





Vertical Profiles of Ozone Concentration Collected by an Unmanned Aerial Vehicle and the Mixing of the Nighttime Boundary Layer over an Amazonian Urban Area

Patrícia Guimarães ^{1,2}, Jianhuai Ye³, Carla Batista ^{1,2}, Rafael Barbosa ^{1,2}, Igor Ribeiro ^{1,2}, Adan Medeiros ², Rodrigo Souza ^{2,*} and Scot Martin ^{3,4,*}

¹ Post-graduate Program in Climate and Environment, National Institute of Amazonian Research and Amazonas State University, Manaus, Amazonas, 69060-001, Brazil; guimaraespc.uea@gmail.com (P.G.); cestefanibatista@gmail.com (C.E.); rgb.barbosa@gmail.com (R.B.); igorgeoinformacao@gmail.com (I.R.);

² School of Technology, Amazonas State University, Manaus, Amazonas, 69065-020, Brazil; adan_medeiros@hotmail.com (A.M.); souzaraf@gmail.com (R.S.)

³ School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, 02138, USA; jye@seas.harvard.edu (J.Y.)

⁴ Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts, 02138, USA; scot_martin@harvard.edu (S.M.)

* Correspondence: scot_martin@harvard.edu; souzaraf@gmail.com. Tel.: +1-617-495-0627 (S.M.); +55-92 98815-2749 (R.S.);

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Flight 1 - 19MAR2018 20:00 LT



Figure S1. Vertical profiles of ozone concentration, potential temperature, and specific humidity from surface to 500 m. The case classification of each data set is provided in the inset text. Classifications include (case 1) a normal, undisturbed, stratified nighttime atmosphere based in 23 ozone profiles, (case 2) a turbulently mixing atmosphere based in 16 ozone profiles, and (case 3) a complex atmosphere characterized by both stratified and turbulent components based in 18 ozone profiles. The case classification is discussed in the main text (Section 3). The height of NBL based in ozone concentration is showed (grey color). The dotted line represents the limit of detection for ozone (3 ppbv). The horizontal bars represent measurement uncertainty. Local time (LT) is 4 h earlier than UTC.





Flight 2 - 19MAR2018 20:30 LT



Figure S1 (continued).





Flight 3 - 19MAR2018 21:00 LT



Figure S1 (continued).





Flight 6 - 19MAR2018 23:00 LT



Figure S1 (continued).





Flight 7 - 19MAR2018 23:30 LT



Figure S1 (continued).





Flight 9 - 20MAR2018 21:00 LT



Figure S1 (continued).





Flight 21 - 23MAR2018 22:00 LT



Figure S1 (continued).





Flight 24 - 26APR2018 20:00 LT



Figure S1 (continued).





Flight 31 - 7MAY2018 20:30 LT



Figure S1 (continued).





Flight 32 - 7MAY2018 21:00 LT



Figure S1 (continued).





Flight 36 - 8MAY2018 20:00 LT



Figure S1 (continued).





Flight 38 - 8MAY2018 21:00 LT



Figure S1 (continued).





Flight 39 - 8MAY2018 22:00 LT



Figure S1 (continued).





Flight 42 - 8MAY2018 23:30 LT



Figure S1 (continued).





Flight 43 - 8MAY2018 00:00 LT



Figure S1 (continued).





Flight 44 - 10MAY2018 20:00 LT



Figure S1 (continued).





Flight 49 - 10MAY2018 23:30 LT



Figure S1 (continued).





Flight 51 - 11MAY2018 19:30 LT



Figure S1 (continued).





Flight 53 - 11MAY2018 20:30 LT



Figure S1 (continued).





Flight 54 - 11MAY2018 21:00 LT



Figure S1 (continued).





Flight 55 - 11MAY2018 21:30 LT



Figure S1 (continued).





Flight 56 - 11MAY2018 22:00 LT



Figure S1 (continued).





Flight 57 - 11MAY2018 23:00 LT



Figure S1 (continued).





Flight 4 - 19MAR2018 22:00 LT



Figure S1 (continued).





Flight 5 - 19MAR2018 22:30 LT



Figure S1 (continued).





Flight 11 - 22MAR2018 20:30 LT



Figure S1 (continued).





