m land cover, 1 km soil type, 250 m vegetation cover/amount) but the corresponding atmospheric measurements remain much coarser spatially. Improving the horizontal resolution of PBL thermodynamic profiles to ~1 km at global scales is therefore crucial for the ability to understand and model the impact of surface heterogeneity on PBL structure and convection. In addition, vertical profiles of temperature and water vapor at 100-400 m resolution, and diurnal sampling of PBL growth (either via temperature and water vapor profiles or independent PBL height estimates) in combination with high resolution surface variables (land surface temperature, soil moisture, land cover, soil types, and screen-level meteorology) would provide crucial improvements in resolving, understanding and predicting L-A interactions across heterogeneous landscapes.

Q3.4-L: How does PBL thermodynamic structure and evolution modulate local and remote processes and feedbacks that govern hydrological and climatic extremes?

Quantifying the strength and nature of land surface-PBL coupling, including those relationships described above, has direct implications for improved understanding and prediction of extreme events. The connections between surface fluxes, relative humidity near the surface, PBL growth and entrainment, and stability and convection can lead to feedbacks that support locally or synoptically short or long-term extremes such as drought, heatwaves, and floods. For example, rapidly drying soil leads to reduced PBL relative humidity, increased PBL growth, increased entrainment of dry warm air, which in turn leads to further increase of the vapor pressure deficit and promote additional soil drying. Without any reset from precipitation, this feedback can persist and create drought and heatwave conditions, with each day amplifying these effects further until the surface is desiccated. Similarly, for given PBL stability and synoptic conditions, wet soils can promote further precipitation. Therefore, soil moisture alone (which we currently have in the POR of current spaceborne sensors, e.g., SMAP) cannot be predictive of future drought or flooding events and observations of the PBL structure and evolution, which are key to the generation of these feedbacks, are needed. PBL observations would also enable the evaluation and representation of these feedbacks and inherent land-atmosphere interactions in coupled models used to predict extreme events. Requirements to achieve these goals include temperature and water vapor profiles in the PBL at diurnal timescales (4 times per day or more), PBL height derived independently or from temperature and water vapor profiles (the latter of which would require vertical resolution ~100-400m), and synergy of measurements with global observations of soil moisture, surface fluxes, and surface characteristics.

Land-atmosphere interactions also have remote effects (e.g., on precipitation), as demonstrated in numerous modeling studies. It is well known that soil moisture anomalies affect the precipitation development over downstream adjacent areas. The remote effect on precipitation from tropical land state anomalies (e.g., over the Amazon) has also been demonstrated. Schubert et al. (2014), in their study of the Eurasian heatwaves suggest that these remote effects are communicated by propagation of Rossby waves. More recently the remote impact on precipitation of land surface temperature anomalies over high-altitude plateaus (e.g., Tibet, western U.S.) through Rossby wave propagation has also been demonstrated through the GEWEX LS4P (Impact of Initialized Land Temperature and Snowpack on Sub-seasonal to Seasonal Prediction) project. In order to document this process from observations, global scale thermodynamic profiles in the PBL are needed. In addition, L-A interactions may potentially affect the upstream movement and development of weather systems. For instance, Galarneau and Zeng (2020) showed that a drier land may generate an anomaly in the synoptic flow pattern that slightly changes the hurricane path before its landfall, leading to a large change of hurricane movement and precipitation due to hurricane-synoptic flow interactions. Again most, if not all, of these studies have used modeling tools, and observational data are urgently needed to characterize and quantify such remote effects. The existence of these remote effects emphasizes the need for global-scale PBL observations, only possible from space, that ground (column) or point based observations will not be able to address. Specifically, improved horizontal, vertical, and temporal sampling of temperature and water vapor profiles, following the specific requirements above, across large (synoptic) scales with synergistic and regional land surface observations (and anomalies) will enable progress of such studies and model predictions.

4.5 PBL MIXING, MODELING AND AIR QUALITY

As described above, buoyancy plays a fundamental role in PBL physics leading to a variety of different types of convective and stable PBLs. Buoyancy (a key source or sink of turbulent kinetic energy) is essentially determined by the temperature and water vapor structure of the PBL. In this context, the PBL temperature and water vapor structure plays a critical role in the vertical transport of atmospheric constituents (and as such in air quality) between the surface and the atmosphere, within the PBL, and at the interfaces between the PBL and the free atmosphere above. This critical role naturally applies to all types of constituents including aerosols and greenhouse gases. Being able to better observe, model and predict the PBL thermodynamic structure (including the PBL height) will lead to better air quality forecasts and more reliable climate change projections that involve coupled ecosystem models. For example, it is well recognized that the poorly constrained and modeled mixing between the PBL and the free troposphere introduces large errors in pollution dispersion models (e.g., Angevine et al., 2014) and carbon flux inversions (e.g., Lauvaux and Davis, 2014). Aerosol pollution within the PBL can further feedback on the PBL mixing through its interaction with solar radiation which has been shown to amplify poor AQ conditions (e.g., Petäjä et al., 2016).

To better model and predict the PBL thermodynamic structure there is a need for a better understanding of PBL turbulent and convective mixing, and more realistic models and parameterizations of this mixing – since while it is the PBL thermodynamic structure that sets the buoyancy that generates the mixing, it is this turbulent and convective mixing that in turn sets the thermodynamic structure. The development of theories and models of PBL turbulent mixing has been at the heart of much of modern turbulence research in the first half of the 20th century with the work of Richardson, Taylor, Prandtl, von Karman and Kolmogorov (e.g., Davidson et al., 2011).

The concept that turbulent mixing is best represent by an eddy-diffusivity (ED) approach originates in the late 19th century with Reynolds and Boussinesq, was significantly advanced and improved by Taylor, Prandtl, von Karman and Kolmogorov (e.g., Frisch 1995), and later implemented as a PBL parameterization from the start of weather and climate prediction modeling (e.g., Estoque 1960). The key concept behind the ED approach is that turbulent mixing can be well represented by a diffusion model (akin to molecular diffusion) in which the ED coefficient depends on key characteristics (such as the turbulent kinetic energy – TKE) of the PBL turbulent flow (rather than depending on the fluid itself as for molecular diffusivity). To close (solve) ED parameterizations, a relation between the ED coefficient and some of the key characteristics of the PBL turbulent flow like a turbulent mixing length and TKE is necessary. ED parameterizations are present in some form in every atmospheric model and are particularly successful in representing turbulent mixing in stable and neutral PBLs. However, the different types of convective PBL regimes pose significant challenges to the ED approach.

Mixed Layer (ML) models were introduced in the 1960s for both dry and stratocumulus topped PBLs as a simple way to represent (parameterize) convective PBLs (e.g., Lilly 1968). The key concept behind ML models is that the mean (moist conserved) thermodynamic properties such as potential temperature and water vapor (for the dry case) are well-mixed (i.e., constant) in the vertical within the PBL and that the PBL is capped by a strong inversion at its top. To close (solve) ML models there is a need to specify a PBL top-entrainment relation that determines the mixing of properties between the PBL and the free troposphere above. Although ML models have rarely been used explicitly as parameterizations in weather and climate models – mostly because pure well-mixed PBLs represent only a fairly limited fraction of the PBL types all over the globe - the conceptual framework of ML models and in particular the importance of the top-entrainment concept has influenced PBL science in important ways. ML models have also been used more recently in utilizing PBL observations such as PBL profiles (Denissen et al. 2021) and PBL height (Rey-Sanchez et al. 2021) to infer surface states and fluxes, and address processes driving land-atmosphere interactions. To be clear, PBL top-entrainment is a key concept even for PBLs that are not fully well-mixed and plays an important role in a variety of contexts including in helping determine (in AQ) how much of a particular PBL chemical constituent is mixed across the PBL top.

Neither ED or ML models are able to realistically represent PBLs that are dominated by cumulus moist convection (i.e., conditionally unstable PBLs). The Mass-Flux (MF) approach attempts to explicitly represent the plumes/thermals associated with moist convection in the atmosphere and was originally developed in the 1950s and 1960s as a model of atmospheric convection (e.g., Arakawa 1969). Since the 1980s the MF approach became the standard for moist convection parameterization (shallow and/or deep) in weather and climate models (e.g., Tiedtke 1989).

A key problem in weather and climate models in terms of vertical mixing parameterizations (including, and in particular, in the PBL) is that in each model there are different parameterizations (typically based in separate ED and MF approaches) that attempt to represent this mixing in a modular fashion – i.e., different manifestations of vertical mixing (stable PBL, dry convective PBL, stratocumulus PBL, shallow and deep moist convection) are represented by separate modules (algorithmically and code-wise). This artificial modularity introduces a variety of problems including the coupling and transition between physical regimes. During the last 20 years there have been some attempts to unify the parameterization of PBL mixing and moist convection in weather and climate models.

The Eddy-Diffusivity/Mass-Flux (EDMF) parameterization is a unified approach that merges (at the theoretical, algorithmic and code level) in an optimal manner the parameterization of small-scale processes, using the ED approach, with the parameterization of larger (PBL depth and plume/thermal) scale processes, using the MF approach (e.g., Siebesma and Teixeira 2000; Siebesma et al. 2007; Sušelj et al. 2013). EDMF has been implemented operationally in a variety of global weather prediction models and is being tested in a few climate models. Higher-Order Closure (HOC) methods address the parameterization problem by adding additional prognostic equations for higher moments of the probability density functions (PDFs) of thermodynamic properties and use these equations to estimate the PDF properties and the consequent vertical mixing of thermodynamic variables (e.g., Golaz et al. 2002a, b; Larson et al. 2002). Observations can help determine which unified approaches are closer to reality since each approach is based on different PDFs of thermodynamic properties. For example, some HOC models assume double-Gaussian PDFs of thermodynamic properties while multi-plume EDMF models assume a single Gaussian blended with multiple discrete PDF components (i.e., multiple plumes/thermals).

PBL clouds are intrinsically related to PBL turbulent mixing and the sub-grid (i.e., within a model horizontal gid-box) distribution of clouds (i.e., cloud fraction, mean liquid/ice water, standard deviation of liquid/ice water within the grid-box) is associated with the PBL mixing parameterizations. The sub-grid representation (parameterization) of PBL clouds (often referred to as ‘cloud macrophysics’) has been pursued in a fairly empirical manner over the last few decades. A physically-based and mathematically rigorous approach was proposed in the late 1970s and is based on PDFs of moist conserved temperature and water variables within a horizontal model grid-box (Mellor 1977; Sommeria and Deardorff 1977). These PDF approaches have been implemented in weather and climate models and pose interesting theoretical, modeling and observational challenges. In particular, what the specific shape of the PDF of thermodynamic properties should be is a critical question. If in nature, the PDFs of moist conserved variables are essentially Gaussian, that would require that only variances and co-variances need to be known to estimate cloud cover and liquid/ice water. But if the PDFs are more complex, the cloud macrophysics problem becomes more challenging to solve. In general, a more accurate knowledge of the PDFs of thermodynamic properties across a variety of PBL regimes would lead to more reliable estimates of key PBL mixing quantities such as scalar variance and co-variance. Global observations from space of temperature and water vapor at horizontal resolutions of 1 km, or finer, would be uniquely valuable in this context.

As is discussed in detail throughout this PBL science chapter, the role of mesoscale heterogeneity in PBL mixing and the thermodynamic structure is absolutely fundamental. However, its impact is still not fully understood. This mesoscale heterogeneity can be triggered by surface heterogeneities but is often associated with the intrinsic non-linearities of the Earth's moist rotating atmosphere (e.g., frontal systems, tropical cyclones, mesoscale convective systems). To be able to observe these interactions between mesoscale processes and PBL mixing from a global perspective, space-based observations are essential.

As mentioned, PBL vertical mixing determines the vertical structure of atmospheric constituents (from gases to aerosols) and is critical for air quality (AQ) characterization and prediction. This mixing also plays a key role in weather prediction and on how climate responds to increased greenhouse gases. In addition, PBL vertical mixing modulates the manner in which these constituents interact with radiation (both longwave and shortwave) and cloud microphysics. The development of realistic PBL parameterizations of vertical mixing in weather, climate and AQ models has been a longstanding challenge but recent developments in terms of unified PBL parameterizations are promising. In order to address these issues from a global perspective, observations from space of quantities related to PBL mixing would represent a very significant advance towards our understanding of PBL vertical mixing and its role in weather, climate and air quality.

Q4.1: What are the main PBL mechanisms responsible for vertical transport of atmospheric constituents (e.g., entrainment, turbulent diffusion, thermals/plumes)?

Several of these parametrizations have specific critical parameters or formulations that require observations or high-resolution models such as LES for their determination and calibration. Because of its nature, in-situ observations and LES case-studies can only focus on fairly constrained situations from a temporal and spatial perspective. A global perspective would be essential to make sure that these PBL parameterizations are developed, evaluated and calibrated for a diversity of physical settings. Space-based observations could provide a uniquely global perspective on PBL mixing but the technological challenges of observing the PBL in a remote manner from space have hindered progress in this respect.

Global space-based observations of key parameters and processes behind the different parameterizations is a challenging, yet critical, issue, given the importance of sampling the diversity of physical conditions constraining the possible PBL thermodynamic states. This grand challenge demands novel approaches and ways of thinking on how to best utilize space-based observations to provide estimates of these key parameters and processes associated with PBL mixing. Critical potential examples include:

- PBL top entrainment controls the growth of the PBL and the mixing between the PBL and the free troposphere. To reliably study PBL top entrainment and mixing using satellite observations would require measurements of PBL height with sufficient horizontal (1-10 km) and temporal (hours) resolution within large horizontal domains combined with measurements of PBL thermodynamic structure close to the PBL top with sufficient vertical resolution (100-200 m).
- PBL vertical mixing and cloud (macrophysics) parameterizations are based on specific assumptions about the shapes of the spatial PDFs of thermodynamic variables. Space-based observations can clarify if, and in which circumstances, Gaussian, double-Gaussian

or more complex PDFs are better representations of the PBL thermodynamic small-scale variability and help determine which unified parameterizations are more realistic. This would require PBL thermodynamic information at horizontal resolutions of 1 km or better.

- Measurements of quantities such as the variance of the spatial (horizontal) PDFs of thermodynamic variables could help estimate (under certain assumptions and specific circumstances) other key parameters related to PBL mixing such as eddy-diffusivity, mixing length and turbulent kinetic energy. This would require PBL thermodynamic information at horizontal resolutions of 1 km or better coupled with the best possible vertical resolution.

Q4.2: What are the optimal methods to more effectively use space-based PBL observations in order to develop and evaluate unified PBL parameterizations in weather and climate models?

Global or near-global data sets are uniquely valuable for global weather and climate model parameterization development, validation and tuning. For PBL and cloud parameterizations, fundamental development often proceeds via single-column modeling with individual observation-based canonical case studies often involving LES data. Global data sets substantially expand that power by enabling parameter optimization across all observable conditions, including many that may have received little attention during development. A forward simulation approach (comparing forward-simulated quantities with observations) can be seamlessly incorporated if that offers substantial added value.

Recent studies have demonstrated the potential use of PBL observations to further the development of unified PBL parameterizations in weather and climate models. Optimizing future space-based mission design requires consideration of a variety of open questions regarding such methods, including:

- What are the trade-offs between differing revisit and swath characteristics for constraining weather and climate models, and reanalysis? Relatively infrequent revisit and lack of swath coverage are not necessarily a limitation to parameterization evaluation in climate models, but could limit the utilization of such observations in data assimilation.
- How important are overpass diurnal coverage and latitude extent to parameterization evaluation? For global continental PBLs, for instance, it seems possible that a relatively wide range of nocturnal time periods could be used to evaluate residual layer top height, and that could serve as a reliable proxy for maximum PBL height. Evaluating any such hypotheses, which could yield valuable insights into optimal yet affordable mission design, requires dedicated studies. Such studies should include climate and weather model developers, who know the most about parameterization sensitivities and likely directions for high-impact improvements.
- What collocated instrument combinations could provide robust constraints on both PBL heights and thermodynamic profiles? Forward simulation approaches to optimally use differing combinations of instrument capabilities are likely required to evaluate mission architectures. Ideally, these should be evaluated using the complexity of conditions encountered in actual climate and weather models globally, including the wide range of regional characteristics discussed above (e.g., marine, polar, convective).

The answers to these and similar questions underline the importance of establishing methodological approaches to the use of space-based PBL data sets for model development as a mission design consideration.

4.6 PRELIMINARY SCIENCE AND APPLICATIONS TRACEABILITY MATRIX (SATM)

To conclude this chapter, the overarching PBL vision, the science goals, science questions, the geophysical variables and measurement requirements, and the potential measurement technologies from space are summarized in the following preliminary SATM tables:

Overarching PBL Vision	Science Goal	Science Questions
Globally characterize the thermodynamic structure of the PBL	**G1. PBL, Convection and Extreme Weather**	**Q1.1**: What is the role of mesoscale variability (e.g., cold pools, aggregation) in the interactions between PBL and convection? **Q1.2**: How does the thermodynamic structure of the PBL and lower troposphere foster a transition to deep convection? **Q1.3**: What is the role of PBL and surface processes in the diurnal cycle of precipitation?
	G2. Cloudy PBL	**Q2.1**: How do the PBL thermodynamic structure and cloud properties covary and interact with each other, and how does it depend on cloud type? **Q2.2**: How are these PBL-cloud interactions mediated by turbulent surface fluxes and overlying free tropospheric thermodynamic conditions? **Q2.3**: What is the role of mesoscale variability in modulating the vertical structure of the cloudy PBL temperature and water vapor?
	G3. PBL and Surface Interaction	**Q3.1**: What is the impact of surface heat fluxes on the PBL thermodynamic structure (and vice-versa)? **Q3.2**: Which processes control the water vapor near (~ 100 m above) the surface? **Q3.3**: What is the impact of surface heterogeneity on the PBL thermodynamic structure and convection initiation? **Q3.4**: How does PBL thermodynamic structure and evolution modulate local and remote processes and feedbacks that govern hydrological and climatic extremes ?
	G4. PBL Modeling, Mixing and Air Quality	**Q4.1**: What are the main PBL mechanisms responsible for vertical transport of atmospheric constituents? (e.g., entrainment, turbulent diffusion, thermals/plumes) **Q4.2**: What are the optimal methods to more effectively use space-based PBL observations in order to develop and evaluate unified PBL parameterizations in weather, climate and air quality models?

Goal	Science Questions	Geophysical Variables and Measurement Requirements	Potential Measurement Technologies from Space
G1. PBL, Convection and Extreme Weather	**Q1.1**: What is the role of mesoscale variability (e.g., cold pools, aggregation) in the interactions between PBL and convection? **Q1.2**:How does the thermodynamic structure of the PBL and lower troposphere foster a transition to deep convection? **Q1.3**: What is the role of PBL and surface processes in the diurnal cycle of precipitation?	• Spatial distributions of **T** and **q** in clear and cloudy conditions to measure PBL mesoscale variability (0.5-1 km vertical resolution) • To estimate variability within 10-100 km requires **T** and **q** at 1 km horizontal resolution or better • PBL height Temporal sampling to characterize storm evolution: • For weather - multiple times per day in same locations • For climate - statistical sampling of diurnal cycle	**Horizontal/Vertical resolution – combination of:** • IR sounding (1 km horizontal resolution, clear sky) • MW sounding (5 km horizontal resolution, through clouds) • SW observations of related variables (~100m horizontal resolution) • DIAL/DAR measures nadir water vapor curtains with 200 m vertical resolution **Temporal sampling**: • For weather - i) GEO IR sounder, ii) CubeSat constellation or iii) LEO complementing operational CrIS, IASI, MW sounders • For climate - LEO inclined orbits

Goal	Science Questions	Geophysical Variables and Measurement Requirements	Potential Measurement Technologies from Space
G2. Cloudy PBL	**Q2.1**: How do the PBL thermodynamic structure and cloud properties covary and interact with each other, and how does it depend on cloud type? **Q2.2**: How are these PBL-cloud interactions mediated by turbulent surface fluxes and overlying free tropospheric thermodynamic conditions? **Q2.3**: What is the role of mesoscale variability in modulating the vertical structure of the cloudy PBL temperature and water vapor?	• **T** and **q** profiles (in PBL and free troposphere) with high vertical resolution (100-200 m) in clear and cloudy conditions • **T** and **q** profiles at horizontal resolutions as in G1 • PBL height • Cloud properties (synergistic measurements) • Radiative fluxes (synergistic measurements) • Surface fluxes (based on synergistic measurements)	**Horizontal resolution as in G1:** Combination of IR, MW and SW. **Vertical resolution:** • DIAL measures **q** profiles, 200 m vertical resolution from space in clear sky (2D curtain) • DAR measures **q** profiles, 200 m vertical resolution from space in cloudy sky (2D curtain) • GNSS RO measures **T** or **q** profiles with 100 m vertical resolution from space (scattered sampling)

Goal	Science Questions	Geophysical Variables and Measurement Requirements	Potential Measurement Technologies from Space
G3. PBL and Surface Interaction	**Q3.1**: What is the impact of surface heat fluxes on the PBL thermodynamic structure (and vice-versa)? **Q3.2:** Which processes control the water vapor near (~ 100 m above) the surface? **Q3.3:** What is the impact of surface heterogeneity on the PBL thermodynamic structure and convection initiation? **Q3.4:** How does PBL thermodynamic structure and evolution modulate local and remote processes and feedbacks that govern hydrological and climatic extremes?	• PBL **T** and **q** resolution: Minimum: Mixed-layer mean **T** and **q** + PBL height Enhanced: 100-200 m vertical resolution Diurnal sampling: weather and climate sampling as in G1 • **T** and **q** high vertical resolution close to surface • **Surface properties:** surface temperature, soil moisture, surface fluxes, heterogeneity, vegetation (synergistic platforms and observations) • **Near surface:** T and q (2m), winds (10m) (synergistic observations, analyses and reanalyses)	**Horizontal resolution as in G1:** Combination of IR, MW and SW. **Temporal sampling as in G1:** For weather - i) GEO IR sounder, ii) CubeSat constellation or iii) LEO complementing operational CrIS, IASI, MW sounders. For climate - LEO inclined orbits **Vertical resolution as in G2:** DIAL, DAR and/or RO.

<table>
<tr><th>Goal</th><th>Science Questions</th><th>Geophysical Variables and Measurement Requirements</th><th>Potential Measurement Technologies from Space</th></tr>
<tr><td>G4. PBL Modeling, Mixing and Air Quality</td><td>Q4.1: What are the main PBL mechanisms responsible for vertical transport of atmospheric constituents? (e.g., entrainment, turbulent diffusion, thermals/plumes)

Q4.2: What are the optimal methods to more effectively use space-based PBL observations in order to develop and evaluate unified PBL parameterizations in weather, climate and air quality models?</td><td>• Variables related to PBL transport/mixing (e.g., T and q spatial variance, PBL top entrainment)
• Combinations of different instruments with high vertical (100-200 m) and horizontal (< 1 km) resolutions of T and q
• PBL height measurements with high horizontal resolution (~1 km)
• Cloud properties and radiative fluxes (synergistic measurements)
• PBL winds (synergistic measurements or analyses)</td><td>Horizontal resolution as in G1: Combination of IR, MW and SW.
Temporal sampling as in G1: For weather: i) GEO IR sounder, ii) CubeSat constellation or iii) LEO complementing operational sounders. For climate: LEO inclined orbits
Vertical resolution as in G2: DIAL, DAR and/or RO.
PBL height: from T and/or q profiles (see above) and/or measurements of cloud, aerosol properties</td></tr>
</table>

5. PBL APPLICATIONS

This chapter summarizes a range of PBL applications. As mentioned earlier, the PBL is where humans reside, and any impact of extreme weather and climate affects humans and ecosystems through the PBL. Many applications require predictions of PBL conditions at different time scales ranging from hourly, daily, weekly, subseasonal-to-seasonal (S2S), decadal, and climate projection scales. Furthermore, different applications have different needs from a spatial resolution perspective, from order 10 meters for urban applications to order 10 kilometers for climate applications. Improving these predictions is therefore timely and even urgent. The prediction skill for each of these applications will be improved with advances in PBL science and technology to span a global measuring system of the PBL. In all of these applications, the improvements start with improved datasets, such as those provided by this potential PBL effort. That is, the advances in PBL research science will be used to inform and advance PBL applied science.

These applications require good characterization of the PBL (e.g., initial conditions for forecasting), which can be based on measurements or specification from data assimilation. The characterization includes the spatial distribution of the PBL height and the vertical distribution of temperature and water vapor (as well as other geophysical variables such as winds, clouds, and aerosol particles) over the region of interest. These applications also require good predictive models to estimate the variables of interest at the desired forecast lead-time. These predictive models frequently are highly complex models that attempt to represent the myriad of physical processes at work in the PBL in order to represent the evolution of its thermodynamic and kinematic structure. Thus, a detailed thermodynamic profiling dataset in the PBL that spans the globe will allow the physical parameterizations within these models to be improved, leading to better results from the application point-of-view. In this way, advances in research brought by new generations of measurements are of direct benefit to the different applications discussed in this chapter.

Many of the applications also require additional models of various types to translate PBL related forecasts into the information needed by decision makers in the various areas (e.g., agriculture and wildfires applications need their own crop or fire models). All of these applications have significant impacts on decision support; i.e., impactful actions may be taken based upon the current or projected state of the PBL, which could have ramifications on safety (saving lives and property), health of communities, food and security, financial savings, and more.

PBL applications span several different time and space scales; critical examples include:

- High-impact meteorology – Better measurements and understanding of PBL processes will provide major improvements to the prediction of severe weather (e.g., tornadoes, hurricanes, and winter storms) at the shortest time scales (from hours to days) and to the prediction of monsoon onset and meteorological and hydrological drought at the S2S time scales (e.g., Higgins and Gochis 2007; Schubert et al., 2014; Cohen et al. 2015; Mukhopadhyay et al. 2020; Wang et al. 2020a). In all of these cases, important physical processes leading to variability in the spatial distributions of temperature and water vapor are not adequately represented in the meteorological models used by emergency managers for weather and seasonal forecasting. Better PBL thermodynamic datasets, both locally at high-spatial and temporal resolution for dynamic convective storms and globally for longer-term forecasting challenges, will allow the physical processes in these impactful meteorological events to be better understood and represented in predictive models.
- Climate projections – This application depends strongly on the accurate representation of PBL processes such as turbulence, convection and clouds, and the interaction between the PBL, the surface (land, ocean, ice) and the large-scale circulation in climate models. For example, (i) PBL thermodynamic, cloud and aerosol processes are critical for an accurate representation of a variety of PBL regimes including shallow marine clouds (e.g., Wood

2012) and mixed-phase polar clouds (e.g., Morrison et al. 2012), both of which are critical for properly modeling the Earth's radiative energy budget; (ii) the frequency of important atmospheric blocking events in climate models is sensitive to PBL parameterizations (e.g., Lindvall et al. 2017), a problem that is less severe in data assimilation systems such as re-analyses. Thus, improving PBL parameterizations in climate models ultimately provides decision makers better tools for applications that require climate projections (e.g., energy policy and infrastructure investments).

- Air quality (AQ) – The accuracy of AQ monitoring and prediction depends on the understanding and accurate representation of PBL processes in data assimilation systems and prediction models. Better measurements and understanding of PBL height, PBL thermodynamic and mixing processes as well as how these processes influence atmospheric chemistry (e.g., interactive chemical species, like NO_x and O_3, and particulate matter) will lead to better monitoring and prediction of air quality at the shorter times scales (e.g., Haman et al. 2014; Miao et al. 2019; Lin et al. 2008). PBL height observations in particular can improve the simulation of surface-emitted constituents in both chemistry transport models and coupled chemistry models (e.g., Reen et al. 2014). PBL processes determine the overall stability of the lower atmosphere and influence the emission, transport, dispersion, deposition, and chemical transformations of harmful substances in the atmosphere. The deposition of pollutants close to the surface is especially dependent on the atmospheric stability of the lower atmosphere. These better measurements and understanding are critical to predicting the transport and dispersion of pollutants, dust, radiological and biological constituents, and greenhouse gases (GHG) such as carbon dioxide and methane at the daily, seasonal, and climate time scales.
- Dispersion – The dispersion of atmospheric pollutants is highly dependent on the stability and dispersive conditions of the PBL. Dispersion models (e.g., Stein et al. 2015) offer a complete system for computing simple air parcel trajectories as well as complex transport, dispersion, chemical transformation, and deposition simulations. Some examples of dispersion applications include tracking and forecasting the release of radioactive material, smoke from wildfire, windblown dust, pollutants from various stationary and mobile emission sources, allergens and volcanic ash. Dispersion products are used for operational applications at the National Weather Service as well as by other U.S. government agencies (e.g., EPA, DOE, DOD), academia, and private companies.
- Hydrometeorology – Hydrological models depend strongly on the output of atmospheric models (particularly precipitation), and are increasingly integrated into Earth System models that can include groundwater, lateral flow, and surface hydrology coupled fully to the atmosphere. Uncertainties in the state of the PBL, or in processes at work within the PBL, can result in marked errors in the predictions from hydrometeorological models (e.g., Mockler et al. 2016; Santanello et al. 2018). This can affect short-term (i.e., hourly) flash flood forecasts, forecasts on the multi-day to weekly time scale important for reservoir management, as well as longer term S2S and climate predictions that provide information on large-scale drought, flash drought, or inundation situations and how these might change with time.
- Agriculture – PBL observations and forecasts are critical for both short-term (e.g., will freezing conditions exist tonight that need to be mitigated to protect a fruit crop) and S2S timescales (to help mitigate both drought and inundation conditions). PBL observations for coupled prediction models are also critical to develop improved representation of land-atmosphere interactions that (i) reflect real-world irrigation demands and applications, and (ii) are due to the intrinsic relationships and feedbacks amongst soil moisture, evaporation, and PBL thermodynamics (e.g., Meza et al. 2008). Improved thermodynamic profiling datasets in the PBL are needed to improve our understanding of these land-atmosphere

feedbacks (Wulfmeyer et al. 2015) and ultimately the implications of these feedbacks for agriculture.

