Evaluating WRF Simulations of Planetary Boundary Layer Processes during the Baltimore – Washington, DC DISCOVER-AQ Field Campaign

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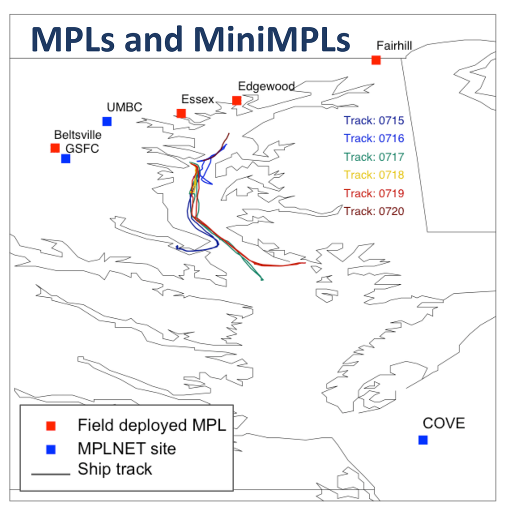
Introduction

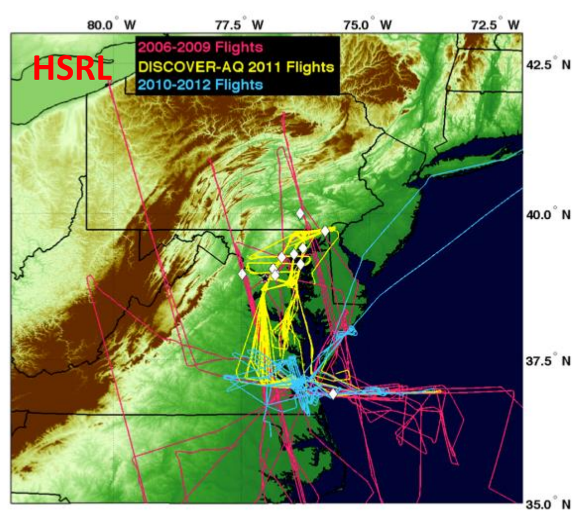
The accurate representation of the planetary boundary layer (PBL) in meteorological models is crucial for weather, air quality and greenhouse gas simulations. Urban regions present a challenge to meteorological models owing to the influence of the dense urban landscape and diversity of land use on fine scale meteorological features. They also contribute a disproportionate amount of emissions impacting regional air quality and global greenhouse gas levels. As part of an ongoing study of the PBL in urban regions we are evaluating high resolution WRF simulations over the Washington DC – Baltimore area. Initially we are focusing on the Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ) field measurement campaign that took place over the Washington DC – Baltimore area during July 2011. The evaluation is using the following.

1. Micro Pulse Lidar (MPL) measurements from the NASA MPL network (**MPLNET,** *Welton et al., 2001, JAOT, 19*)
2. Measurements from other MPLs and MiniMPLs deployed for DISCOVER-AQ
3. Airborne High Spectral Resolution Lidar (**HSRL,** *Scarino et al., 2014, ACP, 14*)
4. **CALIPSO** Cloud-Aerosol Lidar with Orthogonal Polarization (**CALIOP**) satellite measurements *[McGrath-Spangler and Denning, 2013, JGR Atmospheres, 118, doi:10.1002/jgrd.50198, 2013]*
5. Radiosondes, ozonesondes and other *in situ* observations.

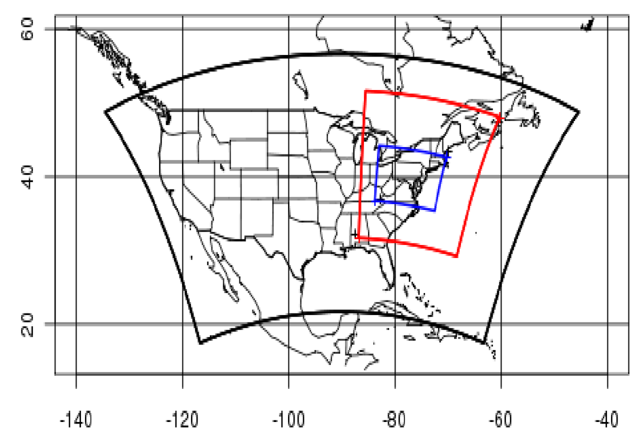
The lidars (MPL, MiniMPL, HSRL, and CALIOP) measure aerosol backscatter from which information about the PBL including the height of the top and the presence of different layers such as the residual layer may be retrieved.