Flight 12 - 22MAR2018 21:00 LT



Figure S1 (continued).





Flight 13 - 22MAR2018 22:00 LT



Figure S1 (continued).





Flight 15 - 22MAR2018 23:00 LT



Figure S1 (continued).





Flight 16 - 22MAR2018 23:30 LT



Figure S1 (continued).





Flight 25 - 26APR2018 20:30 LT



Figure S1 (continued).





Flight 26 - 26APR2018 21:00 LT



Figure S1 (continued).





Flight 27 - 26APR2018 21:30 LT



Figure S1 (continued).





Flight 37 - 8MAY2018 20:30 LT



Figure S1 (continued).





Flight 46 - 10MAY2018 22:00 LT



Figure S1 (continued).

Figure S1 (continued).

Flight 48 - 10MAY2018 23:00 LT

Figure S1 (continued).

Flight 50 - 10MAY2018 00:00 LT

Figure S1 (continued).

Flight 52 - 11MAY2018 20:00 LT

Figure S1 (continued).

Flight 8 - 20MAR2018 20:30 LT

Figure S1 (continued).

Flight 10 - 20MAR2018 21:30 LT

Figure S1 (continued).

Flight 14 - 22MAR2018 22:30 LT

Figure S1 (continued).

Flight 17 - 23MAR2018 20:00 LT

Figure S1 (continued).

Flight 18 - 23MAR2018 20:30 LT

Figure S1 (continued).

Flight 19 - 23MAR2018 21:00 LT

Figure S1 (continued).

Flight 20 - 23MAR2018 21:30 LT

Figure S1 (continued).

Flight 22 - 23MAR2018 22:30 LT

Figure S1 (continued).

Flight 23 - 23MAR2018 23:00 LT

Figure S1 (continued).

Flight 28 - 26APR2018 22:00 LT

Figure S1 (continued).

Flight 29 - 26APR2018 22:30 LT

Figure S1 (continued).

Figure S1 (continued).

Flight 33 - 7MAY2018 21:30 LT

Figure S1 (continued).

Flight 34 - 7MAY2018 22:00 LT

Figure S1 (continued).

Flight 35 - 7MAY2018 23:00 LT

Figure S1 (continued).

Flight 40 - 8MAY2018 22:30 LT

Figure S1 (continued).

Flight 41 - 8MAY2018 23:00 LT

Figure S1 (continued).

Flight 45 - 10MAY2018 21:30 LT

Figure S1 (continued).

Figure S2. Box-whisker statistics plots of (a) ozone concentration, (b) potential temperature, and (c) specific humidity at the top of the NBL during the wet season of 2018. Results are shown for (case 1) a stratified atmosphere based in 23 ozone profiles and (case 2) a turbulent atmosphere based in 16 ozone profiles. For each box-whisker plot, the median (box line) of the combined data sets, quartiles (blue box edges), and the minimum and maximum values (black lines) are represented excluding outliers.

Figure S3. Vertical profiles of ozone concentration segregated by hour from 20:00 to 00:00 (LT) for the combined data set of case 1 (i.e., normal stratified atmospheres) based in 23 profiles. Local time (LT) is 4 h earlier than UTC.

Figure S4. Boundary layer heights segregated by hour from 20:00 to 00:00 (LT) as (blue color) determined by the UAV measurements of this study and as (green color) reported for the Global Data Assimilation System (GDAS).[51] Local time (LT) is 4h earlier than UTC.

Figure S5. Calibration curve for the POM with calibration factors of S = 1.00 and Z = +1 ppbv applied.

Study	Experiment	Description	NBL Height
Fisch [26]	Rondônia Boundary Layer Experiment (RBLE 2 and RBLE 3)	Data collection from radiosonde and tethered balloon, period of 14 days, 4 profiles per night, during the dry season, over forest and pasture	190–300 m over forest 140–190 m over pasture
Santos [10]	Experiment and Wet Season Mesoscale Campaign (WetAMC- LBA)	Data collection from radiosonde and tethered balloon, period of 58 days in dry and wet seasons, over forest and pasture	180–330 m (dry) and 152–282 m (wet) over forest 120–230 m (dry) and 210–227 m (wet) over pasture
Neves et al. [16]	Radiation, Cloud and Climate Interactions Experiment (RaCCI/LBA)	Data collection from radiosondes, tethered balloon, and sodar, period of 60 days, during the transition from dry to wet season, over pasture	120–190 m by tethered balloon, 110–130 m by radiosonde, 311 to 377 m by sodar

Table S1. Summary of studies of the NBL, usually between 18:00 and 00:00 LT.

