

Quantifying Forest Canopy Shading and Turbulence Effects on Boundary Layer Ozone over the United States

Chi-Tsan Wang¹, Patrick C. Campbell^{1,2,3,*}, Paul Makar⁴, Siqu Ma¹, Irena Ivanova^{1,2,3}, Bok H. Baek¹, Wei-Ting Hung^{1,2,3}, Zachary Moon⁵, Youhua Tang^{1,2,3}, Barry Baker³, Rick Saylor³, and Daniel Tong¹

¹ Center for Satellite and Earth Science Research (CSER), George Mason University, Fairfax, VA, U.S.

² Cooperative Institute for Satellite Earth System Studies (CISESS)

³NOAA Air Resources Laboratory

⁴ Environment and Climate Change Canada (ECCC), Toronto, ON, Canada.

⁵ Earth Resources Technology, Inc., Laurel, MD, USA

*Corresponding authors: Patrick C. Campbell (Email: patrick.c.campbell@noaa.gov; Telephone:307-760-5178)

Supplementary material:

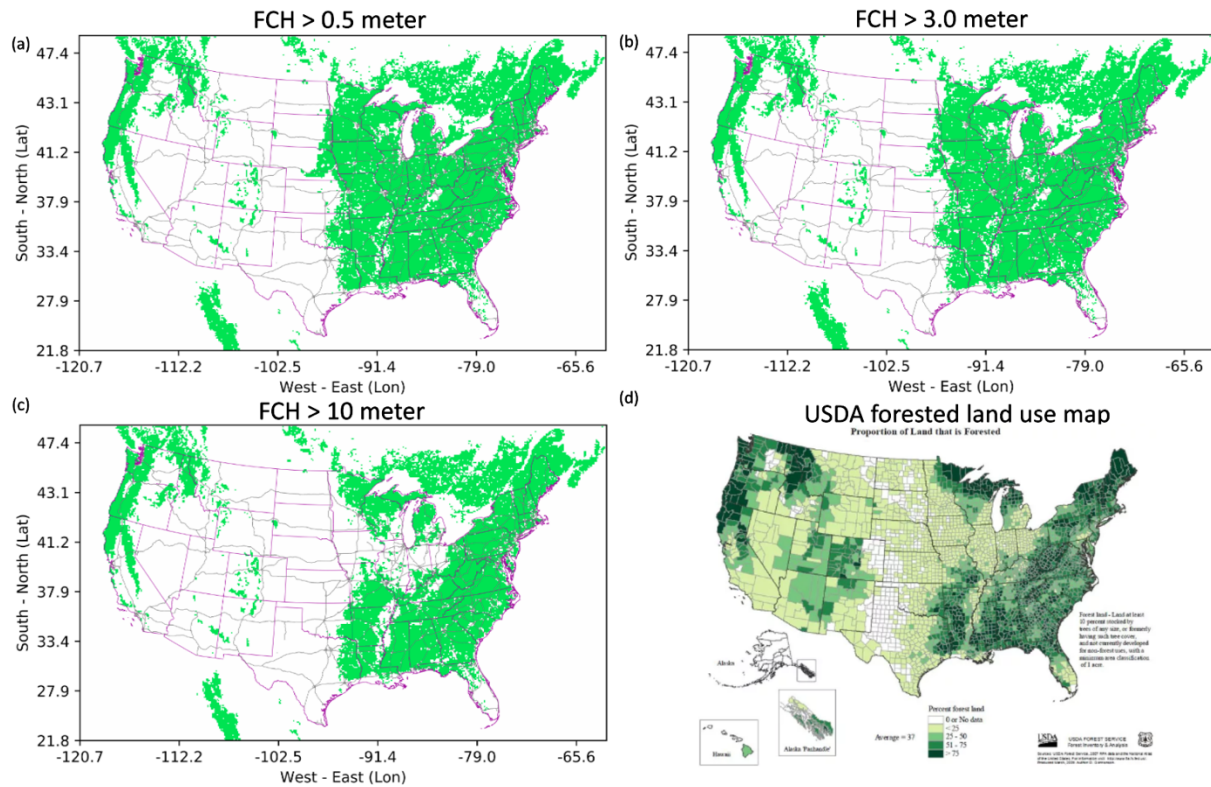


Fig S1. Contiguous canopy threshold regions (green shading) based on Section 2.1 and Figure 1 using different test conditions for FCH > a) 0.5 m, b) 3.0 m, and c) 10.0 m, and d) compared to a USDA forested land use map (<https://research.fs.usda.gov/>). We note that the contiguous canopy threshold regions in green shading best agree with the USDA map when using c) FCH > 10.0.

