Beyond the "Big Leaf" Model at NOAA

Explicit Effects of Forest Canopy Shading and Turbulence on Boundary Layer Ozone in UFS-SRW Air Quality Model

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Executive Summary

- New vegetative canopy data applied in UFS-AQM framework produces a physically realistic canopy effect: reduces ozone (via photochemistry), modifies the meteorology (via turbulent eddy diffusivities) and improves UFS-AQM model performance (lower mean biases).
- The gas-phase photochemistry is split on three sub-canopy layers (Makar et al., 2017) leading to a daytime canopy shading effect. The sub-canopy diffusivity effects is currently approximated and leads to reduced vertical mixing.
- Ongoing work is to split the diffusion processes (affecting mass) on sub-canopy layers. We anticipate even larger effect on boundary layer ozone and meteorology in the final version.
  → *Evaluations and future implementation for the UFS-AQMv8 are continuing.*

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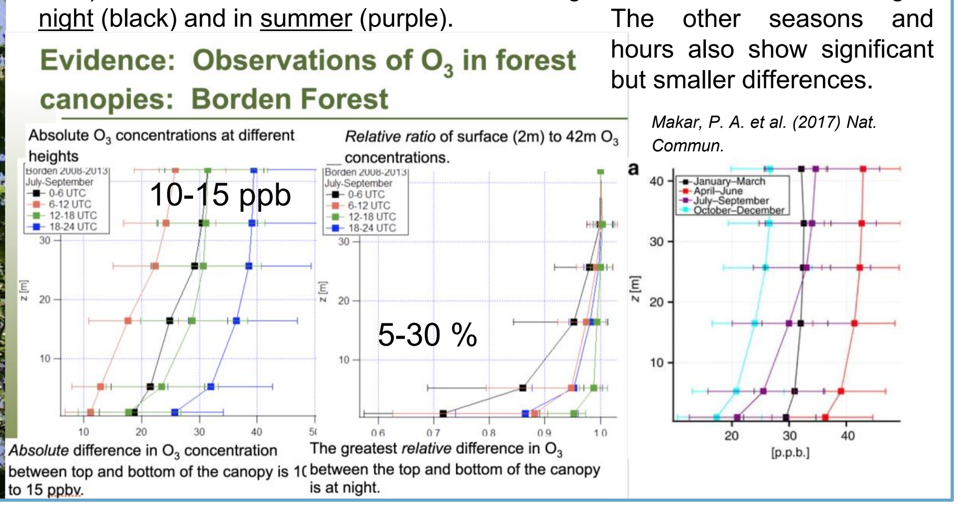
- NOAA's Weather Program Office FY2022 In-Canopy Processes Research Project

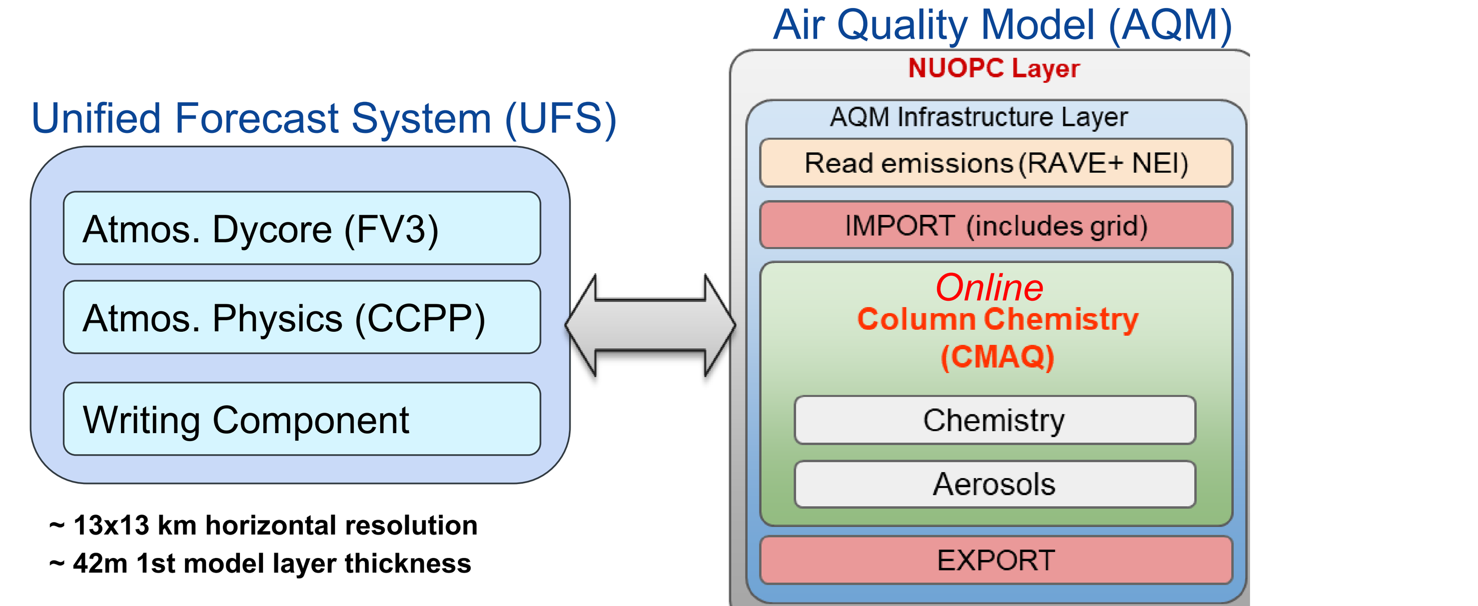
Borden Forest Research Station, ON, Canada

