

Supporting Information for

Observations of new particle formation, modal growth rates, and direct emissions of sub-10 nm particles in an urban environment

Alyssa Zimmerman¹, Markus D. Petters^{1*}, Nicholas Meskhidze^{1*}

¹Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University,
Raleigh, NC, USA

*Correspondence to: mdpetter@ncsu.edu and nmeskhi@ncsu.edu

Table of Contents

Table S1. Class A NPF event statistics. Estimated start and detection times are rounded to the nearest 15 min. interval	S5
Table S2. Class B NPF event statistics. Detection times are rounded to the nearest 15 min. interval.....	S6
Table S3. PB event statistics. Event times are rounded to the nearest half hour	S7
Figure S1. Map of the Raleigh metro area. Interstates 440 and 540 are the inner and outer loops of the beltway. Jordan Hall, where scanning mobility particle sizer measurements were performed is located 4.8 km west of downtown Raleigh. The Raleigh-Durham International Airport is 17 km NW of Jordan Hall	S8
Figure S2. Map of North Carolina State University Campus. The scanning mobility particle sizer measurements were performed in Jordan Hall. The Cates Ave. Steam Plant, Yarbrough Drive Steam Plant, and Centennial Campus Utility Plant are 0.3 km NNE, 0.9 km NE, and 0.7 km SSE of Jordan Hall.....	S9
Figure S3. Normalized spectral number density from the SMPS during the spring 2019 deployment	S10
Figure S4. Normalized spectral number density from the SMPS during the winter 2019 and spring 2020 measurement campaign	S11
Figure S5. Normalized spectral number density from the SMPS with growth rate overlay (top) and number concentration (bottom) for a Class A NPF event on November 24, 2019. The 5–10 nm number concentration is shown in blue and < 55 nm shown in red. Vertical gridlines are spaced every 2 hr.	S12
Figure S6. Normalized spectral number density from the SMPS with growth rate overlay (top) and number concentration (bottom) for a Class B NPF event on March 30, 2020. The 10–20 nm number concentration is shown in blue and < 55 nm shown in red. Vertical gridlines are spaced every 2 hr.	S13
Figure S7. Normalized spectral number density from the SMPS with growth rate overlay (top) and number concentration (bottom) for a Class C NPF event on January 19, 2020. The 5–10 nm number concentration is shown in blue and < 55 nm shown in red. Vertical gridlines are spaced every 2 hr	S14
Figure S8. The 2.5–11 nm number concentration measured during mobile deployment 1 on March 4, 2020.....	S15

Figure S9. The 2.5–11 nm number concentration measured during mobile deployment 2 on March 19, 2020.....S16

Figure S10. The 2.5–10 nm number concentration measured during mobile deployment 5 on May 11, 2020.....S17

Figure S11. The 2.5–10 nm number concentration measured during mobile deployment 6 on May 15, 2020.....S18

Figure S12. Vehicular traffic counts from Western Blvd. retrieved from NCDOT between February 1 and May 31, 2020. The vertical red lines represent important dates in the COVID-19 social distancing timeline. Vertical ticks are spaced two weeks apart. 1: 3/14 K-12 public schools were closed statewide; 2: 3/17 Restaurants and bars mandated to close; 3: 3/23 Gatherings with 50 or more people were banned and service sector businesses mandated to close; 4: 3/30 statewide stay at home order. 5: 5/8 statewide stay at home order lifted, phase one of re-opening begins.....S19

Figure S13. Comparison of the hourly median 5–10 nm number concentration on days with low morning and evening boundary layer before and after COVID-19 social distancing measures. Shaded areas represent the 25th and 75th quartiles of the data. Pre-COVID-19 encompasses days from spring 2019 and winter/spring 2019/2020 prior to March 14, 2020. During COVID-19 days include days between March 14, 2020 and May 15, 2020S20

Figure S14. Annual PM_{2.5} variation for 2019 (black) and 2020 (red). The shaded blue area represents the variation in concentration between 2010 and 2019S21

Figure S15. Diurnal variability for Class A, B, and C NPF days. Data corresponds to 30 min. time average integrated SMPS concentration for 5–10 and 10–40 nm size ranges. Solid lines are the median concentration. Shades are the interquartile range.....S22

Figure S16. Hourly average PBLH (blue), temperature (red), relative humidity (orange), solar radiation (black), wind speed (purple), and wind direction (black) during regular, NPF and PB event days. Shaded areas represent the 25th and 75th quartiles of the data.....S23

Figure S17. Hourly average CO (blue), NO₂ (red), O₃ (orange), PM_{2.5} (black), and PM₁₀ (purple) during regular, NPF and PB event days. Shaded areas represent the 25th and 75th quartiles of the data.....S24

Figure S18. Normalized spectral number density from the SMPS (top) and 5–10 nm number concentration (bottom) for a PB event. The event begins at 21:00 on December 12th and ends by 07:00 on the 14th. Vertical gridlines are spaced every 2 hr.....S25

Figure S19. Normalized spectral number density from the SMPS with growth rate overlay (top) and number concentration (bottom) for a Class B NPF and PB event on January 21, 2020. The 10–20 nm number concentration is shown in blue and < 55 nm shown in red. Vertical gridlines are spaced every 2 hrS26

Figure S20. Elevation (shown in ft.) map of Raleigh, NC.....S27

Figure S21. Elevation (shown in ft.) map of NC State’s campusS28

Supporting Information Tables

Table S1. Class A NPF event statistics. Estimated start and detection times are rounded to the nearest 15 min. interval.

Estimated Start Time	Start Time Range	Detection Time	5–10 nm GR (nm hr ⁻¹)	R ²	10–20 nm GR (nm hr ⁻¹)	R ²	20–30 nm GR (nm hr ⁻¹)	R ²
Nov. 24, 2019 09:15	07:31 – 10:45	9:30	5.6	0.98	9	0.93	5.8	0.87
Dec. 04, 2019 10:30	08:52 – 12:07	12:30	1	0.66	3.2	0.91	3.6	0.82
Dec. 05, 2019 09:15	04:21 – 14:05	12:45	1.7	0.83	2.3	0.96	3.7	0.75
Jan 05, 2020 07:30	05:54 – 09:09	9:45	0.9	0.92	1	0.5	2.8	0.86
Jan. 06, 2020 10:00	07:12 – 12:52	11:30	2.4	0.93	2.1	0.97	2.9	0.89
Jan. 08, 2020 10:15	06:16 – 14:23	12:15	2.6	0.84	1.8	0.97	3.4	0.94
Jan. 28, 2020 09:30	06:15 – 12:45	11:15	2.3	0.86	4.6	0.87	NaN	NaN
Feb. 27, 2020 09:30	07:32 – 11:36	10:30	2.7	0.96	1.6	0.97	2.6	0.88
Mar. 01, 2020 10:15	08:59 – 11:25	10:45	2.8	0.97	1.4	0.84	1.8	0.89
Mar. 07, 2020 08:15	06:56 – 09:23	9:00	1.8	0.89	1.3	0.88	1.7	0.93
Apr. 02, 2020 10:30	08:36 – 12:40	11:30	2.9	0.91	5.5	0.96	0.9	0.8
Apr. 03, 2020 10:30	08:07 – 12:59	11:30	3.2	0.93	1.8	0.81	1.5	0.84
Apr. 22, 2020 10:00	08:26 – 11:41	11:30	1.4	0.84	3.5	0.98	2.3	0.97
Apr. 27, 2020 08:45	08:21 – 09:10	9:00	2.1	0.96	5.1	0.97	1.8	0.85
May 07, 2020 08:30	07:41 – 09:18	11:00	0.4	0.69	2.4	0.92	1.9	0.89

*NaN indicates no available data.

Table S2. Class B NPF event statistics. Detection times are rounded to the nearest 15 min. interval.

Detection Time	10–20 nm GR (nm hr ⁻¹)	R ²	20–30 nm GR (nm hr ⁻¹)	R ²
Apr. 27, 2019 12:00	4.8	0.97	2.5	0.91
May. 18, 2019 07:45	3.4	0.81	6.6	0.88
Dec. 12, 2019 13:15	1.3	0.92	0.1	0.01
Dec. 20, 2019 15:00	2.2	0.9	0.8	0.46
Dec. 31, 2019 07:00	0.7	0.25	1.4	0.48
Jan. 7, 2020 17:30	1.9	0.9	1.4	0.59
Jan. 17, 2020 14:00	1.6	0.93	3.9	0.93
Jan. 21, 2020 13:45	2.6	0.97	3.3	0.97
Feb. 15, 2020 12:00	0.7	0.59	1.5	0.79
Feb. 21, 2020 12:15	3.5	0.96	1.8	0.92
Mar. 13, 2020 23:30	1.8	0.6	4.2	0.72
Mar. 14, 2020 12:00	3.5	0.96	3.7	0.96
Mar. 20, 2020 23:30	5.2	0.92	8.3	0.91
Mar. 30, 2020 12:30	2.3	0.82	1.2	0.81
Apr. 4, 2020 12:30	5.9	0.97	3.4	0.96
Apr. 5, 2020 11:00	7.4	0.87	2.1	0.87
Apr. 9, 2020 08:45	6.5	0.81	8	0.85
Apr. 16, 2020 16:15	2.7	0.97	4.9	0.95
Apr. 21, 2020 22:45	13.1	1	3.8	0.93
May 4, 2020 12:00	1.7	0.85	5.5	0.98
May 9, 2020 14:45	5.9	0.79	1.3	0.89

Table S3. PB event statistics. Event times are rounded to the nearest half hour.

