

We appreciate both reviewers for their helpful comments and suggestions. We revised the manuscript accordingly. We present our responses and changes below. Reviewers' comments and suggestions are in *italic*. Authors' responses are in **bold**.

Response to Referee #1:

This manuscript summarizes the sensitivity of OMI NO₂ trend to several factors such as a baseline trend (over the ocean), surface albedo, and lightning filter. I found the information in the manuscript is useful. The paper is well organized and presentations are neat. But I think that general conclusions (or contents in the abstract) are misleading and some important analyses are missing. I suggest to revise the manuscript before final publication based on the comments below.

This research focuses on improving OMI NO₂ retrieval (instead of sensitivities) in trend analysis by removing the ocean trend (due to increasing stripes), using MODerate-resolution Imaging Spectroradiometer (MODIS) albedo in deriving air mass factors (AMFs), and applying the lightning flash filter. The three corrections are necessary for NO₂ trend analysis using OMI NO₂ retrieval.

First, I do not agree with the authors in the abstract line 14-15 (“how to improve OMI NO₂ retrievals for more reliable trend analysis”) and line 23-25 (“we recommend future studies to apply these procedures to ensure the quality of satellite based NO₂ trend analysis, especially in regions without reliable long-term in situ NO₂ measurements”). I think the agreement between the trends in surface monitored data (AQS) and those in standard OMI (Table 1) is already good, considering uncertainties in the satellite retrievals and the spatial coverage of the surface monitors. The authors need to clarify the spatial resolution of the OMI data (used in the trend analysis) and the spatial extent (or representativeness) of the ground-based observations.

We added in the abstract “However, the current OMI tropospheric NO₂ retrievals are not designed for analyzing multi-year tropospheric NO₂ trends.” **It is not surprising that satellite data need to be reprocessed in trend analysis, which is true for all observation-based trend studies.**

The reason Table 1 results may be conceived to be “already good” (at for coincident data) is because we showed only annual trends. It did show that for all data, the effects of our recommended data processing are > a factor of 2 for West, Midwest, and South (comparing the OMI column with and without the lightning filter). We now emphasized this point in the abstract and conclusions.

We further make the points that (1) processed OMI data show smaller trends (Figure 8) and (2) using surface data alone will have a tendency to overestimate NO₂ trends (Figure 9). Lastly, Figs. 4-7 show that on a seasonal basis, the effects of the data processing we recommended can be much larger than the annual mean changes of Table 1.

To deal with the surface measurement representativeness, we only compare to regional trends from surface observations, which are much more statistically representative. Previous studies did the same. As discussed above, we show the effects of site locations on the trend analysis in Fig. 10 (and Table 1). This point has not been emphasized previously and needs to be accounted for in future studies.

It is exciting to see better agreement between the trends from AQS and the final OMI (lightning filter) in Table 1. But I am not sure that these two should agree exactly.

As our research focuses on the regional relative trend difference, we expect that the surface NO₂ trends and NO₂ VCD trends should be very close (They are both affected by chemical non-linearity and may show trends different from emission trends). We stated this in Section 3.1, “The NO₂ relative trends from

both datasets are expected to be close on a regional basis where surface emissions of NO_x dominate the observed surface concentrations and tropospheric VCDs of NO₂.” **As the reviewer already pointed out that the trends between surface and OMI coincident data are already in reasonably good agreement for annual trends, which is a reflection of this reasoning. We showed in this paper what improvements can be made further, the physical reasons, and the implications for understanding regional NO₂ trends.**

Figure 4 shows that the effects of different OMI retrievals are not clear except DJF in Midwest and Northeast. If summertime or typical ozone season satellite data are used for the trend study, it is not worth trying different retrievals or corrections suggested in this study.

We do not quite understand this comment. Figure 4 only shows the effects of adding ocean and MODIS corrections only, which can be quite large for some regions and some seasons already. These effects obviously need to be understood. Figure 7 shows the effects of adding lightning filter to the previous two corrections. We think that it shows clearly that all three corrections are necessary for doing trend analysis.

In general, the manuscript reports the impact of uncertainties of satellite tropospheric NO₂ retrievals on the trend analysis. This is a sensitivity test study that provides useful information and can be a good reference to summarize the uncertainties in the OMI NO₂ based trend analysis. However, I do not think it has broad and substantial impacts to change or shape future research.

One thing missing is a validation of a priori model NO₂ profile or near surface NO₂. According to this study, NO₂ columns (potentially NO_x emissions) decrease by ~40% for 10 years. How does satellite NO₂ column retrieval change if a priori profiles come from the model results incorporating this reduced NO_x emission (e.g., 40% reduction to 70% reduction considering a potential error in the emission).

We need to clarify that this work is not a sensitivity test study but proposing three necessary corrections to satellite retrievals used in trend analysis. Due to the chemical non-linearity (Gu et al., 2016), the NO₂ VCD trend differs from NO_x emission trend. As NO₂ columns decrease by ~40%, the NO_x emissions decrease by less than ~40%.

Lamsal et al. (2015) reported that using 2005 emission profile results in an underestimation of generally less than 2% of overall 2005-2010 NO₂ reduction in polluted regions and that the trend is less sensitive to the vertical profile assumption in highly polluted areas (Section 2.2.2 and Figure 3, Lamsal et al., 2015). This is about an underestimation of about 0.3% yr⁻¹, which could be used to explain the residual discrepancy (0.0-0.4% yr⁻¹) between OMI-based and in situ NO₂ trends.

The proper way to estimate the effects of NO_x emissions on NO₂ VCDs is to perform proper inverse modeling of NO_x emissions (e.g., Gu et al., 2014). However, the satellite data still need to be processed such that factors we discussed in this work do not introduce artifacts in tropospheric NO₂ column trends. In the inverse modeling by Gu et al. (2014), the effects of AMF changes on inverse modeling will be accounted for, which we believe is the proper method for deriving NO_x emission trends. That is to say that all proper inverse modeling studies of NO_x emission trend should include AMF calculation that is derived from the a posteriori (not a priori) NO_x emissions and it is the appropriate method of quantify the relative small effects. We added this point to the last sentence in the conclusions.

We revised the sentence in Section 2.3, as follows:

“The yearly variations of meteorology and anthropogenic emission changes have little impact in polluted areas on trend analysis results using OMI data (Lamsal et al., 2015).”

We revised one sentence in Section 3.1.3, as follows:

“The remaining seasonal difference of the trends reflects in part the nonlinear photochemistry (Gu et al., 2013) [and the effects of NO_x emission changes on NO₂ retrievals \(Lamsal et al., 2015\).](#)”

Final comment is to elaborate the correction of NO₂ measurements by molybdenum converter. The plot in supplementary material (Figure S1) can include more details for the 7 sites. The diurnal variation in each season (if not month) and standard deviation in the plot will be helpful to characterize the ratios between surface NO₂ concentrations of chemiluminescence to photolytic instruments. The plots for each site (7 sites) will be useful for readers.

The diurnal variation of the ratio is irrelevant to this research, as OMI overpasses only at around 13:30 local time. Due to the lack of photolytic instruments in each site, we used the averaged ratio between chemiluminescent to photolytic NO₂ measurements in 7 available sites. The individual plots for these 7 sites can be misleading due to data availability. As we stated in Section 2.1, this correction will affect absolute trends but not relative trends, which are what we analyzed in this study. We added the 95th percentile confidence intervals to Figure S1.

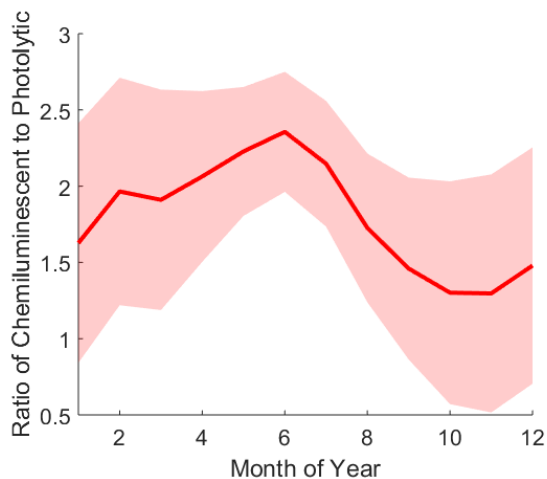


Figure S1. The ratios between surface NO₂ concentrations of chemiluminescence to photolytic instruments. The ratios are calculated for each month from 7 sites with coincident photolytic measurements. The shaded area shows the 95th percentile confidence intervals.

Response to Referee #2:

The manuscript Reconciling the differences between OMI-based and EPA AQS in situ NO₂ trends by Zhang et al. is an investigation of the differences between trends in tropospheric NO₂ columns derived from the OMI satellite instrument and those derived from the EPA AQS network. This is an important and interesting research question, as in remote areas one often has to rely on remote sensing data in order to get reliable measurements of air quality. The manuscript falls well within the scope of AMT.

That being said, the manuscript fails to convince the reader regarding the comparability of the two datasets to begin with. Also, the manuscript is often too imprecise.

Most of the following points are minor and can be fixed by providing more precise information about what the authors did exactly, but they should be addressed before publication in AMT:

1 Comparing VCDs and surface concentrations

The authors fail to convince the reader why OMI VCDs, which are the integrated NO₂ content of the troposphere at a given location, should be comparable to the in-situ surface concentrations of the AQS dataset. There have been numerous studies trying to relate the two measures to each other, and it should be clear to the authors that in order to compare the two, one has to take special caution. This becomes most problematic in the discussion of the effect of the lightning filter, where the authors leave the impression that lightning leads to "wrong" OMI VCDs.

As our research focuses on the regional relative trend difference, we expect that the surface NO₂ trends and NO₂ VCD trends should be very close (They are both affected by chemical non-linearity and may show trends different from emission trends). We stated this in Section 3.1, "The NO₂ relative trends from both datasets are expected to be close on a regional basis where surface emissions of NO_x dominate the observed surface concentrations and tropospheric VCDs of NO₂." We showed in this paper what improvements can be made further, the physical reasons, and the implications for understanding regional NO₂ trends.

To deal with the surface measurement representativeness, we only compare to regional trends from surface observations, which are much more statistically representative. Previous studies did the same. As discussed above, we show the effects of site locations on the trend analysis in Fig. 10 (and Table 1). This point has not been emphasized previously and needs to be accounted for in future studies.

We added in the abstract "However, the current OMI tropospheric NO₂ retrievals are not designed for analyzing multi-year tropospheric NO₂ trends." It is not surprising that satellite data need to be reprocessed in trend analysis, which is true for all observation-based trend studies. We made strong points that standard OMI tropospheric NO₂ VCD data will introduce errors. We believe that our analysis results support these points.

Having said that, we understand the reviewer's point on lightning NO_x. We clarified the discussion by adding "While lightning NO_x is part of OMI NO₂ observations, we treat the influence of lightning on the OMI tropospheric VCD trend as a bias for comparison purposes in this study since AQS data are not as strongly affected by lightning."

We added in the conclusions "While lightning NO_x is part of OMI NO₂ observations, we treat the influence of lightning on the OMI tropospheric VCD trend as a bias for comparison purposes in this study since AQS data are not as strongly affected by lightning. Furthermore, lightning NO_x effects need to be removed when using satellite observations to understand the effects of changing anthropogenic emissions."

