Responses to review of "Integration of Airborne and Ground Observations of Nitryl Chloride in the Seoul Metropolitan Area and the Implications on Regional Oxidation Capacity During KORUS-AQ"

We would like to thank the thoughtful comments from the reviewers. We have revised the paper after carefully considering each comment. Reviewer comments are in *black*, authors' responses are in *blue*, parts that have been added to the manuscript are in ***bold blue***.

Anonymous Referee #1

The authors have addressed most of my comments. However, there are two important points requiring author's further consideration and follow up.

First is on CIMS. More information on the sampling line needs to be provided. What is the length? How often was it cleaned? Although ClNO2 has small loss in the sampling line, N2O5 can be converted to ClNO2 (i.e., give positive bias) if the sample line is not washed frequently. Was this potential bias tested during the field study? If not, need to mention this interference to ClNO2. Also please provide information on CIMS's sensitivity and detection limit or give a reference on them.

The information requested is added to the manuscript as below:

> **(Ln 124-127) "The lengths of the inlet lines of the three CIMS systems were 20 - 30 cm. The PTFE inlet line at the TRF site was washed on a weekly basis and the ones at the OP and DC-8 were not washed routinely during the campaign due to difficulties on detaching the inlet. The potential bias of interactions of Cl_2 and $ClNO_2$ inside the inlet were not tested but the artifacts have been shown to be negligible in various field conditions (Riedel et al., 2012; Thornton et al., 2010; Liao et al., 2014)."**
>
> **(Ln 155-156) "The averaged sensitivity of Cl_2 was 31.5 ± 11.2 Hz/ppt and $ClNO_2$ was 19.7 ± 1.5 Hz/ppt. The 2 sigma detection limits of Cl_2 and $ClNO_2$ were 2.9 and 1.5 ppt, respectively, over 30 min."**

Another concern is on the attribution of second morning peak. I am still not convinced that it is caused by horizontal transport.

From the chemical point of view, the ClNO2 is formed after sunset, and such formation process continues throughout the night until sunrise. Starting from sunrise, the production of N2O5 and then ClNO2 should be negligible (due to the short lifetime of NO3 after sunrise), but the loss of ClNO2 from photolysis starts to govern the ClNO2 levels which results in decreasing ClNO2 in a certain bulk of air mass.

From the transport point of view, ClNO2 can be produced in the west coast of Korea during the night, and the westerly wind brings ClNO2 to the middle of Korea, and such transport should happen continuously. If the wind doesn't change significantly during the second peak (as in the present study), the same bulk of air mass from the west coast should influence the observation site continuously. And according to the chemical budget of ClNO2 (in the previous point), the ClNO2 level in this bulk of air mass should decrease after the sunrise, and no second peak should be observed.

However, the second peaks were always observed between 7-8 a.m., not before nor after. Such phenomenon is most likely linked to the break-up of the nocturnal boundary layer and the entrainment process after the sunrise. In fact, there is evidence for this downward transport. In figure 6(b), for the second morning peak, ClNO2 increases concurrently with ozone and SO2, which can be interpreted as transport of ozone and SO2 (from elevated point source) from the nocturnal layer. The aircraft measurements at 8:00 did not record elevated ClNO2, maybe because the aircraft did not sample the ClNO2 rich airmass at right location/time.

Therefore, I advise the author to carefully re-consider the explanation of the second morning peak.

We agree on the comments by referee #1 on the possibility of vertical transport of $ClNO_2$ rich air from the residual layer from the west part of the ground sites. We have revised the manuscript and the conclusion of our study accordingly.

Manuscript revised as below:

> **(Ln 11-12) "...these high levels of $ClNO_2$ in the morning are likely from vertical or horizontal transport of air masses from the west."**
>
> **(Ln 299-300) "Therefore, horizontal or vertical transport from local sources would be the most likely explanation for the high $ClNO_2$ in the morning."**
>
> **(Ln 320-325) "However, it is possible that the air mass that was measured by the DC-8 was not representative of the air mass aloft at the west side of the ground observation sites. Backtrajectory analysis initialized at 9:00 local time showed that the TRF site was affected by both the residual layer and below (Figure S10). The enhancement of O_3 and SO_2 concurrent to elevation of $ClNO_2$ could be due to the transport from the residual layer where pollution from high point sources from the other day was trapped within. From the current dataset, it would be difficult to derive a clear conclusion on whether the cause of the significant $ClNO_2$ in the morning was dominantly of transport from horizontal, vertical, or both."**
>
> **(Ln 355-357) "However, there is still a possibility of the contribution of vertical transport from the residual layer. Although the current data set is limited for us to**

pinpoint on the vertical locations (i.e., boundary layer v.s. residual layer), it is clear that the $ClNO_2$ rich air masses were mostly transported from the west coast where there are significant sources of precursors.”

Additional analysis has been added in the supporting as below:

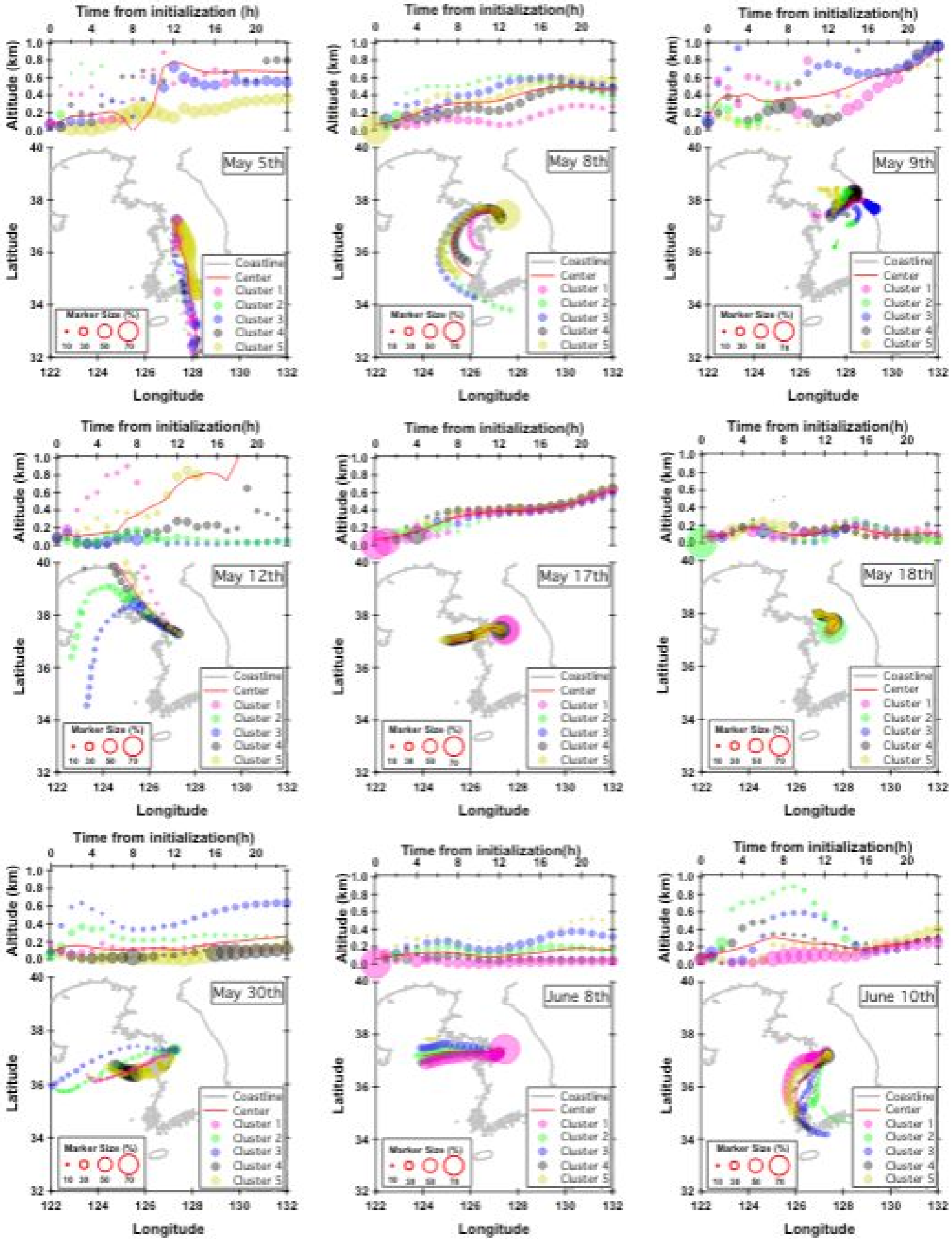

Figure S10. FLEXPART backtrajectories of the selected days when a second $ClNO_2$ peak was observed at TRF. Each run was initialized at 9:00 local time and each marker is an hour backward of its previous. The red line represents the center of the mass-weighted particles and the clusters are factional contributions of airmasses in percentage.

Minor points:

1. Response (1) and the corresponding changes in the manuscript, “during a severe have event” should be “during a severe haze event”.
Changed

2. Response (20) and the corresponding changes in manuscript, “ClONO2 and HOCl were set to 0.06”. Do you mean “the uptake coefficients of ClONO2 and HOCl were set to 0.06”?
Yes, the corresponding part has been written as below:
“...γ_{ClONO2} and γ_{HOCl} were set to 0.06”

Anonymous Referee #2

The authors have provided a thoughtful response to the original review. While the manuscript has been greatly improved, there are a few remaining issues that have not been fully addressed in the updates. The primary concerns are (1) the description of each type of box model simulation and (2) the role of vertical vs. horizontal mixing as a primary source of surface-level ClNO2.

Lines 112 – 114 – The authors have improved the manuscript with a description of the meteorological events observed during the study. However, neither Figure 2 nor 3 appear to explicitly show the meteorological conditions as described in this section. The only indicator seems to be the source contribution from the ocean. Please clarify how the different meteorological conditions are represented in these time series. In addition, please define or explain a ‘Rex block pattern’.
Line 232 – Same comment here. It is not clear how Figure 3 represents the different meteorological conditions experienced at the sites. Please update the figure or add clarification in the text.

We were referring to the arrows at the bottom of Figures 3a and 3b for showing the time frames of when the different meteorological conditions governed during the observation period. Reference to ‘Figure 3’ has been removed from the sentence for less confusion and the caption for Figure 3 has been revised as below:

> **(Figure 3 caption) “...The time frames for each meteorological condition that dominated during the observation period are classified in black arrows at the bottom of the Figures 3a and 3b.”**

An additional explanation on the ‘Rex block pattern’ has been added as below:

> **(Ln 116-117) “Rex block patterns were observed during the blocking period (June 1st - 6th). During this period, a high pressure system was adjacent to a low pressure over the Korean peninsula resulting in more local influence with occasional stagnation.”**

Line 232 only mentions about source contribution analysis and not about different meteorological conditions. Therefore, no changes have been made for Line 232.

Line 238 – Please specify that the stagnation events reported in Baasandorj et al., 2017 are during the winter season.

The related sentence has been re-written as below:

> **(Ln 250-252) "Previous studies have shown that these stagnant conditions can result in enhanced levels of N_2O_5 driven by high ozone and NO_2, as shown in Baasandorj et al. (2017) during a wintertime observation in the Salt Lake Valley, Utah."**

Section 2.3 – While the authors have provided many details in their update, it remains unclear exactly how the simulations were setup, how many different types of simulations were run (and what the similarities and differences were), as well as important missing details about the model treatment of boundary layer dynamics and deposition.

First, the authors need to state explicitly in the Section 2.3 of the main text what the duration of each model simulation was (i.e., 72 hours?) and the frequency at which the model was constrained with observations (i.e. every 100 minutes?). Currently, the supplement indicates a discrepancy where it states that the model duration is 1 day. However, it becomes apparent later in the main text that (at least) two different types of simulations were conducted (both 72 hour and 1 day simulations). The setup details (e.g., duration, initialization time, constraint frequency, any chemical/physical differences, number of simulations, etc.) are needed for each type of simulation in order to avoid confusion later. For instance, on Line 219, it is unclear what the 'end points' of 72-hour simulations are. Are these final mixing ratios at the end of different simulations? What time of day are the simulations set to end? How many individual simulations were run and what were the differences between them? At the moment, Section 2.3 reads as if there was only one type of simulation used.

Second, the authors need to include additional information about how boundary layer dynamics are treated in both the 72 and 24-hour simulations. For instance, how does the model treat the separation of the surface and residual layer at night and the entrainment of O3 in the morning? Does the model include deposition? These details are missing from both the main text and the supplement and are important for the accurate simulation of O3 production.