Evidence of the effect of canopy on near-surface ozone comes from observations in the forest research community, such as the Borden Forest Research Station (44° 19′ N, 79° 56′ W) located at the north end of Canadian Forces Base (CFB) Borden in one of the largest continuous swaths of forest in Southern Ontario. Shown are average O3 profiles during 5-year period from above the canopy (42m) to surface (1.5m), segregated by season (right pannel) and hour of day (left and middle pannel). These obs indicate 10-15 ppb (5%-30%) reduction in O3 concentrations, with the greatest differences occurring at night (black) and in summer (purple). The other seasons and hours also show significant but smaller differences.



Makar, P. A. et al. (2017) Nat. Commun.

Online CMAQ Within the UFS-AQM Framework



~ 13x13 km horizontal resolution
~ 42m 1st model layer thickness

https://github.com/ufs-community

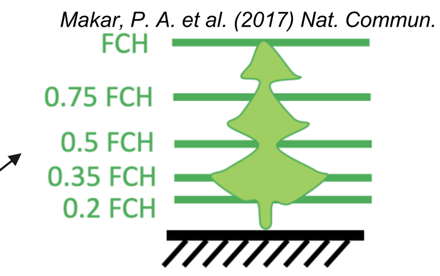
Huang et al., *BAMS*, (2025)

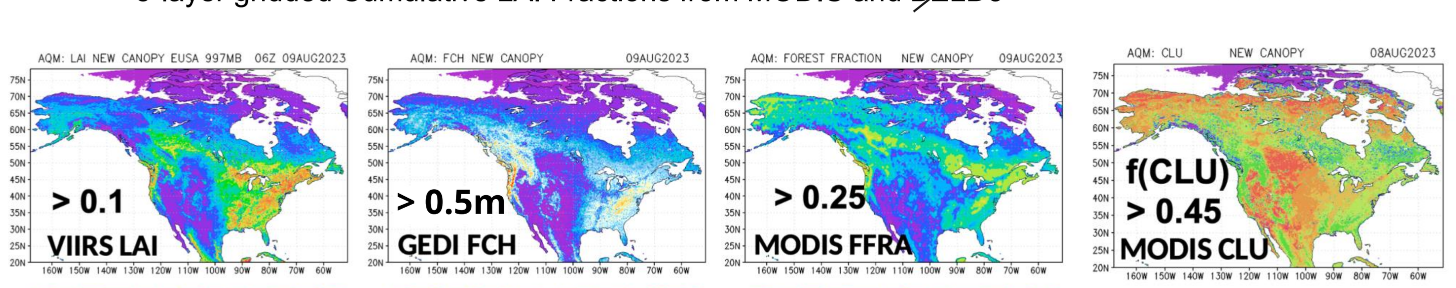
Current operational National Air Quality Forecast Capability (NAQFC) *https://airquality.weather.gov/*