- Renewable energy – Improved PBL weather forecasts can help integrate both wind and solar energy more efficiently into the grid. There is a strong dependence of wind speed and the downstream impacts of wind turbines on the near-surface stability and thermodynamics (e.g., Emeis 2014). Many wind power plants have been installed in mountainous terrain due to the repeatable orographic forcing of the wind, but complex terrain poses different challenges to the ability to observe and model the PBL (e.g., Shaw et al. 2019). Similarly, the US is expanding wind energy to coastal marine locations, with concurrent needs for weather forecasting, including improved wave forecasting which relies on an accurate representation of PBL conditions (e.g., James et al. 2018). A synergistic use of atmospheric modeling and observations of the vertical profile of atmospheric stability will be needed to improve the understanding of PBL processes in complex terrain and in coastal regions. In addition, solar energy is strongly affected by the presence of clouds, and PBL clouds are extremely difficult to realistically simulate in any model. This community requires improved predictions of PBL clouds, which requires an improved understanding of PBL thermodynamic properties and processes that lead to the formation and dissipation of these clouds.
- Marine weather – Marine weather forecasts are of significant value to a wide range of societal needs from economic to national security. Two of the most important aspects of weather that affect traditional maritime industries such as shipping, and emerging industries associated with ocean mining and marine biotechnology, are PBL winds and high waves particularly associated with extreme weather events. Coastal weather impacts industries, such as the burgeoning offshore wind energy industry, which is affected by a variety of PBL conditions. Coastal low-level jets and sea breezes can have a large impact on the air quality in coastal cities through their strong influence on PBL evolution (e. g., De Tomasi et al. 2011). Storm surges associated with tropical and winter storms affect lives and property near the coasts. Dense fog and spray in high winds impact visibility and creates hazardous operating conditions. These conditions in the marine PBL are most difficult to forecast. The difficulty of operating in the marine environment ranging from poor visibility to high seas conditions places a premium on marine weather forecasts, particularly of extreme events such as hurricanes and winter storms. The improved characterization of the spatial variability of the profile of temperature and water vapor, especially in coastal regions, is essential for many of these applications.
- Fisheries – At time scales of days to weeks, the PBL has a remarkable influence on the thermodynamics and dynamics of the upper ocean in upwelling regions where fisheries often play a critical economic role. At time scales of the order of weeks to months, marine heat waves across the world's oceans result in local warming of the ocean and also in thermal displacement, a measure of how far mobile species must move to track their ocean surface temperature habitats. At seasonal time scales, a better prediction of El Niño evolution provides relevant information to the management of fisheries off the west coast of South America. A better prediction of ENSO relies to a large extent on the proper characterization of Kelvin wave propagation across the tropical Pacific basin, which in turn depends on the ocean mixed layer depth. This depth is strongly influenced by surface fluxes, hence by processes occurring in the PBL. At climate scales, long-term temperature shifts associated with ocean warming have important implications for coastal communities if the locations of commercial fish species shift (e.g., Rice and Garcia 2011; Fiechter et al. 2015; Tommasi et al. 2017; Hobday et al. 2018; Morley et al. 2020).
- Ecosystems – The distribution of biodiversity on Earth is intimately linked to atmospheric processes and biological diversity acts to stabilize ecosystem functioning. For example,

the characterization of changes in diurnal environmental cycles are important to understanding marine and terrestrial animal movement and habitat use, while seasonal changes are important in driving migratory and dispersal patterns. Ecosystem modeling requires an accurate description of bioclimatic variables, such as temperature (and temperature extremes), water vapor and precipitation. PBL hydrometeorological and air quality processes also influence ecosystem dynamics and therefore the evolution of ecosystems at climate time scales (e.g., Xia et al. 2017; Jacox, et al. 2020).

- Transportation – On short time scales, these include aviation weather forecasts (e.g., fog, ceiling heights, turbulence, convection), road conditions (e.g., icing conditions), sea conditions (e.g., wave forecasting) and operations for unmanned aerial systems (UAS) (e.g., Watkins et al. 2010). In addition, maritime transport is amongst the most important modes of transport and shipping used worldwide, with approximately 90% of traded goods carried by ship. Improving the accuracy of marine weather forecasts, as discussed above, is crucial to marine transport. All of these transportation applications require profiles of temperature and water vapor near the surface.
- Urban – Many urban processes occur at high spatial resolution because of the impact of buildings and changes to the surface roughness and albedo on the temperature, water vapor, and wind patterns in a city. Models that predict these geophysical variables need new datasets to evaluate them in order to fully understand the interplay between the atmosphere and the urban landscape, and thermodynamic profiles are among the highest priority. This is especially true for cities located in coastal regions, where land-sea breezes impact the thermodynamic structure and PBL height (Bauer 2020). These urban processes are critical to understand and predict urban air quality (Li et al. 2017).
- Wildfire applications – At short time-scales, the near surface profiles of temperature and water vapor are important for the prediction of how hazardous a fire may become (e.g., Potter 2012; Strada et al. 2012). Water vapor profiles are useful for understanding the evolution of drought-like conditions and the state of the surface fuels, both of which are linked to hazardous wildfire events. These applications require improved characterization of temperature and water vapor profiles, especially in complex terrain where wildfires are difficult to fight.
- Radio wave propagation – Knowledge of the near real-time thermodynamic structure of the atmosphere, especially surface-based and elevated inversions, helps to characterize and predict the existence and locations of ducting layers that affect how radar energy propagates (e.g., Atkinson et al. 2001); this is extremely important for military and homeland security applications.
- Infectious diseases – The transmission of many infectious diseases strongly depends on weather and climate conditions in the PBL where humans and animals that carry these diseases reside. Near-surface water vapor and temperature have been shown to play key roles in the transmission and seasonality of respiratory diseases such as influenza (e.g., Shaman and Kohn, 2009). Models forecasting diseases like influenza at scales from weekly to seasonal have been used increasingly by stakeholders such as the Centers for Disease Control and Prevention, including models driven by environmental conditions (e.g., Biggerstaff et al. 2018). The COVID-19 pandemic has further highlighted the need to understand associations between transmission and weather conditions for informed decision-making (e.g., Moriyama et al., 2020). Climate variability, specifically the El Niño-Southern Oscillation (ENSO), has been shown to influence the year-to-year variation of seasonal outbreaks of cholera in Bangladesh (Martinez et al. 2017). Vector-borne diseases such as Dengue, Zika and West-Nile Virus are carried by mosquitos whose lifecycles are influenced by thermodynamic conditions in the PBL and a changing climate

can result in expanded regions of associated disease risk (e.g., Santos-Vega et al. 2016; Iwamura et al. 2020). Improved understanding of the complex interaction between humans, disease carriers and the environment and applications of these relationships in forecasting and monitoring requires datasets of thermodynamic near-surface variables across a wide range of spatial and temporal resolutions.

Adequate horizontal and vertical resolution for many of these PBL applications are crucial. For example, the forecast needs for a UAS delivery system in an urban environment may require horizontal resolutions of the order of 10s of meters; atmospheric chemistry and AQ applications often require resolutions of the order of 100s of meters; and hydrometeorological and storm-scale weather prediction models can often be successful with resolutions of the order of a few kilometers. Adequate resolution is also needed for the applications that have requirements in areas of the globe characterized by strong horizontal gradients in the surface properties such as mountainous and coastal regions, regions with open seas and ice, and urban environments. Additionally, many of these applications require observations from different climatic regimes. This suggests that observations need to come from a range of sources; for example, satellite observations to sample different climatic regimes, and airborne or surface-based observations to provide local higher temporal/spatial resolution observations.

Many of these applications are used for decision support in an operational framework. Many require more research in order to improve our basic understanding of PBL processes and to represent this understanding in the models that generate the forecasts used for these applications. The applications also require that we improve our ability to initialize these models with PBL observations, thus most of the applications discussed here rely heavily on improving both the data assimilation and modeling systems discussed in a following chapter. The improvements that are needed in these applications will drive new research (applications-to-research process, A2R).

We note that many of these efforts tie closely to the program areas of the NASA Applied Sciences Program, and the links are further discussed in Section 9.2.

6. PBL MODELING AND DATA ASSIMILATION

From the discussions in the previous chapters, it is clear that in order to address key PBL science and applications questions, a future global PBL observing system requires modeling and data assimilation as essential components of an integrated PBL framework. This chapter covers key aspects of modeling and data assimilation, including scientific targets such as the unification of PBL parameterizations across scales, the role of modeling and data assimilation in the context of a potential PBL mission, and PBL Observing System Simulation Experiments (OSSEs).

6.1 MODELING

Modeling plays a fundamental role in better understanding, monitoring and predicting the PBL, and its variety of manifestations and interactions. It is fair to state that modeling of the PBL started with the first modern studies of turbulence in the early 20th century – several of the key physical concepts devised during this period still play a critical role in current PBL models and parameterizations as is discussed in chapter 4. PBL modeling activities can be divided in essentially four categories (or types) of models that cover a wide span of spatial and temporal scales: i) Large-Eddy Simulation (LES); ii) regional/mesoscale; iii) global short- and medium-range weather prediction; and iv) global climate (Earth system) prediction models.

LES models, originally developed in the late 1960s and early 1970s (e.g., Lilly 1967; Deardorff 1970; Schumann 1975), have been over the last few decades an essential element in PBL science and parameterization development. LES are fully three-dimensional (3D) models that explicitly resolve individual PBL thermals and clouds. Typical grid resolutions range between 1 m and 100 m depending on the PBL regime, while computational domain sizes are typically from about 10 km to 100 km. LES are designed to explore the interplay between the small-scale turbulent dynamics, often associated with clouds and thermals, and the larger-scale environmental conditions that give rise to them. LES are models in which most of the energy-containing motions are explicitly computed while motions smaller than a certain cutoff scale, usually the computational grid spacing, are parameterized. These parameterizations of LES sub-grid flow are often more reliable than the parameterizations of sub-grid flow in mesoscale, regional or global atmospheric models. Figure 6-1 shows the 3D PBL cloud structure from an LES simulation of a shallow cumulus case (Matheou and Chung 2014) from the Rain in Cumulus over the Ocean

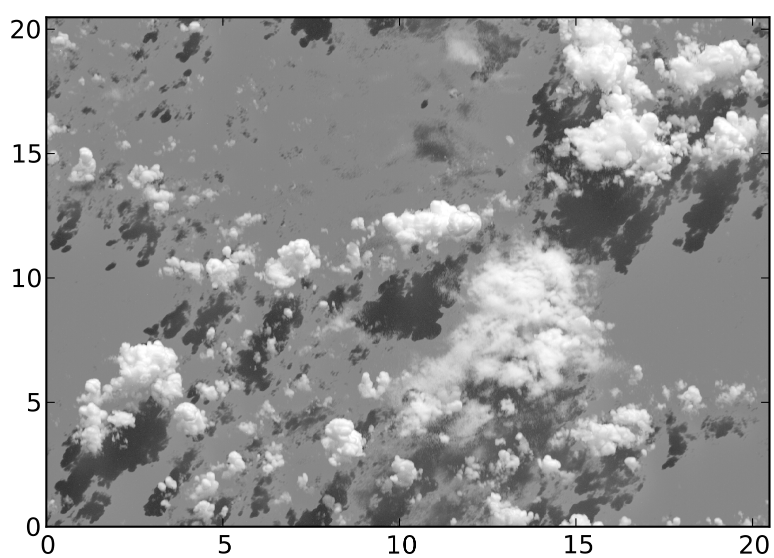

Figure 6-1. Cloud structure from an LES simulation of the shallow cumulus RICO case (domain x and y axis are in km) illustrating the realism of LES for generating PBL virtual data. From Matheou and Chung (2014).

(RICO) field campaign, illustrating well the exceptional realism of some LES in generating PBL virtual data. These LES data can be utilized for a variety of purposes, including (i) better understanding of PBL physics, (ii) PBL parameterization development and (iii) Observing System Simulation Experiment (OSSE) studies.

Regional and global atmospheric models all have horizontal resolutions (from about 1 to 100 km) that are not fine enough to resolve PBL turbulent and convective flows (as LES does) and as such, PBL turbulence, convection and clouds need to be parameterized (e.g., Teixeira et al. 2008). Different approaches to PBL parameterization in atmospheric models have been developed over the last few decades, but several of these parameterizations tend to be modular – i.e., representing one specific manifestation of PBL turbulent mixing such as the stratocumulus-topped PBLs. To avoid this modularity, a recent focus of the PBL parameterization community has been to develop unified PBL parameterizations that represent in an integrated manner all the different manifestations of turbulence and convection in the atmosphere (including deep moist convection). In particular, approaches based on the unification of the Eddy-Diffusivity (ED) approach for small-scale mixing and the Mass-Flux (MF) approach for PBL-scale plumes/thermals, referred to as EDMF (e.g., Siebesma and Teixeira 2000; Siebesma et al. 2007; Šušelj et al. 2013), and on higher-order closures such as the Cloud Layers Unified By Binormals (CLUBB, e.g., Golaz et al. 2002a, b; Larson et al. 2002) have been recently successfully implemented operationally in global weather and climate models.

The equations and numerical algorithms of PBL parameterizations are often quite similar across these different modeling applications (from regional to global, and from weather to climate), which allows for significant cross-pollination of ideas within the PBL parameterization community. Several regional/mesoscale and global atmospheric models are used for operational weather prediction (from hours to months depending on the modeling systems and the applications) and in this context issues related to the interaction of PBL parameterizations with data assimilation are critical to consider (see below). Besides the unification of PBL parameterizations, critical physical aspects that the parameterization community has been recently focusing on include the interaction of PBL with deep convection, PBL clouds, and the interaction with the surface.

A fundamental PBL parameterization problem that the community has recently been focusing on is the issue of scale-adaptive PBL parameterizations – i.e., parameterizations that explicitly depend on the horizontal resolution of the model they are imbedded in, and are able to realistically adapt to the resolution so that the behavior of the parameterization changes appropriately for different model resolutions. Developing and testing these parameterizations may need additional observations, especially as these resolutions are often in the turbulence gray zone (i.e., between about 100 m and 1000 m).

As described in detail in chapter 5, regional and global atmospheric models are also used for a variety of applications besides weather, seasonal and climate prediction, including dispersion of contaminants in the atmosphere and renewable energy forecasting. In this context, PBL modeling also plays a key role and much research has been recently devoted to PBL modeling and parameterization in these areas.

While PBL parameterizations are quite similar across weather and climate models, relevant science questions and problems do exhibit some key differences, with important implications for PBL parameterization priorities and observational requirements. It is well understood that climate models require tuning to radiative balance because the combined effect of many parameter uncertainties on radiative budgets far exceeds both observational and basic process constraints on those budgets. Such uncertainties are not limited to cloud physics parameters, although those are most commonly used for tuning to radiative balance because of their outsize influence on shortwave and longwave radiative budgets. Since climate models do not employ approaches such as data assimilation in their most important projection exercises, it can be expected that they may exhibit some unique sensitivities to PBL and other physical parameterizations compared with weather models and data assimilation systems.

In climate projections, relatively small differences in the predicted evolution of cloud properties in a warming world can lead to roughly a factor of two to four uncertainty in how much the surface is projected to warm. In the case of PBL clouds, a very high priority is therefore placed on the PBL cloud processes that most impact radiative fluxes either directly or indirectly, including cloud fraction, optical depth, mesoscale organizational state, processes that control transitions from stratocumulus to cumulus, and the efficiency of water vapor venting from the PBL at lower latitudes. As discussed, temperature and water vapor profiles play a key role in these processes.

Assessing the value of specific PBL observations for weather (e.g., initial state) or for climate predictions (e.g., for narrowing uncertainties in climate projections) is a critical topic that needs to be addressed in a focused manner by the PBL community during the next few years. As an aside, we note that a data set that is unsuitable for NWP data assimilation (e.g., insufficient swath width or revisit frequency) may nonetheless be highly suitable for statistical climate model evaluation. An overall goal of the community should be a better understanding and modeling of the PBL in the larger context of Earth System Science – in particular, the role of the PBL in coupling between the atmosphere and land/ocean/ice surfaces.

6.2 DATA ASSIMILATION

The fundamental goal of any data assimilation procedure is to minimize the difference between a prior atmospheric state, typically a short-term forecast, and observations while maintaining a physically consistent state. By using the error characteristics of both, the system gives more weight to the observations in regions of high model uncertainty. Furthermore, modern ensemble-based methods allow for flow-dependent cross-correlations between the atmospheric state variables, allowing localized measurements to influence the model's initial state at other locations away from where the observations were made.

Data assimilation algorithms aim to effectively combine pieces of information from a broad range of observation types in order to minimize this uncertainty. For some observations, the links are straightforward - conventional observations generally map simplistically between observation and model (or state) space. For other observations, the process can be more complex. For example, satellite radiances from atmospheric sounders and bending angle retrievals from GNSS radio occultation measurements require complex forward models to convert between observation and state space. Core to any attempt to assimilate spaceborne measurements is the need to accurately convert between the model and state space (e.g., Derber and Wu 1998; Healy and Thepaut 2006), and therefore the need for forward models that can be used to accurately simulate the observations but also be utilized efficiently within the data assimilation procedure.

For the PBL, the use of these observations in data assimilation is often complicated by the underlying complexities translating into analysis uncertainties. In radiance assimilation, PBL-sensitive observations generally have a strong surface contribution. Over the ocean, these observations generally have a larger impact due to surface homogeneity, while over land and sea ice, surface heterogeneity translates to emissivity uncertainty. If not fully handled or understood, this translates to observation uncertainty. In radio occultation, it is difficult to partition the information content near the surface between the temperature and water vapor components of the fundamental observational sensitivity to atmospheric density, and this difficulty increases towards the PBL as water vapor increases. In operational data assimilation, it is common to avoid using these RO observations in the lower troposphere for these reasons. This is further complicated when trying to assimilate direct estimates of the PBL height, as the measurements are often a proxy of other retrieved quantities in observation space. Furthermore, the model PBL height is often a diagnostic variable. Current efforts are investigating the use of ensemble methods to propagate the

PBL height measurements into state space (Tangborn et al. 2021). In terms of assimilating retrieved thermodynamic PBL profiles, there has been recent work assimilating profiles from surface-based instruments such as the Atmospheric Emitted Radiance Interferometer (AERI) and DIAL into regional models for NWP impact assessment (Thundathil et al. 2020; Degelia et al. 2019; Hu et al. 2019). As is the case for PBL height, further development of assimilation strategies to properly incorporate PBL profiles into various model configurations (including coupled land-PBL assimilation) will be required over the next decade in order to realize the full value of these profile observations.

One of the key issues regarding the analysis of the PBL within the context of a data assimilation system is the sensitivity of the PBL, which is largely parameterized, to its initial conditions. If the parameterizations have a fundamental inability to retain information from the data assimilation procedure, then that information will not be retained when projected forward by the model into short and medium range forecasts, including the next background state. Core to understanding the role of a future spaceborne satellite mission targeting the PBL, it will be critical to know how the information content of the PBL observations will be retained in a data assimilation system.

Just as in modeling, data assimilation must deal with different problems and considerations to be undertaken when considering the role of spatial, vertical, and temporal resolution, particularly as they relate to the scales of the models that are leveraged as the background state. However, the traditional resolution gap between mesoscale/regional models and global models is collapsing as modern computing advances have led towards a realm of global mesoscale modeling, but these models are resource intensive. To develop these models and their fundamental assimilation capability towards PBL will require a commitment to advance both the computing and scientific capabilities. Furthermore, there is an important role for LES models in the context of data assimilation. Unlike other atmospheric models, LES models are able to almost fully resolve the small-scale turbulent PBL flow. These LES models, coupled in some form with mesoscale or global weather models, could be used to assimilate PBL observations in specific focused regions and regimes.

A large component of data assimilation in global earth system models and reanalysis is related to the advancement of coupled data assimilation across the land, ocean, and atmosphere. Specific to this is the extension of the atmosphere from weather prediction to coupled weather, chemistry, and constituent processes. The PBL plays a fundamental role in how these Earth system components physically interact. Thus, just as the PBL plays an important role in the science across these systems, data assimilation has a fundamental need to advance alongside the science to allow for better observational constraints across the different Earth system components.

In summary, the key challenges for data assimilation of PBL information are related to three main developments: i) forward operators, ii) current solvers (e.g., variational, EnKF) versus cutting edge solvers (e.g., non-Gaussian methods such as particle filter), and iii) the utility of parameter estimation. The role of data assimilation in the exploitation of a complex architecture with multiple PBL observational systems is a critical topic for focused future investigations by the PBL community.

6.3 THE FORMULATION AND ROLE OF OSSES IN THE CONTEXT OF A FUTURE PBL MISSION

The traditional NWP OSSE (Atlas et al. 1985; Arnold and Dey 1986) focuses on using simulated observations in conjunction with a data assimilation system to quantify the potential impact of future observing systems on weather forecasts. At its core, the observations are simulated from a free-running model integration known as a 'nature run'. This nature run serves as not only a basis for simulation but also an underlying truth to the assimilation and forecast solutions.

A shortcoming of this traditional NWP OSSE, as is the case with any simulated study, is a fundamental lack of underlying error in the system - be it observation errors, model errors, and forecast errors. This may be particularly true with OSSEs that target the PBL, where parameterizations are used in even the highest resolution NWP models. A critical problem for traditional NWP OSSEs is that nature runs are often not realistic. In the case of the PBL, the typical resolution of nature runs is still fairly coarse and as such does not resolve critical aspects of the PBL. For effective simulator experiments applicable to the PBL, nature runs that realistically approximate PBL structure are absolutely essential. LES should play a key role in this context in bridging resolution issues that traditional global OSSEs lack. Nonetheless, in the context of a spaceborne mission, the simulations must still be globally representative. This could be achieved by using LES models to simulate a large variety of PBL case studies that should appropriately sample the variability of PBL physics and types.

The metrics for the traditional NWP OSSEs - generally metrics of forecast error reduction - will likely not be the best metrics in assessing the information content gained via observations in a PBL-targeted mission. As there is still much work to be done to develop data assimilation methods suitable for and targeted at the PBL, it is not advisable to rely on a traditional NWP OSSE to determine the prioritization of observation types without further development. It may be more suitable to consider a more symbiotic approach to mission development and preparedness - where a coordinated strategy can be leveraged not only for assessing potential observation types, but also to serve as a leveraging point for PBL-specific data assimilation development. This work can be performed in sync with targeted efforts at leveraging Program Of Record (POR) observations that are unutilized (e.g., spaceborne estimates of PBL height) or underutilized (e.g., surface-sensitive passive radiance measurements) in current data assimilation systems. At the core, data assimilation can provide four-dimensional estimates of the PBL state, but there needs to be further development for data assimilation to optimally do this.

The term OSSE is also often generalized to include sampling, measurement simulation, and remote sensing retrieval studies (Zeng et al. 2020). The fundamental foundation is similar – obtain a suitably realistic reference representation of nature, simulate a variety of measurement types by converting the nature run into observation space, and make assessments based on those results. In a sampling study, the goal may simply be to assess how often a phenomenon will be measured as a result of orbit or information content. Sampling experiments may be made more sophisticated by incorporating measures of the difference between the sub-sample and the full sample (e.g., via information theory). More advanced measurement simulation approaches may integrate (potentially joint) retrieval methods (or even data assimilation or fusion) to perform retrieval inversions on the simulated data to map the virtual observations back into geophysical space. If the various sources of uncertainty are properly accounted for, the result can be used to determine whether measurement requirements have been met. In either case, the underlying concept - comparing simulated information content to the underlying virtual true state – is at its core and is not that different from the traditional NWP OSSE.

From both a data assimilation and retrieval perspective, a multi-scale approach towards the generation of simulated observations should be considered. This is core to the pre-launch assessment of information content within proposed PBL-targeted mission architectures. The linkage between the high spatial resolution of LES, mesoscale/regional, global, and climate models will be useful in generating simulated observations at the proposed instrument resolutions while containing the sub-scale measurement variability which the instruments will be sensitive to but perhaps unable to explicitly resolve.

These varying methods have complementary roles in both the pre-launch evaluation of a PBL mission and in the post-launch exploitation of the PBL-targeted data. Data assimilation methods are advantageous in that they more-readily fuse spatially irregular data and impose a physical constraint by leveraging the physical laws coded into atmospheric models. Retrievals benefit from an ability to include more complexity in the solution due to their limited spatiotemporal dimensionality. In both cases, the mathematics and underlying physics are often similar if not nearly identical, but the assumptions used to make the solution practical differ.

If a common software infrastructure is utilized, multiple forms of an OSSE can benefit mutually from PBL-focused developments. In data assimilation, many centers employ 1D+4D variational approaches in their implementation strategies. For microwave all-sky assimilation at ECMWF, the approach was developed using a 1D+4D variational approach before it was fully integrated into the 4D-Var solution. At the U.K. Meteorological Office, a 1D-Var preprocessor has been used as a steppingstone for integration into the 4D-Var assimilation. NOAA NESDIS has experimented with the use of the Multi-Instrument Inversion and Data Assimilation Preprocessing system (MIIDAPS) retrieval (Boukabara et al. 2011) as a preprocessor for the assimilation systems. From the retrieval perspective, the inclusion of better prior information from physically consistent solutions (e.g., a short-term forecast) may allow for better information content exploitation. From a data assimilation perspective, better first-guess knowledge may be available via physical retrievals that then can translate into an improved four-dimensional state.

Furthermore, approaches to perform analogues to OSSEs for climate models should be considered in the context of the PBL. For instance, climate models have been used to assess the characteristics of GNSS-RO observations required to constrain expected decadal trends of temperature. In this “OSSE for climate monitoring”, realistic estimates of both observational errors (instrument- and retrieval processing-related) and sampling errors (due to spatial-temporal under-sampling) were made and compared to projected decadal trends in temperatures. Recent studies have used a similar approach to establish the required length of uninterrupted spaceborne lidar and radar measurements and intercalibration requirements in order to constrain cloud feedbacks, with particular relevance for the future ACCP mission. Studies targeted to investigate the impact of specific PBL observables should include use of the CMIP6 archive, bespoke novel diagnostics for comparison with observations from candidate architectures, and should pursue multiple lines of investigation (e.g., predicted global circulation patterns that are sensitive to PBL representation in climate models, impact on predictions from seasonal to longer timescales, climate sensitivity, and others to be systematically identified).

NASA has already developed a number of capabilities that address several of the aforementioned issues. The Global Modeling and Assimilation Office (GMAO) has numerous OSSE capabilities - ranging from NWP applications to constituent-targeted studies. Recent collaborative efforts have extended these capabilities to collaborators outside the GMAO. At JPL, retrieval capabilities have been developed to provide a modular and extendable framework to tie different retrieval methods into simulator trade space studies. Other tools have also been funded by NASA to investigate constellation configuration and design to map mission requirements onto constellation architectures (Le Moigne et al. 2017). These tools, however, do not share a common infrastructure, existing capabilities are largely disconnected, and use of OSSEs for climate applications requires foundational development. An effort to determine how to bridge the capabilities of these tools would provide NASA with a more sophisticated capability to design a PBL mission. Moreover, it could provide a more complete end-to-end capability to also provide a broad suite of simulated data on which data assimilation and retrieval algorithms could be developed in unison, rather than isolation, with the target of mission preparedness. A fundamental requirement to a unified effort would be the mutual effort to integrate into a community-based framework that will likely set the groundwork for the next decade. From a data assimilation perspective, the Joint Effort for Data assimilation Integration system will serve as the basis for data assimilation across multiple earth system components at the GMAO for the foreseeable future. Additionally, it will provide a model-agnostic infrastructure that will allow for data assimilation methods to be performed across different models, resolutions, and solution methods.

6.4 SUMMARY

In general, a key finding of this chapter is that for PBL modeling, data assimilation and OSSE studies, there should be a concerted effort by NASA to harmonize and coordinate the diverse PBL modeling and data assimilation activities and capabilities that already exist and are funded by NASA: from global weather modeling and data assimilation at GMAO to climate modeling at GISS, and from LES modeling and PBL parameterization development to instrument forward models and retrievals. Such harmonization and coordination would be of great value for the creation and optimal utilization of a future PBL global observing system.

7. PROGRAM OF RECORD

Observations from research and operational satellites have been essential for advancing science and applications and for demonstrating new capabilities. While observations from operational systems are critical to sustaining forecast systems, their synergistic use for research is equally important. The operational utilization of new research instruments has led to improved weather and air quality forecasts. For example, observations from the infrared and microwave sounders and Global Navigation Satellite System radio occultation (GNSS-RO) are routinely incorporated in operational NWP models. Cloud top Atmospheric Motion Vectors (AMVs) derived from geostationary satellites are also assimilated operationally to improve forecasts. Furthermore, geostationary observations provide the environmental perspective needed for interpreting profile observations from low earth orbiting polar satellites such as Aqua, CALIPSO, and CloudSat. The ability to leverage research and operational satellite observations to extend the POR until a new and improved PBL observing system is realized is critical.

The increasing demands for higher spatial and temporal resolutions to address many aspects of PBL science and applications require new remote sensing technologies and sampling strategies from both research and operational satellite systems. Existing and future POR geostationary sensors provide high temporal resolution over a given hemisphere, while low-Earth orbiters provide global coverage with higher spatial resolution but with less timely sampling. CubeSats provide opportunities not only to test new technologies and focused sampling strategies but also to fly low-cost missions and constellations. The Afternoon Constellation (A-Train) as well as GNSS based constellations such as COSMIC and CYGNSS have demonstrated the value of formation flying and should pave the way for future PBL mission strategies.

In the last two decades, the science community has benefited from a number of weather and climate focused satellite missions that have enabled breakthroughs in understanding key atmospheric properties and processes. These satellites together form the POR, which will be continued throughout their instrument/spacecraft lifetime and will be supplemented in the future with planned satellite missions. Additionally, airborne measurements and surface-based networks serve to bridge the spatial and temporal observational gaps. Table 7-1 provides a list of the most critical elements of the existing and planned space-based observing system POR capable of measuring PBL parameters, and summarizes some of their relevant characteristics and current limitations.

Table 7-1. Key Spaceborne PBL Measurements of temperature (T), water vapor (q), and PBL height (PBLH) from the current and future (in blue) POR.

Instrument Type	Instrument (Platform)	Physical Parameters	Resolution and Accuracy *	Applicability or Limitations
Hyperspectral IR	AIRS (Aqua) CrIS (Suomi NPP, JPSS) IASI (MetOp) IRAS/HIRAS (FY-3 series) IASI-NG (MetOp-SG) IRS (MTG) [GEO]	T, q profiles	T: 1 km (v) 14 km (h) 1 K (a) q: 1-2 km (v) 14 km (h) 10% (a)	Clear sky; Limited vertical resolution
Microwave Radiometer	AMSU (Aqua, MetOp) MHS (MetOp) ATMS (Suomi NPP, JPSS) MWHS/MWHS-2 (FY-3 series) MWS (MetOp-SG) TROPICS	T, q profiles	T: 2-4 km (v) 40 km (h) 1-2 K (a) q: 2-4 km (v) 40 km (h) 10-20% (a)	Limited vertical resolution

GNSS-RO	GRAS (MetOp) IGOR (TSX, TDX, KOMPSAT-5, PAZ) TriG (COSMIC-2, Sentinel-6) TriG-Lite (GRACE-FO) GNOS/GNOS-2 (FY-3 series) Commercial GRAS-2 (MetOp-SG)	T, q profiles, PBLH	T: 200-500 m (v) 1x100 km (h) 1-2 K (a) q: 200-500 m (v) 1x100 km (h) 0.5-1 g/kg (a) PBLH: 100-200 m	T & q retrieval not fully decoupled; Limited horizontal resolution and sampling; known bias & depth penetration
Lidar	CALIOP (CALIPSO) ICESat-2 ATLID (EarthCARE) HSRL/Backscatter (ACCP)	PBLH	PBLH: 100-200 m	PBLH from aerosol and cloud
Multi-hyperspectral Imagery	OLI, TIRS (Landsat 8+) Commercial Imagers MODIS (Terra, Aqua) MISR (Terra) VIIRS (Suomi NPP, JPSS) ABI (GOES 16+) AHI (Himawari 8+) FCI (MTG-I) GMI (GPM Core) AMSR-2 (GCOM-W) WSF-M (WSF-M) EMIT (EVI-4) SBG ESAS 17 (HyspIRI)	PBLH (CTH/CTT) TPW	CTH: 200-300 m TPW: 10 m-1 km (h) 3-5 mm (a))	PBLH from cloud top (cloudy PBL only) Daytime only Lacks vertical resolution (TPW only)

** (a): accuracy, (h): horizontal resolution, (v): vertical resolution*

7.1 PBL HEIGHT

The PBL height, which is the vertical depth of the PBL, is a critical parameter for a variety of PBL science and applications topics and questions. It determines the volume available for the dispersion of pollutants and consequently the concentration of pollutants near the surface. It plays a key role in the mixing that takes place at the PBL top and at the surface (e.g., surface heat and water fluxes). The PBL height is involved in many predictive and diagnostic methods and/or models to assess pollutant concentrations, and is often an important parameter in some atmospheric models (e.g., as a key term in some PBL mixing parameterizations). However, unlike geophysical variables like temperature and water vapor, which are key prognostic variables of the fundamental partial differential equations that describe the balance of energy and water in vapor phase in the atmosphere, the PBL height is a diagnostic quantity and, in this context, is a parameter whose definition and estimation is not as straightforward.

