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Interactive comment on "Sudden changes in nitrogen dioxide emissions over Greece due to lockdown after the outbreak of COVID-19" *by* Maria-Elissavet Koukouli et al.

Anonymous Referee #1

We thank Reviewer #1 for offering us the possibility to enrich our article. Point-by-point replies to all comments are given in maroon colour below.

Major comments

1) My major concern is the fact that only 2019 data are used to define the drop due to COVID-19 measures. Do we know that March and April 2019 are representative for the area ? Can we eliminate the possibility of extreme high values during this period? TROPOMI NO2 is not available from earlier periods, but there are retrievals from other satellites. The spatial resolution is poorer and some works have already pinpointed that there are hotspots that were ignored due to larger pixel size. Also, we should know what is the usual variability of NO2 in the area. Are these drops something usual or it is something extremely rare? Hence, some work should be done in order to properly compare the absolute levels and provide to some reference values before defining the drop during the lockdown. Also, the same should be done with in-situ data (where available).

This is of course a very sensible comment which we have tackled by calculating and including in the manuscript climatological means over Athens both from satellite observations, using OMI/Aura since 2005, and in situ observations, using both EEA/Greek Ministry of Environment data since 2005 – for consistency with the satellite observations. These findings were added in Section 3.2, Figures 7 & 8, and discussion therein.

2) The other major concern is the meteorological variations and how they are used in the model. The CMT model is not described in detail. Reading paragraph 2.2 multiple times, it is not clear what are the inputs of the model, hence, it is impossible to interpret the results. Also, since the comparisons in the literature are show low correlation coefficient for this model, I think some comparison (for a non-lockdown period) should be presented. Figure 1 is not appropriate for understanding the credibility of the output. Additionally, any information on the variation of key parameters (mainly Boundary Layer, wind speed and Solar Irradiance) during the period would be very useful for understanding the conditions. What was the parameter that driven the theoretical increase in Patra (figure 5 upper plot). Keep in mind that the stricter lockdown period was April 2020, were the drops are lower (even increase is observed at Volos). Thus, the discussion about the meteorological conditions how they affected the NO2 columnar retrievals should be deeper. There are number of findings that cannot be explained, hence question the validity of the approach. Both the approach and the results should be justified thoroughly.

Since this manuscript was submitted a paper presenting the CTM, the model simulations over Greece for NO_2 profiles and columns, as well as extensive comparison/validation against S5P/TROPOMI, MAXDOAS and in situ surface measurements has been published in Skoulidou et al., 2020. We have hence updated Section 2.2, i.e. the presentation of the CTM used in this work, to include findings from the Skoulidou et al. paper, references to specific conclusions, as well as deleting the original Figure 1 which, indeed, did not add much to our document. Furthermore, we have reported in detail all the meteorological parameters that the CTM ingests from the Operational ECMWF forecast datasets, including the temperature and wind fields for the eight weeks studied over Athens in Figures S5 & S6. We are not aware of any publication that has performed sensitivity studies/validation of how the ECMWF meteorology affects the NO_2 output parameters of the LOTOS-EUROS CTM, hence we proceed on faith that the well-established operational ECMWF forecast datasets are of high accuracy and suitable for such air quality studies. Since the methodology chosen in this work to account for the meteorological variability relies of computing differences, and is not based on absolute values, it is justifiably assumed that any systematic error of the CTM ingestion and subsequent analysis based on the meteorological fields, is filtered out. Furthermore, we have included the convolution of the LOTOS-EUROS profiles to the TROPOMI averaging kernels, an operation performed by a LOTOS-EUROS module. As a result, some numerical findings that were indeed surprising have changed without however altering the main take away message of this work. It has indeed been found that over locations with low tropospheric NO_2 columns, small loads, within the detectability of the satellite observations may lead to large, unphysical differences. A discussion to that effect had been added in Section 3.1 and the abstract/conclusions were changed accordingly.

Skoulidou, I., Koukouli, M.-E., Manders, A., Segers, A., Karagkiozidis, D., Gratsea, M., Balis, D., Bais, A., Gerasopoulos, E., Stavrakou, T., van Geffen, J., Eskes, H., and Richter, A.: Evaluation of the LOTOS-EUROS NO2 simulations using ground-based measurements and S5P/TROPOMI observations over Greece, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2020-987, in review, 2020.

Some specific comments:

L58-61 I think here some details should be added about the monthly values, the seasonal cycle and the extreme values of this period. Since, these data are available, I would recommend a timeseries figure at least for Athens and Thessaloniki.