Vegetative Canopy Data in UFS-AQM Framework

- The land models in the current UFS applications have simple LAI and FCH
  - canopy effect on radiative fluxes (T) near the surface not included
  - canopy effect on biogenic emissions not included
- We introduce new gridded (1-km) vegetative canopy data (*Hung, W.-T. et al., 2024*):
  - Leaf area index (LAI) from VIIRS (monthly)
  - Canopy clumping index (CLU) from MODIS (monthly)
  - Forest fraction (FFRAC) from MODIS
  - Forest canopy height (FCH) from GEDI
- 5-layer gridded Cumulative LAI Fractions from MODIS and BELD3

Makar, P. A. et al. (2017) Nat. Commun.





https://repository.library.noaa.gov/view/noaa/65705 https://doi.org/10.25921/qzm2-zg29

Vegetative Canopy Approach in UFS-AQM Framework

Approach: Vegetative canopy modulates photolysis and vertical diffusion. We split the chemistry on 3 sub-canopy layers with variable height located at 1, 0.5 and 0.2 canopy height (Makar et al. 2017), while ensuring mass conservation before returning to the original model layers (for advection, deposition, other physical processes)

Photolysis:

$$P(\theta, z) = e^{-\frac{G(\theta)\,\Omega(\theta)\mathrm{LAI}(z)}{\cos(\theta)}}$$

Probability of beam penetration (i.e., fractional light penetration; Nilson, 1971; Monsi and Saeki, 1953) depends on LAI, leaf projection (G), clumping index (Ω), and solar zenith angle (θ).

Diffusion:

Modified turbulent diffusivity is scaled to 1st model layer and depends on variance in Eulerian vertical velocity (σ_w^2) and turbulent length scale (T_L)

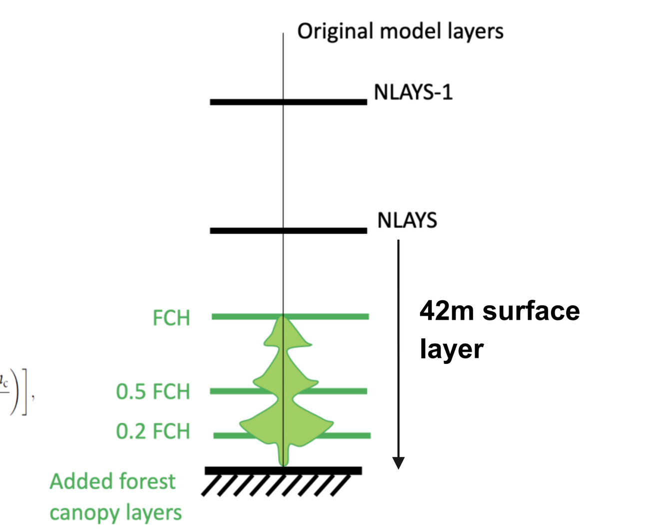
$$K_{can}(z) = \frac{K_{mod}(z_1)}{K_{est}\left(\frac{z_1}{h_c}\right)} K_{est}\left(\frac{z}{h_c}\right),$$

$$K_{est}\left(\frac{z}{h_c}\right) = \sigma_w^2\left(\frac{z}{h_c}\right) T_L\left(\frac{z}{h_c}\right),$$