The planetary boundary layer height (PBLH) is retrieved from the MPL and MiniMPL data using the new MPLNET Version 3 algorithm. This algorithm does a better job of distinguishing the residual layer from the PBL top and is less susceptible to clouds than the previous algorithm *[Lewis et al., 2013, JGR Atmospheres, 118, doi:10.1002/jgrd.50570,2013]*.

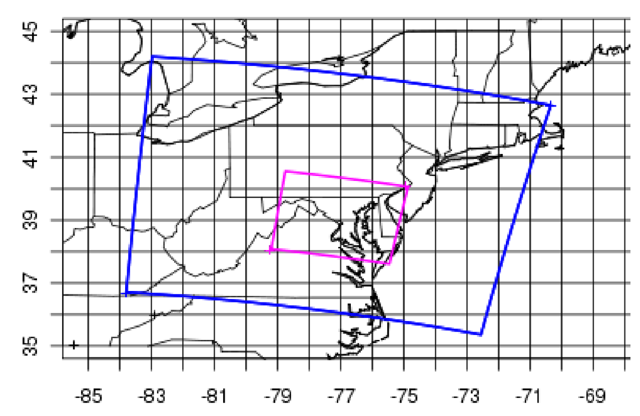




WRF Modeling



WRF 27, 9, and 3 km domains



3 and 1 km domains

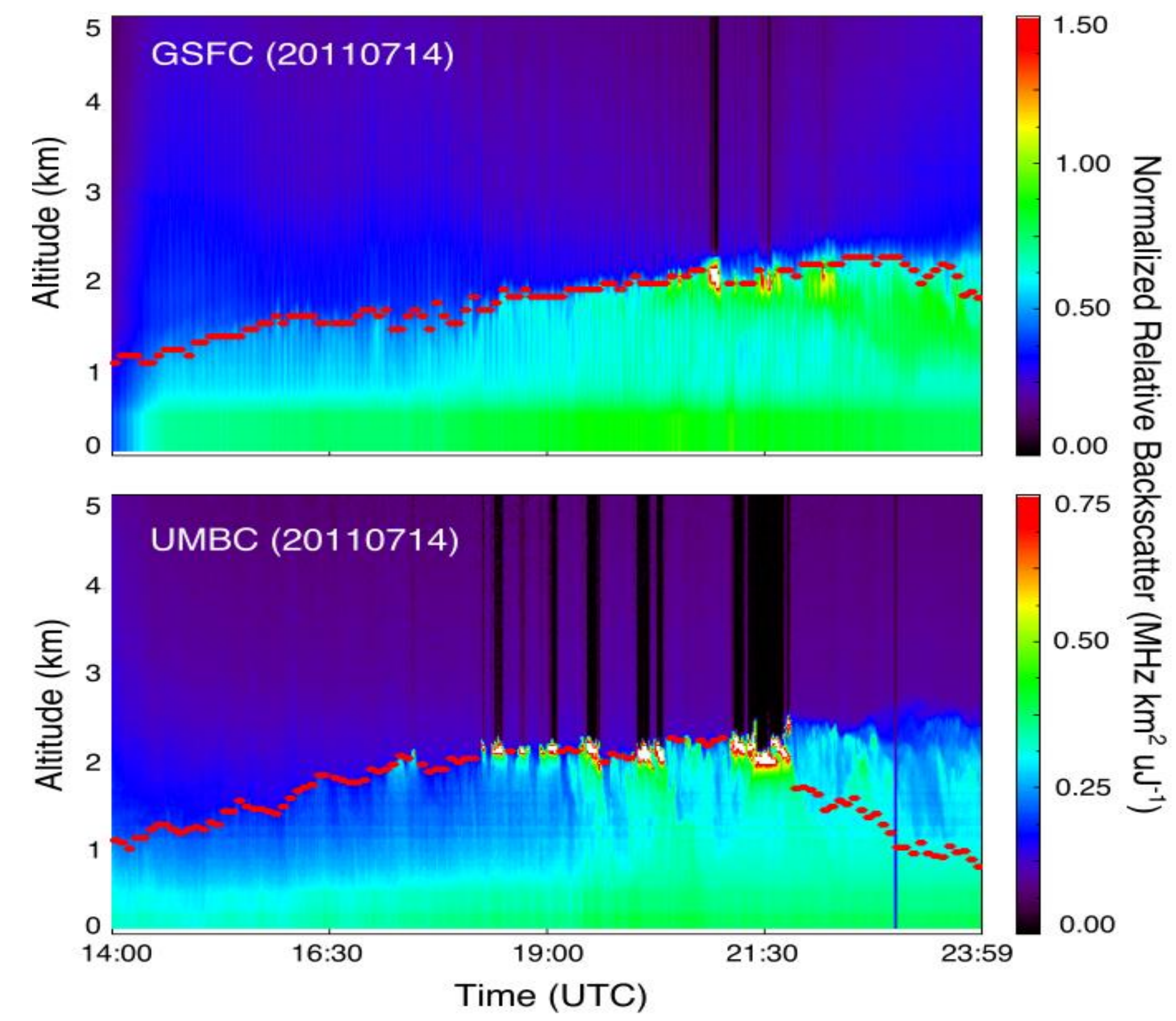
- Advanced Research WRF Version 3.6.1 with 4 nest levels of 27, 9, 3, and 1 km
- 59 vertical levels with 34 below 2 km
- Mellor Yamada Janjić (MYJ) and BouLac PBL schemes
- Noah land surface model
- Building Environment Parameterization (BEP) + Building Energy Model (BEM) Multi-layer urban canopy model (UCM)
- Muti-Sensor Ultra-high Resolution (MUR) 1 km sea surface temperature (SST) analysis – superimposed diurnal cycle based on buoys in Chesapeake Bay.
- Initial and boundary conditions from North American Regional Reanalysis (NARR)
- Daily re-initialization and grid nudging above PBL
- Simulated DISCOVER-AQ period of July 1 – 31, 2011
- A number of different configurations are tested with and without the BEPBEM UCM and the MURSST as shown in the table below. Runs without MURSST use the NARR SST field.

