UNDERSTANDING AND UTILIZING PBL HEIGHT DATA FROM MULTIPLE OBSERVING SYSTEMS IN THE GEOS SYSTEM

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Motivations

- Measurement of PBL was designated as an incubation program by the 2018 Decadal Survey
- The accuracy of PBL height simulation is a key issue in many applications, e.g., forecasting near-surface meteorology, air quality
- Any single observing system can sample only a fraction of the global PBL space-time structure and physical aspects
- The GEOS data assimilation system provides the critical capability to assimilate a wide range of observations in combination with model physics

Objectives:

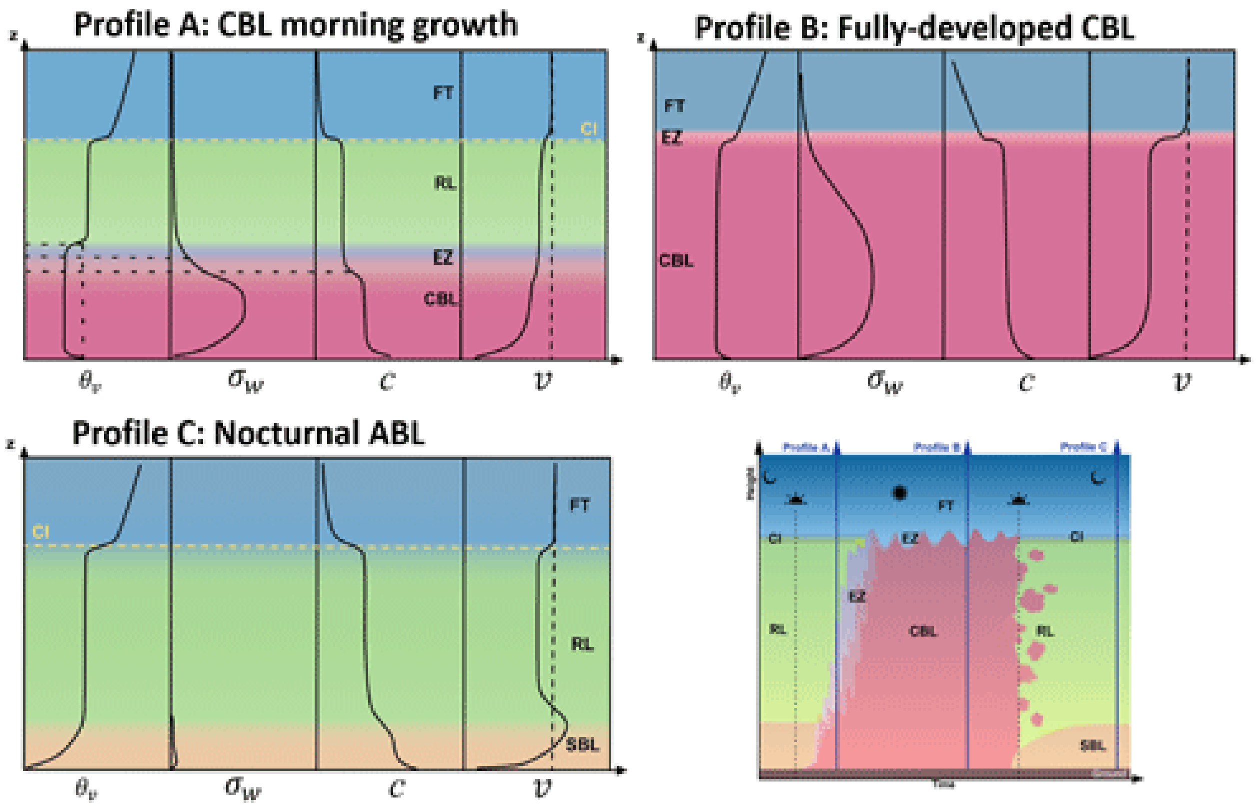
- Develop optimal global data assimilation strategies for PBLH data from multiple observing systems
- Assess combined impacts from PBLH, GNSS RO and window/surface-sensitive radiances on PBL thermodynamic structure in the GEOS
- Develop methods to assess and improve retention of PBL observation information in model forecast

The GEOS 4D Hybrid Ensemble-Variational Data Assimilation System

- Finite Volume dynamical Core + GEOS physics
- A deterministic hybrid analysis system + an ensemble assimilation system running concurrently
- Assimilates about 4.5 million observations per analysis cycle

$$J(\mathbf{x}'_c,\mathbf{a}) = \underbrace{\beta_c \frac{1}{2}(\mathbf{x}'_c)^T \mathbf{B}_c^{-1}(\mathbf{x}'_c)}_{\text{Departure from BKG}} + \underbrace{\beta_e \frac{1}{2}\mathbf{a}^T \mathbf{L}^{-1}\mathbf{a}}_{\text{Ensemble term}} + \frac{1}{2}\underbrace{\sum_{k=1}^{K}(\mathbf{H}_k \mathbf{x}'_{(t)k} - \mathbf{y}'_k)^T \mathbf{R}_k^{-1}(\mathbf{H}_k \mathbf{x}'_{(t)k} - \mathbf{y}')}_{\text{Departures from observations}}$$

- Background error covariances project observation info onto analysis variables
- Handles amplitude error well, but not displacement error
    - Displacement error in the background will smear out the PBL structure and result in poor PBL analysis



Idealized vertical profiles of atmospheric variables during the idealized diurnal evolution of atmospheric boundary layer (Kotthaus et al. 2023)

- **The unique feature of PBL: often marked by the base of capping inversion**
  - A sharp gradient of vertical temperature or specific humidity profile
  - Ensemble **B** is characterized by the decoupling between the errors in the PBL and the above atmosphere
- **PBLH data are sensitive to observing method & choice of retrieval algorithm**
- **Use a model definition appropriate for each observation type to compute differences between PBLH data and model PBLH (OmFs).**

Why PBL height data assimilation?

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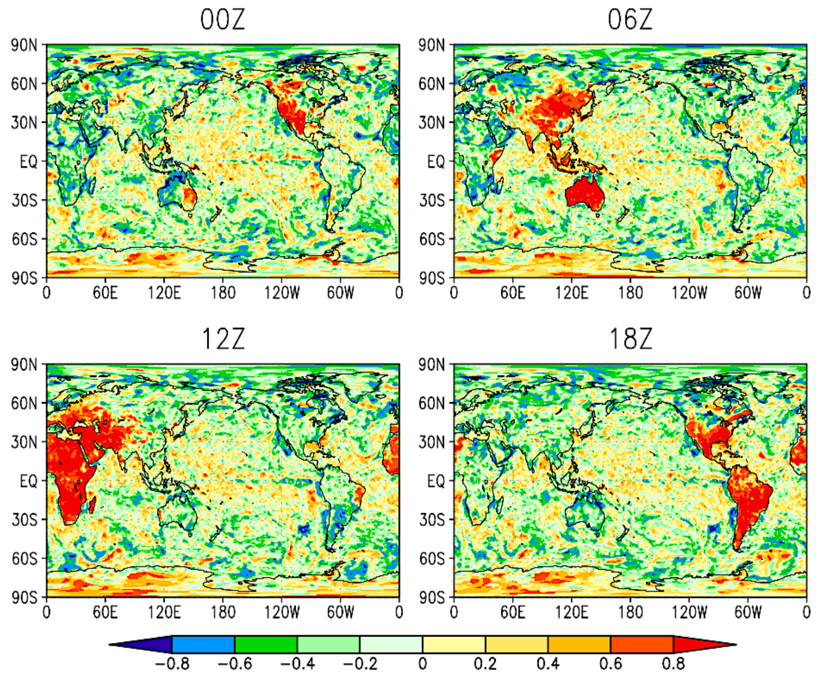
- **Generate global PBL height (PBLH) analysis & monitor PBLH data online**
  - Improve model physics and performances of other applications such as air quality
  - models tend to “lose” impact of optimal initial condition first, while impact of optimally identified parameter values persists longer
- **Capture the location of capping inversion,** which may be lost or obscured if direct measurements themselves are assimilated
  - Benefit the use of all other observations in the lower troposphere
- **Alleviate limitations/sensitivities of observations or observation operators**. E.g.,
  - Assumed particle properties have less of an impact on the gradient of attenuated total backscatter (ATB) vertical structure
  - The GNSS-RO refractivity negative bias due to the presence of critical refraction layers typically doesn’t impact PBL height retrieval
- **Provide additional info for thermodynamic variables through correlated background error covariances**
- **PBLH data available from multiple observing system**
  - Different data coverages and temporal/spatial resolutions
  - Under different meteorological conditions