Third, on line 34 in the supplement, it is unclear what the authors mean by 'all the measured parameters'. Does this mean that all concentrations are held constant? All rate constants? All photolysis frequencies? Please clarify.

As stated in the first sentence of the 2.3 modeling section, there were 3 types of simulations carried out each represented in Figure 5, 8, and 10.

We revised it as below for clarification:

> **(Ln 158-160) "We used Framework for 0-D Atmospheric Modeling (F0AM v3.1) for simulating three types of simulations: 1) daytime Cl_2 production (Figure 5), 2) in-situ**

> **$ClNO_2$ production in the morning (Figure 8), and 3) testing the impact of measured $ClNO_2$ on the regional tropospheric chemistry (Figure 10).”**
>
> **(Ln 182-183) “More details on the setup of the box model and the main differences between the three types of simulations are in the supplement material (S3).”**

The duration of each of the model simulations are in the supplementary. The supplementary does not indicate that the model duration was 1 day. As stated in the supplementary, simulations for Figure 5 and Figure 8 are not runs simulating (or constrained with) a diurnal variation. Each step was constrained with a constant meteorology (e.g, j value) and observation at that time point to simulate Cl_2 or $ClNO_2$ at the corresponding time. These information can be found in the supplementary. For clarification, the sentences has been re-written as below:

> **(Supporting Information, Line 31-34) “The meteorology and the constrained trace gas observations corresponding to each time point were kept constant throughout the 72 hours of integration time and the final points of each of these 72 hour runs are shown in Figure 5.”**
>
> **(Line 165-167) “For simulations presented in Figures 5 and 8, a constant meteorology and trace gas observation set, collected at the corresponding time point, were constrained throughout the model run. For Figure 10, the model was constrained with a diurnal variation of the parameters.”**
>
> **(Line 181-182) “Boundary layer height, emissions, and depositions were not considered in the model.”**
>
> **(Line 335-336) “Since the box model simulations in our study did not take into consideration boundary layer height dynamics, emission, and deposition, this net production rate is the result of just chemical production and loss.”**

Paragraph on line 246 –In this section, instead of referring to the boundary layer at night, please clarify that the boundary layer splits into a nocturnal surface layer and a residual layer. This distinction will help clarify that the authors are discussing N2O5 and ClNO2 profiles at night in this section. In addition, since this is the first discussion of elevated N2O5/ClNO2 aloft, it seems to make more sense to move lines 278-281 to line 255.

The paragraph on line 246 wasn’t necessarily discussing about the residual layer but rather the possibility of higher $ClNO_2$ levels being present in the upper part of the nocturnal surface layer. On the other hand, the paragraph starting from lines 278-281 discusses specifically on $ClNO_2$ in the residual layer in the early morning. Therefore, to the best of our judgement, we would like to keep the sentences as they are.

Line 256 – Suggest changing this sentence to, “According to Baasandorj et al. (2017), O3 was completely titrated at the surface in Salt Lake Valley, Utah, while elevated mixing ratios of N2O5 were observed at 155m AGL, at a site along the valley wall.” These changes are meant to clarify that Baasandorj study reported ground measurements only, whereas the current text indicates that aircraft or tower measurements were collected.

The sentence has been re-written as suggested.

Line 258 – Specify the altitude range of data reported by Young et al. (2012).

The information on the altitude has been included as suggested:

> **(Line 271-273) “...showed a relatively uniform $ClNO_2$ profile throughout the nocturnal boundary layer as O_3 did not change significantly within the observed altitude range (< 600 m).”**

Lines 277 & 294 – Please clarify, when the authors state, ‘transport’, do they mean only horizontal transport or both vertical and horizontal transport? It seems that the authors are arguing that high ClNO2 levels are being transported horizontally to the ground sites from other (non-measured) sources to the west of the sites. It also seems possible, however, that ClNO2 is being produced aloft at night in the west and these concentrations are being transported both horizontally and vertically in the morning as the air parcel moves. Please clarify and discuss any evidence for the role of horizontal vs. vertical transport from the western region. In light of this possibility, it seems that the role of vertical mixing cannot be completely ruled out, as is currently suggested in the discussion section. I would suggest that the paragraph starting on line 278 clarify that while aircraft measurements collected to the south/east of the sites provided limited evidence of the role of vertical mixing contributions to elevated surface-level ClNO2, there may be enhanced vertical contributions from air parcels arriving from the west

We agree to the referee #2 comment. We have revised the manuscript and included additional FLEXPART analysis in the supporting information as below:

Manuscript revised as below:

> **(Ln 11-12) “...these high levels of $ClNO_2$ in the morning are likely from vertical or horizontal transport of air masses from the west.”**
>
> **(Ln 299-300) “Therefore, horizontal or vertical transport from local sources would be the most likely explanation for the high $ClNO_2$ in the morning.”**
>
> **(Ln 320-325) “However, it is possible that the air mass that was measured by the DC-8 was not representative of the air mass aloft at the west side of the ground observation sites. Backtrajectory analysis initialized at 9:00 local time showed that the TRF site was affected by both the residual layer and below (Figure S10). The enhancement of O_3 and SO_2 concurrent to elevation of $ClNO_2$ could be due to the**

transport from the residual layer where pollution from high point sources from the other day was trapped within. From the current dataset, it would be difficult to derive a clear conclusion on whether the cause of the significant $ClNO_2$ in the morning was dominantly of transport from horizontal, vertical, or both."

(Ln 355-357) "However, there is still a possibility of the contribution of vertical transport from the residual layer. Although the current data set is limited for us to pinpoint on the vertical locations (i.e., boundary layer v.s. residual layer), it is clear that the $ClNO_2$ rich air masses were mostly transported from the west coast where there are significant sources of precursors."

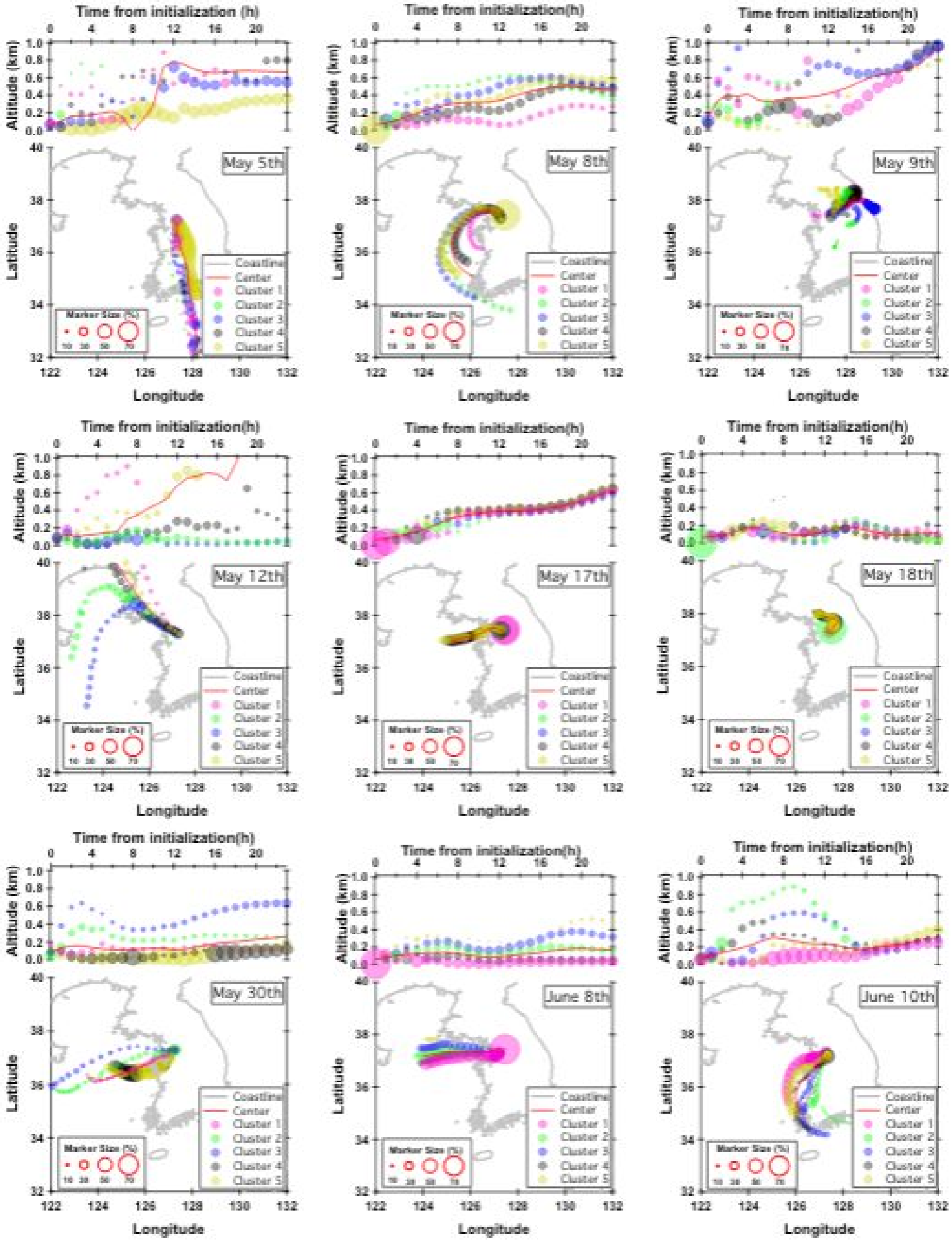

Figure S10. FLEXPART backtrajectories of the selected days when a second $ClNO_2$ peak was observed at TRF. Each run was initialized at 9:00 local time and each marker is an hour backward of its previous. The red line represents the center of the mass-weighted particles and the clusters are factional contributions of airmasses in percentage.

Figure 3 – With the author updates, it is now clear why the Cl2 data appear to have an offset in Figure 3. The below LOD data points, however, appear to be included in later figures, such as Figure 4. Please clarify why below LOD data were removed in Figure 3 and not others.

We removed data below the detection limit in Figure S7. In Figure 4, we included the Cl_2 data that were below the detection limit to allow comparison to $ClNO_2$ levels when there was limited O_3 and Cl_2 but significant $ClNO_2$. The caption of Figure 4 has been revised for clarification:

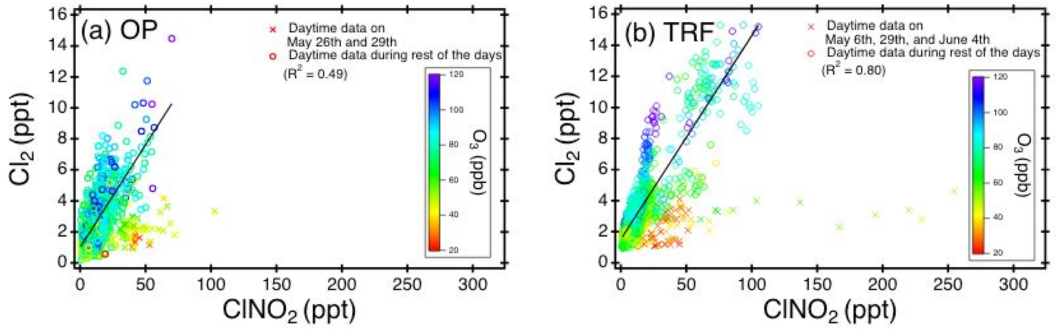

Figure 4. Scatter plot of daytime (11:00 - 18:00 local time) $ClNO_2$ and Cl_2 at (a) OP and (b)TRF, color coded with measured O_3. 5 min averaged data for the whole campaign were used for both sites. Data points of Cl_2 below detection limit (2.9 ppt, 2σ, over 30 min) are shown for the purpose of comparison to observed $ClNO_2$ levels.

Supp. Line 38 – Please clarify why dry surface area was used to calculate gamma(N2O5). This assumption will artificially increase the N2O5 rate constant as gamma(N2O5) is typically calculated using the wet aerosol surface area.

In our study, dry surface area from observations were not used in deriving the gamma(N_2O_5). As described in the paper, it was derived based on the Bertram and Thornton (2009) study where they used an empirical pre-factor in the equation. Other parameters used in deriving gamma are described in the Supporting Information section 3. The estimation by Bertram and Thornton (2009) can be an overestimation as mentioned in the first round of reviewer comments. However, the purpose of the box model simulations was to make sense whether the observed $ClNO_2$ levels were in the range that could be explained by in-situ chemistry. The box model results significantly underestimated the observations (~50 times), therefore leading to a conclusion that the second $ClNO_2$ peak in the morning is likely not from in-situ production.

Equation 1 – Please check the formatting of this equation in the final manuscript.
Will check the formatting.