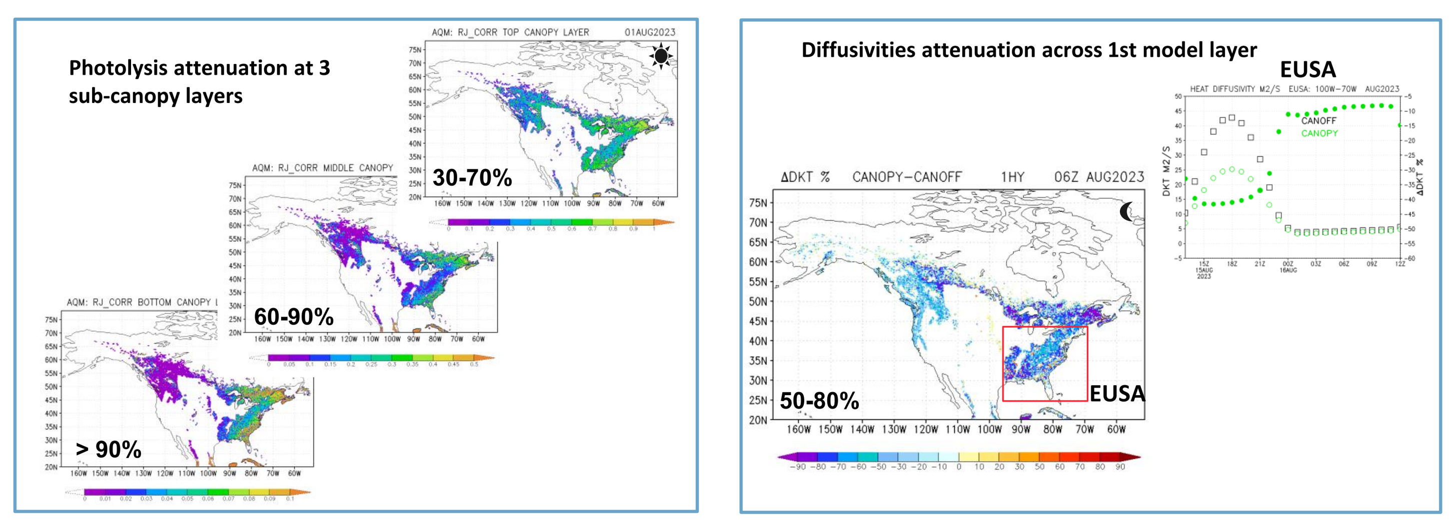
$$T_L\left(\frac{z}{h_c}\right) = \frac{h_c}{u^*}\left[0.256\left(\frac{z-0.75h_c}{h_c}\right) + 0.492\exp\left(\frac{-0.256z/h_c}{0.492}\right)\right],$$

*Note: Diffusion is not using 3 sub-canopy layers, but rather is currently using an approximate integrated approach:

$$K_{can}(z) = \frac{\int_{z_{j-\frac{1}{2}}}^{z_{j+\frac{1}{2}}} \frac{K_{mod}(z_1)}{K_{est}\left(\frac{z_1}{FCH}\right)} K_{est}\left(\frac{z}{FCH}\right) dz}{z_{j+\frac{1}{2}} - z_{j-\frac{1}{2}}}$$