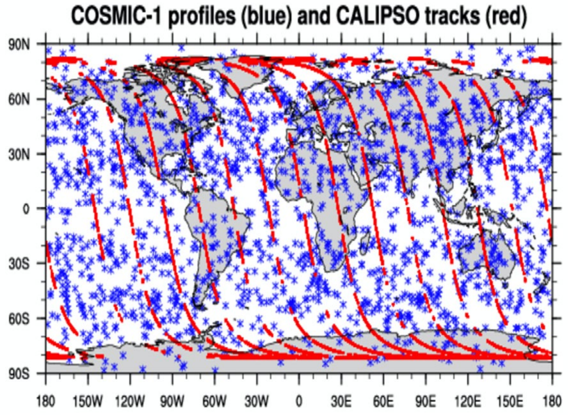


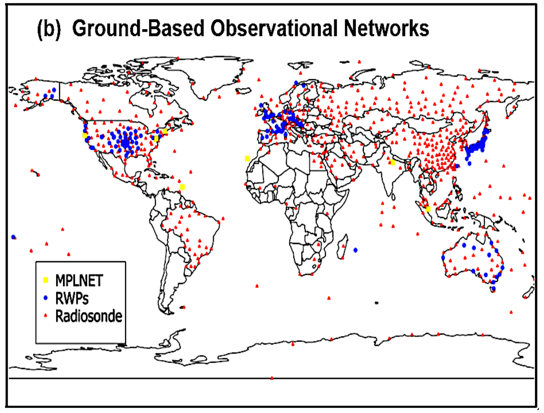
Perturbation correlation coefficient between PBLH & T at about 925 hPa

Strategy for assimilation of PBLH data from multiple observing systems

- **Develop PBLH data assimilation methodology: use PBLH control variables in 4D EnVar**, instead of construction of complicated observation operators
  - Thinning, spatial-temporal resolution handling
  - Quality control
  - Background error covariance

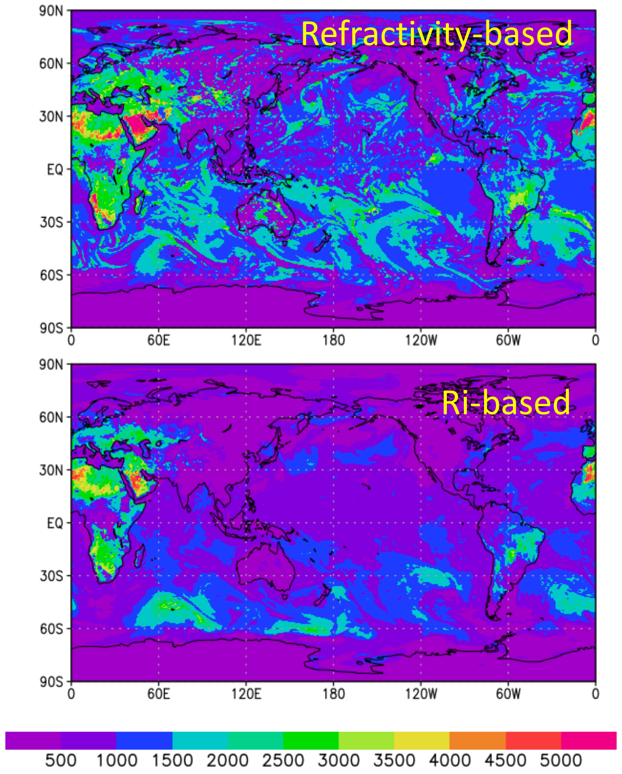
- **Generate & compare model PBLH simulations consistent with PBLH data:**
  - **PBL height data derived from**
    - Radiosonde
    - GNSS RO
    - Space-based lidars (CALIPSO, CATS and ICESat-2)
    - Ground-based lidar MPLNET and Radar Wind Profile
  - **Model PBLH definitions**
    - Ri-based
    - KH-based
    - Refractivity-based
    - Attenuated total backscatter based





Data distribution

Model PBLH

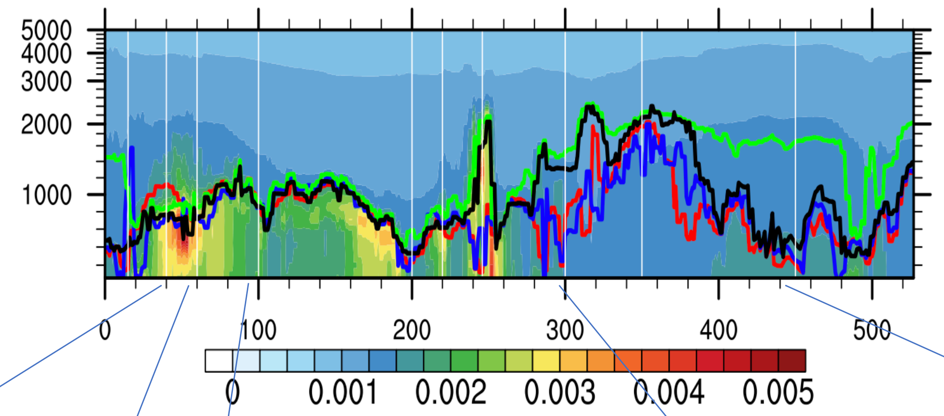


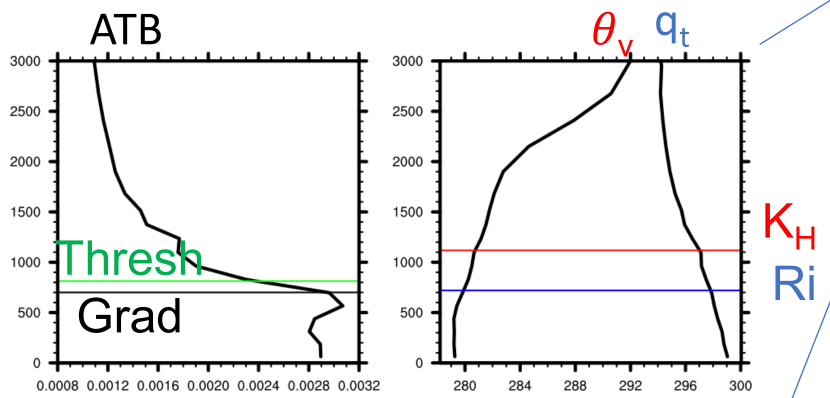
Model PBLH definition: GEOS backscatter-based PBLH (under development)