Additional Minor Comments:
Line 6 – Change to, '…sites, the slope of which were dependent on O3 levels."
Changed

Line 29 – The authors have appropriately cited the discrepancies between field and laboratory results. It remains unclear, however, where the 'recommended' value comes from. Could the authors please specify. I only ask because both field and lab measurements have reported a wide range of values from < 1x10-4 to > 0.04.
The sentence regarding the 'recommended' value has been removed.

Line 62 – Change to, '…reported the highest-recorded mixing ratio of ClNO2 (8.3 ppbv)…'
Paragraph staring on line 65 – The authors might also want to include the recent modeling paper by X. Wang (2019) ACP, who simulated ClNO2 production in GEOS-Chem and found large contributions of this chemistry to daytime radical production.

Line 62 has been changed accordingly and Wang et al., (2019) has been added as below:

> **(Line 84-87) "A recent study by Wang et al. (2019) updated the standard version of the GEOS-Chem (Chen et al., 2017; Sherwen et al., 2016) to better track partitioning between aerosol chloride and gas-phase chlorine species. Comparison between their model simulations with and without $ClNO_2$ production showed enhanced O_3 up to 8 ppb during the winter season in Europe due to prolonged nighttime."**

Line 112 – Figure 3 is referenced before Figure 2.
Reference to 'Figure 3' has been removed.

Line 122 – Change, 'However' to 'In addition'
Changed

Line 129 – What is the 'blower' that the authors refer to? This isn't indicated in Figure S1.

The information of the blower has been added as below:

> **(Line 132-134) "A total of ~ 3000 standard liters per minute (slpm) was drawn in with a blower with an additional flow of 4 slpm drawn at the end of the inlet to reduce the residence time and 1 slpm was sampled into the CIMS."**

Line 149 – There are NOy species in addition to HONO and NO2 that would need to be subtracted to quantify the ambient ClNO2. These include, but are not limited to N2O5, NO3, NO, and HNO3. Please clarify whether these species were included in the subtraction or note that they were not and state the resulting bias.

As shown in Thaler et al., (2011), this method has been shown to not produce any other gas-phase NO_y byproducts. Therefore, we did not subtract the compounds mentioned in the comment from the total NO_y.

Line 165 – Just to clarify, ClNO2, Cl2, and ClONO2 photolysis frequencies were not included in TUV, but the authors incorporated the measured values into the F0AM model, correct? If so, please adjust the text accordingly.

Re-written as below:

> **(Line 174) "...taken directly from the DC-8 measurements to be used in the model runs in this study."**

Line 188 – Please report observations averaged over the same time period (i.e. 10 minutes) so that mixing ratios at different sites can be compared directly. Check for consistency throughout the manuscript when mixing ratio from the aircraft and ground sites are reported and compared to each other.

The $ClNO_2$ and Cl_2 observations from OP has been replaced with a 5 min averaged data.

Line 191 – Different nighttime correlations between Cl2 and ClNO2 may not only indicate different sources, but potentially different loss processes as well.

Re-written as below:

> **(Line 203-204) "This implies that the sources or potentially loss processes of Cl_2 and $ClNO_2$ were not consistent at night."**

Line 216 – Change, '1229 runs…' 'to '1229 points…'. Unless the authors did run 1229 simulations that were each 72-hours in duration.

We ran 1229 simulations, each for a 72 hour duration.

Line 310, 335 and abstract – The authors should specify that the percent increases only account for the chemical production of O3. This is an important point because net O3 production observed from the ground will also be influenced by the morning entrainment of O3 from aloft (which doesn't seem to be included in the model here).

Changes in boundary layer height and entrainment of O_3 from the residual layer in the early morning are not considered in the model. The following has been added as below for clarification:

> **(Line 12-13) "Box model results show that chlorine radical initiated chemistry can impact the regional photochemistry by elevating net chemical production rates of ozone by ~ 25 % in the morning."**
>
> **(Line 335-336) "Since the box model simulations in our study did not take into consideration boundary layer height dynamics, emission, and deposition, this net production rate is the result of just chemical production and loss."**

Line 324 – Change ‘on the’ to ‘of the’
Changed

Figure 4 – It is unclear why modeled Cl2 is compared to observed and not modeled ClNO2. This comparison could help provide additional validation of the model.

The purpose of the model was to validate whether the current understanding of the heterogeneous reactions can explain the daytime observed positive correlation between Cl_2 and $ClNO_2$ and its dependency on O_3 rather than reproducing the observed $ClNO_2$ levels from model simulations. The initial chlorine radicals can be produced from $ClNO_2$ photolysis, which were constrained with observations in the model. Other gas-phase precursors of chlorine radicals that are generated in the model include HCl, $ClONO_2$, Cl_2, and HOCl.

Supplement:
Section S3. – When the authors state that ‘average’ values were used, does that mean that a single value was used throughout the entire model simulation? Please clarify. Also, in this section, please change Figure references ‘Figure 4’ and ‘Figure 5’ to ‘Figure S4’ and ‘Figure S5’.

Since we did not have any aerosol size distribution data collected at the ground sites, we used airborne data measured over the sites at altitude below 1 km. Since the aerosol data collected airborne did not have a significant variation within 1 km, we used the average value for the box model simulations. Figures 4 and 5 in section S3 is referring to the figures in the main manuscript not the supporting information.

Revised as below:

> **(Supporting Information, Line 46-49) “Since we did not have any aerosol size distribution data collected at the ground sites, aerosol surface area was taken from airborne measurements. An averaged value was used from data retrieved below 1 km over the SMA. The airborne data did not show a significant vertical dependence within the daytime boundary layer.”**

References

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Integration of Airborne and Ground Observations of Nitryl Chloride in the Seoul Metropolitan Area and the Implications on Regional Oxidation Capacity During KORUS-AQ 2016

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Abstract. Nitryl chloride ($ClNO_2$) is a radical reservoir species that releases chlorine radicals upon photolysis. An integrated analysis of the impact of $ClNO_2$ on regional photochemistry in the Seoul Metropolitan Area (SMA) during the Korean-United States-Air Quality (KORUS-AQ) 2016 field campaign is presented. Comprehensive multiplatform observations were conducted aboard the NASA DC-8 and at two ground sites (Olympic Park, OP; Taehwa Research Forest, TRF), representing an urbanized area and a forested region downwind, respectively. Positive correlations between daytime Cl_2 and $ClNO_2$ were observed at both sites, ~~which were dependant~~ the slope of which were dependent on O_3 levels. The possible mechanisms are explored through box model simulations constrained with observations. The overall diurnal variations of $ClNO_2$ at both sites appeared similar but the night time variations were systematically different. For about half of the observation days at the OP site the level of $ClNO_2$ increased at sunset but rapidly decreased at around midnight. On the other hand, high levels were observed throughout the night at the TRF site. Significant levels of $ClNO_2$ were observed at both sites for 4-5 hours after sunrise. Airborne observations, box model calculations, and back trajectory analysis consistently show that these high levels of $ClNO_2$ in the morning are likely ~~due to the~~ from vertical or horizontal transport of air masses ~~within the boundary layer~~from the west. Box model results show that chlorine radical initiated chemistry can impact the regional photochemistry by elevating net ~~ozone production rates~~ chemical production rates of ozone by $\sim$ 25 % in the morning.

1 Introduction

Nitryl chloride ($ClNO_2$) is a night time radical reservoir that generates chlorine radicals ($Cl^{\cdot}$) upon sunrise (R1), with a lifetime (τ_{ClNO2}) of $\approx$ 30 minutes at midday in the northern hemisphere mid-latitude summer, under clear sky conditions ($J_{ClNO2} \approx 5.47\times10^{-04}$ s^{-1},(Madronich and Flocke, 1998)). It is produced through heterogeneous reaction of chloride (Cl^-) containing aerosols and dinitrogen pentoxide ($N_2O_5(g)$), which is generated from an equilibrium reaction with gas-phase nitrate radical ($NO_3^{\cdot}$) and nitrogen dioxide (NO_2) (R 2-4, (Finlayson-Pitts et al., 1989)). In acidic aerosols ($\approx$ pH 1.8), uptake of N_2O_5 (g) can also produce gas-phase chlorine (Cl_2, R5), resulting from enhanced $ClNO_2$ uptake coefficient of up to 3 - 4 orders of magnitude higher than neutral pH (Roberts et al., 2008). However, this reaction has yet to be proven in ambient conditions.

During the day, N_2O_5 exists at low levels due to its thermal instability (Malko and Troe, 1982) and the short lifetime of NO_3 ($\tau_{NO3} < 5$ s) from photolysis and reaction with NO (Wayne et al., 1991). Particulate Cl^- and chlorine containing gas species can come from both natural sources such as sea salt and biomass burning (Blanchard, 1985; Woodcock, 1953), and anthropogenic sources such as steel making, incineration, bleaching processes, and coal-fired power plants (Hov, 1985; Reff et al., 2009; Tanaka et al., 2000; Lee et al., 2018; Fu et al., 2018). The efficiency of $ClNO_2$ production depends on heterogeneous loss of N_2O_5, which is a function of the N_2O_5 aerosol uptake coefficient (γ_{N2O5}), aerosol surface area, and N_2O_5 mean molecular speed, as well as the yield of $ClNO_2$ (ϕ_{ClNO2}) (e.g., Thornton et al. 2003; Schweitzer et al. 1998; Behnke et al. 1997; Hu and Abbatt 1997; Bertram and Thornton 2009). ~~The recommended value of γ_{N2O5} in a typical continental boundary layer ranges from 0.01 to 0.04.~~ Many recent studies ~~, however,~~ have reported discrepancies between field derived and laboratory parameterized γ_{N2O5} (e.g., Brown et al. 2009; Chang et al. 2016; Morgan et al. 2015; Phillips et al. 2016; McDuffie et al. 2018b; Tham et al. 2016; Wang et al. 2017a, b, c) and ϕ_{ClNO2} (e.g., McDuffie et al. 2018a; Riedel et al. 2013; Ryder et al.

2015; Tham et al. 2018; Thornton et al. 2010; Wagner et al. 2013; Wang et al. 2017b, c). In a nocturnal boundary layer, $ClNO_2$ can accumulate to significant levels due to its long lifetime ($\tau_{ClNO2} > 30$ h) with slow loss mechanisms through heterogeneous uptake (Behnke et al., 1997; Frenzel et al., 1998; George et al., 1995). At sunrise, $ClNO_2$ rapidly photolyzes to generate chlorine radicals ($Cl^{\cdot}$), which can react with most volatile organic compounds (VOCs). For alkanes, $Cl^{\cdot}$ has up to 1 - 2 orders of magnitude larger rate constants than hydroxyl radicals (e.g., $k_{OH+n-C4H10} = 2.4 \times 10^{-12}$, $k_{Cl+n-C4H10} = 2.2 \times 10^{-10}$ at 298 K) (Atkinson, 1997; Atkinson and Arey, 2003). Therefore, $Cl^{\cdot}$ can potentially influence the radical pool (HO_x-RO_x) and ozone (O_3) level, which can also affect the formation of secondary aerosols. This influence can be most prominent in the morning when concentrations of other oxidants are low (i.e., $NO_3^{\cdot}$ and $^{\cdot}OH$) (Finlayson-Pitts, 1993; Hov, 1985; Young et al., 2014).

$$ClNO_{2(g)} + hv \rightarrow Cl^{\cdot}_{(g)} + NO_{2(g)} \tag{R1}$$

$$NO_{2(g)} + O_{3(g)} \rightarrow NO^{\cdot}_{3(g)} + O_{2(g)} \tag{R2}$$

$$NO^{\cdot}_{3(g)} + NO_{2(g)} \rightleftharpoons N_2O_{5(g)} \tag{R3}$$

$$N_2O_{5(g)} \xrightarrow{\gamma(N_2O_5),Cl^-(aq)} (2-\phi) * HNO_{3(g)} + \phi * ClNO_{2(g)} \tag{R4}$$

$$ClNO_{2(g)} + Cl^-_{(aq)} + H^+_{(aq)} \rightarrow Cl_{2(g)} + HNO_{2(aq)} \tag{R5}$$

The first ambient measurements of $ClNO_2$ were carried out by Osthoff et al. (2008), from a ship sampling along the south-eastern U.S. coast in 2006. In that study, $ClNO_2$ was observed up to ∼1 ppbv at night time, particularly during the time period influenced by urban pollution and ship plumes of the Houston ship channel. Since then, a growing number of measurements reported significant levels of $ClNO_2$, especially in polluted coastal regions with sources from natural and anthropogenic chloride and nitrogen oxides. Riedel et al. (2012) measured up to ∼2 ppbv of $ClNO_2$ off the coast of Santa Monica Bay, on board the research vessel Atlantis. Recent studies show that high levels of $ClNO_2$ are also present in mid-continental regions. Thornton et al. (2010) measured up to ∼ 400 pptv in Boulder, Colorado, which is ∼ 1,400 km away from the coastline. Mielke et al. (2011) reported up to ∼ 250 pptv in Calgary, Alberta, Canada, during spring, which is ∼ 800 km from the coastline. Back trajectory analysis results showed that the observations were most likely not influenced by marine airmasses. More recently (in the past 5 years), increasing number of $ClNO_2$ observations have been conducted in Asia consistently showing significant levels of $ClNO_2$ present in the boundary layer (e.g., Tham et al. 2018, 2016; Wang et al. 2016, 2017c, 2014; Yun et al. 2018; Liu et al. 2017). $ClNO_2$ observations at semi-rural (Wangdu of Hebei province) and urban (Hong Kong, Jinan) regions in China have measured up to 2 ppbv and 776 pptv respectively (Tham et al., 2016; Wang et al., 2017b). At the mountain top (957 m above sea level) in Hong Kong, up to 4.7 ppbv of $ClNO_2$ was reported (Wang et al., 2016). The high levels of $ClNO_2$ in these studies were mostly correlated with continental pollution in vicinity (e.g., power plant plumes, biomass burning). A recent study by Yun et al. (2018) reported the ~~highest~~ highest-recorded mixing ratio of $ClNO_2$ (8.3 ppb), during a severe ~~have~~ haze event in a semi-rural site downwind of the Pearl River Delta in the winter. Overall, observations have shown that $ClNO_2$ is ubiquitous in the tropospheric boundary layer.

