River Breezes for Pollutant Dispersion in GoAmazon2014/5

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Atmospheric
Chemistry
and Physics
Discussions

1   **Abstract**

2   The effect of river breezes on pollutant plume dispersion or canalization in the central

3   Amazon was evaluated. A pollution plume changes atmospheric composition downwind of

4   Manaus, a city of 2 million people positioned at the confluence between two wide rivers. Herein,

5   to evaluate the effects of river breezes, two cases were modeled at the mesoscale for March

6   2014. The first case, "with rivers" (wR), simulated the transport and chemistry of the Manaus

7   pollution plume as the rivers were in reality. The second case, "without rivers" (woR), carried

8   out simulations for which all rivers and floodable areas were replaced by forest. The three main

9   conclusions are as follows: (1) Between the two cases, alterations in wind speeds were maximum

10   at local noon, and river breezes influenced horizontal wind fields from surface up to 150 m in

11   altitude, suggesting a capping height of 150 m on most days for the influence of river breezes on

12   pollutant concentrations. In agreement with this modeling result, data sets collected at 500 m by

13   aircraft flights showed no apparent influence of the underlying rivers on plume dispersion. The

14   flights traversed the plume downwind of Manaus during the *Observations and Modeling of the*

15   *Green Ocean Amazon* (GoAmazon2014/5) Experiment. (2) Between the wR and wOR cases,

16   changes to downwind concentrations of O_3, NO_x, and CO pollutants were < 6% as a monthly

17   average at the supersite "T3" of GoAmazon2014/5, which was 70 km downwind of Manaus and

18   located between the two main rivers. As single events at T3, maximum one-hour concentration

19   differences were 39 ppb for O_3, 5 ppb for NO_x, and 26 ppb for CO. (3) For a focus on the surface

20   layer of the rivers (0 to 150 m in height), river breezes increased the monthly average O_3, NO_x,

21   and CO surface concentrations by 25%, 25%, and <5%, respectively. In addition, strong

22   canalization occurred 5% of the time based on a difference of 10 ppb in the surface

23   concentrations of at least two of O_3, NO_x, and CO between the wR and wOR cases. In

24   conclusion, although pollutants dispersed by river breezes could at times be a strong effect on

25   observed pollutant concentrations in the surface river boundary layer, overall most pollution was

26   transported at heights well above the effects of the river breezes and moved downwind along the

27   trajectories of the dominant trade winds.

Atmospheric
Chemistry
and Physics
Discussions

1. Introduction

28

29　　Amazonia represents the single largest hydrographic basin of water volume on Earth

30　(Sioli, 1984). Land coverage by rivers constitutes 5% of the total 7 million square kilometers of

31　the Amazon basin during dry season, while in the wet season the rivers increase in horizontal

32　extent by flooding, reaching a surface coverage of 11% of Amazonia (Hess et al., 2015). An

33　important confluence of wide rivers occurs nearby Manaus, a city of more than 2 million people

34　located at {3.0° S, 60.0° W} in the central Amazon (Figure 1). The Rio Negro ("Black River")

35　flows from the northwest to join the Amazon River, known in Brazil as the Rio Solimões to the

36　west of Manaus and the Rio Amazonas to the east of Manaus. River width around Manaus varies

37　from 2 km in narrow sections to 20 km in broader sections.

38　　Wide rivers such as these can induce important atmospheric processes, among which are

39　river breezes (Oliveira and Fitzjarrald, 1993; Dias et al., 2004; dos Santos et al., 2014). River

40　breezes arise from the unequal heating of land and water bodies. In the morning, land heats faster

41　than water, inducing an ascendancy of air over the land and a corresponding subsidence over the

42　river. In this way, surface winds go from the river toward the land. At an altitude of a few

43　hundred meters, the circulation cell is closed, and the winds go from the land to the river, with

44　subsidence over the central portion of the river. The height of the cell depends on the thermal

45　characteristics of the circulation. At night, the opposite behavior occurs (i.e., the cell reverses)

46　because the river cools more rapidly than land.

