EGUSPHERE-2025-107 Author's comment to RC1 by Anonymous Referee #4 (Miriam Latsch et al.)

Legend: Referee comments in **black**, author comments in **blue**, changes in the manuscript text in **green**

Summary:

The authors present a sophisticated approach for detecting persistent pollution tracks along shipping lanes, using careful filtering of combined 6 years of TROPOMI NO2 data. The resultant maps clearly reveal multiple tracks in each of the earth's oceans. The study is noteworthy in its detailed presentation of the methods used and the detection of tracks not previously identified in satellite data or that may otherwise be unknown. The authors test a variety of approaches, describing the pros and cons of each and perform quantitative model comparisons. I have only a few minor suggestions for clarification and possible modification of the filtering techniques that might overcome some of the shortcomings pointed out by the authors.

Overall, the authors have done due diligence in rigorous testing of their algorithm and particularly in their thorough analysis of the sources of the tracks visible in their final product. I believe a version of the paper close to its present form is worthy of publication. Below are a few minor corrections and suggestions.

We want to thank Referee #4 for the positive feedback, helpful comments, and advice on our manuscript. Detailed responses to the reviewer's comments can be found below. We hope that we have incorporated all suggestions and comments in a satisfactory way. At the end of this document, you will find a general section on additional changes we made during the review process.

Comments:

(1) There is a tradeoff between capture of fine detail, enhancement of weaker signals and suppression of coastline artifacts. Might a dynamic box size – smaller near coastlines and larger over open waters – mitigate some of these concerns? For a given track, the enhancement would also vary with box size, but this approach would allow all tracks to be captured in a single map. A track out at sea could be followed to and along a coastline without being lost in the clutter. SciPy generic_filter does not directly support spatially varying footprint sizes, but it should be straightforward to develop code for this. Depending on the difficulty of implementing this in the present study, it would be interesting to see an approach like this tested over a small region.

Thank you for this idea which we included in the manuscript as an additional test. We added a discussion of the advantages and disadvantages of this approach as follows to our manuscript in Section 3, starting in Line 201:

"Nevertheless, another approach was tested, using two different box sizes depending on the distance from the coastline. This method of individual box sizes allows the implementation of the smaller box size of 0.25° for pixels close to the coastline, while the standard box size of 1° is used for all other pixels that are further away from the coastal pixels and in the open oceans. The advantages and disadvantages of this method are discussed below for a selected region, the seas around Europe, Africa and Asia (see Fig. B2). Figure B2b shows the NO_2 signals of the different box sizes with a coastal area of 50 pixels (~1.5°) from the shoreline, within which the smaller box size is used. In this case, the shipping lanes in narrow ocean regions such as the Persian Gulf are well resolved, the separated shipping routes in the Atlantic Ocean and the English Channel are visible, and the large NO_2 values near the coast caused by the scene inhomogeneity and high-pass filter effects are removed. However, the shipping lanes near land pixels that have the largest NO_2 values at a box size of 1°, such as the busy shipping route in the Indian Ocean from Sri Lanka to Indonesia and the shipping lanes in the Mediterranean Sea, are reduced or even canceled due to the smaller box size resolution, as in the Black Sea. Therefore, the effect of a smaller coastal region of only 17 pixels (~0.5°) on the NO_2 signals is also investigated (Fig. B2c). Under this specification, the well-defined shipping lanes near the coast are displayed clearly and without interruptions. However, this coastal region is not wide enough to visualize the small-scale NO_2 signals in narrow regions such as the Persian Gulf. The main advantage of this approach is that the artifacts of high NO_2 values near the coast caused by the high-pass filtering are compensated for in most regions, regardless of the width of the coastal region. However, the effect of this method on the visualization of shipping lanes largely depends on the region and its proximity to the coast. In some areas, such as the southeast of South Korea and Japan, inserting the values of the smaller box size close to the coast separates the artefacts from the land and thus could be perceived as shipping signals. The bottom line is that this method can significantly improve the detection of shipping signals and reduce background levels for specific regions, but its results are not consistent on a global scale. Therefore, the following analysis uses the standard box size of 1° to provide an overview of our method, which can be applied globally."