Event Year	Event Times	Event Duration	Avg. 5–10nm Conc. (cm ⁻³)	Event Threshold (cm ⁻³)	Frac. of Scans > Threshold	Event Rainfall Total (mm)
2019	Apr. 19 03:30 – 21:00	17.5	1028.88	500	0.64	20.6
	Apr. 29 04:00 – 13:00	9.5	774.19	550	0.6	0
	May 05 22:00 – May 06 15:00	17	4067.75	950	0.69	0.6
	May 21 07:00 – 19:30	12.5	2281.24	950	0.65	0
	May 31 14:00 – Jun. 01 13:00	23	997.3	850	0.38	11.2
	Jun. 03 06:00 – Jun. 04 07:00	25	2734.33	900	0.8	0
	Nov. 15 01:00 – Nov. 18 10:00	81	5792.97	2000	0.93	0
	Nov. 29 01:30 – 13:30	12	2660.52	1000	0.96	0
	Dec. 07 06:30 – Dec. 08 18:30	36	2717.05	2000	0.38	0
	Dec. 10 23:30 – Dec. 11 13:30	14	12892.84	3000	0.79	0
	Dec. 12 22:30 – Dec. 14 04:30	30	32128.57	1500	0.98	0
	Dec. 23 00:00 – Dec. 25 15:00	63	4888.68	2000	0.65	0
Dec. 29 08:30 – 21:30	13	1975.76	500	0.96	0	
2020	Jan. 17 00:00 – 17:30	17.5	3351.46	1000	0.75	0
	Jan. 20 09:00 – Jan. 24 06:00	93	2490.58	1000	0.75	40.5
	Jan. 30 08:00 – Feb. 01 04:00	44	3116.21	1000	0.71	0
	Feb. 12 01:00 – 08:30	7.5	5787.47	1000	1	0
	Feb. 14 10:00 – Feb. 15 13:30	27.5	3045.31	1000	0.77	0
	Feb. 19 06:30 – 16:30	10	11745.07	4500	0.81	0
	Feb. 20 15:00 – Feb. 21 17:00	26	45739.75	3000	0.92	1.4
	Mar. 15 03:00 – Mar. 16 16:00	37	1710.59	1000	0.51	0
	Mar. 21 09:00 – Mar. 23 10:00	49	3267.14	1000	0.45	0
	Mar. 25 03:30 – 20:00	16.5	7393.1	1500	0.44	0
	Mar. 31 19:30 – Apr. 01 13:30	18	33413.51	1500	0.73	0
	Apr. 12 13:00 – Apr. 13 06:00	17	3821.25	1500	0.91	0.8
	Apr. 15 01:00 – 16:00	15	10836.35	1500	0.87	0
	Apr. 20 08:30 – 15:30	7	69913.19	2500	1	0
	Apr. 29 13:00 – Apr. 30 10:30	21.5	6792.6	1000	0.98	0.9

Supporting Information Figures

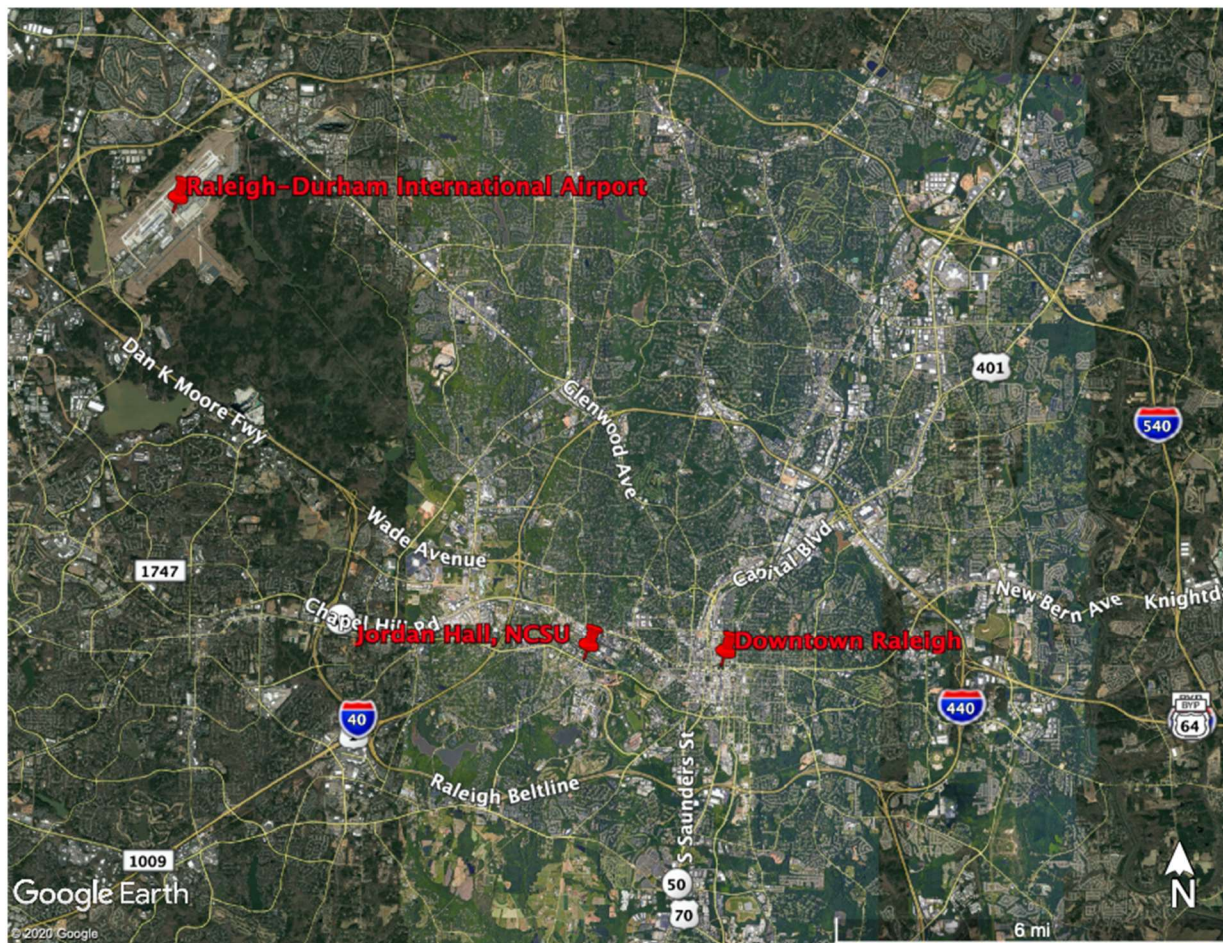


Figure S1. Map of the Raleigh metro area. Interstates 440 and 540 are the inner and outer loops of the beltway. Jordan Hall, where scanning mobility particle sizer measurements were performed is located 4.8 km west of downtown Raleigh. The Raleigh-Durham International Airport is 17 km NW of Jordan Hall.



Figure S2. Map of North Carolina State University Campus. The scanning mobility particle sizer measurements were performed in Jordan Hall. The Cates Ave. Steam Plant, Yarbrough Drive Steam Plant, and Centennial Campus Utility Plant are 0.3 km NNE, 0.9 km NE, and 0.7 km SSE of Jordan Hall.

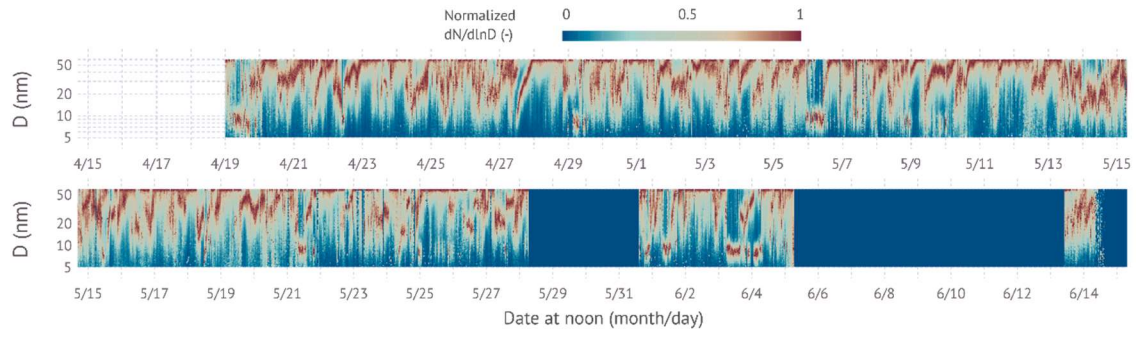


Figure S3. Normalized spectral number density from the SMPS during the spring 2019 deployment.

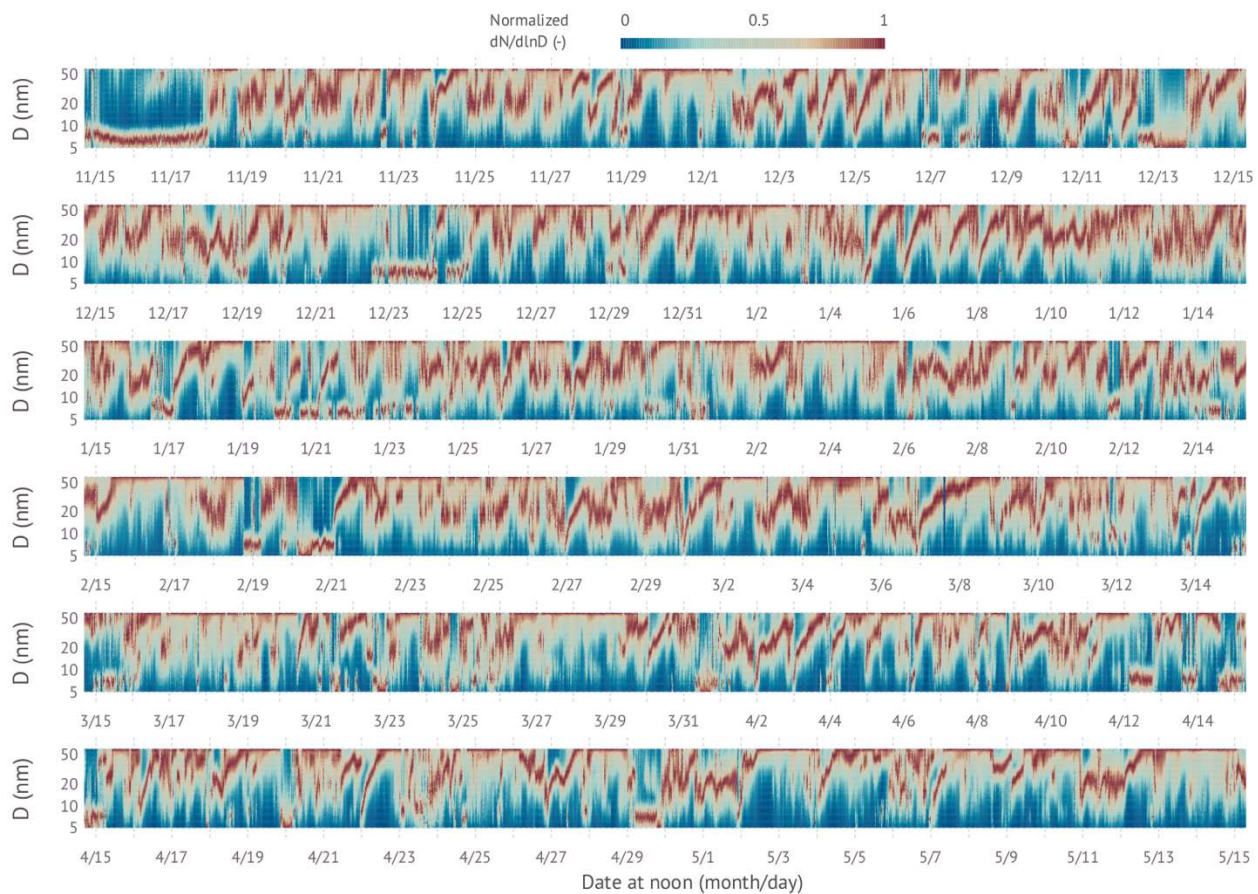


Figure S4. Normalized spectral number density from the SMPS during the winter 2019 and spring 2020 measurement campaign.

