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

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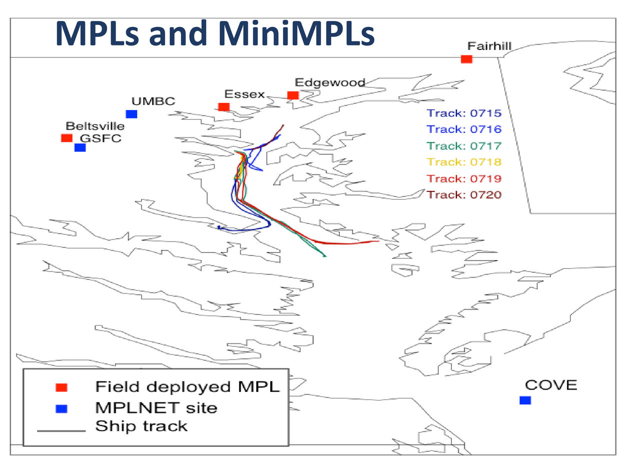
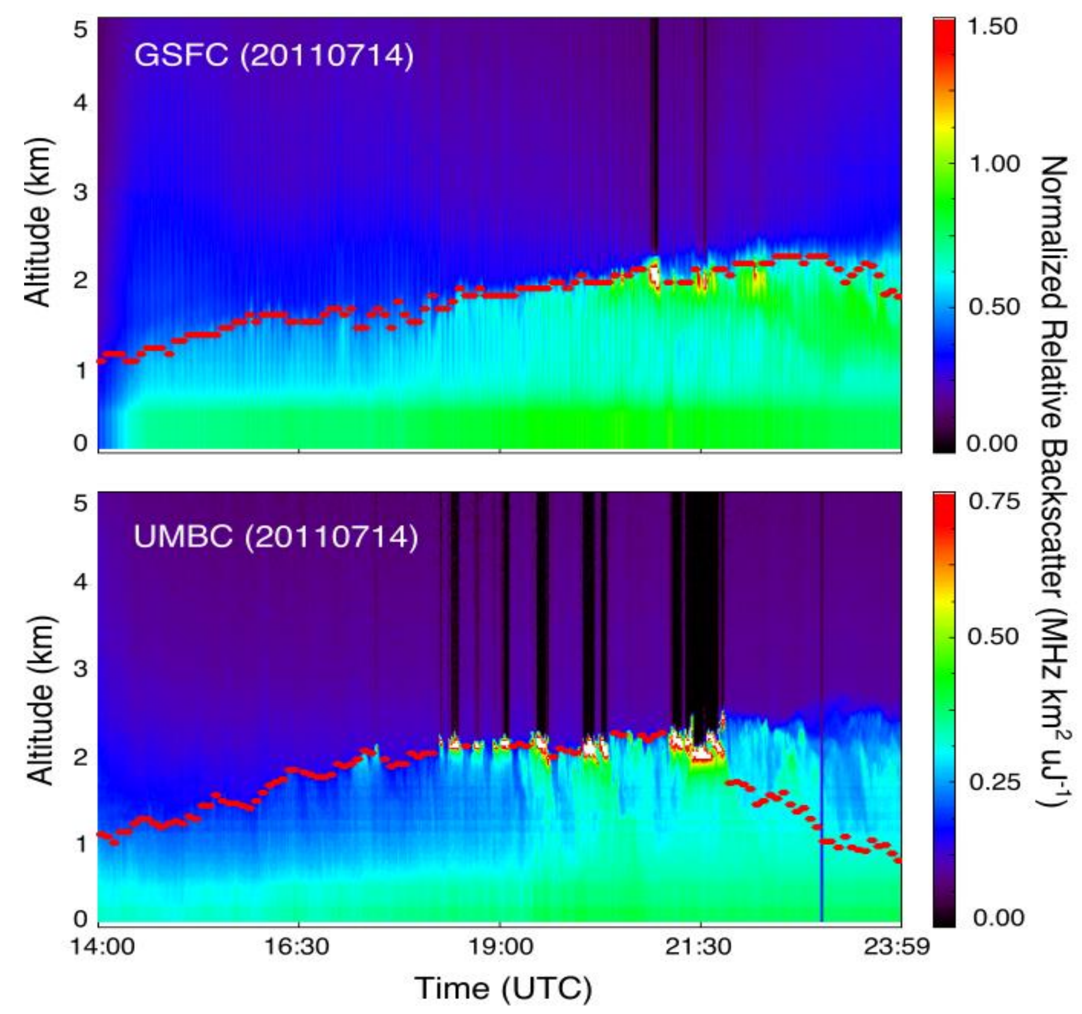
Introduction

