Improving Boundary Layer Data Assimilation Using Observation Data from Multiple Observing Systems in the NASA GEOS System

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Motivation and Objectives

- The Planetary Boundary Layer (PBL) was recommended as one of the most important Targeted Observables by the 2017 Earth Science Decadal Survey (National Academies of Sciences, Engineering, and Medicine 2018).
- A future global PBL observing system requires modeling and data assimilation as essential components (Texeira et al. 2021).
- What we aim to achieve by assimilating PBL height **(**PBLH) data are:
  - **Generate the first global PBLH analysis (with proper model PBLH definitions) and monitor various PBLH data online**
    - Different physical PBLHs depending on observing system or retrieval algorithm → need for an optimal strategy for using these data together
  - **Capture the location of capping inversion**
    - Benefit the use of all other observations in the lower troposphere
  - **Provide additional info for thermodynamic variables through background error covariances**

Status of PBL height data assimilation

- Developed model-based PBLH definitions corresponding to the PBLH data (Zhu et al. 2024).
- Developed data synergy strategy and infrastructure to add the capability in the GEOS for global assimilation of PBLH data from multiple observing systems.

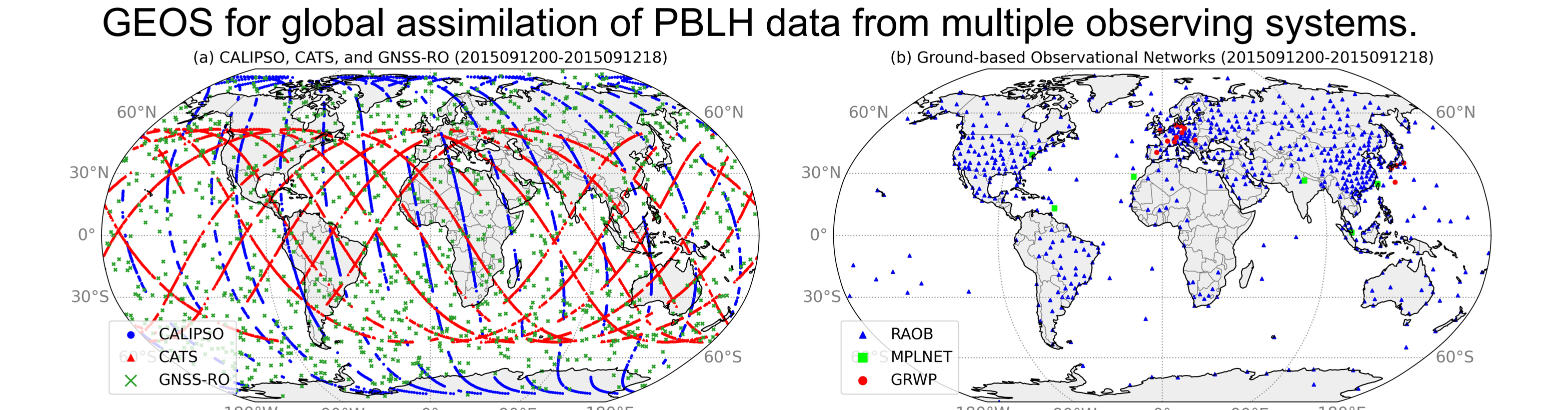
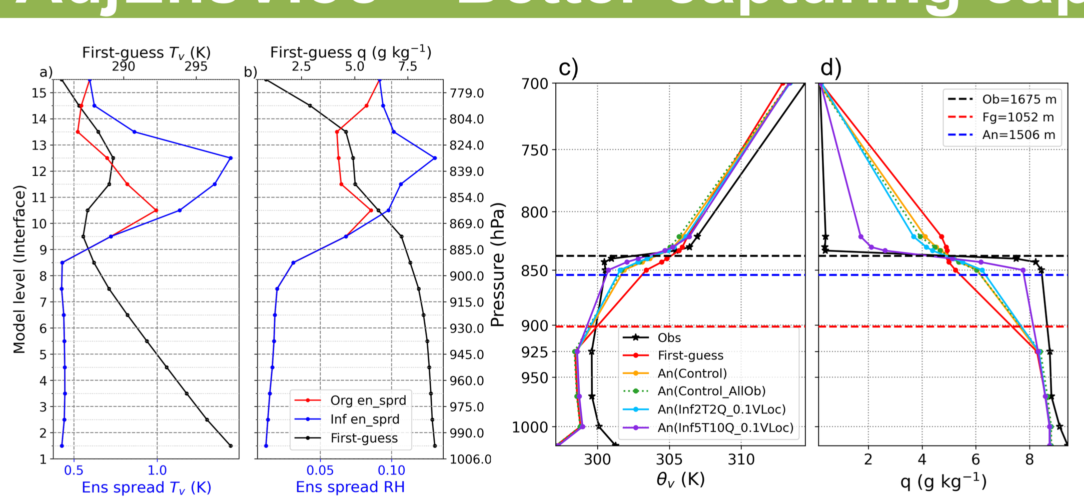