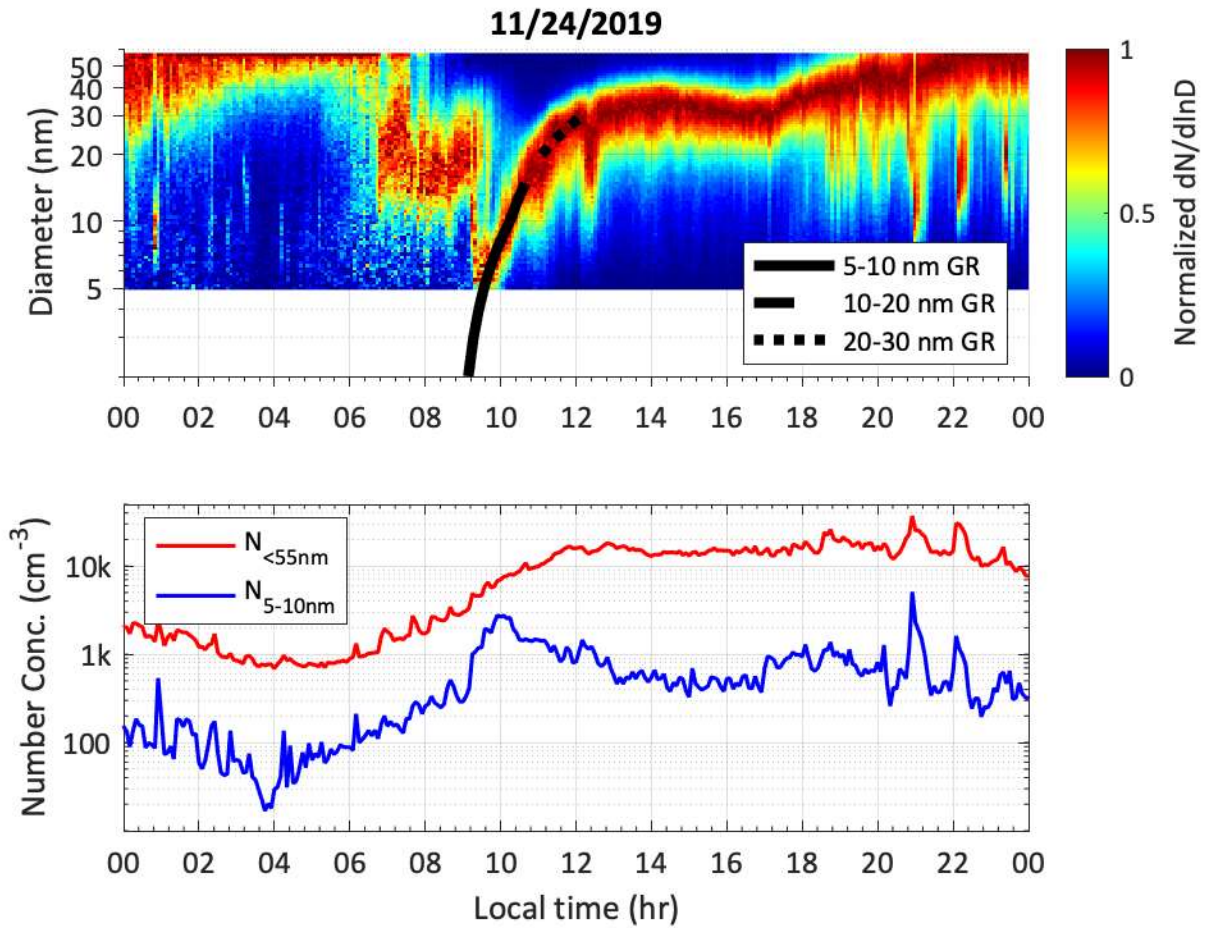


Figure S5. Normalized spectral number density from the SMPS with growth rate overlay (top) and number concentration (bottom) for a Class A NPF event on November 24, 2019. The 5–10 nm number concentration is shown in blue and < 55 nm shown in red. Vertical gridlines are spaced every 2 hr.

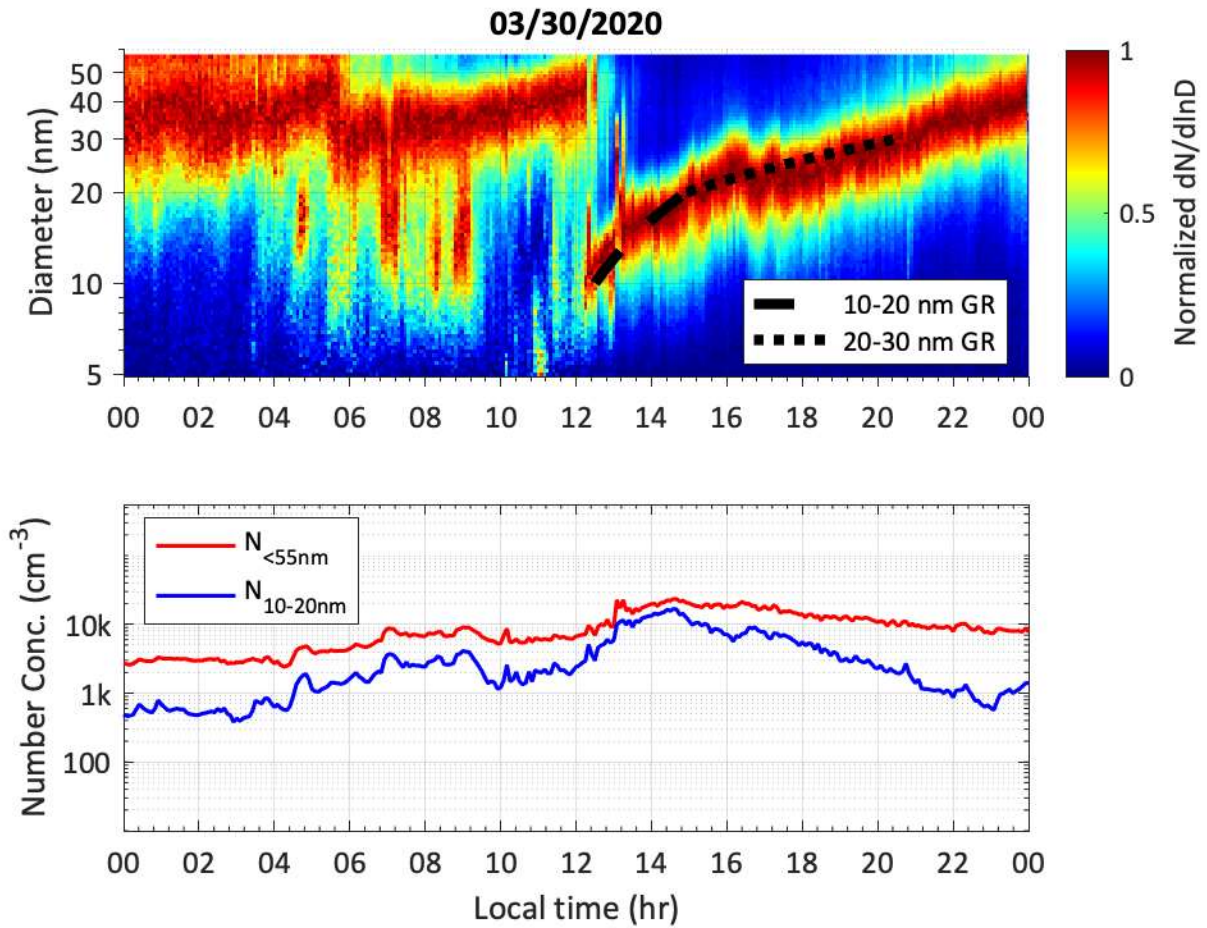


Figure S6. Normalized spectral number density from the SMPS with growth rate overlay (top) and number concentration (bottom) for a Class B NPF event on March 30, 2020. The 10–20 nm number concentration is shown in blue and < 55 nm shown in red. Vertical gridlines are spaced every 2 hr.