However, measurements are still limited, as discrepancies remain between global chemical transport models and observations. Uncertainties in model simulated $ClNO_2$ can arise from limited emission inventories, low resolution of the grid, uncertainties in γ_{N2O5} and ϕ_{ClNO2} parameterization, complexity of the terrain, and meteorological conditions and these have been dealt in previous studies (e.g., Zhang et al. 2017; McDuffie et al. 2018b, a; Lowe et al. 2015; Sarwar et al. 2012, 2014; Sherwen et al. 2017). For instance, smoothing out local $ClNO_2$ peaks by diluting local NO_x emissions, will result in limited NO_3 and N_2O_5 production. According to Sarwar et al. (2012, 2014), the CMAQ model with a finer grid (i.e. 12 km) simulated $ClNO_2$ that corresponded better to the observations, compared to the model runs with coarser grid size (i.e., 108 km), embedded with similar chemistry. Another modeling study by Sherwen et al. (2017) compared the $ClNO_2$ levels between the GEOS-Chem simulations and observations in inland areas (i.e., London, UK and a mountain top near Frankfurt, Germany) during the summer of 2015. Compared to observations, the simulations underestimated the $ClNO_2$ maxima levels by $\sim$ 7 times in inland areas (Sherwen et al., 2017). Modeling studies have consistently suggested the significance of $Cl^{\cdot}$ initiated reactions in regional and global O_3 production and in the lifetime of VOCs in the troposphere (Knipping and Dabdub, 2003; Tanaka et al., 2000, 2003; Sarwar et al., 2014; Sherwen et al., 2016; Simon et al., 2009). Sarwar et al. (2014) explored the production of $ClNO_2$ from sea salt and biomass burning and its impact in the Northern Hemisphere by including $ClNO_2$ formation chemistry in the Community Multiscale Air Quality (CMAQ v 5.0.2) model. The results showed that, compared to the simulations without $ClNO_2$ formation, monthly 8 h wintertime maximum O_3 and $\cdot$OH increased up to 15 % and 20 %, respectively. The impact was the largest in China and Western Europe. In the Hong Kong-Pearl River Delta (HK-PRD) region, Li et al. (2016) simulated up to $\sim$ 1 ppbv of $ClNO_2$ originating from sea salt, biomass burning, and anthropogenic emissions (e.g., coal combustion) with the Weather Research and Forecasting coupled with Chemistry (WRF-CHEM) model. This resulted in $\sim$16 % O_3 increase in the planetary boundary. Another modeling study of WRF-CHEM embedded with an updated chlorine chemistry, simulated 3-6 % of surface O_3 increase in the North China Plain and Yangtze River Delta during the summer (Zhang et al., 2017). A recent study by Wang et al. (2019) updated the standard version of the GEOS-Chem (Chen et al., 2017; Chen et al., 2016) to better track partitioning between aerosol chloride and gas-phase chlorine species. Comparison between their model simulations with and without $ClNO_2$ production showed enhanced O_3 up to 8 ppb during the winter season in Europe due to prolonged nighttime.

East Asian countries are of particular interest due to the rapid economic growth in the past decades with high anthropogenic emissions from densely populated megacities (e.g., Shanghai, Guangzhou, Beijing, Tokyo, Seoul). The majority of the world's megacities are situated in coastal regions (Neumann et al., 2015) with high NO_x emissions and abundant sources of chloride from both anthropogenic and natural origin. These regional characteristics likely promote $ClNO_2$ production. Moreover, considering that nearly half the population in the world lives near the coast, defined as $<$ 100km from coastline (Hinrichsen, 1998), a careful evaluation of the impact of $ClNO_2$ on local tropospheric chemistry is crucial. In this study, we present $ClNO_2$ observation results from the Korean - United States Air Quality (KORUS-AQ) study conducted in the Seoul Metropolitan Area (SMA), South Korea during late Spring (May 2 to June 12, 2016). The field campaign was an international collaboration between the National Institute of Environmental Research (NIER) of South Korea and the National Aeronautics and Space Administration (NASA) of the United States with the aim to better understand the impact of a megacity on regional air quality.

A comprehensive suite of measurements were deployed at two super sites (Olympic Park site, OP; Taewha Research Forest, TRF) and aboard the NASA DC-8 to make airborne observations over the South Korean peninsula and the Yellow Sea. We present observational and box model results to evaluate the impact of $ClNO_2$ towards regional air quality in SMA.

2 Methods

2.1 KORUS-AQ 2016 Field Campaign and Observation Sites

We present observations carried out at Olympic Park, (OP; lat:37° 30’ 32.904" N, lon:127° 7’ 20.136" E), Taehwa Research Forest (TRF; lat: 37° 19’ 14.484" N, lon:127° 18’ 32.58" E) and on the NASA DC-8. The two ground sites were within the SMA region, which is the second largest metropolitan area in the world with a population of $\sim$ 24 million (Park et al., 2017). As shown in Figure 1(a), the OP site is located in the southern part of Seoul, surrounded by high rise residence buildings and close to major freeways. The TRF site is in the middle of a forested area, $\sim$ 26 km southeast of the OP site. Previous studies have shown that the TRF site is affected by both aged anthropogenic air masses from the city and fresh biogenic emissions from the forest (Kim et al., 2016, 2015). Both sites were $\sim$ 50 km to the east of the nearest coastline. Figure 1(b) shows the flight tracks of the NASA DC-8, during the KORUS-AQ campaign. Spiral patterns were conducted near the TRF site to measure a vertical profile of the troposphere. Airborne observations were carried out during the daytime, between 8:00 and 17:00 local time. A summary of the analytical techniques of the measurements presented in this study are shown in Table 1. Meteorology during the observation period can be classified into dynamic (May 4th - 16th), stagnation (May 17th - 22nd), transport (May 25th - 31st), and blocking period~~as shown in Figure 3~~. During the stagnant period, high pressure system was persistent in the Korean peninsula resulting in local air masses to be more dominant within the SMA compared to the dynamic and transport (May 25nd - 31st) periods. Rex block patterns were observed during the blocking period (June 1st - 6th)~~, which also resulted~~. During this period, a high pressure system was adjacent to a low pressure over the Korean peninsula resulting in more local influence with occasional stagnation.

2.2 Chemical Ionization Mass Spectrometry and Calibration

A THS Instruments LLC Chemical Ionization Mass Spectrometer (CIMS), using iodide (I^-) as the reagent ion was used for measuring Cl_2 and $ClNO_2$ at the two ground supersites and on the NASA DC-8. The system was similar to what is described in Slusher et al. (2004) and Liao et al. (2011), and the inlet configuration during the campaign is shown in Figure S1. Ambient air was sampled through a stainless steel donut shaped inlet at TRF and a Polytetrafluoroethylene (PTFE) tube inlet at OP. The stainless steel donut inlet has been shown to effectively avoid wall loss of reactive halogens during previous campaigns (Liao et al., 2011). ~~However, artifacts of $ClNO_2$ or~~ The lengths of the inlet lines of the three CIMS systems were 20 - 30 cm. The PTFE inlet line at the TRF site was washed on a weekly basis and the ones at the OP and DC-8 were not washed routinely during the campaign due to difficulties on detaching the inlet. The potential bias of interactions of Cl_2 ~~from interactions on the inlet has~~ and $ClNO_2$ inside the inlet were not tested but the artifacts have been shown to be negligible in various field conditions

(Riedel et al., 2012; Thornton et al., 2010; Liao et al., 2014). Therefore, the use of different types of inlets (e.g., the use of the donut), described above, at the two ground sites and on the DC-8 is not expected to be an issue for the quantitative comparisons in this study. The sampled air went through the first 3-way valves to be delivered to an ambient or charcoal scrubber mode for background, alternating every 5 minutes. The second 3-way valve was for heated (150 ^{o}C) and unheated cycles. $ClNO_2$ and Cl_2 were only quantified during the unheated cycles to avoid any potential artifacts as described in Liu et al. (2017). ~~Additional flow of 4~~ A total of 3000 standard liters per minute (slpm) was drawn in with a blower with an additional flow of 4 slpm drawn at the end of the inlet to reduce the residence time and 1 slpm was sampled into the CIMS. All the inlet parts, after the blower, including the fittings and tubings, were made of PTFE. In the flow tube, the target compounds form clusters with I^- (R 5-6, (Huey, 2007; Huey et al., 1995; McNeill et al., 2006)), which were generated by flowing 1 slpm N_2 through a methyliodide (CH_3I) permtube oven maintained at 50 ^{o}C . Polonium (NRD LLC, Static Master, Model: 2U500, Activity: 20 mCi) was used as the radioactive source for ionization. Clusters of Cl_2 isotopes were detected at the mass to charge ratio *(m/z)* of 197 and 199, and $ClNO_2$ was measured at 208 and 210. The natural abundance of Cl_2 and $ClNO_2$ isotopes are approximately 9:6:1 ($^{35}Cl^{35}Cl$: $^{35}Cl^{37}Cl$: $^{37}Cl^{37}Cl$) and 3:1 ($^{35}ClNO_2$: $^{37}ClNO_2$) respectively. Mass 201 ($^{37}Cl^{37}Cl$) was not considered in the data processing due to artifacts.

$$ClNO_{2(g)} + I^- \rightarrow IClNO_2^-{}_{(g)} \quad \text{(R6)}$$

$$Cl_{2(g)} + I^- \rightarrow ICl_2^-{}_{(g)} \quad \text{(R7)}$$

Calibrations of Cl_2 and $ClNO_2$ were carried out during and after the campaign. Cl_2 in a cylinder (Airgas, 10 ppm in N_2) was diluted with zero air to be sampled in either ambient or scrubber (charcoal) mode (Figure S1). The Cl_2 in the cylinder was quantified through the method described by Liao et al. (2012) and was 8.84 ± 0.43 ppm. $ClNO_2$ was synthesized, based on Thaler et al. (2011). Briefly, Cl_2 gas in N_2 was passed through a pyrex reservoir (diameter = 1.3 cm, length = 5.5 cm) containing a bed of NaCl (MACRON) and $NaNO_2$ (Sigma Aldrich) with a molar ratio of 10 to 1. This slurry mixture contains NO_2^- that reacts with the flowing Cl_2 to generate $ClNO_2$. The output flow was further diluted with 4 L min^{-1} of zero air in order to sufficiently provide gas flow. The flow containing synthesized $ClNO_2$ was then analyzed at *m/z* of 208 and 210 with the CIMS. NO_2 and NO-NO_y were simultaneously measured with a Cavity Ring Down Spectroscopy (CRDS, Los Gatos Research, detection limit: 10 pptv, precision: 50 pptv at 1σ, model: 907-0009-0002) and chemiluminescence (CL, Thermo Scientific, detection limit: 50 pptv, model: 42 i) respectively. $ClNO_2$ is detected as NO_y in the CL through conversion to NO on the heated (325 ^{o}C) molybdenum catalytic converter (Williams et al., 1998). The efficiency of the conversion was assumed to be unity. Therefore, $ClNO_2$ could be determined by comparing the three instruments and subtracting the byproducts (HONO and NO_2) from the total NO_y. The averaged sensitivity of Cl_2 was 31.5 ± 11.2 Hz/ppt and $ClNO_2$ was 19.7 ± 1.5 Hz/ppt. The 2 sigma detection limits of Cl_2 and $ClNO_2$ were 2.9 and 1.5 ppt, respectively, over 30 min.