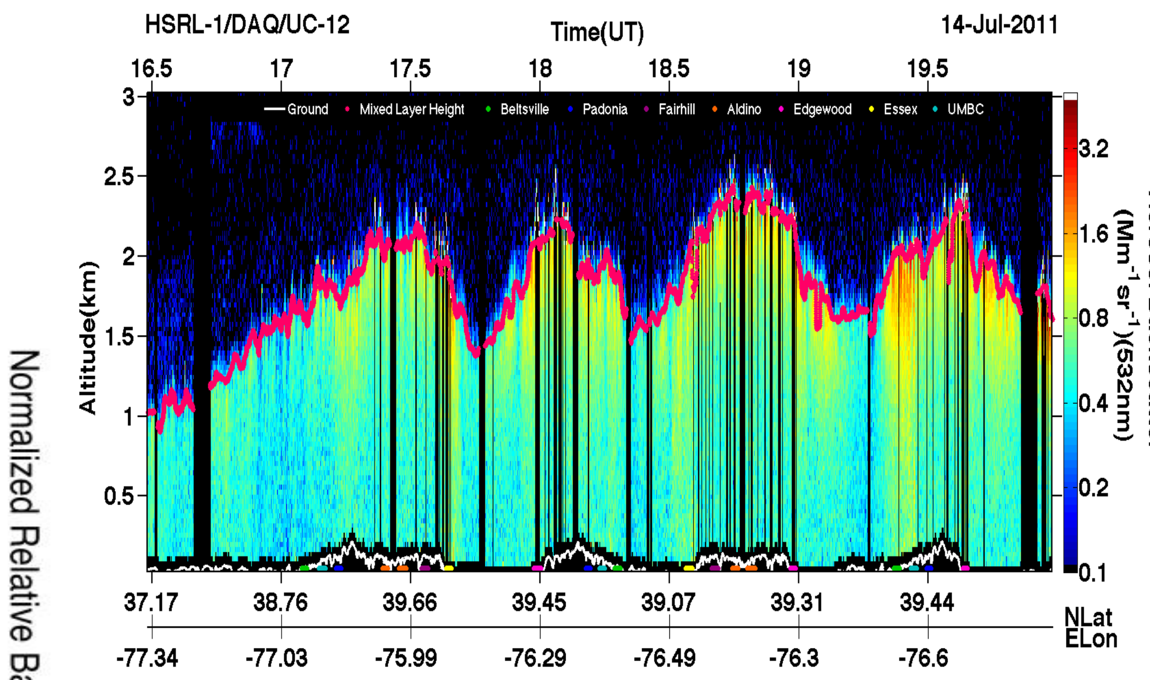
WRF run configurations for the DISCOVER-AQ simulations