The corresponding Figure, which displays the NO_2 signals using the two box sizes for two different coastal region thresholds of 50 and 17 pixels, is added to the Appendix.

(2) Line 36: "Satellite retrievals of tropospheric…"

The beginning of this sentence has been changed as suggested.

(3) Line 120: "…are used to high-pass filter…"

Thank you. "filtering" has been changed to "filter".

(4) Lines 138-139: CH flagging selects both clear scenes and cloudy scenes with low clouds. Is there a cloud-fraction threshold for the cloudy scenes?

The CH flagging includes cloudy scenes with a cloud height of less than 2 km and situations in which no clouds are present, as no threshold value for the cloud fraction is defined for this flagging criterion. We thought this was explained in the sentence in lines 138-140; however, we have changed it slightly to clarify this setting:

"The cloud height (CH) flagging uses only pixels without clouds (clear-sky scenes) and with clouds at altitudes below 2 km (with no CF threshold) to avoid higher clouds that may shield the shipping NO_2 from the satellite view."

See also our reply to comment (8), where we discuss other settings for the CH flagging.

(5) Line 182: "In the northern hemisphere, the higher NO2 signal is detected only when the sea-ice extent is minimal (June – November), while during the winter season…"

Thank you for your suggestion. Here, we have examined the Antarctic region but incorrectly assigned the summer and winter months of the southern hemisphere. The sentence has been changed to:

"In the Ross Sea, the higher NO_2 signal is detected only when the sea ice extent is minimal (from December to April), while during the winter season (from June to November), the characteristic sea ice pattern dominates the TROPOMI NO_2 data in the polar region."

(6) Lines 257-258: "…to investigate the individual impacts of various flagging criteria…"

Thank you, this has been implemented.

(7) Line 323: "…smaller NO2 values than the other criteria…"

Thank you, this has been implemented.

(8) Lines 322-326: The differences in peak heights for CH flagging between the Indian Ocean and the Atlantic are attributed to the greater number of cloudy cases in the Atlantic. Is this because CH flagging, in general, includes both clear and low-altitude cloudy scenes?

Thank you for your comment. The CH flagging includes both cloudy scenes with low clouds and clear-sky scenes, as no cloud fraction threshold is defined. When distinguishing between cloudy and clear-sky scenarios, the CH-flagged curves in the Indian and Atlantic Oceans behave differently, as discussed in the following.

The CH-flagged cross-sections of the shipping lanes near the coast of Portugal change for different settings, just as we expected (Figure 1). When the predominantly cloud-free scenes (CF<0.1) are considered in addition to those measurements having cloud heights below 2 km (Figure 1b), the CH-flagging curve is higher than the curve that has only the CH threshold (Figure 1a). This fact can be explained by clouds shielding NO_2 from the satellite, as shipping NO_2 is located below the clouds. As a logical consequence, the NO_2 column is larger in clear-sky scenes, as NO_2 can be detected at all altitudes. If the clear-sky scenes are excluded with a CF threshold of 0.1 (Figure 1c) or a stricter CF threshold of 0.2 (Figure 1d), the NO_2 columns are lower than that in Figure 1a. Here, the scenes where clouds shield

NO_2 dominate, resulting in a generally smaller NO_2 column. These results may indicate that NO_2 is trapped at low altitudes in this region.