Fig. 1. Illustration of complementary data coverage and spatial scales of PBLH data. (a) Space-based GNSS-RO (green) and lidars CALIPSO (blue) and CATS (red) and (b) ground-based radiosonde (blue), MPLNET (green) and global radar wind profiler (red).

AdjEnsVloc – Better capturing capping inversions



- AdjEnsVloc (**adj**ustment of Tv and RH **ens**emble spread and **v**ertical **loc**alization length scale using PBLH data; Zhu et al. 2024) enables inflated ensemble spread to peak at observed PBLH level.
- Analyses profiles and inversion representation are improved.
- The larger the ensemble spread inflation, the more significant improvement can be obtained.

Fig. 2. Vertical profiles of first guess (black) and ensemble spread of (a) Tv and (b) RH without (red) and with (blue) AdjEnsVloc at a radiosonde station. Vertical profiles of radiosonde observation (black solid), corresponding first guess (red solid), and analyses of (c) virtual potential temperature, (d) q. Horizontal dashed lines indicate PBLH from observation (black), first guess (red), and analysis (blue).

Comparisons of PBLH data with model PBLH in the GEOS system

- Comparison between PBLH derived from observations and from model in the GEOS system (O-F: Observation minus Forecast)
- Period: 2015/Aug/23 – 2015/Sep/18

Obs	Obs type	Obs PBLH	Model PBLH	Consistency
Raob	Radiosonde obs	**Ri (Bulk Richardson number)-based**	**Ri-based**	Y
CALIPSO	Space-based lidar	ATB (Total Attenuated Backscatter)-based	Ri-based	N*
CATS	Space-based lidar	ATB-based	Ri-based	N*
MPLNET	Ground-based lidar	ATB-based	Ri-based	N*
GRWP	Ground-based radar	Refractivity-based	Ri-based	N*
GNSS-RO	GNSS-RO	**Refractivity-based**	**Refractivity-based**	Y

***Inconsistency is temporary, until we can update the GEOS model with the Goddard Chemistry Aerosol Radiation and Transport (GOCART)-2G to enable the implementation of consistent model PBLH definitions for lidar and radar.**