47　　These river breeze circulations at day and night can be important for the local weather

48　and pollutant dispersion. For instance, during times of weak trade winds Dias et al. (2004) found

49　that river breeze circulation explained the occurrence of clouds on the eastern bank yet an

Atmospheric
Chemistry
and Physics
Discussions

50 absence on the western bank at the confluence between the Amazon and Tapajós rivers, about

51 600 km to the east of Manaus.

52   Oliveira and Fitzjarrald (1993, 1994) studied the river breezes in the Manaus region

53 during the Amazon Boundary Layer Experiments (ABLE) (Garstang et al., 1990; Harriss et al.,

54 1990). Based on observations of the meridional component of wind speed, the river breezes were

55 reported as more intense during the dry season than in the wet season, as explained by greater

56 contrast between river and land temperatures given the greater average insolation of the dry

57 season. Simulations further suggested that the river breeze induced by the Rio Negro

58 significantly affected the surrounding daytime surface winds to a distance of 20 km from the

59 rivers (Oliveira and Fitzjarrald, 1994). The modeled distance was further than initially expected

60 based on earlier modeling studies, and the key difference appeared to be an improved

61 representation of the planetary boundary layer (PBL) in the model.

62   As part of the Large-Scale Biosphere-Atmosphere Experiment in Amazonia-Cooperative

63 LBA Airborne Regional Experiment-2001 (LBA-CLAIRE-2001), Trebs et al. (2012) traveled by

64 boat to four locations on the Rio Negro and one on the Solimões River. Daily reversals in surface

65 winds were attributed to river breezes. Measurements were made of NO, NO_2, and O_3 surface

66 concentrations, and pollution was identified at surface river locations from 10 to 150 km

67 downwind from Manaus. On at least one day, a reversal in wind direction caused by the

68 afternoon influence of the river breeze was associated with a shift in concentrations

69 representative of background and polluted conditions. Manaus pollution directed by the river

70 breezes appeared to be the explanation. The important data sets of this study were, however,

71 overall sparse (i.e., 8 days of July 2001; Manaus population of 1.2 million at that time), and the

72 recommendation by the authors was therefore to implement long-term monitoring stations

Atmospheric
Chemistry
and Physics
Discussions

73   downwind Manaus and to apply mesoscale modeling to better understand river breeze effects on

74   the dispersion of the Manaus pollution plume.

75   In 2014 and 2015, the Observations and Modeling of the Green Ocean Amazon

76   (GoAmazon2014/5) Experiment was carried out to study the effects of pollutant outflow from

77   Manaus on atmospheric chemistry, regional climate, and terrestrial ecosystems of an otherwise

78   typically clean background environment (Martin et al., 2016). Under fair-weather conditions, the

79   pollution plume was carried westward by equatorial trade winds (Kuhn et al., 2010; Martin et al.,

80   2017). The GoAmazon2014/5 terrestrial supersite, called "T3", was 70 km to the west of Manaus

81   (Figure 1).

82   An important question for the GoAmazon2014/5 experiment was to what extent river

83   breezes might disperse or canalize Manaus pollution, thereby possibly influencing the

84   interpretation of data sets collected at the T3 supersite. For a limiting case of full river

85   canalization, no pollution would reach the T3 site. For an opposite limiting case of weak or no

86   river breeze effects, all pollution would follow the stable trade winds when fair-weather

87   conditions prevailed, and air parcels sampled at the T3 site would be interpreted in a fully

88   Lagrangian framework downwind of the Manaus source region. Between these limiting cases,

89   partial dispersion of the Manaus pollution plume would be possible. In the context of these

90   possibilities and in light of the work of Oliveira and Fitzjarrald (1993, 1994) and Trebs et al.