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. As part of an ongoing study of the PBL in urban regions We are evaluating high resolution WRF simulations over the Baltimore - Washington DC area focusing on the Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ) field measurement campaign of 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***)** and 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.

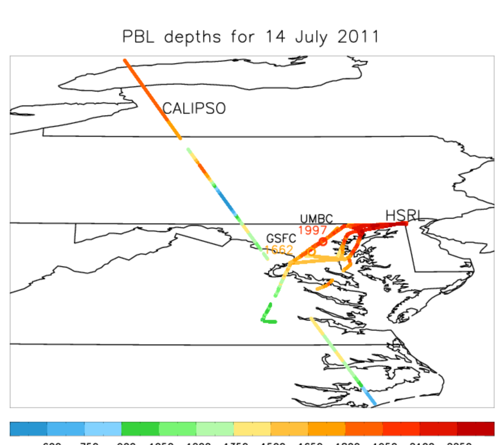
The lidars (MPL, MiniMPL, HSRL, and CALIOP) measure aerosol backscatter from which information about the PBL including the height (PBLH) of the top and the presence of different layers such as the residual layer may be retrieved *(e.g. Lewis et al., 2013, JGR Atmospheres, 118, doi:10.1002/jgrd.50570,2013).*

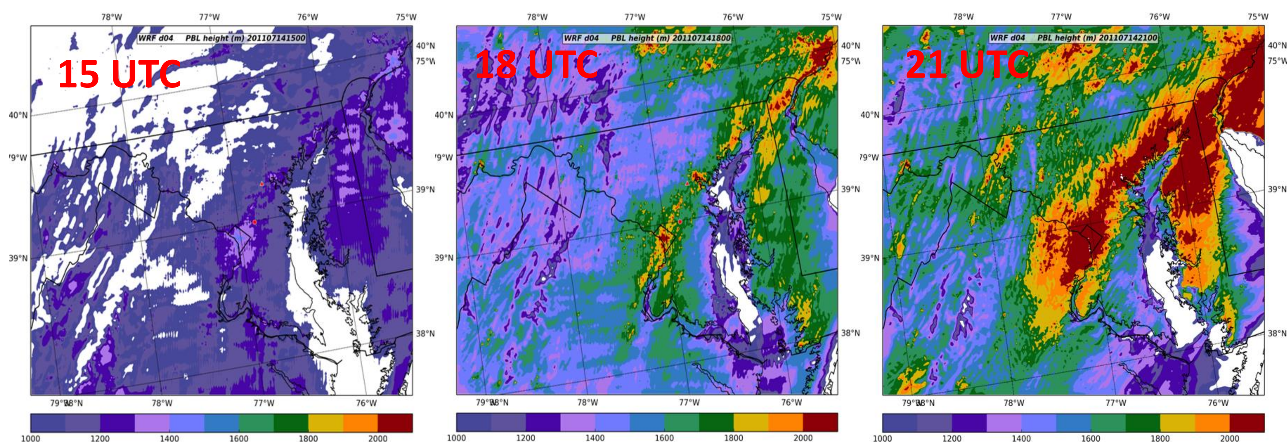




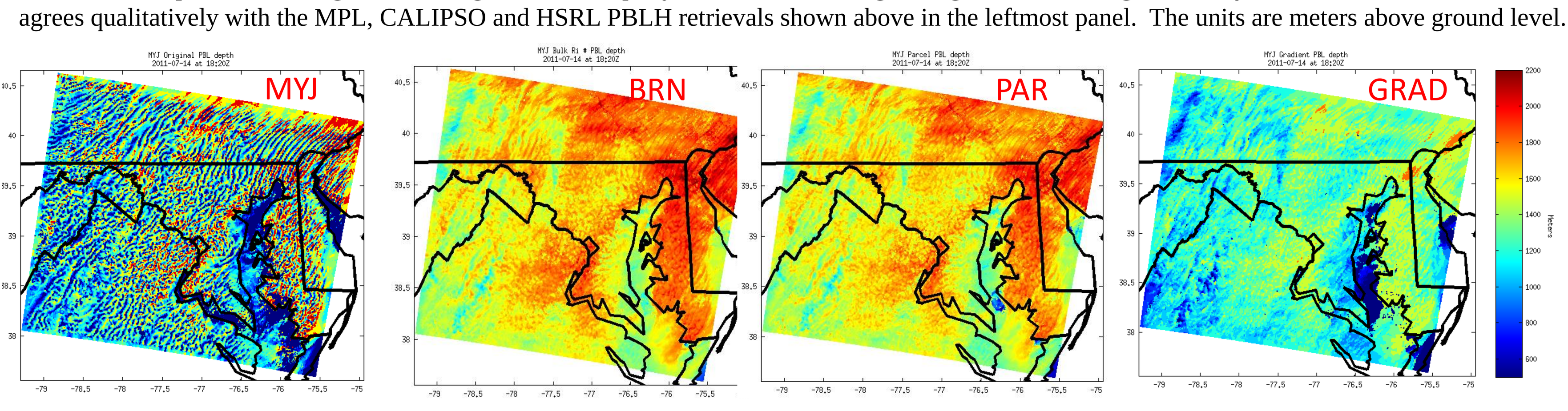
The plot to the left shows the locations of the MPL and MiniMPL deployments. There were 6 units deployed on land and one MiniMPL on the NOAA ship in Chesapeake Bay whose tracks are shown in the plot to the left. The COVE MPLNET site was not operating. Above are time-height curtain plots of aerosol backscatter measured on July 14, 2011 from the MPLs at the Goddard Space Flight Center (GSFC) and University of Maryland Baltimore County (UMBC). The retrieved PLBHs are shown as red lines. Gaps indicate times at which retrievals could not be performed due to insufficient data quality and areas where clouds have been screened.