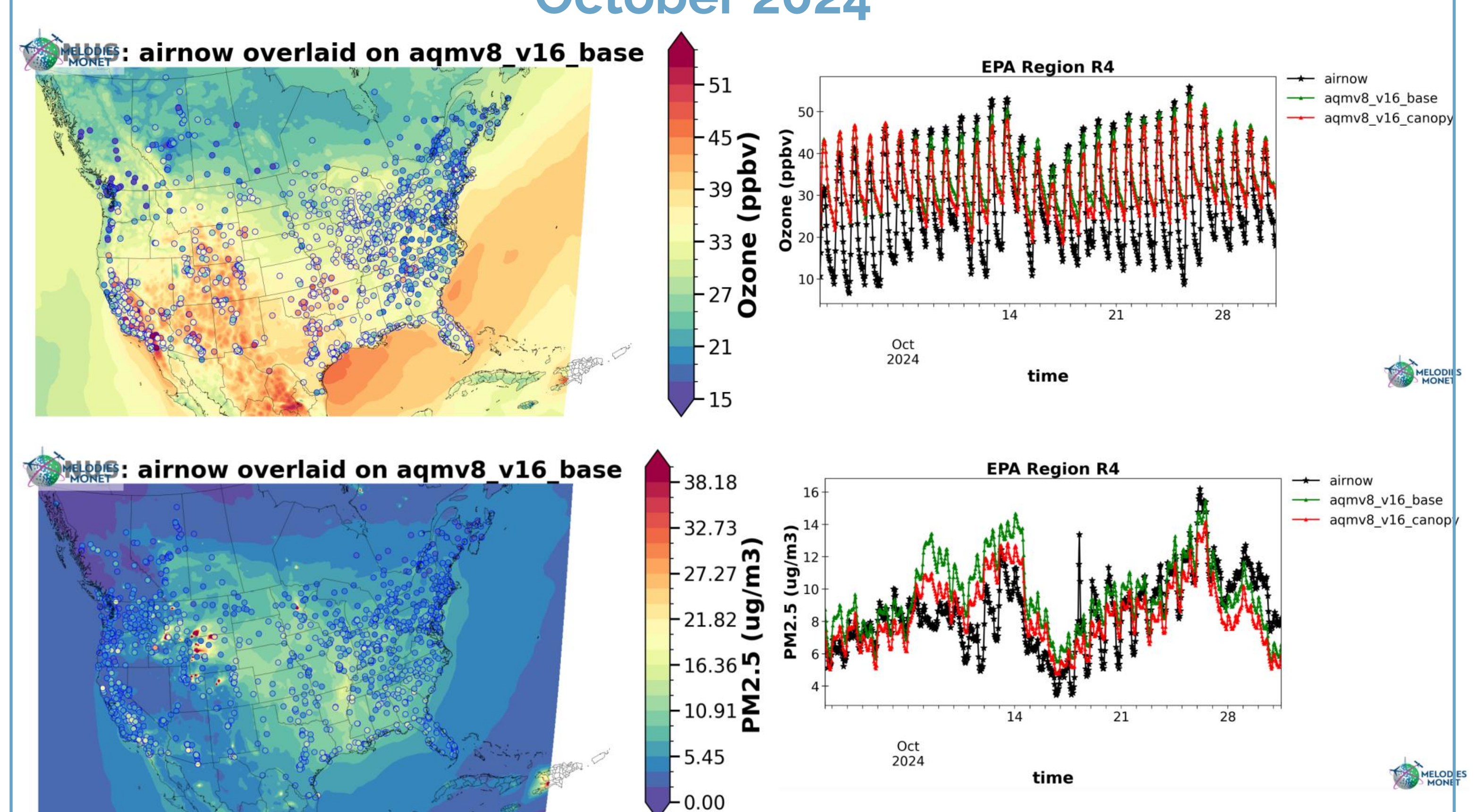
Attenuation to Photolysis & Turbulent Eddy Diffusivities



We apply attenuation weights to the photolysis in each of the 3 successive canopy layers (left). The photolysis attenuation inside the canopy, which is based on the 5 cumulative LAI fractions, is much larger than when we integrate the attenuation over the 1st model layer (42m) (not shown), which will dilute the photolysis attenuation relative to