91   (2012), the study herein presents an analysis of how the rivers around Manaus affect downwind

92   pollutant dispersion or canalization. The analysis uses mesoscale WRF-Chem modeling and

93   GoAmazon2014/5 data sets.

Atmospheric
Chemistry
and Physics
Discussions

2. Simulations

2.1 *Model Description*

The *Weather Research and Forecast model coupled with Chemistry* (WRF-Chem) is described by Grell et al. (2005). Version 3.6.1 was used for the present study. A two-domain configuration was used (Medeiros et al., 2017). The inner domain represented an area of 302 km × 232 km, had a horizontal resolution of 2 km × 2 km, and had 38 vertical layers from ground to 160 hPa. The outside boundaries of the inner domain were forced by data from an outer domain. The outer domain represented an area of 1050 km × 800 km, had a resolution of 10 km × 10 km, and had 38 vertical layers from ground to 160 hPa. Both domains were centered on {2.908° S, 60.319° W}. The meteorology of the outside boundary of the outer domain was forced by the *Climate Forecast System Reanalysis* (CFSv2) product of the National Center for Environment Prediction (NCEP) at a temporal resolution of 6 h and a spatial resolution of 0.5° (Saha et al., 2011). The inputs of surface temperature were also considered based on CFSv2 product. The chemical composition of the outside boundary of the outer domain was forced by the Model *for Ozone and Related chemical Tracers* (MOZART-4) (Emmons et al., 2010).

Data of the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite at a resolution of 500 m were used for land cover (Channan et al., 2014). These data were used as obtained for the case of "with rivers" (wR). For the case of "without rivers" (woR), the rivers and main flooded areas of MODIS land cover were replaced by forest in the pre-processor of the WRF-Chem model.

The physics parametrizations used in the simulations were described previously (Ying et al., 2009; Misenis and Zhang, 2010; Gupta and Mohan, 2015), including for the study region in the central Amazon (Medeiros et al., 2017). The parametrizations treated the physics of the

Atmospheric
Chemistry
and Physics
Discussions

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117　surface layer (Grell et al., 1994), the land surface (Chen et al., 1997), the boundary layer (Hong

118　et al., 2006), shortwave radiation (Chou and Suarez, 1999), longwave radiation (Mlawer et al.,

119　1997), cloud microphysics (Lin et al., 1983), and cumulus clouds (Grell and Freitas, 2014). At

120　Figure S1, the comparison between observed and simulated temperature, relative humidity and

121　wind speed at "T3" supersite show that the simulations performed herein represent the diurnal

122　cycle of these variables.

123　　　For chemical parametrizations, the *Model of Emissions of Gases and Aerosols from*

124　*Nature* (MEGAN, version 2.1) (Guenther et al., 2012) was used for biogenic emissions.

125　Anthropogenic emissions from transport, power, and industry for Manaus in 2014 were based on

126　the emission inventory of Medeiros et al. (2017). The *Regional Acid Deposition Model*

127　(RADM2) was used to simulate gas-phase chemistry (Chang et al., 1989).

128　2.2 *Model Runs*

129　　　Simulations of the wR and woR cases were carried out for all days in March 2014. Other

130　characteristics between the two simulations remained the same. This approach aimed to isolate

131　the river breeze effects on the transport of pollutants downwind of Manaus. For time zero, the

132　inner and outer domains were both initialized to CFSv2 and MOZART-4. A spin-up time of 24 h

133　was used, which was sufficient to fully replace the air of the inner domain. After the spin-up

134　period, simulations in lots of 72 h were performed for March 2014 as a balance between

135　conserving computing resources and avoiding excessive numerical drift (Medeiros et al., 2017).

136　**3. Data Sets**

137　　　Data sets were collected during the first intensive operating period (IOP1) of the

138　GoAmazon2014/5 project by instrumentation of the G-159 Gulfstream I (G-1) of the ARM

139　Aerial Facility (AAF) of the USA Department of Energy (Schmid et al., 2014; Martin et al.,

Atmospheric
Chemistry
and Physics
Discussions

140   2017). Concentrations of O_3 (Thermo Scientific Model 49i), NO_x (airborne NO_x analyzer, Air

141   Quality Devices), and CO (Los Gatos 23r) were measured. The aircraft performed 16 flights

142   during IOP1. Data sets of two flights (March 14 and 21) were chosen for analysis herein based

143   on flight tracks over both river and land while cutting across the Manaus pollution plume at an

144   altitude of approximately 500 m. There were no flights at lower altitude.