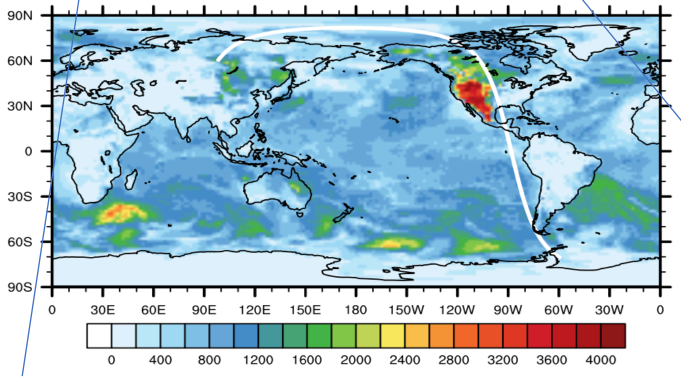
- **Attenuated Total Backscatter (532nm) as a diagnostic in GOCART2G (version 2.1.3)**
  - **ATB from GOCART2G is clear-sky**

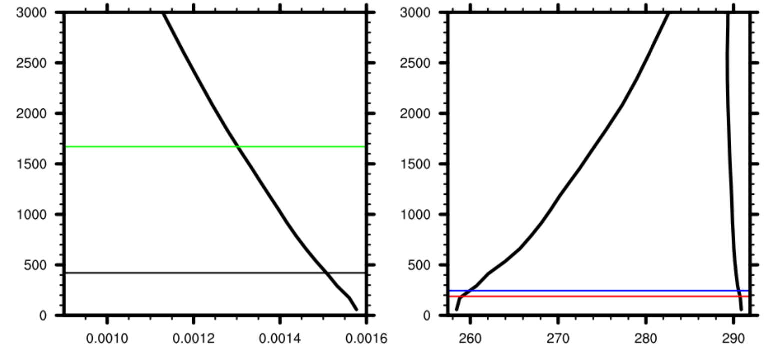
- **PBLH retrieval algorithms**
  - **Maximum Variance Method** (McGrath-Spangler and Denning)
    - Identify co-located local maxima of vertical std dev (3 pts) of ATB
    - This produced very few usable profiles
      - Low model vertical resolution?
      - Lack of cloud in GEOS ATB?
      - Coding error?
  - **Threshold Method (**Palm / Melfi)
    - Use average ATB from 200-400m as reference.
    - Threshold set to 0.85 x reference (*original algorithm used 0.7, but PBLH was too deep)
    - Scan up from 300m until cross threshold, interpolate
  - **Gradient Method**
    - Calculate first derivative of ATB from 300-5000m
    - PBLH is height of minimum