Ideally, since the PBL is the turbulent layer of the atmosphere adjacent to the surface, the PBL height should be defined on the basis of the amount of turbulence characterized by the profile of variables like turbulent kinetic energy (TKE). Unfortunately, turbulent (i.e., higher moment) variables like TKE are notoriously difficult to observe from a local perspective let alone from a global perspective. Instead, quantities like the Richardson number, which can be estimated using mean values of geophysical variables that are easier to observe, are used in lieu of variables like TKE. The PBL is often convective, and in these convective PBL regimes, the vertical gradients of temperature, water vapor or relative humidity (or other combinations of mean thermodynamic variables) are used successfully to estimate the PBL height fairly accurately. The main issue in this context is obtaining temperature and water vapor profiles with vertical resolution that is fine enough for accurate estimates of the PBL height.

A critical aspect related to defining PBL height is that in many circumstances the PBL height is not well defined or may not even exist, as the PBL itself may not be well defined. These circumstances include: i) in deep convection situations the PBL is often not well defined because intense vertical mixing and transport takes place across the full troposphere rather than just within the PBL; ii) over land during nighttime there often is a turbulent residual layer (from the previous daytime convective PBL) overlaying a stable PBL close to the surface; iii) in certain regions/regimes (e.g., polar) there are turbulent cloud layers fairly close to the surface that are decoupled from a stable PBL close to the surface.

In practice, several methods have been used for estimating the PBL height from observations and from model forecasts or reanalysis. Observation-based estimates include the use of radiosondes (e. g., Seidel et al. 2010), aircraft (e. g., Dai et al. 2014), sodar (e. g., Contini et al. 2008), radar wind profilers (e. g., Molod et al. 2015), ceilometers (e. g., Caicedo et al. 2020), surface-based and airborne, and space-borne elastic backscatter lidar (e. g., Scarino et al. 2014; Luo et al. 2014, 2016), water vapor lidar (e. g., Turner et al. 2014), and Global Navigation Satellite System Radio Occultation (GNSS-RO) (e. g., von Engeln et al. 2005; Ao et al. 2012). Seibert et al. (2000) described multiple PBL height estimation methods and concluded that the applicability of a particular PBL height method is dependent on the meteorological conditions and that different methods can result in large differences in the estimated PBL height. The wide range of PBL height estimates that can result from the same data is also demonstrated by Sivaraman et al. (2013), who applied three estimation techniques (parcel, Liu and Liang (2010); gradient, Heffter (1980); and Bulk Richardson, Sørensen et al. (1998)) to radiosonde data over the Southern Great Plains and found correlations among the different estimates of the order of 0.7, mean absolute difference of the order of 200 m and that the biggest differences occur during neutral conditions. Von Engeln and Teixeira (2013) produced a global climatology of PBL height using ECMWF reanalysis data and have also shown that slightly different estimation methods can lead to significant differences in PBL height for specific PBL regimes.

Table 7-2. Different methods to estimate PBL height, the corresponding summarized physical basis, and the required observations, model or reanalysis fields for each method.

PBLH Method	Physics	Observations	Models/Reanalysis
Gradient Method	Height of inversion	T & q profiles, radiosondes, aircraft, satellite retrievals	Profiles of T & q
Parcel Method	Buoyancy	T & q profiles, radiosondes, aircraft, satellite retrievals	Profiles of T & q
Threshold of bulk or gradient Richardson number	Turbulence/stability	T, q & winds profiles, radiosondes, aircraft, satellite retrievals	Profiles of T, q & winds
Backscatter Maximum	Bragg scattering	Backscatter or SNR profiles, satellite, ground-based or aircraft	Forward model to estimate backscatter from model state
Thresholds in aerosol amount and vertical distribution.	Mixing of tracers/constituents	Aerosol profiles, space-based airborne, & surface-based lidars	Aerosol profiles
Maximum water vapor variance	Mixing of moist PBL air with dry free tropospheric air	Aircraft and ground-based water vapor lidars	Profiles of q

Threshold in turbulent kinetic energy/eddy diffusion coefficient	Turbulent intensity	Turbulent fluxes, eddy covariance measurements (profiles) from in situ sensors or Doppler lidar	Parameterization estimates
Vertical gradient in bending angle or refractivity	Temperature and/or water vapor changes at the top of the PBL	Bending angle and/or refractivity profiles	Forward model to compute refractivity or bending angle from model state (T, q, p)
PBL cloud height	PBL stratiform cloud tops often coincide with PBLH	PBL cloud height, ground-based or satellite measurements	Model PBL clouds

Each of the methods above has advantages and limitations. For instance, radiosonde launches, while performed operationally in numerous locations across the world, are often temporally limited to twice per day. Aircraft sampling provides spatial information that is useful, but it is generally limited to particular regions or specific campaigns and is quite expensive. Both elastic backscatter and water vapor lidar have high sampling rate and resolution, but are limited to non-precipitating situations. GNSS-RO has a relatively coarse horizontal resolution of 100 km. Radar wind profilers, elastic lidars (including ceilometers), and water vapor lidars are all quite useful for measuring PBL height because they can be left unattended for extended time periods, can provide a continuous stream of data over time, and there are extensive networks of these lidars and of radar wind profilers in some regions of the world. Reanalysis and model-based estimates are available on a global scale, with high temporal frequency but are subject to uncertainties due to model formulation and PBL parameterizations. Finally, reconciling PBL height estimates from various sources (e.g., from thermodynamic variables and from aerosol backscatter profiles) or definitions (e.g., from model-based Richardson and from TKE approaches) remains a challenge for the community when attempting to combine observational datasets, models, or both. All of these limitations illustrate the lack of a set of comprehensive measurements available globally and at the temporal and spatial resolutions needed for advancing PBL science and applications. In the future, efforts are needed to provide consistent PBL heights across different observations to support model development and evaluation.

7.2 SATELLITE OBSERVATIONS

In this section, we provide a summary of the most impactful space-based POR observations that have been used to study the PBL.

Hyperspectral Infrared Sounding – High-spectral resolution infrared (IR) sounders such as the Atmospheric Infrared Sounder (AIRS; launched in 2002) significantly improve NWP forecast quality by providing critical initial condition information on temperature and water vapor profiles. Similar capabilities from the EUMETSAT Infrared Atmospheric Sounding Interferometer (IASI; launched in 2006, 2012, and 2018) and the NOAA/NASA Cross-track Infrared Sounder (CrIS; launched in 2011 and 2017) have augmented this crucial observational resource. These IR polar-orbiting sounders provide global temperature and water vapor soundings with ~14 km horizontal and ~1 km vertical resolution in the lower troposphere under clear sky conditions.

Measurements from space of PBL temperature and water vapor are extremely challenging because of fundamental physics constraints on probing the atmosphere so close to the surface. IR sounding is sensitive to the PBL structure and is often able (depending on the type of PBL and the process being analyzed) to realistically depict important PBL properties. For example, Martins et al. (2010) used AIRS to characterize the vertical thermodynamic structure of the shallow cumulus PBL and compared profiles from AIRS with sondes from the RICO field experiment. As Figure 7-1 illustrates, there are cases when the key features of the thermodynamic structure are well reproduced by AIRS. These results highlight the ability of IR sounders like AIRS to capture the thermodynamic structure of this important type of PBL despite its limitations in terms of vertical resolution. This is due to the fact that the thermodynamic structure of the shallow cumulus

PBL is often fairly smooth (no sharp gradients) with small amounts of cloud cover, which basically lead to more accurate temperature and water vapor IR sounder retrievals.

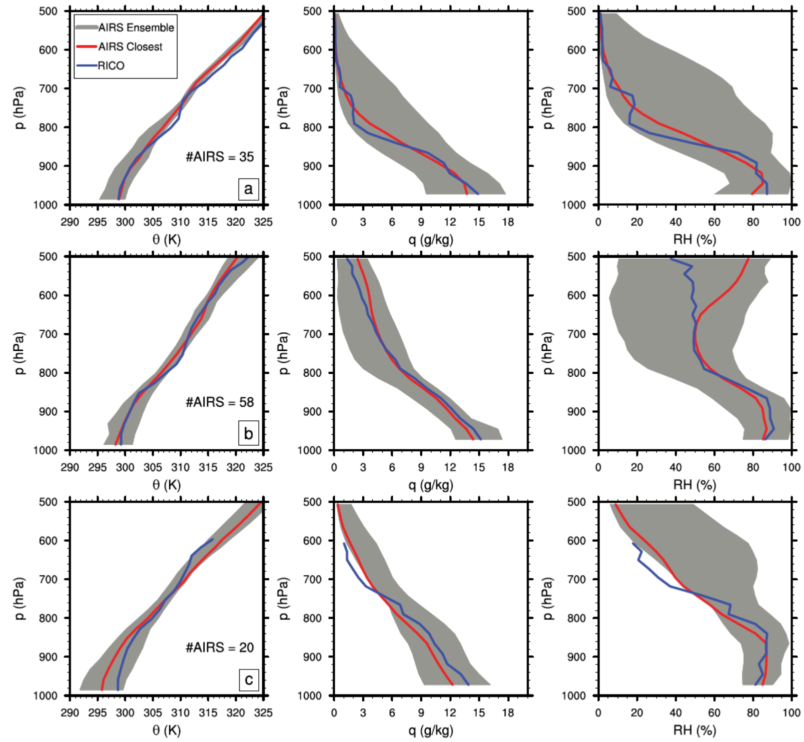

Figure 7-1. Hyperspectral IR sounders like AIRS can provide thermodynamic profiles in the PBL that are in broad agreement with radiosonde observations, although considerable uncertainty exists as partly illustrated by the shaded areas. Three examples of realistic AIRS retrievals of potential temperature (left), water vapor (middle) and relative humidity (right) during the RICO campaign. Sonde data (blue lines); AIRS sounding geographically closest to the sonde (red lines) and the ensemble of AIRS soundings that match the sonde location and time (gray shading). The number of AIRS soundings used in each case is also shown. From Martins et al. (2010).

To evaluate the quality of the AIRS temperature and water vapor profiles for different PBL types over the subtropical oceans, Kalmus et al. (2015) utilized about 500 sondes in the northeast Pacific and the ERA-Interim reanalysis. They found that AIRS-retrieved profiles are on average more accurate than ERA close to the PBL top because of a consistent underestimation of the ERA PBL height. In some circumstances, there is no need for high vertical resolution profiles to depict key aspects of the PBL. For example, bulk measures of the PBL vertical stability (e.g., Lower Tropospheric Stability – LTS – the difference between 700 hPa potential temperature and SST) are often enough to characterize PBL processes in insightful ways (e.g., Yue et al. 2011, 2013; Kahn et al. 2017).

As recognized by the ESAS 2017 decadal survey, a key ‘integral’ variable that characterizes the PBL in a unique manner is the PBL height. For most convective PBLs, the height corresponds to the height of the inversion in potential temperature and water vapor, and consequently in relative humidity. The AIRS project produces a PBL height dataset over the ocean based on the maximum vertical gradient of relative humidity that correctly represents, from a climatological perspective, key areas over the ocean where spatial variability is known to play a key climate role. For example, the growth of the PBL in the eastern subtropical oceans, as it flows along the trade winds toward warmer waters, changing from a shallow PBL (~500 m) close to the west coast of continents (e.g., off California) to a deeper PBL (~2 km) in the subtropical open ocean regions (e.g., close to Hawaii).

The AIRS near-surface temperature and water vapor are also of great relevance to PBL science and applications. This data is at the heart of the AIRS drought product that is now used operationally by the US Drought Monitoring system. AIRS near-surface temperature is also used for climate studies and has been compared to a variety of in-situ and reanalysis datasets (e.g., Susskind et al. 2019). AIRS near-surface water vapor has been used to estimate ocean surface evaporation and to study Arctic climate change (e.g., Boisvert and Stroeve 2015; Boisvert et al. 2015) directly addressing a critical ESAS 2017 question about the consequences of amplified climate change in the Arctic. Other AIRS observations critical for PBL science include integrated water vapor and PBL (low level) clouds. In addition, the bulk thermodynamic structure of the lower troposphere from IR-based profiles has been used for land-atmosphere coupling studies (e.g., CTP-HI; Ferguson et al. 2011), and for assessment of global hydrology and drought/extremes (Roundy and Santanello 2017).

However, the information content in the radiances of POR IR sounders in the lower troposphere is inherently limited. As a result, the ability to capture local vertical gradients of temperature and water vapor is limited, as is detection of the PBL height particularly over land. In addition, retrieval algorithms for IR sounders have been often optimized for full troposphere profile retrieval accuracies rather than for the PBL. Recent efforts involving statistical and neural network approaches to perform more ‘targeted’ PBL retrievals from AIRS have shown promise in extracting the signal of typical PBL structure (e.g., convective well-mixed layer and PBL top inversion). Given the breadth and length of the POR for IR that will continue into the 2030’s, it is important to consider supporting such approaches aimed at quantifying the PBL information that can be obtained from hyperspectral IR sounding, especially with the potential to improve spatial and temporal resolution of these sensors in future missions.

The IR POR will be continued in the future with IASI-NG which is currently planned to continue through 2043 and will have 16,923 spectral channels covering roughly the same bandwidth as IASI, providing twice the spectral resolution (0.25 cm^{-1}) and hence higher vertical resolution resulting from narrower weighting functions. A major advancement of IASI-NG over IASI is the 2× improvement in radiometric noise, leading to reduction in retrieved water vapor uncertainty by ~ 3–5%, although these improvements are realized between 800 and 200 hPa. The vertical resolution and accuracy of IASI-NG water vapor retrievals below 800 hPa will remain approximately the same as IASI, highlighting the need for improved retrievals even with the advent of new technology advances.

EUMETSAT in Europe is launching a geostationary hyperspectral IR sounder in 2021 as part of the MeteoSat Third Generation Satellite series with a spatial resolution of 4 km, and NOAA has proposed geostationary sounders as part of the next-generation GeoXO program with a targeted launch of 2032 (Sullivan 2021). The higher spatial resolution enables better clear sky sounding coverage. However, a prime objective is to support numerical weather prediction, particularly through the improved resolution of the dynamical processes associated with the advection of water vapor structures, though improved nowcasting is also addressed as a goal of a GeoXO IR sounder through its improved temporal resolution. The improved temporal resolution within the viewing geometry of the geostationary satellites, however, is at the expense of global coverage, particularly over the poles. A remaining measurement gap in the hyperspectral IR POR is in the measurement horizontal resolution. Resolution approaching the scale of PBL cumulus clouds (~1 km) is necessary to probe the clear sky in moist convective PBLs in order to quantify mesoscale variability in water vapor and temperature.

Microwave Sounding – Current down-looking passive microwave sounders are limited to only a few spectral channels. Despite their spectral limitations, microwave sounders play a critical role in operational meteorology, because of the key advantage of being only weakly affected by clouds. The impact of MW sounders on operational NWP is significant as they currently provide the most accurate estimate of global total precipitable water vapor and play a critical role in extending IR sounding through cloudy regions.

ATMS combines the capabilities of current generation microwave temperature sounders (Advanced Microwave Sounding Unit, AMSU-A) and microwave water vapor sounders (MHS) currently flying on NOAA's polar-orbiting satellites. ATMS offers improved capabilities over the heritage POR launched in the early 2000s, including reduced volume, mass, power and improved spatial coverage with no gaps in between swaths. ATMS provides more channels, better resolution and a wider swath, leading to improved accuracy of short- and medium-range weather forecasts. ATMS measurements also provide insight into rainfall rates and snow and ice properties.

The MW POR will be maintained through the future launches of the Microwave Sounder (MWS) on MetOp-SG and the NASA Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of SmallSats (TROPICS) mission. The MWS follows a traditional cross-track scanning approach providing a total number of 24 channels, increasing the vertical resolution over the existing POR. Studies suggest that the MW POR does not maximize the information content of the microwave spectrum (Aires et al. 2015). Hyperspectral measurements or adaptive channel selection have the potential to improve the capabilities of microwave sounders to constrain temperature and water vapor in the PBL. Furthermore, the existing POR has only two orbits, which is less than that required to meet many PBL science objectives. Rapid advancements in CubeSat technologies have led to hyperspectral IR and MW sounder mission concepts potentially allowing for better temporal sampling of atmospheric phenomena at relatively low cost. The TROPICS mission will provide high temporal measurements over the tropics to improve understanding of storm evolution and dynamics. TROPICS comprises a constellation of CubeSats in three low-Earth orbital planes to achieve high temporal sampling.

GNSS-RO – A unique and valuable addition to both the NWP and PBL observing systems has come from the ability to profile temperature and water vapor using radio signals of opportunity from GNSS satellites. GNSS-RO provides high vertical resolution measurements of refractivity of ~ 100 m and good horizontal resolution of ~ 1 km perpendicular to the signal path. However, it has a coarse horizontal resolution of ~100 km along the signal path due to its limb sounding geometry. Launched in 2006, the COSMIC mission composed of six microsatellites was a first step at demonstrating an approach based on constellations of GNSS-RO satellites. These soundings have had a significant positive impact on weather forecasting, especially over the Southern Hemisphere, where there are few in situ observations.

GNSS-RO measurements can be used to retrieve high vertical resolution profiles of refractivity, which is a function of temperature and water vapor, through the PBL, irrespective of cloudiness or precipitation conditions (Kursinski et al, 1997). These profiles can be used to detect sharp changes in water vapor and temperature that occur at the top of the PBL that provide an estimate of the PBL height (e.g., Guo et al. 2011; Ao et al. 2012). GNSS-RO profiles are especially effective in detecting PBL height capped by strong inversion layers that typically occur over the subtropics (e.g., marine stratocumulus) (Xie et al., 2012; Ho et al. 2015). Figure 7-2 shows a comparison of PBL height from COSMIC over the Southeast Pacific Ocean with ECMWF analysis and radiosonde soundings from the VOCALS field campaign. Excellent agreement was found between GNSS-RO and radiosonde, while the ECMWF PBL was systematically shallower. GNSS-RO data have since been used to study the seasonal and diurnal variability of the PBL height (Ao et al. 2012; Chan and Wood, 2013) and to assess different PBL parameterizations from climate models (Kubar et al. 2020).

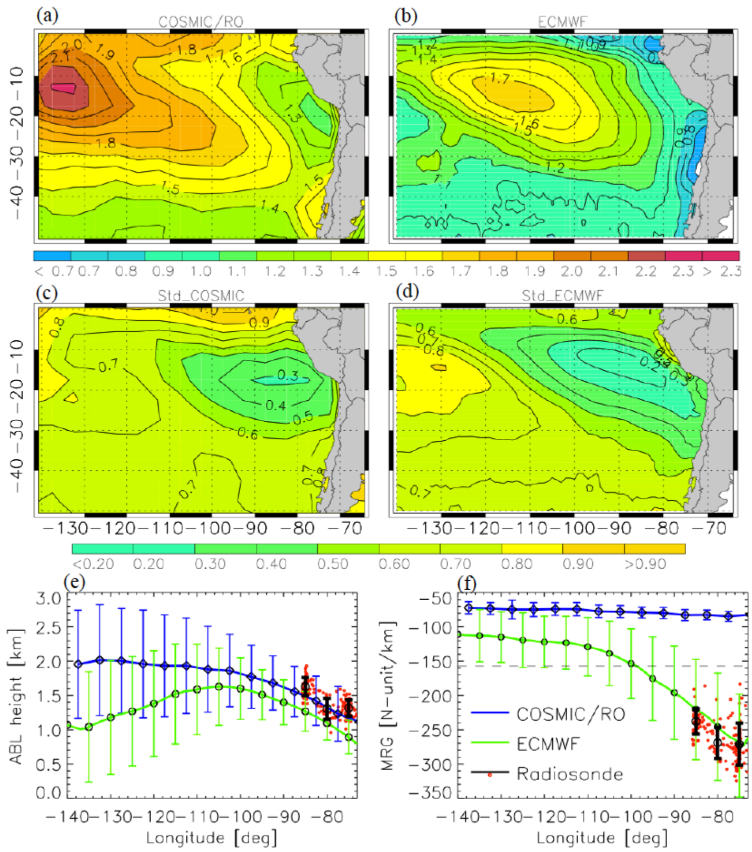

Figure 7-2. High vertical-resolution GNSS-RO refractivity profiles provide accurate estimates of PBL height. This figure shows PBL (referred to as ABL in the image) height obtained from COSMIC GNSS-RO and ECMWF over the Southeast Pacific Ocean. Comparison with radiosondes and ECMWF reveals a systematic PBL height low bias in ECMWF and a systematic RO bias in the minimum refractivity gradient (MRG). From Xie et al. (2012).

A limitation of the past measurements such as COSMIC is that as many as 50% of the profiles do not extend below 1 km above the surface in the tropics (Ao et al. 2012). This might be related to signal tracking errors under low signal-to-noise ratio (SNR) conditions. The recently launched COSMIC-2 constellation, and other operational POR missions such as Sentinel-6 and the EPS-SG series of satellites, have improved SNRs and better signal tracking capabilities that should enable better profile penetrations. Potentially promising developments come from commercial data providers who have launched small satellites (3U-6U CubeSats) that have been shown to have profile penetration into the PBL comparable to COSMIC. A large number of these small satellites can drastically improve the density of RO observations, allowing us to study the PBL at smaller spatial and temporal scales.

The RO POR has only utilized signals of opportunity from GNSS transmitters. A handful of studies have explored the feasibility of dedicated RO transmitters that could have specially selected frequencies optimized for measuring both signal refraction and absorption (Kursinski et al. 2002). The utility of these non-GNSS RO measurement approaches specifically for PBL sounding has not yet been adequately evaluated and these promising approaches are not part of the POR.

Lidar – Space-based lidar observations (ICESat-I:2002-2009, CALIPSO: 2006-Present, CATS:2015-2017, ICESat-2: 2018-present) provide vertical distributions of aerosols and clouds, which can be used to characterize global PBL height. Approaches have been developed using the vertical gradient in aerosol concentration from CALIPSO to estimate PBL height and applied with success over the oceans. Stratiform PBL clouds are capped by PBL top inversions; thus, lidar top heights of stratiform PBL clouds are good indicators of PBL height. These approaches have been used to produce global, monthly to seasonal PBL height products from CALIPSO. As illustrated in Figure 7-3, CALIPSO lidar derived PBL height and mixed layer height (MLH) show characteristic PBL spatial variations from stratocumulus regimes near the west coast of continents to cumulus regimes over the open ocean.

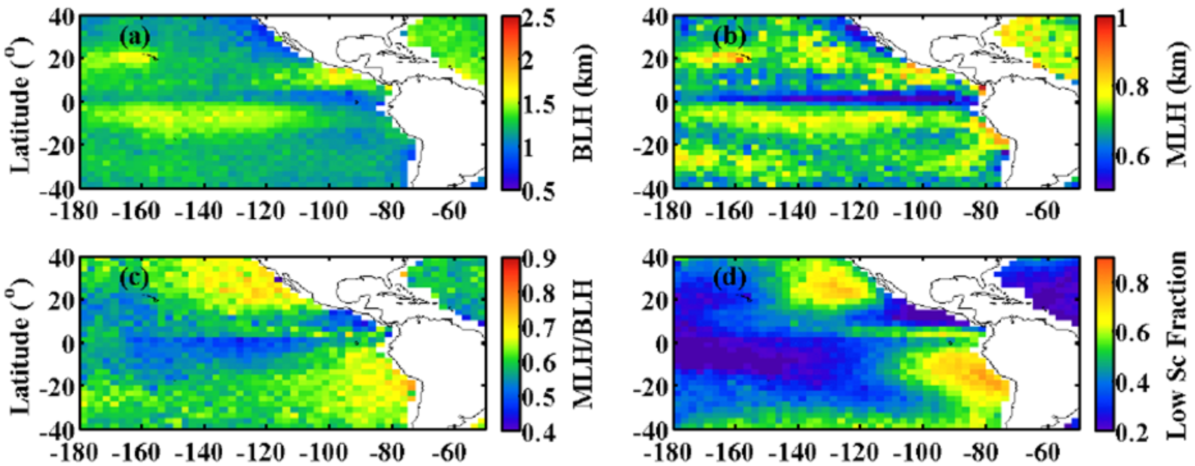

Figure 7-3. Lidar observations such as those from CALIPSO can be used to infer the vertical structure of the PBL. This figure shows detailed spatial distributions of PBLH (a), MLH (b), ratio of MLH and PBLH (as a proxy for decoupling) (c), and low cloud fraction (d) based on 4-year CALIOP measurements. From Luo et al. (2016).

However, aerosol structures over land are more challenging to use for PBL height determination due to the response of the PBL to solar heating and the complicating effect of previous day residual aerosol layers. Nocturnal PBLs are normally undetectable by satellite lidar as the aerosol gradient that is detected is most likely the residual PBL layer from the previous day. In addition, mid/high clouds obscure the ability of CALIPSO to sense aerosol gradients in the lower troposphere. Even with its high pulse energy CALIPSO is still challenged during daytime, under low aerosol loading conditions, and over land where PBL heights can be highly variable. Further, the narrow beam of these lidar observations limits the swath width and in turn return times are of the order of ~16 days globally, which limits the temporal resolution to ~monthly means and also lacks diurnal cycle information for a given location.

More recent earth-orbiting missions like the CATS lidar on the ISS and ICESat-2 have leveraged high rep rate lasers and photon counting receivers to achieve high sensitivity to aerosol variability within the PBL at night. However, this approach introduces more solar background noise in daytime measurements, which decreases the horizontal resolution that can be obtained. One advantage of both CATS and ICESat-2 is that, unlike CALIPSO, they are not in a sun-sync orbit and can provide statistical information on the diurnal PBL cycle. There is ongoing work using machine learning to identify the PBL height in challenging scenes from these lidars and these advancements may have broad application to future spaceborne lidar systems regardless of architecture for improved PBL height estimation. Likewise, efforts based on ground networks of ceilometers and MPLNET are underway to develop automated PBL height detection (e.g., Caicedo et al. 2020).

Additionally, the recent launch of the ADM-Aeolus lidar has demonstrated the capability of UV lidar in providing for the first-time atmospheric dynamics through atmospheric wind retrievals using Rayleigh and Mie Doppler shifts. Although the primary focus of this mission is to provide line of sight wind profiles, Aeolus also has an aerosol channel based on a high spectral resolution lidar technique. Although Aeolus has some skill in retrieving the enhancement in aerosol within the lower troposphere, it currently does not have the sensitivity or resolution to resolve the variability within the PBL.

The lidar derived PBL height POR will be continued through the future launch of aerosol cloud lidars such as the ATLID HSRL instrument on EarthCARE and the HSRL/backscatter lidar on ACCP. These future space based lidars will have marked improvement in daytime SNR compared to the POR and will enable significant enhanced skill to estimate the PBL height from aerosol gradients at PBL top. The improved lidar SNR coupled with different orbit inclinations will provide insight on both the diurnal variability as well as extend the longer-term climatology created by the current POR. With the continued improvement and availability of elastic lidar measurements from space, efforts are needed to develop comprehensive and well-evaluated operational PBL height algorithms to provide a reliable PBL height dataset across different instruments and missions to support a wide range of applications.

Multi-hyperspectral Imagery – This instrument class is characterized as passive nadir remote sensing that focuses on spatial mapping versus vertical profiling. Various classes of imagery exist spanning a range of spectral, spatial, and temporal resolutions. At the finest resolutions, ranging from tens of centimeters to tens of meters, imagers are largely measuring solar-reflective or broadband IR radiation, with the primary application being geospatial surface analysis. While these observations may have limited direct PBL applicability, they are fundamentally important to understanding the small-scale variability within a scene, particularly over land. Due to their fine spatial resolution, they typically fly in low earth orbits, have narrow swaths, and have poor temporal revisit rates. Imagers in this class span both government and commercial sources, including but not limited to LandSat, Maxar (formerly DigitalGlobe), and Planet constellations. Other planned missions such as EMIT (Earth Surface Mineral Dust Source Investigation), the Geosynchronous Littoral Imaging and Monitoring Radiometer (GLIMR), and the Surface Biology and Geology (SBG) mission will provide hyperspectral measurements in visible to shortwave infrared (VSWIR) wavelengths that allow for the retrieval of column water vapor at high spatial resolution (~ 100 m) (Thompson et al. 2020).

Low earth orbiting imagers like the NASA MODIS and NOAA/NASA VIIRS instruments provide global coverage over most of the globe, and geostationary imagers like the NOAA GOES Advanced Baseline Imager (ABI), Meteosat SEVIRI, and JMA Advanced Himawari Imager provide temporal refresh rates of the order of ten minutes over their observing disk. The applicability of these observations to PBL are in terms of height estimates as proxied by cloud height retrievals, and cloud/surface small-scale variability characterization in lower spatial resolution satellite soundings. They also have the capability to retrieve total precipitable water (TPW) using split-window techniques.

Some of these imagers are multi-angle, multi-look imagers like the multi-angle imaging spectroradiometer (MISR) instrument, which image the same scene multiple times from different fore and aft viewing angles. These instruments can also retrieve (cloudy) PBL height using stereoscopically-derived cloud top heights (CTH) as a proxy. For example, Karlsson et al. (2010) showed that the stereo CTH from MISR is able to capture on average the PBL height variation in portions of the stratocumulus to cumulus transition off the coast of California. PBL cloud observations from MISR also helped to better characterize Arctic clouds and their radiative impacts (Kay et al. 2008; Wu and Lee 2012). However, the stereo technique on a single LEO satellite suffers from an aliasing problem in which errors in along-track wind and CTH are highly correlated (Mueller et al. 2017).

Finally, as resolutions increase towards tens of kilometers, spectral imaging in the microwave becomes feasible. Instruments like the GPM Microwave Imager (GMI), the Advanced Microwave Scanning Radiometer 2 (AMSR-2), and the upcoming DoD Weather System Follow-on Microwave (WSF-M) instruments fall into this category. Their direct PBL applicability may be limited to surface temperature retrieval, but there are potential indirect scientific links to their sensitivity to precipitation and columnar TPW measurements.

7.3 SUBORBITAL OBSERVATIONS

Suborbital PBL thermodynamic data include long records in a few individual places, an extensive collection of short-lived and well-instrumented field campaigns and a few regional or global networks of long records of PBL height and other PBL related properties. Data from orbital and suborbital platforms serve to complement each other by providing information at different temporal, spatial and vertical resolutions. For example, well-designed suborbital measurements can give information about the heterogeneity of the land surface. In addition, surface-based observations can serve as 'ground-truth' for proposed incubator instruments and can provide data at places and times when satellite-based measurements cannot be obtained. Finally, surface-based observations of PBL could be used in the context of atmospheric data assimilation. Advanced data assimilation systems, could provide the capability of combining the model PBL representation with a wide range of observations including PBL height. This capability would allow for the generation of much needed long-term analysis records of PBL height for many applications and the improvement of the representation of PBL thermodynamic structures.

Surface-based PBL measurements are available from the global radiosonde network, active lidar, IR and MW passive radiometer, and in situ towers. Although oceanic field experiments often carry out meteorological measurements (including atmospheric sondes), it should be noted that these measurements are very limited over the ocean. More permanent locations in the global oceans are from island sites, which may not accurately define the marine PBL over the open ocean. Twice-daily radiosonde measurements provide the longest record of PBL water vapor and temperature profiles on record (e.g., Li et al. 2020). This can be supplemented with upper air measurements from commercial aircraft (AMDAR), which provides high temporal sampling of the PBL near major airports (Zhang et al. 2020). Multi-year aerosol measurements from lidar networks, such as the MPLNET (Lewis et al. 2013), and from radar wind profilers such as the NOAA profiling network (NPN) (Molod et al. 2015, 2019) have been used for PBL height characterizations and also to help interpret the results from more challenged space-borne lidar measurements. Raman lidar, DIAL, IR and MW sounders have all been deployed from research aircraft to provide high spatial resolution water vapor and temperature profiles for a wide range of airborne science investigations that ultimately tie back to PBL processes. The synergy of multiple remote sensing measurements, such as those available at the DOE/ARM sites (Sisterson et al. 2016; Verlinde et al. 2016; Miller et al. 2016), along with similar sites in Europe (shown in Löhnert et al. 2015) and elsewhere, provides simultaneous water vapor, temperature, aerosol, and wind measurements to better characterize PBL structure and processes.