145   **4. Results and Discussion**

146   4.1 *Height of River Breeze Circulation Cell*

147   The effect of river breezes on horizontal wind speeds was evaluated. As monthly means,

148   the left column of Figure 2 presents the wR case, and the right column shows the differences

149   between the wR and woR cases. The rows represent plots at surface, 100-m altitude, and 500-m

150   altitude. Comparison between columns shows that the river breezes significantly affected mean

151   surface wind speeds but that the effects decreased with altitude.

152   The change of horizontal wind speeds with altitude is presented in detail in Figure 3

153   through height cross sections along points A, B, and C above the Rio Negro nearby Manaus (cf.

154   Figure 1). Panels in Figure 3 show wind speed differences between the wR and woR cases for all

155   times as well as for 00:00, 06:00, 12:00, and 18:00 (local time). In the absence of solar radiation

156   (i.e., at 00:00 and 18:00 local), the differences in horizontal wind speeds were relatively small.

157   The strongest differences were at noon corresponding to maximum daily solar irradiance, as

158   expected, because of the largest thermal gradients between land and river at these times (Oliveira

159   and Fitzjarrald, 1993, 1994; Dias et al., 2004; Fitzjarrald et al., 2008; de Souza and dos Santos

160   Alvalá, 2014; dos Santos et al., 2014; de Souza et al., 2016). The river breeze effect was

161   confined to less than 150 m, as shown in the monthly average plot of Figure 3. Across individual

162   days, the maximum and minimum heights for significant noontime river breeze effects were 300

163   and 60 m, respectively (results not shown). Overall, the results of Figures 2 and 3 lead to the

164   conclusion that the river breeze effect on wind speeds was confined on most days to below 150

165   m in altitude, even under high noontime solar irradiance.

166   For comparison, aircraft data sets of O_3, NO_x, and CO concentrations from 500-m altitude

167   are plotted in Figure 4 (Martin et al., 2017). Carbon monoxide was mostly inert on the time

168   scales of the simulations, oxides of nitrogen were significantly lost during downwind transport,

169   and ozone was a secondary pollutant rapidly produced within Manaus and over the nearby rivers,

170   quickly reaching steady-state concentrations (Medeiros et al., 2017; Rafee et al., 2017). The

171   panels of the left column of Figure 4 show that the flight paths intercepted the Manaus pollution

172   plume in the planetary boundary layer on March 14 from 10:20 to 11:20 (local time; UTC - 4 h).

173   The panels of the right column show that interception took place on March 21 from 13:00 to

174   14:00. Below each map, concentrations along the flight tracks are plotted, and the red shading

175   represents times that the aircraft was over a river. The results show that there was no obvious

176   influence of river breezes on the dispersion of the Manaus pollutant plume at 500 m. Although

177   Figure 4 shows only two flights, which were selected for substantial data coverage over both

178   river and land during a single flight, all 16 flights from March 2014 were investigated, and a

179   strong river breeze effect was not apparent in any of them (analysis not shown). The aircraft data

180   sets thus corroborate the tendencies represented in Figures 2 and 3 that the effects of rivers

181   presence on plume dispersion are confined to the surface boundary layer over the rivers,

182   typically below 150 m.