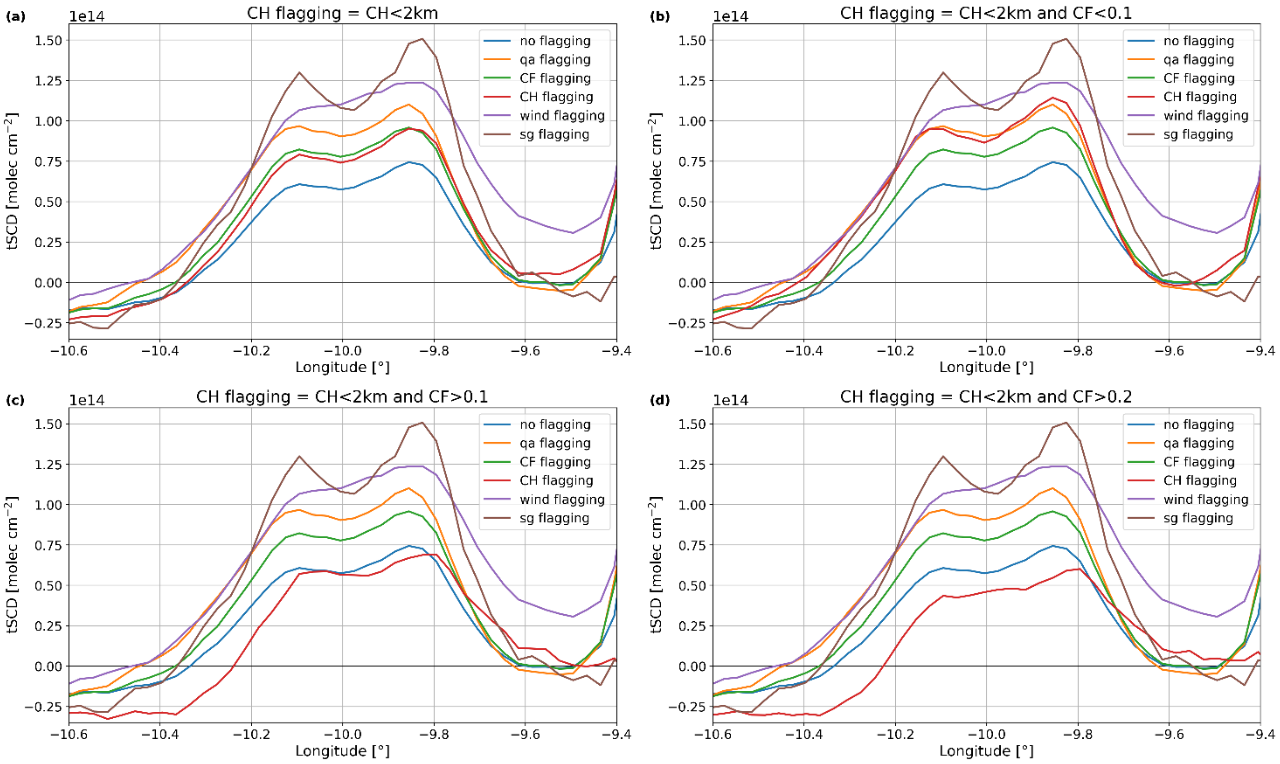


Figure 1: Testing different settings of the CH flagging for the shipping lanes in the Atlantic Ocean; the other flagging criteria are unchanged. (a) The CH flagging is only defined by a cloud height threshold of 2 km. (b) CH threshold as before, but mainly clear-sky scenes are included with a CF threshold of 0.1. (c) CH threshold as before, but clear-sky scenes are excluded with a threshold of 0.2. (d) CH threshold as before, but the CF threshold included more slightly cloudy scenes with a threshold of 0.1, thus, clear-sky scenes are still excluded.

In contrast, the cross-sections of the Indian Ocean shipping lane show an entirely different behavior when comparing the various settings for the CH flagging. When only clear-sky scenes are included (Figure 2**Fehler! Verweisquelle konnte nicht gefunden werden.**b), the peak of the CH-flagged curve is comparable in height to that of the curve without a CF threshold (Figure 2**Fehler! Verweisquelle konnte nicht gefunden werden.**a). A significant difference between the two regions is that the CH-flagged curve, together with the wind-flagged curve, has the highest NO_2 values compared to the other flagging criteria. If the clear-sky scenes are excluded, i.e. only situations with cloud cover are considered (Figure 2c and d), the NO_2 columns of the CH-flagged curves are even higher than with other flagging settings and exceed the previously defined y-axis scale. Figure 2c and, especially, Figure 2d show many oscillations in the CH-flagged curve due to the significantly reduced number of measurements within this CH flagging, indicating that clear-sky scenes dominate in this region. These high NO_2 peaks in cloudy scenes might be because some of the NO_2 is located above the clouds, which, as the reflectivity is increased, leads to higher NO_2 slant columns. This could be explained by the fact that the clouds are at lower altitudes in the Indian Ocean than in the Atlantic Ocean or that there is more vertical mixing over the warm Indian Ocean.

