Norrköping, 31 May 2017

Response to Referee #2

We thank the referee for constructive comments that lead to substantial improvements in the revised manuscript. Based on comments by both referees, a major revision of the manuscript is carried out. In particular we have tried to address the following three concerns.

1) The entire analysis is revised to investigate the sensitivity of our results to using OMI retrievals under cloud-cleared versus cloudy conditions. The analysis of AIRS and reanalysis datasets is also revised accordingly.
2) The revised analysis is now based on individual months (instead of seasons) to take into account even the monthly variability.
3) A stronger case is made to clarify precise contribution of the present work.

Please find below point-by-point reply to your general and specific comments.

In their manuscript "Typical meteorological conditions associated with extreme nitrogen dioxide (NO2) pollution events over Scandinavia", Thomas and Devasthale report on a study evaluating the meteorological conditions under which the highest tropospheric NO2 columns are observed in OMI data over Scandinavia. Their results show, that such events are linked to situations in which transport from the polluted regions in Europe towards Scandinavia occurs, that such events are mostly observed in winter and spring and that they persist for several days. The topic of the study (impact of meteorology and long-range transport on pollution) is interesting and fits well into ACP. The paper is also well written, clearly structured and to the point.

We thank the referee for encouraging comments.

I have however several concerns with respect to the relevance and also the methodology of the study which need to be addressed before the paper can be considered for publication.

General points

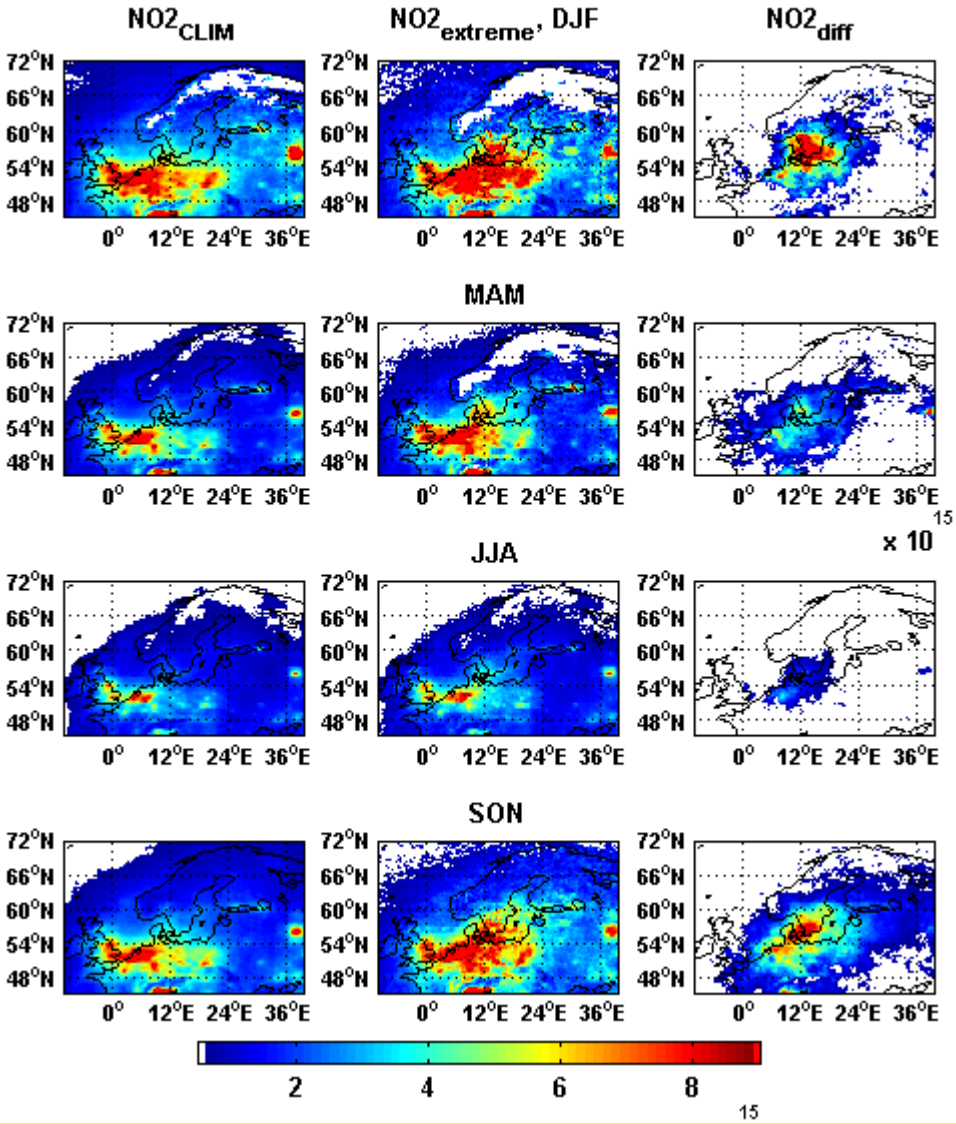
• Probably the most important point is that I'm not sure what the relevance of the results presented in this manuscript really is. It is not surprising that pollution transport from Germany and the Benelux countries impacts on Southern Scandinavian air quality. As there is no attempt made to quantify the impact in absolute or relative terms, the study does little more than confirming what one would have guessed anyways. I think it would be good to try to become more quantitative in the sense of how many days are affected, what are the mean and maximum anomalies, and what is the relation to pollution from local sources.