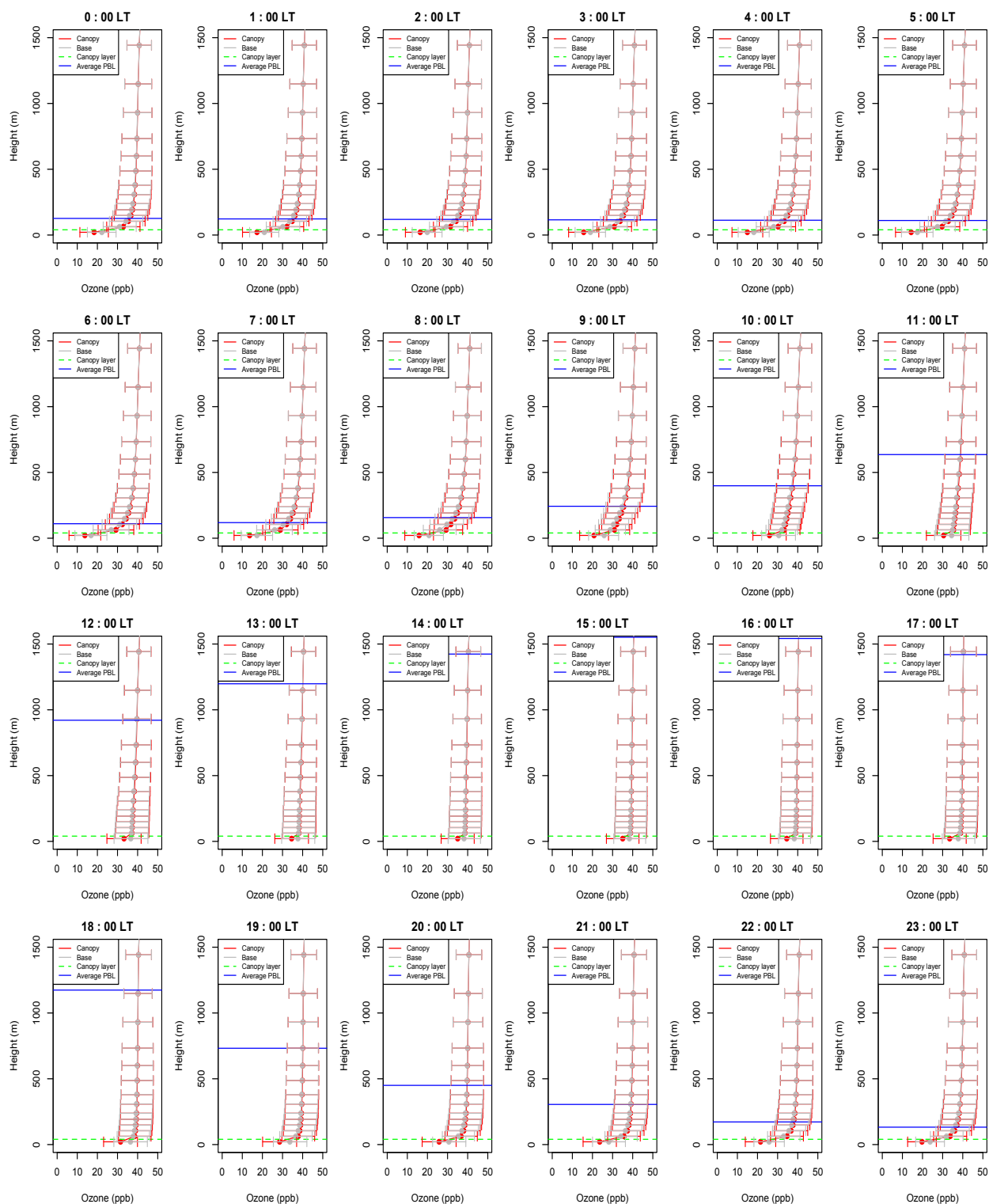


Fig. S2 The diurnal hourly vertical O_3 profiles of Base (gray) and Canopy (red). The dots in each layer are average O_3 concentration in regions of canopy effects in Fig. 2 and the range bars are the standard deviation range. The blue Line is the hourly average PBL height, and below the green dash line is the canopy effect layer.