2.3 Modeling

We used Framework for 0-D Atmospheric Modeling (F0AM v3.1) for simulating three types of simulations: 1) daytime Cl_2 production (Figure 5), 2) in-situ $ClNO_2$ production in the morning (Figure 8), and 3) testing the impact of measured $ClNO_2$ on the regional tropospheric chemistry (Figure 10). F0AM is a MATLAB based open-source box model. Detailed descriptions of the model can be found in Wolfe et al. (2016). Each step of the model was constrained with the averaged meteorology parameters (e.g., pressure, temperature, relative humidity) and trace gases observed in the two ground sites during the campaign. The constrained trace gases include $ClNO_2$, Cl_2, O_3, NO, NO_2, CO, CH_4, and 20 non-methane hydrocarbons including 8 alkanes (i.e., ethane, propane, iso-butane, n-butane, iso-pentane, n-pentane, n-hexane, and n-heptane), that have relatively high reaction rate constants with Cl·. For simulations presented in Figure 5 and 8, a constant meteorology and trace gas observation set, collected at the corresponding time point, were constrained throughout the model run. For Figure 10, the model was constrained with a diurnal variation of the parameters. Photolysis rate constants were derived through the hybrid method (Wolfe et al., 2016) in the F0AM box model. This method uses clear sky solar spectra from the tropospheric ultraviolet and visible radiation model (TUV v 5.2) and cross sections and quantum yields suggested by IUPAC. To capture the effects of pollution on photolysis rates, the ratio of the measured J_{NO2} to the F0AM modeled J_{NO2} was calculated. This ratio was then applied to other photolysis rate constants calculated in the model. Measured J_{NO2} was taken from the DC-8 actinic flux measurements (Charged-coupled device Actinic Flux Spectroradiometer; CAFS) when flying near SMA at altitudes under 1 km. A diurnal cycle was applied to the DC-8 measurement to determine j-values at other times of day. Photolysis rate constants of $ClNO_2$, Cl_2, and $ClONO_2$ were not present in the F0AM model and therefore taken directly from the DC-8 measurements to be used in the model runs in this study. The Master Chemical Mechanism v3.3.1 (MCM) was taken from http://mcm.leeds.ac.uk/MCM and embedded in the box model. MCM v3.3.1 has a detailed gas photochemistry (i.e., 5832 species and 17224 reactions), including the oxidation of CH_4 and 142 non-methane primary emitted VOCs (Jenkin et al., 2015). Since MCM v3.3.1 only includes Cl· reactions with alkane species, additional chlorine chemistry was embedded in the model, similar to what Riedel et al. (2014) reported. This was done by including multiple Cl· precursors (e.g., Cl_2, $ClNO_2$, HCl, $ClONO_2$, HOCl) and Cl· reactions with non-alkane VOCs, such as alkene, alcohol, aromatics, alkynes, ketones, organic acids and nitrates. All the reactions embedded in the model can be found in the supplementary of Riedel et al. (2014) and Wolfe et al. (2016). Boundary layer height, emissions, and depositions were not considered in the model. More details on the setup of the box model and the main differences between the three types of simulations are in the supplement material (S3). The FLEXible PARTi-cle dispersion model (FLEXPART v9.1, https://www.flexpart.eu) was used for the air mass source contribution (Figure 3) and backward trajectory analysis (Figure 9). The backward trajectories reported in our study were initialized 9:00 LST at TRF, following it 24 hours back in time. Only the center of the mass-weighted particles are shown in Figure 9 and clusters are included in the supporting information. These clusters represent fractional contributions of air masses (Figure S10). The trajectories were driven by the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) with a 0.25 degree resolution. Influence of air mass originating from the ocean at TRF and OP was calculated every 6 hours following an air mass 5 days back in time. Meteorology was driven by WRF with a 5 km horizontal resolution. Since emissions of CO are very low in the ocean, and assumed to be inert in the model, it was used as a tracer for contribution of air originating from the ocean within a given air mass at each ground site.

3 Results and Discussions

3.1 $ClNO_2$ Observations

Figure 2 shows the temporal variation of trace gases measured during the campaign at (a) the OP site (May 17th - June 11th) and (b) the TRF site (May 5th - June 11th). The OP site, which was located near heavy traffic, showed high levels of NO_x throughout the campaign. During most nights (except for May 24th - 26th, 30th - 31st, and June 6th - 7th), O_3 was completely titrated by NO. On the other hand, at the TRF site, which is a forested region downwind of the urban area, O_3 remained at $\sim$ 30 ppbv throughout the night. During the measurement period, measureable amounts of $ClNO_2$ were observed at both ground sites (Figure 3). The maximum observed $ClNO_2$ was $\sim$800 pptv (~~10~~ 5 min averaged) and $\sim$2.5 ppbv (5 min averaged) at the OP and TRF sites, respectively. At both sites, $ClNO_2$ started accumulating at sunset and rapidly photolyzed upon sunrise, which was $\sim$5:30 local standard time (LST) during the campaign. Nighttime relationship between $ClNO_2$ and Cl_2 varied day by day and did not show a clear correlation. This implies that the sources or potentially loss processes of Cl_2 and $ClNO_2$ ~~was~~ were not consistent at night. This is similar to Riedel et al. (2012), where they reported a wide range of correlation between Cl_2 and $ClNO_2$ off the coast of LA.

Daytime (11:00 - 18:00, LST) $ClNO_2$ was up to $\sim$100 pptv at OP and $\sim$250 pptv at TRF (Figure 4). The level showed a positive correlation with Cl_2, especially in relatively high O_3 conditions ($>$ 50 ppbv). When O_3 was relatively low ($<$ 50 ppbv), Cl_2 production was suppressed, while $ClNO_2$ was not necessarily limited. Excluding the days with low O_3 (i.e., May 26th and 29th for OP and May 6th, 29th, and June 4th for TRF), the relationship between daytime $ClNO_2$ and Cl_2 showed positive correlation with R^2 of 0.49 and 0.80 for OP and TRF, respectively. This positive correlation is consistent with the results reported by Liu et al. (2017) in the North China Plain. In their study, up to $\sim$ 450 pptv of both Cl_2 and $ClNO_2$ was measured during the daytime (10:00 - 20:00, LST), with strong correlation of R^2 = 0.83. Cl_2 levels were also suppressed in low O_3 and OH conditions during low solar radiation periods. Therefore, the authors suggested that daytime Cl_2 levels could be positively related to photochemical activities. Considering the short lifetime of Cl_2 and $ClNO_2$ during the day (i.e., 11:00 - 18:00 LST in our study), the levels we observed are likely affected through local production. According to Liu et al. (2017), the ~~airmass~~ air mass showed moderate correlation to SO_2 with possible influences from power plants. However, in this study, the $ClNO_2$ measured at both the OP and TRF sites was weakly correlated with SO_2 (R^2 = 0.02), which implies that the air masses that we sampled are not fresh emissions from power plants.

The first possibility we explored is the direct generation of Cl_2 from reactions in acidic particles. $ClNO_2$ is very insoluble ($\gamma_{ClNO2} \approx 10^{-6}$ (Rossi, 2003)) in near-neutral pH. However, according to Roberts et al. (2008), γ_{ClNO2} can increase up to 3 orders of magnitude in acidic surfaces ($\sim$ pH 1.8) leading to direct production of gas-phase Cl_2. Aerosol acidity was mostly below pH 2 during the campaign, based on thermodynamic calculations, constrained with airborne observations (Figure S3). Therefore, the efficiency of this reaction in ambient conditions requires further investigation. Another possibility is the autocatalytic production of Cl_2 from heterogeneous reactions of gas-phase $ClONO_2$ (i.e., $ClONO_{2(g)}$ + $Cl^-{}_{(aq)}$ + $H^+{}_{(aq)}$ $\rightarrow$ $Cl_{2(g)}$ + HNO_3, (Gebel and Finlayson-Pitts, 2001; Deiber et al., 2004)) and HOCl (i.e., $HOCl_{(g)}$ + $Cl^-{}_{(aq)}$ + $H^+{}_{(aq)}$ $\rightarrow$ $Cl_{2(g)}$ + H_2O, (Vogt et al., 1996)) on particles. These reactions are also favored as particle acidity increases. In order to further investigate its possibility, daytime Cl_2 was simulated by constraining the box model with measurements of $ClNO_2$ and other trace gases corresponding to each data point in Figure 4. Based on the availability of parameters, we were able to simulate 1680 and 1229 runs for the OP and TRF, respectively. This corresponds to more than 96 % of the daytime data points shown in Figure 4. γ_{ClONO2} and γ_{HOCl} were set to 0.06 (Deiber et al., 2004; Hanson et al., 1994; Hanson and Ravishankara, 1994), which is an upper-limit of previous laboratory studies, and the yields were assumed to be unity. HCl generation from hydrogen abstraction of VOCs by $Cl^{\cdot}$ were included in the mechanisms used in the model runs. The end points of the 72 hour simulation results are presented in Figure 5. As shown in the Figure, the box model simulations were able to reproduce the positive correlation between Cl_2 and $ClNO_2$. Moreover, modeled Cl_2 was suppressed in low O_3 conditions, which corresponds to the observations. This can be explained by $Cl^{\cdot}$ reacting with O_3, producing $ClO^{\cdot}$, leading to gas-phase $ClONO_2$ and HOCl production. These can react on acidic aerosols to generate Cl_2. Sources of $Cl^{\cdot}$ could be from photo-labile gas-phase chlorine compounds (e.g., Cl_2, $ClNO_2$, $ClONO_2$, HOCl) or oxidation of gas-phase HCl by OH. Although the reaction between HCl and OH is relative slow (k = 7.86×10^{-13} cm^3 $molecule^{-1}s^{-1}$ at 298K, (Atkinson et al., 2007)), it has been reported to be a significant source of $Cl^{\cdot}$ in the daytime (Riedel et al., 2012). A sensitivity test was carried out by comparing modeled Cl_2 between runs with and without HCl production from oxidation of VOCs by $Cl^{\cdot}$ (Figure S4 c,d). The results show that production of Cl_2 was suppressed by 40 - 70 % when HCl was not generated in the model. This significant contribution of gas-phase HCl as a $Cl^{\cdot}$ source, should be an upper-limit as the deposition of HCl was not considered in the model. Nonetheless, our analysis leads us to conclude that the mechanisms we have explored could be the main contributors of the daytime Cl_2 production during KORUS-AQ.

3.2 Sources of $ClNO_2$

FLEXPART source contribution analysis shows that the level of $ClNO_2$ at the ground sites was highly correlated with the origin of the air mass (Figure 3). During the nights shaded in red in Figure 3 (OP: May 20th, 22nd, June 2nd, and 7th; TRF: May 11th, 19th-22nd, June 2nd, and June 6th-7th), there was limited production of $ClNO_2$ at the surface. These periods mostly corresponded to meteorological conditions of stagnation or blocking events, which both resulted in localized air masses to be more dominant with limited influence from the west coast. Stagnation events can be characterized by low wind speeds and increased atmospheric stability, possibly leading to enhanced levels of pollutants like NO_x. Previous studies have shown that these stagnant conditions can result in enhanced levels of N_2O_5 (Baasandorj et al., 2017) driven by high ozone and NO_2. However, ClNO driven by high ozone and NO_2, as shown in Baasandorj et al. (2017) during a Wintertime observation in the Salt Lake Valley, Utah. However, $ClNO_2$ production was limited during stagnation events in this study. This is likely due to limited availability of chloride as shown in submicron particle measurements of aerosol mass spectrometer (AMS) at the ground site for OP and airborne over TRF (Figure 3). Whether the chloride is from the ocean or anthropogenic emissions is uncertain since large point sources, such as power plants or petrochemical facilities, are also present along the west coast of the SMA. On the nights of May 20th and May 22nd, rapid changes in air quality were observed with fast shifts in O_3, SO_2, and

CO. This corresponded with changes in $ClNO_2$ and Cl_2 (Figure S7). These events suggest the importance of boundary layer advection in controlling the $ClNO_2$ levels in the region.