WRF PBL Development

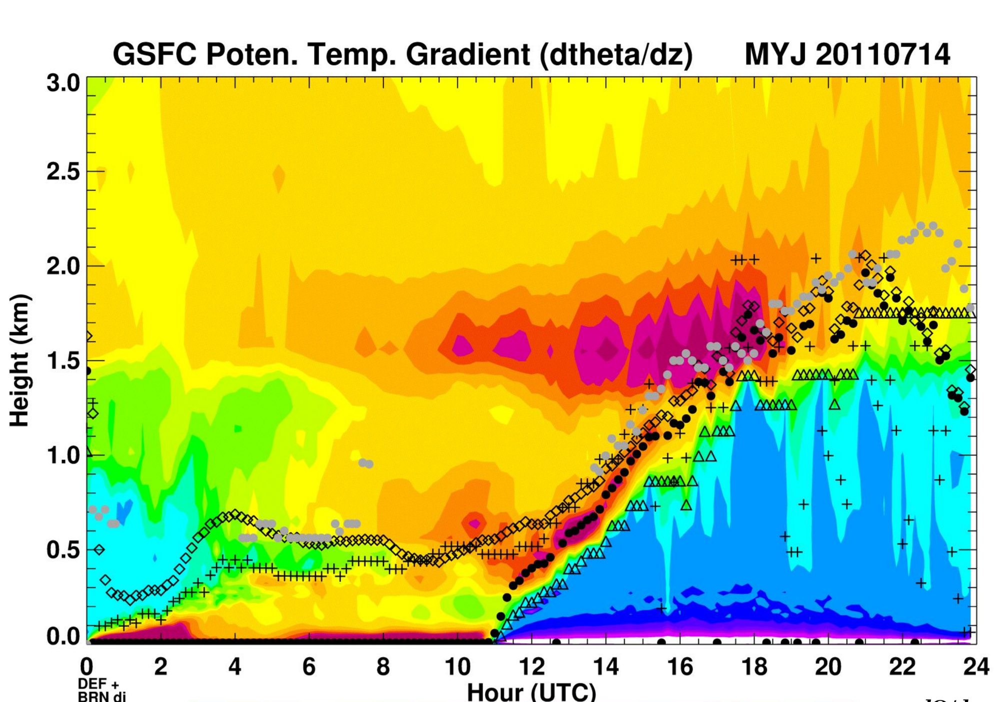




The daytime growth of the PBL is not uniform in regions with large cities. As demonstrated by the WRF simulation using the BouLac PBL scheme, shown above in the 3 panels to the right, the PBL grows more rapidly in the cities leading to large urban - rural gradients by late afternoon. This simulated pattern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



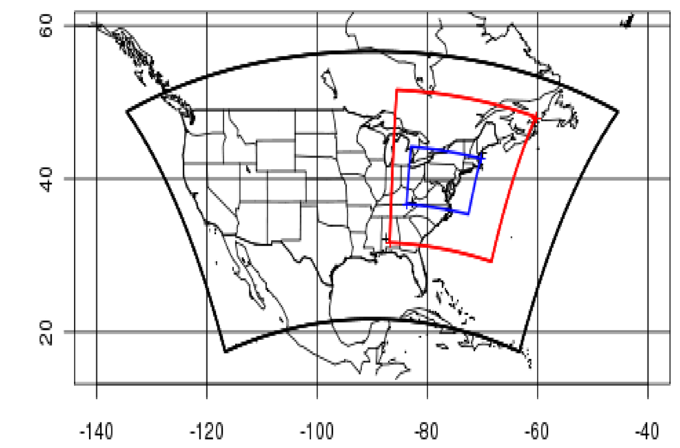
Each PBL scheme used in WRF has a different method for diagnosing the PBLH. The MYJ PBLHs for the afternoon of July 14, 2011 shown in the far left panel above are diagnosed using turbulence kinetic energy (TKE) thresholds which are highly dependent on vertical motion. At the 1 km grid scale of the WRF 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.



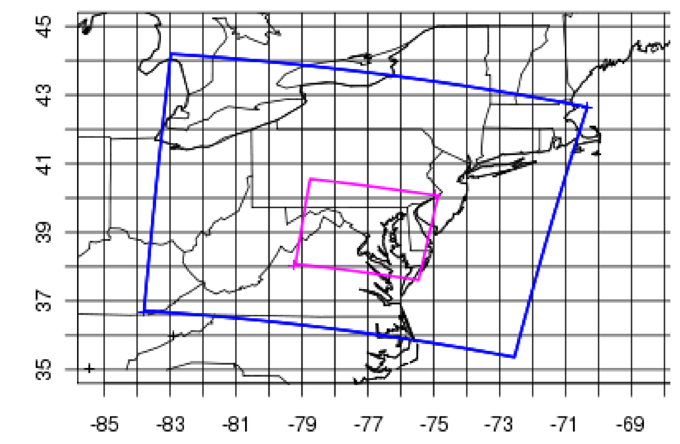
Time-height cross-section of WRF simulated vertical potential temperature gradients ($d\Theta/dz$) at GSFC shows the diurnal evolution of the PBL structure. The PBLHs retrieved from the MPL measurements are shown as grey dots. The WRF PBLHs are shown for the MYJ PBL diagnostic (black plus signs), BRN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

Note the large PBLH fluctuations for the MYJ PBLH diagnostic (black plus signs) due to the TKE fluctuations associated with the resolved turbulent eddies. These are artifacts of the manner in which MYJ computes PBLH from TKE. 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 Modeling



