# RC#2

Review of the manuscript by Riess et al. “Improved monitoring of shipping $NO_2$ with TROPOMI: decreasing $NO_x$ emissions in European seas during the COVID-19 pandemic”

The manuscript presents an analysis of ship emissions over European seas based on TROPOMI $NO_2$ observations. The authors also analyse the effects of COVID-19 restrictions on shipping and the relative decrease in emissions. The manuscript has sufficient elements of novelties as it provides a deeper analysis of the capabilities of TROPOMI $NO_2$ observations for ship emission monitoring, after a first paper dedicated to the detection of individual plumes by Georgoulias et al. (2020). I recommend publication after addressing the following comments:

We want to thank reviewer #2 for their comments. Please see below for replies to the specific comments

1. You mention the NO2 profiles used in NO2 retrieval from TM5 at 1x1degrees: Can you comment on the possible uncertainty related to such coarse resolution and on their accuracy over sea in particular?

The reviewer brings up an important point. Coarse a-priori profiles likely underestimate the $NO_2$ concentrations in the boundary layer over busy shipping lanes and overestimate $NO_2$ concentrations outside of the shipping lanes, as the emission spatial patterns are not resolved by the model grid. This issue for TROPOMI $NO_2$ retrievals is in line with earlier findings for other satellite instruments: coarse-gridded TM3 profiles used for GOME were estimated to give rise to an error of 10% on the retrieved columns (Boersma et al., 2004). Heckel et al. [2011] found that coarse resolution a-priori profiles can cause errors larger than $2*10^{15}$ molec/cm$^2$ for individual pixels for OMI. This error has a systematic component and can therefore not be averaged out, further highlighting the importance of high-resolution a-priori information.
We are currently analyzing low-altitude aircraft measurements over the North Sea to improve our understanding of $NO_2$ vertical profiles over sea, and the capability of TM5 to simulate these.

2. Did you assess how the FRESCO+wide perform over ice/snow surfaces? Can you comment on that?

No, we did not assess this as ice conditions are uncommon in the study areas of this paper.

3. How do your simpler emission estimates from AIS compare to the estimates from STEAM model? And why don't you use STEAM emissions for the analysis of changes? Not available for 2020? Also, you use this CAMS-STEAM emission data in Fig. 1 and 2, maybe you should introduce this dataset a little bit earlier.

STEAM emissions for 2020 are not available yet to our knowledge. We have not attempted a comparison on a single-ship basis either as the data were not available to us.
We now introduce CAMS-STEAM data earlier in the same paragraph.

4. L340-… This statement is not supported, are you implicitly referring to your figure 10c? if yes, please make that connection.

A reference to Figure 10c has been added in the revised manuscript.

5. Can you address and discuss a bit more the uncertainties on these monthly $\beta$ values at such coarse resolution when you use it here for the emission change estimates? Also, how could monthly $\beta$ values change between 2006 and 2020 due to meteorology or other factors?

This is a good point, which made us reconsider and revise our choice of $\beta$ values. We now replace the $\beta$ values from Verstraeten et al. [2015] by those calculated specifically for shipping lanes as in Vinken et al. [2014]. The latter have the advantage of being simulated at a higher spatial resolution of $50\times70$ km$^2$, and have been calculated with a plume-in-grid ship emission parameterization, which is more representative for monthly averaged $NO_2$ signals over shipping lanes than from Verstraeten et al. [2015] where ship emissions are instantaneously diluted over 200×300 $km^2$ grid cells. The $\beta$ values of Vinken show a similar seasonality as those of Verstraeten et al. [2015], but are lower by ±25%, which better reflects the polluted character of our selected areas, as discussed in detail in Vinken et al. [2014], section 3.2.

The $NO_2$ signals studied here represent changes in mean shipping lane $NO_2$ columns and not individual plumes. Figure 1(c) and Figure 9 also clearly show that the areas where $NO_2$ columns show changes have a width in the order of 100km, which is comparable to the resolution of the $\beta$ values from Vinken et al. [2014]. The resolution of $\beta$ values from Vinken et al. [2014] can thus be considered appropriate for our purpose.