Please note that the main aim of the study is to quantify typical meteorological conditions during the extreme pollution events and not to show that the transport from Germany and the Benelux countries impacts on Southern Scandinavian air quality. The latter conclusion, while still interesting since it is based on observationally constrained datasets, is the bi-product from the inferral of the combined analysis of circulation patterns and changes in humidity and cloudiness. The emphasis is rather given on describing meteorological conditions and whether and how they differ from the climatological conditions.

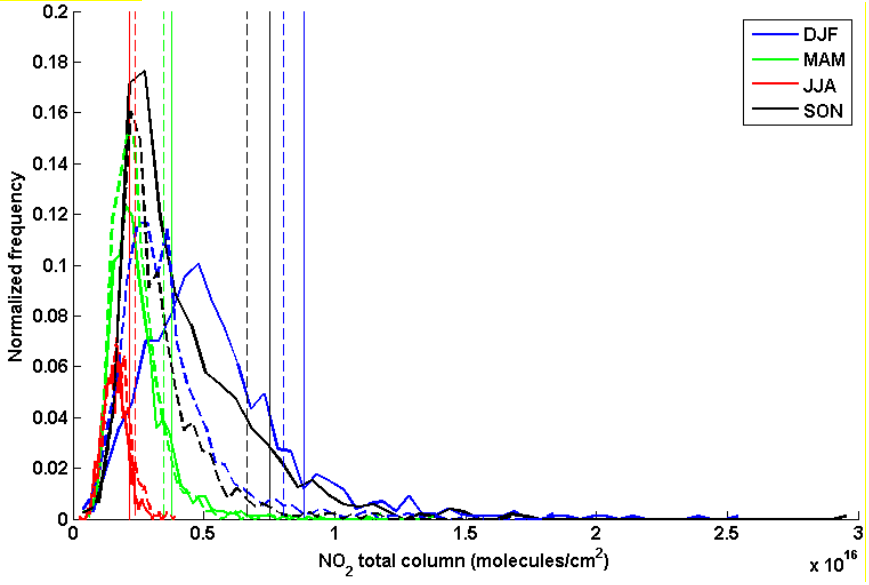
• A second very important point is the use of OMI satellite data without separating cloud free and cloudy situations. While the argument for this approach is clear as many transport events are associated to clouds, such data cannot be easily interpreted as for cloudy conditions, the assumptions made in the retrieval become very important for the results. In the current manuscript, this point is not addressed at all and I think the authors need to investigate differences between cloudy and clear sky averages in order to better understand the impact of clouds on the satellite data. They also need to discuss uncertainties linked to the satellite retrievals.

This is indeed a good point, which is also raised by another referee. We have now carried out sensitivity analysis to check to what extent our selection of extreme events, the spatial distribution of NO2 and corresponding humidity anomalies are affected by restricting to only clear-sky conditions.