WRF 27, 9, and 3 km domains



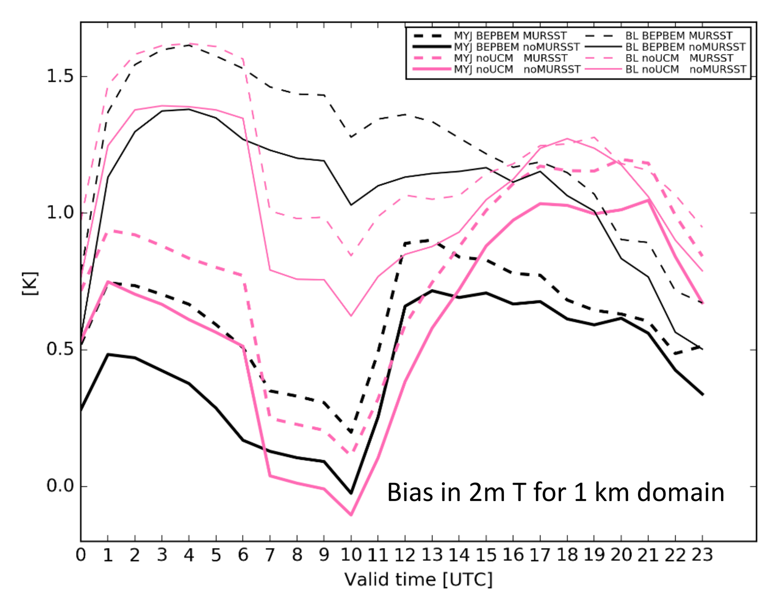
WRF 3 and 1 km domains

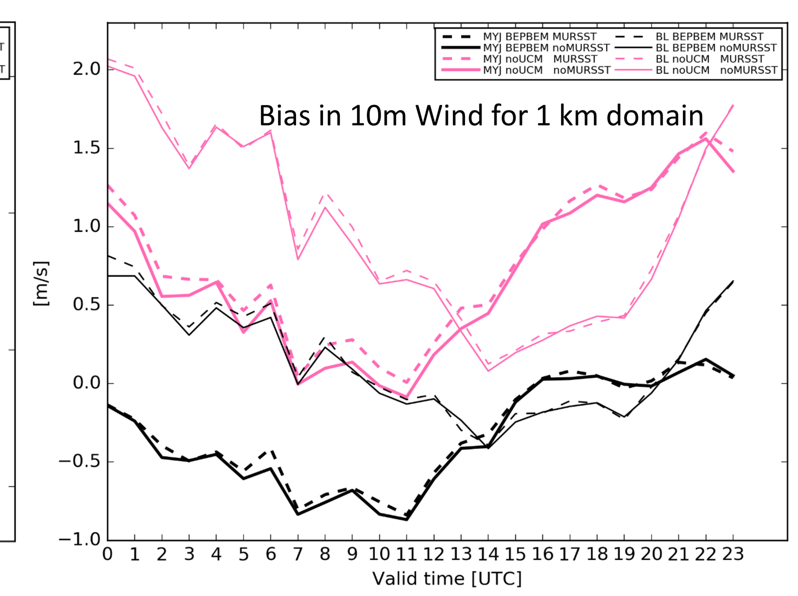
WRF run configurations for the DISCOVER-AQ simulations

