Reply to Referee 1

We would like to thank Referee 1 for the constructive and positive view of our work. Below we address the comments on a point-by-point basis, aligning some of them with the comments of Referee 2.

Response to comments in the summary

Referee: In this work, the authors proposed a new method of using Laplacian filter on near real time CO_2 concentration data to qualitatively detect potential CO_2 sources and sinks in small areas.
This idea essentially boils down to using Laplacian filter to perform edge detection on digital images, and specifically in this work, the CO_2 concentration datasets are used as input digital images and the objects of interests are the CO_2 sources and sinks. The Laplacian filter are widely used in digital image processing/computer vision for edge detection purposes and generally performs well since the filter calculates the second derivatives of the given image and detects edges regardless of direction, but using the filter on CO_2 concentration data can impose some challenges including the shape of the object of interests can be often irregular and diffusive (as opposed to detecting made-made structures that often have crisp edges), and the spatial resolution of CO_2 concentration datasets.
Overall, it's good to introduce image-based methods of CO_2 sources and sinks detection to the general community of earth sciences, but revisions and clarifications are needed to resolve some confusions in the manuscript.
Reply: We agree with the comments on the specific challenges related to the characteristics and limitations of the method. However, we have stated in the paper that the CO_2 sinks and sources have been preliminary detected and that additional tools are needed to obtain more accurate results. The proposed digital filtration method is based on multiplication, difference and sum operations. All three operations can be applied to any CO_2 concentration value without mathematical limitations. A specific limitation of the digital filtration is described in lines 58-62. To avoid repetition, we will not include it in the *Anticipated changes*. Technical limitations in the resolution of satellite datasets (the resolution of a sensor) can pose an indirect challenge to preliminary detection, which can be partially overcome by matching the resolution of a dataset to the expected sizes of the areas to be detected.
Another challenge is the nature of the area of interest, which includes many individual characteristics, e.g. topography, complex ecosystem, natural or industrial origin, etc. These are more important in the following stages, which depend on the objectives and do not affect this preliminary stage. At the current stage of our work, we are exploring the ability of digital filters to capture and detect changes in various characteristics of natural processes, using CO_2 sinks and sources as an example, and focusing on the fact that these changes occur in near real-time and on their sign.
Anticipated changes: We will add the following sentences to the manuscript after line 18: "Applying digital filtration to CO_2 sinks and sources preliminary detection can be challenging due to their nature and behaviour. Industrial objects have more stable emission characteristics. Natural objects have a clear seasonal and also daily periodic dependence. This leads to the need for continuous observations in near real-time mode. Another potential challenge for satellite datasets are technical limitations in the resolution of satellite datasets (the resolution of a sensor), which indirectly challenge the preliminary detection. At the current stage of our work, we do not focus on the reasons that may affect the accuracy of detection, but aim to explore the ability of digital filters to capture and detect changes in various

characteristics of natural processes, for example, for the preliminary detection of CO_2 sinks and sources”.

Response to main comments:

Referee: For the paragraph starting around line 70: Detailed assumptions are needed for equation (2): Why would you assume the inequality? As described in previous paragraphs, for the ‘small area’ and a short time period, if the emitting rate of CO_2 is stable and the removal rate of CO_2 is also stable (external and internal), why would CDC(t_1) be greater than CDC(t_0) at any given location (X, Y, or Z)?
Reply: A CDC measurement is performed for ≈ 0.3 seconds (time for the satellite to scan all 9 areas in Fig. 1a), so the parameters from equation (1) can be considered constant during one measurement. The minimum time step between measurements in the dataset selected is 3 hours. Therefore, the concentrations at t_0 and t_1 in inequality (2) are different. Inequality (2) can be explained by natural processes - continuous changes in temperature, humidity and other characteristics leading to changes in the level of CO_2 emissions, e.g. from a swamp (Fig. 1a), and corresponding changes in CO_2 concentration in neighbouring forest areas. Distance from a source and wind direction also affect concentration.
Anticipated changes: We will change the paragraph before inequality (2) to: “For example, at t_0, we expect different concentrations at points X, Y and Z – $CDC_X(t_0)$, $CDC_Y(t_0)$ and $CDC_Z(t_0)$, respectively, and assume that concentrations are related according to inequality (2):”.
And after inequality (2), we will add the following sentences: “Inequality (2) can be explained by natural processes – continuous changes in temperature, humidity and other characteristics that lead to changes in the CO_2 emissions, e.g. from a swamp (Fig. 1a), and corresponding changes in the CO_2 concentration in neighbouring forest areas. Distance from the source or wind direction also affect the concentration. The time step for observing changes in CO_2 concentrations is 3 hours in the selected dataset”.