1) Ri-based Raob vs model PBLH

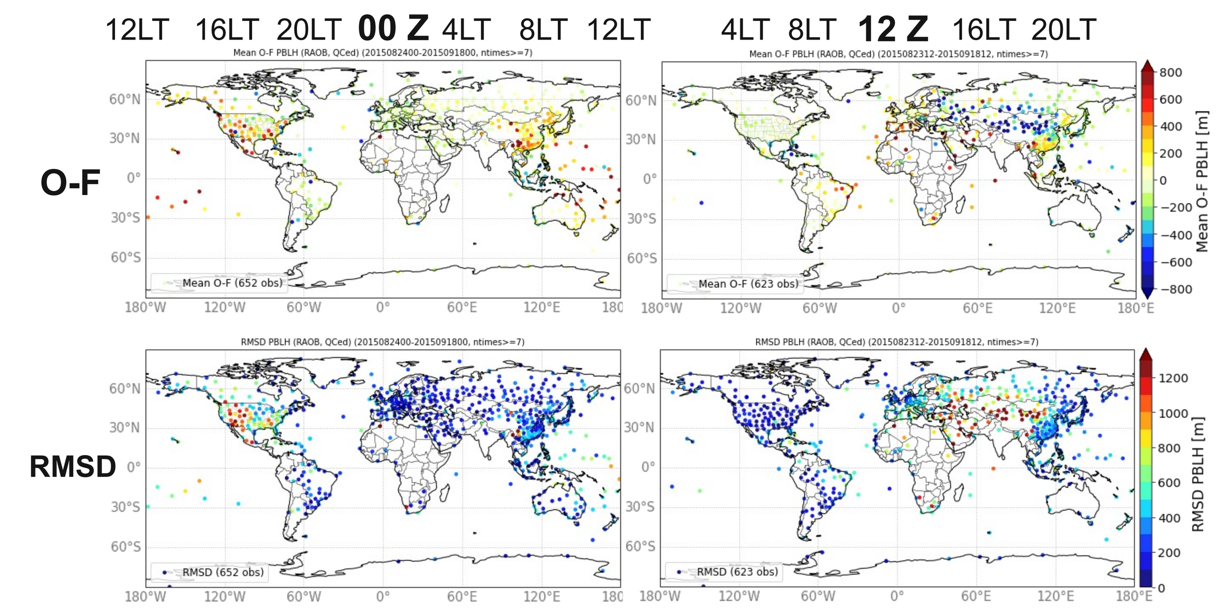
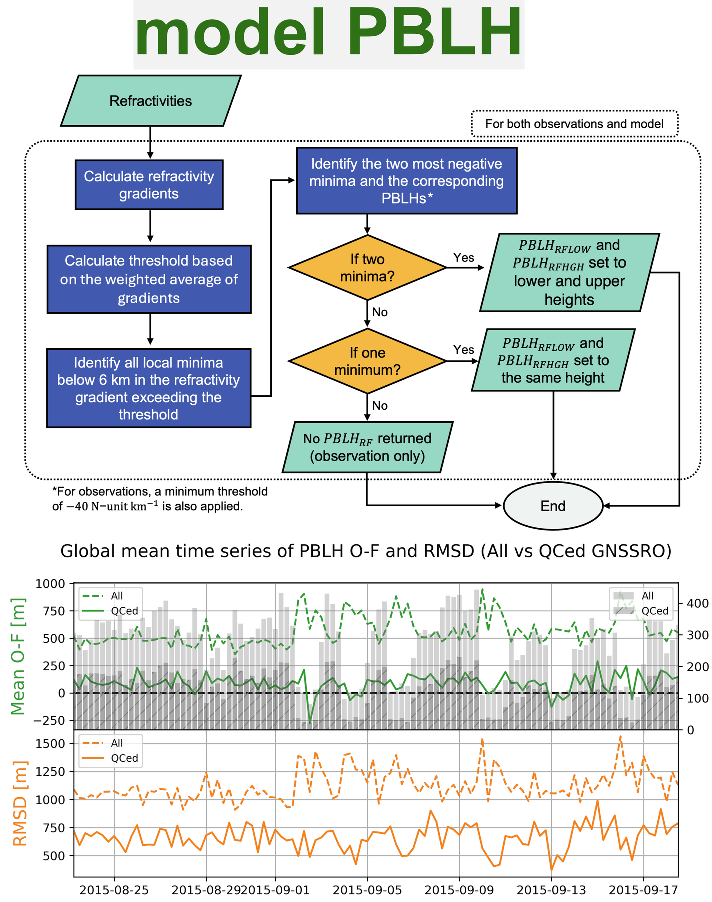


Fig. 3. (top) Mean O-F and (bottom) RMSD of PBLH derived from radiosonde at 00/12 UTC

- The estimates of PBLH are derived from radiosonde based on a bulk Richardson number defined in Seidel et al. (2012).
- Radiosonde PBLH O-F error is sensitive to elevation. Stations with elevation > 3 km are excluded and obs error is inflated if station elevation > 1 km. Mixed surface type is excluded.
- A relatively larger mean O-F at stations whose local time is either morning or daytime.