below the canopy since the model layer is only partially covered by the canopy close to the surface.

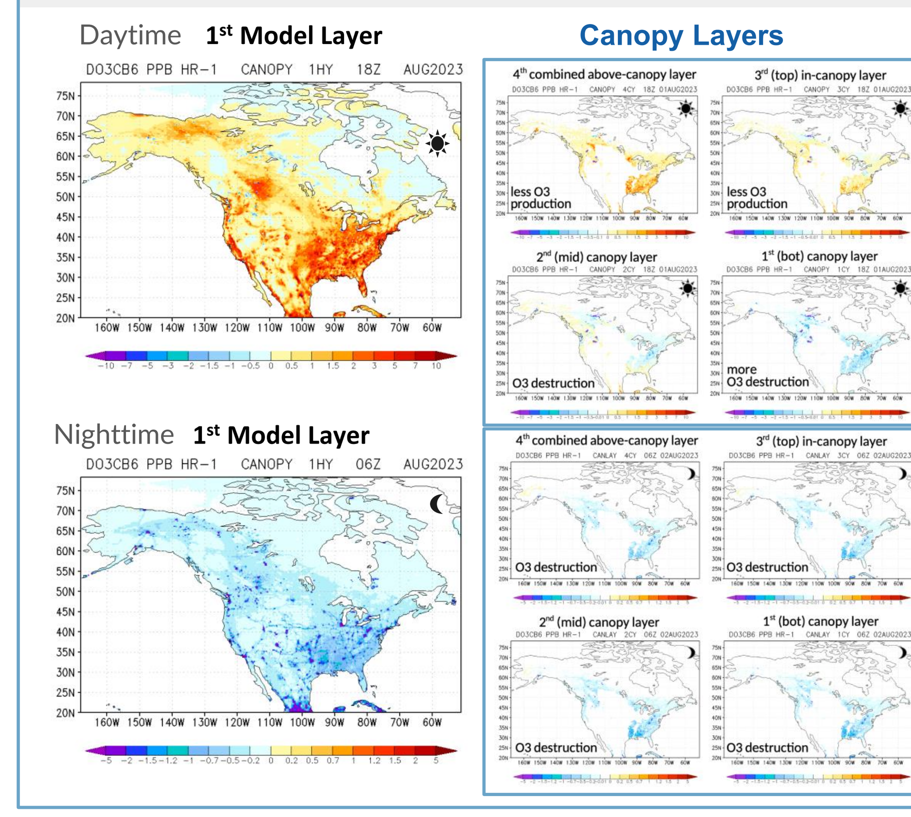
In the results here, the correction to the turbulent eddy diffusivities is calculated as an integral over the 1st model layer (42 m) (right), hence the canopy effect on the PBL is underestimated. We expect a lot larger diffusivities effect when using the multi-layer sub-canopy approach (under testing).