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

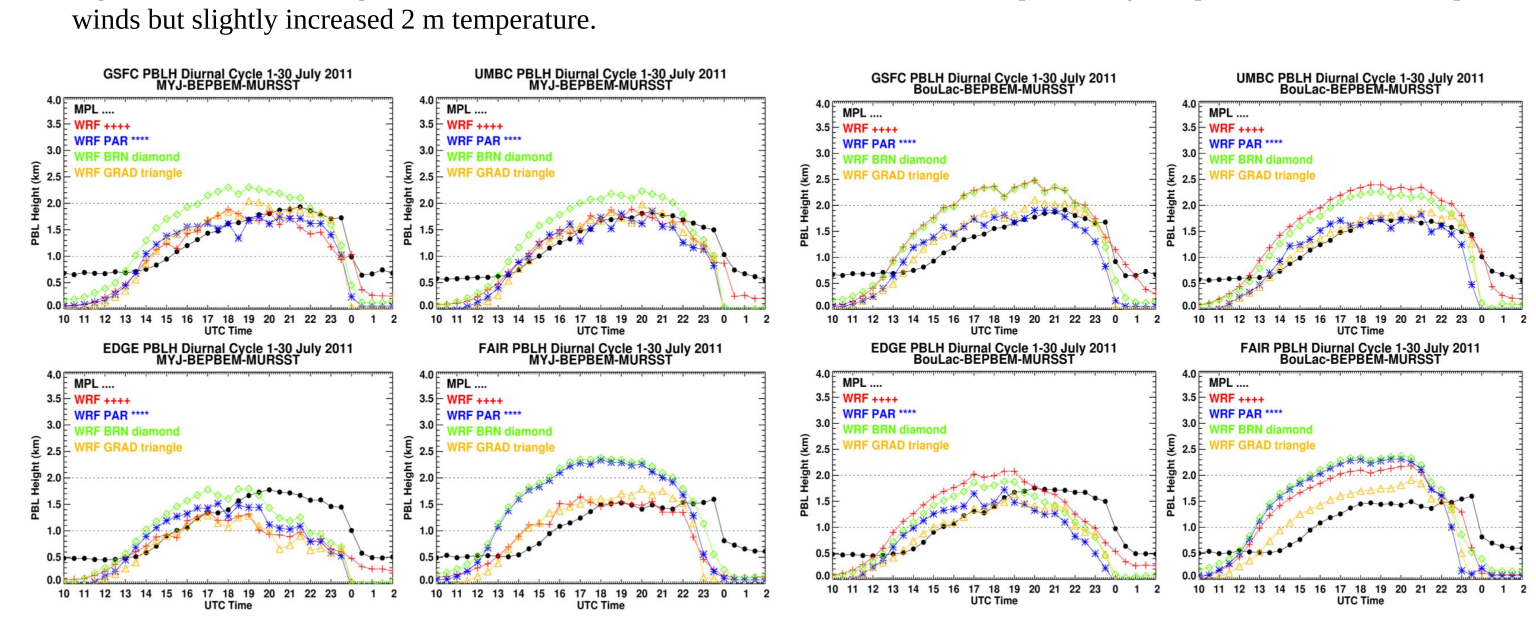
- Advanced Research WRF Version 3.6.1 with 4 nest levels of 27, 9, 3, and 1 km
- 59 vertical levels with 34 below 2 km
- Mellor Yamada Janjić (MYJ) and BouLac PBL schemes
- Noah land surface model
- Building Environment Parameterization (BEP) + Building Energy Model (BEM) Multi-layer urban canopy model (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
- Eight 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 Evaluation