Different diurnal variations of $ClNO_2$ were observed between OP and TRF (Figure 6). The measurements were averaged over selected days (OP: May 18th-20th, 22nd, 23rd, 29th, June 4th; TRF: May 5th, 8th, 9th, 12th, 17th, 18th, 30th, June 8th, 10th) that showed these two distinct profiles at each site. The description on these profiles are further explained in the following sentences. At the TRF site (Figure 6b), far from direct NO emissions, significant levels of $ClNO_2$ were sustained throughout the night during most of the observation period with rapid photolysis upon sunrise. On the other hand, at OP (Figure 6 (a)), $ClNO_2$ started to increase upon sunset, followed by a rapid drop at around 22:00 LST. The trend was consistent with slower nitrate radical production rate ($d[NO_3]/dt = [NO_2][O_3]k$, where $k = 3.52 \times 10^{-17}$ at 298 K,(Atkinson et al., 2004)) as O_3 was titrated to zero by NO close to midnight. The wind direction, SO_2, and CO did not correlate. This suppressed $ClNO_2$ production in urbanized regions with high NO levels, have also been reported by Osthoff et al. (2018). However, significant levels of N_2O_5 and $ClNO_2$ could have been present in the upper part of the surface layer as shown in previous studies (Baasandorj et al., 2017; Young et al., 2012; Yun et al., 2018). According to Baasandorj et al. (2017), O_3 was completely titrated at the surface in Salt Lake Valley, Utah, while elevated mixing ratios of N_2O_5 were observed at 155 meters above ground level, at a site along the valley wall.On the other hand, airborne measurements at the LA basin (Young et al., 2012) showed a relatively uniform $ClNO_2$ profile throughout the boundary layer as O_3 did not change significantly within the measured altitude(< 600 m). During the 2015 Megacity Air Pollution Study (MAPS, Seoul, 2015), a Cavity Ringdown Spectrometer (CRDS) was installed on top of the Seoul tower in May - June that measured that measured N_2O_5, NO_x, and O_3 (Brown et al., 2017). The elevation of the measurement site was 360 m above sea level (ASL), allowing for sampling further away from direct NO emissions. In their study, the average nighttime O_3 mixing ratio was around 50 ppbv and N_2O_5 was observed most nights, with mixing ratios reaching up to 5 ppbv. Therefore, it is very likely that $ClNO_2$ levels higher than the surface measurements could have been present at higher elevation during the observation period.

At both sites, $ClNO_2$ levels started to increase or sustained after the first 2-3 hours of rapid net loss upon sunrise. In the morning, $ClNO_2$ positively correlated to Cl_2 levels, but did not follow the nitrate production rate at the site (Figure S8). Box model simulations, initially constrained with observed $ClNO_2$ level, showed rapid photolysis upon sunrise (Figure S5, red dashed line). At TRF, this corresponded to the measurements until 7 - 8 am LST, when a second $ClNO_2$ peak was observed (Figure 6b). This $ClNO_2$ peak in the morning was observed about half the observation days during the campaign. With the net $ClNO_2$ production rate from the observation, and the loss rate from the simulated $ClNO_2$ from photolysis, a production rate of 400 pptv h^{-1} would be required to reconcile the observation. In the case of $ClNO_2$ observed on May 5th at TRF (an insert of Figure S6b), a maximum of 2.5 ppbv h^{-1} of $ClNO_2$ production rate was required in the morning to reconcile the observations. At OP, 18 pptv h^{-1} was required for the 7 averaged days. The $ClNO_2$ production rate required in the morning at TRF was much higher than the previous studies that have also reported high sustained levels of $ClNO_2$ in the morning (i.e., 20 - 200 pptv h^{-1}) (Faxon et al., 2015; Bannan et al., 2015; Tham et al., 2016). In these previous studies, three possibilities have been suggested that could explain the high sustained levels of $ClNO_2$ in the early morning : ~~1) entrainment of $ClNO_2$ from residual layer, 2) in-situ generation of $ClNO_2$, and 3) transport of $ClNO_2$ within the boundary layer.~~1) in-situ generation of $ClNO_2$, 2) transport of $ClNO_2$ within the boundary layer, and 3) entrainment of $ClNO_2$ from residual layer. Each possibility is explored below.

~~At night time, the nocturnal boundary layer is decoupled from the residual layer (Stull, 1988), where the pollution from the previous day resides. Being removed from direct NO emissions near the surface, N_2O_5 can effectively accumulate in the residual layer, with the major loss process being heterogeneous reaction on aerosols. Therefore, high levels of NO_2 and O_3 formed during the day can be trapped in the residual layer resulting in significant levels of $ClNO_2$ persisting throughout the night. Figure 7, shows (a) regional and (b) vertical distribution of airborne $ClNO_2$ throughout the campaign in the morning (8:00 - 8:30 LST) over the SMA region (lat: 37^o 12' 0" N - 37^o 38' 60" N, lon: 126^o 54' 0" E - 127^o 47' 60" E). During 3 flights (i.e., May 25th, May 31st, and June 10th), $ClNO_2$ was observed in the residual layer with a max of $\sim$ 230 pptv. However, the remaining flights observed an average of 17 ± 56 pptv of $ClNO_2$ (black circles). Even the three days (i.e., May 25th, 31st, and June 10th), that $ClNO_2$ was observed in the residual layer, the level (max 230 pptv) could not reconcile the observed levels at the TRF site, which was 342 ± 330 pptv when averaged over the corresponding 3 days at 8:00 - 8:30 LST.~~

In order ~~further~~to explore the possibility of in-situ formation, box model simulations of $ClNO_2$ production from heterogeneous reaction of N_2O_5 and chloride containing aerosols were conducted. N_2O_5 was calculated assuming a photo-stationary state of $NO_3^{\cdot}$ (Brown et al., 2005). Aerosol surface area was taken from airborne observations over TRF. Based on the box model results in Figure 8, even with an assumption of 100 % yield, $ClNO_2$ from heterogeneous reaction was not able to reconcile the observed level. Box model simulation on gas phase production of $ClNO_2$ (i.e., $Cl\cdot_{(g)} + NO_{2(g)} + M \rightarrow ClONO_{(g)} + M$, $Cl\cdot_{(g)} + NO_{2(g)} + M \rightarrow ClNO_{2(g)} + M$) showed at most 2-10 pptv of $ClNO_2$ and ClONO (Figure S6).

Therefore, ~~the third possibility, local transport within the boundary layer,~~ horizontal or vertical transport from local sources would be the most likely explanation for the high $ClNO_2$ in the morning~~based on our analysis~~. Although $ClNO_2$ readily photolyzes during the day ($\tau_{ClNO2} \approx$ 30 min at midday), the lifetime could be significantly long enough in the early morning to allow for transport of $ClNO_2$ to the ground sites. Based on the NCAR TUV v5.2 model, the lifetime of $ClNO_2$, averaged between 5:30 and 8:30 LST was $\sim$ 2 hours under clear sky conditions. Figure 9 shows back trajectory analysis initiated at 9 am local time at TRF. At high $ClNO_2$ days with the morning peaks, most of the air masses were from the west. During KORUS, the DC-8 did not fly to the west of the SMA in the early morning. However, there are large point sources, such as petrochemical facilities and industries, and vehicular emissions to the west and south west of the SMA region. Sullivan et al. (2019) reported that this resulted in enhanced levels of O_3 in receptor regions (i.e., Taehwa Research Forest) downwind when westerlies were prevalent. Therefore, favorable conditions such as high chloride content in aerosols from both anthropogenic and natural sources and high levels of NO_x-O_3 could have lead to significant levels of $ClNO_2$ to build up and transported to TRF before being completely photolyzed. During the campaign, influence of large biomass burning was negligible as reported in Tang et al. (2018, 2019).

At night time, the nocturnal boundary layer is decoupled from the residual layer (Stull, 1988), where the pollution from the previous day resides. Being removed from direct NO emissions near the surface, N_2O_5 can effectively accumulate in the residual layer, with the major loss process being heterogeneous reaction on aerosols. Therefore, high levels of NO_2 and O_3 formed during the day can be trapped in the residual layer resulting in significant levels of $ClNO_2$ persisting throughout the night. Figure 7, shows (a) regional and (b) vertical distribution of airborne $ClNO_2$ throughout the campaign in the morning (8:00 - 8:30 LST) over the SMA region (lat: 37^o 12’ 0" N - 37^o 38’ 60" N, lon: 126^o 54’ 0" E - 127^o 47’ 60" E). During 3 flights (i.e., May 25th, May 31st, and June 10th), $ClNO_2$ was observed in the residual layer with a max of $\sim$ 230 pptv. However, the remaining flights observed an average of 17 ± 56 pptv of $ClNO_2$ (black circles). Even the three days (i.e., May 25th, 31st, and June 10th), that $ClNO_2$ was observed in the residual layer, the level (max 230 pptv) could not reconcile the observed levels at the TRF site, which was 342 ± 330 pptv when averaged over the corresponding 3 days at 8:00 - 8:30 LST. However, it is possible that the air mass that was measured by the DC-8 was not representative of the air mass aloft at the west side of the ground observation sites. Backtrajectory analysis initialized at 9:00 local time showed that the TRF site was affected by both the residual layer and below (Figure S10). The enhancement of O_3 and SO_2 concurrent to elevation of $ClNO_2$ could be due to the transport from the residual layer where pollution from high point sources from the other day was trapped within. From the current dataset, it would be difficult to derive a clear conclusion on whether the cause of the significant $ClNO_2$ in the morning was dominantly of transport from horizontal, vertical, or both.

3.3 Impacts of $ClNO_2$ on O_3

Cl· produced from $ClNO_2$ photolysis can influence the local air quality through reactions with VOCs followed by enhanced production of O_3. The possible impact of Cl· initiated reactions on the local chemistry were investigated by running box model simulations constrained with measured $ClNO_2$. A 24 hour diurnal variation of $ClNO_2$ was averaged over the same selected days as in Figure 6, and these were constrained throughout the model simulations. The results illustrate that when the model was constrained with $ClNO_2$ and Cl· initiated chemistry, higher levels of O_3 were simulated (Figure 10) compared to the base runs without $ClNO_2$. The averaged net O_3 production rate was enhanced by up to 2 % and 25 % at OP and TRF in the morning and by 1 % and 2 % when averaged during the day. The OP had 7 times lower Cl· than the TRF site due to low $ClNO_2$ levels ($\sim$60 pptv) in the morning. Since the box model simulations in our study did not take into consideration boundary layer height dynamics, emission, and deposition, this net production rate is the result of just chemical production and loss. For ·OH, the net production rate at TRF increased by 2 % in the morning. The results particularly from TRF are comparable with the previous study in the mountaintop site in Hong Kong, China (Wang et al., 2016). The enhancement of O_3 (max - min) was higher than their moderate $ClNO_2$ case (11 %) but lower than the high $ClNO_2$ plume case (41 %).

4 Conclusions

Comprehensive measurements of $ClNO_2$, Cl_2, other trace gases, and aerosol concentrations and properties have been conducted on the NASA DC-8 and at two ground sites during the KORUS-AQ 2016 field campaign. The observed averaged diurnal variations are largely consistent with the previous observations and our understanding on the photochemistry of $ClNO_2$. The presence of $ClNO_2$ was substantially suppressed during strong stagnation events, which could have prevented the transport of chloride near the coast. During the night, Cl_2 and $ClNO_2$ levels were not correlated while moderate to strong positive relationships were observed at daytime. Through box model simulations, we presented a quantitative analysis ~~on~~ of the daytime observations. The results showed that heterogeneous reactions of $ClONO_2$ and HOCl in acidic aerosols may be responsible for the positive correlation between Cl_2 and $ClNO_2$, as well as its dependency on O_3. The second $ClNO_2$ peak in the morning, observed 4-5 hours after sunrise, required a significant source of $ClNO_2$ (up to 2.5 ppbv h^{-1}). Previous studies have attributed high sustained $ClNO_2$ in the morning to transport from the residual layer (Tham et al., 2016; Wang et al., 2016). In this study, box model runs of heterogeneous and gas-phase production of $ClNO_2$ could not reconcile the observed levels. ~~Moreover, airborne observations~~ Airborne observations near the ground sites in the early morning showed negligible $ClNO_2$ levels in the residual layer in most of the days. ~~Therefore, local transport of~~ However, there is still a possibility of the contribution of vertical transport from the residual layer. Although the current data set is limited for us to pinpoint on the vertical locations (i.e., boundary layer v.s. residual layer), it is clear that the $ClNO_2$ ~~from highly polluted airmasses from the west is the most plausible explanation~~rich air masses were mostly transported from the west coast where there are significant sources of precursors. This shows that different meteorological or chemical conditions of the sites can lead to various causes of high $ClNO_2$ levels in the early morning. Finally, box model simulations constrained with observations suggest that Cl· initiated chemistry can lead up to ∼25 % increase of net chemical O_3 production rate in the morning.