The values reported here are extracted by the official EU/EEA report [EEA, 2019] and were not calculated by the co-author team. The purpose of this section is to introduce the author to the levels of air quality over Greece in a general manner, since most times the air quality over heavily polluted sites is reported in literature, such as Eastern China, US cities and power plants, the Po Valley in Italy, the Benelux area, etc, and scientists are more familiar with those. More detailed analysis on the in situ observations over Athens, including a climatological study and discussion thereof performed by the co-author team, has been included in Section 3.2, Figure 8, as Figures S3 & S4 of the updated supplement.

L102 Some literature should be provided about any possible biases among OMI and TROPOMI retrievals.

In the original version of the article, where no OMI/Aura data were used, it was not deemed important to mention such biases. We have now included an analysis of the OMI/Aura long term observations to examine whether the months studied in this work follow the climatological means or not, see Section 3.2 and Figure 7.

L119 It should be noted here, that a lot of industrial activities didn't stop during the lockdown or they were just slow downed. Thus, workers were moving to industrial areas and probably some behaviors could be explained by that (eg Elefsina from in situ measurements).

We have added this comment in the section.

L.130 The way it is stated gives the impression that TROPOMI retrievals of NO2 commence at August 2019. Please restate to be clear.

Reworded accordingly.

L143 ROCRV please explain the abbreviation

Abbreviation and reference altered as per ACP rules.

L145 This behavior should be considered more. Since during the drop of this period, NO2 values became very similar to background ones, some noise could be added.

This is of course correct and we have added a discussion in the revised text over locations that had low tropospheric NO_2 loads to begin with.

2.2 Is there any estimation on the diurnal cycle of NO2 in the area? Is the overpass time of TROPOMI representative? This should also be discussed when selecting the output step of the CTM. Also, please provide details on the input of CTM as asked in general comments.

We have updated this section to include information on the meteorological fields input in the CTM and references to the Skoulidou et al., 2020, paper where the model set up and simulations over Greece are presented and validated. The TROPOMI overpass time over Greece represents the decline in the NO_2 created by early morning traffic, while comparisons between TROPOMI and the CTM runs were also included in the aforementioned article. Since the LOTOS-EUROS includes a module which performs the convolution to the satellite AKs, the model finds the closest output time to the satellite observations. This is, for most days, 12:00, while – in case of two orbits covering the domain in the same day – the previous hour may also be chosen. Again, this time is also after the expected NO_2 peak due to traffic emissions.

L208 State what this meteorology includes.

The relevant text was added in Section 2.2.

L211 This expectations should be justified properly.

The original phrase "*We cannot of course exclude the possibility that the LOTOS-EUROS model has biases in the resulting NO_2 column depending on the meteorological conditions, for example due to uncertainties in mixing under stable conditions*,…" was erroneously inserted after a long discussion within the co-author team on quantifying the possible meteorology-related biases of the LOTOS-EUROS CTM for our Skoulidou et al. work. The statement about mixing under stable conditions refers to the night time biases revealed by the work of Skoulidou et al., 2020, for night time comparisons between in situ and model surface concentrations, where stable conditions are expected.

As we are not aware of a study which examines possible meteorology biases in Lotos-Euros, and based on the high acclaim that the CTM holds by the community, we have to take it on faith that indeed possible meteorology-induced biases for 12:00 UTC cancel out in this methodology which is based on differences and not absolute values.

L215 Are there any data or statistics of the clear days during 2020? Also, provide some some information of the actual number of days used (with qa>0.75) for monthly averages. How does cloudy days affect the photochemistry of NO2?

In this work we have chosen pixels with associated qa > 75, hence permitting observations where a very small percentage of the pixel may be covered by clouds, as recommended by the relevant TROPOMI Product User Manual, https://sentinel.esa.int/documents/247904/2474726/Sentinel-5P-Level-2-Product-User-Manual-Nitrogen-Dioxide. Statistics on the available pixels/days for the monthly mean analysis [Section 3.1] and the weekly analysis over Athens [Section 3.2] have been added. A discussion on cloudiness parameters affecting the photochemistry of NO_2 was not included in this text since only one specific hour of the day is discussed for the entire text.

L241 The fact that during the harsher lockdown, NO2 decrease was not as high as in March (when 1/3 of the month was almost with normal activities) should be discussed. Could be a sampling issue?