2) Refractivity-based GNSS-RO vs model PBLH



- Refractivity-based PBLH data are derived from GNSS-RO considering the lowest minimum among multiple minima and compared with consistent definition of model PBLH (Ao et al. 2012; Zhu et al. 2024).
- Implemented QC: excluded obs with steep slopes globally, mixed surface type, refractivity profiles whose lowest observation level > 500 m. Also, inflated obs error if the distance between adjacent observations is less than 125 km.
- Mostly positive O-F bias and larger O-F RMSD over land.

Fig. 4. (Top) Flowchart for the calculations of refractivity gradient based model and observed PBLH to handle multiple minima of refractivity gradients in the lower troposphere, (Bottom) global mean time series of PBLH O-F mean and RMSD at every analysis time.

Summary

- Generated **global Ri-based PBLH data derived from radiosonde observations and refractivity gradient-based PBLH data derived from GNSS-RO**
- Developed strategy for PBLH data assimilation in the GEOS system, **ingested PBLH data from multiple observing systems**, and implemented corresponding **thinning and quality control** procedures including gross error check
- **Evaluated departures of model** Ri- and refractivity-based **PBLH simulations from PBLH data** for 27 days (2015 Aug-Sep)
  - All PBLH data capture daytime CBL
  - Different features of space-based ATB-based PBLHs (CALIPSO vs CATS) → greater CATS O-F
- **Developed the method AdjEnsVloc to improve background error covariances** in the lower troposphere using PBLH data

3) Space-based lidar PBLH (CALIPSO, CATS) vs Ri-based model PBLH: *inconsistent* comparison

3a) CALIPSO

- PBLH data are derived using McGrath-Spangler and Denning, 2012, 2013 (Maximum variance method).
- QC: High latitude data are excluded to alleviate aloft aerosol effect (stable boundary layer) and mixed surface type is excluded.
- Moving average and thinning are applied.