Nevertheless, surface-based remote sensing measurements have very limited spatial coverage, especially over the ocean. Similar measurements from airborne platforms have been used to overcome many limitations of surface-based measurements. Dropsonde measurements provide essential knowledge of hurricane PBL structure. Airborne DIAL and Raman lidar measurements have been used to track environmental water vapor and temperature structures of fast-moving storms to study storm-PBL interactions. The synergy of surface-based and airborne measurements has been used to collect multiple parameters for specific PBL process studies. Furthermore, these suborbital measurements provide essential data for space-based instrumentation and retrieval algorithm development and validation.

7.4 ROLE OF COMMERCIAL DATA

NASA has established the Commercial SmallSat Data Acquisition (CSDA) Program to identify, evaluate, and acquire data from commercial sources that support the research and application efforts within the Earth Science Division (ESD). Through CSDA, NASA is acknowledging the potential impact that commercial data may have in complementing existing NASA research, with particular emphasis on the collection via constellation approaches. This "New Space" sector is providing industry the ability to rapidly develop and launch new instrumentation that may, in fact, directly relate to not just ESD, but to observations of the PBL specifically.

An existing applicability of the CSDA program to PBL was seen in the pilot evaluation of commercial GNSS-RO measurements (NASA 2020). Initial analysis has shown that despite their relatively low SNR, the penetration depths through the atmosphere were capable of resolving the PBL height structure in a manner comparable to COSMIC. As these and other commercial RO constellations grow, there is a fundamental question as to how these data can complement the fleet of science-grade instruments flown by the international space agencies.

The rapid expansion of this sector also requires forethought as to what new observations may become available. Current CSDA vendors have focused on GNSS-derived science and high spatial resolution imagery. However, industry is also developing further technologies that could expand this portfolio into different domains of spectral resolution and coverage, including but not limited to the thermal IR and MW.

There is a strong need for NASA to make sure that the utilization of commercial data is done in a harmonized manner with publicly-funded data, and in a way that does not hinder scientific and technological progress in publicly-funded Earth science enterprises and programs. Particularly critical is to ensure that the licensing agreements established are not restrictive to the point that they would hamper scientific progress.

7.5 IMPROVING UTILITY OF THE POR FOR CURRENT AND FUTURE APPLICATIONS

Table 7-1 might leave the impression that several PBL data sources already exist that could meet some measurement requirements for PBL height and thermodynamic profiles identified in the ESAS 2017 decadal survey (see Table 3-1). This could be partially correct in some cases but to a currently unknown and highly under-utilized degree, perhaps primarily because the extended knowledge base required to effectively use data sets that offer only indirect or infrequent information specifically on PBL quantities is currently generally lacking. From this perspective, the PBL Incubation activity is naturally taking place within a context in which some existing data sets from technologies listed above may contain substantial PBL information content that has not yet been efficiently mined.

For instance, ICESat-2 lidar observations provide the unique advantage of diurnal sampling globally on a precessing low-Earth orbit to very high latitudes, thus presenting some unique advantages over CALIPSO lidar sun-sync sampling. An ICESat-2 PBL height data set is now being prepared, but can be expected to suffer from the limitations of lidar discussed above, such as sensitivity to the nocturnal residual layer height over mid-latitude continents rather than the underlying stable nocturnal PBL height. That said, residual layer height is a strong indicator of maximum daytime unstable PBL height. Furthermore, issues associated with aliasing near-surface extinction discontinuities for PBL height could be partially ameliorated by taking a forward simulation approach, in which extinction profiles calculated from model outputs are compared directly with extinction inferred or directly measured (depending on the lidar).

Similarly, current GNSS-RO PBL height algorithms rely on the detection of sharp vertical gradients in refractivity and are subject to similar uncertainties due to the residual layer and other water vapor layers aloft. An advanced multi-layer detection algorithm can therefore be beneficial. In addition, GNSS-RO has known retrieval biases within the PBL which can be significantly improved using column water vapor retrieved from collocated passive MW or IR sounders (Wang et al. 2017). This suggests that novel multi-sensor retrieval or data fusion/assimilation approaches should lead to improved characterization of the PBL.

In short, there exists significant value in supporting the innovative use of POR observations of PBL temperature and water vapor profiles, and PBL height in weather and climate modeling, in addressing PBL science and application questions, and in developing value-added products for PBL studies. Actively funding advancement in the use of existing and near-term POR data sets specifically for PBL information content could serve to harness that content in existing data sets, in addition to offering significant potential advances in data mining and/or data-model comparison strategies that can set the stage for future PBL mission elements.

7.6 EARTH SCIENCE DESIGNATED OBSERVABLE SYNERGY

As of this writing, the Designated Observables (DO) studies are coming to a close and the teams are on the cusp of transitioning to pre-formulation (pre-Phase A). Of the five DOs, PBL has synergies with Surface Biology and Geology (SBG - https://sbg.jpl.nasa.gov), Aerosols, and Clouds, Convection and Precipitation (ACCP - https://vac.gsfc.nasa.gov/accp/). Both SBG and ACCP envision launches around 2027-28 and ACCP plans a second launch about 2029-30.

7.6.1 SURFACE BIOLOGY AND GEOLOGY (SBG)

There are a number of potential synergies and connections between measurements being formulated for SBG and PBL that will help address a subset of high priority PBL science questions. SBG comprises two sets of measurements—hyperspectral measurements in visible to shortwave infrared (VSWIR) wavelengths, and multispectral measurements in thermal infrared wavelengths (TIR)—that cover a range of terrestrial, surface, and aquatic interests. Most relevant to the PBL are SBG's observations of land surface temperature (LST). In addition, SBG will address surface albedo, surface fluxes (namely evapotranspiration (ET)), vegetation health and function, and geologic and natural hazards (volcanic events and landslides). The novel aspects of SBG include 60 m spatial resolution for LST, which when combined with international partners and POR measurements (e.g., Landsat) can provide observations globally every 3 days, at the same time of day (1:30 pm), with the exception of Landsat. ET derived from LST and other datasets can likewise be estimated at these very high resolutions, capturing the natural heterogeneity in surface properties, processes, dry and wet anomalies, and corresponding LST and ET responses. Also, quite relevant to the PBL are measurements of column integrated water vapor at high horizontal resolution, which when combined with coincident sounding observations from the POR can be exploited to understand turbulent and mesoscale spatial variability within the PBL. These mesoscale circulations are key to land-atmosphere interactions and interactions of the PBL with convection initiation.

A number of land and land-atmosphere focused science questions rely not only on improved PBL profiles and/or PBL height, but also on synergistic observations of land surface states and fluxes. These include LST, surface fluxes, roughness, and vegetation conditions observed or derived by SBG. Although the spatial resolution of PBL measurements is likely to be coarser (1 km or greater) than those of SBG, knowledge of the actual surface heterogeneity and fluxes is critical in capturing the true nature of land-atmosphere interactions, feedbacks, and mesoscale circulations. In addition, foundational LES studies used for OSSE or impact studies will need to be prescribed with accurate high-resolution surface properties and fluxes of the order of 60-100m such as those captured by SBG. Likewise, land surface models driven by high resolution surface data, and employing LST or flux assimilation at these realistic scales will enable improved coupled models and a more direct assessment of new PBL observation impacts on NWP and climate prediction.

In terms of how new PBL measurements can impact SBG science, the most obvious connection lies in improved near-surface temperature and water vapor from PBL profiles. These quantities are required in most surface flux gradient approaches to estimating ET and sensible heat flux. Current ET algorithms as implemented for ECOSTRESS cannot use the near-surface temperature gradient directly to quantify the latent heat flux due to the lack of routine, globally unbiased estimates of the latter. With the availability of more routine and unbiased mixed-layer and near-surface temperature and water vapor from future PBL observations, high resolution ET estimation can benefit from physical constraints imposed by the gradient approach at the coarser 1 km scale. In addition, the use of new, improved PBL height estimates from space can be used in ET (e.g., ALEXI) approaches, while improving over their current mixed-layer model assumptions. Another potential impact of new PBL data on SBG is that information on temperature and water vapor profiles can serve as a useful prior for SBG's atmospheric correction routines and thereby improve the accuracy and precision of surface reflectance and temperature retrievals.

7.6.2 AEROSOLS, CLOUDS, CONVECTION AND PRECIPITATION (ACCP)

The two atmospheric science DO's were studied together by the Aerosols, Clouds, Convection and Precipitation team. The strong connections between PBL and ACCP observations present a number of opportunities for addressing critical PBL science. ACCP measurements span a wide range of spectrum across microwave, millimeter and submillimeter wave, IR, visible and UV using a combination of active profilers and passive imagers. Key combinations of measurements are deployed in both polar sun-synchronous and mid-latitude inclined orbits to capture a global view over various sampling time scales. ACCP observations cover the PBL regimes of interest and can help answer questions in the PBL science areas of convection and extreme weather; cloudy PBL; land-atmosphere interactions; and mixing and air quality. ACCP's polar orbit is well suited to all these regimes with regular sun-synchronous sampling. ACCP's inclined orbit can help address diurnal variability particularly over land and in deep convection.

ACCP is complementary and brings context to PBL observations. A number of PBL questions center around the relationship between the PBL and clouds and convection. Answering these questions requires PBL thermodynamic profiles along with characterization of convection, cloud and precipitation properties and profiles. ACCP brings several innovative observations to bear including Doppler radar measurements of convective cloud vertical motion; combined passive millimeter wave, VSWIR, radar and high-spectral resolution lidar measurements of cloud profiles and properties; and radar profiling near the surface for cold cloud processes. Cloud top height and dynamics may be elucidated with ACCP's multi-angle stereo cameras coupled with lidar, which often have direct relevance to PBL height. Deep convection variability over land will be captured by Doppler radar in inclined orbit. Benefiting the PBL air quality science area, ACCP's lidars will characterize aerosol properties and distribution, and in turn provide an independent estimate of the PBL height. While the PBL TO primarily seeks the detailed thermodynamic structure of the PBL, ACCP brings the vertical distribution and motion of cloud, precipitation and aerosol particles inhabiting the PBL. As a result, ACCP will inform upon PBL regimes and processes for both clear and cloudy PBL conditions.

7.7 LOOKING TO THE FUTURE

The POR provides a rich set of observations that have been utilized to improve our understanding of key PBL processes. Because of the strong diurnal cycles and the multi-scale nature of PBL processes, a combination of geostationary and polar orbiting satellites, airborne platforms, and surface-based networks have often been required. MW and IR sounders have and will continue to serve as the most widespread source of temperature and water vapor profiles. GNSS-RO has also shown significant promise within the past decade in providing high vertical resolution profiles within and above the PBL. While this observing network has contributed (and will continue to contribute) critical insights to our current understanding of PBL processes, it is clear that several science questions and applications require observations with higher vertical, horizontal, or temporal resolution. New complementary measurement techniques, sensor technologies, and observing system architectures beyond the POR will be highly desirable.

8. PBL TECHNOLOGY AND OBSERVING SYSTEM ARCHITECTURE

The PBL is a ubiquitous feature of the atmosphere that varies in time and space with a broad range of variability spanning time scales from minutes to seasons, and spatial scales from meters to 100's of kilometers. The characteristics of the PBL vary strongly with surface type (land, ocean, ice) and atmospheric conditions. Many factors including radiative forcing, complex terrain, soil moisture, vegetation, surface roughness, winds, and ocean currents influence the coupling between the PBL and the surface. As a result, the PBL can take on many different canonical types including the stable, shear-driven, and convective (including clear and cloud-topped) PBL.

This variability and diversity present a grand challenge in observing the PBL. A full understanding of the variety of PBL types and sub-types on a global scale cannot be addressed adequately with the existing observing infrastructure. This global variability can only be fully observed from space. However, the PBL's complex 3D thermodynamic structure and the wide range of relevant time scales require an integrated observing system including measurements from surface-based, airborne and spaceborne vantages.

A combination of hyperspectral IR, NIR and MW sounders/imagers, GNSS-RO, and backscatter lidar form the POR from space and provide useful but incomplete measurements of temperature and water vapor as well as distributions of PBL heights, all of which are important to a wide range of scientific stakeholders including NWP and climate modeling communities. Today, IR and MW are used together in synergistic retrievals of water vapor and temperature combining their relative strengths, although they have coarse vertical resolution, moderate horizontal resolution and must account for cloud contamination and surface emissivity to ensure high accuracy. GNSS-RO, on the other hand, can provide enhanced vertical resolution but has coarser horizontal resolution compared to IR and MW, and requires a large number of satellites to increase sampling statistics. Limitations of existing datasets from the POR can be ameliorated to some degree with improved retrieval algorithm development efforts. These combined measurement approaches will likely be an integral part of a future space-based PBL observing system. Remaining observational gaps require new measurement approaches and technologies, as well as synergistic retrievals, data assimilation and/or data fusion with observations from the POR and suborbital assets to provide improved PBL products.

As discussed previously, new capabilities not attainable by the POR to address the PBL science requirements and provide the greatest innovation, are three-fold:

1. Improved vertical resolution of water vapor and temperature profiles and accuracy of PBL height
2. Improved horizontal resolution of water vapor and temperature profiles to resolve mesoscale variability
3. Improved temporal coverage of water vapor and temperature profiles and PBL height

As is seen below, these improved capabilities align well with the opportunities for technology development within NASA's reach.

8.1 COMMUNITY TECHNOLOGY SURVEY

The PBL Incubation Program goals call for exploring next-generation measurement approaches that could be ready for spaceborne implementation within 10-15 years. Observing system architectures utilizing airborne observations, surface-based observations, modeling and data assimilation are being considered to complement space-borne remote sensing observations. In line with the findings of the ESAS 2017 decadal survey, the PBL Incubation Study Team has identified PBL thermodynamic profiles (temperature and water vapor) and PBL height collectively as high-priority 'Targeted Observables' that cut across the needs of many of the NASA Earth Science Focus Areas. To evaluate and inform preliminary PBL observing system architecture studies, the

PBL Study Team sought inputs on mature and emerging technology and techniques that can serve future needs for the measurement of the following geophysical observables:

- Vertical profiles of water vapor within the PBL in clear and cloudy conditions
- Vertical profiles of temperature within the PBL in clear and cloudy conditions
- PBL height

The measurement goals for the technology survey are listed in Table 8-1 and represent a wide range of temporal and spatial scales necessary to address PBL science across Earth science disciplines and are representative of needed improvements beyond the POR. The broad nature of the observational goals accommodates the requisite sampling strategies for a diverse yet synergistic set of space-based remote sensing techniques such as active, passive, and occultation remote sensing. Airborne and surface based remote sensors with resolutions and accuracies approaching or exceeding the finest of the goals listed in Table 8-1 are critical for process studies and will help to bridge observational gaps resulting from space-based remote sensor limitations.

Table 8-1. PBL Observational Goals.

Variable	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy
Water Vapor	0.1–100 km	0.1–1km	Minutes-Monthly	10%
Temperature				1 K
PBL Height		N/A		100 m

The study team solicited input on synergistic measurements critical for PBL science which included geophysical observables over land, ocean, and ice, such as surface fluxes of water and energy, aerosol and cloud properties, cloud liquid water path, cloud base, precipitation type and rate, and wind measurements. Additionally, profile measurements of water vapor and temperature that extended above the PBL into the lower free troposphere was explicitly called for to improve understanding of exchange processes. These additional synergistic measurements were only considered if they were measured in addition to one or more of the PBL priority targeted observables cited in Table 8-1 and do not add significant complexity to the measurement/instrument concept.

The PBL Study Team requested information on emerging (Technology Readiness Level (TRL) 2-5) (https://www.nasa.gov/pdf/458490main_TRL_Definitions.pdf) measurement approaches, technologies, and information science to enable the highest possible vertical and horizontal resolution thermodynamic profiling within the PBL from space within the next 10-15 years and technologies that offer the potential to reduce the size, weight and power (SWaP) of established measurement techniques. Reduction in SWaP will play a critical role in establishing distributed constellations of observations to help significantly improve temporal coverage. Measurement approaches such as active optical and microwave, passive optical and microwave, and novel occultation geometries topped the list for space-based submissions. The study team also solicited input on both emerging and mature (TRL$\geqslant$6) suborbital technologies that could be used for future cal/val and process-oriented field studies. One-page measurement and technology charts were also presented during the PBL workshop, many of which were subsumed into the PBL technology survey responses.

The technology survey responses were used to evaluate areas in which the community is already investing effort to advance technologies (as well as retrieval/modeling capabilities) and identify promising solutions which need continued investment to enable a future space-based PBL observing system. The technology survey responses were consolidated into three main categories: orbital technologies/measurements, suborbital technologies/measurements, and information science. Figure 8-1 shows a breakdown of the submissions amongst these three categories. Mature suborbital and emerging orbital technologies accounted for the majority of the survey responses.

Figure 8-2 further breaks down the Orbital (space-based) submissions and shows the apportionment between active and passive orbital technology submissions for both the emerging and mature categories. It comes as no surprise that there are far fewer funded active technology development efforts compared to passive. This in part is due to the complex nature of active sounding technologies and the difficulty in securing sustained funding required to advance critical subsystems such as high peak and average power optical and MW transmitters. The disparity between the active and passive submissions for the mature solutions was far lower, however, the mature technology responses were still dominated by passive IR measurement techniques. One of the only technologies for the orbital active category that was considered mature and ready for immediate implementation was a GNSS-RO receiver subsystem

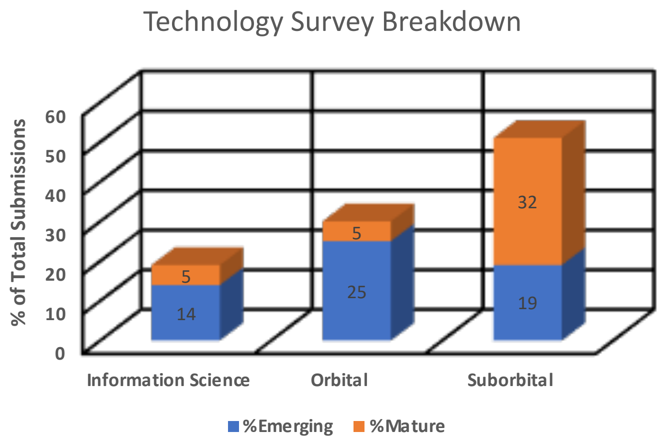

Figure 8-1. Breakdown of the technology survey submissions. The submissions were separated into three categories and further classified as mature or emerging based on the assessed TRL.

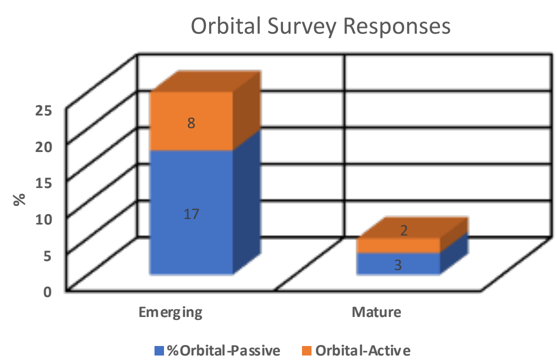

Figure 8-2. Orbital (space-based) statistics showing the breakdown between active and passive orbital technology submissions for both the emerging and mature categories.

As indicated in Figure 8-1, the lion's share of the survey responses focused on emerging and mature suborbital technologies. These submissions were subdivided further into airborne and surface-based categories and the results are summarized in Figure 8-3. It is evident from the survey responses that the community has invested substantial effort in developing and deploying mature airborne and surface based remote and in situ sensors. Additionally, the statistics indicate that there is more effort expended within the community on developing new airborne technologies and measurement approaches compared to those used exclusively for surface-based observations due to the needed spatial coverage of airborne platforms. This is further elucidated in Figure 8-4 where the statistics for the various suborbital measurement techniques and platforms are shown and measurement approaches compared to those used exclusively for surface-based observations due to the needed spatial coverage of airborne platforms. This is further elucidated in Figure 8-4 where the statistics for the various suborbital measurement techniques and platforms are shown and apportioned between the emerging and mature submission categories. The results from Figures 8-3 and 8-4 imply that a future integrated PBL observing system can leverage the emerging airborne active and passive sounding technologies along with the extensive heritage of surface-based networks for targeted process studies and focus future advancement efforts on data access platforms, data assimilation, data fusion, algorithm development (e.g., PBL height retrieval) and cross-calibration across the existing but disparate networks of surface observations.

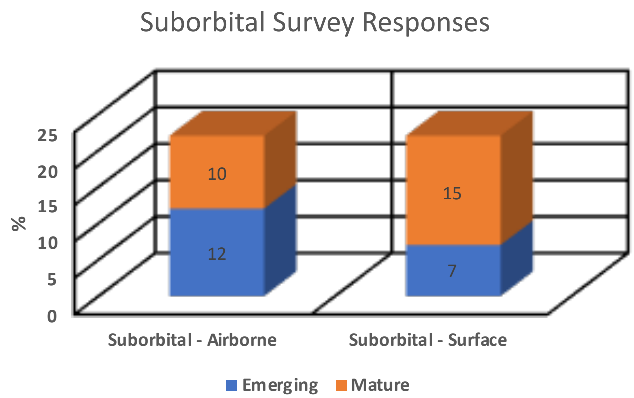

Figure 8-3. Suborbital statistics showing the breakdown between airborne and surface-based technology submissions for both the emerging and mature categories.

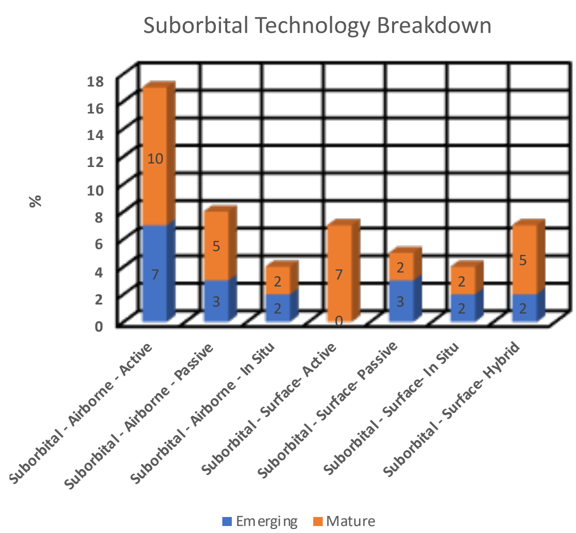

Figure 8-4. Suborbital statistics showing the breakdown between various airborne and surface-based technology submissions for both the emerging and mature categories.

The PBL technology survey shed light on mature and emerging measurement approaches and technologies that when synergistically combined along with modeling, data fusion and assimilation can serve to fill critical observational gaps not possible to fulfil from space. The survey further corroborated the finding from the ESAS 2017 decadal survey that the readiness of high-priority geophysical observables such as high (vertical and horizontal) resolution and accurate profiles of water vapor and temperature are not yet technically mature for cost-effective implementation from space. Table 8-2 provides a summary of the measurement approaches as well as their associated attributes proposed for space-based implementation by the PBL community. The last two columns provide a stop-light representation (proxy for technology readiness) of the maturity of the most promising space-based measurement approaches for profile observations, and when weighted with the other attributes provides a metric by which to identify the most impactful observables/measurement techniques for incubation within the next 7 years. The green and red colors indicate higher and lower level of maturity in the technologies required to enable a given measurement approach, respectively.

Table 8-2. Space-based remote sensing measurement techniques and attributes. The last two columns provide a stop-light representation as a proxy for technology readiness.

Method	Observable(s)	~ PBL Profile Resolution Vertical x Horizontal (PBLH Horiz. Resolution)		Coverage	Conditions	Maturity (space)	
		Current	Emerging			Current	Emerging
Hyperspectral Infrared Sounder	T, q, PBLH, composition, cloud and surface properties (winds from GEO or constellation)	1x14 km (10 km)	1x1 km (1 km)	Large swath, daily global coverage	Clear sky, through tenuous cloud, between broken clouds		
Multi-spectral & Hyperspectral Microwave Sounder	T, q, cloud, precipitation and surface properties (winds from GEO or constellation)	2x40 km (NA)	2x5 km (NA)	Large swath, daily global coverage	All sky (except in heavy precipitation), cloud clearing/combined with IR	Multi-spectral	Hyper-spectral
Backscatter Lidar	Attenuated backscatter, PBLH	(1 km)	(1 km)	Small footprint, line of sight, weekly-monthly revisit	Clear sky, through tenuous cloud, between broken clouds		
Differential Absorption Lidar (DIAL)	q, TPWV, PBLH, attenuated backscatter (aerosol/cloud)	NA	0.2x75 km (1 km)	Small footprint, line of sight, weekly-monthly revisit	Clear sky, through tenuous cloud, between broken clouds	NA	
Raman Lidar	T, q, TPWV, PBLH, aerosol backscatter and extinction	NA	0.2x75 km (1 km)	Small footprint, line of sight, weekly-monthly revisit	Clear sky, through tenuous cloud, between broken clouds	NA	
Differential Absorption Radar (DAR)	In-cloud q, inferred in-cloud T, TPWV, cloud and surface properties	NA	0.2x100 km	Small footprint, line of sight, weekly-monthly revisit	In-cloud profiling, all sky column (except in heavy precipitation)	NA	
GNSS-RO	Refractivity (combination of T and q), PBLH	0.1x100 km (100 km)	0.1x100km (100 km)	# daily soundings scales with # of satellite pairs	All sky		
LEO-LEO RO	Refractivity (T, q), PBLH	NA	0.1x100km (100 km)	# daily soundings scales with # of satellite pairs	All sky	NA	

8.2 OBSERVING SYSTEM ARCHITECTURE

It is widely recognized that a comprehensive PBL observing system will require an active and passive sampling strategy from ground, air, and space to cover the full range of thermodynamic scales. As evident from the measurement attributes in Table 8-2, improved horizontal and vertical resolution from space-based observations compared to the POR have the most potential for improving our understanding of PBL processes (e.g., Table 3-1). IR and MW sounders and GNSS-RO form the backbone of the space-based POR with respect to profiling temperature and water vapor. Elastic backscatter lidar, IR sounding, imaging, and GNSS-RO provide estimates of PBL height by measuring aerosol gradients, temperature and water vapor gradients, cloud top height, and refractivity gradients, respectively.

As modern IR sounders already employ a hyperspectral approach, increasing spectral resolution will likely yield diminishing returns in terms of increasing vertical resolution. Where IR sounders stand to gain the most is from deploying them in geostationary orbit, and from increasing horizontal spatial resolution and decreasing size, weight, and power (SWaP) to enable distributed constellations for higher temporal sampling of water vapor and temperature profiles as well as PBL height and winds (using constellations of CubeSats). Increasing the horizontal resolution of IR measurements has two important consequences for PBL sounding: (1) it increases the retrieval yield by minimizing cloud contamination within the observation field of view and (2) it provides the most practical approach to resolve mesoscale variability within the PBL. On the other hand, current spaceborne MW sounders are limited to 10-20 spectral channels resulting in vertical resolution of around 2 km throughout the troposphere and into the PBL. Where MW sounders stand to gain the most is from increasing the number of spectral bands to include more channels or bandwidth at the line edges and continuum to provide increased sensitivity. MW sounders have yet to employ analogous hyperspectral approaches to take advantage of additional bandwidth for improved sensitivity and vertical over-sampling; however, emerging technologies look to overcome some of the practical limitations associated with implementing this approach such as implementing RF-photonics or adaptive channel selection. Spatial resolution of MW sounders is aperture-limited and would stand to benefit from high-frequency (100-200 GHz) lightweight deployable antennas to reduce SWaP and/or stowed volume for larger apertures.

For GNSS-RO, horizontal resolution is a fundamental limitation of the technique and cannot be overcome with improved instrumentation. However, a significant increase in the density of GNSS-RO measurements from a large LEO constellation of GNSS-RO receivers could help better constrain the horizontal variability of the PBL. While current GNSS-RO observations have proven useful for sensing the PBL height and in some situations the vertical structure of the PBL, the technology can be further optimized to improve its accuracy and profile penetration, especially in the low latitudes. LEO-LEO RO approaches that utilize frequencies different that the GNSS exist at the concept level and may provide further improvements in the RO technique with regard to the PBL thermodynamic structure.

Elastic backscatter lidar has utility in measuring global distributions of aerosol layer heights and cloud top heights as a proxy for PBL height. The lidar can observe the aerosols within the PBL and algorithms seek out the backscatter gradient present across the PBL top. The resolution and accuracy of the height estimates are largely limited by the lidar SNR, especially during the daytime, and improvements are expected from higher-SNR lidar to be deployed by ACCP.

As indicated by the summary of the POR capabilities (Table 7-1) and community survey responses (Table 8-2), no PBL active sounding technologies have been implemented in space beyond the existing high TRL GNSS-RO approach. Recent developments in active optical and microwave technologies have enabled new measurement approaches for water vapor and temperature profiles in clear and cloudy conditions and are paving the way for future implementation from space-based platforms. Active optical (e.g., lidar) and microwave (e.g., radar) profilers benefit from high vertical resolution and accuracy but lack the spatial coverage of their passive IR/MW sounder counterparts. Turner and Lohnert (2020) have demonstrated the utility of using high vertical resolution profiles of water vapor from surface-based lidar as a constraint on surface-based IR and MW sounder retrievals as a means to improve vertical resolution and accuracy of their retrieved water vapor profiles, as well as to reduce uncertainties in their derived temperature profiles. Although demonstrated from ground, such synergistic retrievals have the potential to overcome fundamental limitations of the space-based (as well as suborbital and surface-based) POR and have the potential to enable new PBL science by translating the accuracy and vertical resolution of the active sounders to the wide swath of the passive sounders. Thus, the need to improve vertical resolution of water vapor profiles, followed by horizontal and temporal resolution improvements, emerged as the highest priority. In addition, routine estimates of PBL height from the vast surface-based networks of active and passive sensors (e.g. ceilometers), enabled by future algorithm development for automated PBL height detection (see section 7.4), can be used synergistically with spaceborne measurements to constrain and refine thermodynamic profile retrievals.

8.2.1 INTEGRATED OBSERVING SYSTEM AND SYNERGIES

Measuring PBL temperature and water vapor profiles as well as PBL heights at all of the spatiotemporal scales set forth by the ESAS 2017 decadal survey simultaneously is likely too large of a task for a single space-based instrument or technology. Additional properties such as winds, cloud properties, and precipitation are important parts of the PBL targeted by other NASA programs or missions. Thus, the PBL Study Team envisions an integrated observing system with a hybrid architecture from space, airborne, and surface-based vantage points. Figure 8-5 shows an incarnation of the envisioned integrated observing system. This study targets the key NASA space-based contributions including emerging high resolution active sounders but also highlights opportunities for collaboration with other domestic and international agencies and institutions to create an optimized PBL observing system.