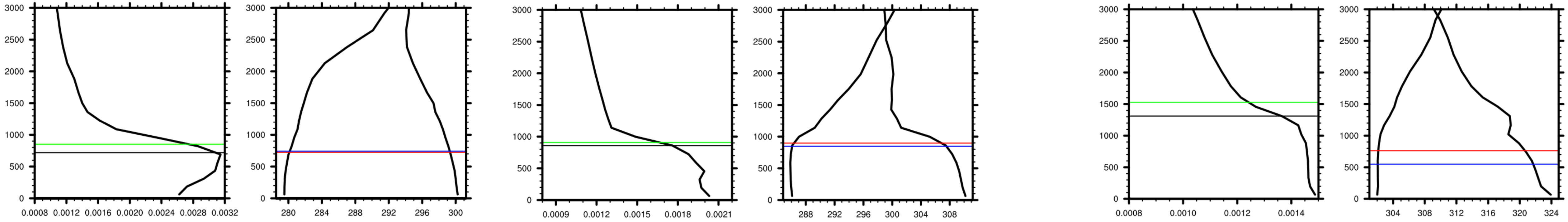
Model PBLH comparison









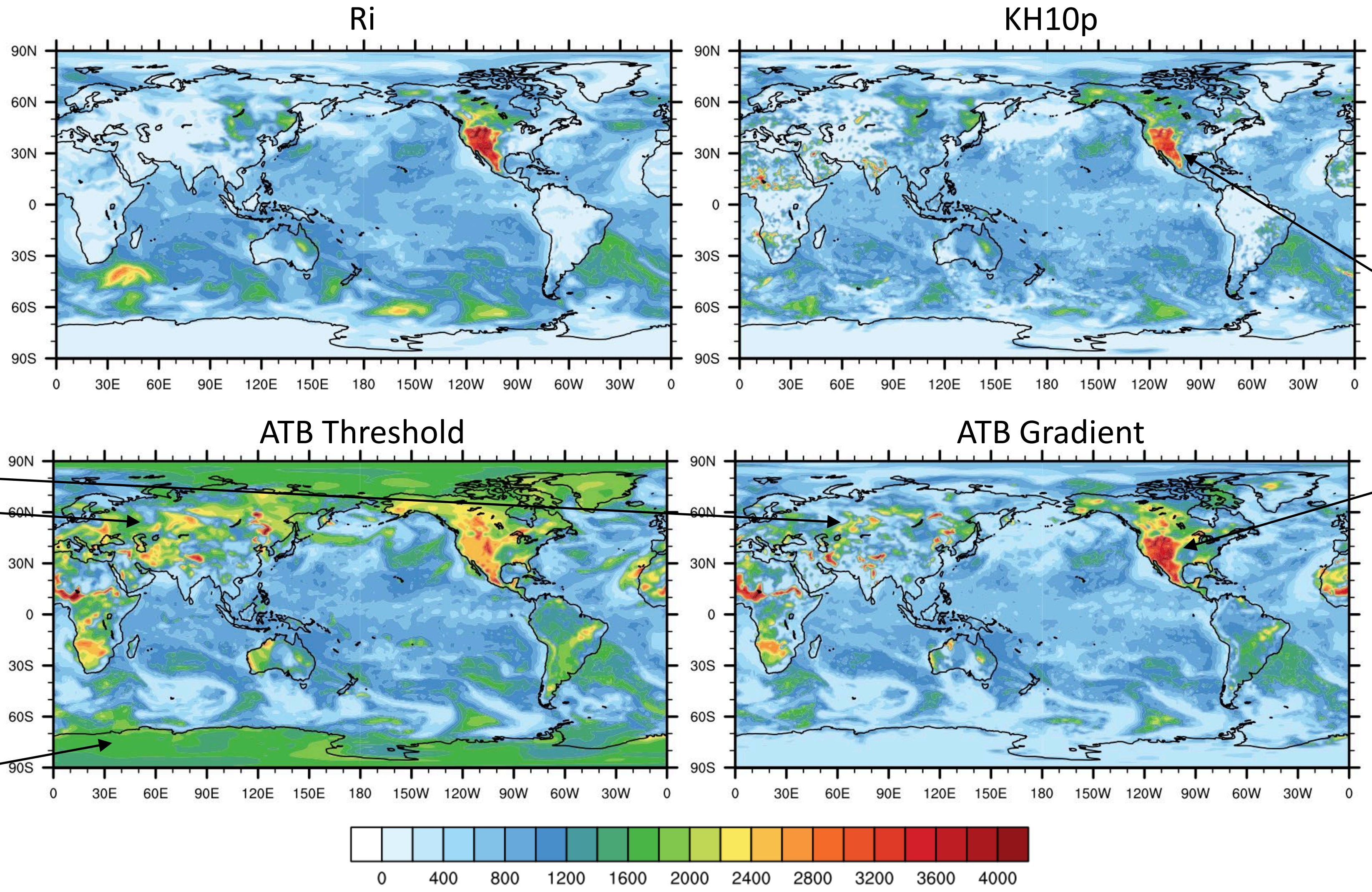


Model PBLH map

Good agreement over ocean

Remains elevated at night

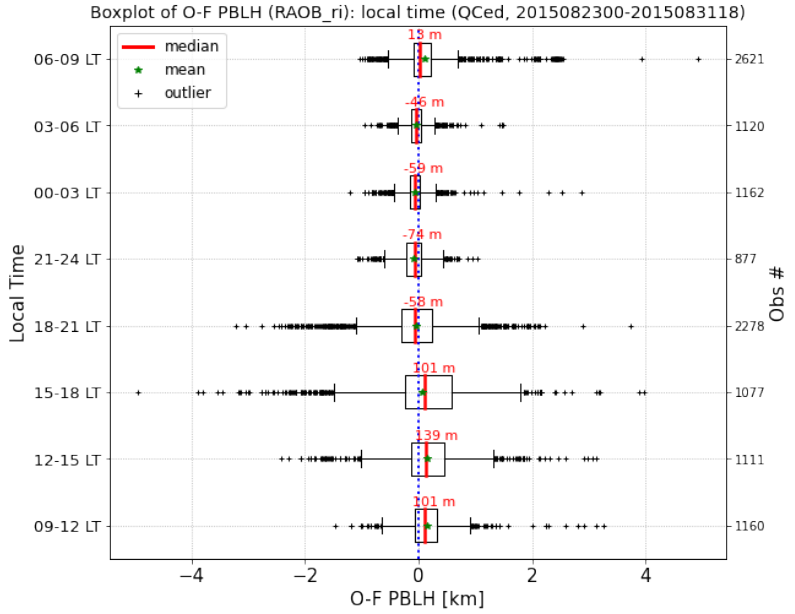
Large polar PBLH

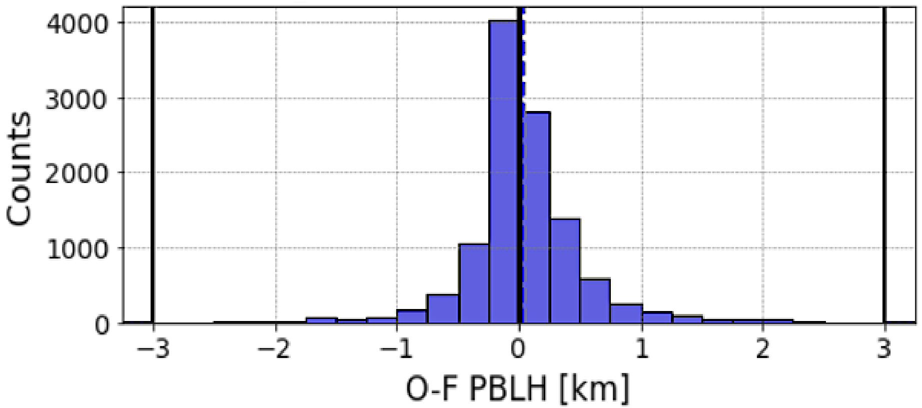


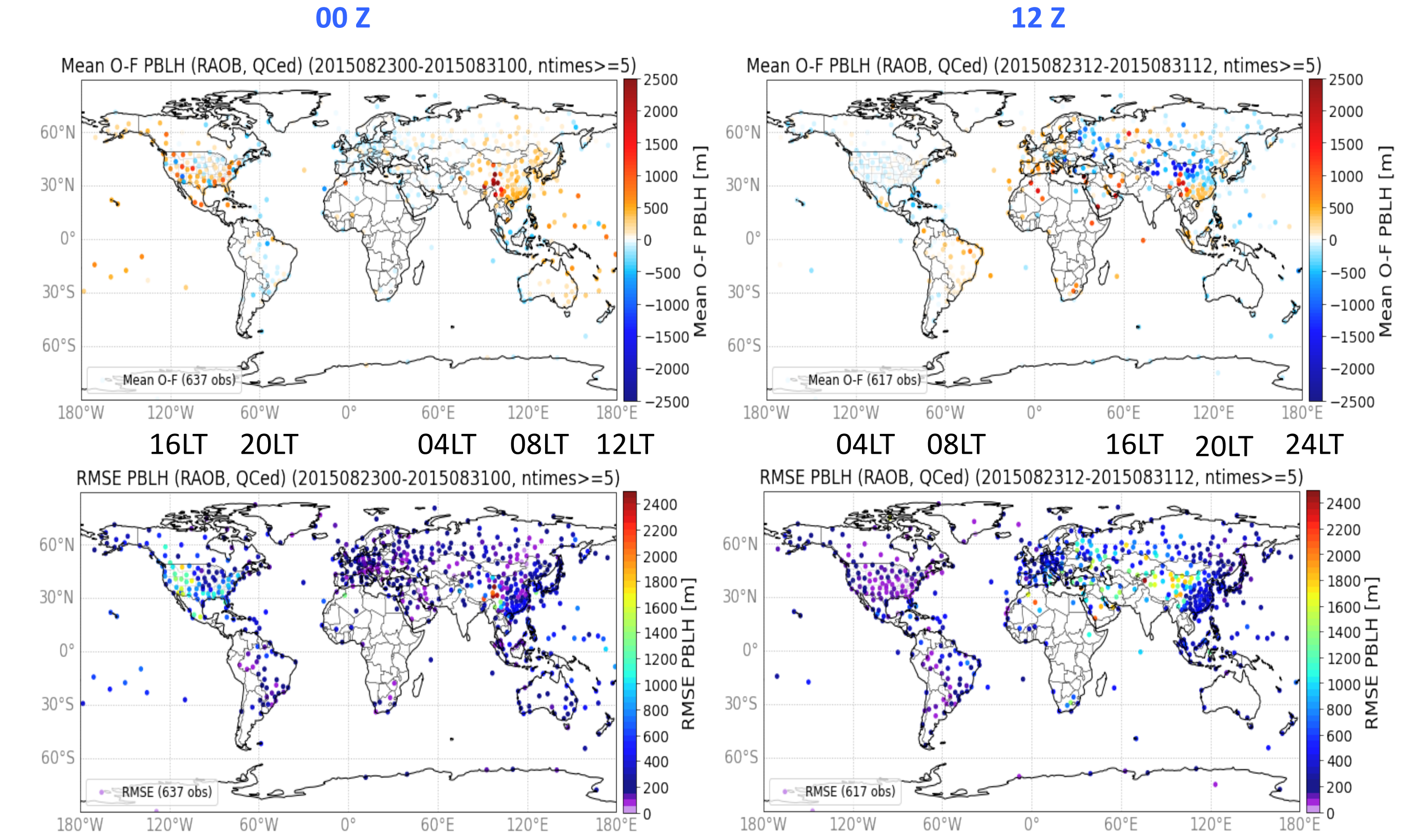
All methods capture elevated daytime CBL