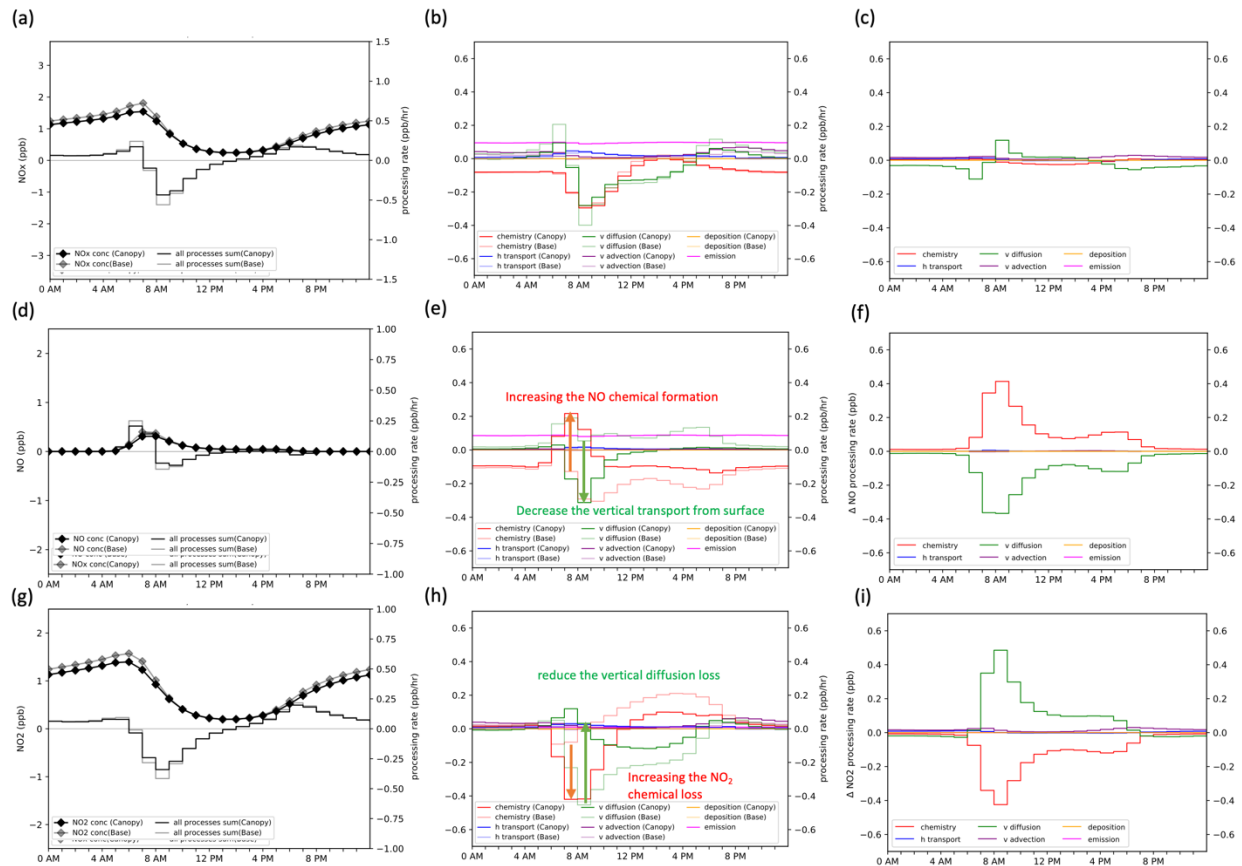


Fig. S3 Hourly average second layer (40 - 80 m AGL) process analysis result for (a) NO_x concentration and net process; (b) NO_x explicit processing rates; (c) delta (Canopy- Base) NO_x processing rate (d) is NO concentration and net process; (e) is NO explicit processing rates; (f) delta (Canopy- Base) NO processing rate (g) is NO₂ concentration and net process; (h) is NO₂ explicit processing rate and (i) delta (Canopy- Base) NO₂ processing rates at Canopy effect locations in August 2019 for two scenarios.

Table S1 Ozone average daily daytime and nighttime process analysis summary tables.