In a revised manuscript, the authors should include a summary of the problems arising from comparing the

integrated satellite to the in-situ point measurements, should reference relevant literature, and should make sure that they consider these differences in the comparisons of the relative trends. Also, they should explicitly discuss the problems arising from comparing relative trends of these two different measures.

Table 1 shows that even though the annual trends for coincident data can be conceived as “already good”, the effects of our recommended data processing are > a factor of 2 for West, Midwest, and South (comparing the OMI column with and without the lightning filter). We now emphasize this point in the abstract and conclusions. We did not add criticisms of any specific previous study because it is inappropriate to speculate if “good” agreement between in situ and OMI trends for coincident data is the reason that previous studies did not study the data processing procedures we recommended.

We further make the points that (1) processed OMI data show smaller trends (Figure 8) and (2) using surface data alone will have a tendency to overestimate NO₂ trends (Figure 9). Lastly, Figs. 4-7 show that on a seasonal basis, the effects of the data processing we recommended can be much larger than the annual mean changes of Table (1).

The lightning leads to inaccurate OMI retrieved NO₂ VCDs. Current models have difficulty simulating lightning NO_x and low-pressure system meteorology correctly across different years (as stated in Section 2.3.3 and 3.2), which affects NO₂ vertical profiles and subsequently leads to inaccurate AMFs and NO₂ VCDs.

We updated the manuscript regarding potential factors contributing to the divergence between OMI-based and in situ NO₂ trends.

“Lamsal et al. (2015) also found the divergence between the annual trends inferred from the two datasets, i.e. -4.8% yr-1 vs -3.7% yr-1 during 2005-2008, and -1.2% yr-1 vs -2.1% yr-1 during 2010-2013. There are several potential factors attributing to the discrepancies between trends from satellite and ground-based measurements: interferences by the oxidation products of NO_x from the chemiluminescent instruments (Lamsal et al., 2008, 2014, 2015), the differences of sampling time between OMI (~13:30 local time) and AQS (hourly) measurements (Tong et al., 2015), a high sensitivity of NO₂ VCDs to high-altitude NO₂ in contrast to the high sensitivity of surface NO₂ concentrations to surface NO_x emissions (Duncan et al., 2013; Lamsal et al., 2015), spatial representativeness of satellite pixels (Lamsal et al., 2015), and high uncertainties of satellite retrievals in clean regions (Lamsal et al., 2015).”

To understand how various factors and the retrieval procedure affects-affect the resulting OMI derived trends and their differences from those derived from the surface AQS measurements, we utilize a regional 3-D chemistry transport model (CTM), a radiative transfer model (RTM), and the Mann-Kendall method (Mann, 1945; Kendall, 1948) to calculate OMI-based NO₂ seasonal relative trends during Dec-Jan-Feb (DJF), Mar-Apr-May (MAM), Jun-Jul-Aug (JJA), and Sept-Oct-Nov (SON) (Section 2).”

2 Definition of the relative trends

• 07/05: *It is not entirely clear how exactly the authors calculate the relative trends. Is it a linear trend, calculated by linear regression? By default, the Mann-Kendall test is non-parameteric. If the authors use the Sen slope estimator as relative trend, they should explicitly say so. Otherwise, the authors should explicitly say what the reference value is for the relative trends (i.e., 2005, or average of the whole period, or . . .).*

Thank you. We are using Mann-Kendall method with the Sen’s slope estimator. We now mention this in the abstract and Section 3.

“The Mann-Kendall method with the Sen’s slope estimator is applied to derive the NO₂ seasonal and annual trends for four regions at coincident sites during 2005-2014.”

“We apply the Mann-Kendall method with the Sen’s slope estimator to calculate the relative trend of NO₂ for each season, i.e. DJF, MAM, JJA, and SON, during 2005-2014. We ~~construct~~ compute the uncertainties of the trends with 95th percentile confidence intervals using the Mann-Kendall method a confidence level of 95%.”

• In some places, the authors do give an uncertainty of relative trends. However, they do not give enough detail about how these trend uncertainties are being calculated. If they indeed use the Sen slope estimator from the Mann-Kendall test as relative trend, it is unclear how they define the uncertainty of this estimate. This is however crucial in order to evaluate if the improvements in the agreement of OMI and AQS relative trends are statistically significant at all. Furthermore, in some Figure captions the authors indicate 95% confidence intervals; please briefly describe in the text how these are derived.

We use Mann-Kendall method with the Sen’s slope estimator to estimate the relative trends. The uncertainties are given as the 95th percentile confidence intervals. We now state this in Section 3: “We compute the uncertainties of the trends with the 95th percentile confidence intervals using the Mann-Kendall method.”

• Another point regarding the trend calculations is the uncertainties of the relative trends. The notion of difference between OMI and AQS trends only makes sense if there is some way of assessing if these differences are statistically significant at all.

The uncertainties, the 95th percentile confidence intervals, are shown as the error bars in Figure 7.

3 Importance of yearly varying NO_x emissions

05/04: The authors claim that the yearly variations of [. . .] anthropogenic emission changes have little impact on trend analysis results, and they cite a paper by Lamsal et al. (2015). However, in the cited paper, Lamsal et al. state (Sect. 2.2.1):

In this work, we further improve the operational OMI NO₂ retrieval [. . .] by using new a priori NO₂ profiles [. . .] with year-specific emissions. The year-specific emissions not only improve the representation of the NO₂ vertical distribution, but also capture the yearly changes in NO₂ profile shapes. The latter is critical due to rapid decline in the U.S. NO_x emissions in recent years [. . .].

Since the present study deals with the time period 2005–2014, I do not see how the authors’ choice to use fixed 2010 NO_x emissions is backed by the cited work by Lamsal et al. Given the fact that the study period does include the years of economic crisis, the authors’ choice to use fixed emissions is questionable. I strongly suggest some quantitative assessment of the influence of using fixed emissions.

Lamsal et al. (2015) reported that using 2005 emission profile results in an underestimation of generally less than 2% of the overall 2005-2010 NO₂ reduction in polluted regions and that the trend is less sensitive to the vertical profile assumption in highly polluted areas (Section 2.2.2 and Figure 3, Lamsal et al., 2015). This equals to an underestimation of about 0.3% yr⁻¹, which could be used to explain the residual discrepancy (0.0-0.4% yr⁻¹) between OMI-based and in situ NO₂ trends.

The proper way to estimate the effects of NO_x emissions on NO₂ VCDs is to perform NO_x emission daily retrieval inversion modeling (Gu et al., 2014) to derive daily NO_x emissions. We added this point to the last sentence in the conclusions. However, obtaining more reliable satellite NO₂ retrievals (as in this study) is a prerequisite to such NO_x emission inversion (for trend analysis).

We revised the sentence in Section 2.3, as follows:

“The yearly variations of meteorology and anthropogenic emission changes have little impact in polluted areas on trend analysis results using OMI data (Lamsal et al., 2015).”

We revised one sentence in Section 3.1.3, as follows:

“The remaining seasonal difference of the trends reflects in part the nonlinear photochemistry (Gu et al., 2013) and the effects of NO_x emission changes on NO₂ retrievals (Lamsal et al., 2015).”

4 Reconciling chemiluminescent and photolytic in-situ measurements

The authors claim that calculating a correction factor for the chemiluminescent in-situ data by taking the average ratio of chemiluminescent to photolytic measurements. This would only work properly if the reasons for the high bias of the former instruments were identical at all measurement stations. While it is true that this correction does not influence the relative trends, the authors should at least mention this.

Thank you. We now clarify this in Section 2.1, as follows:

“We correct the chemiluminescent NO₂ data by the observed ratio assuming that the inter-annual change is small and the high bias of the chemiluminescent measurements is identical at all sites.”

5 Importance of individual sources of AMF uncertainty

04/28: The authors claim that the first two factors are most important for the NO₂ trend analysis, but fail to back up their claim.

We revised this sentence as follows:

“We find that the ~~The~~ NO₂ VCD trend analysis is particularly sensitive to the first two factors and we will discuss these in the following sections.”

6 Time span of lightning filter

06/20: The authors' choice of lightning filter (72hrs / 90km) seems arbitrary and needs to be justified. As the authors correctly state, the lifetime of NO_x in the free troposphere can reach up to one week. By making their filter only 90km wide, a back-of-the envelope calculation quickly shows that the NO_x produced by a single lightning occurrence can easily be transported considerably further within 72hrs than only 90km. The authors seem to be aware of this inconsistency, because they introduce an additional filter for the Northeast which depends on lightning occurrence in the South, implying a transport distance of many hundreds of kilometers.

We have stated this in Section 2.3.3, “Since lightning usually occur along the track of a thunderstorm, the 90 km radius is more a constraint on lightning NO_x effects across the track. The extended period of 72 hours is to ensure that we exclude data affected by lightning NO_x.”. We chose such filter constraints in order to balance between data availability and validity. The current constrains of 72 hours and a 90 km radius can ensure enough data (remove 2-27% data). Increasing the radius greatly will remove too much data. We discussed that our lightning filter is crude and needs improvements.

7 *Minor comments*

- 04/18: *NO₂ partial VCDs*

Revised as suggested.

- 05/06: *Which trends? Those with the default albedo, or those with the update? . . .)*

Revised as follows:

“The derived tropospheric NO₂ VCD relative trends with default surface reflectance are referred as “Standard”.”

- 05/09: *I personally find the name ocean trend misleading, as it has nothing to do with the ocean (except for the geographical location of the clean background region). Maybe the authors can come up with a name that somehow indicates the origin of the trend (e.g., instrument drift).*

The relative trend in remote ocean potentially may stem from the similar reasons as the “hot” pixels of OMI. However, the nature of this trend is not fully understood. Thus, we decide to use the term ‘ocean trend’ to indicate that this trend is calculated at clean ocean region.

- 07/10: *It seems that there are four different OMI-based NO₂ trends*

We revised this sentence as follows:

“The ocean trend removal, MODIS albedo update, and lightning filter are then added in sequence to compute three different OMI-based NO₂ trends (in addition to “Standard”) to compare to the AQS in situ results.”

- 07/15: *To avoid confusion, please explicitly mention that these are absolute differences of the relative trends.*

We now clarify this as follows:

“OMI-based trends generally underestimate the decreasing trends by up to 3.7% yr⁻¹ (the absolute difference between relative trends) except for the large overestimation in the Midwest and the Northeast regions during DJF.”

- 09/05: *trends of OMI data are less — than what?*

We revised this sentence to prevent ambiguity.

“Without the lightning filter, AQS decreasing trends are stronger while than the decreasing trends of OMI data are less (Fig. 7).”

• 09/07: OMI VCDs are not overestimated when not filtering for lightning NOx - the lightning NOx is part of the VCD. It leads to worse agreement between OMI and AQS trends, but then again, these are two fundamentally different measures anyways.

Yes, but for trend analysis, lightning signals need to be removed because they are sporadic and mask out the trends due to anthropogenic emission changes in an unpredictable manner.

• 09/11: What is a reduction of decreasing surface trends? Misleading phrase, since the trends are decreasing trends to begin with. Maybe it'd be better to say stronger decreasing trends or something similar.