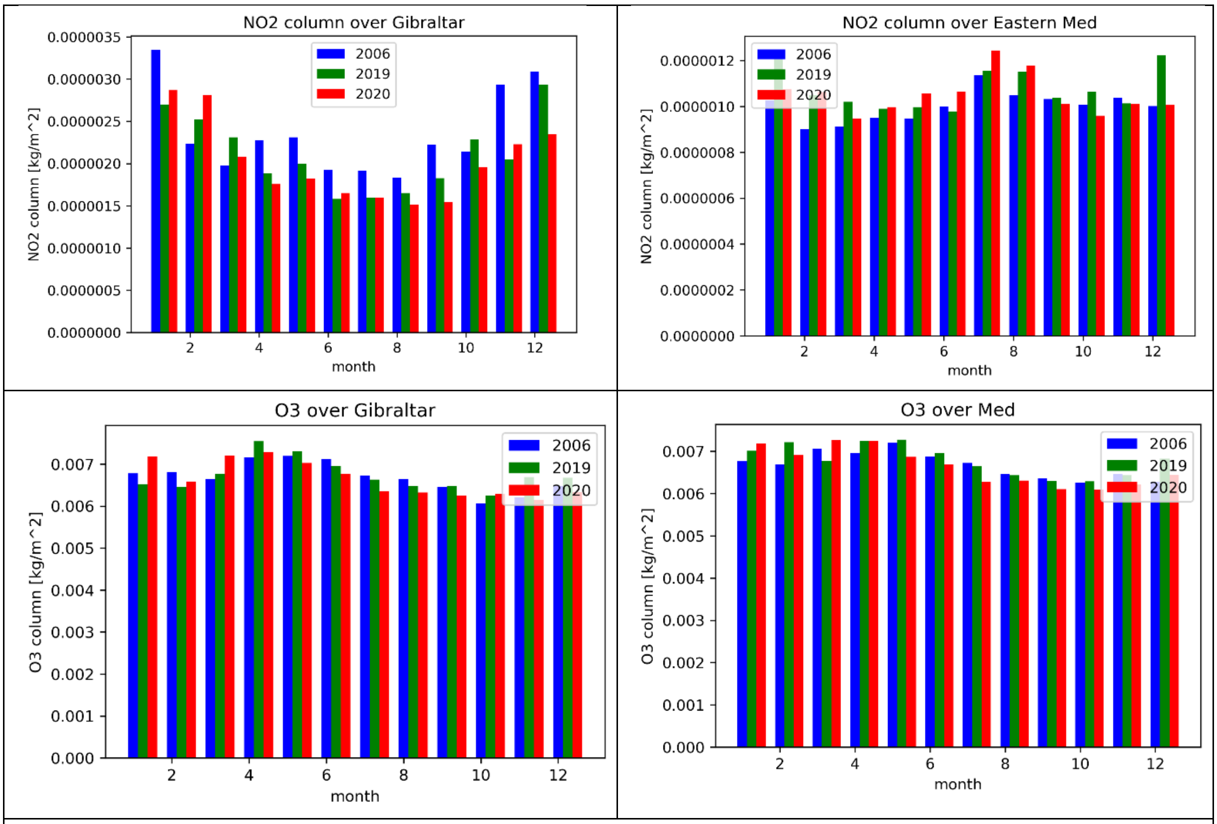


Figure 1. Monthly mean (12UTC) $NO_2$ (top) and $O_3$ (bottom) tropospheric columns for Gibraltar (left, 5°W-0°E, 35°N-37°N) and Eastern Mediterranean (right, 32°N-36°N,15°E-20°E) from EAC4.

To evaluate possible changes in chemical regime between 2019 and 2020, we studied the EAC4 re-analysis of atmospheric composition (Inness et al., 2021). $NO_2$ and $O_3$ monthly mean columns show only modest year-to-year variability between 2006 and 2019, as shown in Figure 1. This suggests modest variability in the chemical regimes (and therefore $\beta$) between 2006 and 2019.

To assess the possible influence of meteorological differences on $NO_2$ columns, we compared CAMS European Air Quality Forecast data for the same months in 2019 and

2020 (METEO FRANCE et al., 2020). These simulations take differences in meteorology into account but keep $NO_x$ emissions constant for 2019 and 2020. The monthly mean $NO_2$ columns for 12UTC are shown in Figure 2.