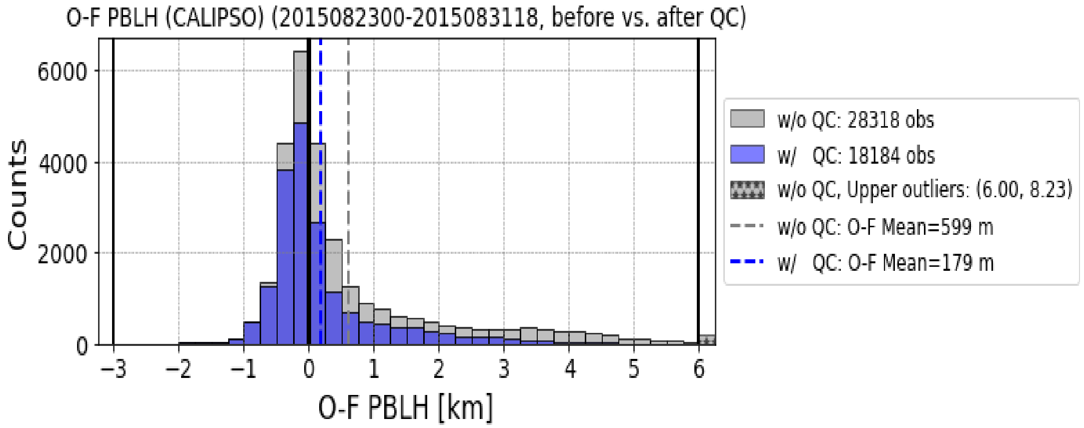
Radiosonde PBLH data comparison with Ri-based PBLH

- Mainly concentrated over land, only available at 00 and 12UTC
- PBLH data excluded when PBLH <= 0 or PBLH > 6 km
- No significant OmF bias w.r.t. local time



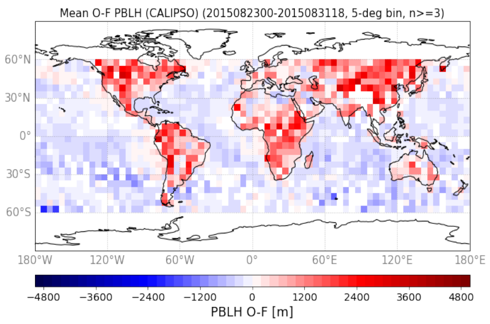




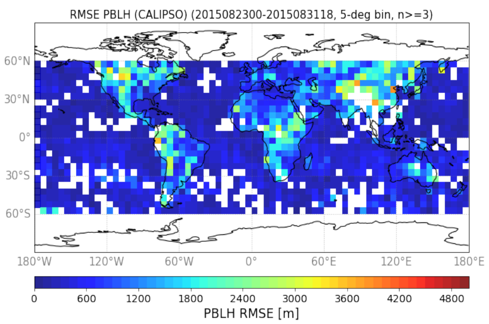


Quality control applied here to exclude PBLH data

1) When PBLH obs <= 0 or obs > 6 km or
2) |lat| > 60° or
3) local time > 5 pm or < 10 am* or
4) sfc type = coastlines

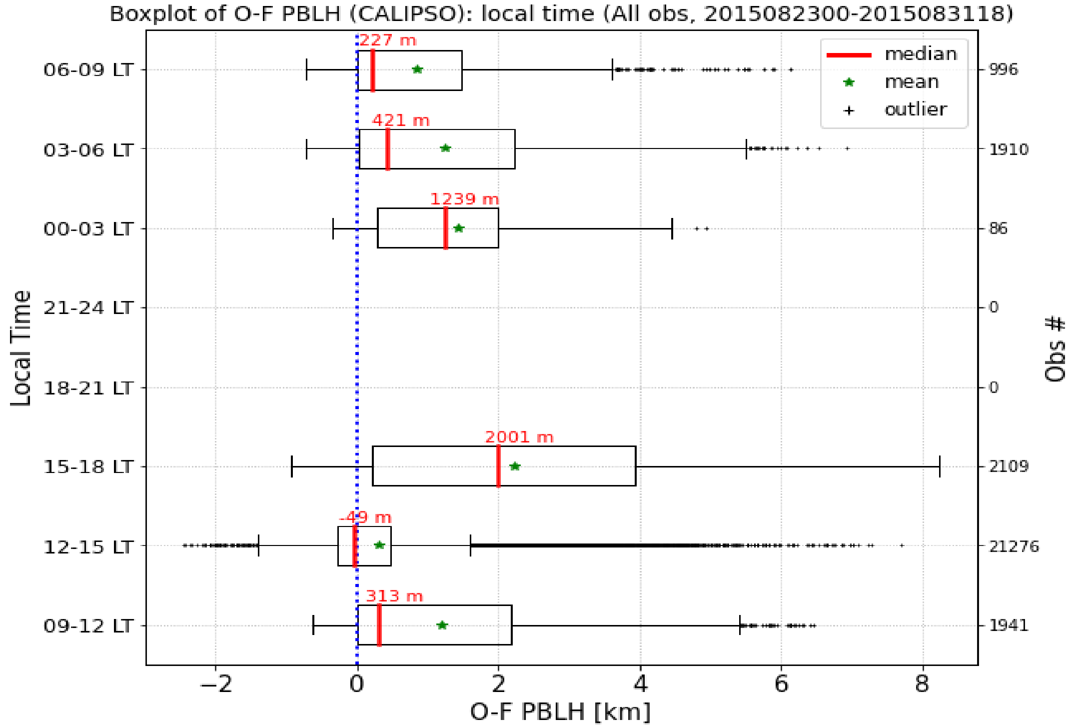


Positive/negative OmF bias over land/ocean



Larger OmF RMSE over land

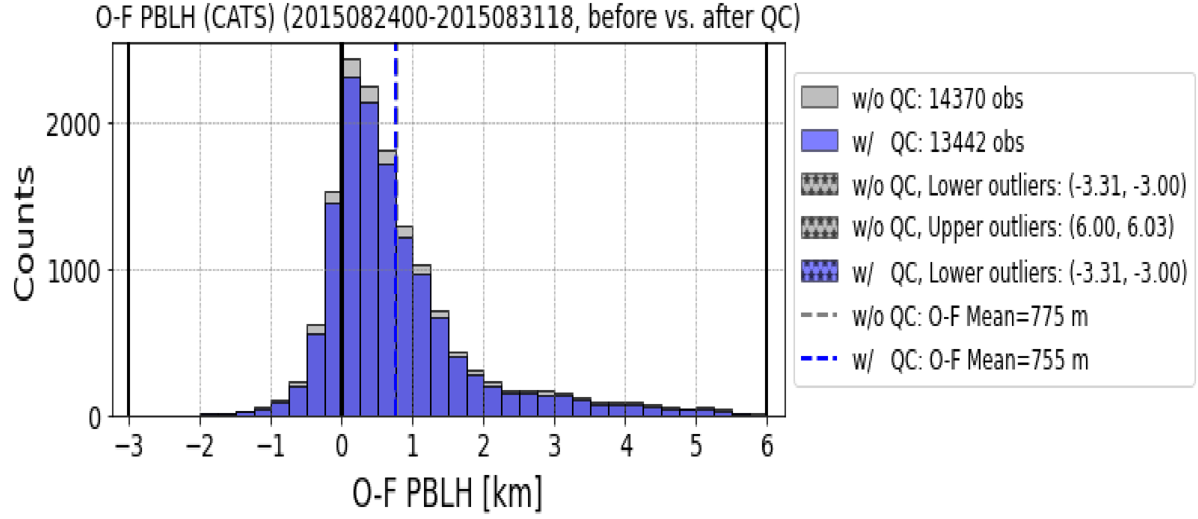
CALIPSO PBLH data comparison with Ri-based PBLH