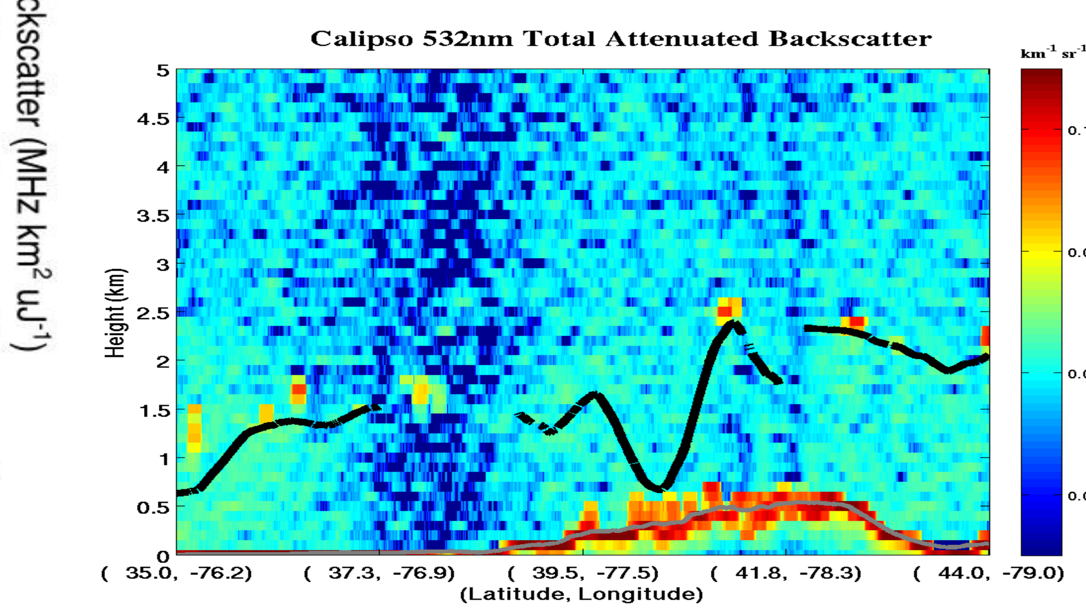
Configuration Name	PBL Scheme	BEPBEM UCM	MURSST
MYJ-BEPBEM-MURSST	MYJ	yes	yes
BouLac-BEPBEM-MURSST	BouLac	yes	yes
MYJ-noUCM-noMURSST	MYJ	no	no
BouLac-noUCM-noMURSST	BouLac	no	no
MYJ-BEPBEM-noMURSST	MYJ	yes	no
BouLac-BEPBEM-noMURSST	BouLac	yes	no
MYJ-noUCM-MURSST	MYJ	no	yes
BouLac-noUCM-MURSST	BouLac	no	yes

Lidar Data

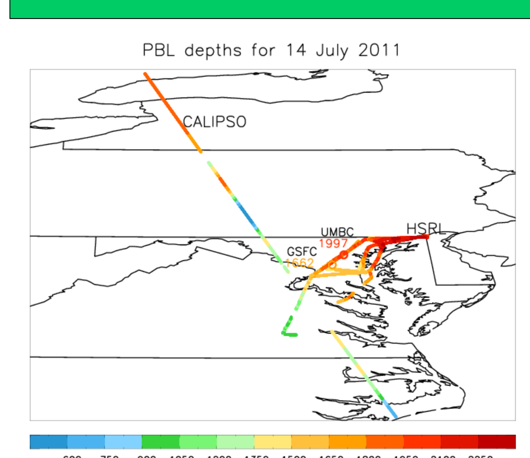
These plots show time height curtain plots of aerosol backscatter measured on July 14, 2011 from the MPLs at GSFC and UMBC (top left), HSRL (top right) and CALIPSO (bottom right). The retrieved PLBHs are shown as red dots or black or red lines. Gaps indicate times at which retrievals could not be performed due to insufficient data quality and areas where clouds have been screened. CALIPSO has an overpass time of ~ 1:30 LST.