183   4.2 *Effects of River Breezes on Downwind Concentrations*

184   The "T3" GoAmazon2014/5 terrestrial supersite was located at {-3.2133 N, -60.5987 E},

185   approximately 70 km to the west of Manaus and in the dominant direction of prevailing trade

Atmospheric
Chemistry
and Physics
Discussions

186   winds that passed through Manaus (Figure 1). The panels in the top row of Figures 5, 6, and 7

187   show O_3, NO_x, and CO concentrations, respectively, at the T3 location for the wR case as the

188   blue line, the woR case as the red line, and their difference as the black line. The pollutant

189   concentrations did not change greatly in the presence or absence of the rivers. Quantitatively, the

190   perturbations caused by the presence of the rivers on the O_3, NO_x, and CO concentrations were

191   less than 6%. Maximum one-hour concentration differences were 39 ppb for O_3, 5 ppb for NO_x,

192   and 26 ppb for CO across the month. The overall implication is that the effects of the trade winds

193   on transport largely dominated over the influence of river breezes in this region when

194   considering the larger part of Manaus pollutant outflow, in agreement with the modeling and

195   observational results of section 4.1.

196   4.3 *Surface River Concentrations*

197   Two locations "R1" and "R2" were chosen to evaluate pollutant dispersion and

198   canalization in the river surface layer (0 to 150 m). Based on the prevailing trade winds location

199   R1 at {-3.0699 N, -60.2199 E} consistently intercepted the urban outflow (Figure 1). By

200   comparison, location R2 at {-2.9800 N, -60.4901 E} was nominally outside of the trajectories of

201   the trade winds that passed over and then downwind of Manaus. For the analysis, the simulated

202   pollutant concentrations at R2 were compared to those at R1 in the wR and woR cases to test the

203   extent of river canalization of the plume, meaning transport of air parcels along the river rather

204   than in the prevailing direction of the synoptic-scale trade winds.

205   The time series of the simulated O_3, NO_x, and CO concentrations at the R1 and R2

206   locations are plotted in Figures 5, 6, and 7. Blue lines show the wR case, red lines show the woR

207   case, and black lines represent their difference. At R1, the differences of (wR - woR) were

208   significant, in particular for concentrations of O_3 (+28.4%) and NO_x (+26.0%) (Table 1, monthly

Atmospheric
Chemistry
and Physics
Discussions

209   means). Strong differences were also simulated at R2 for O_3 (+25.5%) and NO_x (+25.6%). The

210   river breezes thus shifted the surface level dispersion pattern of the Manaus plume. At both sites,

211   the differences were smaller (< 5%) for CO concentrations because regional background

212   concentrations exceeded the Manaus contribution. Absolute changes (± ppb) for four time

213   periods across the day are listed in Table S1 of the Supplementary Material. The difference

214   between the wR and woR cases exceeded 10 ppb at R2, which can be called strong canalization,

215   for at least two pollutants at 5% frequency for March 2014.

216   An example of strong canalization occurred for the simulation on March 2 at 13:00 (local

217   time). The three columns of Figure 8 show the wR case, the woR case, and their difference, all at

218   surface altitude. The three rows show results for O_3, NO_x, and CO. For the wR case, a small

219   portion of the pollution plume traversed the course of Rio Negro to the northwest, following the

220   local wind field. A boat collecting surface samples would report increases of O_3 by 20 ppb and of

221   CO by 10 ppb. Overall, comparison of the wR and woR case shows that the simulated plume was

222   tighter with less transverse spreading in the absence of rivers. In both the wR and woR cases,

223   most pollution followed the predominant direction of the trade winds, and the effects of river

224   canalization on diverting the plume were small by comparison.

225   In summary, this study evaluated the effects of river breezes on pollutant plume

226   dispersion or canalization in the central Amazon. The simulations showed that the horizontal

227   monthly mean wind speeds were significantly altered by river breezes to altitudes of 75 m as

228   monthly 24-h means and to 150 m for monthly averages across the maximum noontime solar

229   radiation. The strongest effects of river breezes on pollutant dispersion were thus from 0 to 150

230   m above the river surface. Aircraft data confirmed the absence of observable effects of river

231   breezes on plume dispersion at flight level (500 m). Overall, the perturbation on pollutant

232   concentrations downwind of Manaus at "T3" GoAmazon2014/5 supersite was modeled as below

233   6%, consistent with pollutant transport mostly above 150 m. At river surface level, the monthly

234   average O_3, NO_x, and CO surface concentrations increased by 25%, 25%, and <5%, respectively.