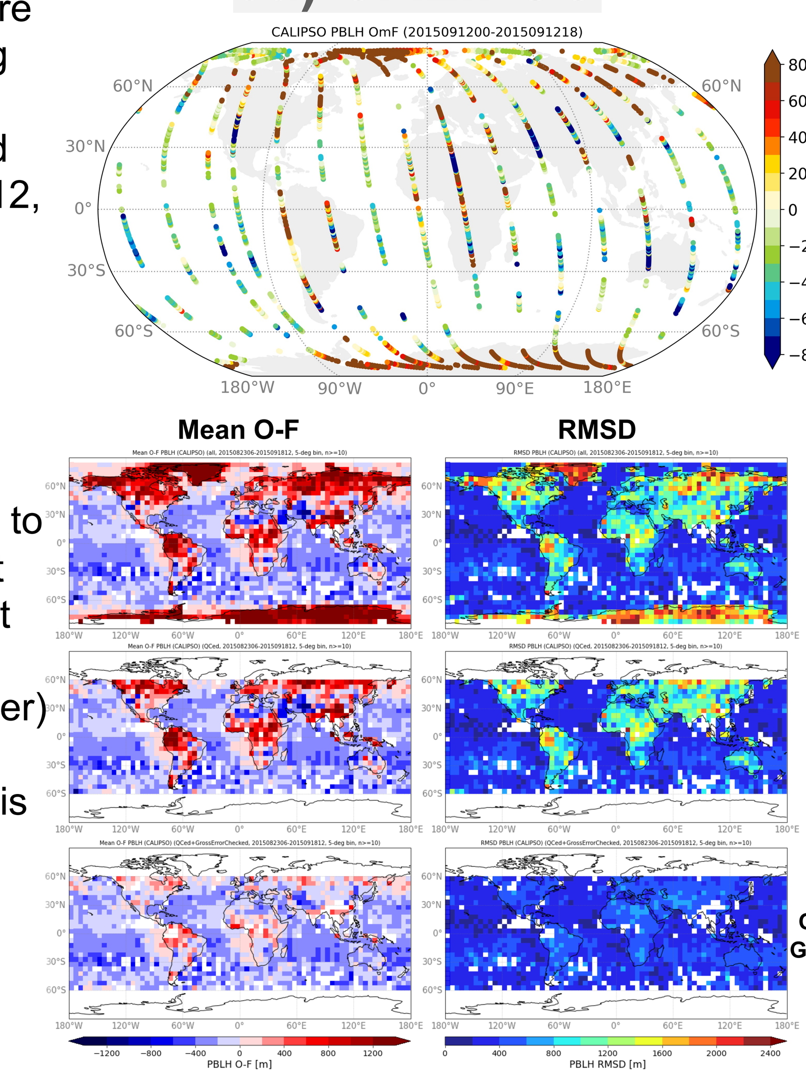


Fig. 5. (Top) OmF distributions of CALIPSO and (bottom) mean of CALIPSO PBLH OmF (left) and RMSD (right) in every 5 degree lat/lon gridbox.

3b) CATS

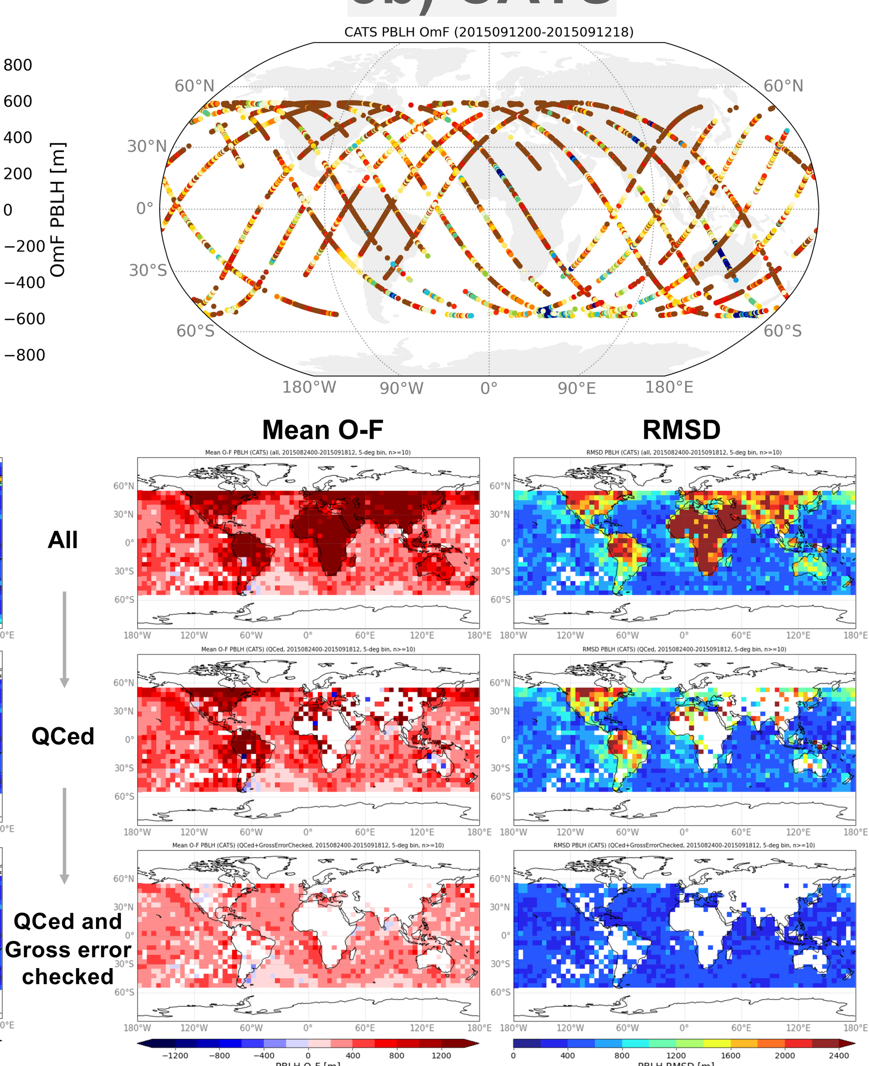
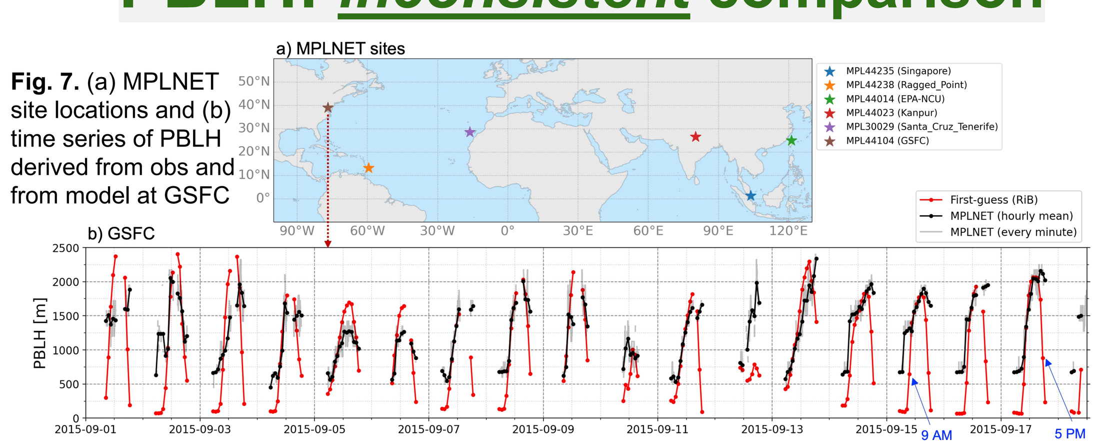