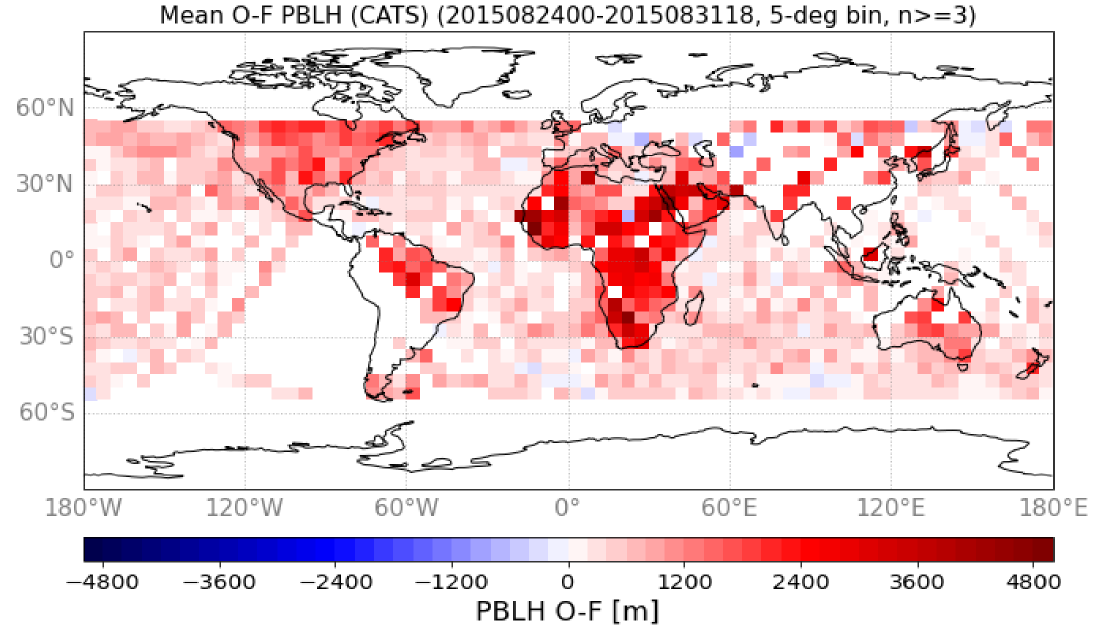


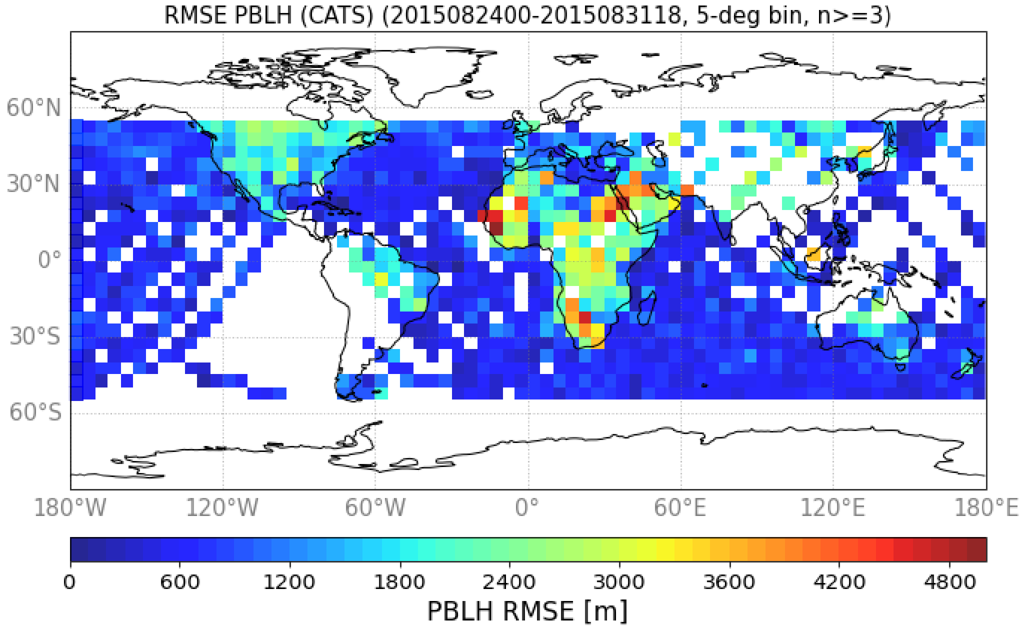
Significant positive OmF bias between local time 5pm and 10am, associated with residual layer

CATS PBLH data comparison with Ri-based PBLH

- Use the QC flag (>1) provided by Palm 2023
- Positive OmF bias, with larger bias over land
- Larger OmF RMSE over land
- Additional gross error check will be added







CALIPSO vs CATS PBLH data

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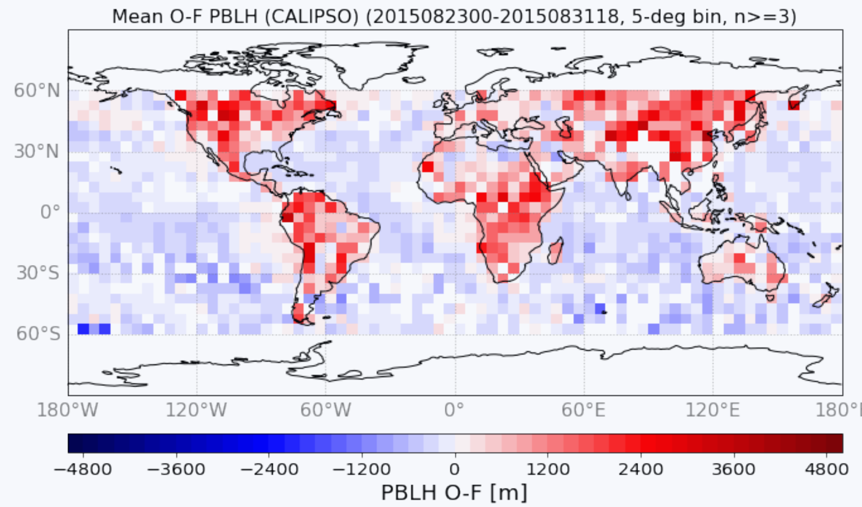
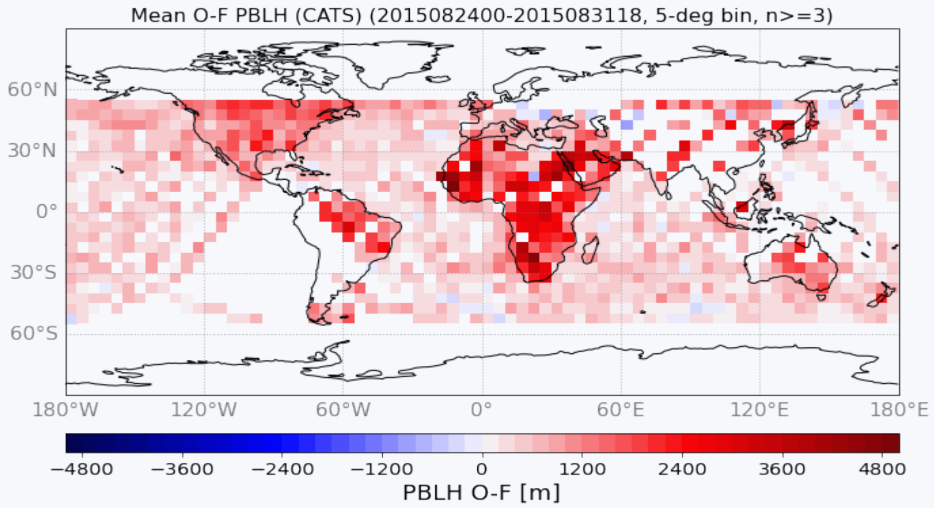
CALIPSO