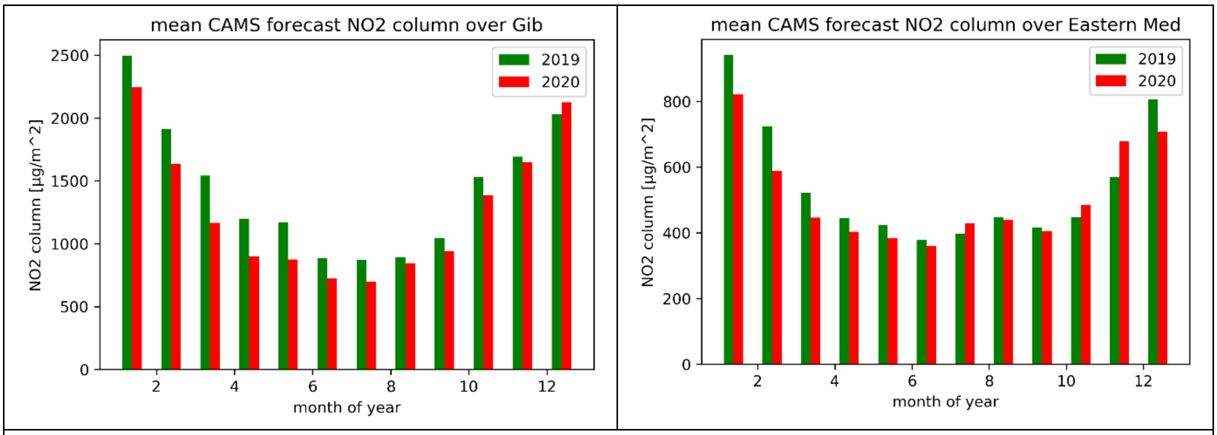


Figure 2. Monthly $NO_2$ column for 12UTC CAMS ensemble mean forecast in the Strait of (left, 5°W-0°E, 35°N-37°N) and Eastern Mediterranean (right, 32°N-36°N,15°E-30°E) in 2019 (green) and 2020 (red).

Over Gibraltar, the CAMS model ensemble mean predicts 5%-20% reductions in $NO_2$ columns for January to November 2020 relative to January-November 2019. For the Eastern Mediterranean the CAMS ensemble predicts lower $NO_2$ columns for all months in 2020 compared to 2019 with the exception of July and November.
The CAMS forecasts therefore suggest that the observed changes in TROPOMI shipping $NO_2$ are caused by both emission changes as well as meteorological differences, since meteorology alone cannot explain the observed increases in January-March nor the reductions in April-December. In the revised manuscript we use the changes in predicted $NO_2$ columns to estimate the uncertainty imposed by meteorological variability on the inferred $NO_x$ emissions.

We now include a discussion on the assumptions and uncertainties associated with the top-down $NO_x$ emission estimates in Section 3.5, as suggested by the referee. We estimate the uncertainty of the top-down emission changes to be driven by uncertainties in the $\beta$ values, from assumption on meteorological representativeness and from the area selected to be:

$$dE^2 = (\sigma_{area} * \beta)^2 + (\sigma_{meteo} * \beta)^2 + (dN * \sigma_{\beta})^2$$

Where *dN* is the relative change in TROPOMI $NO_2$, $\sigma_{area}$= 5% as the sensitivity of the TROPOMI $NO_2$ to the area of study, $\sigma_{meteo}$= 16% for Gibraltar and 11% for the Eastern Mediterranean the impact of meteorology (and therefore transport & lifetime changes) on column changes, $\sigma_\beta$ the combined spatial and temporal variability of $\beta$ in the area of study estimated to be 0.15 (dimensionless) from the spatial spread and the year-to-year variability in the $\beta$ values. These uncertainties are now included in the revised manuscript and shown as error bars in Figure 10(d-f) and F1(d-f).

While single TROPOMI $NO_2$ columns have substantial (random and systematic) uncertainties, these largely cancel out when taking the relative differences between months in different years. Averaging over space and over a month smoothes out the random error while the systematic errors cancel out largely in the relative changes studied here. This renders the uncertainty introduced by the satellite measurements to be negligible in our estimates of emission changes between 2019 and 2020.

**Technical comments:**

L128-L129 “in order to distinguish between bright reflecting layers at the Earth’s surface
from reflecting surfaces in the lower atmosphere.”: remove “between” or replace “from” with “and”

”From” has been replaced with “and”.

L359-360 you just said this in the previous paragraph, maybe rephrase here

This has been rephrased.

## References


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METEO FRANCE, Institut national de l'environnement industriel et des risques (Ineris), Aarhus University, Norwegian Meteorological Institute (MET Norway), Jülich Institut für Energie- und Klimaforschung (IEK), Institute of Environmental Protection – National Research Institute (IEP-NRI), Koninklijk Nederlands Meteorologisch Instituut (KNMI), Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek (TNO), Swedish Meteorological and Hydrological Institute (SMHI), & Finnish Meteorological Institute (FMI). (2020). *CAMS European air quality forecasts*. https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-europe-air-quality-forecasts?tab=overview

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