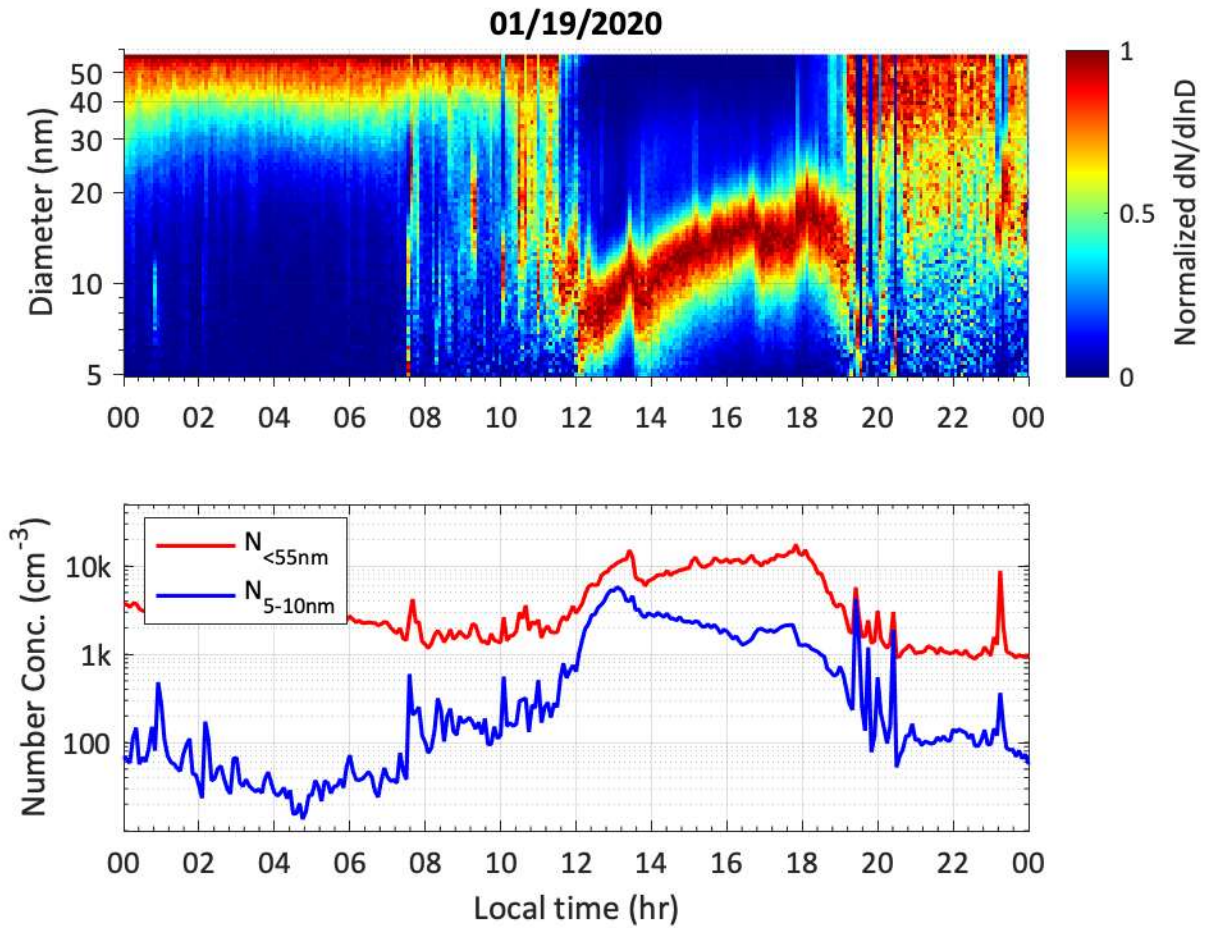


Figure S7. Normalized spectral number density from the SMPS with growth rate overlay (top) and number concentration (bottom) for a Class C NPF event on January 19, 2020. The 5–10 nm number concentration is shown in blue and < 55 nm shown in red. Vertical gridlines are spaced every 2 hr.

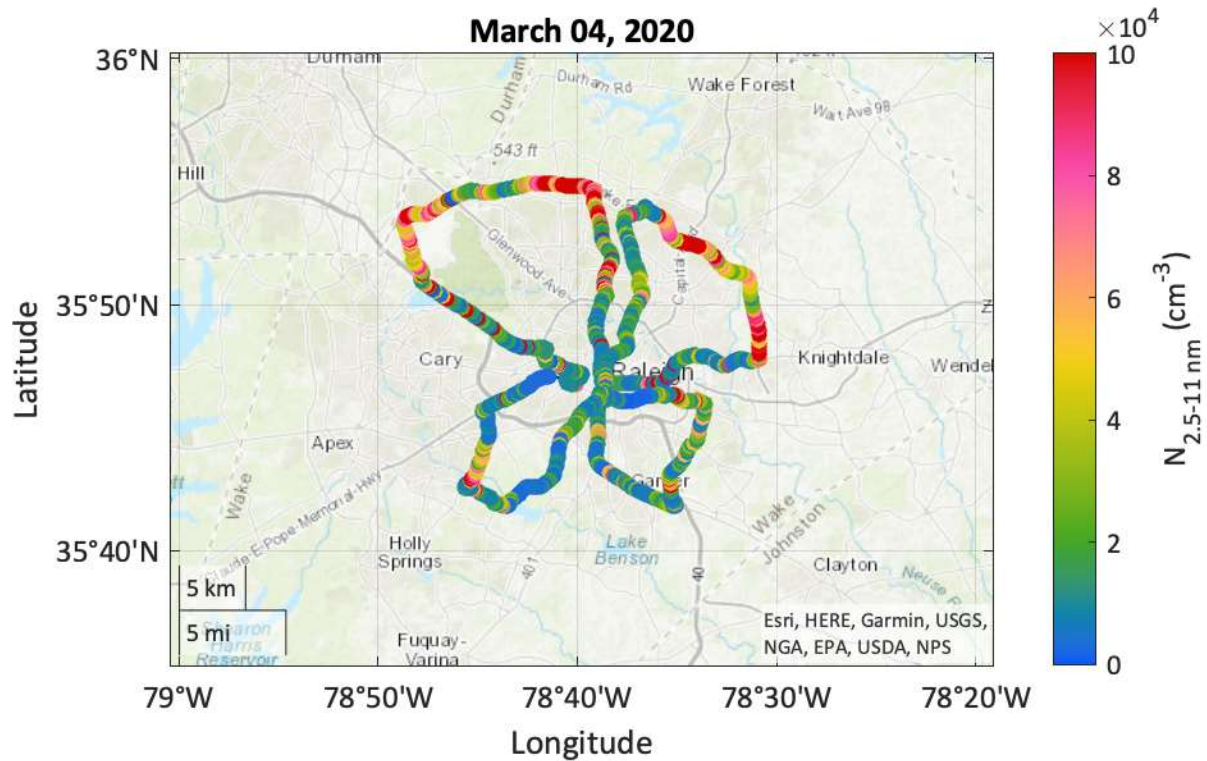


Figure S8. The 2.5–11 nm number concentration measured during mobile deployment 1 on March 4, 2020.

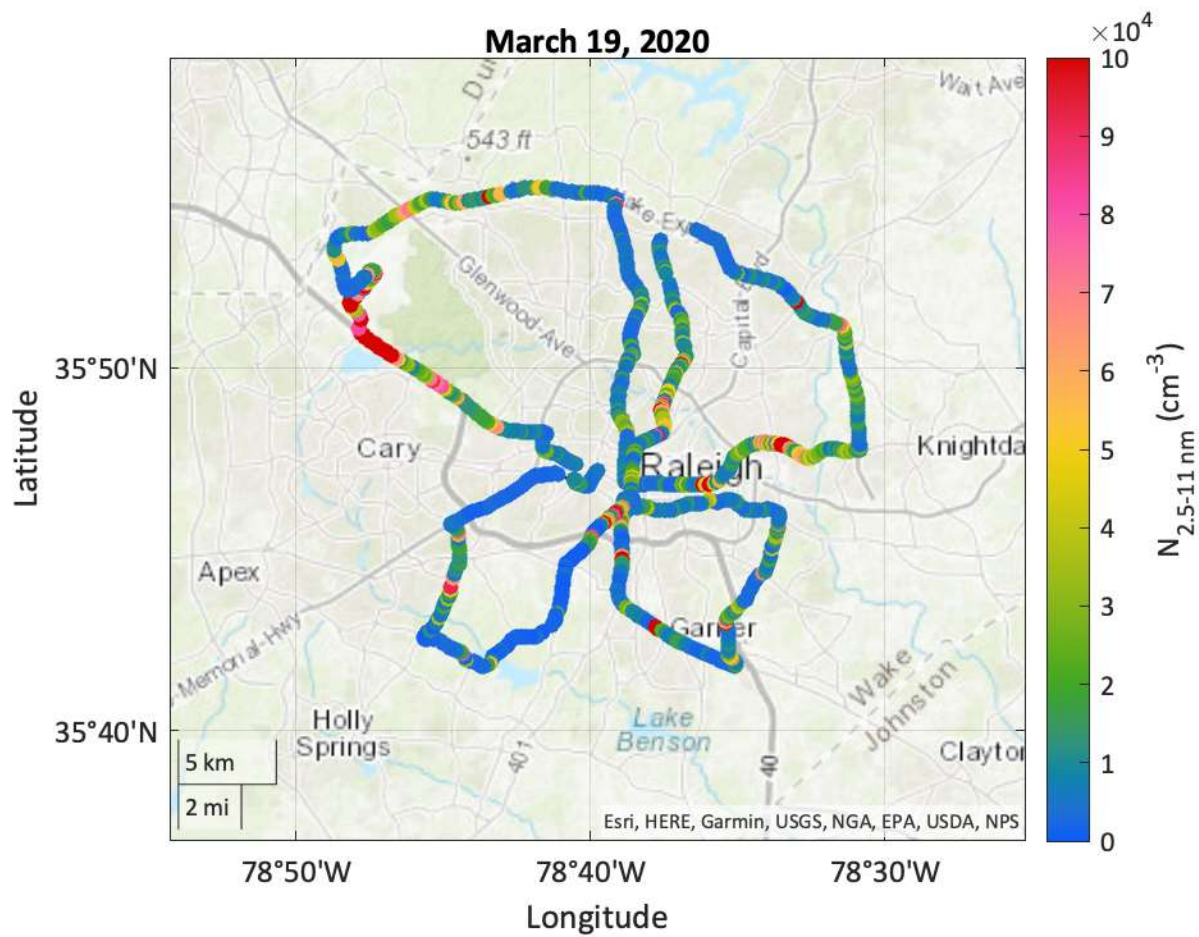


Figure S9. The 2.5–11 nm number concentration measured during mobile deployment 2 on March 19, 2020.