We revised the term accordingly.

“Therefore, the ~~reduction of weaker~~ decreasing surface trends likely reflects a reduction of low-pressure dilution effect.”

• 09/12: Again, OMI VCDs are not biased due to lightning, see above.

We see the reviewer’s point here. We clarified the discussion by adding “While lightning NOx is part of OMI NO₂ observations, we treat the influence of lightning on the OMI tropospheric VCD trend as a bias for comparison purposes in this study since AQS data are not as strongly affected by lightning.”

We added in the conclusions “While lightning NOx is part of OMI NO₂ observations, we treat the influence of lightning on the OMI tropospheric VCD trend as a bias for comparison purposes in this study since AQS data are not as strongly affected by lightning. Furthermore, lightning NOx effects need to be removed when using satellite observations to understand the effects of changing anthropogenic emissions.”

• 09/13: reduction of decreasing trends — see above

We revised the term accordingly.

“Similarly, as anthropogenic emissions decrease, the positive bias of tropospheric VCDs due to lightning NOx becomes larger, likely resulting in ~~reduction of weaker~~ decreasing trends.”

• 09/15: OMI VCDs are not wrong when they include lightning NOx – the authors should therefore not make the qualitative statement corrected here. Filtered would be better.

Revised as suggested.

“We consider the lightning effects on surface NO₂ trends to be mostly meteorological driven not by lightning NOx directly (e.g., Ott et al., 2010; Lu et al., 2017) and hence the ~~corrected filtered~~ OMI NO₂ data are likely closer to emission related concentration changes.”

• 09/29: I would assume that the driving factor in stronger decreasing trends close to anthropogenic source

regions is the decreasing emissions in those, resulting in less transported NO_x in those areas.

If the atmospheric lifetime of NO_x is the spatially homogeneous and the predominant source is anthropogenic, the reduction of NO_x emissions will result in the same reduction (relative change) of NO_x concentrations in rural and urban regions alike. The chemical non-linearity leads to changing atmospheric lifetime of NO_x in response to NO_x emission changes and subsequent more evident reduction in urban areas. Also, in rural areas where the dominant NO_x sources are biogenic, such as, soil and lightning, the NO_x concentration relative changes will be smaller if the reduction (relative change) of NO_x emissions are the same. We have already stated these in Section 3.2: “The larger decrease near the anthropogenic source regions reflect in part the nonlinear photochemistry (Gu et al., 2013) and in part to a stronger influence of NO_x sources such as soils in rural regions.”

• 10/03: *Since comparing VCDs to surface concentrations is a difficult issue to begin with, I would not blame the OMI retrievals for the differences – when comparing apples and oranges, why should one blame one and not the other for the differences? Saying that the OMI data are not designed for trend analysis doesn't make sense. If one has to design a dataset in order to be able to do trend analysis, maybe there just are no significant trends in the underlying data to begin with?*

We have to disagree. All observation data need to be corrected when they are used for trend analysis. OMI retrievals are no different. It is more complex than, say, global surface temperature data because the retrieval is much more complex. Even for something as simple as surface temperature, one must be very careful when using the observation-based trends (especially for the early part of the dataset).

• *In Fig. 1a-d, it is not clear if positive numbers mean that the OMI trend or the AQS trend is higher. Please update the Figure caption with a mathematically precise description (e.g., "OMI relative trend minus AQS relative trend").*

We updated the caption as follows:

“Panel (a) through (d) show the regional difference (OMI-based relative trends minus AQS relative trends) of annual relative trends between coincident OMI-based and AQS in situ data.”

• *Fig. 3: Please update the Figure caption with a precise indication of the units, e.g., "number of days [. . .] per REAM grid cell". Also, please spell out cloud-to-ground instead of CG in the caption.*

Revised as suggested.

“Number of days with NLDN detected cloud-to-ground (CG) CG lightning per model grid cell per year during 2005-2014. The lightning occurrences are calculated using the REAM grid resolution.”

• *Fig. 6: Please indicate NO₂ somewhere in the Figure caption. Also, the legend for the OMI data should be something like OMI (lightning filter); after all, the data show trends of OMI NO₂ columns and not of the lightning filter.*

We revised the legend and the caption.

“Seasonal relative trends of NO₂ calculated from the AQS in situ measurements (“AQS”, black line) and those derived from OMI data after applying the lightning filter (“OMI (lightning filter)”, red line). The error bars represent 95th percentile confidence intervals. The coincident data points are less than those used in

~~Figure 5 and therefore the AQS trends are not the same. Same as Figure 5 but for coincident AQS (black line) and OMI data (redline) after applying the lightning filter. The coincident data points are less than used in Figure 5 and therefore the AQS trends are not the same.”~~

• Fig. 7: I don't understand what the figure legends are the same as in Figs. 6 and 8 is supposed to mean. Please clarify.

• Fig. 7: Please explicitly indicate in the Figure caption if statistically insignificant trends are shown or not.

We corrected the typos regarding the Figs. 4 and 6. We further clarified the confidence intervals of the error bars as follows:

“The error bars represent 95th percentile confidence intervals. The relative trends are shown in Figs. ~~64~~ and ~~86~~. The figure legends are the same as in Figs. ~~64~~ and ~~86~~ but with the AQS trends subtracted from the OMI-based trends.”

• Fig. 9a: There is something wrong with the Figure caption, it does not contain a complete sentence (maybe there's just a of missing?). Please indicate what the barbs on the individual data points mean.

Revised as follows:

“(a) The “Lightning filter” OMI-based NO₂ relative trend as a function 2005-2014 averaged OMI tropospheric NO₂ VCD... The error bars represent 95th percentile confidence intervals. ~~Red~~The red line shows a least-squares regression.”

• Fig. 9b: Please be specific about which OMI NO₂ data you show in this Figure, using the nomenclature from earlier. As explained above, the notion of corrected is misleading.

Revised as follows:

“The corrected OMI tropospheric NO₂ data (“Lightning filter”) are used.”

Reconciling the differences between OMI-based and EPA AQS in situ NO₂ trends

Ruixiong Zhang¹, Yuhang Wang¹, Charles Smeltzer¹, Hang Qu¹, William Koshak², K. Folkert Boersma^{3,4}

¹School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA

²NASA-Marshall Space Flight Center, National Space Science & Technology Center, 320 Sparkman Drive, Huntsville, Alabama, USA

³Meteorology and Air Quality Group, Wageningen University, the Netherlands

⁴Royal Netherlands Meteorological Institute, De Bilt, the Netherlands

Correspondence to: Yuhang Wang (yuhang.wang@eas.gatech.edu)

Abstract. With the improved spatial resolution than earlier instruments and more than ten years of service, tropospheric NO₂ retrievals from the Ozone Monitoring Instrument (OMI) have led to many influential studies on the relationships between socioeconomic activities and NO_x emissions. However, the current OMI tropospheric NO₂ retrievals are not designed for analyzing multi-year tropospheric NO₂ trends. This study focuses on how to improve OMI NO₂ retrievals for more reliable trend analysis. We retrieve OMI tropospheric NO₂ vertical column densities (VCDs) and obtain the NO₂ seasonal trends over the United States, which are compared with coincident in situ surface NO₂ measurements from the Air Quality System (AQS) network. The Mann-Kendall method with the Sen's slope estimator is applied to derive the NO₂ seasonal and annual trends for four regions at coincident sites during 2005-2014. The OMI-based NO₂ seasonal relative trends are generally biased high compared to the in situ trends by up to 3.7% yr⁻¹, except for the underestimation in the Midwest and Northeast during Dec-Jan-Feb (DJF). We improve the OMI retrievals for trend analysis by removing the ocean trend, using the MODerate-resolution Imaging Spectroradiometer (MODIS) albedo data in air mass factor (AMF) calculation, and applying a lightning flash filter to exclude lightning affected OMI NO₂ retrievals. These improvements result in close agreement (within 0.3% yr⁻¹) between in situ and OMI-based NO₂ regional annual relative trends. Thus, weThe derived OMI-based annual regional NO₂ trends change by a factor of > 2 for the South, the Midwest, and the West and seasonal changes can be even larger. We recommend future studies to apply these procedures to ensure the quality of satellite-based NO₂ trend analysis, especially in regions without reliable long-term in situ NO₂ measurements. We derive optimized OMI-based NO₂ regional annual relative trends using all available data for the West (-2.0%±0.3 yr⁻¹), the Midwest (-1.8%±0.4 yr⁻¹), the Northeast (-3.1%±0.5 yr⁻¹), and the South (-0.9%±0.3 yr⁻¹). The OMI-based annual mean trend over the contiguous United States is -1.5%±0.2 yr⁻¹. It is a factor of 2 lower than that of the AQS in situ data (-3.9%±0.4 yr⁻¹); the difference is mainly due to the fact that the locations of AQS sites are concentrated in urban and suburban regions.

1 Introduction

Nitrogen dioxide (NO_2) is an air pollutant. At high concentrations, it aggravates respiratory diseases and can lead to acid rain formation (e.g., Lamsal et al., 2015). It is also a key player to produce another pollutant, ozone (O_3), through photochemical reactions in the presence of Volatile Organic Compounds (VOCs) under sunlight. Tropospheric NO_2 is emitted both anthropogenically and naturally (e.g., Gu et al., 2016). Anthropogenic fossil fuel combustions and biomass burnings emit mostly nitrogen monoxide (NO) under high temperature, which is later oxidized by O_3 into NO_2 . Major natural NO_2 sources include lightning and soils.

Surface NO_2 concentrations are regulated by the U.S. Environmental Protection Agency (EPA) through the National Ambient Air Quality Standards (NAAQS). NO_2 is measured routinely at the EPA Air Quality System (AQS) sites (Demerjian, 2000). Although the AQS network continually provides valuable hourly NO_2 measurements, AQS sites are mostly located in urban and suburban regions, leaving large regions of rural areas unmonitored. Satellite data provide a better spatial coverage than the in situ measurements.

Several satellites were launched to monitor tropospheric NO_2 vertical column densities (VCDs), such as the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY), the Global Ozone Monitoring Experiment-2 (GOME-2), and the Ozone Monitoring Instrument (OMI). For trend analysis, the tropospheric NO_2 products from OMI surpass the others for a relatively high spatial resolution and over one decade of continuous operation (Boersma et al., 2004; Boersma et al., 2011). Thus, OMI NO_2 retrievals are widely applied in NO_2 and NO_x emission trend studies (e.g., Lin et al., 2010, 2011; Castellanos et al., 2012; Russell et al., 2012; Gu et al., 2013; Lamsal et al., 2015; Lu et al., 2015; Tong et al., 2015; Cui et al., 2016; Duncan et al., 2016; de Foy et al., 2016a, 2016b; Krotkov et al., 2016; Liu et al., 2017). Tong et al. (2015) reported that the reduction rates calculated from OMI NO_2 VCDs and AQS surface NO_2 data at eight cities were -35% and -38% from 2005 to 2012, respectively. Lamsal et al. (2015) also found the divergence between the annual trends inferred from the two datasets, i.e. $-4.8\% \text{ yr}^{-1}$ vs $-3.7\% \text{ yr}^{-1}$ during 2005-2008, and $-1.2\% \text{ yr}^{-1}$ vs $-2.1\% \text{ yr}^{-1}$ during 2010-2013. There are several potential factors attributing to the discrepancies between trends from satellite and ground-based measurements: interferences by the oxidation products of NO_x from the chemiluminescent instruments (Lamsal et al., 2008, 2014, 2015), the differences of sampling time between OMI (~13:30 local time) and AQS (hourly) measurements (Tong et al., 2015), a high sensitivity of NO_2 VCDs to high-altitude NO_2 in contrast to the high sensitivity of surface NO_2 concentrations to surface NO_x emissions (Duncan et al., 2013; Lamsal et al., 2015), spatial representativeness of satellite pixels (Lamsal et al., 2015), and high uncertainties of satellite retrievals in clean regions (Lamsal et al., 2015).