Data availability. Dataset used in this study is open to public and can be downloaded at https://www-air.larc.nasa.gov/missions/korus-aq/

Author contributions. DJ, RS, DG, YL, DT, SK, and GH designed and executed field measurements for collecting $ClNO_2$ and Cl_2; BAN, JLJ, and PCJ provided the airborne AMS data; CK ran the FLEXPART analysis; TM and JS provided O_3 measurements; DRB provided the WAS data; DS and AG provided the PTR-ToF-MS data; RL provided NO_x and O_3 data; BA provided the data from LARGE; SRH and KU provided data from CAFS; HS provided AMS data at OP; SH provided HCHO measurements at TRF; YL, DK, and JA provided CO measurements at TRF. DJ and SK prepared the original manuscript, and all other authors contributed in editing the manuscript.

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Table 1. Summary of the measurements carried out during the KORUS-AQ 2016 field campaign, used in this study.

Compound	Method		
	TRF	OP	DC-8
NO	^{a}CL	^{b}FRM	^{c}CL
NO_2	^{d}CRDS	^{e}CAPS	^{c}CL
O_3	^{f}DIAL	^{g}SL-UV	^{c}CL
SO_2	^{h}PF	^{i}UV florescence	x
CO	^{j}IR	^{k}NDIR	x
$ClNO_2$,Cl_2	^{l}CIMS	^{l}CIMS	^{l}CIMS
VOCs	^{m}PTR-ToF-MS	^{o}QCL	^{p}PTR-ToF-MS
	^{n}TILDAS		^{q}WAS
chloride (< 1 μm)	x		
nitrate (< 1 μm)	x	^{r}ToF-AMS	^{s}HR-ToF-AMS
sulfate (< 1 μm)	x		
surface area (< 200 *nm*)	x	x	^{t}SMPS
surface area (200 *nm* - 5 μm)	x	x	^{u}LAS
Jvalues	x	x	^{v}CAFS

^{a}Chemiluminescence with a molybdenum converter (Thermo Scientific 42i - TL), ^{b}Chemiluminescence detector (Federal Reference Method, Teledyne T200U), ^{c}NCAR 4-channel chemiluminesecence (Weinheimer et al., 1994), ^{d}Cavity Ring Down Spectroscopy (Los Gatos Research NO_2 analyzer), ^{e}Cavity Attenuated Phase Shift spectroscopy (Teledyne T500U CAPS analyzer), ^{f}NASA TROPospheric OZone DIfferential Absorption Lidar (Sullivan et al., 2014), ^{g}UV photometric method (2B 211), ^{h}Pulsed fluorescence method (Thermo Scientific 43i-HL), ^{i}UV florescence method (KENTEK), ^{j}Infrared CO analyzer (Thermo Scientific 48i-HL), ^{k}Non-Dispersive Infrared CO analyzer (KENTEK), ^{l}Chemical Ionization Mass Spectrometer (Slusher et al., 2004), ^{m}Proton-Transfer-Reaction Time-of-Flight Mass Spectrometer (IONICON), ^{n}Tunable Infrared Laser Direct Absorption Spectroscopy (Aerodyne), ^{o}Quantum Cascade Laser spectrometer (Aerodyne), ^{p}University of Oslo/Innsbruck Proton-Transfer-Reaction Time-Of-Flight Mass Spectrometer (Müller et al., 2014), ^{q}Whole Air Sampler (Colman et al., 2001), ^{r}Aerosol Mass Spectrometer (Aerodyne), ^{s}University of Colorado, Boulder,Aerosol Mass Spectrometer (Nault et al., 2018), ^{t}NASA, Scanning Mobility Particle Sizer, ^{u}NASA, Laser Aerosol Spectrometer, ^{v}NCAR, Charged-coupled device Actinic Flux Spectroradiometer (Shetter and Müller, 1999)

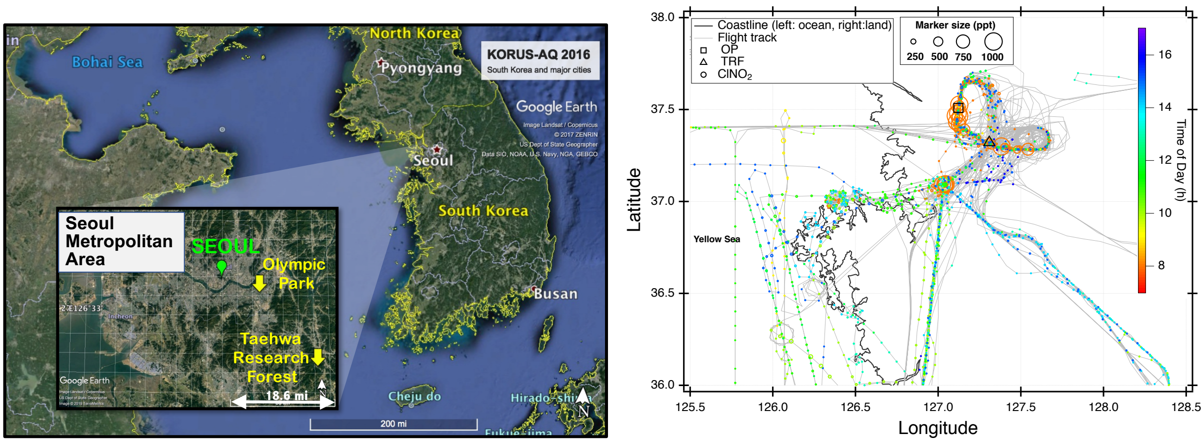

Figure 1. (a) Location of two ground sites (Taehwa Research Forest and Olympic Park) where the chemical ionization mass spectrometer (CIMS) was installed during the KORUS-AQ 2016 field campaign (b) Airborne measurements of $ClNO_2$ and DC-8 flight tracks during the whole campaign. The $ClNO_2$ data points are 60 sec averaged and color coded by time of day of the measurement. The marker size is proportional to the mixing ratio of $ClNO_2$.

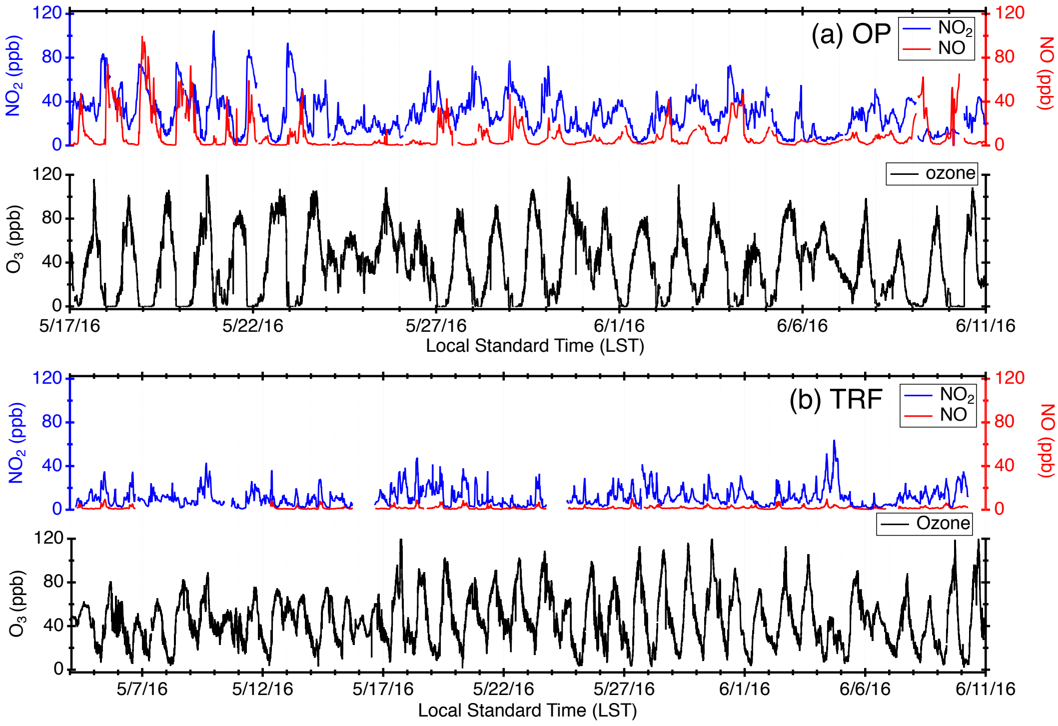

Figure 2. Temporal variation of trace gases measured at the (a) Olympic Park site (OP) and (b) Taehwa Research Forest (TRF). For both OP and TRF, the frequency of the averaged data is 10 min for NO_x and 1 min for O_3.

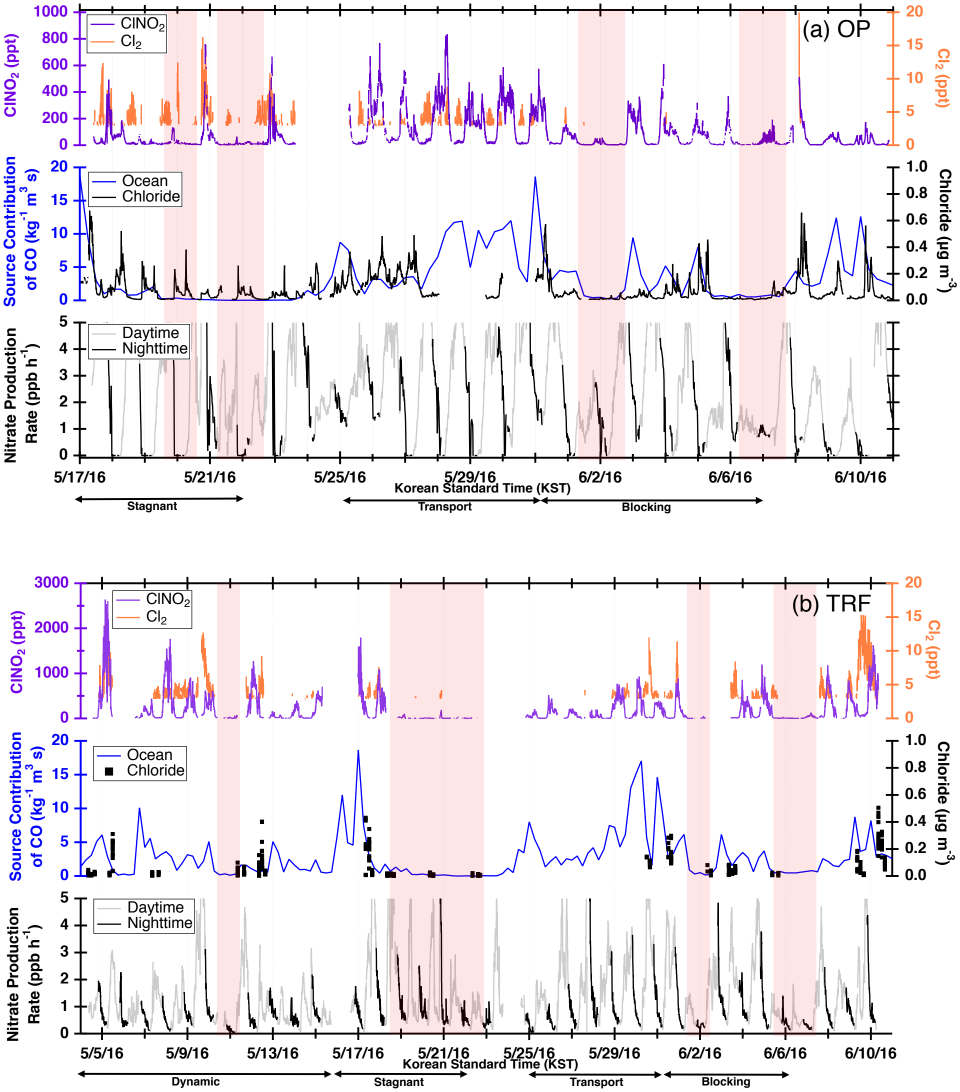

Figure 3. ClNO$_2$ and Cl$_2$ observation results at (a) OP and (b) TRF averaged over ~~10 min and~~ 5 min~~respectively~~. FLEXPART back trajectory analysis were made for source contribution of CO-like substance originating from the ocean, assuming inert CO. Aerosol chloride mass concentration (ambient μg m^{-3}) was measured at the ground for the OP site and on the NASA DC-8 for TRF. For the airborne chloride, measurements below 1 km over the TRF site is shown. Red shades are the time frames with limited ClNO$_2$ production. The time frames for each meteorological condition that dominated during the observation period are classified in black arrows at the bottom of the Figures 3a and 3b

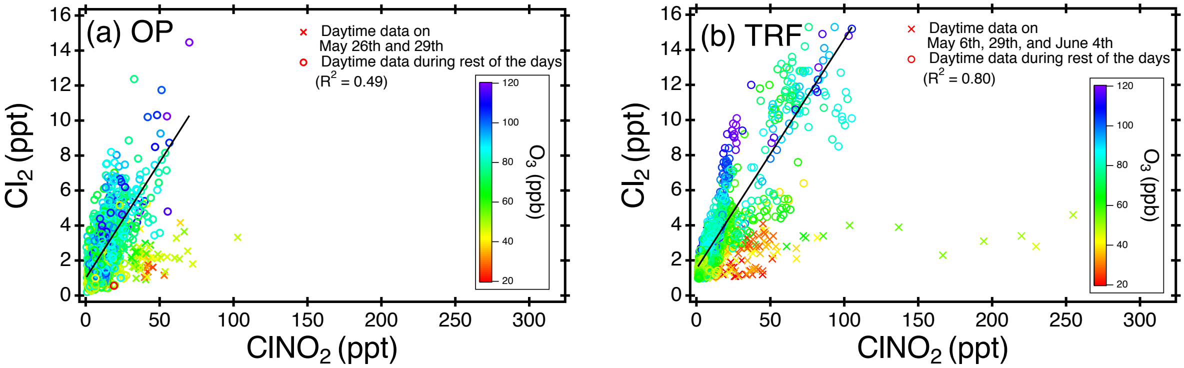

Figure 4. Scatter plot of daytime (11:00 - 18:00 local time) ClNO$_2$ and Cl$_2$ at (a) OP and (b)TRF, color coded with measured O$_3$. 5 min averaged data for the whole campaign were used for both sites. Data points of Cl$_2$ below detection limit (2.9 ppt, 2σ, over 30 min) are shown for the purpose of comparison to observed ClNO$_2$ levels.