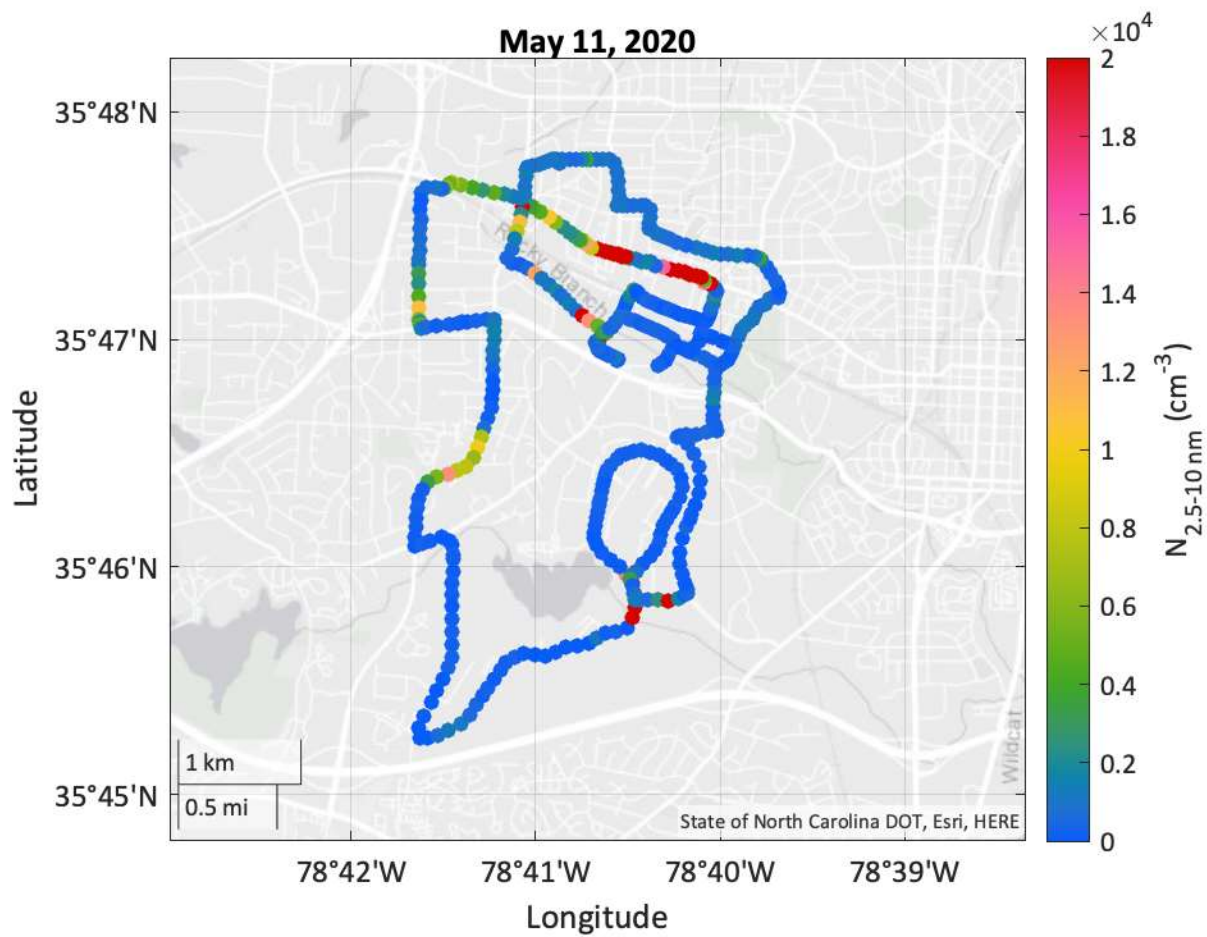


Figure S10. The 2.5–10 nm number concentration measured during mobile deployment 5 on May 11, 2020.

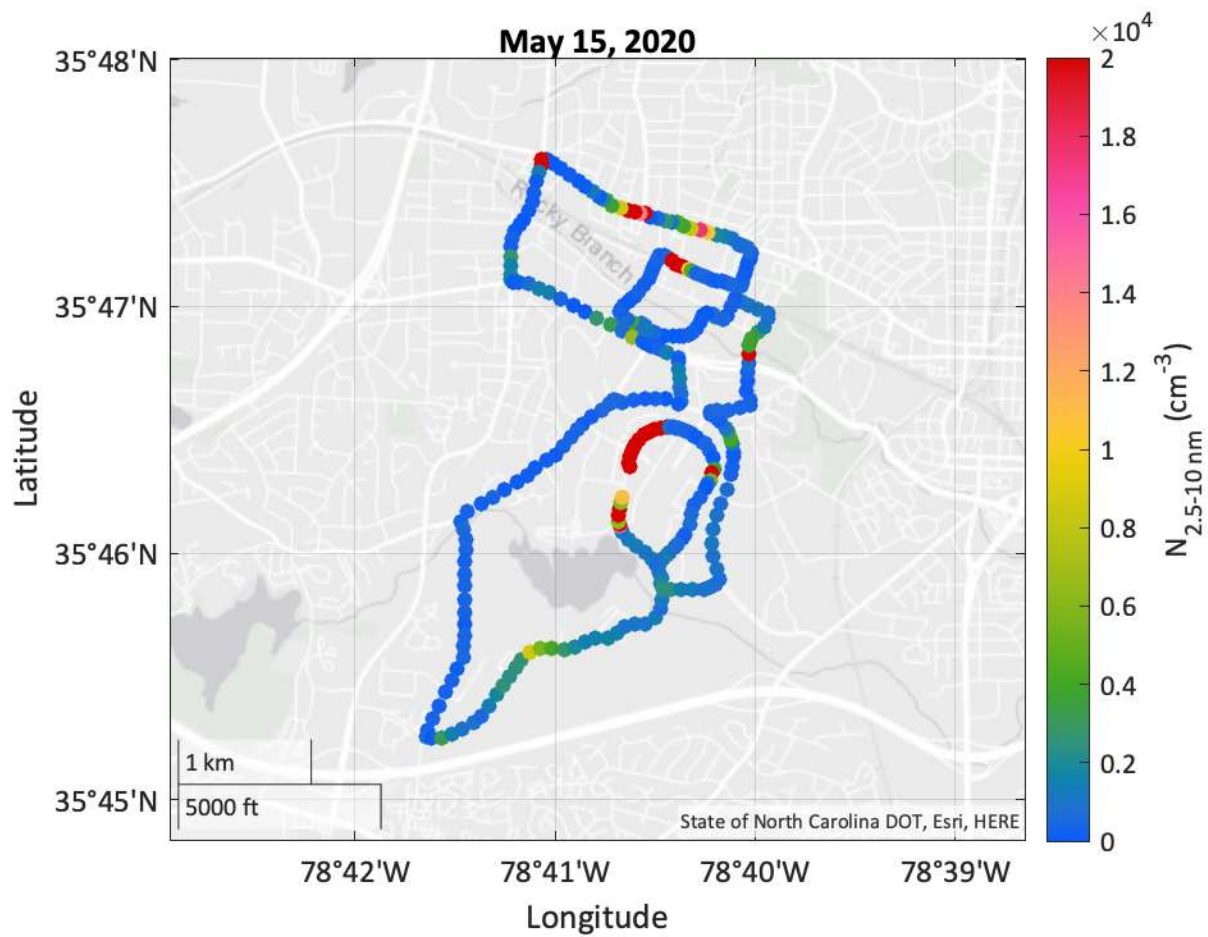


Figure S11. The 2.5–10 nm number concentration measured during mobile deployment 6 on May 15, 2020.

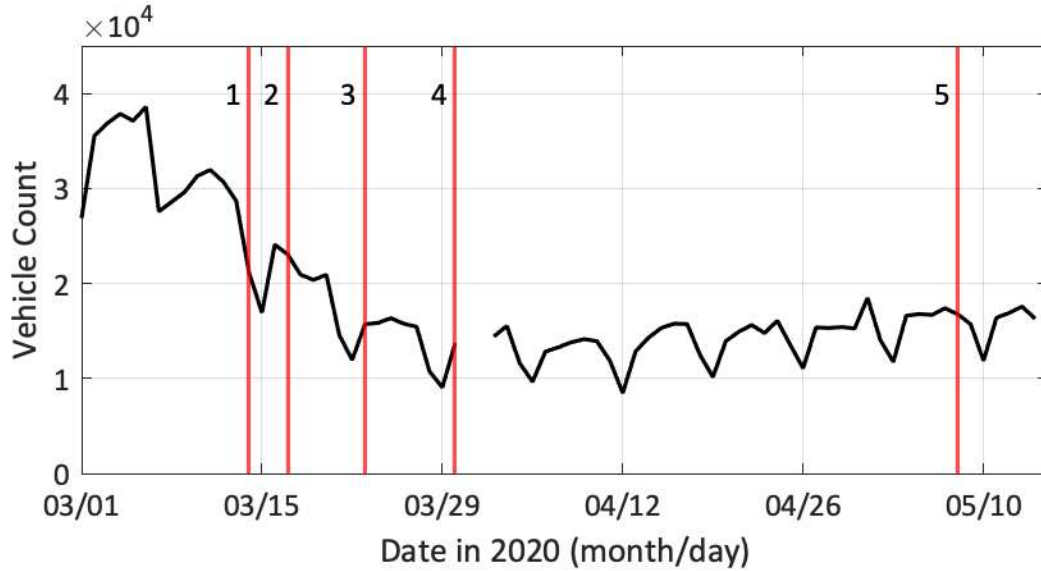


Figure S12. Vehicular traffic counts from Western Blvd. retrieved from NCDOT between February 1 and May 31, 2020. The vertical red lines represent important dates in the COVID-19 social distancing timeline. Vertical ticks are spaced two weeks apart. 1: 3/14 K-12 public schools were closed statewide; 2: 3/17 Restaurants and bars mandated to close; 3: 3/23 Gatherings with 50 or more people were banned and service sector businesses mandated to close; 4: 3/30 statewide stay at home order. 5: 5/8 statewide stay at home order lifted, phase one of re-opening begins.