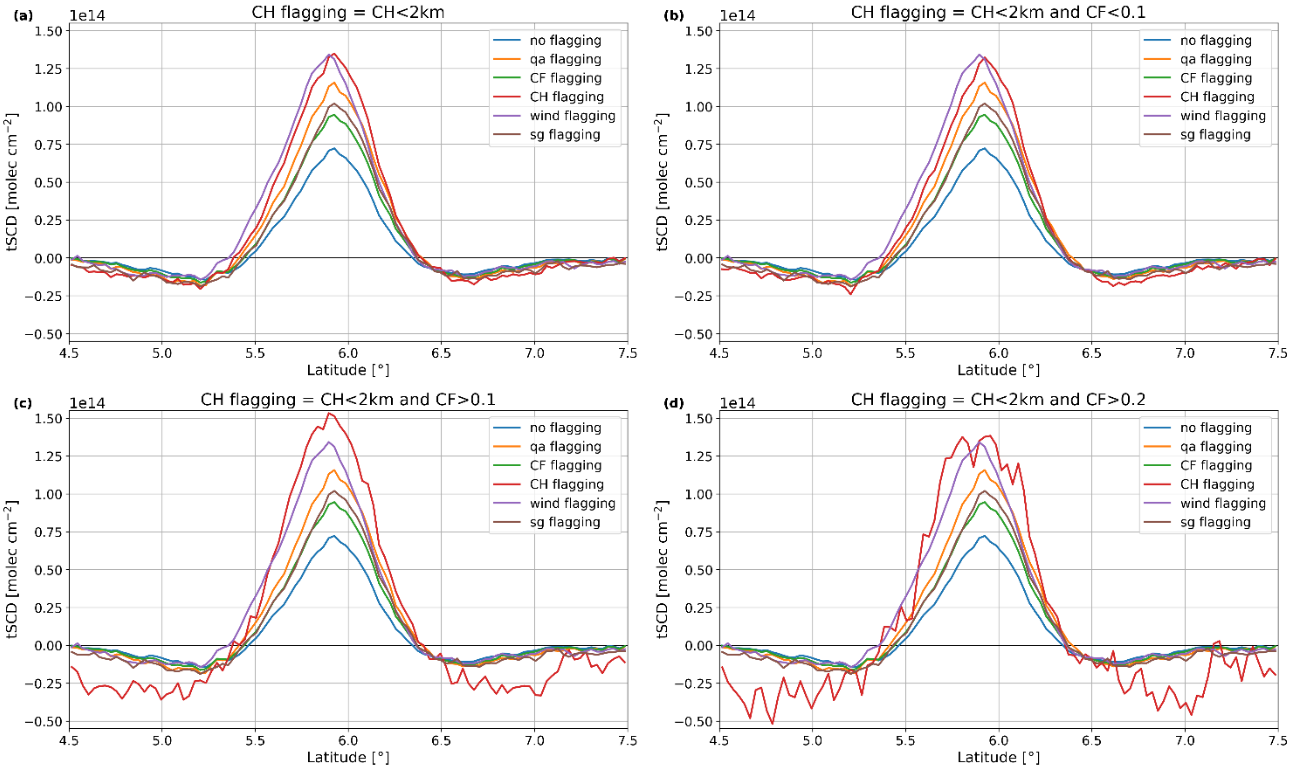


Figure 2: As Figure 1, but for the shipping lane in the Indian Ocean.

Because we only want to give an overview of the impacts of the various flagging criteria on the NO_2 column and do not want to go into these details, we decided to change only the sentence in lines 138-140 slightly to clarify the definition of the CH flagging, as stated in the answer to your comment (4).