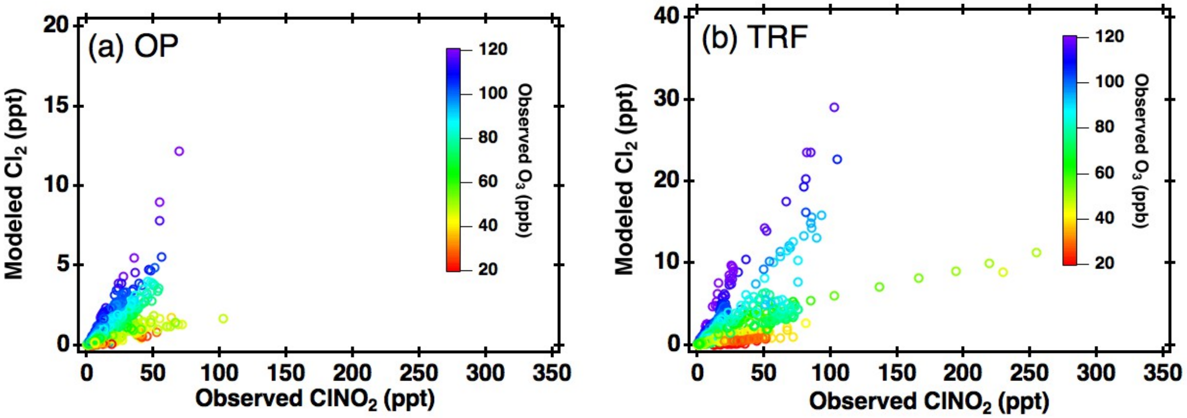

Figure 5. Correlation between box model simulated daytime (11:00 - 18:00 local time) Cl_2 and measured $ClNO_2$ at (a) OP and (b)TRF, color coded with measured O_3.

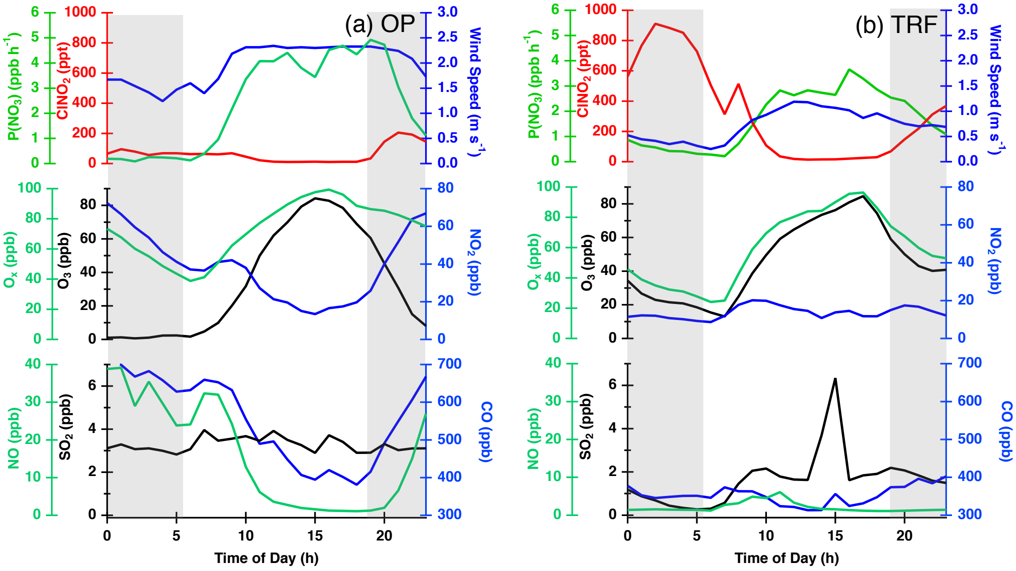

Figure 6. Diurnal variation of ClNO$_2$ and other trace gases measured during the campaign and averaged over selected days at (a) OP (7 days) and (b) TRF (9 days). Night time is shown as grey shades.

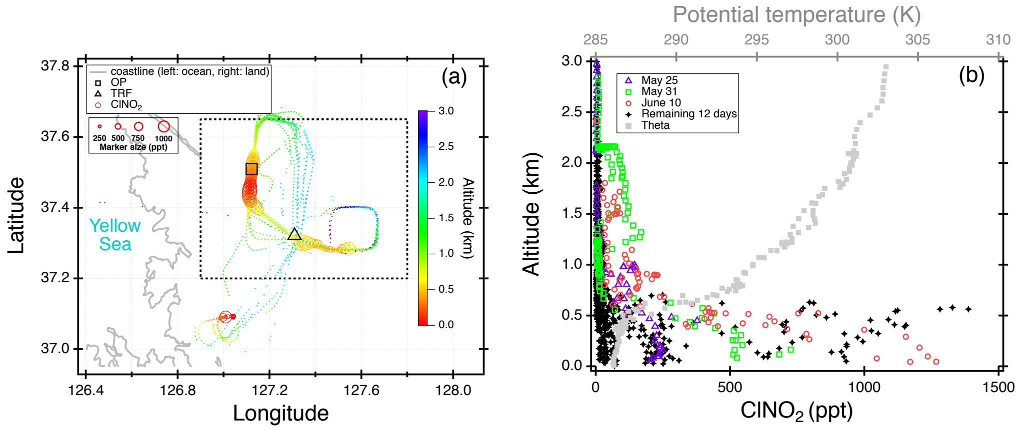

Figure 7. (a) Regional and (b) vertical distribution of airborne $ClNO_2$ measured over the Seoul Metropolitan Region (SMA) in the morning (8:00 - 8:30 local time).

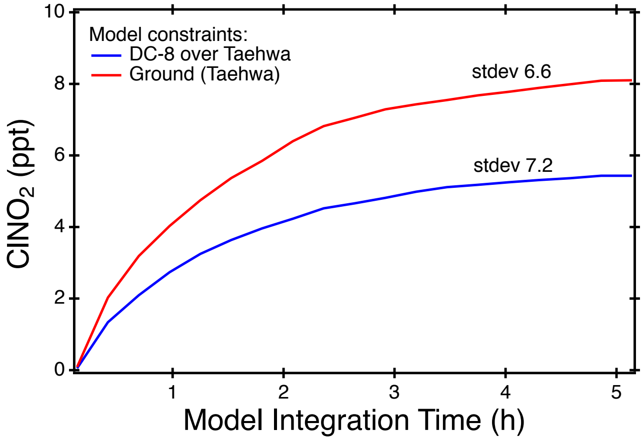

Figure 8. Steady state $ClNO_2$, simulated from a box model constrained with airborne measurements (blue) and ground site data from TRF (red), when there was a morning $ClNO_2$ peak. Averaged values of the model runs are shown here with standard deviations.

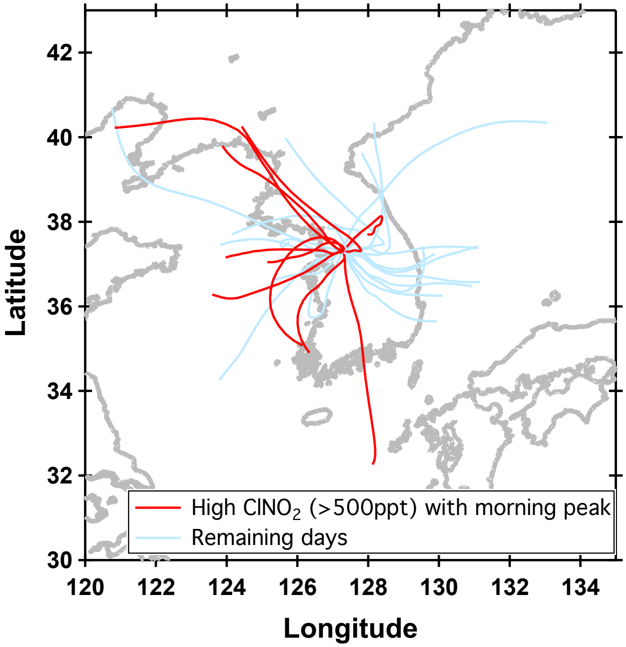

Figure 9. FLEXPART back trajectories from Taehwa Research Forest. Trajectories were initialized at 9 am local time and went 24 h backwards. Only the center trajectories with the highest percentage of airmasses are presented. Trajectories for days with high levels of $ClNO_2$ ($>$ 500 pptv) at night are in red and the remaining days are shown in sky blue.

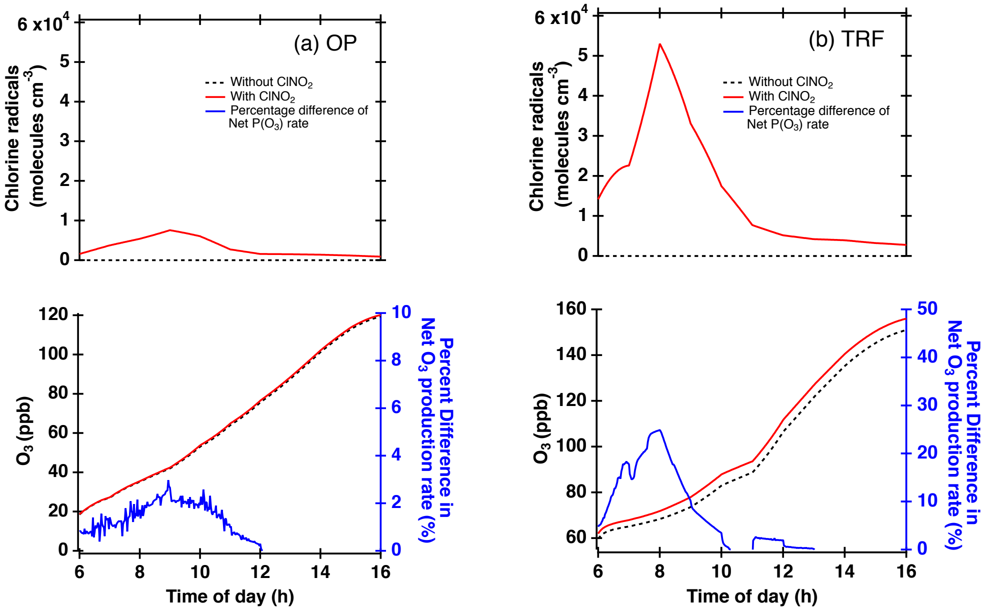

Figure 10. Box model simulations of chlorine radicals and O$_3$ at (a) OP and (b) TRF, constrained with ClNO$_2$ and other trace gases observed during the field campaign. Percent difference of net O$_3$ production rate (NetP(O$_3$), blue line) was calculated from the difference of the NetP(O$_3$) between simulations with and without ClNO$_2$ constrained in the model (i.e., 100*(wClNO$_2$ - woClNO$_2$)/woClNO$_2$).