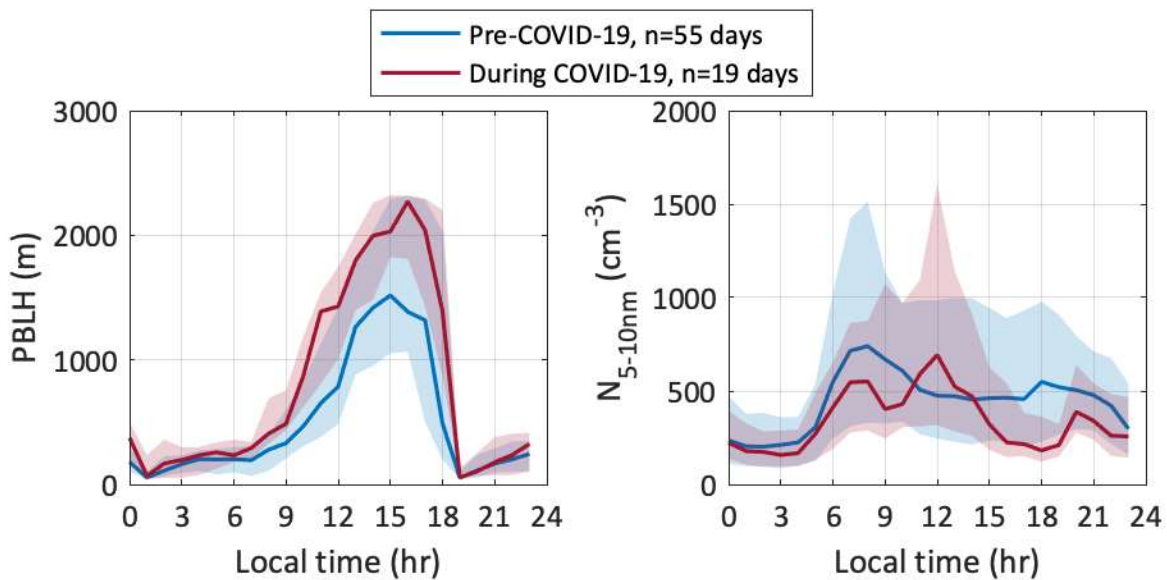


Figure S13. Comparison of the hourly median 5–10 nm number concentration on days with low morning and evening boundary layer before and after COVID-19 social distancing measures. Shaded areas represent the 25th and 75th quartiles of the data. Pre-COVID-19 encompasses days from spring 2019 and winter/spring 2019/2020 prior to March 14, 2020. During COVID-19 days include days between March 14, 2020 and May 15, 2020.

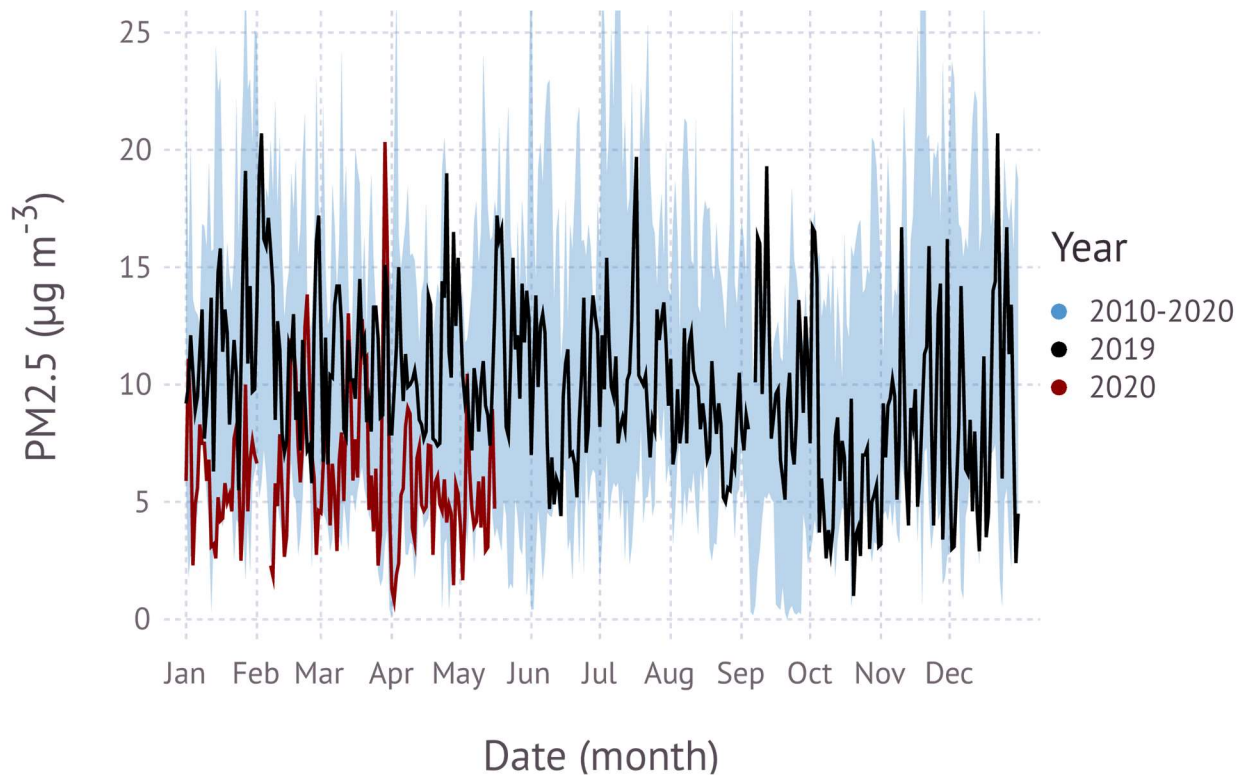


Figure S14. Annual PM_{2.5} variation for 2019 (black) and 2020 (red). The shaded blue area represents the variation in concentration between 2010 and 2019.

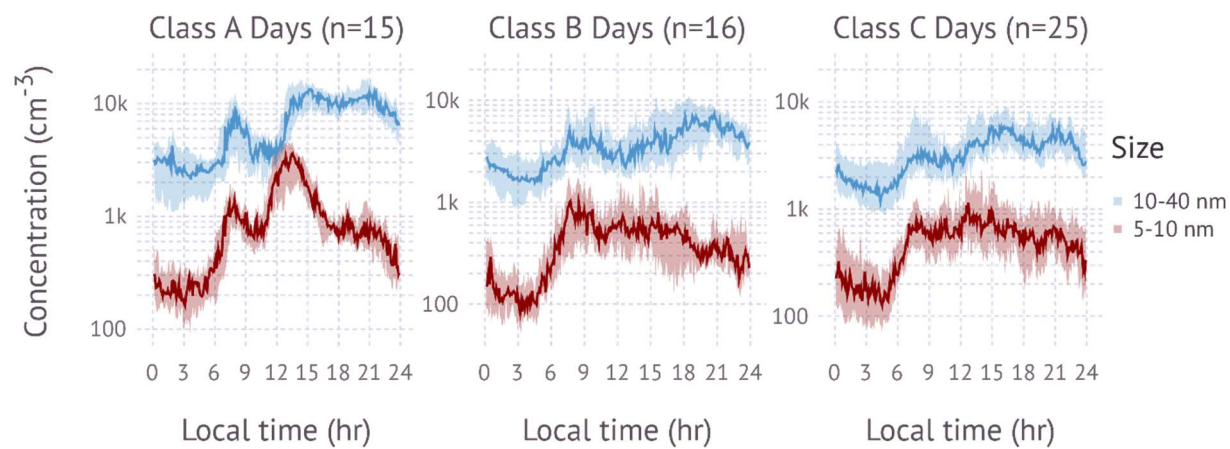


Figure S15. Diurnal variability for Class A, B, and C NPF days. Data corresponds to 30 min. time average integrated SMPS concentration for 5–10 and 10–40 nm size ranges. Solid lines are the median concentration. Shades are the interquartile range.

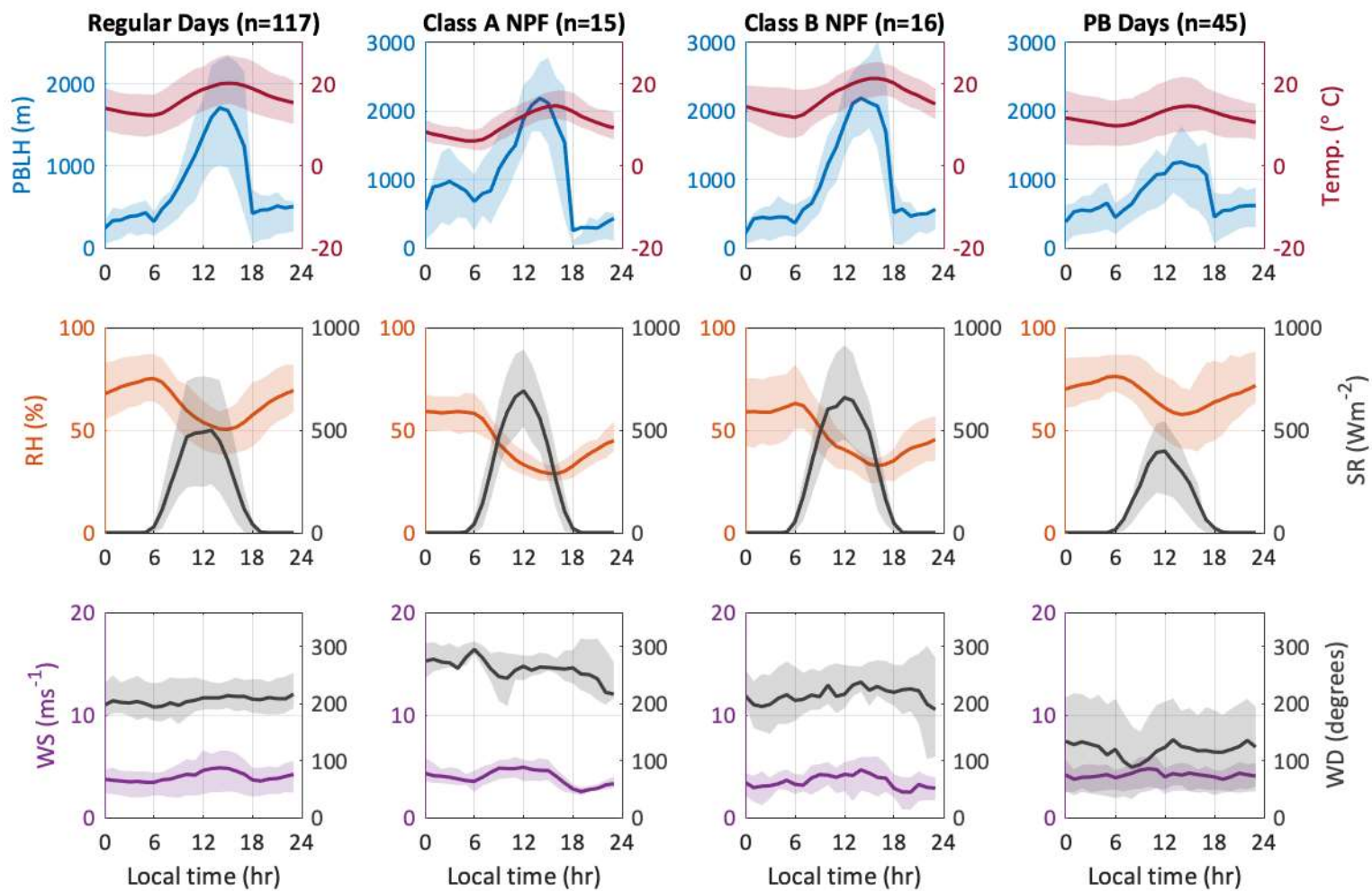


Figure S16. Hourly average PBLH (blue), temperature (red), relative humidity (orange), solar radiation (black), wind speed (purple), and wind direction (black) during regular, NPF and PB event days. Shaded areas represent the 25th and 75th quartiles of the data.