Referee: “Equation (1) and equation (2) seems identical, any reason why equation (2) needs to appear?”
Reply: We assume that the Referee had equations 2 and 3 in mind. Equation 2 is a mathematical interpretation of the dependence of the CO_2 data in Figure 1b. Equation 3 is an initial set of relationships that ground the relationships in Equation 4. So, they had different functional aims.
Anticipated changes: We will delete Equation 3, retain Equation 4 (#3 in the new numbering) and change the text of the explanatory paragraph after Equation 2 to: “If, at $t_1 > t_0$, the concentrations change according to (2) while all internal environmental conditions remain stable, this will result in a simultaneous multi-point (X-Z) increase in CDC as shown in (3)”.

Response to comments on the figures in the appendix:

Referee: I am confused about the figures in appendix: how Figure A1 and Figure A2 are related? It seems Figure A2(a) is served as validation for results in Figure A1 (line 138) and Figure A2(b) and Figure A2(c) are for a completely different case study regarding CO_2 sinks (line 158). If that’s the case, why Figure A2(a) is together with and Figure A2(b) and Figure A2(c)?

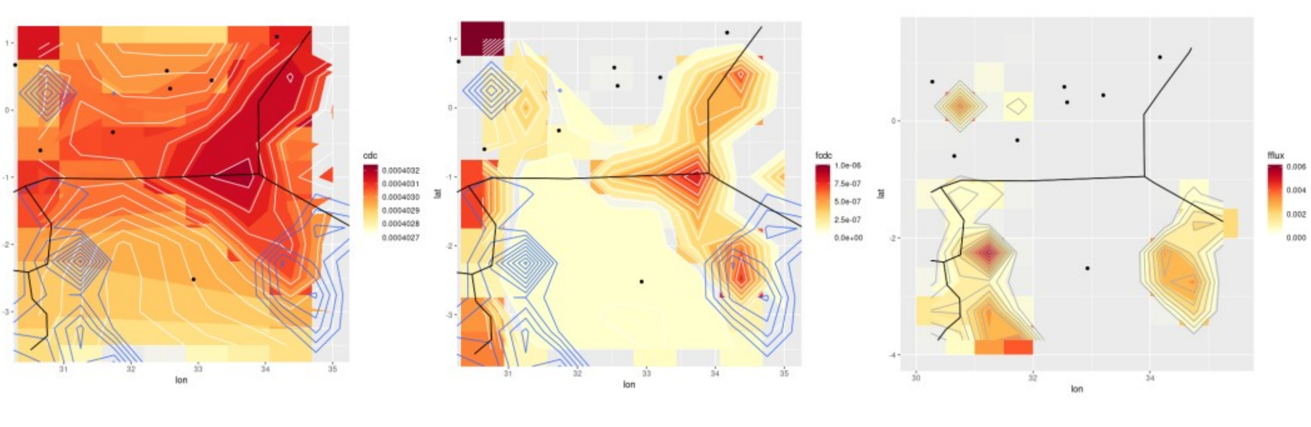
Reply: We thank the Referee for pointing this out. Figures A1 and A2 are not related. Line 138 has a typo. It should read Figure A1(b) instead of Figure A2(a).

Anticipated changes: We will correct the numbering in Figure A1 along with the changes in the following comment.

Referee: Could you also clarify what are the isolines on both figures and the way to interpret? If the pixels in Figure A1(a) are already CO_2 concentrations, then how are the isolines calculated and what do those lines mean?