To understand how various factors and the retrieval procedure affects/affect the resulting OMI derived trends and their differences from those derived from the surface AQS measurements, we utilize a regional 3-D chemistry transport model (CTM), a radiative transfer model (RTM), and the Mann-Kendall method (Mann, 1945; Kendall, 1948) to calculate OMI-based NO_2 seasonal relative trends during Dec-Jan-Feb (DJF), Mar-Apr-May (MAM), Jun-Jul-Aug (JJA), and Sept-Oct-Nov (SON) (Section 2). To reconcile with the AQS

based regional NO₂ trends, we find that three procedures are essential to ensure the quality of trend analysis using OMI tropospheric NO₂ VCDs, including the ocean trend removal, the MODerate-resolution Imaging Spectroradiometer (MODIS) albedo update in calculating the air mass factors (AMFs), and the lightning filter (Section 3.1). With these procedures implemented, the differences between OMI-based and AQS in situ annual relative trends are within 0.3% yr⁻¹ of coincident measurements for all the four regions. Finally, we estimate the OMI-based annual relative trends across the nation in Section 3.2. Conclusions are given in Section 4.

2 Methods

2.1 EPA AQS surface NO₂ measurements

The in situ surface NO₂ measurements from the U.S. EPA AQS network are used in this research. Sites with a continuous measurement gap of more than 50 days are removed and the observations of 140 remaining sites are used (Fig. 1). The AQS chemiluminescent analyzers are equipped with molybdenum converters to measure ambient NO₂ concentrations. These analyzers are known to have high biases, since the converters are not NO₂ specific and they measure some fractions of peroxyacetyl nitrate, nitric acid and organic nitrates (Demerjian, 2000; Lamsal et al., 2008). In addition to chemiluminescent analyzers, several NO₂ specific photolytic instruments were deployed since 2013. By utilizing the data from both chemiluminescent and photolytic measurements at coincident sites during the overpassing time of OMI, we calculate the observed NO₂ concentration ratio between both measurements in Fig. S1 in the Supplement. The ratio peaks at 2.3 in June and decreases to 1.3 in November, indicating that the chemiluminescent analyzers overestimate by 27%-132% than photolytic instruments. This finding is in agreement with Lamsal et al. (2008). We correct the chemiluminescent NO₂ data by the observed ratio assuming that the inter-annual change is small- and the high bias of the chemiluminescent measurements is identical at all sites. This correction may contribute to the differences between in situ and OMI based absolute NO₂ trends but do not significantly affect the relative trends (since the correction is canceled out in computing relative trends). In this study, we only examine the relative trends and therefore the analysis results are not affected by the uncertainties in the in situ NO₂ measurement corrections.

2.2 REAM model

We use a 3-D Regional chEmical trAnsport Model (REAM) in the simulation of NO₂ profiles. REAM has widely been used in atmospheric NO₂ studies, including vertical transport (Choi et al., 2005; Zhao et al., 2009a; Zhang et al., 2016a), emission inversions (Zhao et al., 2009b; Yang et al., 2011; Gu et al., 2013, 2014, 2016), and regional and seasonal variations (Choi et al., 2008a, 2008b). The model has a horizontal resolution of 36 km with 30 vertical layers in the troposphere, 5 vertical layers in the stratosphere, and a model top of 10 hpa. In this study, the domain of REAM is about 400 km larger on each side than the contiguous United States (CONUS). Meteorology inputs driving transport process are simulated by the Weather Research and

Forecasting model (WRF) assimilations constrained by National Centers for Environmental Prediction Climate Forecast System Reanalysis (NCEP CFSR, Saha et al., 2010) 6-hourly products. The KF-eta scheme is used for sub-grid convective transport in WRF (Kain and Fritsch, 1993). We run the WRF model with the same resolution as in REAM but with a domain 10 grids larger on each side than that of REAM. REAM updates most of the meteorology inputs every 30 minutes while those related to convective transport and lightning parameterization are updated every 5 minutes. The chemistry mechanism expands that of a global CTM GEOS-Chem (V9-02) with aromatics chemistry (Bey et al., 2001; Liu et al., 2010, 2012a, 2012b; Zhang et al., 2017). For consistency, the GEOS-Chem (V9-02) simulation with $2^\circ \times 2.5^\circ$ resolution is used to generate initial and boundary conditions for chemical tracers.

Anthropogenic emissions of NO_x and other chemical species are from the U.S. National Emission Inventory 2008 prepared using the Sparse Matrix Operator Kernel Emission (SMOKE) model. Biogenic emissions are simulated online using the Model of Emissions of Gases and Aerosols from Nature (MEGAN) algorithm (v2.1, Guenther et al., 2012). We parameterize lightning emitted NO_x as a function of convective mass flux and Convective Available Potential Energy (CAPE) (Choi et al., 2005). NO_x production per flash is set to 250 moles NO per flash, and the emissions are distributed vertically following the C-shaped profiles by Pickering et al. (1998). For recent model evaluations of REAM with observations, we refer readers to Zhang et al. (2016a, 2016b), Cheng et al. (2017), and Zhang et al. (2017).

2.3 OMI-based NO₂ VCDs

We retrieve the tropospheric NO₂ VCDs using the tropospheric slant column densities (SCDs) from the Royal Dutch Meteorological Institute (KNMI) Dutch OMI NO₂ product (DOMINO v2, Boersma et al., 2011). OMI onboard the Aura satellite was launched in July 2004 and is still active. OMI overpasses the equator at about 13:30 Local Time (LT) and obtains global coverage with a 2600 km viewing swath spanning 60 rows. It has a ground level spatial resolution up to 13 km x 24 km (at nadir). The spatial extent of the OMI pixels will not affect our analysis as we focus on regional trend analysis. SCDs are retrieved by matching a modeled spectrum to an observed top-of-atmosphere reflectance with the Differential Optical Absorption Spectroscopy (DOAS) technique within a fitting window of 405-465nm. The stratospheric portion of SCDs are estimated and subsequently removed with a global CTM TM4 with stratospheric ozone assimilation (Dirksen et al., 2011). Deriving tropospheric VCDs from the remaining tropospheric SCDs requires the calculation of AMFs. Being an optically thin gas, tropospheric AMF for NO₂ can be calculated from AMF for each vertical layer (AMF_l) weighted by NO₂ partial VCDs at the corresponding layer (x_l) (Boersma et al., 2004), as shown in equation (1).

$$\text{tropospheric AMF} = \frac{\text{tropospheric SCD}}{\text{tropospheric VCD}} = \frac{\int AMF_l x_l dl}{\int x_l dl} \quad (1)$$

As the vertical distribution of NO₂ is usually unknown, we typically substitute x_l by an a priori profile ($x_{l, \text{a priori}}$) from a CTM. AMF_l is the sensitivity of NO₂ SCD to VCD at a given altitude (Eskes and Boersma, 2003), and is computed using the Double Adding KNMI (DAK) RTM (Lorente et al., 2017). As a result, the

retrieved tropospheric NO₂ VCD computation depends on the a priori NO₂ vertical profile, the surface reflectance, the surface pressure, the temperature profile, and the viewing geometry (Boersma et al., 2011). Previous studies have addressed the sources of uncertainties in NO₂ retrievals, including surface reflectance resolutions (Russell et al., 2011; Lin et al., 2014), lightning NO_x (Choi et al., 2005a; Martin et al., 2007; Bucselo et al., 2010), a priori CTM uncertainties (Russell et al., 2011; Heckel et al., 2011; Lin et al., 2012; Laughner et al., 2016), surface pressure and reflectance anisotropy in rugged terrain (Zhou et al., 2009), cloud and aerosol radiance (Lin et al., 2014, 2015), and boundary layer dynamics (Zhang et al., 2016a). ~~The~~We find that the NO₂ VCD trend analysis is particularly sensitive to the first two factors and we will discuss these in the following sections.

AMFs are derived using the pre-computed altitude-dependent AMF lookup table, which is generated by the DAK RTM. We use the NO₂ profiles from REAM, temperature and pressure from CSFR, viewing geometry and cloud information from DOMINO v2 product. We use the REAM results of 2010 to avoid the uncertainty introduced by yearly variation of NO₂ profiles. The yearly variations of meteorology and anthropogenic emission changes have little impact in polluted areas on trend analysis results using OMI data (Lamsal et al., 2015). We use the surface reflectance from DOMINO v2 product as default (Kleipool et al., 2008), and update it using a surface reflectance product with a higher temporal resolution (Section 2.3.2). The derived tropospheric NO₂ VCD relative trends with default surface reflectance are referred as “Standard”.

2.3.1 Ocean trend removal

For trend and other analyses of OMI tropospheric VCDs, the data of anomalous pixels must be removed. The row anomaly initially occurred in June 2007 and subsequently in later years affected rows 26-40 (Schenkeveld et al., 2017). Additional anomalies can be found in some years in rows 41-55. For trend analysis from 2005-2014, we exclude rows 26-55, consistent with our understanding of the row anomaly (Schenkeveld et al., 2017), and following the flagging in the DOMINO v2 data product. In addition, the data of coarse spatial resolution from rows 1-5 and rows 56-60 are also excluded, as suggested by Lamsal et al. (2015). Furthermore, we exclude OMI data with cloud fraction > 0.3 to minimize retrieval uncertainties due to clouds and aerosols (Boersma et al., 2011; Lin et al., 2014).

Fig. 2a shows that there is an apparent increasing trend of the averaged tropospheric SCDs in the remote ocean region (Fig. 2b) with minimal marine traffic. This trend reflects the increase in the magnitude of the stripes (step-wise SCD variability from one row to another) in time, which originates from the use of a constant (2005-averaged) solar irradiance reference spectrum in the DOAS spectral fits throughout the mission and the weak increase of noise in the OMI radiance measurements (Boersma, personal communication, 2017; Zara et al., 2018). Fig. 2a shows that there is a positive annual trend of $1.75 \pm 0.45 \times 10^{13}$ molecules cm⁻² yr⁻¹. The ocean trend is insensitive to the region selection in the remote North Pacific (varies within 10%). We only analyze OMI tropospheric column trends over the CONUS for grid cells with 2005-

2014 averaged VCDs $> 1 \times 10^{15}$ molecules cm^{-2} , which tends to minimize the effect of the background noise. However, removing this background ocean (absolute) trend has a non-negligible effect in reducing the OMI relative trend (Fig. 1). We refer to such derived (relative) trend data as “Ocean”. An alternative method is to subtract monthly SCDs of the remote ocean region from the OMI tropospheric SCD data. Although the end results are essentially the same as the trend removal method, noises are added to the SCD data (Fig. 2a), making it more difficult to understand the effects of the MODIS albedo update and the lightning filter (next sections). We therefore choose to use the (absolute) trend removal method here.