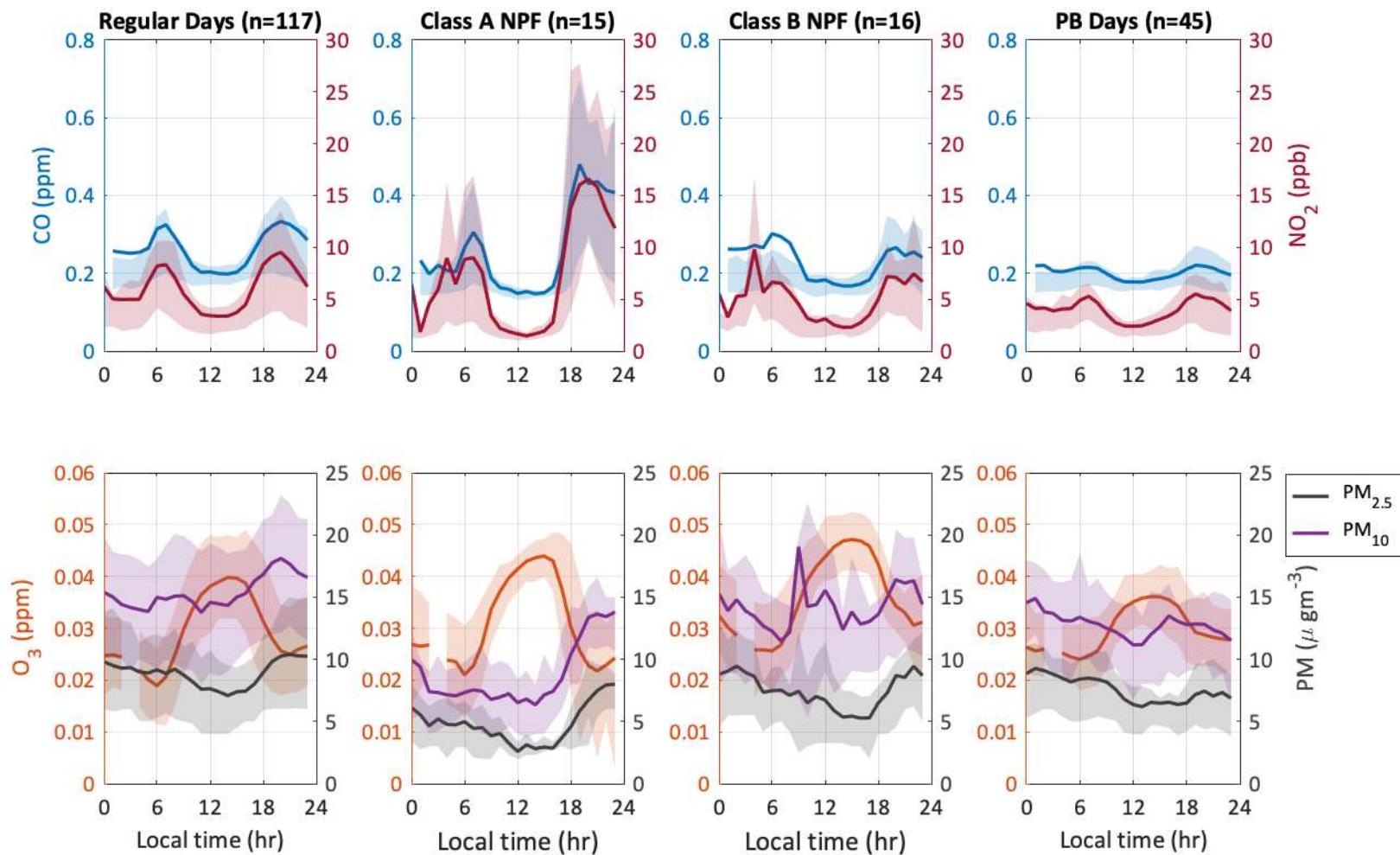


Figure S17. Hourly average CO (blue), NO₂ (red), O₃ (orange), PM_{2.5} (black), and PM₁₀ (purple) during regular, NPF and PB event days. Shaded areas represent the 25th and 75th quartiles of the data.

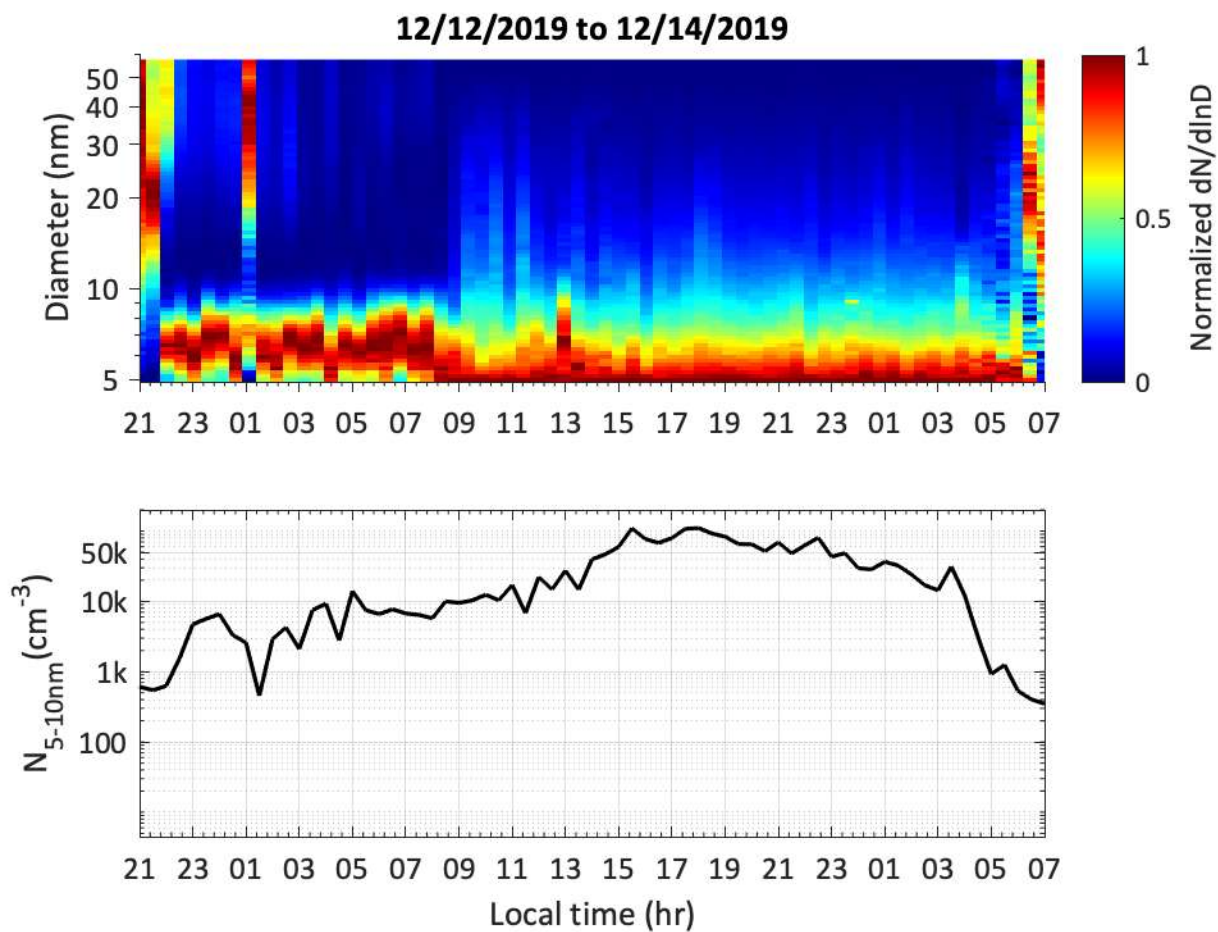


Figure S18. Normalized spectral number density from the SMPS (top) and 5–10 nm number concentration (bottom) for a PB event. The event begins at 21:00 on December 12th and ends by 07:00 on the 14th. Vertical gridlines are spaced every 2 hr.