Fig. 6. Same as Fig. 5 except for CATS

- PBLH data are derived using Palm et al, 2021 (Threshold method).
- QC: QC flag <=1 (provided by Palm 2023), night-time data over land (associated with aloft aerosol), and mixed surface type are excluded.
- Moving average and thinning are applied.
- **Positive O-F bias**: larger bias over land than over ocean **(greater O-F bias than CALIPSO)**

4) MPLNET vs Ri-based model PBLH: *inconsistent* comparison

Fig. 7. (a) MPLNET site locations and (b) time series of PBLH derived from obs and from model at GSFC



- The patterns of MPLNET PBLH data (Lewis et al. 2016) and model Ri-based PBLH agree well.
- At GSFC, **clear diurnal cycle**, MPLNET PBLH tends to be higher than model PBLH before 9am & after 4pm.

5) GRWP PBLH vs Ri-based model PBLH: *inconsistent* comparison

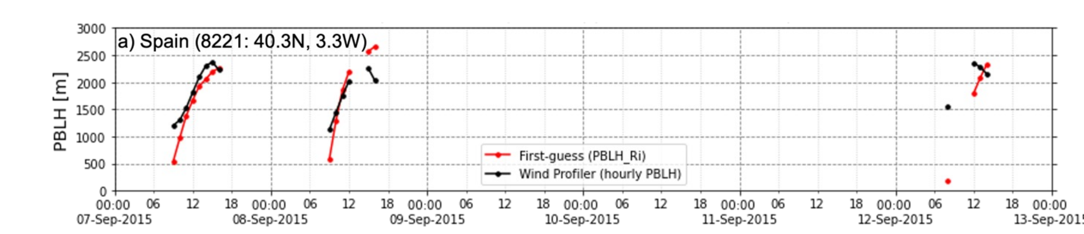


Fig. 8. Time series of Ri-based model PBLH (red) and PBLH derived from Radar Wind Profiler at the station 8221 (Spain) (black).