Indeed the differences observed by TROPOMI in March are stronger than in April. This was curious to us as well, which is why we followed advice and studied the climatological mean 2005-2018 and the deviations of years 2019 and 2020 sensed by the OMI/Aura satellite sensor (see Figure 7 and discussion in Section 3.2). The OMI/Aura observations agree with TROPOMI, in the sense that larger differences are found for the months of March than the months of April between 2019 and 2020. Furthermore, the ground-based Multi-Axis Differential Optical Absorption Spectroscopy, MAXDOAS, station in Athens also reported higher columns in March 2019 than April 2019, which again leads to smaller differences for April 2020 than for March 2020. See Section 6.3.4, page 52, of the official quarterly validation report of the TROPOMI Mission Performance Center, https://mpc-vdaf.tropomi.eu/ProjectDir/reports/pdf/S5P-MPC-IASB-ROCVR-08.01.01-

20200921_FINAL.pdf. These findings are also discussed in our new manuscript in Sections 2.1 & 3.2.

Figure 2 It seems that another NO2 hotspot is located at western Macedonia, possibly in the coal mining and thermal factories area. Probably it would be interesting to focus also on that (probably compared with the statistics of energy demand provided in 1.2)

Indeed, near the Greek border where the main lignite-burning power plant complex of Ptolemaida is located there exists a similar power plant in Northern Macedonia, in Novaci. We often observe outflow and inter-regional transport of pollutants in the area, bringing higher overall pollutant loads due to this geographical proximity of the sources and the prevailing winds and topography of the region.

Table 2 I recommend to provide also the number of days used for each monthly average retrieval.

We have added the statistics for the available pixels in the text discussing the findings of the monthly analysis.

L 280-291 I suggest to focus more on these in-situ data. Plots from the supplement could be useful here. Also, it would be useful to calculate also the monthly mean with the days with TROPOMI retrievals in each case and compare directly the differences.

Unfortunately, comparing in-situ data [i.e. surface concentrations] directly to satellite tropospheric columnar assessments is not an easy task, nor does it guarantee meaningful results, as you are aware I am sure. We have however included a discussion on what the in situ observations show, both from the climatology aspect, as well as for the lockdown months in question in Section 3.2 Indeed, there appears to be a disagreement between the magnitudes of the decreases between in situ and space-born observations, both from OMI and TROPOMI. We can only postulate that the air quality stations are much more sensitive to instantaneous changes in traffic conditions on the point locations they are situated, which the space-born sensors with their larger field of view cannot resolve.

Figure 5 lower plot. These is the main conclusion of the work. Still, if the meteorology variations was properly subtracted, the results for Patra and Herakleion are unexplainable. Further investigation is needed on these cases. Any possibility of an artifact should be eliminated before considering as a valid conclusion. Again, sampling from satellite and meteorological inputs are the main sources of concern for these results.

From this analysis it became apparent that for the cases of low monthly mean levels, such as those over the smaller Greek cities, the variability within the standard deviation introduced large absolute and relative differences between the satellite 2020/2019 difference and the CTM 2020/2019 difference. As a result we have added a discussion in Section 3.1, as well as altered the abstract & conclusions.

L311 This is also a crucial finding about the naval activities. I would consider moving the figure to main manuscript instead of the supplement.

Since we composed this article, we have worked separately on the topic of shipping emissions and we indeed realized that there are a lot of interesting findings that can be extracted for this activity. We have hence decided to remove all shipping references from this article in favor of the autonomous work on the subject of shipping activities we are currently preparing for publication.

Figure 6. How these weeks were selected? Sampling reasons? Please explain explicit. Also, I suggest to use the in-situ data in order to validate the areas that have the larger differences.

For Figure 6 [now Figure 5] we wished to show, in a pictorial way, the variability of the NO_2 across some of the weeks studied and we picked the weeks with the highest possible amount of observations across the pixels studied for the case of Athens. We have added a discussion on what the in situ stations show in Section 3.2 as well as Figure 8, and Figures S3 & S4 in the supplement.

Figure 6 Lower plot. Also, the last week have a high increase when subtracting meteorology. Although the end of the lockdown was announced, this is very strange. It could be explained with low values in 2019 (when this was orthodox Easter week), but I think some investigation needed also for that.

Even though we have every confidence that the meteorology is well taken care of by LOTOS-EUROS, we have added the weekly meteorological mean vector wind directions and speeds, as well as the surface temperature, in Figures S5 & S6 in the supplement. The mean vector wind speed and direction, overlain as arrows in Figure S5, is very similar with mostly predominant northern winds and very few cases of southerly winds. In the equivalent rose diagrams, Figure S6, we note again that the main wind directions appear similar between the two periods [2019 in the left and 2020 in the right column] apart from the last week of April [bottom row] were indeed the two weeks had very different directions, for the same magnitude.