UFS-AQM Predictions of O3 and PM2.5 Concentrations October 2024



Monthly mean spatial distribution of Ozone in ppbv and PM2.5 in μg m^{-3} in October 2024 overlaid with the observed concentrations at collocated AirNow sites. Shown is an experiment without the canopy parameterization on. The typical biases in UFS-AQM can be seen, particularly O_3 overestimation over EUSA, and $PM_{2.5}$ overestimation predominantly outside of regions with forest fires.
Time series of O3 and PM2.5 from the experiments base (green lines) and canopy (red lines) at colocated AirNow sites (black lines) averaged over EPA region R4. The canopy effect is seen by reductions of O3 and PM25 both daytime and nighttime.

Canopy Impact on Ozone Chemistry



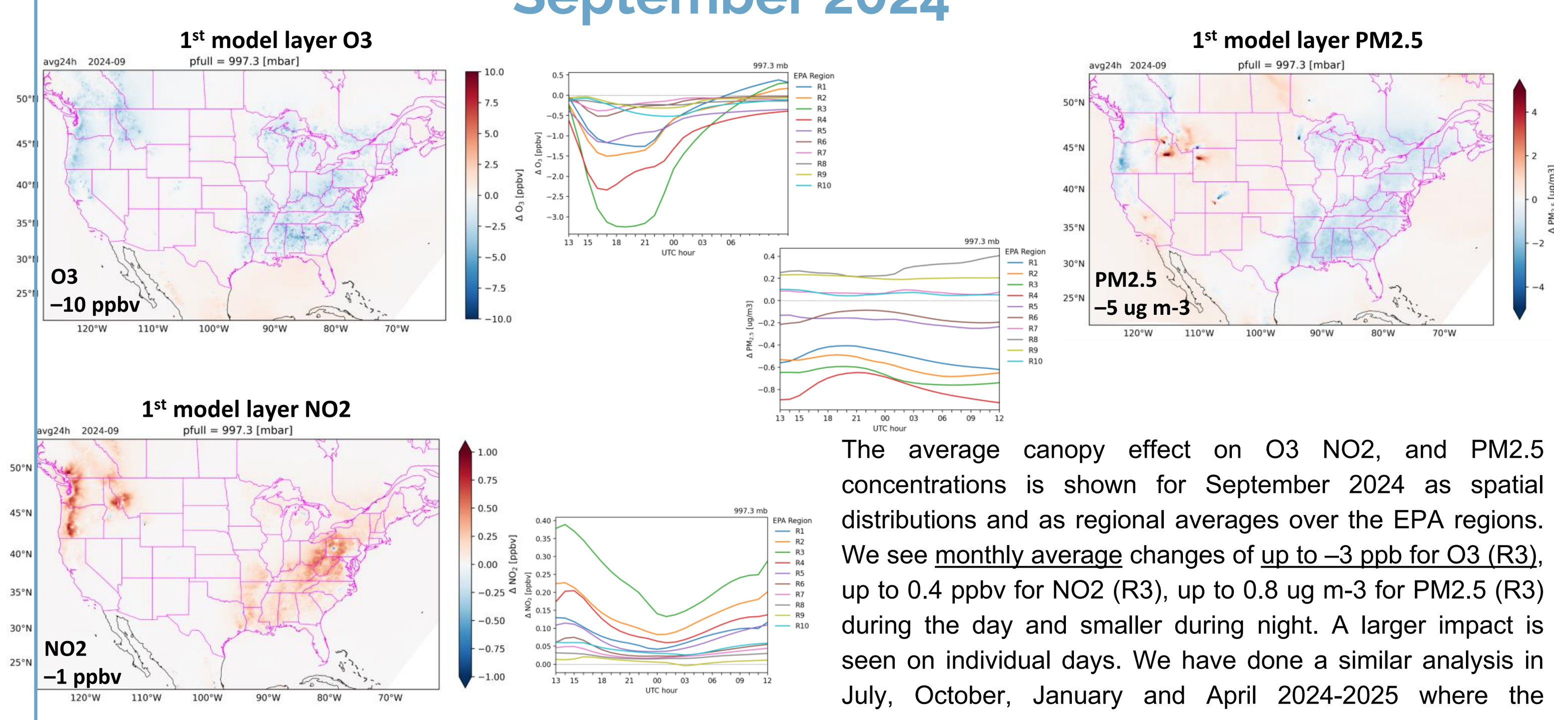
Summer, e.g., August 2023

Daytime shift of photochemical regime away from ozone production and/or towards enhanced ozone destruction in the surface layer.

Less vertical mixing in the canopy traps chemicals (NOX) favouring less O3 production or even destruction in darkest bottom most areas of canopy.

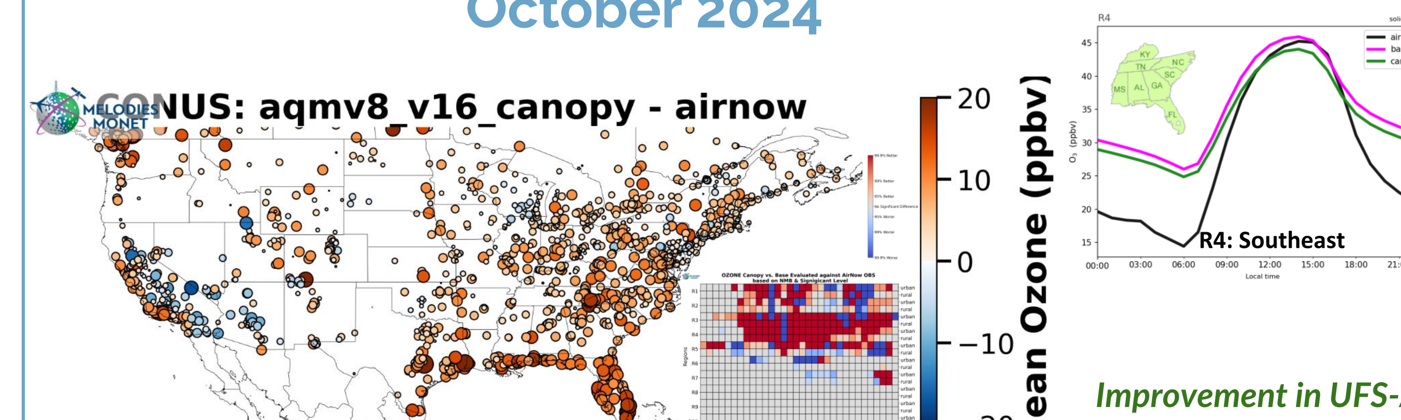
Nighttime chemistry is controlled by atmospheric stability, with an increase in stability near the surface at night may allow the build-up of chemicals favouring ozone destruction (via, for example, 'titration' reactions with NOX). **C**anopy reduces the vertical mixing even further during already stable nighttime, and allows less transport of higher ozone downward from the 2nd to the 1st model layer.