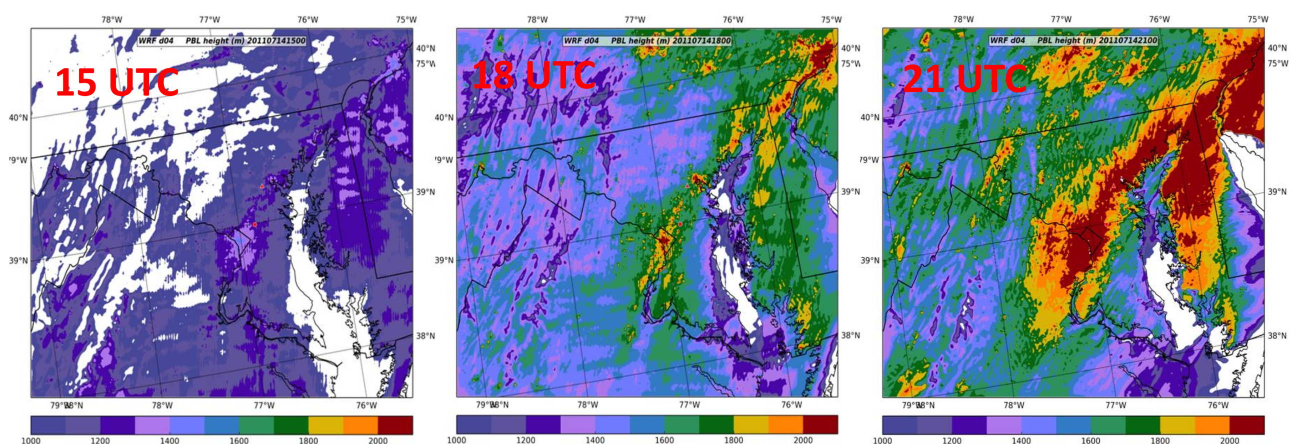




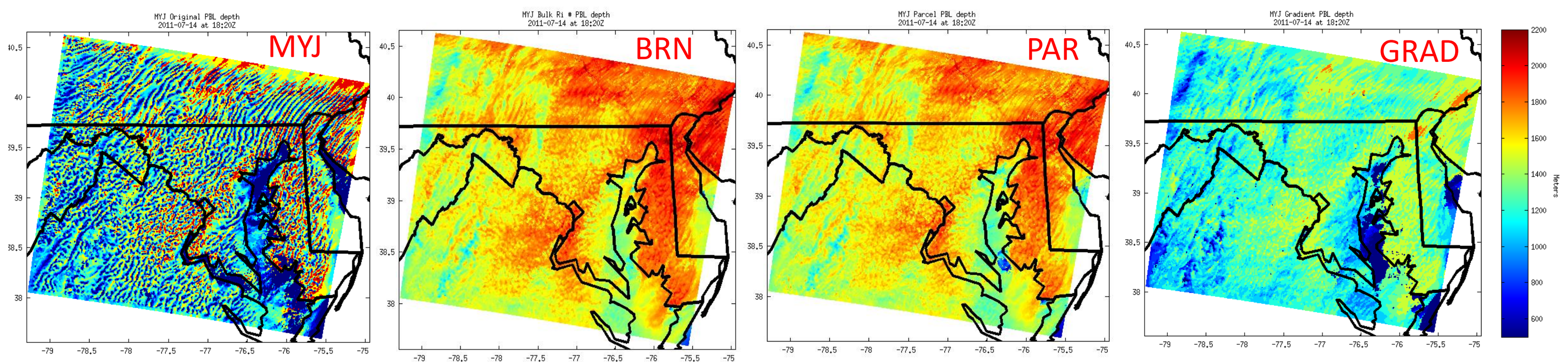


WRF PBL Development

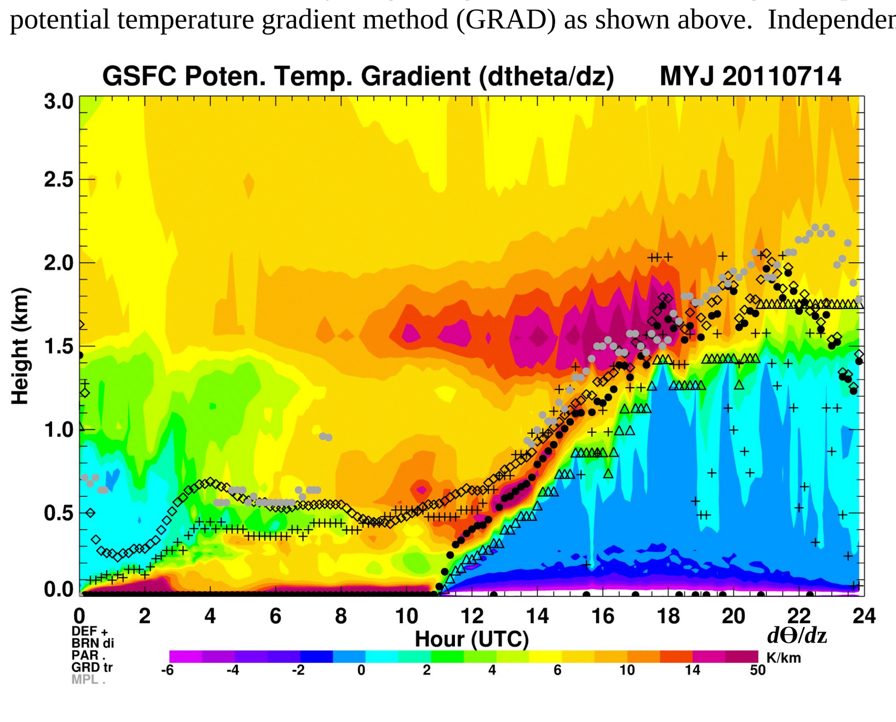




The daytime growth of the PBL is not uniform in regions with large cities. As demonstrated by the WRF simulation using the BouLac PBL scheme, shown above in the 3 panels to the right, the PBL grows more rapidly in the cities leading to large urban - rural gradients by late afternoon. This simulated pattern agrees qualitatively with the MPL, CALIPSO and HSRL PBLH retrievals shown above in the leftmost panel. The units are meters above ground level.



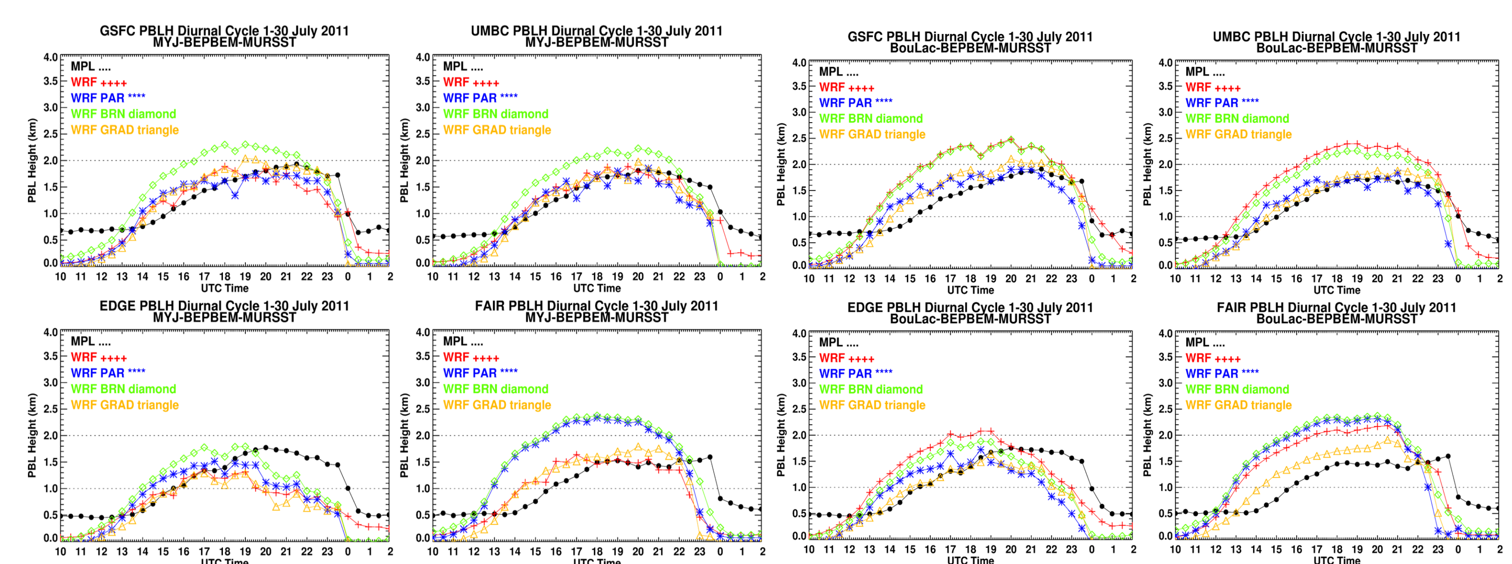
Each PBL scheme used in WRF has a different method for diagnosing the PBLH. The MYJ PBLHs for the afternoon of July 14, 2011 shown in the far left panel above are diagnosed using turbulence kinetic energy (TKE) thresholds which are highly dependent on vertical motion. At the 1 km grid scale of the WRF inner domain the larger turbulent eddies within the convective boundary layer (CBL) and their associated vertical motions are partially resolved. A grid size comparable to the scale of the largest turbulence motions was termed the "terra incognita" by *Wyngaard [2004, JAS, 61]* and violates the assumption of the PBL scheme that turbulent motions are much smaller than the grid scale. For the TKE-based MYJ scheme this leads to the high variability in the PBLHs. This issue can be addressed using spatial or temporal averaging (*e.g. LeMone et al., 2013, MWR, 141*) or by diagnosing the PBLH with WRF grid output using independent methods such as the Bulk Richarson Number (BRN), Parcel Method (PAR), or potential temperature gradient method (GRAD) as shown above. Independent PBLH methods are also helpful for comparing WRF simulations using different PBL schemes.

