Utilizing the DOE-ARM Enhanced Soundings for Local Coupling Studies (ESLCS) Campaign to Highlight the Importance and Limitations of PBL Retrieval from Space

Joseph A. Santanello, Jr.[1], Alexander J. Schaefer[1,2], Craig Ferguson[3], Volker Wulfmeyer[4], Dong Wu[1], Erica McGrath-Spangler[1,5], Jasper Lewis[1,6], and Dave Whiteman[1]

1 – NASA-GSFC, Greenbelt, MD ; 2 – UNC Charlotte, Charlotte, NC ; 3 – SUNY, Albany, NY ; 4 – U. Hohenheim, Germany ; 5 – USRA, Columbia, MD ; 6 – UMBC, Baltimore, MD

Satellite Instruments

- The **convective PBL over land** serves as a key component and modulator of L-A interactions, such that **PBL structure and evolution** are key observables of Earth's coupled system.
- In-situ (e.g. radiosonde) and ground-based approaches to PBL remote sensing are limited and discontinuous in nature.
- Here we assess the ***capabilities and limitations of routine PBL retrieval from satellite*** in terms of resolution and accuracy needed to be useful for L-A, hydrology, cloud/convection, pollution, or model development applications.

Local Land-Atmosphere Coupling ('LoCo') Diagnostics

- **The LoCo Working Group (see BAMS overview article; Santanello et al. 2018)** formed under GEWEX-GLASS over a decade ago has focused on developing quantitative and integrative metrics of L-A interactions and feedbacks in the water and energy cycle.
- These diagnostics connecting the land and PBL are applicable to both models and observations across a range of scales: local-global, diurnal-climate.

Goals of LoCo

- Evaluate the '**links in the chain**' and their sensitivities to land-PBL perturbations as follows:

$$\Delta SM \rightarrow \Delta EF \rightarrow \Delta PBL \rightarrow \Delta ENT \rightarrow \Delta T, q_{2m} \blacktriangleright \Delta Clouds/P$$

(a) (b) (c) (d)

SM: Soil Moisture PBL: Mixed-layer properties
ENT: Entrainment fluxes
EF: Evaporative Fraction P: Precipitation

- The majority of LoCo metrics require information on the state and/or evolution of the PBL on diurnal timescales.
- As a result, the ARM-SGP region was selected as a testbed for L-A interactions and an intensive field campaign with enhanced radiosonde launches.

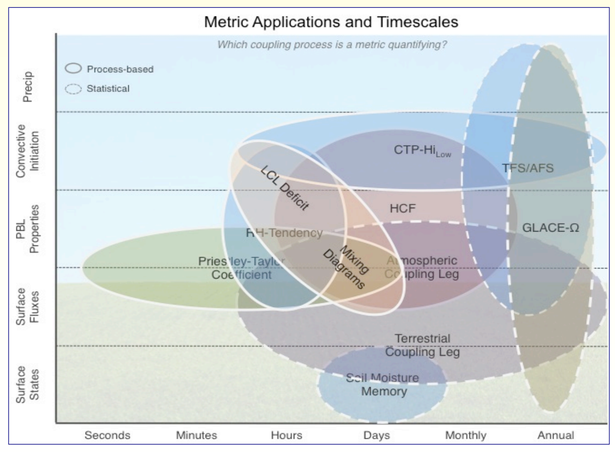


Figure 1: Suite of LoCo metrics of L-A coupling that can be applied to models and observations, as described in Santanello et al. (2018).

Satellite Instruments

IR Sounding/AIRS: Atmospheric Infrared Sounder aboard NASA's Aqua satellite. AIRS uses a hyperspectral infrared spectrometer with over 2300 channels to retrieve vertical profiles of temperature and humidity. Two recent algorithm versions (V6 and 6.28) are compared in this study.

IR Sounding/GOES: GOES/GOES-R retrieves thermodynamic soundings using 19-channels in the IR with high temporal (hourly+) and spatial (<10km) resolution, but with broad weighting functions and coarse vertical resolution.

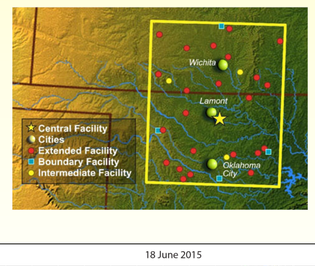
Lidar/CALIPSO: Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations. Composed of Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), Infrared Imaging Radiometer (IIR), and Wide Field Camera (WFC). CALIOP (used here) uses a laser to measure backscatter from aerosols (Hostetler et al. 2006) at 532 nm.