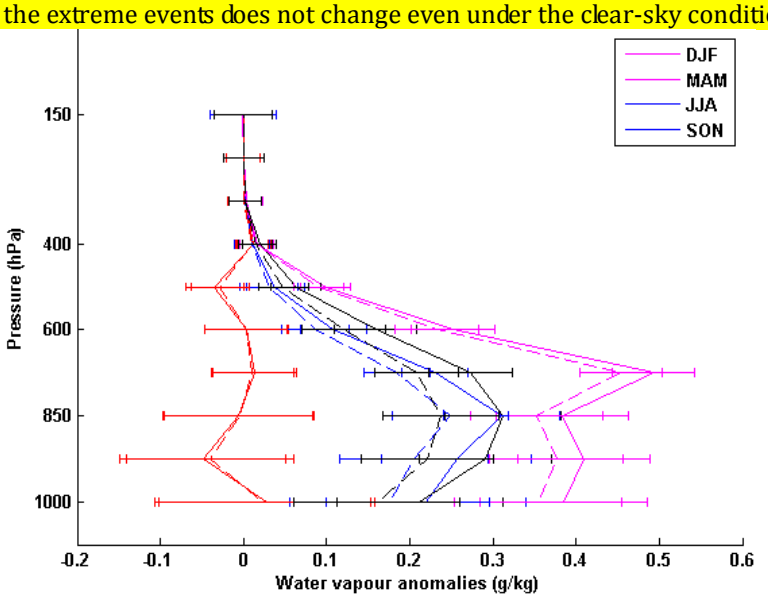
- A figure below shows the spatial distribution of NO2 during only clear-sky conditions for climatological conditions, during extreme events and the differences between the two. This figure can be compared to Fig. 3 in the manuscript. It can be seen that the general distribution of NO2 and its anomalies in the figure below are quite similar to Fig. 3.



- A figure below shows a comparison of the NO2 histograms over the center of the study area. The solid lines show NO2 distribution under all-sky conditions and dotted lines under clear-sky. The differences in the summer half year are minimal. The differences in the winter half year are not large enough to change either the spatial distribution of NO2 as shown above or to affect the tendencies of specific humidity anomalies as shown below.



- We further investigated the vertical structure of specific humidity anomalies under clear-sky conditions. A figure below shows the comparison thereof. Once again it is seen that the general tendency that humidity is increased during the extreme events does not change even under the clear-sky conditions.



These results provide us confidence that our analysis is most likely not affected by the contamination from clouds.

• The tacit assumption made in this study is that NO2 observed from satellite (partly above clouds) is indicative of enhanced NO2 levels on the ground. I'm not convinced that this is always the case during transport events and it would be good to support the timing and location of their extreme NO2 events by at least some surface observations showing that in deed air quality on the ground was also poor during the satellite observed pollution events.

This is also a good point, but we have to admit that addressing this would be out of the scope of the present study. As mere users of satellite data sets we have to put faith in these data sets (and the work done by the respective Science Teams) and hope that the tropospheric columns would capture the variability and coupling between the concentrations in the free troposphere and near-ground. If the referee insists and the extra time is granted by the editor, we would be happy to cross-check with surface observations. We also kindly request the referee if he/she would point out to us relevant references that discuss such discrepancy.

Definition of extreme cases is another critical aspect and I think that given the large seasonality of NO2, monthly thresholds would be better than seasonal thresholds. I'm also a bit confused by the relevance of Figure 2b) showing the number of extreme events per month – isn't the number of extreme events per season constant the ways the authors define their thresholds, and therefore the distribution over months just reflecting the seasonality of NO2?

In the updated version of the manuscript, Fig. 2b is dropped as this was also demanded by the other referee. We have further revised the entire analysis and based it on the monthly instead of seasonal thresholds. Please note that the major conclusions do not change even when we select extreme events based on the monthly thresholds.

• Considering Figure 3, I'm wondering why the situations with higher NO2 over Southern Scandinavia appear to also have higher than normal NO2 over the supposed source regions. Does this mean that under these conditions, pollution is accumulating in general? If this would be simple transport from Central Europe to Scandinavia, I would expect to see less NO2 in the source region or what am I missing here?

Please note that to qualify for being an extreme event over Southern Scandinavia, the pollutant levels in the source regions also need to be higher than usual together with favourable circulation patterns.

<u>Minor points</u>
• Line 40: Add soil emissions

Added.

• Line 47: Does NO2 really affect psychological health?

It has been claimed that it does, but indirectly by affecting physical health and thereby psychological. In the

revised version, the reference to psychological health is removed.

• Figure 3: Are these total or tropospheric columns?

Only tropospheric columns are analysed. It is now clarified in the revised manuscript.

• Figure 6: Not sure what is “the same as in Fig. 5” here

This is clearly a mistake. Thanks for pointing it out. The Figure 6 shows the specific humidity anomalies (averages during extreme events minus climatological conditions).

• Figure 7 a / b are difficult to read (too many lines)

We agree that there are too many lines in those figures, but it was necessary to do so to show climatological conditions. For a quick and easy reference to the reader, the average values of wind speeds are also shown in those subplots.

• While the article is overall well written, there are many places in which I would add / remove articles. I therefore recommend another round of proof reading to fix these and other small English problems.

We have tried to fix misplacing of articles in the revised version.