Table S2. Summary of flights and the estimated NBL heights for the period from 19 March 2018 to 11 May 2018 at 3.0918° S and 60.0175° W in the urban area of Manaus. Local time (LT) is 4 h earlier than UTC. Wind and wind velocity are from a weather station at ground level. The estimated NBL heights are based on profile cases 1 or 2 (see main text). "N/A" denotes that no estimate was made. The NBL height is also estimated by the Global Data Assimilation System [58,59] applied to the UAV flight location. The system stability classification is also listed.

Flight Number	Date	Time (LT)	Sky Cover	Ca se	Groun d Wind Directi on	Grou nd Wind Veloc ity (m s ⁻¹)	UAV Determi ned NBL Height (m)	GDAS Estimat ed NBL Height (m)	GDAS Stability Class
1	19MAR20 18	20:00	Clear	1	Е	0.1	300	50	Neutral
2	19MAR20 18	20:30	Clear	1	Е	0.3	140	50	Neutral
3	19MAR20 18	21:00	Clear	1	Е	0.6	160	N/A	N/A
4	19MAR20 18	22:00	Partly cloudy	2	Е	0.3	345	N/A	N/A
5	19MAR20 18	22:30	Partly cloudy	2	SE	0.1	270	N/A	N/A
6	19MAR20 18	23:00	Partly cloudy	1	Е	0.3	250	116	Neutral
7	19MAR20 18	23:30	Partly cloudy	1	Е	0.6	200	116	Neutral
8	20MAR20 18	20:30	Cloudy	3	NE	0.8	N/A	50	Neutral
9	20MAR20 18	21:00	Cloudy	1	E	0.9	260	N/A	N/A
10	20MAR20 18	21:30	Cloudy	3	E	0.8	N/A	N/A	N/A
11	22MAR20 18	20:30	Cloudy	2	SE	0.2	360	50	Neutral
12	22MAR20 18	21:00	Cloudy	2	E	0.1	290	N/A	Slightly stable
13	22MAR20 18	22:00	Partly cloudy	2	NE	0.1	330	N/A	N/A
14	22MAR20 18	22:30	Partly cloudy	3	Е	0.3	N/A	N/A	N/A
15	22MAR20 18	23:00	Partly cloudy	2	Е	0.2	315	61	Slightly stable
16	22MAR20 18	23:30	Cloudy	2	N/A	N/A	270	61	Slightly stable
17	23MAR20 18	20:00	Cloudy	3	S	0.1	N/A	50	Neutral
18	23MAR20 18	20:30	Partly cloudy	3	S	0.2	N/A	50	Slightly stable

19	23MAR20 18	21:00	Cloudy	3	SE	0.1	N/A	N/A	N/A
20	23MAR20 18	21:30	Cloudy	3	S	0.1	N/A	N/A	N/A
21	23MAR20 18	22:00	Partly cloudy	1	S	0.1	370	N/A	N/A
22	23MAR20 18	22:30	Partly cloudy	3	S	0.1	N/A	N/A	N/A
23	23MAR20 18	23:00	Cloudy	3	S	0.1	N/A	50	Slightly stable
24	26APR201 8	20:00	Cloudy	1	S	0.1	220	50	Neutral
25	26APR201 8	20:30	Partly cloudy	2	N/A	N/A	330	50	Neutral
26	26APR201 8	21:00	Partly cloudy	2	N/A	N/A	225	N/A	N/A
27	26APR201 8	21:30	Partly cloudy	2	S	0.1	300	N/A	N/A
28	26APR201 8	22:00	Partly cloudy	3	NW	0.5	N/A	N/A	N/A
29	26APR201 8	22:30	Partly cloudy	3	NW	1.0	N/A	N/A	N/A
30	7MAY201 8	20:00	Partly cloudy	3	NE	0.3	N/A	57	Slightly stable
31	7MAY201 8	20:30	Partly cloudy	1	N/A	N/A	380	N/A	N/A
32	7MAY201 8	21:00	Partly cloudy	1	NE	0.2	380	N/A	N/A
33	7MAY201 8	21:30	Partly cloudy	3	W	0.2	N/A	N/A	N/A
34	7MAY201 8	22:00	Cloudy	3	NW	0.1	N/A	N/A	N/A
35	7MAY201 8	23:00	Partly cloudy	3	Е	0.5	N/A	62	Slightly stable
36	8MAY201 8	20:00	Clear	1	Е	0.3	300	62	Neutral
37	8MAY201 8	20:30	Cloudy	2	S	0.4	240	62	Neutral
38	8MAY201 8	21:00	Clear	1	NW	0.3	390	N/A	N/A
39	8MAY201 8	22:00	Clear	1	NW	0.1	340	N/A	N/A
40	8MAY201 8	22:30	Cloudy	3	NW	0.3	N/A	N/A	N/A
41	8MAY201 8	23:00	Partly cloudy	3	W	0.2	N/A	50	Slightly stable
			5						