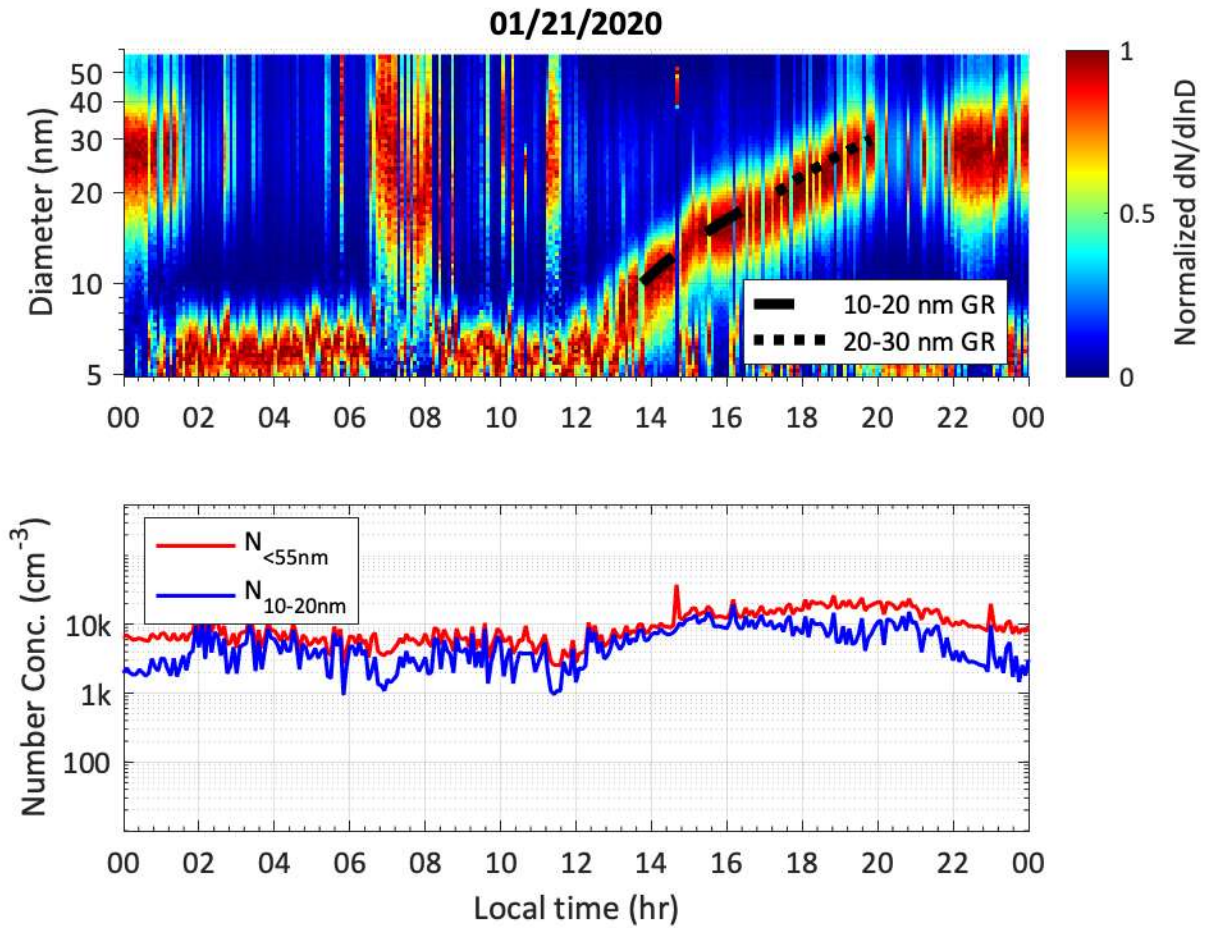


Figure S19. Normalized spectral number density from the SMPS with growth rate overlay (top) and number concentration (bottom) for a Class B NPF and PB event on January 21, 2020. The 10–20 nm number concentration is shown in blue and < 55 nm shown in red. Vertical gridlines are spaced every 2 hr.

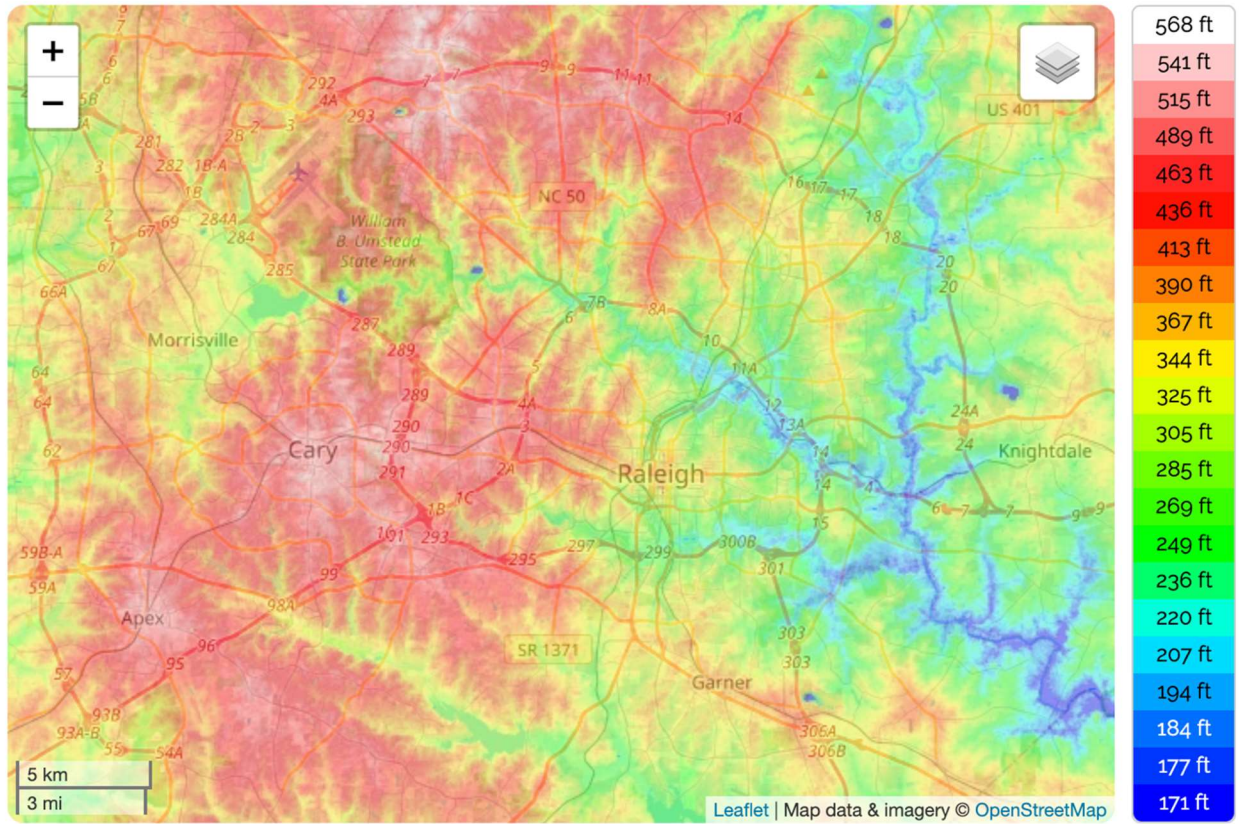


Figure S20. Elevation (shown in ft.) map of Raleigh, NC.

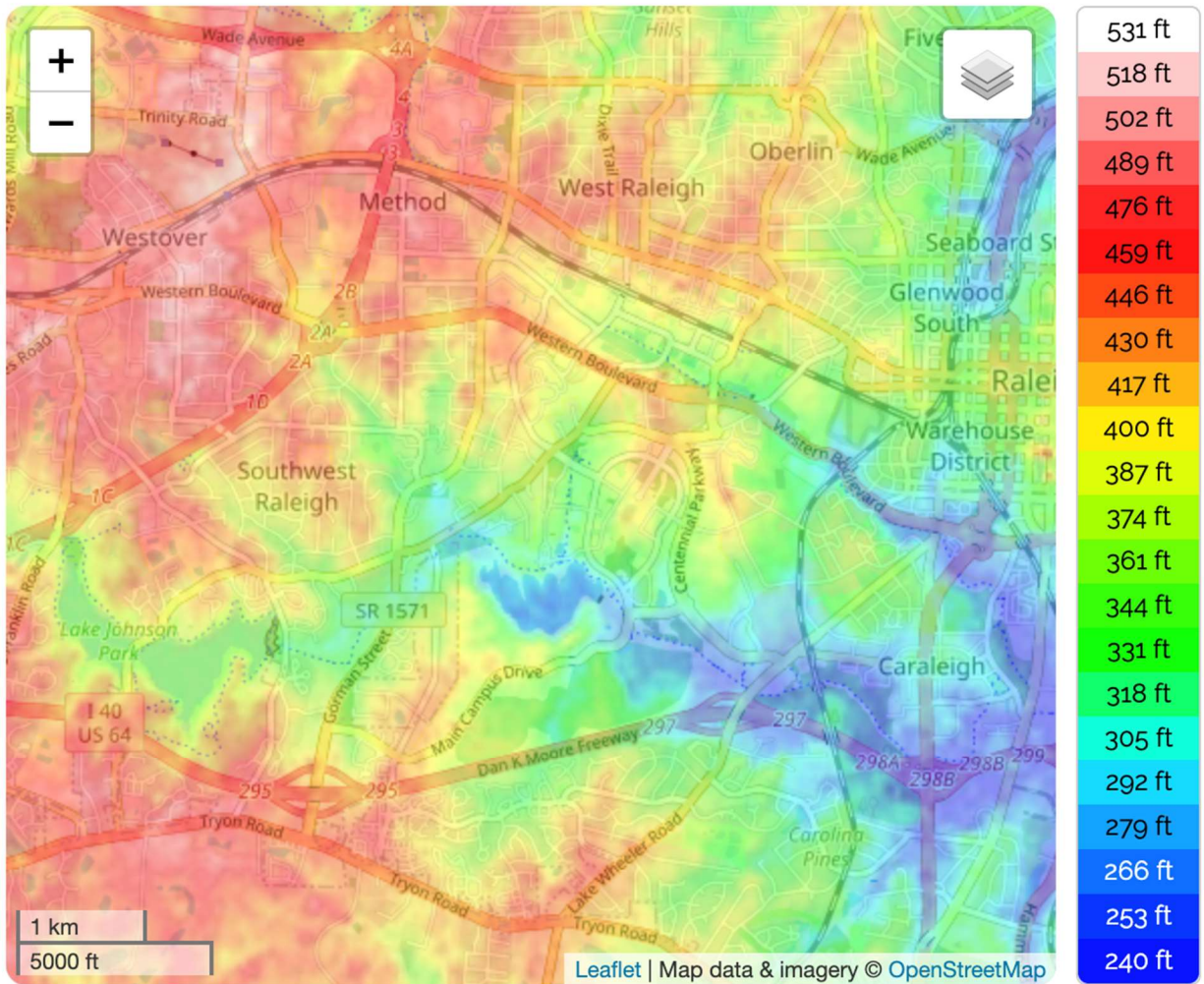


Figure S21. Elevation (shown in ft.) map of NC State’s campus.