- PBLH data are derived using McGrath-Spangler and Denning, 2012, 2013
- OmF bias: positive over land, negative over ocean
- Larger OmF RMSE over land than over ocean
- **PBLH data are derived only during daytime (incl. high latitude polar daytime)**
- PBLH data are quality controlled w.r.t local time to alleviate residual layer effect
- PBLH data at high latitudes are removed



CATS

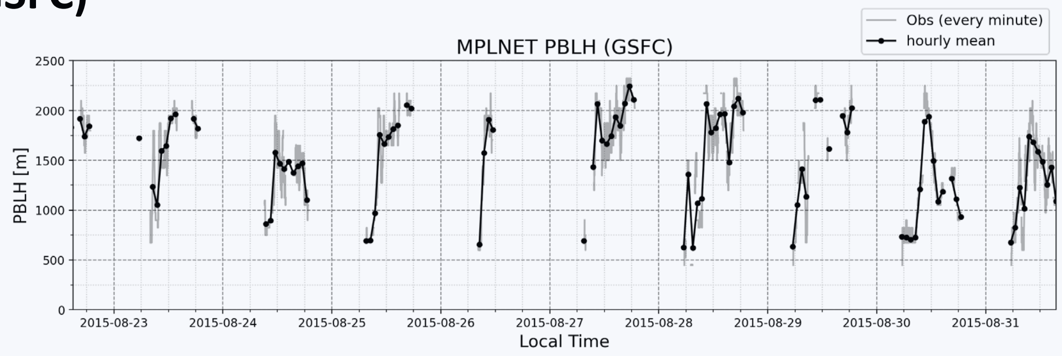
- PBLH data are derived using Palm et al, 2021
- Positive OmF bias: larger bias over land than over ocean
- Larger OmF RMSE over land than over ocean
- **PBLH data are considered better quality at night than daytime due to larger signal-to-noise ratio at night**
- Derived PBLH at night may be actual residual layer
- Quality control flags from the data file are used



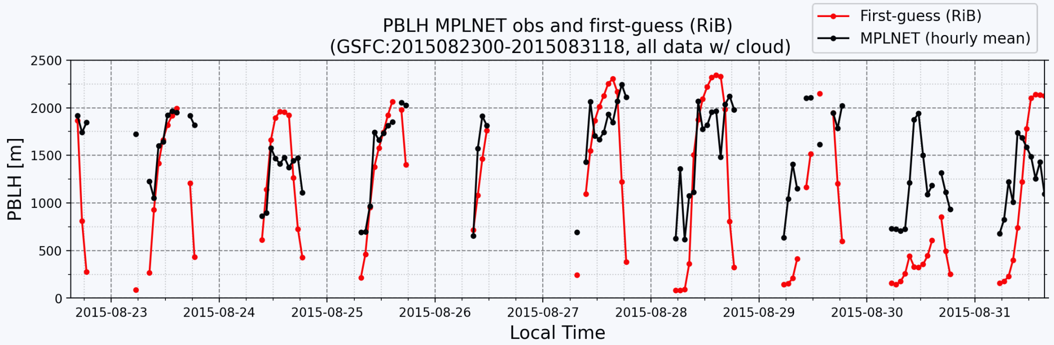
MPLNET PBLH data comparison with Ri-based PBLH

❑ (GSFC)

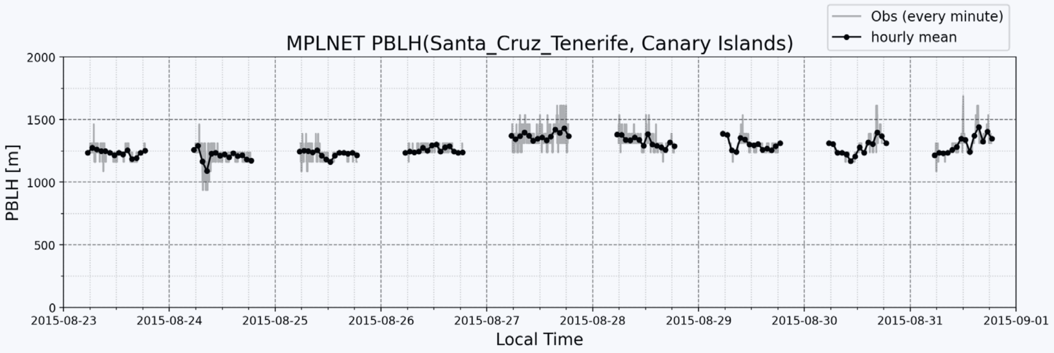
OBS (every minute and hourly mean)