2.3.2 MODIS albedo update

The albedo data used to calculate the AMF_l in “Standard” and “Ocean” versions of trend analysis are from the DOMINO v2 products, which are the climatology of averaged OMI measurements during 2005-2009 with a spatial resolution of $0.5^\circ \times 0.5^\circ$ (Kleipool et al., 2008) and is valid for 440 nm. We recalculate the AMF_l using the MODIS 16-day MCD43B3 albedo product with 1km spatial resolution, which combines data from both MODIS onboard Aqua and Terra satellites (Schaaf et al., 2002; Tang and Zhang, 2007). Aqua and Terra have an equatorial overpassing time of 13:30 LT and 10:30 LT, respectively. The band 3 (459nm-479nm) is used to match the NO_2 fitting window (405nm-465nm). The albedo is spatially integrated to the geometry of OMI pixels and is temporally interpolated to match OMI overpassing dates. In order to maintain the consistency of the DOMINO retrieval algorithm (Boersma et al., 2011), we only use the MODIS data to improve the temporal variations of albedo data used in the retrieval. We scale the MODIS albedo data such that the mean albedo during 2005-2009 is the same as the OMI climatology at $0.5^\circ \times 0.5^\circ$. We recalculate OMI tropospheric VCDs using the MODIS albedo data as described. We recalculate the relative OMI trend and remove the ocean (absolute) trend (Section 2.3.1). We refer to this version of OMI relative trend data as “MODIS”.

2.3.3 Lightning event filter

Over North America, lightning is a major source of NO_x in the free troposphere and its simulations in CTMs are uncertain (e.g., Zhao et al., 2009a; Luo et al., 2017). The large temporospatial variations of lightning NO_x make it difficult to compute satellite based NO_2 trends by changing the vertical distributions of NO_2 affecting the AMF calculation (e.g., Choi et al., 2008b; Lamsal et al., 2010) and the SCD values. Given the difficulty to simulate lightning NO_x accurately across different years, we use a lightning filter to remove potential effects of lightning NO_x on the basis of the flash rate observations of cloud-to-ground (CG) lightning flash data detected by the National Lightning Detection NetworkTM (NLDN) (Cummins and Murphy, 2009; Rudlosky and Fuelberg, 2010). NLDN only reports the ground point of a CG lightning flash, while the CG lightning flash can extend horizontally to tens of kilometers. A CG lightning flash can affect the NO_2 retrievals not only in the model grid cell where the CG lightning is located but also the nearby model grid cells. The atmospheric lifetime of NO_x in the free troposphere can be up to 1 week. Therefore, we exclude the OMI NO_2 data within a radius of ~~90km~~90 km of the NLDN-reported CG lightning location (about two

model grid cells around the grid cell where the CG lightning is located) for a period of 72 hours after the lightning occurrence. Since lightning usually occur along the track of a thunderstorm, the 90 km radius is more a constraint on lightning NO_x effects across the track. The extended period of 72 hours is to ensure that we exclude data affected by lightning NO_x. Figure 4 shows the distribution of the number of days of 2005-2014 with lightning detection. The Southwest monsoon and the South regions have more lightning days than the other areas. While there are fewer lightning flashes in the Northeast than the South (Fig. 3), large amounts of lightning NO_x can be produced by high flash ratios of severe thunderstorms and they can be transported northward from the South to the Northeast (Choi et al., 2005). We therefore further filter OMI NO₂ data in the Northeast on the basis of CG lightning flash rates in the South. If the average CG flash rate in the South exceeds the 95th percentile value of the NLDN observations, which is 0.035 flash km⁻² day⁻¹ (Fig. S2 in the Supplement), we exclude in the analysis the Northeast OMI data in the following 72 hours. Excluding the OMI data based on CG lightning data implicitly removes the data affected by cloud-to-cloud lightning collocated with CG lightning. The lightning filter removes about 2%, 27%, 20%, and 19% of OMI data, which are coincident with AQS data, for the West, the Midwest, the Northeast and the South, respectively. We refer to this version of OMI relative trend data as “Lightning filter”.

3 Results and discussion

We group the analysis results into different regions: (a) West, (b) Midwest, (c) Northeast, and (d) South (Fig. 1), following the regional divisions by the United States Census Bureau. To make a fair comparison between the in situ and OMI-based trends, we only use spatially and temporally coincident in situ and OMI NO₂ observations in Section 3.1. We apply the Mann-Kendall method with the Sen’s slope estimator to calculate the relative trend of NO₂ for each season, i.e. DJF, MAM, JJA, and SON, during 2005-2014. We constructcompute the uncertainties of the trends with the 95th percentile confidence level of 95%-intervals using the Mann-Kendall method. Note that when we compare in situ and OMI-based trends, the lightning filter also removes in situ NO₂ data, which are coincident with the OMI NO₂ data affected by lightning. This leads to slightly different in situ NO₂ trends between Fig. 4 and Fig. 6 (Section 3.2.3). We first compute the trends using the “Standard” OMI VCD data. The ocean trend removal, MODIS albedo update, and lightning filter are then added in sequence to compute three different OMI-based NO₂ trends (in addition to “Standard”) to compare to the AQS in situ results. A subtlety in the comparison is that the coincident data change when the lightning filter is applied. As a result, the AQS in situ results in this set of comparison differ from those in the other three sets.

3.1 In situ and “Standard” OMI-based trends

Fig. 4 shows that both AQS in situ and “Standard” OMI-based seasonal relative trends are negative for all seasons across the regions. OMI-based trends generally underestimate the decreasing trends by up to 3.7% yr⁻¹ (the absolute difference between relative trends) except for the large overestimation in the Midwest and the Northeast regions during DJF. The overestimates in these two regions are 3.0% yr⁻¹ and 1.1% yr⁻¹,

respectively. On average, the differences between OMI-based and in situ seasonal relative trends are 1.6% yr⁻¹, -0.3% yr⁻¹, 1.0% yr⁻¹, and 1.4% yr⁻¹ for the West, the Midwest, the Northeast, and the South regions, respectively. Note that the relative trends are calculated using coincident measurements for the comparisons. The NO₂ relative trends from both datasets are expected to be close on a regional basis where surface emissions of NO_x dominate the observed surface concentrations and tropospheric VCDs of NO₂. The focus of this work is to reconcile the difference between AQS in situ and OMI-based trends, which will be discussed in the following sections.

3.1.1 Improvement due to ocean trend correction

After removing the ocean trend as discussed in Section 2.3.1, the OMI-based NO₂ decreasing trends are more pronounced as shown in Fig. 4 (“Ocean”, blue line) by 0.1-0.9% yr⁻¹. The regional relative trends have different sensitivities to the ocean trend removal due to different tropospheric VCDs levels. In general, the discrepancies between OMI-based and in situ trends are reduced except for the Midwest and the Northeast regions during DJF, which are already biased low. The averaged differences between OMI-based and in situ seasonal relative trends for the West, the Midwest, the Northeast, and the South regions are 1.2% yr⁻¹, -1.1% yr⁻¹, 0.4% yr⁻¹, and 1.0% yr⁻¹. Only in the Midwest region, removing the ocean trend enlarges the difference due to the large winter bias.

3.1.2 Improvement due to MODIS albedo update

The adoption of the up-to-date MODIS albedo (Section 2.3.2) greatly reduces the difference of relative trends in the Midwest during DJF from -3.6% yr⁻¹ (“Ocean”) to 1.3% yr⁻¹ (“MODIS”), the improvement of DJF trend difference is more moderate from -1.7% to 0.5% (Fig. 4). There are no significant changes of the comparisons in other regions or other seasons. Fig. 5 shows the albedo seasonal relative trends for the 4 regions coincident with AQS in situ NO₂ data. The OMI DOMINO v2 incorporates a climatology albedo dataset (Kleipool et al., 2008) with snow/ice albedo adjustment using the NASA Near-real-time Ice and Snow Extent (NISE) dataset (Boersma et al., 2011). The climatology albedo data exhibits no trends. Thus, the trends of albedo mainly originate from the yearly variation of NISE detected snow/ice, followed by OMI sampling variation. The noticeable seasonal trend of the OMI DOMINO v2 albedo dataset is the 3.9% yr⁻¹ increase in DJF of the Midwest and a smaller DJF increase (1.0%) of the Northeast. In contrast, the MODIS albedo dataset exhibits a smaller positive DJF trend (0.8% yr⁻¹), 3.1% yr⁻¹ less than the trend from DOMINO v2, in the Midwest, and a small negative DJF trend (-0.8%) in the Northeast. The comparison to the AQS data shows that the MODIS albedo update leads to better agreement between satellite and in situ trends in winter in these regions (Fig. 4).

3.1.3 Improvement due to lightning filter

As discussed in Section 2.3.3, lightning NO_x affects the retrievals of satellite tropospheric NO₂ VCDs. Fig. 6 shows that the lightning filter significantly reduces the difference between the OMI-based relative trend

and that of the AQS data by 0.5-1.4% yr⁻¹ in the Northeast and 0.9-1.3% yr⁻¹ in the South. As a result, the seasonal trend differences are within 0.9% yr⁻¹ in these two regions except during SON. The lightning filter has little effect on the West and the Midwest. While lightning NO_x can be significant during the monsoon season in some regions of the West (Fig. 3), the average tropospheric NO₂ VCDs are usually < 1x10¹⁵ molecules cm⁻² and lightning affected regions are therefore excluded in trend analysis.

The effect of lightning filter (Fig. 6) cannot be shown in Fig. 4 because the coincident OMI and AQS data points are fewer after applying the lightning filter. We examine the improvements of ocean trend removal, MODIS albedo update, and lightning filter by comparing the differences of different OMI-based seasonal relative trends from the AQS in situ trends in Fig. 7. The previously discussed improvements such as OMI albedo update for the Midwest and the Northeast during DJF are shown. By subtracting the AQS trends, we can now find clear improvements of the lightning filter for the South and the Northeast. There remains seasonal variation of OMI-based trend biases relative to in situ data but the discrepancies of the annual trends after the three discussed procedures are relatively small at 0.3% yr⁻¹, -0.3% yr⁻¹, -0.1% yr⁻¹, and 0.0% yr⁻¹, in the West, the Midwest, the Northeast, and the South regions (Fig. 1), respectively. The remaining seasonal difference of the trends reflects in part the nonlinear photochemistry (Gu et al., 2013) and the effects of NO_x emission changes on NO₂ retrievals (Lamsal et al., 2015).

3.2 OMI-based NO₂ trends

Table 1 summarizes the regional annual trends of coincident AQS in situ and OMI data. The “Standard” OMI data (following the DOMINO v2 algorithm) tend to show less NO₂ reduction than AQS data. After applying the three corrections discussed in the previous section to the OMI data, the agreement with the AQS trends is within the uncertainties of the trends. While lightning NO_x is part of OMI NO₂ observations, we treat the influence of lightning on the OMI tropospheric VCD trend as a bias for comparison purposes in this study since AQS data are not as strongly affected by lightning.