Canopy Impact on O3, NO2, PM25 Concentrations September 2024



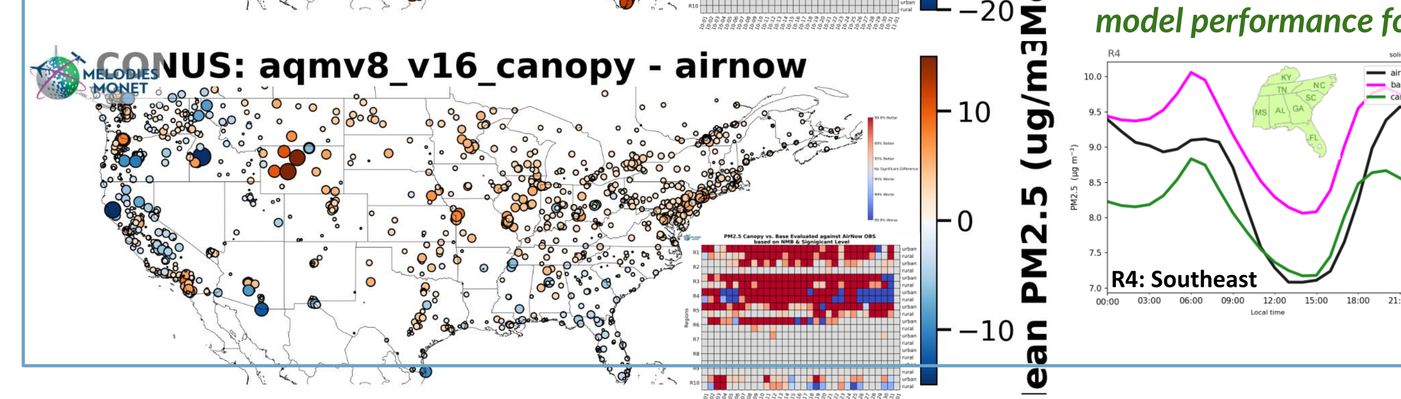
The average canopy effect on O3 NO2, and PM2.5 concentrations is shown for September 2024 as spatial distributions and as regional averages over the EPA regions. We see monthly average changes of up to –3 ppb for O3 (R3), up to 0.4 ppbv for NO2 (R3), up to 0.8 ug m-3 for PM2.5 (R3) during the day and smaller during night. A larger impact is seen on individual days. We have done a similar analysis in July, October, January and April 2024-2025 where the magnitude of the effect varies.

Ozone Evaluation at Colocated AirNow Sites October 2024



O_3	Base	Canopy
MB	6.63	4.91
NMB	23.40%	17.34%
NME	34.90%	35.38%
IOA	0.738	0.735

Improvement in UFS-AQM O3 & PM2.5 model performance for all scores.



PM_{25}	Base	Canopy
MB	1.038	-0.138
NMB	12.14%	-1.61%
NME	42.68%	39.32%
IOA	0.605	0.59

References:

Huang, J.P., I. Stajner, R. Montuoro, F. Yang, K. Wang, H.-C. Huang, C.-H. Jeon, B. Curtis, J. McQueen, H. Liu, B. Baker, D. Tong , Y. Tang, P. Campbell, G. Grell, G. Frost, R. Schwantes, S. Wang, S. Kondragunta, F. Li, and Y. Jung (2024): *Development of the next-generation air quality prediction system in the UFS framework: Enhancing predictability of wildfire air quality impacts,* Bull. Amer. Meteor. Soc. In review.

Hung, W.-T., P. C. Campbell, Z. Moon, R. Saylor, J. Kochendorfer, T.R. Lee, and W. Massman (2024): *Evaluation of an In-Canopy Wind and Wind Adjustment Factor Model for Wildfire Spread Applications Across Scales*. J. of Advances in Modeling Earth Systems. In publication.

Li, W., B.-M. Tang, P. C. Campbell, Y. Tang, B. Baker, Z. Moon, D. Tong, J.P. Huang, K. Wang, I. Stajner, R Montuoro, R. C. Gilliam (2024): *Updates and evaluation of NOAA's online-coupled air quality model version 7 (AQMv7) within the Unified Forecast System*. Geoscientific Model Dev., https://doi.org/10.5194/gmd-2024-107

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