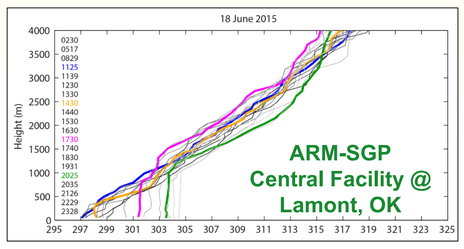
Lidar/CATS: Cloud-Aerosol Transport System aboard the International Space Station (ISS). CATS uses high repetition rate lasers to measure backscatter from aerosols (Yorks et al. 2015) at 1064 nm.

2015 DOE-ARM Field Campaign @ SGP

'Enhanced Soundings for Local Coupling Studies (ESLCS)'

-PIs (C. Ferguson, J. Santanello, P. Gentine)



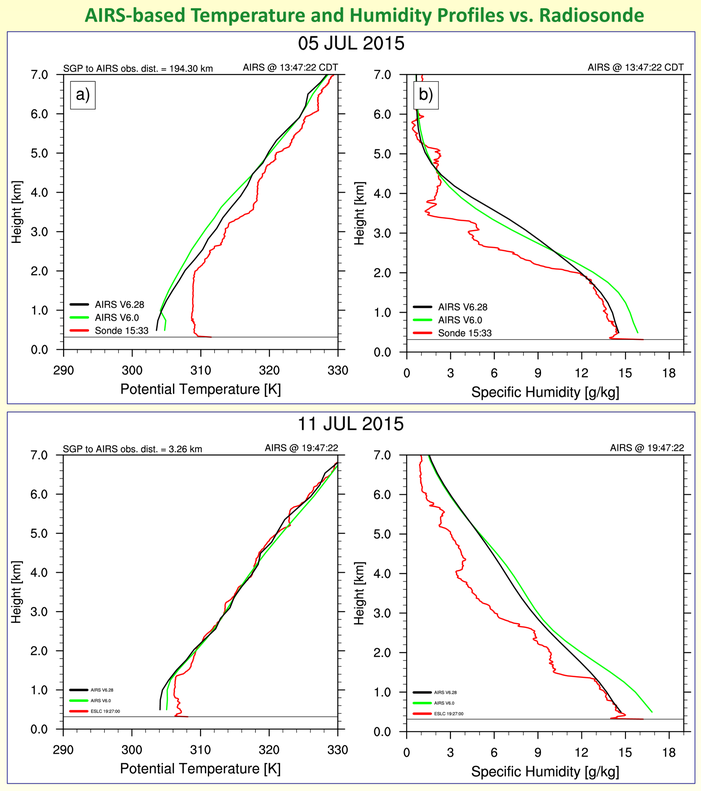


- **Radiosonde Field Campaign**
- **12 IOP days**
- **Hourly+** launches

SGP-ARM CF ESLCS RAOB								
0530/1730	1130			2030				
NLLJ	1130 UTC CTP (J kg^{-1})	1130 UTC HI (K)	1130 UTC 850-700 hPa dT/dz (K km^{-1})	2030 UTC LCL (km)	2030 UTC LFC (km)	2030 UTC q_{PBL} (g kg^{-1})	2030 UTC PBLh (km)	Max. PBLh (UTC time)
0.0	-61	3.5	-4.8	1.3	3.5	13.2	1.2	2.4 (1931)
21.0	354	25.3	-8.8	2.9	4.9	8.6	2.7	2.9 (1829)
15.1	239	11.1	-5.8	1.5	3.1	13.3	2.2	2.5 (1550)
29.5	190	19.8	-7.9	1.4	2.5	18.9	1.3	1.3 (2027)
15.7	186	16.4	-5.2	2.2	3.8	12.3	2.7	2.8 (1229)
15.1	165	22.1	-5.8	2.2	4.1	12.5	1.3	2.1 (1733)
7.6	-8	28.3	-4.3	2.4	n/a	9.5	1.4	1.8 (2230)
7.5	26	36.9	-6.5	2.3	n/a	10.0	1.8	2.2 (2328)
0.0	112	3.7	-6.0	0.7	3.4	15.2	0.9	2.9 (1428)
0.0	-141	37.3	-5.2	2.1	n/a	8.6	1.0	1.0 (2028)
0.0	159	5.7	-5.8	1.5	3.0	14.5	2.1	2.1 (2030)
0.0	374	21.7	-8.0	1.7	5.3	12.0	0.6	2.3 (1629)