Without the lightning filter, AQS decreasing trends are stronger ~~while~~than the decreasing trends of OMI data ~~are less~~ (Fig. 7). The lightning trend in the NLDN data is unclear due in part to the changing instrument sensitivity (Koshak et al., 2015). If lightning NO_x is not accounted for in OMI retrieval, tropospheric NO₂ VCDs are overestimated. On the other hand, lightning accompanies low pressure systems which mix the atmosphere vertically and tend to reduce surface NO₂ concentrations when anthropogenic emissions are high such as urban and suburban regions. Therefore, lightning has opposite effects on surface and satellite trends. The low-pressure dilution effect on surface NO₂ concentrations depends on anthropogenic emissions (since the end point of dilution is the background NO₂ value). Therefore, the ~~reduction of weaker~~ decreasing surface trends likely reflects a reduction of low-pressure dilution effect. Similarly, as anthropogenic emissions decrease, the positive bias of tropospheric VCDs due to lightning NO_x becomes larger, likely resulting in a ~~reduction of weaker~~ decreasing trends. We consider the lightning effects on surface NO₂ trends to be mostly meteorological driven not by lightning NO_x directly (e.g., Ott et al., 2010; Lu et al., 2017) and hence the ~~corrected~~filtered OMI NO₂ data are likely closer to emission related concentration changes.

The AQS in situ NO₂ annual relative trends (coincident with OMI data with lightning filter) are most significant in the Northeast (-5.2±0.6% yr⁻¹) and the West (-4.2±0.5% yr⁻¹), followed by the South (-3.0±0.5% yr⁻¹) and the Midwest (-2.8±0.6% yr⁻¹) regions. The nationwide annual trend is -4.1±0.4% yr⁻¹, which is consistent with the previous studies (Lamsal et al., 2015; Lu et al., 2015; Tong et al., 2015; de Foy et al., 2016b; Duncan et al., 2016; Krotkov et al., 2016). The significant NO₂ reductions result from updated technologies and strict regulations (Krotkov, et al., 2016). The corrected OMI-based NO₂ trends (coincident with AQS data) show similar reduction rates in the West (-3.8±0.4% yr⁻¹), the Midwest (-3.1±0.5% yr⁻¹), the Northeast (-5.3±0.7% yr⁻¹) and the South (-3.0±0.5% yr⁻¹) regions. The nationwide annual trend is -3.9±0.3% yr⁻¹.

One advantage of satellite observations over a surface monitoring network is spatial coverage. The OMI data (“Lightning filter”) coincident with the AQS data show a national annual trend of -3.9±0.3% yr⁻¹ similar to the AQS in situ trend of -4.1±0.4% yr⁻¹. Using all data available (Fig. 8, Table 1), the OMI data (“Lightning filter”) show a much lower trend of -1.5±0.2% yr⁻¹, about half of the AQS trend (-3.9±0.4% yr⁻¹). Fig. 9 shows that the AQS sites, which are mostly urban and suburban sites, tend to be located in regions with high tropospheric NO₂ VCDs. The OMI decreasing trend with corrected data is a function of tropospheric NO₂ VCDs, increasing from 0% yr⁻¹ to -6% yr⁻¹ (Fig. 9). The national annual trend is close to the value of clean regions which contribute much more than polluted regions. The larger decrease near the anthropogenic source regions reflect in part the nonlinear photochemistry (Gu et al., 2013) and in part to a stronger influence of NO_x sources such as soils in rural regions.

4. Conclusions

Using data from the DOMINO v2 algorithm, we find that the computed OMI-based seasonal NO₂ (relative) trends underestimate the decreasing trends of the EPA AQS data by up to 3.7% yr⁻¹. We attribute most of the discrepancies to OMI retrievals since the standard retrieval algorithm was not specifically designed for trend analysis. While lightning NO_x is part of OMI NO₂ observations, we treat the influence of lightning on the OMI tropospheric VCD trend as a bias for comparison purposes in this study since AQS data are not as strongly affected by lightning. Furthermore, lightning NO_x effects need to be removed when using satellite observations to understand the effects of changing anthropogenic emissions.

In this study, we show that removing the background ocean trend (likely a result of the increasing stripes), adopting MODIS albedo data (with better temporospatial resolutions), and excluding lightning influences can bring OMI tropospheric NO₂ VCD trends in close agreement (within 0.3% yr⁻¹) with those of the AQS data. The largest effects of MODIS albedo update are in winter in Midwest and Northeast and those of lightning filter are in the South and the Northeast. After applying these corrections, the derived OMI-based annual regional NO₂ trends change by a factor of > 2 for the South, the Midwest, and the West and seasonal changes can be even larger. We derive optimized OMI-based NO₂ regional annual relative trends using all available data for the West (-2.0%±0.3 yr⁻¹), the Midwest (-1.8%±0.4 yr⁻¹), the Northeast (-3.1%±0.5 yr⁻¹), and the South (-0.9%±0.3 yr⁻¹).

The national annual trend of the corrected OMI data is $-1.5 \pm 0.2\% \text{ yr}^{-1}$, about half of the AQS trend ($-3.9 \pm 0.4\% \text{ yr}^{-1}$). It reflects that the AQS sites are mostly located in the urban and suburban regions, where OMI data show much larger decreasing trends (up to $-6\% \text{ yr}^{-1}$) than rural regions (down to $0\% \text{ yr}^{-1}$). The reasons for the dependence of OMI derived trends on tropospheric NO_2 VCDs and the seasonal/regional trend differences are still not completely understood. Further studies are necessary to improve our understanding of these trends. The observation-based lightning filter implemented in this study is preliminary. Incorporating chemical transport modeling may improve this filter. Moreover, the results presented here represent an alternative and indirect way to assess the importance of lightning NO_x for National Climate Assessment (NCA) analyses described in Koshak et al. (2015), and Koshak (2017). Inversion studies (e.g., Zhao and Wang, 2009; Gu et al., 2013, 2014, 2016) will be needed to understand quantify the emission and AMF changes corresponding to the OMI tropospheric NO_2 VCD trends.

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Data access

The datasets used in this research have been obtained online as follows:

- DOMINO v2 NO_2 retrievals: <http://www.temis.nl/airpollution/no2.html>
- EPA AQS NO_2 data: US Environmental Protection Agency. Air Quality System Data Mart [internet database] available at <http://www.epa.gov/ttn/airs/aqsdatamart>.
- NLDN lightning data: https://lightning.nsstc.nasa.gov/data/data_nldn.html
- MODIS MCD43B3 data: https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mcd43b3

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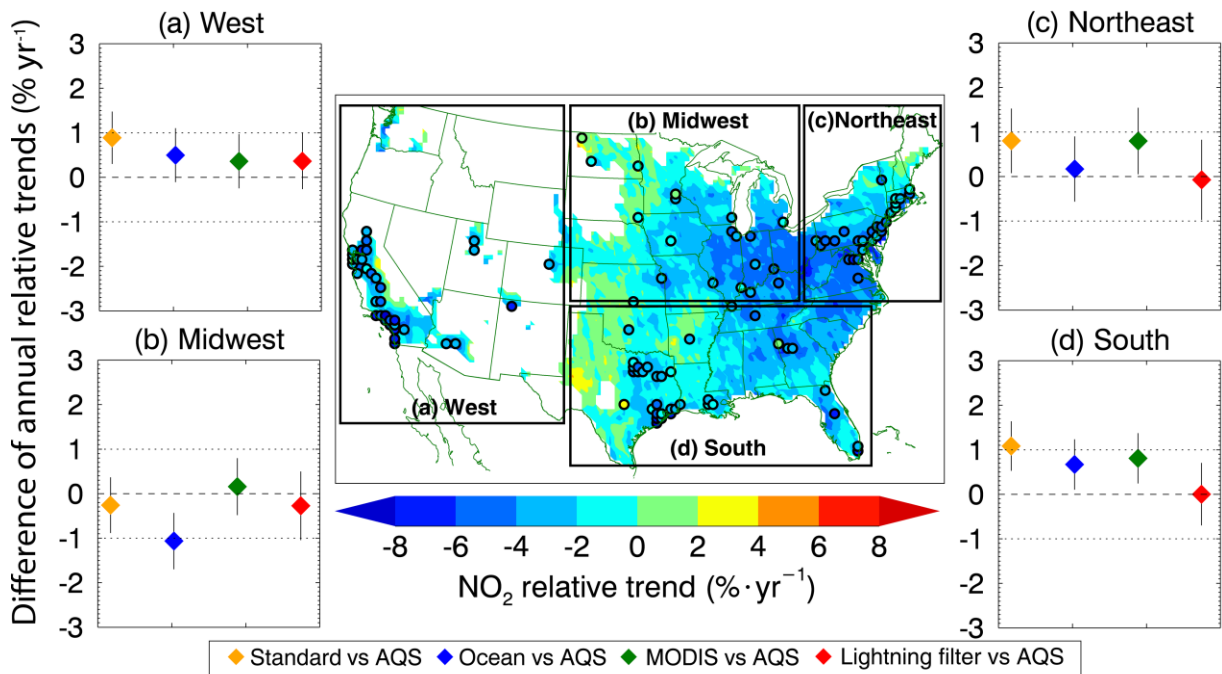


Figure 1. The solid black borders in the center map define the four regions used in this study. The colored background shows the OMI-based NO₂ annual relative trends of the "lightning filter" data. Grid cells with 2005-2014 mean NO₂ VCD values < 1x10¹⁵ molecules cm⁻² are excluded in this study and are shown in white. The black bordered circles represent the locations of AQS sites. Panel (a) through (d) show the regional difference (OMI-based relative trends minus AQS relative trends) of annual relative trends between coincident OMI-based and AQS in situ data. The colored diamonds are for "Standard" (orange), "Ocean" (blue), "MODIS" (green), and "Lightning filter" (red) OMI data, respectively. The different OMI VCD data are described in Section 2.4.