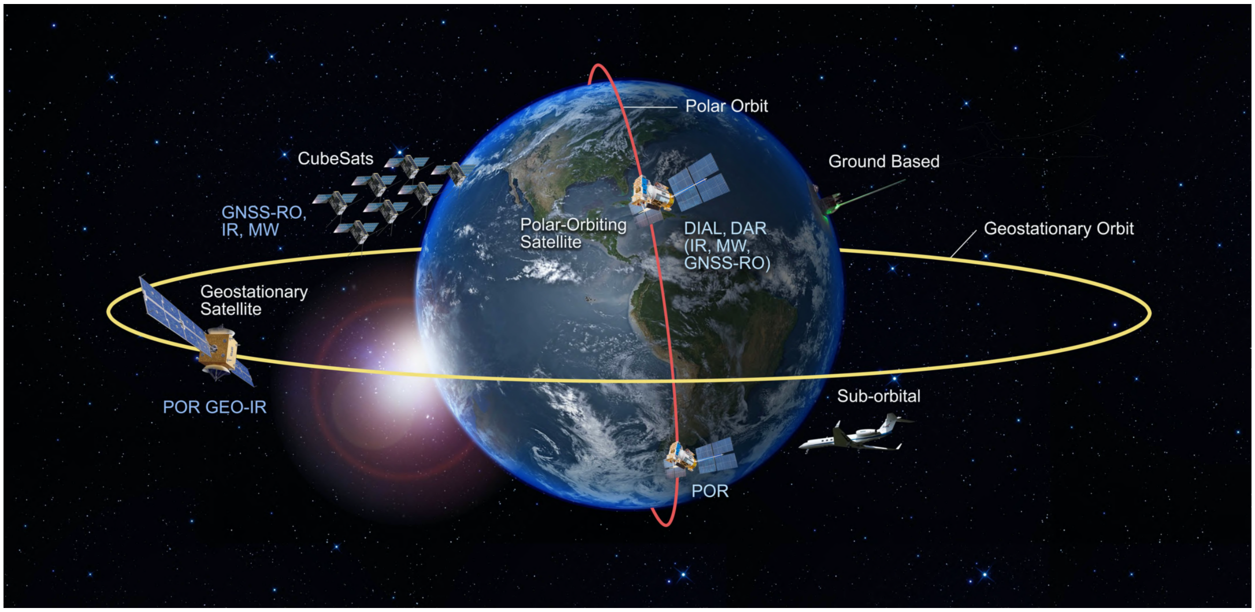

Figure 8-5. Overarching architecture for a future integrated global PBL observing system.

The foundation of a future PBL observing system comprises not only core polar orbiting satellites consisting of active and passive sounders, but also assets in the POR such as the global weather satellite systems (LEO and GEO), hyperspectral IR sounders in GEO (potentially in the GeoXO architecture), and future capabilities foreseen by the ESAS 2017 decadal survey such as atmospheric winds in a separate NASA mission; leverages the key Designated Observable missions ACCP (PBL height via lidar) and Surface Biology and Geology (column water vapor via imaging spectrometer) as opportunity exists; and utilizes commercial and agency-sponsored GNSS-RO capability to the extent possible. This includes using the vast network of ground profilers (supported by NASA, other agencies, and universities and localities) to provide information on temporal and vertical scales not possible to obtain from orbital or suborbital platforms.

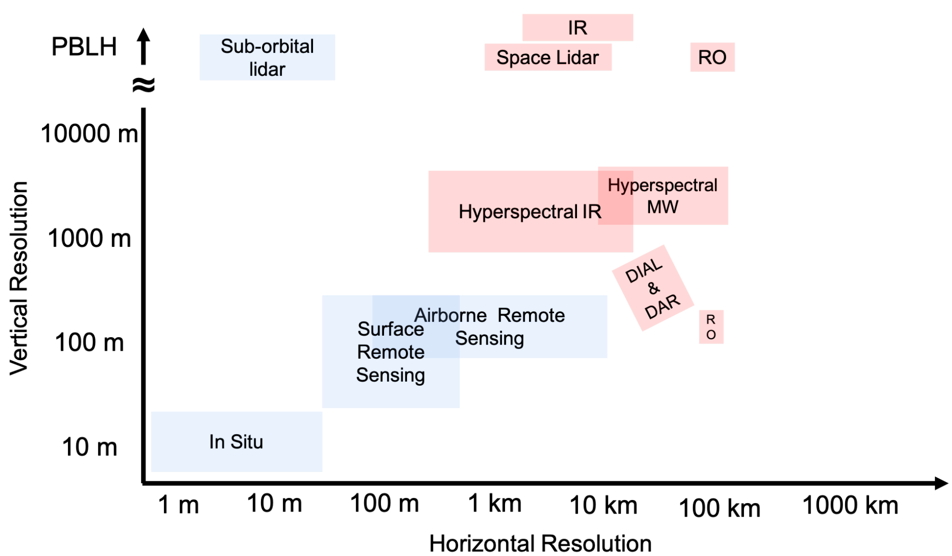

Figure 8-6. Vertical and horizontal resolution for profile measurements of temperature and water vapor for the various measurement techniques employed from different platforms and observing geometries. The blue and red boxes indicate the range of vertical and horizontal resolutions that can be achieved from existing and emerging technologies/measurement techniques from suborbital and space-based platforms, respectively. The DIAL/DAR box is tilted at an angle to highlight the ability of the active sounders to trade vertical and horizontal resolution for precision. The PBL height (PBLH) row at the top of the figure indicates the horizontal resolution for the retrieved PBLH for the various measurement techniques on different platforms.

Airborne measurements will also serve as a critical element to the PBL observing system allowing for advancement of critical technologies, investigation of multi-instrument retrievals, measurements with improved resolution relative to what can be achieved from space, evaluation in different climatic environments, and improved understanding of process level PBL physics for parameterization development as well as to inform future space-based measurement and sampling requirements strategies. Figure 8-6 shows the vertical and horizontal resolutions expected from space-based measurement techniques/technologies as indicated by the orbital focused technology survey responses. The global sampling capabilities of the space-based measurement techniques are complimented with the higher spatial resolutions of airborne and surface-based remote and in situ measurement capabilities as indicated by the community responses to the technology survey. Together, the remote and/or in situ measurement capabilities from the space, airborne, and surface-based vantage points help to cover the wide range of spatial resolutions (Table 8-1) needed to address the PBL science and measurement requirements identified in the SATM.

8.2.2 SPACE-BASED ARCHITECTURE

NASA's opportunity is to provide innovative capability to enable observations of the PBL from space beyond the capability of, while in conjunction with, the POR. As illustrated through the definition of the science goals (summarized in the preliminary SATM) outlined in chapter 4, the geophysical observable likely showing the largest impact to the understanding of key PBL processes is high resolution profiles of water vapor in clear and cloudy conditions. Of the various space-based remote sensing techniques submitted by the community through the technology survey (Table 8-2), the Differential Absorption Lidar (DIAL) and Differential Absorption Radar (DAR) techniques stand apart as being most impactful by striking a delicate balance between exhibiting high vertical resolution and accuracy in clear and cloudy conditions, having strong synergy with the backbone observations of IR/MW sounders, and demonstrating a realistic path to maturing the requisite technologies needed for a future space-based mission within the next 5-10 years.

The space-based architecture envisioned by the PBL Study Team is depicted in Figure 8-5 and comprises the following core measurement techniques/capabilities prioritized by a balance between observational impact and technology development needs from highest to lowest:

- **Differential Absorption Lidar** – High vertical resolution and accurate profiles of water vapor in (mostly) clear sky conditions, profiles of aerosol and cloud properties, and horizontal distributions of column water vapor and PBL heights.
- **Differential Absorption Radar** – High vertical resolution and accurate profiles of water vapor within clouds and precipitation, indirect estimates of temperature profiles within clouds, profiles of cloud properties, and horizontal distributions of column water vapor.
- **Hyperspectral Infrared Sounder** – High spatial and spectral resolution profiles of temperature, water vapor, and composition in (mostly) clear conditions, and cloud properties; potentially in (i) LEO orbit; (ii) constellation of CubeSats or SmallSats for variable time-of-day observations (and wind estimates) and/or (iii) geostationary orbit (EUMETSAT and potentially NOAA GeoXO) as part of the POR.

- **Hyperspectral Microwave Sounder** – High spectral resolution profiles of temperature, water vapor, and surface properties in clear and cloudy conditions; potentially in constellation of CubeSats or SmallSats for variable time-of-day observations.
- **Radio Occultation** – Constellation of GNSS-RO or LEO-LEO RO satellites in distributed orbits for high vertical resolution profiles of temperature and/or water vapor.
- LEO IR, MW and GNSS-RO members of the POR.
- Commercial GNSS-RO POR as available

The active DIAL and DAR measurement techniques are not in the space-based POR and are innovative measurement approaches that help to bridge the observational gap of accurate, vertically resolved water vapor profiles in clear and cloudy conditions, respectively. The DAR measurements of in cloud water vapor along with relationship to saturation vapor pressure further constrains the temperature profile in liquid-phase clouds. These active instruments are complemented with IR and MW sounders that provide daily global coverage in clear and cloudy conditions, albeit with lower vertical resolution and accuracy than the active sounders. There is opportunity to increase both spectral coverage and resolution in MW sounders to oversample the vertical profile. Advances in the sensitivity of IR sounders (e.g., detector NEDT) offer the prospects for a marked increase in spatial resolution. IR and MW sounders also stand to significantly benefit from reduction of SWaP which will enable multiple instruments in constellation which have cross-cutting applications to enable additional observables such as winds through atmospheric motion vectors of water vapor fields and improved spatial/temporal resolution of trace gases (e.g., O_3, N_2O, CH_4, CO_2, CO) for application to air quality. Constellations of GNSS-RO, LEO-LEO RO links, and CubeSat sounders in distributed orbits bracket the core polar orbiting observatory by providing time resolved observations of temperature, water vapor, and other important geophysical variables.

Given the disaggregated approach to the space-based PBL observing system architecture, non-conventional approaches for access to space should be investigated which could lead to substantial cost savings. A non-exhaustive list of opportunities includes the following elements:

- Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA)-based spacecraft buses for larger payloads to enable ride-share launches;
- ESPA-based orbital maneuverable vehicles for multi-instrument deployment;
- Commercial hosted payload as alternative to a government-procured spacecraft;
- Hosting on partner spacecraft (e.g., NOAA or other NASA LEO missions);
- Turnkey cubesat solutions for small payloads.

There is an emerging landscape of non-conventional paths for access to space represented by some of the above. This market has and will continue to rapidly evolve, hopefully further reducing TRL cost and technology barriers. The envisioned architecture has the flexibility to accommodate multiple options for creative, cost effective concepts of operation. For example, active sounders may be possible using an ESPA ring as the bus and take advantage of a rideshare launch to sun-sync orbit. Commercial hosting is still nascent and could see significant growth over the next decade, creating potential opportunity to minimize spacecraft and launch costs for small to moderate size instruments. The "mundane" costs of spacecraft, launch, and operations are not likely to be a barrier to a future architecture. Thus, the focus of investment over the next decade can be on technology and science readiness for a future PBL mission.

8.2.3 SUBORBITAL

Repeated suborbital measurements over seasons and in different geographic regions is critical to the observing strategy to help overcome potential observational gaps of space-based remote sensing in terms of measured geophysical observables, temporal sampling, and resolution in targeted process studies. Suborbital measurements are also critical for interpreting space-based measurements which inherently exhibit lower vertical and/or horizontal resolution. Equally as important, suborbital campaigns provide critical opportunities for advancement of multi-sensor retrievals to increase information content and derive new observables. The suborbital component to the architecture includes airborne remote and in situ sensing, surface-based distributed networks of remote sensors, and utilization of commercial data such as from the AMDAR, TAMDAR, and WVSS-II networks.

An ideal suborbital sampling strategy for process studies, satellite cal/val, and multi-sensor retrievals includes a remote sensing platform comprised of many of the sensors discussed in the architecture above as well as a dedicated in situ platform to provide additional required observables at much higher spatial and temporal resolutions. Two separate aircraft could be required to optimize the sampling strategy between high flying remote sensors and in situ observations within the PBL; e.g., as adopted in the suborbital mission ACTIVATE (Sorooshian et al. 2019). Measurements that could optimally be combined for different PBL suborbital science focused investigations could include:

- Remote sensors such as:
  - DIAL, DAR, Raman Lidar, Doppler Lidar, Infrared Sounder, Microwave sounder, Polarimeter, hyperspectral imager, precipitation/Doppler radar, and up and downwelling broadband and spectrally resolved radiometers.
- In situ observations such as:
  - fast T, q, u, v, aerosol and cloud optical and microphysical properties, cloud water, and composition (CO, CO_2, CH_4, O_3, …) for tracers and coupling weather to AQ.

Although process-driven airborne campaigns require deployment of large suites of remote and in situ observations for extended periods of time, evaluating the performance of new measurement techniques and multi-sensor synergies/retrievals can be carried out with much less complexity and cost. At a minimum there is a pressing need to fly the instruments that comprise the proposed spaceborne architecture together on a common platform along with dropsondes to generate multi-sensor datasets with sufficient in-situ validation data to develop and test synergistic algorithms that optimally merge the complementary datasets. Such datasets do not yet exist, therefore, this minimal airborne activity is seen as a critical component of risk-reduction ahead of a potential mission.

Continuous measurements from surface-based networks help to bridge the gap between orbital and suborbital measurements and the surface. Surface networks have played and will continue to play a pivotal role in PBL science as they provide continuous measurements (e.g., over the diurnal cycle) of T, q, PBL height, aerosol/cloud distributions, and winds at high vertical and temporal resolution. Although it is not foreseen that the primary focus of the NASA PBL Incubation effort will be to invest in technologies to enable future surface-based networks, it is anticipated that a framework will be developed to integrate measurements from a wide range of surface-based remote sensing and in situ networks to create a centralized PBL data repository for easy access by the modeling and data assimilation communities. Targeted investments in already mature technologies, including development of advanced PBL retrieval approaches, should be considered to transition key technologies from research to operations. A non-exhaustive list of surface-based networks that have application to PBL science include a global network of radiosonde stations, MPLNET, DOE-ARM, MicroPulse DIAL network, LOTOS, AERONET, TOLNET, SUOMINET, EARLINET, E-PROFILE (EUMETNET), network of radar wind profilers and ceilometers, as well as many others presented at the PBL workshop.

Surface-based in situ and remote measurements over the oceans will also be critical to closing the observational gap, especially in remote regions (e.g., Southern Ocean, polar regions), which are occluded by dense cloud cover and challenge space-based and airborne remote measurements. Emerging technologies such as uncrewed systems, e.g., saildrones buoy-based profilers, and self-controlled balloons should be considered as an important element to the PBL observing strategy (e.g., NASEM 2018b).

8.3 MEASUREMENT APPROACHES AND TECHNOLOGIES

The measurement techniques identified above can together provide a unique capability to profile temperature and water vapor at high resolution within the PBL, and probe PBL height at all latitudes, in all atmospheric conditions, and diurnally and seasonally to provide the most comprehensive global view of the PBL to date. Figure 8-7 demonstrates the strong observational synergy between the core active and passive sounding technologies. DIAL and DAR provide high resolution profiles of water vapor in clear and cloudy conditions, respectively, as well as along track distributions of PBL height (DIAL) and total precipitable water vapor in all sky conditions. DAR also provides the in-cloud temperature profile in liquid-phase clouds due to the unique relationship between temperature and water vapor in saturated air. The co-located IR/MW sounders enable 3D context and global coverage through wide swath sampling strategies. Although exhibiting lower vertical resolution and information content compared to their active counterparts, the DIAL and DAR water vapor retrievals in clear and cloudy conditions can be used to constrain the passive IR and MW retrievals, resulting in higher resolution and accuracy final retrievals of temperature and water vapor. Additionally, GNSS-RO and LEO-LEO links compliment the core active and passive sounders with high vertical resolution profiles of temperature and/or water vapor, and consequently PBL height, using different orbital geometries to increase coverage.

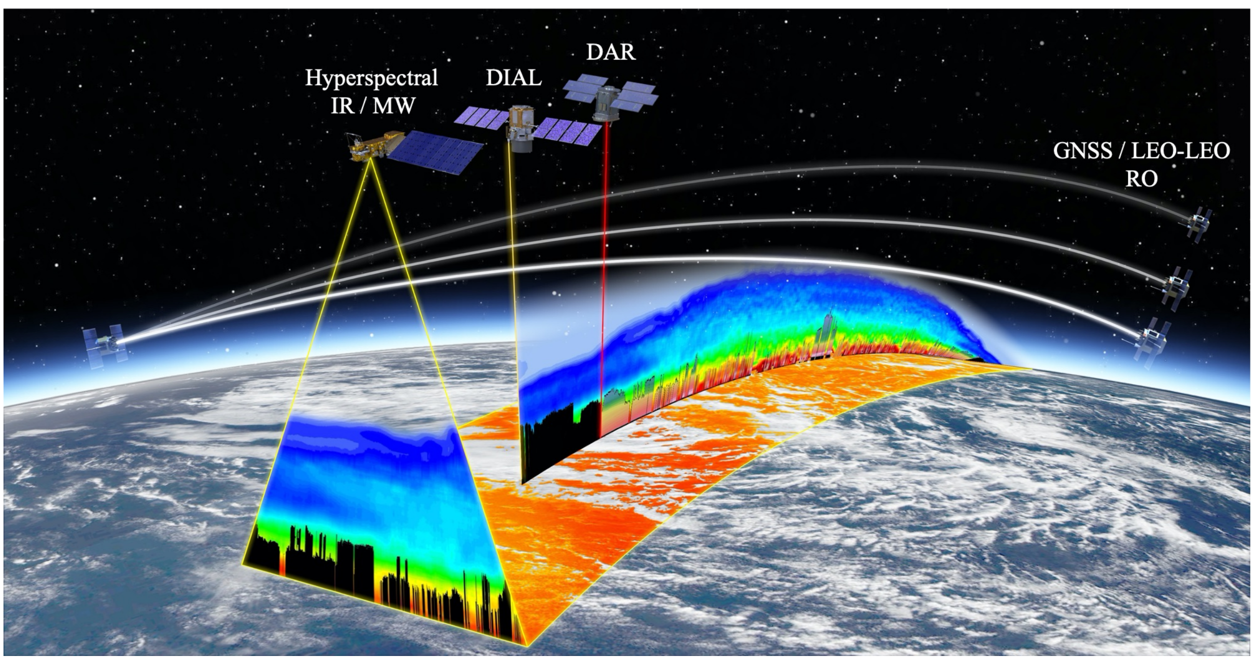

Figure 8-7. An integrated space-based architecture demonstrating the observational synergy between the core active and passive sounding technologies. IR/MW observations provide global coverage of water vapor and temperature profiles with high spatial and moderate vertical resolution in clear and cloudy conditions. DIAL and DAR observations provide high vertical resolution and accurate profiles of water vapor in clear and cloudy conditions, respectively. GNSS and LEO-LEO observations in different inclination orbits provide diurnal coverage of high vertical resolution profiles of water vapor and temperature. Together, the integrated space-based architecture provides full

sky coverage of key PBL variables (water vapor, temperature, and PBL height) with different spatial and vertical resolutions and coverage required to address the goals outlined in the preliminary SATM.

Figure 8-8 summarizes the results of a simple technique-dependent spatial resolution experiment to demonstrate the strong synergy of the core active/passive sounders in retrieving full sky profiles of water vapor and elucidate where the strengths of one measurement technique can be used to overcome the weaknesses of another. The NOAA High Resolution Rapid Refresh (HRRR) cloud and convection resolving model is used as the water vapor nature ('truth') run in Figure 8-8 for which the other remote sensing measurement techniques sample. Clouds of various phases are represented by the white polygons. For the purposes of this simulation the clouds at all altitudes are assumed to be non-precipitating. The top left panel shows the distributions of water vapor mixing ratio throughout the troposphere with a 3 km horizontal resolution and 38 layers below 15 km in the vertical, and ~10 layers within the PBL. A logarithmic color scale is used here to highlight the large dynamic range and variability of the water vapor field as a function of altitude. The panel on the upper right shows a zoom in on the lower troposphere (boxed region in upper left panel) using a linear color scale to further illustrate the highly variable nature of the water vapor field to be sampled by the remote sensors. The PBL height and clouds are represented here by the white dotted line and black bordered polygons, respectively. The other panels in the figure show the expected spatial resolving power of the DIAL, DAR, MW, IR, and RO profilers for a realistic set of instruments specifications (Table 8-2).

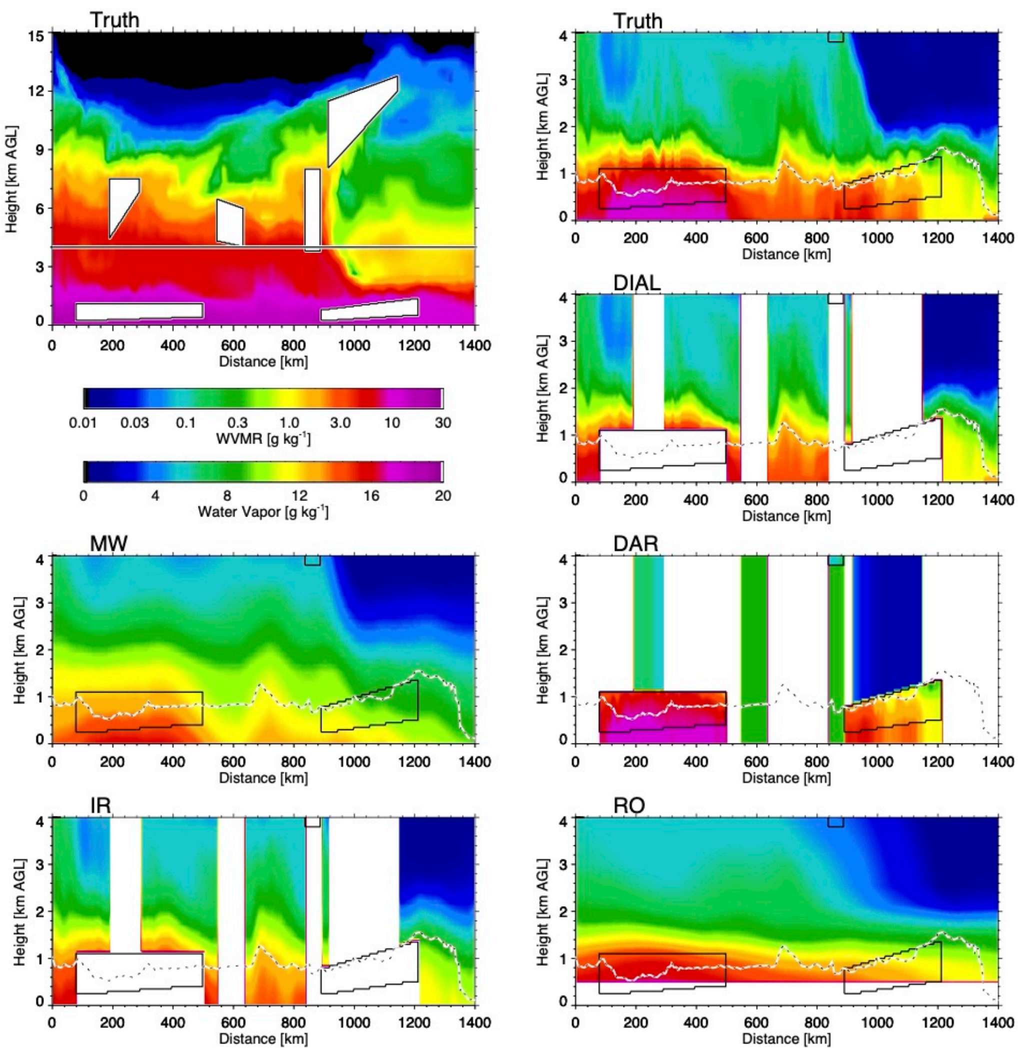

Figure 8-8. Illustration of the observational synergy in Figure 8-7 using the HRRR cloud resolving model as the nature ('truth') run (upper left panel). The white polygons represent clouds, none of which are assumed to be precipitating. The upper right panel shows a zoom in on the upper left (full troposphere) panel of the lower troposphere (0-4 km) and also identifies the PBL height as the white dotted line. The black border boxes here correspond to the clouds displayed as the white polygons in the full troposphere subplot, however, the white shading within those clouds represents the regions that each instrument cannot see below due to attenuation of signal. The remaining panels qualitatively demonstrate the lower tropospheric horizontal and vertical resolution for water vapor retrievals of the various measurement techniques being considered for the space based PBL architecture. The DIAL (or other backscatter lidar from the POR) and RO techniques additionally provide accurate estimates of PBL height with around 2 km (lidar) and 100 km (RO) horizontal resolution, using gradients in aerosol backscatter and refractivity, respectively.

The RO retrievals provide the highest vertical resolution of all of the sounders in addition to providing all sky coverage; however, the lowest part of the profile is obstructed due to signal tracking and SNR limitations, and mesoscale variability is muted by sparse sampling and the large along-track averages as dictated by the occultation geometry. The MW sounder also provides full sky retrievals over ocean and non-precipitating clouds but suffers from coarse vertical resolution due to receiver bandwidth limitations. Although moving to a hyperspectral approach will help to ameliorate the limitation in vertical resolution, the spatial resolution of a single collection aperture system has fundamental lower limits defined by realistic limitations on important system parameters such as the receiver NEDT and collection aperture. The use of moderate size apertures and distributed receivers viewing the same scene can overcome some of the aforementioned signal to noise limitations.

The DIAL and IR sounder retrievals provide the highest vertical resolution after RO along with improved horizontal resolution, however both are limited to operation in clear air or low cloud optical depth conditions. A notable strength of DIAL is the ability to retrieve PBL height with high spatial resolution as well as near surface humidity in clear sky conditions with high vertical resolution and accuracy without assumption on the overlying atmospheric state or condition. DAR, the microwave equivalent of DIAL, provides for the first time in-cloud (save for heavy precipitation) profiles of water vapor (and indirectly temperature) as well as partial columns of water vapor between cloud layers and the surface. The combined DIAL/DAR retrievals provide a high-resolution snapshot of the vertical distribution of water vapor and are placed in context within the surrounding mesoscale field using the swath of the passive sounders. The combination of these five measurement techniques will together provide the most comprehensive view of the PBL thermodynamic state and allow for synergistic retrievals to overcome the gaps of the current and anticipated future POR.

In addition to providing a more complete picture of the PBL thermodynamic structure, the measurement techniques presented in Figure 8-8 can also provide independent, high-resolution observations of proxies that allow for PBL height estimation in all sky conditions. As there will be challenges in achieving high vertical resolution profiles routinely from space for certain PBL regimes and applications, such independent estimates of PBL height itself will remain valuable in addressing a significant subset of science and applications questions. In addition, PBL height can also be used as a constraint to improve vertically or spatially limited thermodynamic profiles retrieved by other sensors, relying on the characteristics of the PBL mixed layer and capping inversion over land and ocean. Of the measurement techniques presented thus far, the active sounders have the highest potential for marked improvement to the resolution, accuracy, and coverage of the PBL height when compared to the POR. The DIAL and RO techniques will have the ability of backscatter lidar (e.g., DIAL, attenuated backscatter (e.g., CALIPSO, ICESat-2, HSRL, or Raman lidar) and GNSS/LEO-LEO profilers to retrieve the PBL height at different horizontal resolutions using gradients in aerosol loading and refractivity at PBL top, respectively. Backscatter lidar provides the highest resolution PBL height retrievals, but lidar retrievals are often occluded by clouds aloft and confounded by residual aerosol layers under stable nocturnal conditions and also during daytime in presence of heterogenous aerosol layers in and above the PBL. Conversely, RO retrievals of PBL height have coarse spatial resolution but are insensitive to clouds and PBL type and allow for all sky retrievals of PBL height. Additionally, IR sounders can provide global coverage of PBL height with high spatial resolution and lower vertical resolution than lidar and GNSS-RO. These wide swath observations of PBL height are achieved by measuring gradients of water vapor and temperature at PBL top. Looking to the future, global coverage of PBL height will further be complemented by the POR (CALIPSO, ICESat-2, lidars deployed as part of ACCP, and MISR) and enabled by other current and emerging stereoscopic imaging techniques which allow for PBL height estimates using cloud top heights determined from IR imagers.

The aforementioned space-based observations would undeniably need to be complemented by suborbital and surface-based measurements to cover processes that span spatial and temporal scales not suitable for space-based geometries, especially over land where the majority of existing surface-based remote sensing infrastructure currently exists. The subsequent sections describe the key measurement approaches identified through the technology survey and identify top level technology advances required to enable a future space-based implementation of the envisioned architecture.

8.3.1 DIFFERENTIAL ABSORPTION LIDAR

The differential absorption lidar (DIAL) technique is mature and has been implemented from aircraft and ground for over 40 years (Browell et al. 1997; Ehret et al. 1998; Späth et al. 2016; Wulfmeyer et al. 2015; Wirth et al. 2009; Ferrare et al. 2004; Spuler et al. 2015; Nehrir et al. 2011, 2017; Bedka et al. 2020). The DIAL technique is a straightforward method by which to retrieve direct profiles of water vapor in clear air conditions, in between broken cloud fields, and under tenuous clouds. In the DIAL technique two single frequency and spectrally close laser pulses are transmitted to the atmosphere nearly simultaneously with one pulse tuned to the center or wing of a gas absorption line and the second pulse tuned to a less absorbing spectral location. The retrieval of water vapor concentration depends only on the differential attenuation of the backscattered signals between the online and offline wavelengths and a priori knowledge of the differential absorption cross section which is well known through spectroscopy. Multiple absorbing wavelengths can be implemented to increase dynamic range throughout the troposphere as well as latitudinally.

Airborne water vapor DIAL systems have been developed over the past 20 years (Browell et al. 1997; Wirth et al. 2009; Bedka et al. 2020). These systems have been developed to support airborne process studies as well as demonstrators for future satellite missions. Airborne and surface-based DIAL systems have routinely demonstrated accuracy and precision of better than 3% and 10%, respectively, within the mid-lower troposphere. The High-Altitude Lidar Observatory (HALO) is an airborne system recently developed to replace the heritage NASA LASE water vapor DIAL with improved dynamic range and resolution and also serves as a technology testbed for NASA to evaluate and advance emerging transmitter and receiver technologies required to enable future space-based DIAL systems. Airborne validation against in situ measurements (Figure 8-9) have demonstrated HALO retrievals of clear air water vapor profiles with a relative precision of better than 10% at 200-300m vertical resolution from the upper troposphere/lower stratosphere down to the PBL (Bedka et al. 2020). Similar vertical resolution, precision, and accuracy could be expected from a space-based DIAL with increased along track averaging, laser power, and collection efficiency/aperture.

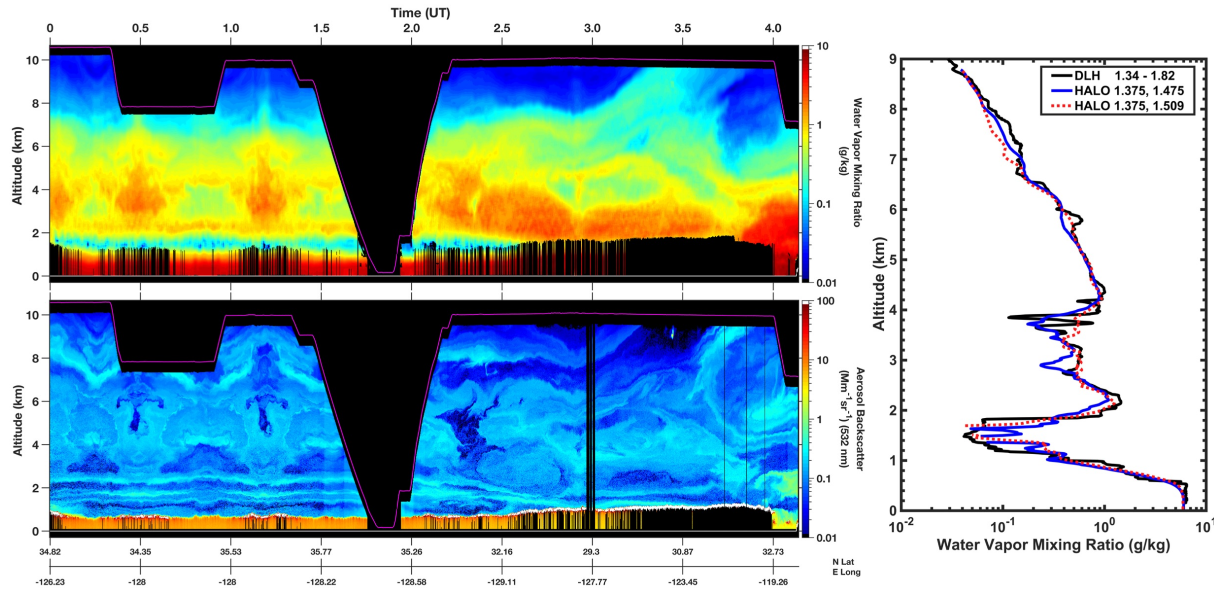

Figure 8-9. (Left) An example of water vapor and aerosol time-height curtains from the HALO DIAL. (Right) Example validation of HALO water vapor retrievals at two different times compared to in situ measurements during an aircraft spiral. Two HALO profiles are spliced together using the times indicated in the legend to account for the heterogeneity in the water vapor field over the spiral location as well as to account for the spatial offset between the HALO and in situ hygrometer spiral (Nehrir, personal communication). DOI: 10.5067/Airborne/Aeolus-CalVal-HALO_DC8_1.