Reply: The blue (dark) isolines in Fig. A1(a) - Fig. 1(c) (in the new numbering) correspond to the intensities of the CO_2 fire fluxes plotted with the geom_contour function from the ggplot library in the R programming environment. The density of the isolines is related to the parameter change rate. Therefore, a higher density indicates a higher rate and a lower density indicates a lower rate of the CO_2 fluxes. The flux change rates are higher near the fireplaces, and the corresponding isolines are located closely. We use isolines to validate the fire source location by plotting filtered CO_2 concentrations and CO_2 fire fluxes in the same panel. Ideally, the highest density of the flux isolines should coincide with the darkest colour for the filtered CO_2 concentrations. The white (light) isolines in Fig. A1(a) and Fig. 1(b) are an additional interpretation of the CO_2 concentrations and filtered CO_2 concentrations, respectively, and help to see the changes in these parameters more precisely than with colour alone. The isolines in Figs. A2(a) - A2(c) (line 149) are also plotted with the geom_contour function and show the filtered CO_2 concentrations. These data are then superimposed with land cover (Fig. A2(b)) and NDVI (Fig. A2(c)) data for preliminary sink area detection.

Anticipated changes: For a better understanding of the algorithm, we will include another figure to show the distribution of the CO_2 fire fluxes with both colours and isolines in it. The proposed Fig. A1(c) is shown below together with the CO_2 distribution in the fire area in Fig. A1(a) and the obtained results in Fig. A1(b).



(a) CDC distribution in the fireplace area and CO2 fire fluxes data

(b) The obtained results and their verification by CO2 fire fluxes data

(c) Verifying CO2 fire fluxes data

Figure A1: Spatial distributions of the CO_2 parameters and the obtained results of the CO_2 source area detection

We will change the sentence “The flux data are presented in Fig. A2a with isolines showing the rate of CDC changes” in line 138 to: “These data are presented in Fig. A1c, which shows the CO_2 fire flux rate with colour intensity and isolines, and in Figs. A1a, A1b in isolines only. The density of the isolines is related to the rate of flux intensity change – higher density corresponds to higher rate and lower density corresponds to lower rate of change”. We will also change the titles of Figure A2 (line 150). The new title of the general figure will be “Figure A2: Spatial distributions of vegetation indices and filtered CDC for CO_2 sink area detection”. New title of Fig. A2(b) will be “Spatial distributions of LC and filtered CDC” and new title of Fig. A2(c) - “Spatial distributions of NDVI and filtered CDC”.

Response to specific notes:

Referee: What is CDC? If it’s CO_2 concentration dataset why it’s not CCD?
Reply: The abbreviation CDC, used for the first time in line 15, stands for Carbon Dioxide Concentration.
Anticipated changes: none.
Referee: Line 138: For the CO_2 flux dataset (Lesley, 2020), that is spatial resolution of the datasets and how is it when compared with the CDC containing the fire event?
Reply: The spatial resolution of the CDC dataset and the CDC fire fluxes dataset are different - 1°x1° and 0.5°x0.5° respectively. The graphical image overlay with a relative placement by the object coordinates was used with ggplot's internal tools for a rough evaluation of the results.
Anticipated changes: We will add these explaining sentences after line 138: “The spatial resolution of the CDC dataset and the CDC fluxes dataset are different, 1°x1° and 0.5°x0.5° respectively. Different resolutions pose a challenge for source validation, so we use graphical image overlay with a relative placement by the object coordinates for a preliminary detection”.

Referee: Does the flux dataset contains the fire event in 2016?
Reply: The flux dataset contains daily fire emissions over the period 2003 to 2017, including the selected fire event in 2016.
Anticipated changes: We will specify the details of the fire fluxes dataset in line 138: “To verify the obtained results, we compared them with a CO_2 fire fluxes data for the above-ground layer that contains daily fire emissions from 2003 to 2017 (Lesley, 2020)”.

Referee: And how are the isolines calculated in the validation plot (Figure A2(a))?
Reply: In Fig. A2(a) (Fig. A1(b) in the new numbering), the isolines are plotted from the CO_2 fire flux dataset using the geom_contour function from the ggplot library in the R programming environment. The validation data of the fire placement are plotted with colour and isolines in the additional Fig. A1(c), with the numbering of the figures in Fig. A1 corrected.
The isolines in Figs. A2(a) - A2(c) (line 149) are also plotted with the geom_contour function, and show the filtered CO_2 concentrations. These data are then superimposed with land cover (Fig. A2(b)) and NDVI (Fig. A2(c)) data for preliminary sink area detection.
Anticipated changes: There are no additional changes as they are already included in the earlier comment on isolines.