235   Differences in surface river concentrations exceeded 10 ppb for at least two pollutants at a

236   frequency of 5% for March 2014. The overall conclusion is that the Manaus pollution plume

237   dispersion could at times be partially canalized leading to significant changes of surface river

238   concentrations even as most pollution passed overhead of the river circulation cell and

239   dominantly followed trajectories along the prevailing overhead trade winds.

Atmospheric
Chemistry
and Physics
Discussions

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and Physics
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Atmospheric
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Discussions

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Atmospheric
Chemistry
and Physics
Discussions

List of Figures

Figure 1. Satellite image of the Manaus region. The Rio Negro comes from the northwest, and the Rio Solimões arrives from the west. The confluence of the two rivers is to the southeast of Manaus, beginning the Amazon River ("Rio Amazonas"). Yellow markers show locations of (i) the measurement supersite called "T3", (ii) two river locations "R1" and "R2" considered in the modeling methodology herein, and (iii) points "A", "B", and "C" along a river cross section, also used in the methodology herein.

Figure 2. Mean horizontal wind speeds for March 2014. The left column represents the base case wR ("with rivers"). The right column represents the difference case (wR - woR) ("with rivers compared to without rivers"). Rows represent altitude as (1) near surface, (2) 100 m, and (3) 500 m.

Figure 3. Difference in mean horizontal wind speed for (wR - woR) ("with rivers compared to without rivers"). Plots are shown as vertical cross sections along points A, B, and C of the Figure 1 as follows: (a) for all of March 2014, (b) at 00:00, (c) at 06:00, (d) at 12:00, and (e) at 18:00, all in local time (UTC - 4 h).

Figure 4. Concentrations of O_3, NO_x, and CO measured by instrumentation on board an aircraft during GoAmazon2014/5 at an altitude of approximately 500 m (Martin et al., 2017). Concentrations are plotted in false color, and the legends on the right-hand side of each row show the scaling. Below each main panel, a line plot shows the concentrations marked by points A through H along the flight paths. Red shading demarcates periods when the aircraft was flying over a river.

Figure 5. Time series of O_3 concentrations at the T3, R1, and R2 locations. The left column plots

Atmospheric
Chemistry
and Physics
Discussions

Open Access

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the cases of wR ("with rivers"; blue) and woR ("without rivers"; red). The right

column shows the difference in concentrations as (wR - woR).

Figure 6. Time series of NO_x concentrations at the T3, R1, and R2 locations. The left column

plots the cases of wR ("with rivers"; blue) and woR ("without rivers"; red). The right

column shows the difference in concentrations as (wR - woR).

Figure 7. Time series of CO concentrations at the T3, R1, and R2 locations. The left column

plots the cases of wR ("with rivers"; blue) and woR ("without rivers"; red). The right

column shows the difference in concentrations as (wR - woR).

Figure 8. Near-surface concentrations of (a) O_3, (b) NO_x, and (c) CO (March 2, 13:00 local time,

UTC - 4 h). The first and second columns represent the cases of wR ("with rivers")

and woR ("without rivers"), respectively. The vector field in each panel shows the

near-surface horizontal winds. The third column shows the difference in

concentrations as (wR - woR). For reference, the locations of T3, R1, and R2 are

marked.

Atmospheric
Chemistry
and Physics
Discussions

Open Access

Table 1. Percent change in pollutant concentration X for the case of wR ("with rivers")
compared to that of woR ("without rivers"), calculated as $(X_{wR} - X_{woR})/X_{wR}$, where X is
the monthly mean at a location T3, R1, or R2 for each of O_3, NO_x, and CO.