Although many surface-based water vapor DIAL systems have been developed and deployed over the past four decades, few airborne DIAL systems have been realized due to the demanding environmental challenges (e.g., vibration, thermal, pressure, and limited availability of size, weight and power resources) often encountered on airborne platforms. NASA and Deutsches Zentrum für Luft- und Raumfahrt (DLR) are some of the only agencies that routinely develop and deploy water vapor DIAL systems in support of scientific airborne campaigns. These DIAL systems also serve as airborne demonstrators and technology testbeds for risk reduction of the key technologies required to enable future space-based DIAL missions. A future study investigating the implementation of global PBL observing system would benefit from international coordination on scientific trade studies elucidating the driving requirements for a future space-based DIAL.

Detailed systems engineering is required to accurately extrapolate the performance of an airborne DIAL to space. Previous and ongoing simulation studies to elucidate the performance of a space-based DIAL indicate that a 10-20 W average power laser transmitter and 1-m class telescope is required to measure the water vapor structure within the lower troposphere with an accuracy and precision of better than 5% and 15%, respectively (Di Girolamo et al. 2008; Ismail and Browell 1989; Nehrir et al. 2017). These performance metrics are achieved using approximately 50-100 km along track averaging and 200-300 m and 500-1000 m vertical resolution in the PBL, and free troposphere, respectively.

To address a wide range of science applications, the vertical and horizontal averaging scales can be traded for precision in post processing. Figure 8-10 demonstrates the expected performance of a notional space-based DIAL in a mid-latitude standard clear air atmosphere from a 500 km orbit. The vertical resolutions of 300 m and 1 km in the PBL and free troposphere, respectively, can be traded for precision based on the atmospheric scene (i.e., aerosol loading and PBL depth) and application. Current best estimates using emerging technologies indicates that a water vapor DIAL with the aforementioned specifications would exhibit a system mass of ~200 kg and system prime power consumption of ~450 W.

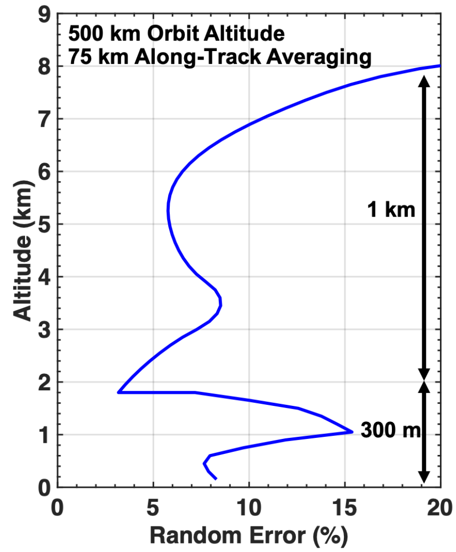

Figure 8-10. DIAL random error simulations from an orbital platform observing a mid-latitude clear air scene. Different vertical averaging in the PBL and free troposphere aloft allow for optimization of the retrieval precision (random error) (Nehrir, personal communication).

Strengths: Able to directly measure profiles of water vapor in clear and broken sky scenes with high accuracy and vertical resolution, ability to optimize precision within the PBL (and aloft) at all latitudes by dynamically tuning the transmitted wavelength to optimize absorption, provides high vertical and horizontal distributions of attenuated backscatter for aerosol and cloud studies, provides high resolution distributions of total precipitable water vapor and PBL height.

Weaknesses: Clouds attenuate lidar signals resulting in little-to-no water vapor profile data beneath clouds with optical depth greater than 1, profile measurements limited to a single line-of-sight curtain below satellite, challenging transmitter and receiver systems (e.g., laser transmitter must be spectrally pure, filters must have very narrow bandwidth and detectors require large dynamic range, high efficiency and low dark noise).

Technology Development Needs

The observed backscattered signal from a lidar decreases as the square of the distance to the scattering target. Consequently, lidar signals from LEO are approximately 2000 times weaker than observed from airborne platforms. To overcome this loss of signal and enable a future space-based DIAL, technology advancement in high power lasers, efficient solar spectral filtering, and high efficiency detectors is required.

1. *High Power Pulsed Laser Sources* – 10-20 W average power pulsed lasers are required to profile the PBL from LEO. Single frequency and frequency agile (shot-to-shot agility across water vapor line) pulsed lasers in the 820 nm or 930 nm spectral bands are required with electrical to optical efficiency >5 % to the NIR spectral band. Higher pulse energy systems approaching 100 mJ and 100 Hz double pulse (on-off pulses within 300-500 μs) repetition frequency (PRF) will have better daytime performance, but electrical efficiency in this regime is currently too low for implementation. Lower pulse energy (3-10 mJ) and high PRF (>2kHz) systems with the same average power have better efficiency and will perform better at night but suffer from degraded daytime performance. High PRF technology shows promise but relies heavily on improved spectral filtering to improve daytime performance.
2. *Spectral Filtering* – To optimize daytime performance (especially in the case of low energy and high PRF lasers), DIAL requires a narrow spectral bandwidth (~10 pm

FWHM) solar blocking filter. Because the DIAL transmitter is frequency agile, sampling the water line over ~ 100-300 pm on a shot-to-shot basis to cover vertical and latitudinal water vapor dynamic range, the solar blocking filter also requires the same amount of frequency agility and accurate knowledge of central frequency. Candidate approaches for frequency agile filters include using phase changing materials, meta materials or liquid crystals. Another approach is utilizing polarization multiplexing to spatially separate the different DIAL spectral components, however this approach increases the number of required detection channels.

3. *Seed Laser Integrated Photonics* – Seed lasers are required to injection seed a high-power pulsed laser to enable single frequency and tunable output at the desired water vapor line. The performance of the seed laser determines the accuracy of the DIAL measurement. A tunable seed laser that is accurately referenced to the desired water vapor line is required. Frequency agility of the order of 100-200 pm (40-80 GHz) is required on a shot-by-shot basis. Integration of all of the optical and microwave components in an integrated photonic circuit would significantly reduce size, weight, and power (SWaP).
4. *High efficiency detectors* – Extremely high quantum efficiency detectors are commercially available. However, their dynamic range is limited, and optical splitting is required to cover the expected DIAL signal dynamic range. Furthermore, these detectors cannot operate in vacuum and require pressure housings. Photon counting detectors with high quantum efficiency in the NIR, low dark and excess noise, and larger linear dynamic range (>2x state-of-the-art) will have the most impact on DIAL performance. An array detector with the same aforementioned operational characteristics would allow for significant reduction in SWaP. SLiK and Black Silicon are potential candidate materials for building high efficiency detector in single and array formats. Integration of the detector with the frequency agile filter based on PCMs or metamaterials would further reduce SWaP.
5. *Telescope Architectures* – The received DIAL signal increases as the square of the collection aperture. Implementation of deployable or distributed collection apertures that meet the stringent optical requirements (supporting field of view of 50 microradians) and increase collection aperture beyond the existing 1 m class telescope would significantly improve SNR or would help to reduce the required laser power to achieve the same precision. Distributed architecture such as the use of Photonic Lanterns offer the potential to massively parallelize the receiver filtering and detection chains by utilizing chip scale integrated optical photonics, however, the trade between SWaP reduction/SNR improvement and introduction of additional sources of bias needs additional study.

8.3.2 DIFFERENTIAL ABSORPTION RADAR

Differential Absorption Radar (DAR) is an emerging measurement approach leveraging the same physical basis as DIAL to measure water vapor profiles within cloudy and precipitating volumes, which are opaque to DIAL. In this way, the two active differential absorption instruments are highly complementary and together can provide near-complete water vapor profiles in all-sky scenarios (except under heavy precipitation). The physical basis for the DAR measurement of PBL water vapor profiles is presented in a series of papers (Lebsock et al. 2015; Cooper et al. 2018; Roy et al. 2018; Millán et al. 2020). The Vapor In-cloud Profiling Radar (VIPR) is an airborne system that has been developed to demonstrate the DAR measurement approach. Surface-based validation against balloon borne radiosondes have demonstrated VIPR retrieved water vapor profiles with an RMS error of 0.8 gm-3 with a 200 m vertical resolution (Figure 8-11).

Systems engineering studies are ongoing to determine the measurement capabilities and spacecraft resource requirements of a space-borne DAR. A notional implementation considers a 100 W peak power transmitter operated with a 25% duty cycle and a 2 m diameter aperture with current best estimate of system mass and average power of 60 kg and 260 W. Results from OSSEs in Figure 8-11 indicate that the horizontal resolution from an orbital platform is approximately 100 km in order to maintain the desired 200 m vertical resolution and better than 1.5 gm-3 precision. Note that, like DIAL, vertical resolution can be traded with precision providing a great deal of flexibility in post-processing to address different science questions. Additionally, layer integrated water vapor between the first cloud layer and the surface can be retrieved to provide insight into sub-cloud water vapor, which provides a strong constraint on the relative humidity near the surface. Finally, it should be noted that in liquid phase clouds DAR also provides an indirect measure of the temperature profile due the well-known relationship between the temperature and the saturation vapor pressure.

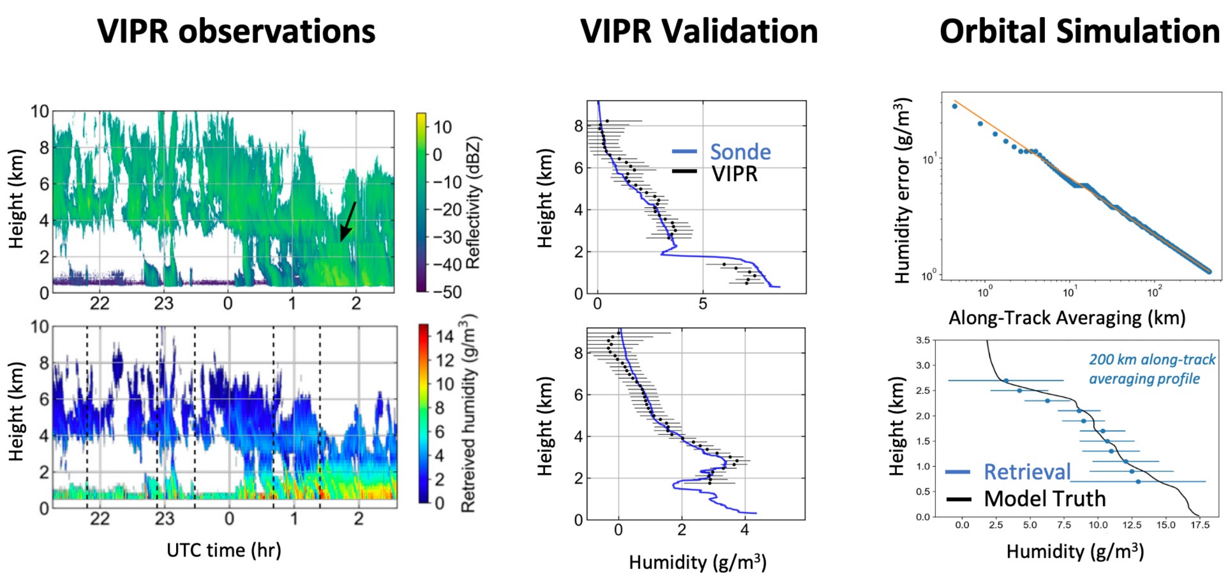

Figure 8-11. An example of a cloud and water vapor curtain from the Vapor In-Cloud Profiling Radar (VIPR; left), example validation of VIPR water vapor retrievals (middle), and results of a simulation of DAR retrieval performance from an orbital platform observing shallow precipitating marine cumulus (Roy, personal communication).

Strengths: Ability to resolve profiles of water vapor (and indirectly temperature) in clouds and weakly precipitating systems; layer integrated water vapor amounts between the surface and first cloud layer as well as between any two cloud layers, ability to derive total column integrated water vapor.

Weaknesses: Inability to profile in cloud-free regions, potential susceptibility to differential scattering effects, non-uniform beam filling due to large footprint, profile measurements limited to a single line-of-sight curtain below satellite.

Technology Development Needs

1. *High-Power Transmitter Sources*: The increased range to target from an orbital platform requires approximately a minimum of 100 W of peak transmit power at G-Band to enable a frequency chirped mode of operation. Candidate technologies to achieve these high-powers include vacuum electronics power amplifiers or massive power combining of miniaturized solid-state sources.
2. *Low Phase-Noise Sources*: The envisioned DAR architecture employs a frequency-chirp with pulse compression to increase radar duty cycle relative to a pure pulsed radar. A side effect of this architecture is increased spread of bright reflections off of

the Earth surface into the adjacent range bins, which can mask the reflections from much weaker cloud targets within the PBL. Mitigating this potential surface-clutter requires oscillators with state-of-the-art phase stability such as could be achieved with radio frequency photonics approaches.

3. *Beam Steering*: Beam steering enables intelligent adaptive scan capability to target cloud and precipitation volumes and maximize signal acquisition. This capability could be achieved through a phased array with electronic beam-steering, mechanical scan, or reflectarray / metamaterial technologies.
4. *G-band Lightweight Deployable Antennas:* An antenna diameter of approximately 2 m is required to enable the DAR measurement. Lightweight deployable antennas provide opportunities for small-satellite implementation of the DAR measurement. Specific to the multi-frequency DAR measurement these antennas must have a large bandwidth spanning up to 20 GHz. Deployable solid antenna's offer the most straightforward approach to achieve these bandwidth requirements.
5. *G-band high-power, low-loss switches and circulators*: current latching ferrite circulators are limited to frequencies below 94 GHz. At G-band, isolation of transmit and receive signals is currently done with a quasi-optical approach. There is a need for RF switch topologies with low insertion loss and high-power handling properties to reduced instrument mass and enable fast switching capabilities at G-band.

8.3.3 HYPERSPECTRAL INFRARED SOUNDERS

Hyperspectral infrared sounders measure upwelling IR radiances from about 3 to16 µm with high spectral resolution to retrieve atmospheric profiles of temperature, water vapor, other gases, and cloud properties. A moderate resolution instantaneous footprint of the order of 12 km per pixel combined with a wide cross-track scanning from low earth orbit provides almost daily global coverage per satellite. The program of record for this approach consists of grating spectrometers such as AIRS on the Aqua satellite, and Fourier Transform Spectrometers such as IASI and CrIS on the S-NPP, Metop and JPSS satellites (Chahine et al. 2006; Clerbaux et al. 2009; Bloom 2001).

The vertical sensitivity, precision and accuracy of profile retrievals from hyperspectral IR sounders depend both on the characteristics of the instrument (spectral resolution, spectral range/coverage, instrument noise, spatial resolution) and on the details of the retrieval algorithm. High spectral resolution provides the ability to resolve absorption line structure, thereby providing a means to distinguish the contribution of different vertical layers within the atmosphere. Increasing the spectral resolution allows both an enhanced ability to resolve vertical structure and to distinguish between absorption features associated with different gases, although in instrument design there are inevitable trade-offs to be made between spectral resolution and instrument noise.

Retrievals of atmospheric profiles from thermal IR sounders present an ill-posed problem, meaning that multiple solutions for the atmospheric state may result in the same radiance spectrum, within the noise of the radiances. For this reason, it is common practice to apply constraints on the retrieval solution. One widely used approach for profile retrievals is optimal estimation (Rodgers 2000). This approach utilizes prior constraints on the retrieval and provides diagnostic output such as vertical sensitivity and error covariances. With optimal estimation, the vertical sensitivity is characterized by the averaging kernel matrix, which represents the sensitivity of the remotely-sensed profile to the true atmospheric state. The width of the rows of the averaging kernel matrix provides a measure of the vertical resolution of the retrieved profile, while the trace of the averaging kernel matrix provides the degrees of freedom for signal (DOFS), or number of independent pieces of vertical information for the target quantity (e.g., the temperature or water vapor profile). Figure 8-12, adapted from Irion et al. (2018), shows a sample averaging kernel for temperature and water vapor from a single-footprint AIRS retrieval. The row sums of the averaging kernel are shown in the dotted black lines and indicate how much a retrieval relies on the measured upwelling radiance data for its results. A value near one at a particular altitude indicates that the retrieval relies mostly on observations while a value near zero means that most of the information comes from the a priori assumption. In this example, the PBL sensitivity is low for temperature, but higher for water vapor. Note that the averaging kernel depends both on the instrument characteristics and on the prior constraints (choices made within the retrieval algorithm). Tighter retrieval constraints and higher instrument noise would both result in weaker dependence of the result on the measured radiance and lower vertical resolution. Therefore, care is needed to ensure that the prior constraints are indeed representative of prior knowledge of the atmospheric variability.

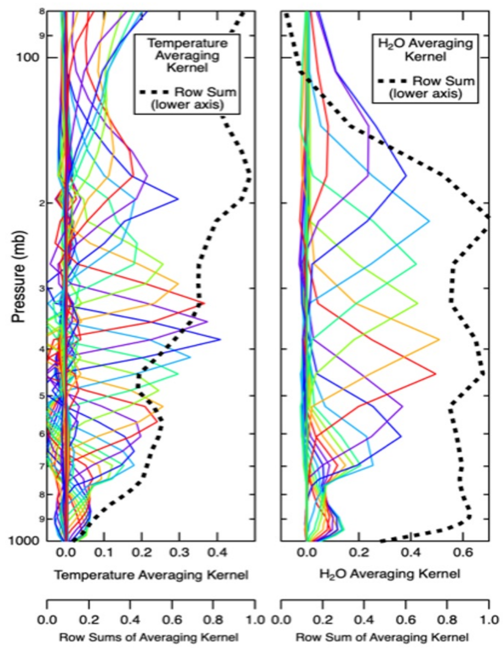

Figure 8-12. Sample of AIRS single foot-print averaging kernels, row sums of the averaging kernels and approximate vertical resolutions for temperature (left) and water vapor (right). From Irion et al. (2018).

Hyperspectral IR sounders have great coverage throughout the atmosphere, but the vertical sensitivity, including sensitivity to the PBL and near surface atmosphere depends on the details of the atmospheric and surface state and may be reduced due to cloud cover or a small vertical temperature gradient. This sensitivity can be characterized using averaging kernels as described above. Since the averaging kernels for hyperspectral IR sounders such as AIRS, IASI, and CrIS are heavily scene-dependent, elucidating absolute sensitivity and resolution from a single observation is not possible. Although the performance of the POR for IR sounders is well documented, there is still a wealth of work ongoing in the community to increase the sensitivity of these retrievals to the PBL and near surface atmosphere.

For example, Wilson et al. (personal communication, 2020) show that for a given set of constraints, an example IR sounder retrieval from an instrument with IASI-like spectral resolution and spectral coverage, with utilization of the full range of available channels, can have up to 2.5 DOFS for PBL water vapor in specific, yet meteorologically and climatologically important, conditions. For water vapor, single profile DOFS for current IR sounders within the PBL vary from zero to about 2.5 with the majority of cases having 1 to 2 DOFS and some PBL regimes and regions of the globe having DOFS as high as 2.5.

Improvements to instrument noise (reduction in noise-equivalent delta temperature, or NEDT) can further increase the information content. Figure 8-13 illustrates how reductions in instrument noise for a IASI-like instrument would impact the DOFS for retrievals of water vapor within the

PBL over the subtropical ocean, in the context of meteorological conditions that are favorable to a good retrieval. Extension of the spectral range to shorter wavelengths (out to 1 µm) would also increase the information content of water vapor retrievals within the PBL by providing additional constraints on the total column.

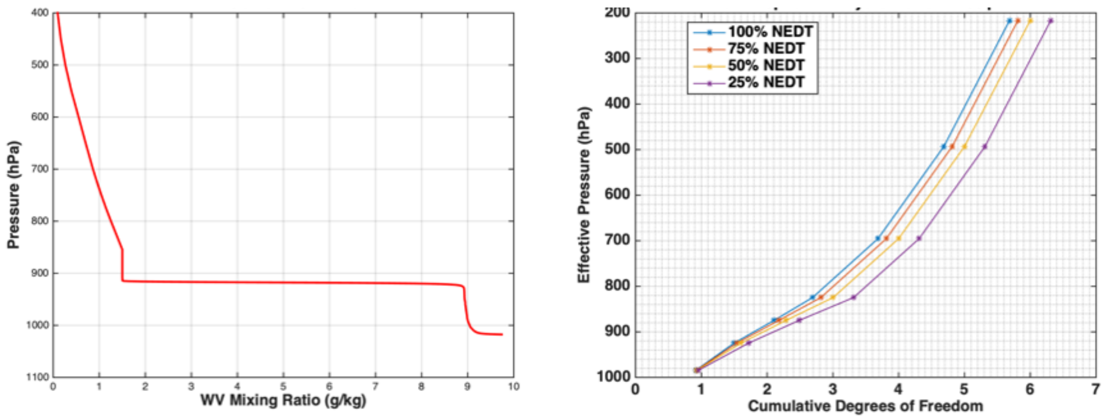

Figure 8-13. (Left) Simulated water vapor profile for a well-mixed PBL over the subtropical ocean from a Large-Eddy Simulation (LES). (Right) cumulative degrees of freedom from IASI with different levels of noise (Wilson, personal communication).

Studies like this one highlight the need for improved algorithm development and also shed light on the utility of multi-sensor (e.g., DIAL/IR sounder) retrievals where active sounders can serve as a high resolution prior to constrain the IR sounder retrieval, which in turn will increase the resolution and accuracy of both temperature and water vapor retrievals.

Current technology demonstrations under development include CubeSat and SmallSat IR sounders capable of achieving much higher spatial resolution than AIRS in the mid-wave IR temperature and water vapor band (approximately 4 to 5 µm) (e.g., Pagano et al. 2019). The mid-wave IR band shows similar vertical resolution to the longwave IR temperature sounding band in the lowest 1-2 km, but greatly reduces the cost and size of the instrument. Current CubeSat and SmallSat IR sounder efforts are focused on the mid-wave IR channels, meaning that future constellation observing systems could lack key longwave IR channels that improve accuracy down to the PBL. New technologies can help to fill this gap in the longwave IR with lower cost uncooled detectors by employing novel computational reconfigurable imaging spectrometer designs (Sullenberger et al. 2017).

IR sounders on LEO with extremely high spatial resolution (< 250 m) or on GEO are also possible with today's technology. However, the higher the spatial resolution, the narrower the swath. For example, a 200 m ground sampling distance from nadir can achieve a 10-20 km swath. NOAA is currently studying the potential of some of these concepts, but a detailed study of a sub-250 m IR sounder for PBL applications has not been performed. Thermal IR imagers with high-spatial resolution (500 m and 500-km swath) can also be used to measure PBL cloud top temperatures and to infer cloud top heights (Carr et al. 2018). IR (and visible) images from GEO and LEO platforms can be combined to perform stereoscopic imaging of PBL cloud-top height and motion. The stereo technique provides a geometric height measurement of tracked features, which yields cloud/aerosol top height retrievals. CubeSat IR sounders (with 1 km spatial resolution) or dedicated low-cost cameras can be used in GEO-LEO (leveraging the POR in GEO) or in LEO-LEO constellations to perform PBL cloud/aerosol height determination. However, exact altitude registration of an identified layer or feature is still challenging for these approaches and further investigation is required on the exact implementation.

It is important to note that international space agencies are also in the process of studying and developing similar technological approaches. The Centre National d'Études Spatiales (CNES), for example, is currently investigating the feasibility of future constellations of miniaturized hyperspectral IR sounders with high horizontal resolutions of approximately 1 km. These small satellites will provide information on temperature and water vapor profiles with a high temporal frequency that will help better detect rapid changes in atmospheric conditions.

Strengths: Temperature and water vapor profiles (with reasonably high information content), sensitivity to trace gases, ability to retrieve cloud properties and surface temperature, good spatial coverage at approximately 14 km horizontal resolution with cross-track scanning instruments in LEO (with strong potential for improvement), equivalent day/night performance for observations and retrievals, horizontal resolutions of the order of 1 km are feasible from LEO, potential to get high spatial (around 5 km) and temporal (around 30 min) resolution from geostationary orbit.

Weaknesses: Vertical resolution of retrievals restricted by physics, optically thick clouds prevent retrievals below the cloud, ill-posed problem (i.e., multiple profiles can provide the same radiance observation) so retrieval framework matters (i.e., choice of appropriate prior constraints is important), vertical distribution of information content depends on the actual atmospheric profile shape and on the thermal contrast between the surface and lowermost atmosphere, spectrally overlapping trace gases can complicate the retrieval algorithm framework, although provide the benefit of retrieving said trace gas profiles which are important for climate and air quality applications.

Technology Development Needs

IR sounders have shown skill in measuring parameters within the PBL including surface and near-surface temperature, PBL temperature and water vapor vertical structure for certain meteorological conditions, PBL height, and PBL cloud properties. Advances in detector and optics technology now enable instruments to be developed with greater spatial, spectral, and temporal resolution for LEO and GEO, potentially improving their value to PBL science requirements.

1. *High Performance Telescopes*: Larger apertures (e.g., as high as 0.5 m) in a small package with a high magnification and good image quality. Wide field refractive, or reflective and deployable designs that facilitate use in SmallSat applications are needed. The wide field enables a longer dwell time to improve signal collection efficiency.
2. *Infrared Spectrometers*: Higher spectral resolution spectrometers that cover a broad spectral band or are targeted to certain trace gas species relevant to the PBL may be required. They must also be wide field to cover a broad spatial area while providing a high resolving power. Investments in grating spectrometers, FTS, etalon, metamaterial filters, spatial heterodyne or other spectrometer forms that reduce size and improve spectral resolution and etendue (i.e., product of collection aperture and field of view) are needed.
3. *Detectors*: The availability of 2D format focal plane assemblies is limited in the longwave infrared (LWIR) temperature sounding band. The “workhorse” HgCdTe detectors exhibit higher dark current and noise spectral density within this region which significantly limits spatial resolution. New materials such as Type II Superlattice or improved formulations of HgCdTe are required in large Megapixel formats to enable sounding within the LWIR band. Associated Read Out Integrated Circuits (ROICs) would be required to realize any future benefits of new LWIR detector arrays. Improvements in ROIC readout speeds to enable very large array formats will help to improve coverage.
4. *Cryocoolers*: IR detectors require cryocooling. Uncooled thermopile and microbolometer detectors will not provide sufficient sensitivity to achieve very high spectral resolution simultaneously with very high spatial resolution. The optical

systems for the PBL spectrometers may also require cooling. Investment in developing new capabilities for active cryocooling that reduce cost and SWaP as well as quantifying the performance of these cryocoolers is important to future compact IR sounders.

8.3.4 HYPERSPECTRAL MICROWAVE SOUNDERS

Microwave (MW) sounders are important components of the global weather satellite and NWP system enabling all-weather, day-night, land-ocean measurements that are sensitive to hydrometeors, temperature and water vapor profiles. The measurement principles of MW sounding are similar to IR sounding and many of the strengths and weaknesses between the two measurement approaches are shared. A microwave sounder measures upwelling thermal emission typically in a number of channels surrounding oxygen (52 to 60 GHz) and water vapor (23 GHz, 183 GHz) emission lines as well as within interspersed spectral windows. The brightness temperature measured at different frequencies depends on water vapor and temperature profiles, clouds and precipitation, and surface properties.

The measured radiance in a given channel depends on the atmospheric transmittance. The transmittance in microwave wavelengths is impacted by wavelength-dependent molecular absorption (water vapor and oxygen lines and smoothly-varying water vapor, oxygen and nitrogen continua) as well as absorption and scattering from liquid water and ice. It is common practice to express the sensitivity of microwave sounder channels to the water vapor and temperature profile in terms of channel weighting functions, which are defined as the partial derivative of the transmittance for a given channel with respect to altitude or pressure and indicate the relative contribution of each atmospheric layer to the measured radiance. The altitude of the peak of the weighting function depends on the strength of the absorption. Its width (which is often coarse) arises from the finite spectral resolution of the channel. This results in a smoothing effect on the retrieved vertical profiles of temperature and water vapor abundances. While different user groups specify the vertical resolution of these MW (and IR) sounders in different ways, the vertical resolution is often most easily interpreted as the full width at half-maximum (FWHM) of the weighting function. Note that weighting functions can also be calculated for IR sounder channels and that an optimal estimation retrieval approach applied to MW sounder radiances can be used to generate MW averaging kernels. The program of record for this approach consists of multi-channel radiometers such as AMSU on the Aqua and MetOp satellites and ATMS on Suomi NPP (Aumann et al. 2003; Weng et al. 2013).

The weighting functions for the Advanced Technology Microwave Sounder (ATMS) instrument are shown in Figure 8-14. Note the frequency channels are selected so that vertical response is approximately Nyquist sampled – the weighting functions overlap, the peak of one coincides with the half-max points of its neighbors. Weighting functions for a hypothetical hyperspectral MW sounder (in the same spectral regions as ATMS) is shown on the right-hand side of Figure 8-14, demonstrating the improvement in vertical coverage resulting from additional spectral-channels with different strengths and hence sensitivity to different parts of the atmosphere.

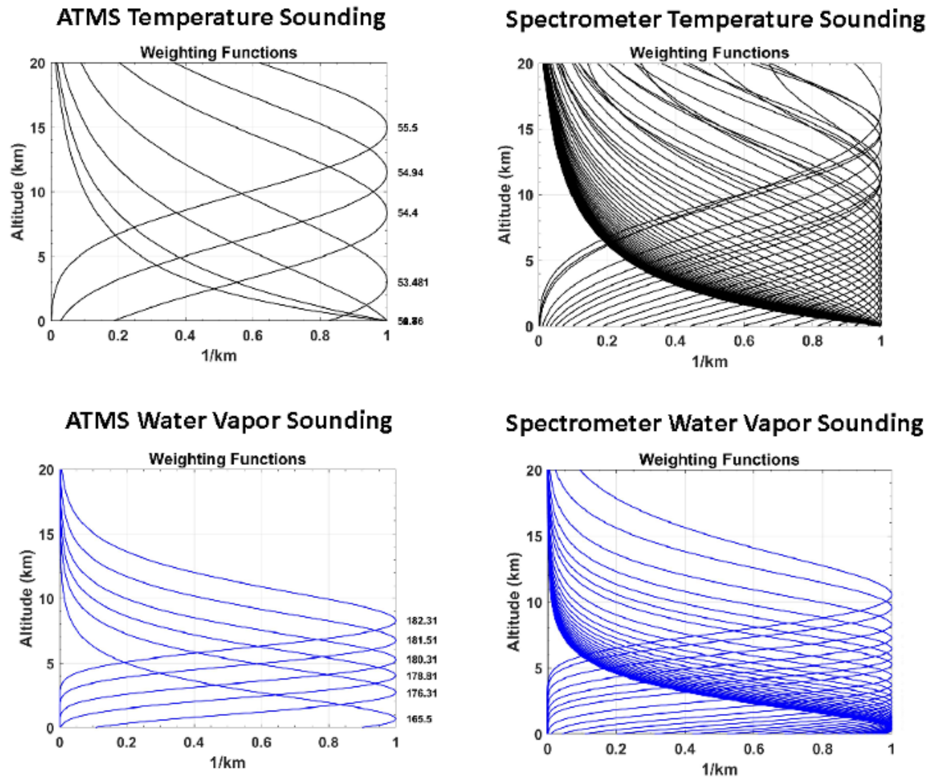

Figure 8-14. (Left) Weighting functions for the ATMS temperature (top) and water vapor (bottom) sounding channels. (Right) Example weighting functions for a hyperspectral MW sounder (Brown, personal communication).