Hyperspectral IR Sounding / AIRS

AIRS-based Temperature and Humidity Profiles vs. Radiosonde



- 2002-present
- 2x daily retrievals
- 1:30am/pm
- 2378 IR channels
- 45km spatial resolution
- 1-2km vertical resolution
  - 1K temperature
  - 20% humidity

L3 Gridded Profiles @ 1-deg Horizontal Resolution

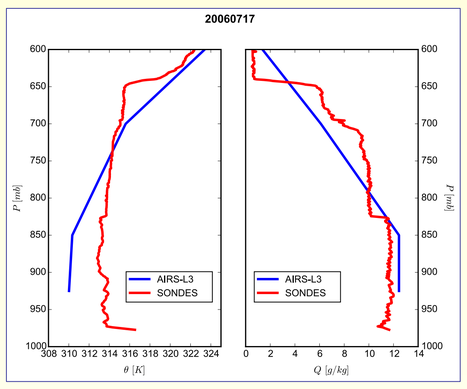


Figure 1: AIRS L2 profile retrievals vs. closest radiosonde launches at SGP site. V6.28 has improved sampling of IR channels sensitive to the PBL and to water vapor.

- **IR-based thermodynamic retrieval** is limited in the lower troposphere due to coarse vertical resolution and weighting functions, and the signal being attenuated by atmospheric, cloud, aerosol, and surface factors.
- Temperature (cold) and humidity biases are common, and PBL height is rarely detectable with 1-2 km vertical resolution.
- Hyperspectral IR retrieval may be improved via higher spatial (1km; CIRAS), temporal (1h; GEO-IR), or spectral (channel selection) resolution, but there remain theoretical limits on lower tropospheric sounding from space.

Lidar / CALIPSO & CATS

- 2006-present
- 14-day revisit time
- 10:30am/pm
- Lidar
  - Backscatter gradient
  - Aerosol density
  - PBL height
- 333m horizontal resolution
- 30m vertical resolution

CALIPSO and CATS Backscatter Retrieval

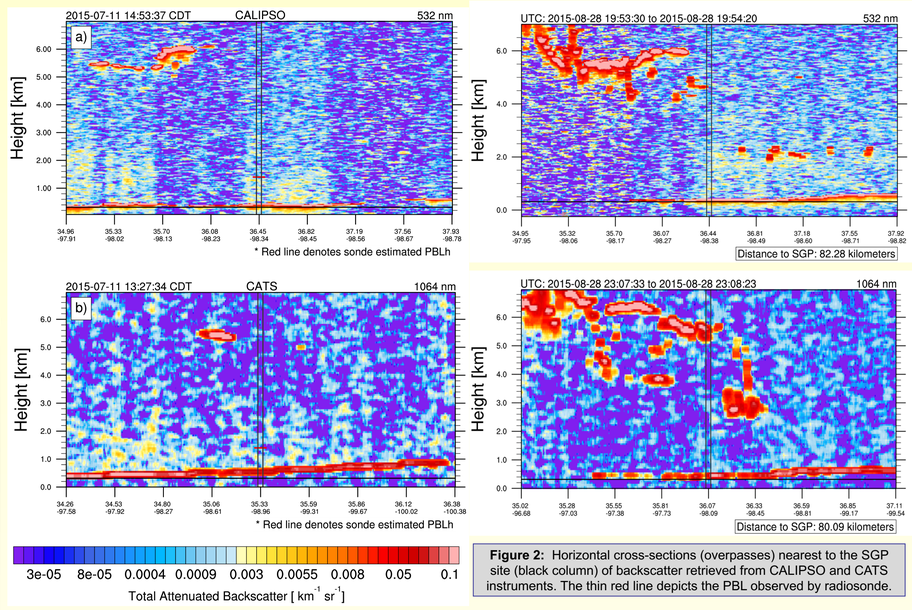


Figure 2: Horizontal cross-sections (overpasses) nearest to the SGP site (black column) of backscatter retrieved from CALIPSO and CATS instruments. The thin red line depicts the PBL observed by radiosonde.