- Global Radar Wind Profiler Planetary Boundary Layer Height (GRWP-PBLH) are retrieved using signal-to-noise ratio data around the globe, specifically in Australia, Europe, and Japan (Salmun et al. 2023)
- The patterns of hourly GRWP PBLH and model Ri-based PBLH generally match well, although some stations show mismatches, especially at coastal area.

Work plan

- Differences between ATB-based PBLH observations and the model's Ri-based PBLH may reflect the "mismatch" in PBLH definitions.
  → This mismatch will be eliminated by using the proper model PBLH definition for each observation type.
- Implement model PBLH definitions for lidar and radar PBLH data.
- Evaluate CNN-based CATS PBLH data

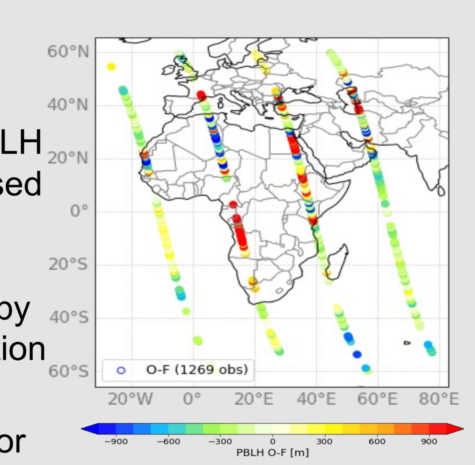


Fig. 9. Example of CALIPSO OmF differences using the model Ri-based PBLH definition.

- Explore an innovative approach to assimilate GNSS-RO refractivity data in the lower troposphere
- Continue to improve PBLH data assimilation, assess PBLH data impact and combined impact with GNSSRO and radiances
- Develop method(s) to retain PBLH data information

References

Ao, C. O., D. E. Waliser, S. K. Chan, J.-L. Li, B. Tian, F. Xie, and A. J. Mannucci, 2012: Planetary boundary layer heights from GPS radio occultation refractivity and humidity profiles. *J. Geophys. Res.*, **117**(**D16**).

Lewis, J. R., J. R. Campbell, E. J. Welton, S. A. Stewart, and P. C. Haftings, 2016: Overview of MPLNET version 3 cloud detection. *Journal of Atmospheric and Oceanic Technology*, **33**(10), 2113-2134.

McGrath-Spangler, E. L., and A. S. Denning, 2012: Estimates of North American summertime planetary boundary layer depths derived from space-borne lidar. *Journal of Geophysical Research: Atmospheres*, **117**(**D15**).

National Academies of Sciences, Engineering, and Medicine, 2018: *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. The National Academies Press, Washington, DC.

Palm, S., P. Selmer, J. Yorks, S. Nicholls, and E. Nowottnick, 2021: Planetary boundary layer height estimates from ICESat-2 and CATS backscatter measurements. *Front. Rem. Sens.*, **(2)**, 716 951.

Salmun, H., H. Josephs, and A. Molod, 2023: Global Radar Wind Profiler Planetary Boundary Layer Height Data. *Bulletin of the American Meteorological Society*, **104**, E1044–E1057.

Seidel, D. J., Y. Zhang, A. Beljaars, J.-C. Golaz, A. R. Jacobson, and B. Medeiros, 2012: Climatology of the planetary boundary layer over the continental United States and Europe. *J. Geophys. Res.*, **117** (**D17106**).

Texeira, J., and Coauthors, 2021: *Toward a global planetary boundary layer observing system: The NASA PBL incubation study team report*. NASA PBL Incubation Study Team.

Zhu, Y., et al., 2024: Utilizing PBL Height Data from Multiple Observing Systems in the GEOS System (I): Assimilation Framework. *Mon. Wea. Rev.*, under review.

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