Furthermore, we updated the sentences in Lines 280-284 regarding the Indian Ocean:

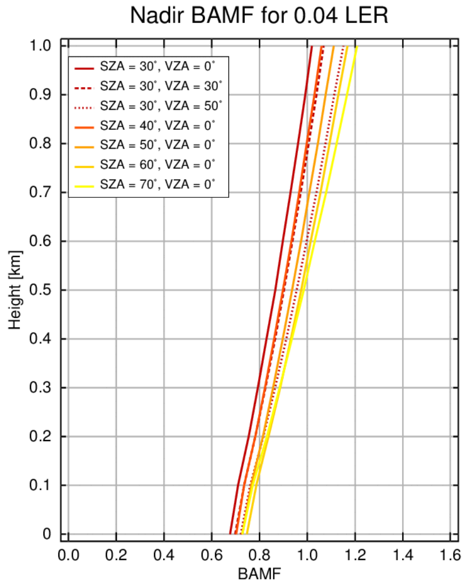
"Flagging for the lowest CHs is among the most effective criteria due to the increased NO_2 peak. In addition to the fact that this flagging criterion includes the clear-sky scenes, one potential reason for this higher peak is that low clouds can reflect more sunlight towards the satellite, enhancing the sensitivity of the TROPOMI instrument for NO_2 above the clouds. This increased sensitivity may lead to higher slant columns of NO_2 in the shipping lanes when only the lowest CHs and clear-sky scenes are considered."

In addition, we changed the sentences in Lines 322-326 to clarify why the CH-flagged curves behave differently in the two regions:

"Comparing the results of this region to the Indian Ocean cross-sections, the curve with CH flagging shows smaller NO_2 values than with the other criteria. It is more similar to that flagged for CF. As low cloud conditions are prevalent in the North Atlantic, the clear-sky scenes do not dominate the curve with CH flagging. Hence, this lower peak can be explained by the fact that the NO_2 in this region is predominantly below the clouds, unlike in the Indian Ocean, where some of the NO_2 is presumably present above the clouds. As a result, the clouds shield the NO_2 in the Atlantic Ocean, resulting in smaller NO_2 slant columns."

(9) Line 388: Please briefly mention why the AMF of 0.8 was chosen. It is a reasonable value, but obviously the AMF can depend strongly on whether clouds are present, etc.

The AMF of 0.8 was chosen as a simple value to be applied to the averaged and filtered slant columns. In a quantitative analysis, the AMF would have to be scene specific and would have to account for varying surface reflectance, clouds, aerosols and different vertical profiles of NO_2. Here, we assumed a surface albedo of 0.04, no aerosols and a vertical mixing of a few hundred meters (see Figure below).



(10) Line 392: “Figure C1b…CAMS data”

(11) Line 394: “…TROPOMI NO2 data (Fig. C1a)…”

(12) Line 398: “…TROPOMI NO2 tVCDs (Fig. 11a)…”

Thank you for pointing that out. The letters of the referenced figure numbers have been corrected for comments (10), (11) and (12), as well as that in Line 398, which is now “CAMS NO2 tVCDs (Fig. 11b)”.

(13) Line 416: Should the sentence read “Inadequate dilution in CAMS could lead to overestimated NOx…” ?

Thank you for this suggestion. The (inadequate) dilution approach in CAMS is commonly described by the term “instant dilution”, which is also used in the study by Vinken et al. (2011). Therefore, we adopted this term in our manuscript. The sentence has been changed to:

“This instant dilution approach in CAMS could lead to overestimated NOx concentrations from shipping over the oceans, as shown by Vinken et al. (2011).”

Other changes made to the manuscript during the review process:

All figures with maps (Figures 2-7, 9-11, B1-B2, and C1-C3) have been changed: The inland water pixels are now also flagged as NaN values to focus on the ocean regions and to reduce the scatter over the continents.
Additionally, Figure B1 and Figure C1: The surface classification mask of the TROPOMI data is now also applied to the CAMS data. Thus, the same pixels are flagged as NaNs for visual consistency. The reason why these water pixels are marked as invalid is that the TROPOMI surface classification mask defines snow and ice pixels over water as land pixels. In this study, only water pixels are included. However, these flagged pixels are irrelevant for this study because they represent the snow and ice edge and, therefore, are not affected by ship emissions.

We added the following sentence to the Acknowledgments:
"We thank the two anonymous reviewers for their comments and suggestions which helped to improve the results and their presentation in this manuscript."