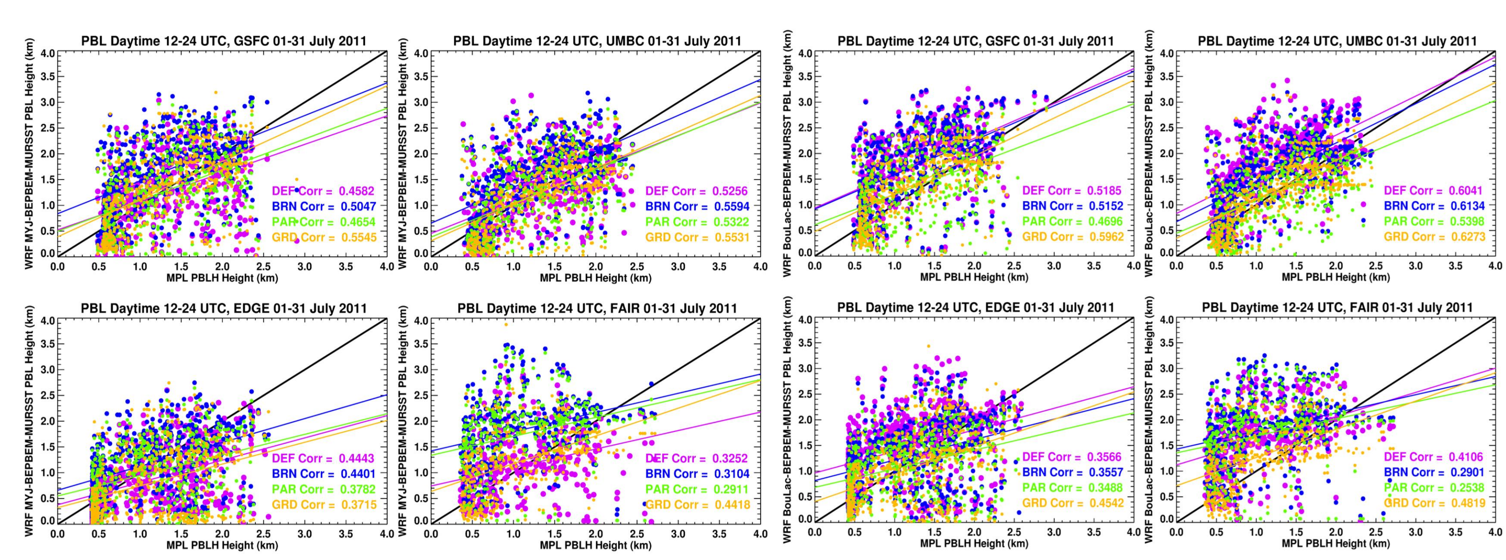


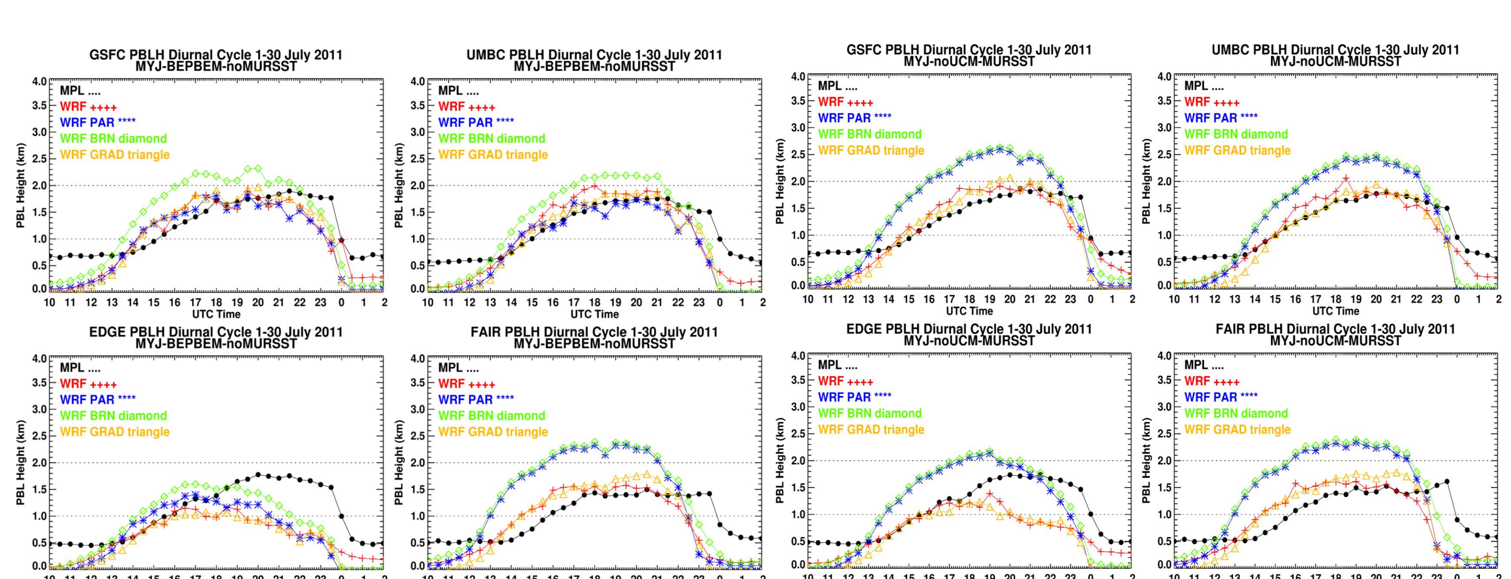
Time height cross-section of WRF simulated vertical potential temperature gradients ($d\Theta/dz$) at GSFC shows the diurnal evolution of the PBL structure. The PBLHs retrieved from the MPL measurements are shown as grey dots. The WRF PBLHs are shown for the MYJ PBL diagnostic (black plus signs), BRN (black diamonds), PAR (black dots), and GRAD (black triangles) methods are also plotted.