Horizontal resolution for microwave instruments is set by their aperture size and is typically interpreted as the diameter of the 3-dB antenna pattern footprint on the surface. Sounder antennas are typically scanned between ~ +/- 60 deg from nadir in a cross-track fashion. This results in varying footprint size from nadir to swath edge. Another implication due to the design of most sounders is varying polarization basis across the swath due to rotation of the scanning reflector.

Instrument noise is determined by system noise temperature, receiver bandwidth and integration time. Unlike optical and active instruments, radiometer noise is not a function of antenna collecting area. Integration time is usually set by antenna scan and spacecraft velocities. Channel bandwidths are set by weighting function needs and radio spectrum regulations. For state-of-the-art MW radiometers such as ATMS, the retrieval uncertainties in the PBL region (800-950 mb) are 1-2 K rms and 10-20% for temperature and water vapor, respectively.

Strengths: Temperature and water vapor profiles with 0-1.5 pieces of information content, relatively insensitive to the presence of non-precipitating clouds, fair spatial coverage at ~50 km horizontal resolution (potentially down to about 5 km in LEO in the future) with cross-track scanning instruments in LEO, equivalent day/night performance for observations/retrievals.

Weaknesses: Vertical resolution of retrievals restricted by physics, precipitating clouds (which by their nature are inhomogeneous in a 50-km footprint) add significant uncertainty to retrievals below the cloud, ill-posed problem (i.e., multiple profiles can provide the same radiance observation) so retrieval framework (i.e., choice of prior constraints) matters (i.e., strong dependence on the prior dataset used), vertical distribution of information content depends on the actual atmospheric profile shape, changes in land surface emissivity with land use and soil moisture must be accounted for in retrievals, diffraction limitations prevent GEO observations unless antenna is markedly larger.

Technology Development Needs

There are two technology vectors for future passive microwave instruments: hyperspectral radiometry and miniaturization.

Hyperspectral MW sounding is an emerging approach to increasing information content or vertical resolution in the PBL by leveraging the heritage and utility of microwave sounding while adopting the increased spectral resolution and coverage approach of hyperspectral IR. Increased spectral coverage increases sensitivity (more bandwidth) by accessing previously unobserved parts of the spectrum, however, similar to IR sounding, there is still an intrinsic limit to the best vertical resolution that can be achieved based on physics. The added spectral diversity also serves the need to detect potential radio frequency interference from emerging 5G systems. Increased spectral resolution increases the sampling density of vertical weighting functions. Studies of the potential of hyperspectral microwave are found in Blackwell et al. (2010) and Aires et al. (2015).

Reducing the mass, power and/or stowed volume of microwave sounders can enable SmallSat implementations, reduce launch cost or increase launch or hosting opportunities. The potential capability is illustrated by microwave CubeSat missions IceCube (Wu et al. 2019), TEMPEST-D (Reising et al. 2018) and the forthcoming TROPICS (Blackwell et al. 2018).

1. *Digital Spectrometers*: Low resolution (16-128 channel) filter banks were proven on the Soil Moisture Active Passive (SMAP) radiometer and the CubeSat Radiometer RFI Technology demonstration. Moderate to high resolution (256-4096) channel digital spectrometers with >4 GHz bandwidth (preferably widely applicable and commercially available) ASICs paired with on- or off-board ADC's with appropriate dynamic range will enable hyperspectral sensing and RFI detection for PBL measurements.
2. *Microwave Photonics and Photonic Integrated Circuits*: Converting microwave signals to the optical domain allows large bandwidths (10's of GHz) of signals to be processed with integrated optics and photonic integrated circuits. Photonic integrated circuits (PICs) for optical up-conversion, filter banks, detection and/or down-conversion will revolutionize radiometer receiver architectures for wideband PBL observation.
3. *G-band (200-GHz) Lightweight Deployable Antennas:* Small-to-moderate size (0.3-1 meter) deployable antennas operating to 200 GHz can reduce mass and stowed-volume for microwave radiometers. This widens the range of available implementation and launch approaches including SmallSat free-flyers launched on ride-shares.

8.3.5 GLOBAL NAVIGATION SATELLITE SYSTEM RADIO OCCULTATION (GNSS-RO) AND LEO-LEO OCCULTATION (LLO)

The GNSS-RO technique measures the carrier phase of the L-band (1-2 GHz) microwave signal transmitted by a GNSS satellite (e.g., GPS) as the GNSS satellite sets or rises above the horizon (Figure 8-15). The phase measurements, along with precise knowledge of the transmitting and receiving satellite position and velocity, can be used to retrieve a vertical profile of bending angle and refractivity (e.g., Hajj et al. 2002). The refractivity is a function of temperature, pressure, and water vapor pressure (e.g., Smith and Weintraub, 1953). The refractivity coefficients that relate these parameters also depend on the composition of the dry air, which is assumed to be known. Retrieval of temperature and water vapor from refractivity in the moist lower troposphere and the PBL is an under-determined problem that requires the use of a priori information (Kursinski and Hajj, 2001; Healy and Eyre, 2000).

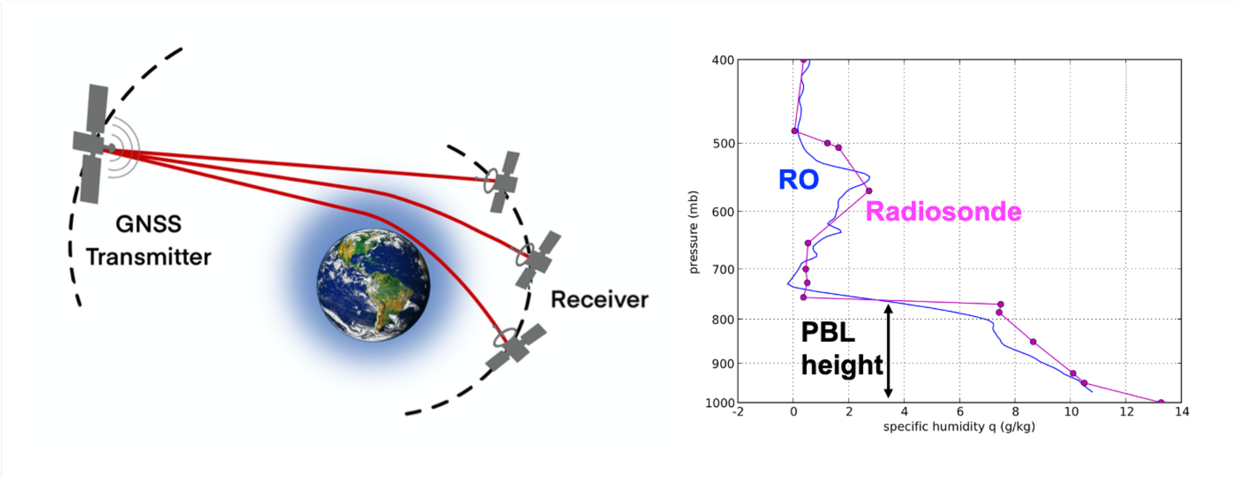

Figure 8-15. GNSS-RO observation geometry. A GNSS receiver on LEO orbit tracks the L-band signals broadcast by a GNSS satellite as the signals passes through different layers of the atmosphere (left). The excess phase delay due to the atmosphere can be used to retrieve a vertical profile of bending angle and refractivity. An example of the retrieved water vapor profile from a COSMIC RO sounding, which shows close agreement with a nearby radiosonde observation. The sharp changes in water vapor profile (which also appears in refractivity) can be used to infer the PBL height (right) (Ao, personal communication).

A single receiver on Low Earth Orbit (LEO) has about 500 occultation sounding opportunities per day per GNSS constellation (e.g., GPS, GLONASS, Galileo, Beidou). Thus, a receiver capable of tracking all four major GNSS constellations can provide ~2000 soundings per day. The spatial distribution of the soundings is statistically uniform in longitude while its latitude distribution varies depending on the orbital inclination of the LEO. The local time sampling will largely depend on the ascending/descending nodes of the LEO orbit. Global distribution with good diurnal cycle coverage can be achieved using a constellation of LEOs in high inclination orbits and evenly-spaced ascending/descending nodes similar to the COSMIC constellation.

As a limb sounding technique, GNSS-RO bending angle and refractivity retrievals have high vertical resolution of better than 100 m in the troposphere, limited only by diffraction within the atmosphere (Gorbunov et al. 2004). Horizontal resolution along the signal path is however fairly coarse, at approximately 100 km (Kursinski et al. 1997). The high vertical resolution refractivity profiles are sensitive to sharp changes in water vapor and temperature at the top of the PBL (Figure 8-15). Thus, they have been utilized to provide an estimate of global PBL heights (e.g., Guo et al. 2011; Ao et al. 2012; Xie et al. 2012; Chan and Wood 2013; Ho et al. 2015).

The L-band GNSS signals penetrate clouds and precipitation without degradation. However, it is known that fine vertical scales of water vapor can lead to strong attenuation of the signals through the tropical troposphere due to defocusing effect. The strong defocusing may be responsible for the insufficient profile penetration in the PBL from COSMIC and similar missions, with only about 50% of the profiles reaching below 1 km altitude in the tropics (Ao et al. 2012). In addition, a negative bias in bending angle and refractivity exists within the PBL especially at low latitudes (Feng et al. 2020), although the large contribution of refractivity bias caused by ducting can be corrected through advanced retrieval techniques (Wang et al. 2020b).

<u>Strengths</u>: High vertical resolution of temperature or water vapor profiles, all-weather capability, independent of day/night/surface emissivity, strong sensitivity to water vapor change across PBL top leading to accurate PBL height determination, low-cost.

<u>Weaknesses</u>: Unable to resolve horizontal inhomogeneities below 100 km scale, retrievals of both temperature and water vapor require prior information, retrieval bias and insufficient depth

penetration in low latitudes, potential surface interference, requires large number of satellites to achieve spatial coverage comparable to passive sounders.

Technology Development Needs

1. *Receiver Technology*: GPS-RO receivers have been in use since the 1990s, starting with the GPS/MET proof-of-concept mission. The first-generation "modern" GPS-RO receivers (BlackJack/IGOR/GRAS) behind missions from CHAMP to COSMIC and MetOp are capable of codeless tracking (needed for tracking encrypted GPS signals) and open-loop tracking (needed in high dynamic signal environments such as the moist troposphere and for tracking rising occultations (Sokolovskiy 2003; Ao et al. 2009)). The second-generation GNSS-RO receivers recently flown or in development (TriG/GRAS-2) are capable of tracking new GPS signals as well as signals from other global navigation systems such as GLONASS and Galileo. This greatly increases the number of RO measurements per receiver. In addition, the new receivers have improved signal tracking and on-board processing capabilities which, along with higher SNRs enabled by beam-forming technology (as demonstrated by the COSMIC-2 mission (Schreiner et al. 2020)), should provide better PBL penetration and potentially less biased retrievals. Further improvements along these trends are likely needed to target the lowest part of the PBL. In addition, due to the presence of strong horizontal irregularities in the PBL, advanced ground processing algorithms that take into advantage of the full spectral content of the signal would need to be developed to optimize PBL retrieval content.
2. *Miniaturization and Commercial Developments*: Another development is the trend towards the miniaturization of GNSS-RO technology. Small companies now have the capabilities to launch their own fleet of GNSS-RO CubeSats and have participated in commercial data buy programs initiated by NOAA and NASA. These low-cost CubeSat constellations could provide an unprecedented number of RO measurements, enabling new science applications that demand better spatial and temporal sampling. The CubeSat platform could also provide a rapid way to test new technologies on orbit and accelerate their adoption.
3. *Innovative Occultation Concepts*: Occultations of GNSS L-band signals exploit a signal of opportunity. This makes the system both cost-effective (since there is no need to launch our own transmitter) and highly efficient (since there are an increasing number of transmitters available). The disadvantage is that we have no control over the nature of the transmitting sources. There is nothing precluding occultation measurements using actively generated signals from satellites in LEO at multiple frequencies other than L-band (Liu et al. 2017). Such LEO-LEO occultation concepts have been considered since the 1990s, although none of these concepts targets the PBL. Useful bandwidth is reserved for radar transmission up through Ka-band. Exploitation of the available spectra using measurements of both signal attenuation and phase has the potential to enable simultaneous retrieval of both temperature and water vapor in the PBL with high vertical resolution and without prior constraints. Furthermore, the continued revolution in miniaturized microwave components and deployable antennas capable of beam steering enables a plausible deployment of trains of small or CubeSats that can be harnessed to make frequent global soundings. Despite the low TRL of these measurement concepts, the potential for their implementation with small satellites and potential access to both temperature and water vapor warrant investment in feasibility studies and instrument development funding conditioned on promising results.

8.3.6 RAMAN LIDAR

Raman Lidar is another powerful active remote sensing approach that has been employed for as long as DIAL. Raman scattering, which includes the pure-rotational Raman spectrum and the vibrational Raman spectrum, provides a unique mechanism for remote sensing of the atmosphere. The vibrational Raman scattering intensity is fundamentally proportional to the number of molecules involved - a feature widely used to remotely measure atmospheric components (Cooney 1970; Philbrick 1994; Turner and Whiteman 2002). The proportion of nitrogen, relative to other dry air components, is a constant. Therefore, the measured ratio of Raman scattering signals from water vapor to that from nitrogen can be accurately translated to a water vapor mixing ratio after the system constant is calibrated (Whiteman et al. 1992). The intensities of low quantum-number transitions of the pure rotational Raman spectrum decrease with increasing temperature, while those of the high quantum-number transitions increase. Thus, temperature can be obtained by combining the measurements of rotational Raman channels for low and high quantum numbers. Although Raman temperature and water vapor measurements require externally-provided calibrations, the calibrations are stable when there are no optical and electrical efficiency changes within the lidar receiving system.

Recent advances in high energy UV lasers and efficient spectral filtering allow for accurate water vapor and temperature profiles to be simultaneously measured (Behrendt and Reichardt, 2000; Mattis et al., 2002; Di Girolamo et al. 2004; Reichardt et al. 2012; Lin et al 2019). Many airborne and surface-based Raman lidars have been developed and deployed over the past four decades (Turner et al. 2002; Whiteman et al. 2010). Recently, airborne Raman lidars flying at low altitude on small aircraft have demonstrated the ability to retrieve water vapor, temperature and aerosol profiles with high horizontal and vertical resolution (1 km and 100 m, respectively) and have led to improved understanding of PBL processes for weather and climate applications. Figure 8-16 shows examples from the MARLi Raman lidar deployed on the King Air, demonstrating Raman's unique ability to simultaneously measure temperature, water vapor, and aerosol profiles with high spatial resolution.

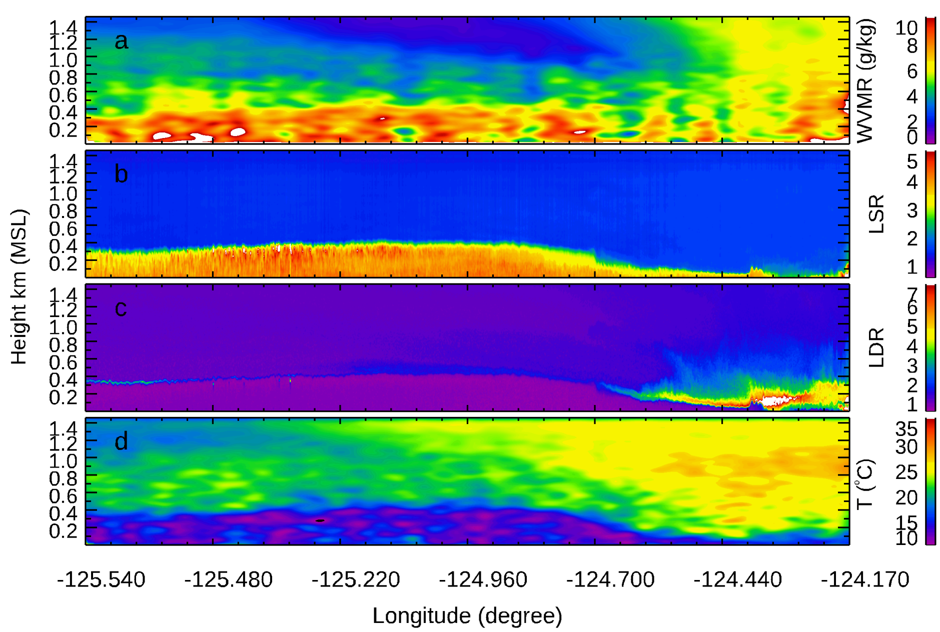

Figure 8-16. (a) WVMR, (b) LSR, (c) LDR and (d) temperature cross-sections along 40° N from the ocean (left side) to the coast around the Shelter Cove on June 30, 2016, based on MARLi measurements from the UWKA. Water vapor mixing ratio (WVMR), Lidar scattering ratio (LSR), Lidar depolarization ratio (LDR) (Wang, personal communication).

Simulation studies (Di Girolamo et al. 2018) of a space-based Raman lidar indicate that a very capable spacecraft is required in terms of mass and power. For a water vapor and temperature profiling Raman Lidar in LEO, a 250 W UV laser and a 4-meter telescope would be required to provide sensitivity in the PBL and throughout the free troposphere. In drier conditions, where the Raman water signal is much weaker, the vertical coverage is reduced, although with 200 m vertical and 50 km horizontal resolution there is still considerable skill to resolve inversions and small-scale features.

It is recognized that a temperature and water vapor profiling Raman lidar would require unrealistic spacecraft resources to achieve the desired performance metrics. Power estimates alone would be >15 kW for just the laser subsystem using current state-of-the-art laser technologies. A more realistic but still challenging variant of this measurement approach would be a temperature only Raman lidar system. A T-Raman system is currently the only nadir-pointing active measurement approach that provides profiles of temperature throughout the troposphere. Because the Raman rotational bands exhibit a scattering cross-section several orders of magnitude stronger than the H2O and N2 vibrational bands required for water vapor profiling, the required UV power and telescope aperture would be approximately 3 kW (using realistic electrical to optical efficiency of ~5% to 1064 nm) and 2 m, respectively. Laser induced contamination and damage for a T-Raman lidar at 50 W UV output (500 mJ at 100 Hz) also poses a significant challenge. Although system requirements are significantly relaxed for a temperature only Raman system, they are still outside the reach of accommodations commonly found on affordable/capable spacecraft. It is for this reason that we find that implementing even a temperature Raman lidar in space within the next decade is beyond the scope of the PBL Incubation effort which aims to advance technologies to an acceptable level of readiness by the 2026 in preparation for the 2027 decadal survey. It is however, recommended, because of the extreme utility of the Raman approach in providing high resolution profiles of temperature, to invest in relevant laser technologies outside of PBL Incubation such as through NASA SBIR and STTR to improve upon laser efficiency from the current ~5% to >10% at 1064 nm. Increasing the efficiency of Nd:YAG laser technology would have far reaching benefits enabling for a wide range of profiling and altimeter lidars. Advances on deployable or distributed telescopes would also be synergetic to other lidar measurement approaches.

Strengths: Ability to measure water vapor and temperature profiles with high vertical resolution in clear and broken-sky scenes, aerosol extinction profiles and lidar ratio can easily be obtained with the same system enabling many aerosol and thin cloud studies (e.g., cirrus extinction profiles, identification of aerosol layers, PBL top).

Weaknesses: Requires external calibration method (i.e., data from another source to calibrate against), clouds (and aerosols to lesser extent) attenuate lidar signals resulting in little-to-no water vapor profile data beneath clouds with optical depth greater than 1, profile measurements limited to a single line-of-sight curtain below satellite, eye-safety considerations, for high energy operation, need for a very high power laser and large telescope due to weak Raman scattering cross-section, significant degradation in SNR during daytime due to solar background contamination.

Technology Development Needs

1. *High electrical-to-optical efficiency 355nm laser*: Raman lidar for temperature profiling would require on the order of 500 mJ at 100 Hz or 250 mJ at 200 Hz (50 W) laser output at 355 nm. Although current commercial diode pumped high pulsed energy YAG 355nm lasers with 30-50 W power are available, their weight and power consumptions are too high and the opto-mechanical design not consistent with operation in space. The primary technology advance to enable a future T-Raman lidar would be to increase the electrical to optical efficiency from the current ~5% to >10%

at 1064 nm to reduce the power consumption to below 1 kW and enable operation on a large satellite platform. Candidate laser technologies include Nd:YAG laser, cryogenic Yb:YAG, Alexandrite laser, and emerging diode pumped Alkali laser. Unlike for DIAL, Raman lasers do not require injection seed or frequency agility, which opens more technical options. Advances in improving the efficiency Nd:YAG laser will benefit many future space-based lidar applications.

2. *Low-weight large telescope*: Raman lidar for temperature profiling would require on the order of 2-m diameter telescope. Although such a size telescope is feasible, a low weight deployable or distributed telescope is needed to make Raman-T lidar feasible. Lidar telescope does not require astronomical quality, but low weight and thermal stability properties are needed. Rigid primary mirror (single physical element or segmented optics), rigid central mirror with folded deployable outer sections, or inflatable optics are possible ways to provide large-aperture, lightweight telescope for Raman-T lidar. Low-weight deployable or distributed large telescopes would advance all space-based lidar applications.
3. *High efficiency narrow-band filters and low electrical noise data system*: For weak Raman signal detections, controlling noise levels are a critical step. Raman lidar needs interference filters with bandwidths around 0.2 to 0.5 nm to collect Raman signals. Thus, filters with improving center wavelength transmission (60% or higher) and decreased outside pass-band transmission (10-6 or lower, 10-8 at the laser wavelength) will increase signals and reduce optical noises. For Raman lidars, data system eclectic noise is often a challenging issue. Developing space-qualified low-noise high-efficient data acquisition systems will improve Raman lidar performance.

8.4 ALGORITHMS AND RETRIEVALS

The roles of retrievals and data assimilation from a scientific perspective were laid out in a previous chapter. In this section, the concepts are laid out in terms of production suites that would be appropriate for a PBL-focused mission.

8.4.1 PRODUCTION SUITE

The development of more sophisticated retrieval and data assimilation algorithms for specific measurement technologies is essential. For example, there is wealth of PBL height information from surface-based networks such as MPLNET and spaceborne sensors such as GNSS-RO, ICESat-2, and CALIPSO that require further algorithm development to enable automated PBL height product development and to reconcile PBL height across thermodynamic, aerosol, and refractivity profiles. However, the production suite of a spaceborne PBL mission that consists of different measurement technologies should target to combine each components' information content in an optimal manner. This can be achieved using joint retrievals, data assimilation or data fusion methodologies, which should be at the core of a PBL global observing system as the one discussed in this report.

As there is this core requirement for merging methodologies to exploit the variety of observations of the full architecture, there is a synergistic approach to how retrievals and data assimilation systems should be co-developed. As the fundamental methods of inversion are derived from a similar mathematical formalism, both communities can benefit from the coordinated use of similar components from a software engineering and integration perspective. There should be a strong push towards the utilization of a common framework for this. In data assimilation, the entire domestic development community, including the NASA Global Modeling and Assimilation Office (GMAO) and interagency partners at NOAA, and the Department of Defense, as well as the United Kingdom Meteorological Office (UKMO) internationally, are moving towards a transition of their data assimilation algorithms to the Joint Effort for Data Assimilation Integration (JEDI). Core to this is an object-oriented approach to the data assimilation system design, where it can be integrated into ocean, atmospheric, land, and coupled Earth system models. The UKMO has already investigated adapting their 1D-Var preprocessor to be JEDI compliant.

Since a significant part of the data assimilation community has committed to this infrastructure, and the UKMO is investigating its utility as a retrieval algorithm, it is worthwhile considering the role of JEDI as the baseline software infrastructure for both multi-instrument retrievals and for data assimilation. Due to its object-oriented design, it would result in specific components being readily transferable between data assimilation and retrievals.

8.4.2 OBSERVATION SIMULATION

As discussed in a previous chapter, OSSEs are critical for the design of a future PBL observing system, including NWP OSSEs and climate model OSSEs to consider the potentially great value of PBL observations for constraining predictions and projections such as equilibrium climate sensitivity. Considering this critical role of OSSEs, there is a need to consider unified approaches to observation simulation that are applicable and useful across the different types of spatial and temporal model scales, and model types and applications.

Large-eddy simulation (LES) models are able to represent most aspects of PBL turbulence in a realistic manner, and as such are absolutely essential tools to create PBL virtual data for retrieval OSSEs. A variety of different PBL types and regions will need to be considered so that LES OSSEs are able to realistically address as many PBL regimes as possible. However, there is still a need for global simulations to fully characterize the nature of a spaceborne mission. As such, global nature run simulations are still desirable to help characterize the time scales not only of the PBL but also of a global, long-duration mission. Synergistic approaches to link the global models that are used to create the global nature runs and LES simulations need to be considered to simulate observations that are of utility to perform OSSEs that will be useful for mission design.

8.4.3 PRODUCT DEVELOPMENT

There needs to be a core effort focused on, and underlying support for, the development of inversion techniques for the PBL, by both retrievals and data assimilation, between now and the launch of a PBL-focused mission. A few key factors need to be considered.

First, the data assimilation systems of today have not been developed to explicitly resolve features in the PBL from spaceborne observations. The systems are generally constructed for the best overall performance based on a set suite of metrics. For the operational NWP centers, the atmospheric analysis procedures generally target short- and medium-range weather forecast quality. The ocean analysis procedures generally target subseasonal-to-seasonal prediction quality. At GMAO, reanalysis is of particular importance for its systems. To develop a PBL-focused assimilation capability, the metrics need to be redefined, and investment is needed to advance these systems. This can and should be performed by targeting PBL information from existing components of the POR (e.g., PBL height estimates from lidar, infrared, and GNSS-RO, as well as surface-based thermodynamic profilers such as AERI, DIAL, and Raman Lidar). Furthermore, OSSEs (both traditional and non-traditional, retrieval and data assimilation) should be leveraged not only for assisting in mission pre-formulation but also for developing methods best-suited for exploitation of new observations targeted for a PBL mission. Examples of multi-sensor product development include joint DIAL/DAR retrievals, and utilization of active derived profiles as priors for IR and MW sounder temperature and water vapor retrievals.

Similarly, the production suite needs to be developed in a forward-looking manner. The paradigm of retrievals being generated on small servers/computing clusters is fading if not already outdated. Even if retrievals are performed on a single processing core with no or limited implicit parallelism, there is a fundamentally exploitable scalability to quickly process large batches of data. Thus, retrieval methods that had previously been considered prohibitive due to computational expense may become more reasonable. Two paradigms exist in terms of future processing: cloud computing and exascale computing.

A consideration is the advancement of parallel computing towards exascale processing capabilities. This is perhaps most applicable to modeling and data assimilation, but there may be commonly exploitable developments in the construct of retrievals if the underlying software infrastructure is consistent between the retrievals and data assimilation. Core to modern supercomputing is that the largest limitations are often in terms of communication and disk I/O. Thus, there needs to be a consideration for how this new paradigm is relevant.

Ultimately, a goal of pre-mission investment should be to develop a system capable of delivering a full set of products that meet the scientific needs laid out in this document. A PBL mission will need to be accompanied by a full set of products ranging from instrument-level to reanalysis-level or Level 0 to Level 4 as defined by the NASA data products processing levels. NASA should ensure that these products are developed well in advance of a full mission by coordinating its technological and scientific investments while leveraging and enhancing the expertise that already exists within the agency and the broader scientific community.

9. NASA OPPORTUNITIES

This chapter relates the study team findings regarding opportunities for investment by NASA in science, technology, and applications over the coming decade to incubate both the technology and research infrastructure in support of a potential PBL mission. It is recognized that a significant amount of the dedicated PBL Incubation funding will be from ESTO and will be devoted to advancing the hardware and software technologies to enable a future PBL mission. However, a central message of this chapter is the critical importance of formally cultivating the development of a unified PBL science, applications, and technology community ahead of the next decadal survey. This critical element of community incubation can be accomplished through either creation of a PBL science funding program or through coordination of existing funding lines.

9.1 RESEARCH AND ANALYSIS

There is already a wealth of expertise regarding the PBL within NASA; however, the breadth of the topic means that this expertise is scattered across disparate elements of the Research and Analysis (R&A) program. A PBL science community must be cultivated through strategic investments within the R&A program to advance a successful future PBL mission. The most straightforward means to establish this community would be through the creation of a new program or initiative within R&A focused on PBL science.

The current Program of Record (POR) has been insufficiently explored with regards to PBL science. Targeted efforts to better exploit the current POR to address PBL science and applications, including PBL modeling and data assimilation, should be prioritized. These include focused efforts to extract from the POR improved PBL temperature and water vapor profiles, and PBL height, potentially through synergistic combinations of measurements, to address specific PBL science questions. Ideally, NASA PBL modeling and data assimilation tools and datasets should be utilized to address PBL science goals and questions. In this context, improvements to PBL parameterization, modeling, data assimilation and retrieval algorithms should be prioritized.

The following priority science goals and questions described in the PBL science chapter and summarized in the preliminary PBL SATM could form the basis for organizing solicitations:

- **PBL, Convection and Extreme Weather**: What is the role of mesoscale variability in the interactions between PBL and convection? How does the thermodynamic structure of the PBL and lower troposphere foster a transition to deep convection? What is the role of PBL and surface processes in the diurnal cycle of precipitation?
- **Cloudy PBL**: How do the PBL thermodynamic structure and cloud properties covary and interact with each other, and how does it depend on cloud type? How are these PBL-cloud interactions mediated by turbulent surface fluxes and overlying free tropospheric thermodynamic conditions? What is the role of mesoscale variability in modulating the vertical structure of the cloudy PBL temperature and water vapor?
- **PBL and Surface Interaction**: What is the impact of surface heat fluxes on the PBL thermodynamic structure (and vice-versa)? Which processes control the water vapor near the surface? What is the impact of surface heterogeneity on the PBL thermodynamic structure and convection initiation? How does PBL thermodynamic structure and evolution modulate local and remote processes and feedbacks that govern hydrological and climatic extremes?
- **PBL Mixing, Modeling and Air Quality**: What are the main PBL mechanisms responsible for vertical transport of atmospheric constituents? What are the optimal methods to more effectively use space-based PBL observations in order to develop and evaluate unified PBL parameterizations in weather, climate and air quality models?

Resources within a potential new PBL Incubation program or initiative and the existing R&A programs could be coordinated to create a PBL working group or science team. The PBL is inherently interdisciplinary, acting as the mediating interface between the surface and the free-atmosphere. An Interdisciplinary Research in Earth Science (IDS) solicitation focused on the PBL and its connections to the various other components of the Earth system would foster a unified PBL community. Where appropriate, the PBL community should draw from across the R&A program through targeted sub-component solicitations within the existing programs. For example, the Modeling, Analysis and Prediction is one of many programs that could focus part of their resources on the PBL. Finally, synergies with upcoming missions should be exploited where they exist. An example is the hyperspectral VSWIR imagery that is expected from the SBG DO mission, which can provide high resolution water vapor products useful for exploring horizontal turbulent and mesoscale variability and land-atmosphere interactions.