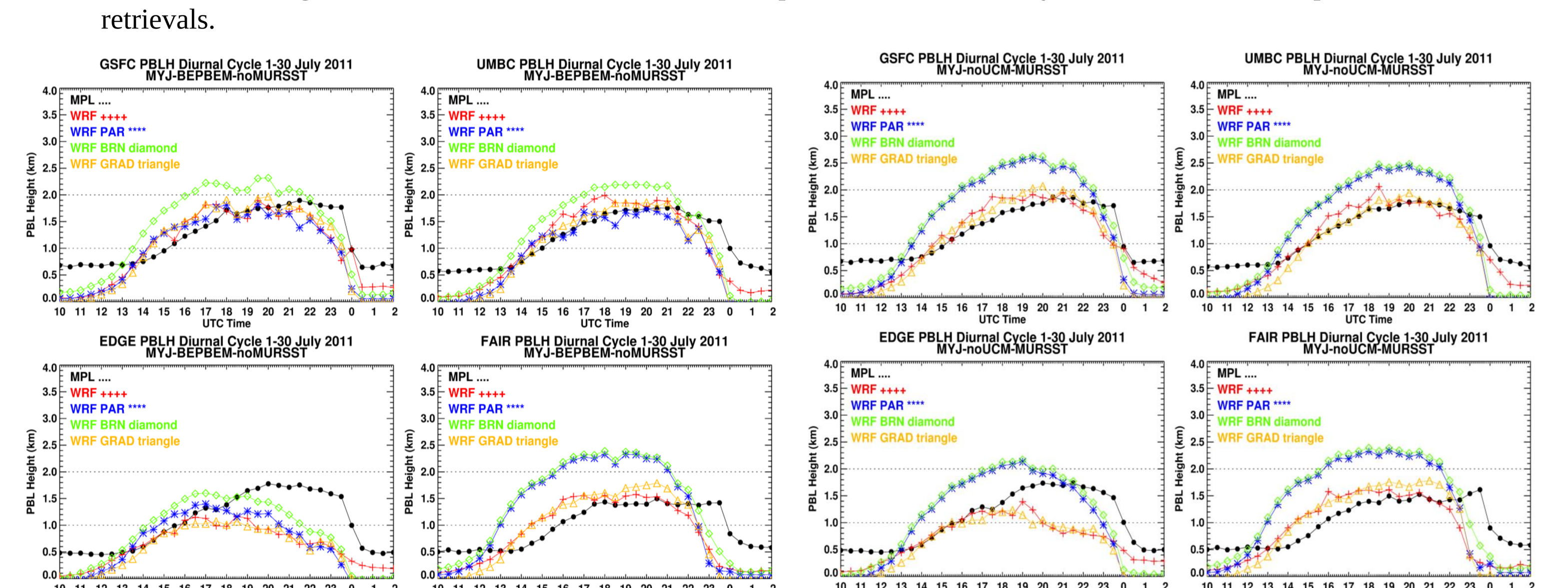


The MYJ configurations produced better overall bias statistics on the inner 1 km domain than the BouLac configurations. The UCM reduced the afternoon 2m Temperature and 10m wind biases, but produced a slightly negative (0.5 m/s) wind bias at night for the MYJ configurations. The MURSST which featured warmer Chesapeake Bay temperatures had little impact on winds but slightly increased 2 m temperature.



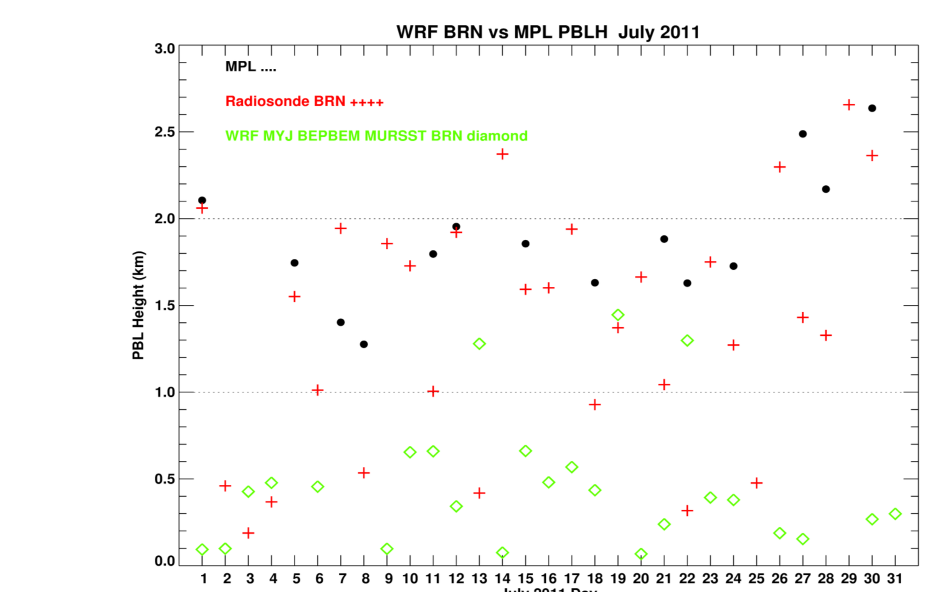
The average WRF and MPL diurnal cycles of PBL growth shown above for the MYJ-BEPBEM-MURSST and BouLac-BEPBEM-MURSST configurations indicate the following:

1. The PBL growth phase of the MYJ-BEPBEM-MURSST simulations is a better match to the MPL retrievals than that of the BouLac-BEPBEM-MURSST simulations that grow PBLHs grow too quickly leading to generally higher afternoon biases. The PBLH biases correspond to the domain-wide surface temperature bias of ~ 1.2 K shown in the bias plots above.
2. Both WRF configurations tend to simulate the PBL collapse ~ 2 hours too early in the afternoon compared to the MPL retrievals.