Nighttime/Residual Layer Retrieval

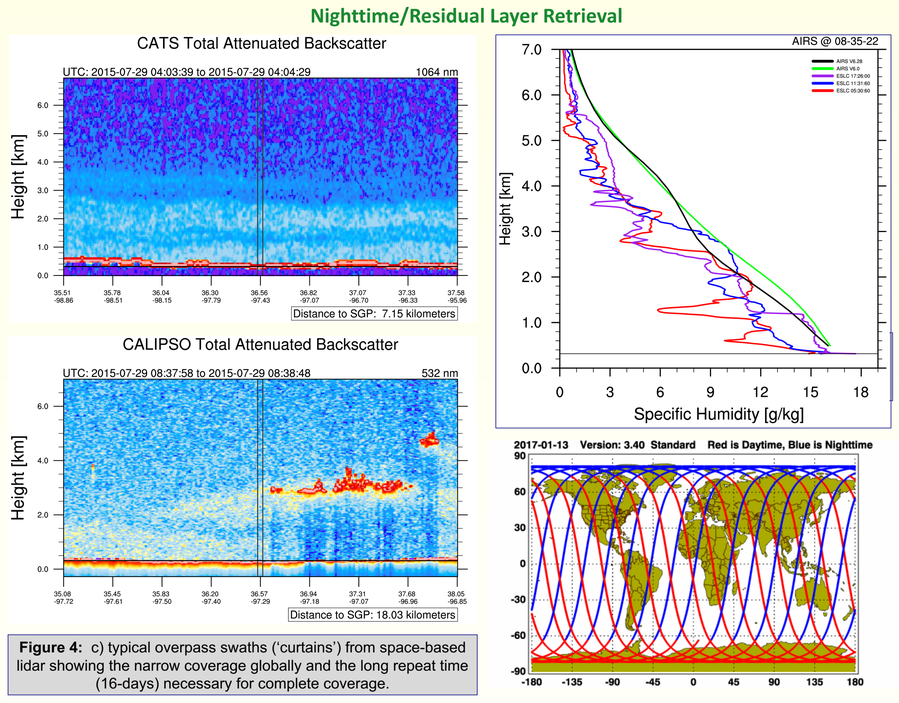


Figure 4: c) typical overpass swaths ('curtains') from space-based lidar showing the narrow coverage globally and the long repeat time (16-days) necessary for complete coverage.

- **Lidar-based PBL height retrieval** using aerosol backscatter is successful in low noise (e.g. nighttime), clear-sky conditions, but it severely limited by spatial coverage and repeat time over the globe.
- PBL height from lidar is thus limited to long-term climatological studies, and does not provide thermodynamic or diurnal information.

Outlook

- As highlighted by the 2017 NAS Decadal Survey, there is an **established and growing need for routine PBL measurements over land** for a range of applications.
- **The PBL remains a major gap in our observational suite**, as today's spaceborne instruments cannot reach the required targets in terms of accuracy or resolution.
- **Other components of WEC cycle monitoring** (e.g. GPM, SMAP, GRACE, SWOT) are now in place, and thus the importance of PBL information will continue to rise.
- **New mission concepts** such as high-spectral GEO and high-spatial AIRS should provide incremental improvements, but it **may require advanced active (Raman or DIAL) sensors** to achieve required PBL targets.
- **Ground-based networks are where the action/development is,** but much needs to be reconciled in terms of PBL height and thermodynamic vs. aerosol-based profiling.
- Ultimately, **it likely will take a combination of ground-based sensors/networks and satellites** to monitor the PBL routinely (diurnally, globally) over the next decade.

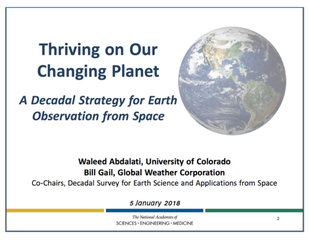
Joseph.A.Santanello@nasa.gov

Ongoing Efforts to Address the PBL Gap From Space

Decadal Survey Mandate

2017 NAS Decadal Survey

- Released January 2018
- Multiple RFI white papers on PBL submitted by L-A community
- Additional (independent) PBL submissions by broader community
- **2007 DS: PBL mentioned zero times as a target**
- **2017 DS: PBL mentioned 129 times(!)**
- Recommended as a high priority, incubator measurement
  - **'High priority'**: Cuts across nearly all panels (Weather, Climate, Hydrology, Ecosystems, Resource Mgmt) and Integrating Themes
    - Most important objective for Weather
  - **'Incubator'**: Measurement/mission approach not mature and needs work – hard problem!