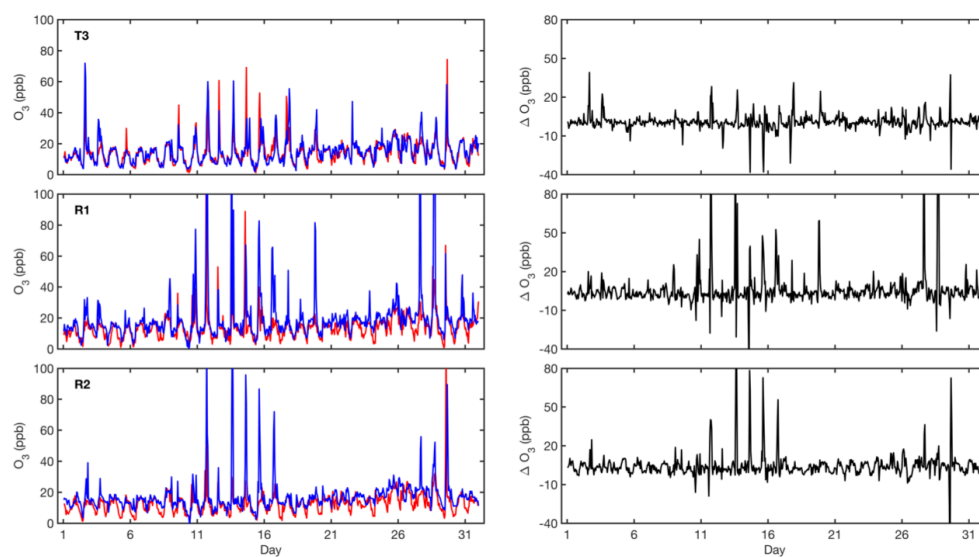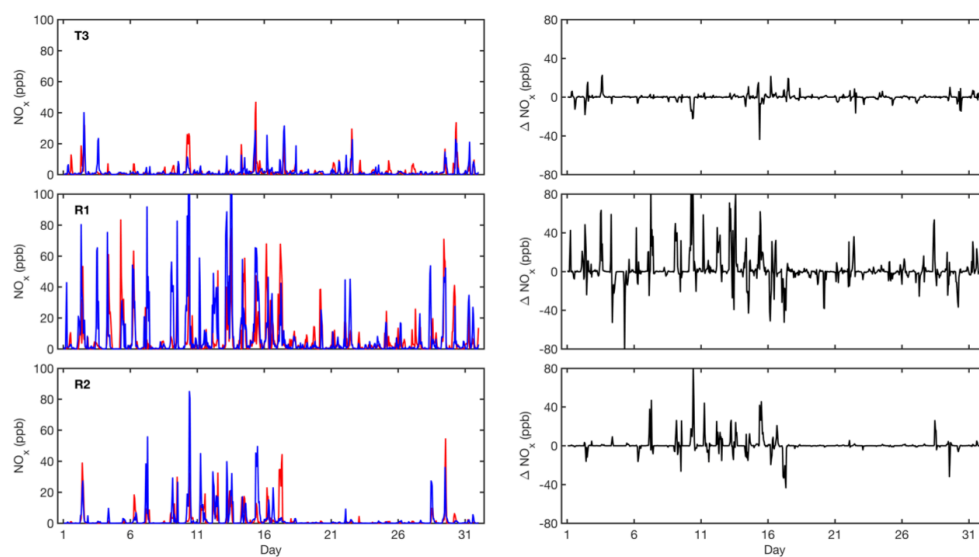|	O_3	NO_x	CO
T3	+5.5%	-4.6%	+1.2%
R1	+28.4%	+26.0%	+2.9%
R2	+25.5%	+25.6%	+2.6%

Figure 1

Figure 2

Figure 3

Figure 4

Atmospheric
Chemistry
and Physics
Discussions

Figure 5

Figure 6

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Chemistry
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Discussions

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Atmospheric
Chemistry
and Physics
Discussions

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Figure 8