Note the large PBLH fluctuations for the MYJ PBLH diagnostic due to the TKE fluctuations associated with the resolved turbulent eddies. These are numerical artifacts resulting from the grid size being comparable to the scale of the largest turbulent eddies. Also note the high $d\Theta/dz$ at ~1.5 km during the early morning hours that suggests that WRF is able to capture the presence of a residual layer.

WRF Evaluation







The PBLHs simulated by WRF were evaluated with retrievals from the MPLs at GSFC, UMBC, Edgewood, MD (EDGE) and Fairhill, MD (FAIR) for July 2011. All PBLH data were averaged over 30 - minute bins and periods during which WRF simulated rain were screened out. Extreme fluctuations associated with the partially resolved turbulent eddies in the CBL were also screened out. Due to MPL signal constraints the current algorithm does not retrieve PBLH below 0.5 km so only daytime statistics are considered. The average simulated and observed PBLH diurnal cycles are shown at the top left for the MYJ-BEPBEM-MURSST and BouLac-BEPBEM-MURSST configurations. Corresponding scatter plots of WRF versus MPL PBLHs are shown in the middle left below the diurnal cycle plots.

1. During the PBL growth phase the average MYJ-BEPBEM-MURSST curves match the MPL retrievals better than the BouLac-BEPBEM-MURSST curves.
2. The BouLac-BEPBEM-MURSST PBLHs grow too quickly leading to generally higher afternoon biases. The PBLH biases are associated with a domain-wide surface temperature bias of ~ 1.2 K.
3. Both simulations collapse the PBL too quickly in the late afternoon.
4. The BouLac-BEPBEM-MURSST correlations are slightly higher but comparable to the MYJ-BEPBEM-MURSST values.

The average diurnal PBLH plots for the MYJ-BEPBEM-noMURSST and MYJ-noUCM-MURSST WRF sensitivity experiments runs are shown at the bottom left.

1. The noMURSST runs used the NARR SST which was colder in the Chesapeake Bay than the MURSST and this resulted in lower simulated PBLHs are EDGE and FAIR located near the shoreline.
2. The noUCM runs had higher surface temperature biases which resulted in slightly higher PBLHs.

Findings and Ongoing Work

1. High-resolution WRF simulations qualitatively capture the general spatiotemporal variability of PBLH in the Baltimore –Washington DC area during DISCOVER-AQ 2011.
2. The MYJ PBL scheme does a little better than the BouLac scheme in matching the diurnal evolution of the PBL, and both PBL schemes appear to collapse the PBL too quickly in the afternoon based on the MPL PBLH retrievals.
3. Work is ongoing to investigate the relationship between the PBL development and the Chesapeake Bay breezes during DISCOVER-AQ.
4. The study is expanding to look at inter-seasonal and inter-annual variability of the PBLH.

Acknowledgements

This work was funded under National Aeronautics and Space Administration (NASA) Grant Number NNH14CM13C. Any opinions, findings and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NASA.