Planetary Boundary Layer	**Diurnal 3D PBL thermodynamic properties and 2D PBL structure** to understand the impact of PBL processes on weather and AQ through high vertical and temporal profiling of PBL temperature, moisture and heights	Microwave, hyperspectral IR sounder(s) (e.g., in geo or small sat constellation), GPS radio occultation for diurnal PBL temperature and humidity and heights; water vapor profiling DIAL lidar; and lidar** for PBL height				X

PBL Measurement Requirements

TARGETED OBSERVABLE	SCIENCE & APPLICATIONS SUMMARY	SCI/APPS PRIORITIES (MF-VL)	RELATED ESAS 2007 and POR	IDENTIFIED NEED/GAP	CANDIDATE MEASUREMENT APPROACH	ESAS 2017 DISPOSITION
TO-13 Planetary Boundary Layer	• Temperature • Water vapor • PBL height	- H-2a - W-1a, 2a, 3a, 10a - - - C-2b, 4a, 7a, 7b, 7c, 7d, 7e	*ESAS 2007:* PATH *POR:* AMSU/Aqua, AIRS/Aqua, CrIS/JPSS, ISA/MetOp, AMSU/MetOp, COSMIC, MHS/MetOp, CALIPSO, GOES-R, AMSR	POR lacks sufficient horizontal and temporal resolution	*Similar to:* **AIRS, AMSU, COSMIC** • Microwave & hyperspectral IR sounders; lidar for PBL height • Sampling with 3-20km horizontal, 0.2-1km vertical, 1-4hr temporal resolution	**INCUBATION** PROGRAM ELEMENT Consider opportunistic use of data from recommended TO-1/2 investment for PBL height

Thermodynamic Profiles
0.5-1 K precision in temperature and 5-10 % in humidity profiles in the lower troposphere.
Bias 0.2-0.5 K in temperature and 2-5 % in humidity.
Spatial resolution:
Mesoscale gamma to beta; the integrating scale of the PBL on diurnal timescales (10-100km).
Vertical resolution: 100-300 m; needed to capture local gradients and inversion layers and estimate the depth of the PBL.
Revisit time: 2x/daily minimum (mid-afternoon to capture maximum PBL depth), diurnal sampling (~1-3 hourly) for process studies.

PBL Height
100m precision in the depth of the daytime CBL, as measured by gradients in backscatter, WV, or T.
Spatial resolution:
Mesoscale gamma to beta; the integrating scale of the PBL on diurnal timescales (10-100km).
Vertical resolution: need to capture local gradients and inversion layers (100-300m).
Revisit time: 2x/daily minimum (mid-afternoon to capture maximum PBL depth), diurnal sampling (~1-3 hourly) for process studies.

Entrainment Fluxes
10% precision in the strength of the PBL-top inversion and gradients in T, WV.
Spatial resolution:
Mesoscale gamma to beta; the integrating scale of the PBL on diurnal timescales (10-100km).
Vertical resolution: need to capture local gradients and inversion layers (100m).
Revisit time: High repetition rate of the observations or laser short for representative averaging of overshooting thermals during single overpass (estimate?)

Workshops/Conferences

DS-PBL Workshop I:
-Held in Spring 2018 @ JPL
-20 invited PBL experts
-Focused on refining requirements and priorities for observing different types of PBLs
-Driven by scientific impact and applications only

DS-PBL Workshop II:
-To be held in Fall 2018 (1-5 Oct) @ Wash, DC
-Open workshop with PBL scientists, technologists, instruments represented
-Focused on assessing ways to achieve PBL observation requirements from space

Session Observing the Boundary Layer from Space

Submitters:
Joao Teixeira, JPL, California Institute of Technology, Pasadena, CA; Joseph A. Santanello, NASA GSFC, Hydrological Sciences Laboratory (617), Greenbelt, MD and Matthew Lebsock, JPL, Aerosols and Clouds, Pasadena, CA

Description:

The planetary boundary layer (PBL) is at the heart of fundamental atmospheric science challenges: (i) cloud-climate feedback (how clouds will respond and impact climate with increased greenhouse gas concentration) is essentially about the interactions between a highly turbulent flow with water phase transitions and radiation, often occurring in the PBL; (ii) the extreme weather and climate change problem is essentially about how deep moist convection, with its roots in the PBL, will respond to a warmer world; (iii) the exchanges of energy, water and carbon between the atmosphere, ocean, land, and ice are mediated by turbulent fluxes in the PBL; (iv) the depth and mixing of PBL air significantly influences air quality and human health.

•**Santanello et al., 2018**: Land-Atmosphere Interactions: The LoCo Perspective. Bulletin of the American Meteorological Society, June edition.

•**Wulfmeyer et al., 2015**. A review of the remote sensing of lower tropospheric thermodynamic profiles and its indispensable role for the understanding and the simulation of water and energy cycles, *Rev. Geophys.*, 53, 819–895.