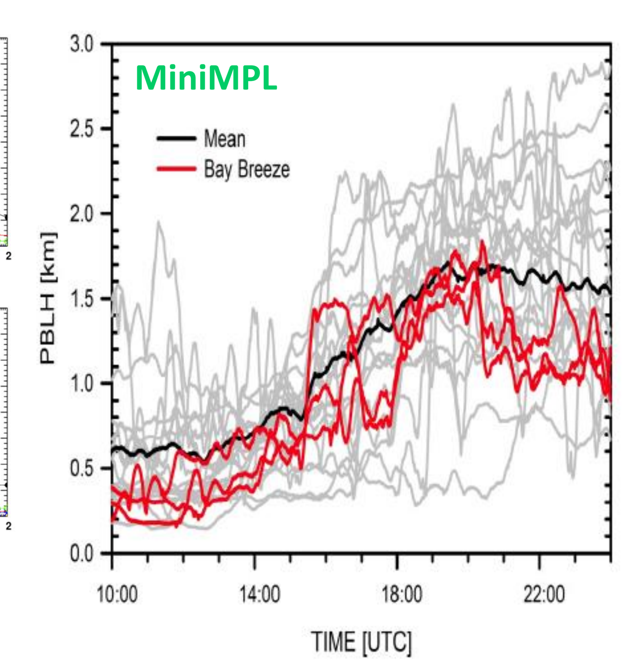


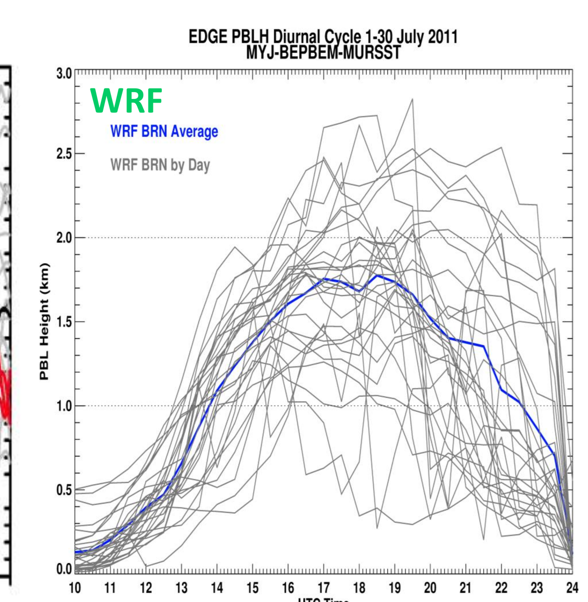
The average diurnal cycle for the MYJ-BEPBEM-noMURSST and MYJ-noUCM-MURSST WRF sensitivity experiments indicate the following:

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



The early PBLH collapse for WRF was further investigated using MPL retrievals and 0000 UTC radiosonde at Sterling, VA (above). There is general agreement between the radiosonde and MPL retrievals at 0000 UTC, which is before sunset in July, but the WRF PBLHs are much lower indicating the collapse was simulated earlier.





In some locations such as Edgewood, MD, near the shoreline of the Chesapeake Bay, early PBLH collapse can be expected due to the onset of the bay breeze. However, a comparison of PBLHs from the MiniMPL retrievals (above left) and the WRF simulations (above right) for each day in July 2011 indicates that the early collapse in WRF was more frequent than observed.

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 2011 - 2014 to investigate inter-seasonal and inter-annual variability of the PBLH.

Acknowledgements

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