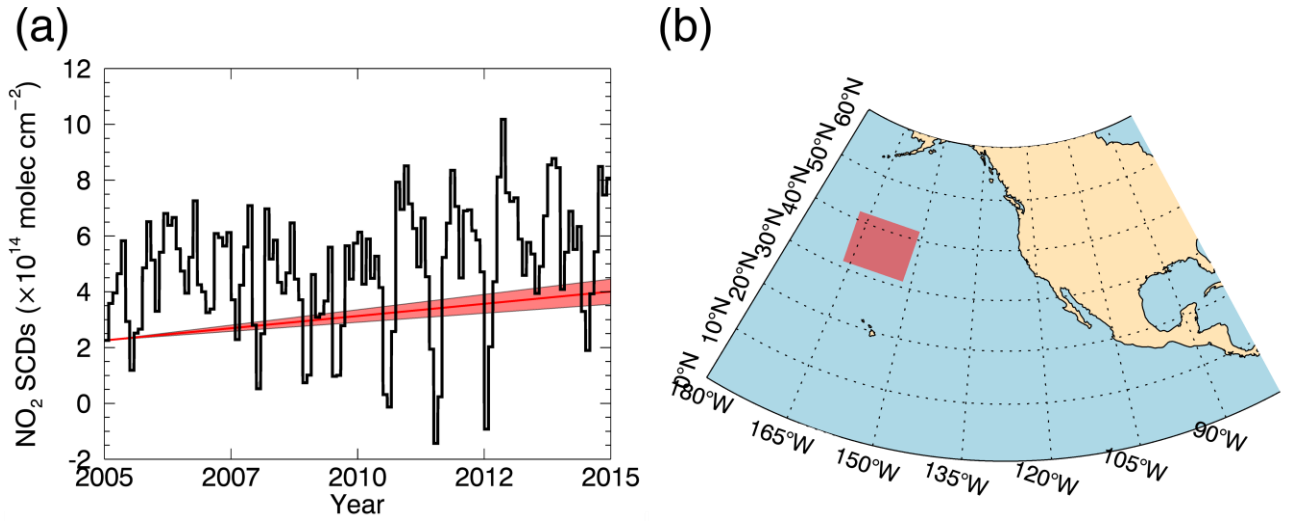


Figure 2. The black line in panel (a) shows the monthly averaged OMI tropospheric NO₂ VCD values in the North Pacific region (red box in panel (b)) from 2005 to 2014. The red line in panel (a) represents the ocean trend used in this research, with the 95% 95th percentile confidence intervals shaded in red.

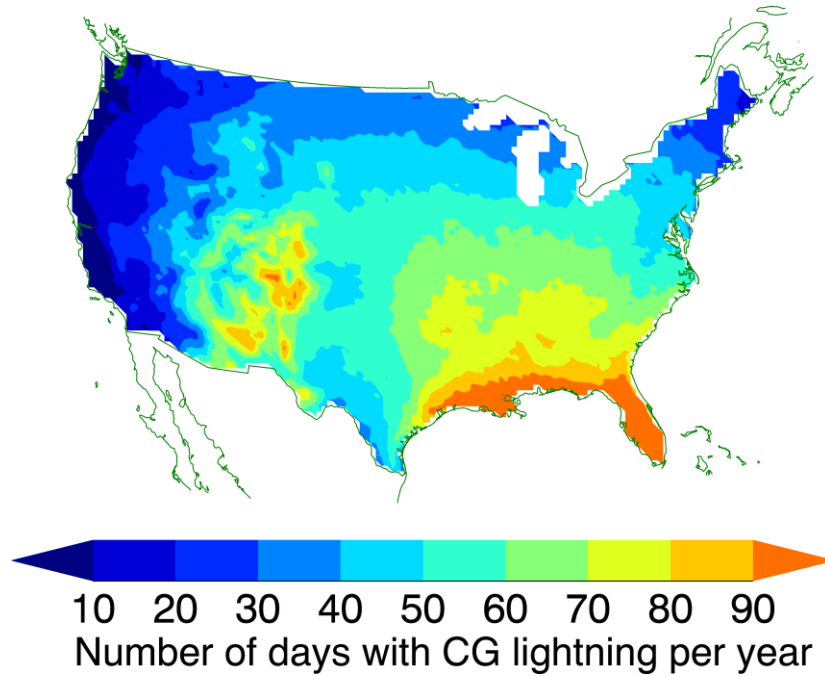


Figure 3. Number of days with NLDN detected cloud-to-ground (CG) lightning per model grid cell per year during 2005-2014. The lightning occurrences are calculated using the REAM grid resolution.

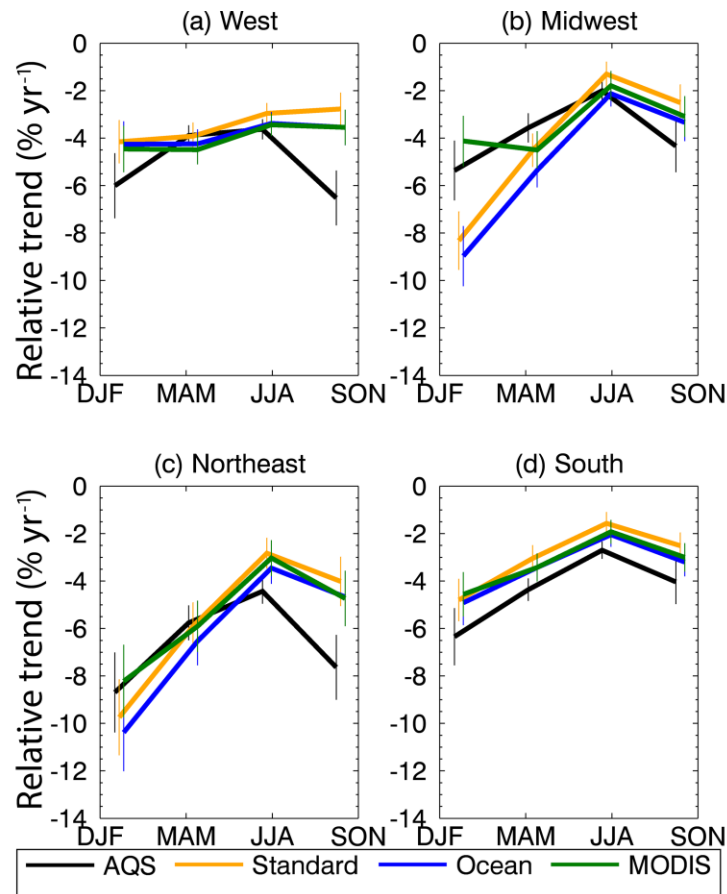


Figure 4. Seasonal relative trends of NO₂ calculated from the AQS in situ measurements (“AQS”, black line) and those derived from different OMI VCD data (“Standard”, orange line; “Ocean”, blue line; “MODIS”, green line). The error bars represent ~~95%~~95th percentile confidence intervals.

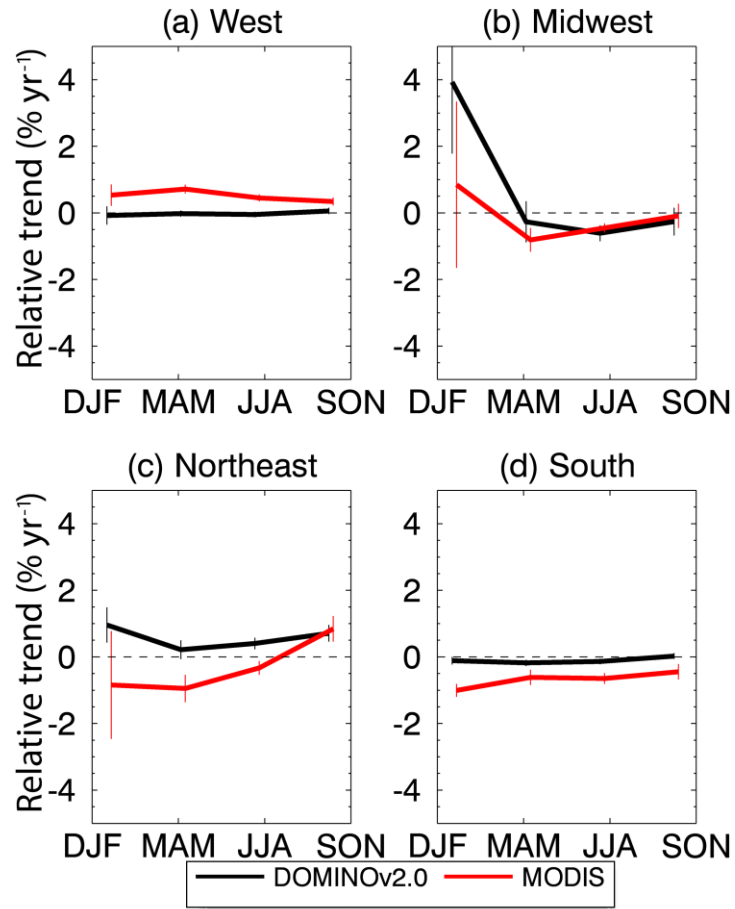
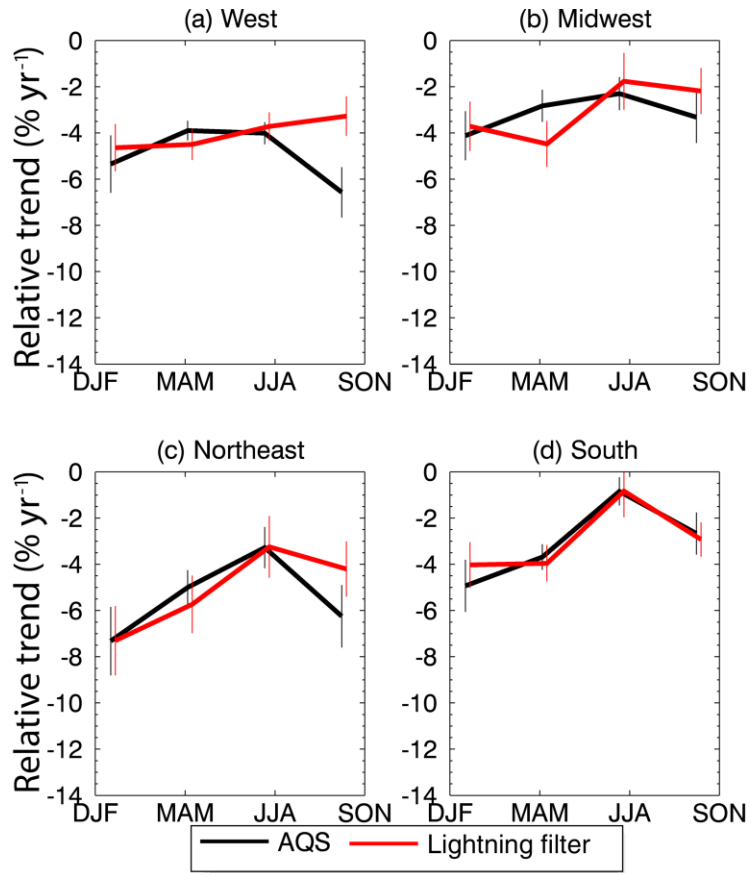


Figure 5. Seasonal relative albedo trends of OMI (black line) and MODIS (red line) surface reflectance products, coincident with AQS in situ data used in Figure 5. The error bars represent 95%⁹⁵th percentile confidence intervals.