Regardless of how the PBL community is funded, a PBL working group or science team that reports to NASA HQ, meets on a regular cadence, draws from across the R&A program, and includes an adequately diverse spectrum of modelling and observational elements, is necessary to maintain the cohesiveness of the PBL community. Meetings should also offer the opportunity for the presentation of developments with regards to formal Incubation activities related to suborbital campaigns, technology developments, potential applications, and a broad spectrum of OSSE-type studies. Furthermore, these meetings would operate as a public interest forum that is open to both U.S. and international participation to inform and engage a diverse array of scientists. Open community sub-groups focused on specific topics (e.g., weather forecasts, climate projections) could be created. These sub-groups should report to the PBL working group or science team (that reports to HQ), and should be encouraged to deliver community-specific findings regarding relevant matters, thus providing an effective NASA earpiece to broad community input.

9.2 APPLIED SCIENCES

The NASA Applied Sciences Program encompasses the program areas of Capacity Building, Disasters, Health and Air Quality, Water Resources, Ecological Forecasting, and Food Security and Agriculture. Each of the specific PBL applications described in Chapter 5 relates to one or more of these program areas. A set of targeted projects in each of these program areas would ensure that existing NASA observations and products are put to their best use by the applications community and maximizes the likelihood that a future PBL mission will provide data that is useful to the applications community. These projects would be essential to increasing the application readiness level (ARL) of potential new measurement capabilities in preparation for a PBL mission.

For example, several of the needs addressed in the AQ application could benefit from a NASA Applied Sciences investment as part of the Health and AQ program area. Another example is the need addressed by the PBL application related to hydrometeorology, which could benefit from investment in projects as part of the Disasters, Food Security and Agriculture, and Water Resources program areas. Other PBL applications mentioned in Chapter 5 that are related to the Food Security and Agriculture program area are Agriculture and Fisheries applications. PBL applications related to the Capacity Building program area are Renewable Energy and Transportation. For example, a community with interests in improved observations and modeling of the PBL is the burgeoning wind energy sector. Federal partners such as DOE have invested in improved observations and modeling for this application, and there are multiple industrial partners that could be brought into the discussion as well. Marine weather is another application that cuts across multiple federal agencies, including NASA, NOAA, DOE, and the U.S. Navy.

A strong applied sciences component, to the PBL science team or working group mentioned above, that assembles members of the Applied Sciences Program, PBL scientists and users, both inside and outside the US government, is necessary to build a platform where these diverse communities can interact effectively, share information and publicize the availability of these

NASA resources. The PBL working group or science team should continue to meet annually throughout the Incubation process with the applied science component fully integrated with the science and technology community. A sub-group of the PBL science team focused on applications should be created, that could organize additional PBL applied sciences meetings if deemed necessary.

9.3 TECHNOLOGY DEVELOPMENT

Hardware: Detailed findings regarding requisite technology investment were outlined in Chapter 8. Here we briefly enumerate the relevant measurement approaches to benefit from investment. Continued investments in advanced instruments and their sub-components in a fashion similar to the existing Instrument Incubator Program and Advanced Component Technology programs are crucial to mature instrument technology readiness. Technology advances that have the potential to reduce instrument SWaP should be prioritized. Investment opportunities in instruments include, but are not necessarily limited to

- Differential Absorption Lidar
- Differential Absorption Radar
- Radio-occultation (including non-GNSS LEO-LEO occultation approaches)
- Hyperspectral infrared sounders
- Hyperspectral microwave sounders

Note that Raman lidar is an exciting technique to measure clear sky temperature and water vapor. However, as discussed in Chapter 8, the study team has determined that even a temperature-only Raman lidar would require unrealistically large spacecraft resources at this time. Instead, it is concluded that Raman technology continue to be advanced outside of the formal Incubation activities.

Software: A comprehensive PBL mission will require multiple complementary instruments and new types of measurements. Significant investments in software tools and infrastructure are needed to support such a mission on several fronts and could be supported under the umbrella of the Advanced Information Systems Technology (AIST) program or similar programs.

- Observing System Simulation Experiments (OSSEs) are needed to demonstrate the utility of the potential PBL measurements. Importantly, the term OSSE includes those beyond the traditional definition of weather forecast/NWP OSSEs, to include sampling, retrieval, and process OSSEs, among others.
- Large Eddy Simulation (LES) models that resolve most of the turbulent and convective flow that characterizes the PBL are required for several of the OSSEs mentioned above; investment in software that would make the development, validation and utilization of LES models more effective is essential for reliable PBL OSSEs.
- Advanced level-2 algorithms will be needed to retrieve atmospheric thermodynamics from the combination of diverse sampling, sensitivity, and spatial averaging capabilities of the candidate active and passive systems. In particular, regarding the diverse measurement characteristics of the instruments proposed in the architecture described in Chapter 8. As noted later in this chapter a crucial element of this activity will be acquiring airborne datasets that include all of the candidate PBL instruments on a common airborne platform to create test data sets.
- It is envisioned that a Level 4 product derived from assimilation of advanced PBL observations has potential to be a key outcome of a PBL mission. To this end, investment in data assimilation research is required on two fronts: (1) Fundamental research in advanced methods for data assimilation (e.g., particle filters, multi-scale techniques,

machine learning), and (2) Applied research in the practical aspects of assimilating non-traditional data streams (e.g., PBL height, spatial variance of thermodynamic variables) or advanced observations (e.g., thermodynamic profiles from active remote sensors) of the PBL. This is necessary to ensure that any future PBL measurements maximally impact atmospheric analyses.

- To ensure that the community takes full advantage of the new PBL observations, unified PBL parameterizations need to be developed, validated and implemented in weather and climate prediction models; For this process to be as effective as possible, investment is needed in software development that, among other aspects, would optimize: (i) the parameterization code in the context of specific weather and climate models, (ii) the utilization of satellite observations for parameterization development, validation and tuning, and (iii) the portability of unified PBL parameterization code components across different models.
- The intelligent integration of existing surface-based PBL observing networks fits the paradigm of New Observing Strategies (NOS). Investment exploiting these networks could be made in terms of producing well-calibrated homogenous long term data products for science and validation of remote sensing observations as well as for assimilation in models.

9.4 SUBORBITAL

In the coming decade suborbital activities will play an important role in two regards: (1) risk reduction through validating measurement techniques and advancing retrieval algorithms, and (2) addressing specific targeted science questions.

While it is not likely that PBL Incubation activities can fund extensive suborbital campaigns for answering science questions, it is critical that a modest effort be made to advance algorithm maturity and evaluate instrument synergy by flying candidate spaceborne PBL instruments together on common platforms in a handful of different meteorological environments. The existing suborbital datasets are inadequate in particular for evaluating the synergies of a multi-sensor observing system that includes both active and passive sounding instruments. New airborne observations including all candidate PBL instruments with dropsonde validation is necessary to demonstrate individual instrument capability and measurement synergies, thereby reducing risk for a future spaceborne mission. Specifically, there is substantial algorithm development work that is required to demonstrate optimal techniques for combining active (radar/lidar) curtain measurements with scanning passive sounders each of which has very different vertical and horizontal resolutions and error characteristics. These risk reduction activities can be accomplished with relatively few flight hours (of the order of several dozen) where the focus should be on maximizing sampling in a diversity of meteorological conditions (e.g., cloud/clear, moist/dry, stable/convective PBL's, tropical/midlatitude/polar).

Suborbital campaigns will always be key in answering science questions that are not addressable using spaceborne assets. Key PBL science goals, questions and a preliminary SATM are discussed and presented in Chapter 4. Incubation funding will be insufficient to realistically address key PBL science questions through dedicated suborbital campaigns. However, there are opportunities to incrementally advance PBL science through suborbital activities as is currently planned for CPEX-AW. For example, PBL science has strong synergies with the ACCP Designated Observable, which is reflected in the PBL focus of several of their proposed flight modules. Adding PBL-specific resources to planned ACCP suborbital activities is a science-multiplier. Where appropriate, coordination should be emphasized between these two complementary programs. Competed EV-S campaigns that address PBL science questions, or that meet PBL incubation goals by flying one or more candidate technologies in the service of science questions outside of the immediate scope of PBL science questions should be considered programmatically favorable.

When possible, NASA should consider opportunities to partner with other agencies that have planned field campaigns which could be enhanced through the addition of NASA's PBL-focused resources. Finally, it is noted that existing suborbital datasets have likely been underexplored in the context of PBL science. Opportunities to leverage existing suborbital datasets in future proposal solicitations for studying PBL processes should be considered. A perceived successful model in this regard is the ACCDAM funding opportunity, which funded proposals that utilize existing suborbital data.

Surface-based networks have been and will continue to be central to the PBL observing system. NASA should incorporate the extensive existing surface-based networks within incubation activities. They serve both as an important source of data for doing science as well as critical infrastructure for cal/val activities. Furthermore, surface-based observations of the PBL could be used in the context of data assimilation. NASA should also explore ways to help improve and complement surface-based observations of the marine PBL which is a significantly under-sampled regime. This could be accomplished through many avenues including by partnering with ocean-going projects funded by other agencies.

9.5 EARTH VENTURE MISSION AND INSTRUMENT

PBL active and passive candidate technologies identified in this report could enable a pathfinder mission concept that could fit within a cost-constrained program, such as the Earth Venture Instrument or Mission opportunities. Such missions could address PBL-specific science questions or could be focused on PBL-related science questions associated for example with the energy, water and carbon cycles at the PBL-surface interfaces, atmospheric composition, or thermodynamic structure across the full atmosphere. An EV-M would be a good opportunity for a pathfinder type mission to demonstrate new measurement techniques that can be implemented in a more holistic sense in a future DO PBL mission.

10. SUMMARY OF KEY FINDINGS

Although the many findings of this document are described in detail across the different chapters, a summary of the key findings is presented in this final chapter. As described in the Executive Summary, a global PBL observing system is critically needed to address fundamental PBL science questions and societal applications. Critical aspects that require a global space-based PBL observing system include:

- Several of the key PBL science questions are about the interactions between PBL thermodynamics and global processes (e.g., the relation between PBL thermodynamic structure and clouds from a **global perspective**) that can only be properly observed from space.
- The interactions between the **mesoscale and PBL thermodynamic structure** are a key PBL science topic, and it is clear that, to properly observe these interactions, a global perspective such as the one provided by space-based platforms is needed.
- Although we can often categorize the PBL in specific types and regimes, the interactions between mesoscale (and large-scale) atmospheric systems and the PBL thermodynamic structure, as well as the constraints of extreme physical environments on Earth, and varying surface conditions, lead to a **wide variety of PBL structures** all around the globe. A space-based PBL observing system will likely lead to the discovery of new types of PBL thermodynamic structures (and their interactions with the overall Earth System) particularly over sparsely observed regions of the world such as the oceans and the polar regions. In this context, a space-based PBL mission will be a **mission of discovery**.

The Science and Applications Traceability Matrix (SATM) discussed in chapter 4 highlights the four PBL science goals as well as specific science questions, geophysical variables and measurement requirements, and potential observing technologies to address these requirements. The four PBL science goals are the following:

- G1. PBL, Convection and Extreme Weather.
- G2. Cloudy PBL.
- G3. PBL and Surface Interaction.
- G4. PBL Modeling, Mixing and Air Quality.

The essential geophysical variables identified as uniquely required to address the four science goals are:

- PBL profiles of temperature.
- PBL profiles of water vapor.
- PBL height.

The SATM leads to the following measurement requirements (that can only be satisfied with a combination of different technologies):

- Vertical resolutions as fine as 100-200 m.
- Horizontal resolutions as fine as 1 km.
- Temporal sampling of at least 4 times per day.

In the Applications chapter it is discussed how the PBL plays a critical role in a variety of applications, namely: high-impact meteorology, climate projections, air quality, dispersion, hydrometeorology, agriculture, renewable energy, marine weather, fisheries, ecosystems, transportation, urban, wildfire, radio wave propagation and infectious disease applications.

From the PBL modeling and data assimilation chapter (chapter 6), the key findings are:

- Unified PBL mixing parameterizations including their interactions with deep convection, clouds, and the surface, should continue to be developed and implemented in weather and climate models.
- Data assimilation systems should focus on developing the capabilities to assimilate PBL observations (i) from the current POR, (ii) for PBL OSSEs and (iii) from future PBL space-borne instruments.
- Joint retrievals should be developed for PBL OSSEs and for airborne experiments using multiple PBL instruments.
- OSSEs should be developed with PBL-focused (i) nature runs, (ii) forward models, and (iii) joint retrievals and/or data assimilation methods.
- Novel OSSE approaches directly involving climate models should be developed to probe the unique value of PBL mission architectures for reducing uncertainties in societally relevant predictions such as climate sensitivity and trends in extreme events.
- For PBL modeling, data assimilation and OSSE studies, there should be a concerted effort by NASA to harmonize and coordinate the diverse NASA PBL activities and capabilities.

From the perspective of a global PBL observing system, the essential components of such a system are:

1. **Differential Absorption Lidar (DIAL) and Differential Absorption Radar (DAR) in Low Earth Orbit (LEO)** to provide high vertical resolution (approximately 200 m) water vapor profiles and high horizontal resolution (1 km) total precipitable water in clear and cloudy conditions, estimates of temperature profiles in liquid phase clouds (DAR), profiles of aerosols and clouds, and high horizontal resolution (1 km) estimates of PBL height (DIAL).
2. **High horizontal resolution hyperspectral IR (1km) and hyperspectral MW (5km) sounders in LEO** to provide 3D temperature and water vapor structure context to DIAL+DAR observations, potentially on SmallSat or CubeSat constellations (to provide higher temporal sampling).
3. **Radio Occultation (RO)** using larger constellations of Global Navigation Satellite System (GNSS-RO) receivers and/or novel orbital configurations and signal frequencies to provide additional high-vertical resolution and temporal sampling of temperature and water vapor profiles, and reliable estimates of PBL height.
4. **Geostationary hyperspectral IR sounding**, taking advantage of international (e.g., EUMETSAT) and national inter-agency (NOAA) collaborations, to dramatically increase temporal sampling of temperature and water vapor profiles.
5. **Modeling and data assimilation** capabilities to optimally assimilate these PBL observations to produce the best state estimate of PBL thermodynamics globally (with a potential focus over the continental United States) every day.

<u>Additional key components include:</u>

- Program of Record (POR) observations from a variety of platforms (space, suborbital, and surface-based).
- Suborbital campaigns focused on technology demonstrations, data fusion, and process studies in different regions.

To achieve this architecture, maturation of the following key technologies is needed:

- Active Instrument Technology

  - Lidar: *High Power Pulsed Laser Sources, Spectral Filtering, Seed Laser Integrated Photonics, High efficiency detectors, Telescope Architectures*
  - Radar: *High-Power Transmitter Sources, Low Phase-Noise Sources, Beam Steering, G-band Lightweight Deployable Antennas, G-band high-power, low-loss latching ferrite circulators*
- Passive Instrument Technology:
  - IR: *High Performance Telescopes, Infrared Spectrometers, Detectors, Cryocoolers*
  - MW: *Digital Spectrometers, Microwave Photonics and Photonic Integrated Circuits, G-band Lightweight Deployable Antennas*
- Radio Occultation Technology:
  - *Receivers, Miniaturization, Commercial Capability, and Innovative Concepts*

In addition to the key findings summarized above in this final chapter, other key findings in the context of specific NASA opportunities include:

- A PBL science community must be cultivated through strategic investments within the R&A program to advance successfully a future PBL mission.
- Targeted efforts to better exploit the current Program of Record (POR) to address PBL science and applications, including PBL modeling and data assimilation, should be prioritized.
- Priority science goals for solicitations should follow the preliminary SATM: G1) PBL, convection and extreme weather; G2) Cloudy PBL; G3) PBL and surface interaction; G4) PBL modeling, mixing and air quality.
- Resources within current and new NASA PBL programs and activities should be coordinated to create a PBL working group or science team.
- Synergies with upcoming missions should be exploited where they exist.
- Targeted projects in each of the applied science program areas would ensure that existing observations are put to their best use by the applications community and maximizes the likelihood that a future PBL mission will provide useful data for applications.
- Observing System Simulation Experiments (OSSEs) are needed to demonstrate the utility of new and higher-resolution PBL measurements across model architectures.
- Large Eddy Simulation (LES) models resolve most of the turbulent and convective flow that characterizes the PBL, and they are required for several of the PBL OSSEs; investment in software that would make the development, validation and utilization of LES models more effective is essential for reliable PBL OSSEs.
- Advanced Level-2 and 3 algorithms will be needed to retrieve atmospheric thermodynamics from the combination of diverse sampling, sensitivity, and spatial averaging capabilities of the candidate active and passive systems.
- Investment in data assimilation research is required on two fronts: (i) fundamental research in advanced methods, and (2) applied research in the practical aspects of assimilating non-traditional PBL data streams or more advanced PBL observations.
- To ensure that the community takes full advantage of the new PBL observations, unified PBL parameterizations need to be developed, validated and implemented in weather and climate prediction models.
- Airborne observations including all candidate instruments along with dropsonde validation are necessary to demonstrate individual instrument capability and measurement synergies.

- There is substantial algorithm development work that is required to demonstrate optimal techniques for combining active (DIAL/DAR) curtain measurements with scanning passive sounders.
- NASA should consider opportunities to coordinate with existing or planned NASA suborbital activities and to partner with other agencies that have planned field campaigns which could be enhanced through the addition of NASA's PBL-focused resources.
- Competed EV-S projects that address PBL science questions, or that meet PBL Incubation goals by flying one or more candidate technologies should be considered programmatically favorable.
- Competed EV-I and EV-M pathfinder projects that address PBL science questions using candidate technologies that can fit within the EV-I and EV-M costs should be considered programmatically favorable.

To conclude this chapter we present a figure that summarizes in a schematic manner the findings of the Study Team regarding a PBL Incubation roadmap for science and technology activities.

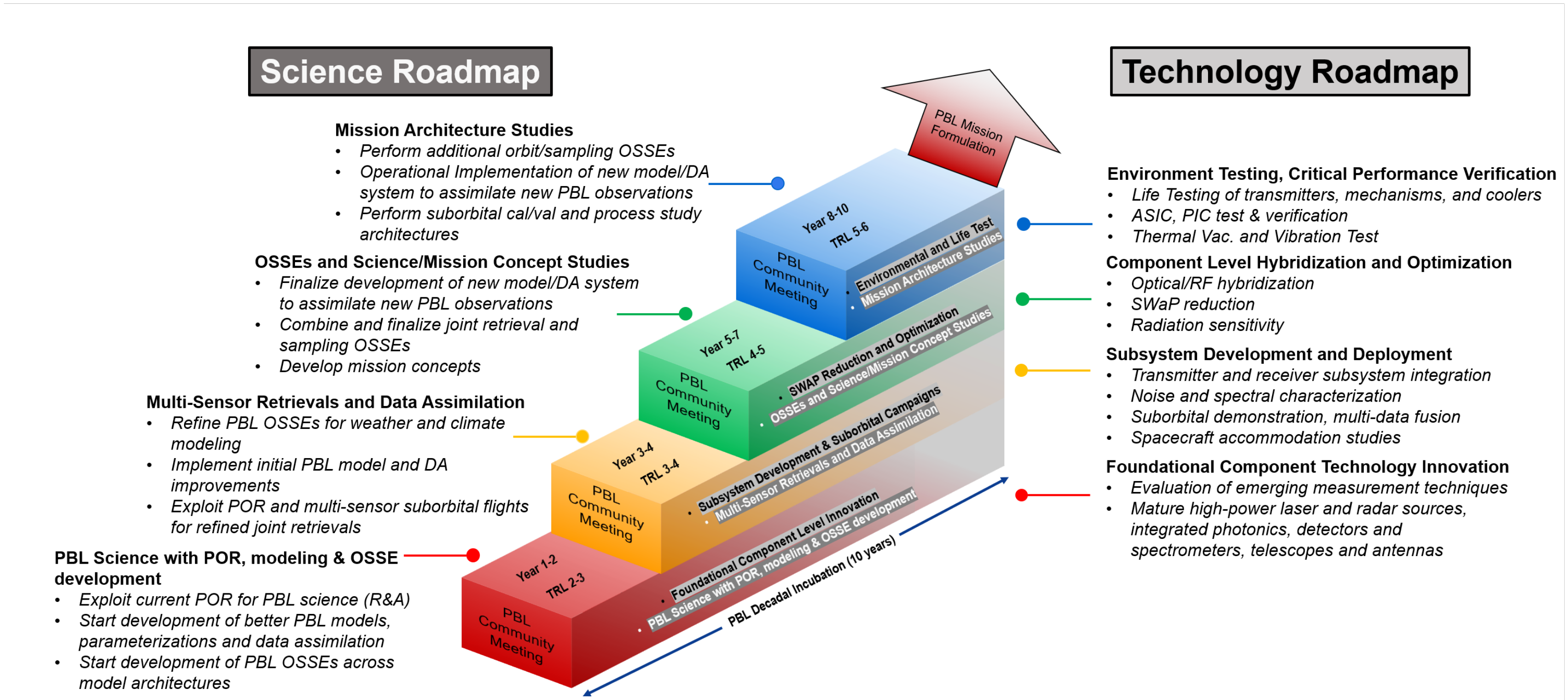

Figure 10-1. Schematic summarizing the PBL Incubation science and technology roadmap.

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B. NASA PBL INCUBATION VIRTUAL WORKSHOP

May 2020 – Agenda

The workshop sessions are a combination of presentations and discussion. These sessions start with invited presentations to set the stage for the discussion. These presentations are followed by short contributed presentations and the rest of each session is a moderated discussion among the participants. The names in the agenda below correspond to the invited speakers. For the (short) contributed presentations, we ask the participants to address at least one of the three key questions: 1) What are the most critical PBL science questions? 2) What are the most important and challenging PBL technology developments? 3) What are the most exciting opportunities?

FIRST WEEK (times are Pacific Daylight Time - PDT)

Tuesday, 19 May 2020

8:00 Introduction and perspective from NASA HQ
8:30 Introduction to PBL Study Team: Science
8:50 Introduction to PBL Study Team: Technology
9:10 High-latitude PBL: M. Tjernstrom (Stockholm U.), A. Fridlind (NASA GISS)
10:40 Break
11:00 PBL and Deep Convection: D. Randall (CSU), G. Elsaesser (NASA GISS)
12:30 Adjourn

Wednesday, 20 May 2020

8:00 PBL over Land and Surface Interaction: G. Svensson (Stockholm U.), J. Vila (U. Wageningen), M. Ek (NCAR), A. Betts (AR)
10:00 Break
10:20 PBL over the Ocean and Air-Sea Interaction: P. Zuidema (U. Miami), R. Wood (U. Washington), C.A. Clayson (WHOI), S. Chen (U. Washington)
12:20 Adjourn

SECOND WEEK

Tuesday, 26 May 2020

8:00 A Global Overview of the PBL: C. Bretherton (U. Washington)
8:30 PBL Applications: A. Steiner (U. Michigan), B. Kosovic (NCAR), J. Doyle (NRL)
10:15 Break
10:30 Weather and Climate Models and Data Assimilation: J. Teixeira (NASA JPL), W. McCarty (NASA GSFC)
12:15 Adjourn

Wednesday, 27 May 2020

8:00 PBL passive remote sensing: V. Payne (NASA JPL), B. Roberts (NASA MSFC)
9:30 PBL active remote sensing: A. Nehrir (NASA LaRC), M. Lebsock (NASA JPL), C. Ao (NASA JPL)
11:00 Break
11:15 In-situ and suborbital opportunities: D. Turner (NOAA GSL), R. Ferrare (NASA LaRC)
12:45 Adjourn

C. ACRONYMS

1D-Var	One Dimensional Variational assimilation
4D-Var	Four Dimensional Variational assimilation
A-Train	Afternoon Constellation
A2R	Applications-to-Research
ABI	Advanced Baseline Imager
ACCDAM	Atmospheric Composition Campaign Data Analysis and Modeling
ACCP	Aerosol Clouds Convection and Precipitation
ADC	Analogue to Digital Converter
ADM-A	Atmospheric Dynamics Mission - Aeolus
AERI	Atmospheric Emitted Radiance Interferometer
AERONET	AEROsol robotic NETwork
AIRS	Atmospheric Infrared Sounder
AIST	Advanced Information System Technology
AMDAR	Aircraft Meteorological Data Relay
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
AQ	Air Quality
ARL	Application Readiness Level
ARM	Atmospheric Radiation Measurement
ASIC	Application Specific Integrated Circuit
ATLID	ATmospheric LIDar
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAM6	Community Atmosphere Model version 6
CAO	Cold Air Outbreak
CAPE	Convective Available Potential Energy
CATS	Cloud-Aerosol Transport System
CHAMP	CHAllenging Minisatellite Payload
CIN	Convective Inhibition
CLUBB	Cloud Layers Unified By Binormals
CMIP6	Coupled Model Intercomparison Project 6
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
CPEX	Convective Processes Experiment
CPEX-AW	Convective Processes Experiment-Aerosols & Winds
CrIS	Cross-track Infrared Sounder
CSDA	Commercial SmallSat Data Acquisition

CTEI	Cloud Top Entrainment Instability
CTH	Cloud Top Height
CTP-HI	Convective Triggering Potential-Low-Level Humidity Index
CYGNSS	Cyclone Global Navigation Satellite System
DA	Data Assimilation
DAR	Differential Absorption Radar
DIAL	Differential Absorption Lidar
DO	Designated Observable
DOD	Department of Defense
DOE	Department of Energy
DOFS	Degrees of Freedom for Signal
DS	Decadal Survey
DTR	Diurnal Temperature Range
DYNAMO	Dynamics of the Madden-Julian Oscillation
E-PROFILE	EUMETNET Profiling Program
EARLINET	European Aerosol Research Lidar Network
EarthCARE	Earth Cloud, Aerosol, and Radiation Explorer
ECMWF	European Centre for Medium-range Weather Forecasts
ED	Eddy-Diffusivity
EDMF	Eddy-Diffusivity/Mass-Flux
EIS	Estimated Inversion Strength
EMIT	Earth Surface Mineral Dust Source Investigation
EnKF	Ensemble Kalman Filter
ENSO	El Niño-Southern Oscillation
EOS	Earth Observing System
EPA	Environmental Protection Agency
EPS-SG	EUMETSAT Polar System - Second Generation
ESAS	Earth Science and Applications from Space
ESD	Earth Science Division
ESPA	Evolved Expendable Launch Vehicle Secondary Payload Adapter
ESTO	Earth Science and Technology Office
EUMETNET	European Meteorological Network
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EV-S	Earth Venture Suborbital
FWHM	Full Width at Half-Maximum
GEO	Geostationary Earth Orbit
Geo-XO	Geostationary and Extended Orbits

GEWEX	Global Energy and Water Exchanges
LS4P	Impact of Initialized Land Temperature and Snowpack on Sub-seasonal to Seasonal Prediction
GHG	Greenhouse Gases
GLACE	Global Land–Atmosphere Coupling Experiment
GLONASS	Global Navigation Satellite System
GMAO	Global Modeling and Assimilation Office
GMIGPM	Microwave Imager
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GRACE	Gravity Recovery And Climate Experiment
GRAS	Global Navigation Satellite System Receiver for Atmospheric Sounding
HALO	High Altitude Lidar Observatory
HgCdTe	Mercury cadmium telluride
HOC	Higher-Order Closure
HRRR	High Resolution Rapid Refresh
HSRL	High Spectral Resolution Lidar
IASI	Infrared Atmospheric Sounding Interferometer
IASI-NG	Infrared Atmospheric Sounding Interferometer - Next Generation
IGOR	Integrated GPS Occultation Receiver
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
IRAS/HIRAS	InfraRed Atmospheric Sounder/High-spectral InfraRed Atmospheric Sounder
IRS	Infrared Sounder
ISS	International Space Station
ITOP	Impact of Typhoons on the Ocean in the Pacific
JEDI	Joint Effort for Data Assimilation Integration
JMA	Japan Meteorological Agency
JPSS	Joint Polar Satellite system
KOMPSAT	Korean Multi-Purpose Satellite
L-A	Land-Atmosphere
LASE	Lidar Atmosphere Sensing Experiment
LASER	Light amplification by stimulated emission of radiation
LCL	Lifting Condensation Level

LDR	Lidar Depolarization Ratio
LEO	Low Earth Orbit
LES	Large-Eddy Simulation
LoCo	Local land-atmosphere Coupling
LOTOS	Lower tropospheric observing system
LSR	Lidar Scattering Ratio
LWIR	Longwave Infrared
LWP	Liquid Water Path
MAGIC	Marine Aerosol GPCI Investigation of Clouds
MARLi	Multi-function Airborne Raman Lidar
MetOp-SG	MetOp-Second Generation Program
MF	Mass-Flux
MHS	Microwave Humidity Sounder
MIIDAPS	Multi-Instrument Inversion and Data Assimilation Preprocessing System
MISR	Mulit-Angle Imaging Spectroradiometer
MJO	Madden Julian Oscillation
ML	Mixed-Layer
MODIS	Moderate Resolution Imaging Spectroradiometer
MPL	Micropulse lidar
MPLNET	Micropulse lidar network
MW	Microwave
MWHS	MicroWave Humidity Sounder
MWS	Microwave Sounder
NASEM	National Academies of Sciences, Engineering, and Medicine
NCAR	National Center for Atmospheric Research
NEDT	Noise-equivalent delta temperature
NOAA	National Oceanic and Atmospheric Administration
NOS	New Observing Strategies
NPN	NOAA Profiling Network
NRC	National Research Council
NWP	Numerical Weather Prediction
OSSE	Oberving System Simulation Experiment
PBL	Planetary Boundary Layer
PBLH	PBL height
PCM	Phase Change Material
PDF	Probability Density Function
PIC	Photonic Integrated Circuits

POR	Program of Record
PRF	Pulse Repetition Frequency
R&A	Research and Analysis
RAINEX	Hurricane Rainband and Intensity Experiment
RFI	Request for Information
RH	Relative Humidity
RICO	Rain in Cumulus over the Ocean
RMS	Root Mean Square
RO	Radio Occultation
ROIC	Reach Out Integrated Circuits
S-NPP	Suomi National Polar-orbiting Partnership
S2S	Sub-seasonal to Seasonal
SATM	Science and Applications Traceability Matrix
SBG	Surface Biology and Geology
SBIR	Small Business Innovation Research
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SLiK	Super Low K factor
SMAP	Soil Moisture Active Passive
SNR	Signal to Noise Ratio
SST	Sea Surface Temperature
STTR	Small Business Technology Transfer
SUOMINET	Suomi Network (of GPS systems of TPW measurements)
SW	Shortwave
SWaP	Size Weight and Power
TEMPEST	Temporal Experiment for Storms and Tropical Systems
TKE	Turbulent Kinetic Energy
TO	Targeted Observable
TOA	Top of Atmosphere
TOLNET	Tropospheric Ozone Lidar Network
TPW	Total Precipitable Water
TriG	Tri-GNSS
TRL	Technology Readiness Level
TROPICS	Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of SmallSats
UAS	Unmanned Aerial Systems
UKMO	United Kingdom Meteorological Office
UNOLS	University National Oceanographic Laboratory System

USGS	United States Geological Survey
UV	Ultraviolet
UWKA	University of Wyoming King Air (aircraft)
VIIRS	Visible Infrared Imaging Radiometer Suite
VIPR	Vapor In-cloud Profiling Radar
VOCALS	VAMOS Ocean Cloud Atmosphere Land Study
VSWIR	Visible to Shortwave Infrared
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
WSF-M	Weather System Follow-on Microwave
WVMR	Water Vapor Mixing Ratio
YAG	Yttrium-Aluminum Garnet