42	8MAY201 8	23:30	Clear	1	NW	0.5	290	50	Slightly stable
43	8MAY201 8	00:00	Clear	1	NW	0.1	320	N/A	N/A
44	10MAY20 18	20:00	Partly cloudy	1	NE	0.8	330	125	Neutral
45	10MAY20 18	21:30	Partly cloudy	3	Е	0.3	N/A	N/A	N/A
46	10MAY20 18	22:00	Partly cloudy	2	Е	0.5	330	N/A	N/A
47	10MAY20 18	22:30	Partly cloudy	2	Е	0.7	240	N/A	N/A
48	10MAY20 18	23:00	Partly cloudy	2	Е	0.3	290	51	Slightly stable
49	10MAY20 18	23:30	Partly cloudy	1	Е	0.1	240	51	Slightly stable
50	10MAY20 18	00:00	Partly cloudy	2	Е	0.2	240	N/A	N/A
51	11MAY20 18	19:30	Clear	1	W	0.3	350	N/A	N/A
52	11MAY20 18	20:00	Clear	2	NW	0.1	330	50	Moderately stable
53	11MAY20 18	20:30	Clear	1	NW	0.4	310	50	Moderately stable
54	11MAY20 18	21:00	Clear	1	NW	0.2	400	N/A	N/A
55	11MAY20 18	21:30	Clear	1	N/A	N/A	200	N/A	N/A
56	11MAY20 18	22:00	Clear	1	N/A	N/A	220	N/A	N/A
57	11MAY20 18	23:00	Clear	1	N/A	N/A	350	50	Slightly stable

Table S3. Results of Cramer's V analysis for the association between the structures of the observed profiles (i.e., cases 1, 2, and 3) and sky conditions (i.e., clear, partly cloudy, and cloudy).

Slaw condition	Occurrence			Cramer's V analysis				
Sky condition	Case 1	Case 2	Case 3	Pearson Chi-square value	Cramer's V value	Significance (<i>p</i> -value)		
Clear	15	1	0					
Partly cloudy	6	12	10	28.33	0.50	< 0.001		
Cloudy	2	4	8					

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Table S4. Comparison of data collection characteristics of radiosondes, tethered balloons, and copter Unmanned Aerial Vehicle (UAV) for typical measurements of potential temperature, specific humidity, and ozone. For comparison purposes, the height between readings, the number of data points, and the time period to collect data correspond to an altitude profile from 0 to 500 m. The UAV characteristics are for the operational conditions of this study. The characteristics of radiosondes and tethered balloons are adapted from Balsley et al. [75].

	Radiosonde	Tethered Balloon	UAV
Ascending Speed (m s-1)	5	1.8	0.5
Data read frequency (Hz)	0.5	0.1	0.1
Height between readings (m)	10	20	5
Dwell time at each reading (s)	2	10	10
Number of data points	50	25	100
Time period to collect data (min)	1.7	4.2	17
Max altitude coverage (km)	> 30	< 1-2	< 2.5
Max Payload weight (kg)	< 3	100	< 5
System cost (10 ³ \$)	10	10-200	5
Cost per profile	Low-High	Low	Very low
Operational wind speed limit (m s ⁻¹)	< 10	< 12	< 8
All weather	Yes	No	No