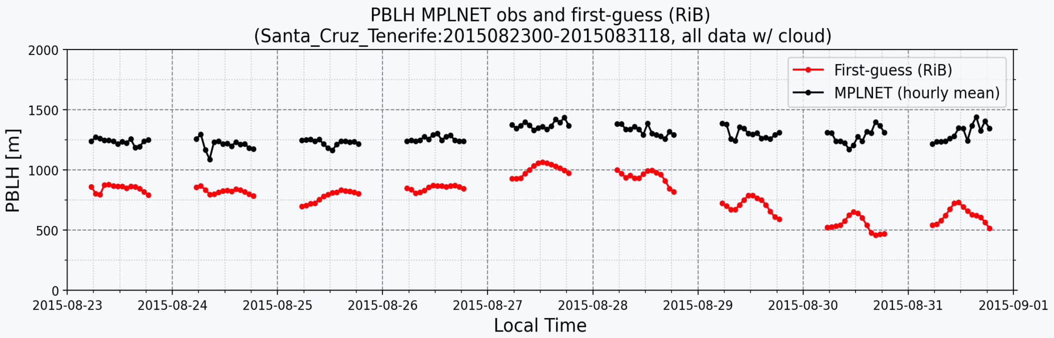


OBS (hourly mean) and first-guess

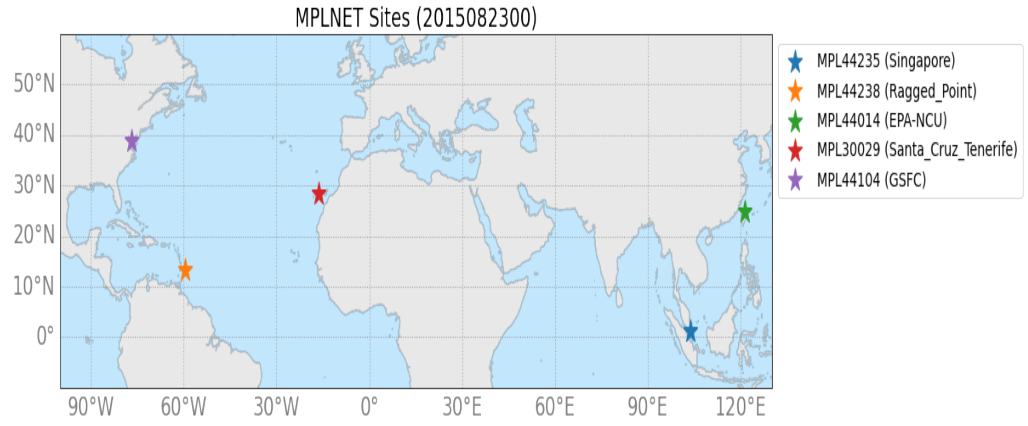


❑ (Santa_Cruz_Tenerife, Canary islands)



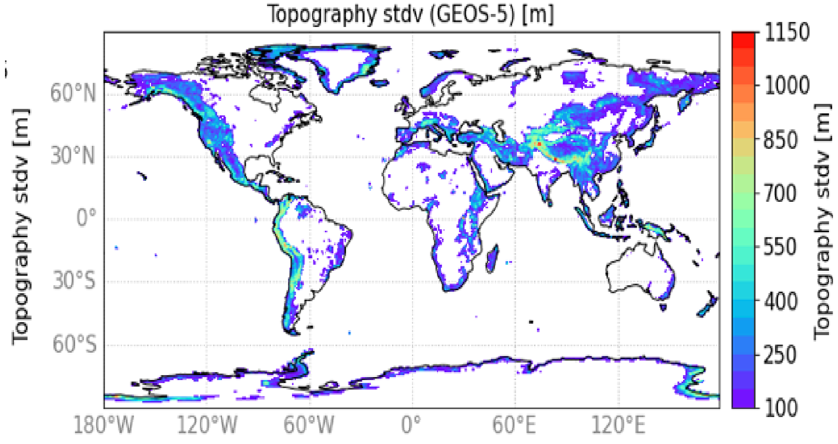


- The patterns of MPLNET PBLH data and model Ri-based PBLH agree well
- At GSFC, **clear diurnal cycle**, MPLNET PBLH tends to be higher than model PBLH before 9am & after 16pm
- At Santa Cruz Tenerife, less daily variation, MPLNET PBLH is consistently higher than model PBLH

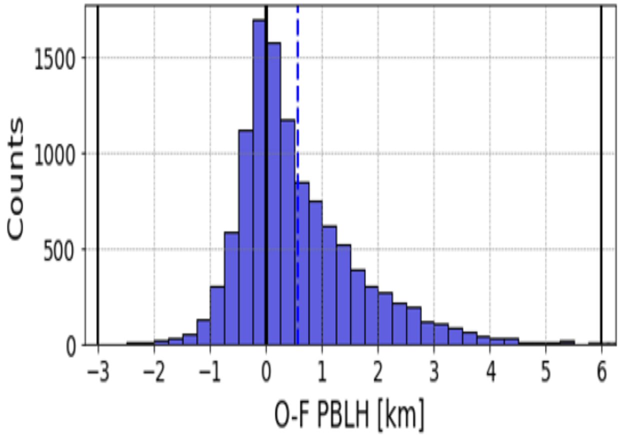


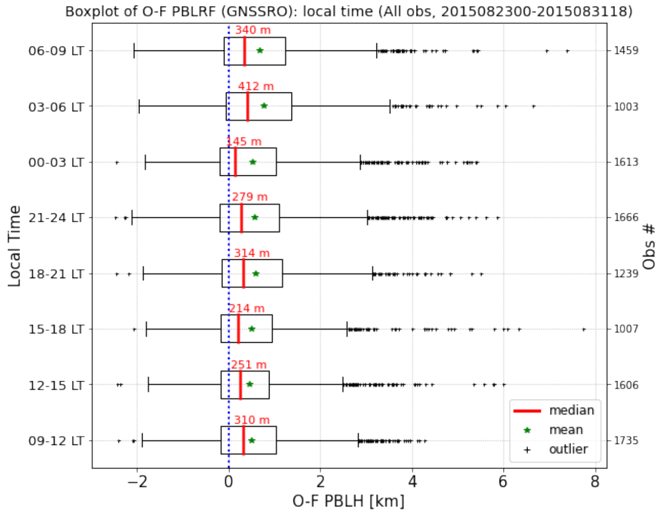
Comparison of GNSS RO PBLH data with refractivity-based PBLH

GEOS surface height STDV>100m

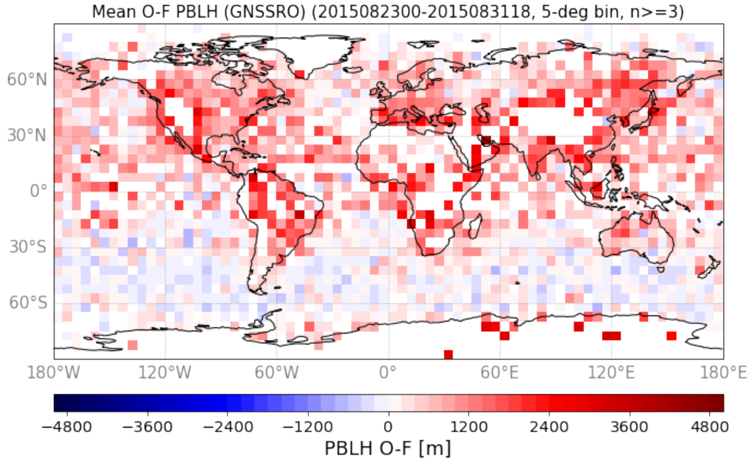


OmF histogram





OmF bias



- Refractivity gradient threshold: **-40 N-unit/km**
- Exclude observation locations with sharp gradient terrain/steep slopes/rapidly varying orography globally
- **O-Fs are not likely to depend on local time.**
- Mostly positive OmF bias and larger OmF RMSE over land

Conclusions

- PBLH data have been generated from multiple observing systems
- In addition to Ri- and KH- based model PBLHs, refractivity-based model PBLH has been constructed, and the development ATB-based PBLH has been underway.
  - Good agreement among definitions in Tropical ocean & Daytime CBL over land
  - Disagreements evident in Polar regions & Nocturnal land / residual layers
- 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.
- Evaluated departures of model PBLH simulations from PBLH data.
  - All PBLH data capture daytime CBL
  - Ground- & space-based ATB-based PBLHs are strongly associated with Residual layer at late afternoon and nighttime

Work Plan

- Need method(s) that produces consistent results for GEOS and observed ATB, will explore model ATB-based PBLH under all weather conditions
- Ingest and compare PBLH data from radar wind profiler with model PBLH
- Refine quality control and add gross error check for all PBLH data
- Develop methods to Improve background error covariances in the lower troposphere
- Perform PBLH data assimilation experiments, assess PBLH data impact and combined impact with GNSSRO and radiances
- Develop method(s) to retain PBLH data information