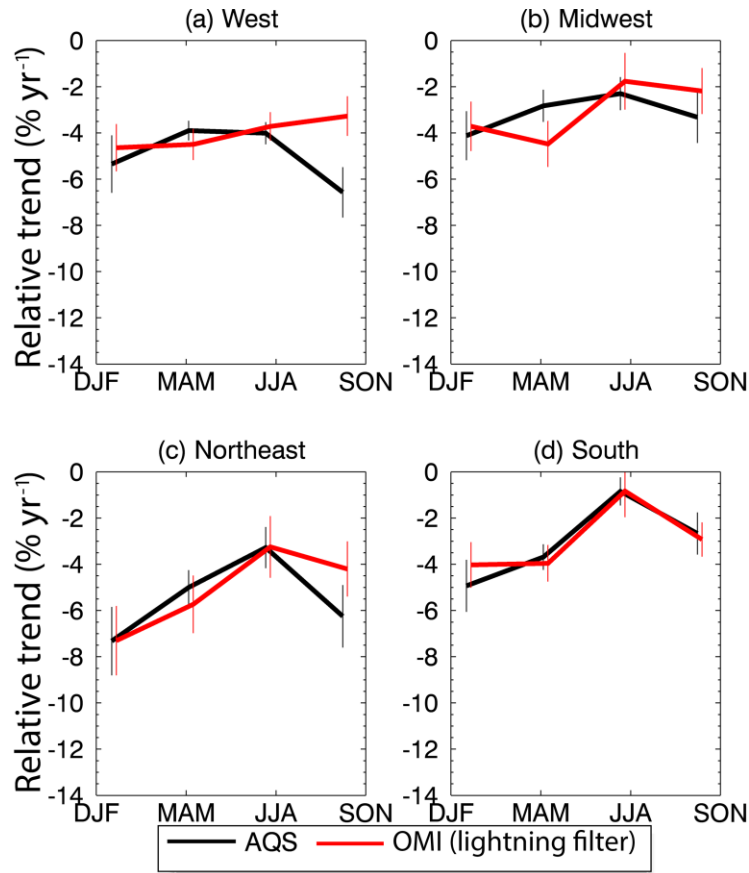


Figure 6. Same as Figure 5 but for coincident Seasonal relative trends of NO₂ calculated from the AQS (in situ measurements (“AQS”, black line) and those derived from OMI data (red line) after applying the lightning filter (“OMI (lightning filter)”, red line). The error bars represent 95th percentile confidence intervals. The coincident data points are less than those used in Figure 5 and therefore the AQS trends are not the same.

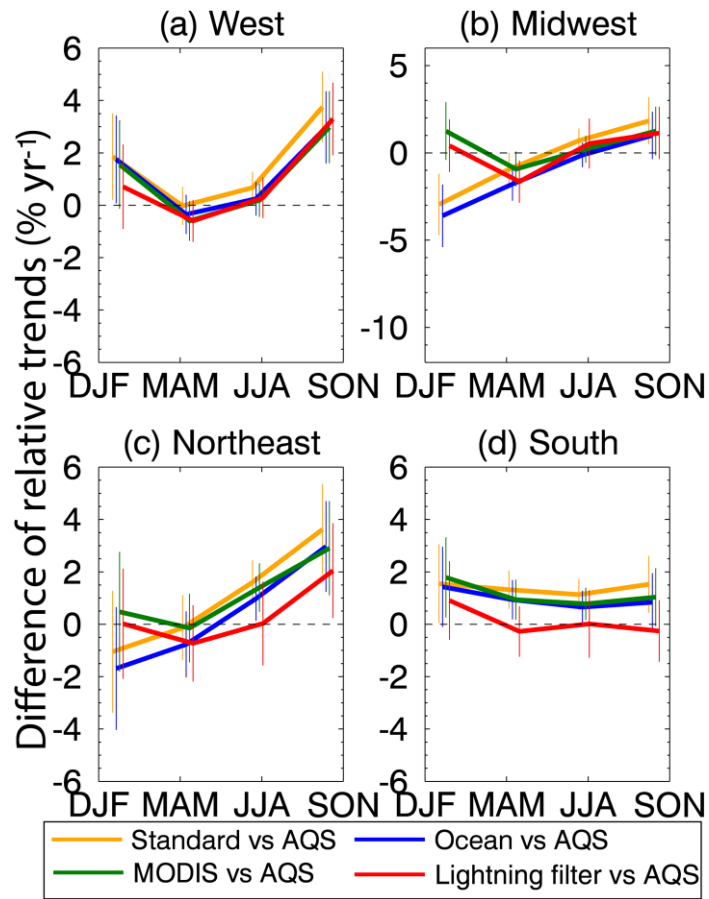


Figure 7. Seasonal differences of OMI-based relative trends from those computed from AQS in situ data. The **error bars represent 95th percentile confidence intervals**. The relative trends are shown in Figs. 64 and 86. The figure legends are the same as in Figs. 64 and 86 but with the AQS trends subtracted from the OMI-based trends.

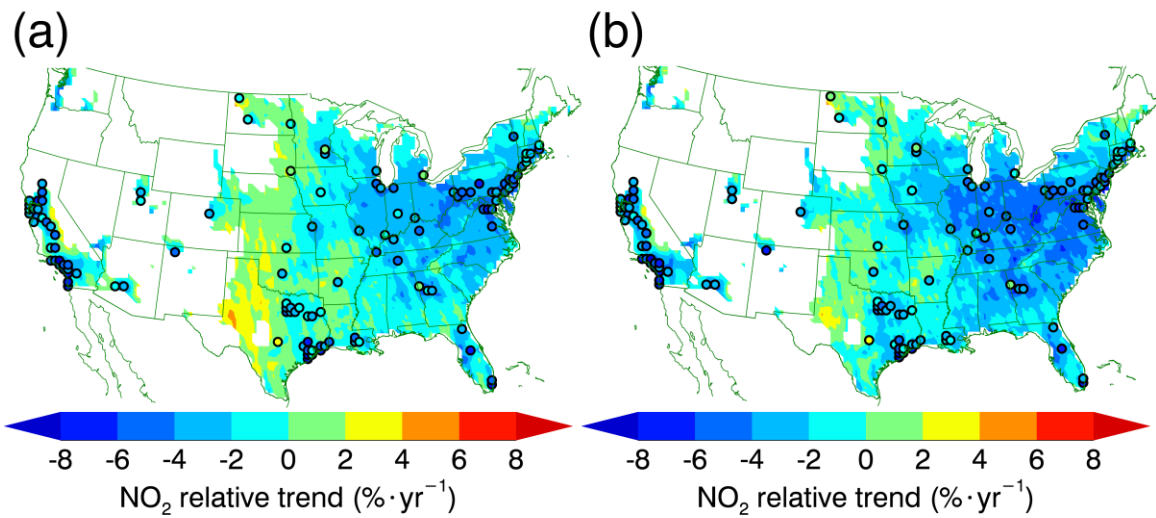


Figure 8: Annual relative trends of OMI-based NO₂ for “Standard” (a) and for “Lightning filter” (b) as the colored background. Black bordered circles indicate corresponding AQS NO₂ trends. Grid cells with 2005-2014 mean NO₂ VCDs < 1x10¹⁵ molecules cm⁻² are excluded in the analysis and are shown in white.

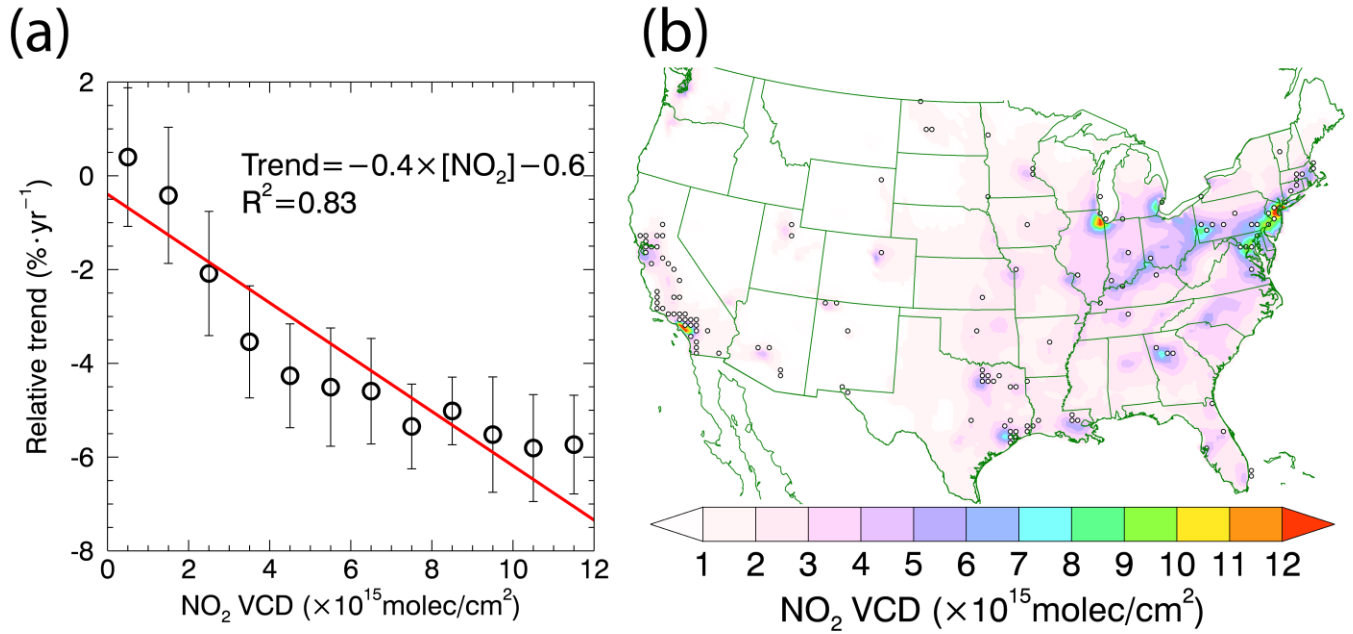


Figure 9. (a) The “Lightning filter” OMI-based NO₂ relative trend as a function 2005-2014 averaged OMI tropospheric NO₂ VCD binned every 1×10^{15} molec/cm². Red The error bars represent 95th percentile confidence intervals. The red line shows a least-squares regression. (b) The distribution of 2005-2014 averaged OMI tropospheric NO₂ VCD. Black bordered circles represent AQS sites. The corrected OMI tropospheric NO₂ data (“Lightning filter”) are used.

Table 1. Annual relative trends calculated with coincident data and all available data. ~~95%~~The 95th percentile confidence intervals from Mann-Kendall method are also listed.

Region	Annual relative trends of coincident data (% yr ⁻¹)				Annual relative trends using all data (% yr ⁻¹)			
	Standard		Lightning filter ^a		Standard		Lightning filter	
	AQS	OMI	AQS	OMI	AQS	OMI ^b	AQS	OMI ^b
West	-4.1±0.5	-3.2±0.4	-4.2±0.5	-3.8±0.4	-4.1±0.5	-0.9±0.4	-4.2±0.5	-2.0±0.3
Midwest	-3.4±0.5	-3.6±0.4	-2.8±0.6	-3.1±0.5	-2.5±0.5	-0.9±0.4	-2.2±0.5	-1.8±0.4
Northeast	-5.8±0.5	-5.0±0.5	-5.2±0.6	-5.3±0.7	-4.7±0.5	-3.0±0.4	-4.1±0.5	-3.1±0.5
South	-3.8±0.4	-2.7±0.3	-3.0±0.5	-3.0±0.5	-3.5±0.4	-0.2±0.4	-3.0±0.5	-0.9±0.3
Nationwide	-4.3±0.4	-3.5±0.3	-4.1±0.4	-3.9±0.3	-4.0±0.4	-0.7±0.3	-3.9±0.4	-1.5±0.2

^a These data include the three corrections of this study, namely, ocean trend correction, MODIS albedo update, and ~~lightning~~ lightning filter screening.

^b The spatial coverage is shown in Figure 1.