Daytime	O ₃ process (ppb)	Base	Canopy	Difference	
First Model layer	O ₃ vertical transport	168	170	2	1.2%
	O ₃ horizontal transport	0.14	0.03	-0.11	-78.6%
	O ₃ deposition (-)	-164	-150	14	-8.5%
	Net chemical Ozone process	14	-6	-20	-142.9%
	O ₃ chemical production	629	157	-472	-75.0%
Second layer	O ₃ chemical reduction	615	163	-452	-73.5%
	O ₃ vertical transport	-3.89	-7.82	-3.93	101.0%
	O ₃ horizontal transport	0.46	0.4	-0.06	-13.0%
	O ₃ deposition	0	0	0	0%
	Net chemical Ozone process	14.1	16.8	2.7	19.1%
	O ₃ chemical production	632.8	634.1	1.3	0.2%
	O ₃ chemical reduction	618.7	617.3	-1.4	-0.2%

Nighttime	O ₃ process (ppb)	Base	Canopy	Difference	
First Model layer	O ₃ vertical transport	45	38	-7	-15.6%
	O ₃ horizontal transport	3.53	9.58	6.05	171.4%
	O ₃ deposition	-60	-53	7	-11.7%
	Net chemical Ozone process	-7.1	-8	-0.9	12.7%
	O ₃ chemical production	44	10	-34	-77.3%
Second layer	O ₃ chemical reduction	51	18	-33	-64.7%
	O ₃ vertical transport	-13.11	-11.38	1.73	-13.2%
	O ₃ horizontal transport	3.95	3.03	-0.92	-23.3%
	O ₃ deposition	0	0	0	0%
	Net chemical Ozone process	-2.35	-2.23	0.12	-5.1%
	O ₃ chemical production	44.9	45.1	0.2	0.4%
	O ₃ chemical reduction	47.25	47.33	0.08	0.2%

Table S2 The average daily total VOC + O₃ reactivity and major individual VOC contribution on surface and second layer at canopy effect regions (see Figure 2).

	Reactions	Base (ppb d ⁻¹)	Canopy (ppb d ⁻¹)	Diff (ppb d ⁻¹)	Diff (%)
First Model layer	R143 & R147: O ₃ + Alkenes	2	2.51	0.51	25.50%
	R156: O ₃ +ISOP	0.56	1.23	0.67	119.64%
	R173: O ₃ +TERP	1.18	1.48	0.3	25.42%
	Total VOC + O ₃	4.05	5.53	1.48	36.54%
Second Model layer	R143 & R147: O ₃ + Alkenes	1.02	0.96	-0.06	-5.88%
	R156: O ₃ +ISOP	0.45	0.56	0.11	24.44%
	R173: O ₃ +TERP	0.55	0.52	-0.03	-5.45%
	Total VOC + O ₃	2.35	2.4	0.05	2.13%

Model performance metric formula definitions:

Common Variables:

M = predicted concentration

O = observed concentration

X = predicted or observed concentration

σ = standard deviation

I. Mean Bias, Mean Error, and Root Mean Square Error (ppb)

$$\text{Mean Bias} = \frac{1}{n} \sum_1^n (M - O)$$

$$\text{Mean Error} = \frac{1}{n} \sum_1^n |M - O|$$

$$\text{Root Mean Square Error} = \sqrt{\frac{\sum_1^n (M - O)^2}{n}}$$

II. Normalized Mean Bias and Error (unitless)

$$\text{Normalized Mean Bias} = \frac{\sum_1^n (M - O)}{\sum_1^n (O)}$$

$$\text{Normalized Mean Error} = \frac{\sum_1^n |M - O|}{\sum_1^n (O)}$$

III. Fractional Bias and Error (unitless)

$$\text{Fractional Bias} = \frac{1}{n} \left(\frac{\sum_1^n (M - O)}{\sum_1^n \left(\frac{(M + O)}{2} \right)} \right)$$

$$\text{Fractional Error} = \frac{1}{n} \left(\frac{\sum_1^n |M - O|}{\sum_1^n \left(\frac{(M + O)}{2} \right)} \right)$$

IV. Correlation Coefficient (unitless)

$$\text{Correlation} = \frac{1}{(n-1)} \sum_1^n \left(\left(\frac{O - \bar{O}}{\sigma_o} \right) * \left(\frac{M - \bar{M}}{\sigma_m} \right) \right)$$

V. Standard Deviation (ppb)

$$\text{Standard Deviation } (\sigma) = \sqrt{\frac{1}{n} \sum_1^n (X - \bar{X})^2}$$