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Interactive Comment

Interactive comment on "Large-scale European source and flow patterns retrieved from back-trajectory interpretations of CO_2 at the high alpine research station Jungfraujoch" *by* C. Uglietti et al.

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General comments: In this paper continuous CO2 and O2, respectively APO, records at the station Jungfraujoch are interpreted using back-trajectory analysis. Source and sink areas are identified by an analysis of the footprints for specific events. The events were classified according to their CO2 and APO concentration and the correlation between the tracers. The authors interpret the typical CO2 and APO (or O2) of the events together with the associated footprint maps in terms of most likely source/sink processes and travel path of the air mass. Back-trajectory analysis as a tool to interpret measurements of trace gases at Jungfraujoch and identify their source and sink regions has been applied already in a large number of studies. The authors apply the method here to CO2 and O2 time series, which is new and potentially interesting. The authors should point out more clearly what the added value of their study is and not already known from previous studies. Fortunately, the authors restrict themselves to a description of the source/sink patterns and processes and do not attempt to estimate source/sink strength. The title of the paper is misleading because it could imply that this study will determine flow patterns in Europe from CO2 measurements at Jungfraujoch. On the contrary, flow patterns known from other sources (like meteorological data) are used to interpret the CO2 time series. In fact, back-trajectories rely on the known flow pattern. In general, the paper is quite well structured and well written. Data, method and results are well presented. However, the description of the data treatment to separate background, long-term trend, seasonal cycle, and short-term variations would profit from a clearer structure. The conclusions section is simply a summary. It could be condensed substantially and focused on unique findings.

Response to general comments: It is true that back trajectory analysis has been a common tool to interpret trace gas measurements at Jungfraujoch. There were only comparatively few studies, however, that have done this in a systematic way using statistical approaches that rely on large numbers of trajectories. A novel aspect of our study is to group trajectories according to specific subsets of points in a tracer-tracer correlation. Previous studies have typically grouped trajectories either according to the characteristics of the trajectories themselves (using e.g. a trajectory clustering method as described in Bankov et al. (1998)), or by differentiating between "pollution events" and "background". While it is interesting to study the transport pathways that lead to specific pollution events, the combination with tracer-tracer correlations adds another (process-related) dimension since different processes can lead to different correlations and hence different clusters of data points. The strength of our approach additionally relies on the analysis of such tracer-tracer correlations and their relation with specific transport histories based on a large number of data points rather than on a few (and

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possibly not representative) case studies only. This is a clear advantage of operational continuous in-situ observations as opposed to campaign studies e.g. from research aircraft. The pathways of individual trajectories are associated with considerable uncertainty while averaging over large numbers of trajectories tends to cancel out such errors (except if they are systematic) resulting in a more robust picture. There is also considerable scatter in the measurements due to the limited instrument precision which additionally calls for such a statistical approach. We have extended the introduction section somewhat to make better reference to previous trajectory studies and to better highlight the specifics of our approach.

Specific comments:

p. 814, l. 20: O2 uptake by dry summer soils is just one possible explanation and it is not shown in the paper that this is the major reason. Therefore it is not supported enough to be mentioned in the abstract.

Yes correct, we removed this sentence from the abstract

p. 815, l. 27: Briefly explain the carbonate buffering system and its effect on atmospheric CO2.

The ocean is the largest reservoir of carbon dioxide. Carbon exists in three forms in the ocean: as carbonic acid (H2CO3, non ionic, about 1% of the total), as carbonate ion (HCO3 -) which is about 91% and as bicarbonate ions (CO3 2-) which is about 8%. The co-existence of these species in seawater creates a chemical buffer system, regulating the pH and the pCO2 of the oceans. In the present day the buffering system maintains the pH of the ocean at an average of 8-13 [Sabine et al., 2004]. Nevertheless we do not think we need to add this statement in the paper. We would only add a reference: Sabine et al., 2004 (Science).

p. 816, l. 23: Although this is not relevant for the results of this study, please specify exactly which version of EDGAR was used, EDGARFT2000 is only available for 2000.

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We used EDGAR version 4.0 which provides data for the year 2005. This will be mentioned in the text and in the figure caption.

p. 817, l. 5: Is this for the European part of Russia?

Yes, the value given by Schulze et al. (2009) was estimated for the European part of Russia. We will change the sentence to " .. while emissions in the European part of Russia are only .."

p. 818, l. 10-12: Moreover,: This information is not relevant in this context.

Right, but the information regarding local contamination is important. We removed the sentence on the accessibility and changed the next sentence to: "The influence of local emissions on the measurements is usually low since all heating is electrical and waste is transported back to the valley."

p. 820, l. 19: Although at least 0.25 degree apart some of the trajectories could start within the same grid box of the meteorological fields. Is this a problem? Are these trajectories different?

Different from Eulerian models this is not a problem in the Lagrangian framework. The trajectories follow different paths (since the wind vectors interpolated onto their points are different) and, depending on horizontal and vertical wind shear, these points become increasingly separated from each other typically reaching distances of several grid cells after a few hours of transport only. Trajectory ensembles can only represent the variability in transport pathways that is associated with grid-resolved flow features (as demonstrated e.g. by the technique of reverse-domain-filling) but they can not represent the full range of pathways which is additionally influenced by turbulence and (subgrid scale) convection.

p. 821, l. 3: Is PBL height directly available in the 3 hr ECMWF forecasts and analyses? Or is it calculated offline? Please specify explicitly.

It is directly available from the ECMWF forecasts and analyses. The sentence will be

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changed to: “Planetary boundary layer heights are available as ECMWF analysis and forecast fields at 3 h resolution.”

p. 821, l. 12-14: Specify the resolution of the footprint maps. Are they on 1 x 1 degree like the meteorology or on a finer grid?

Although the resolution of the map can be chosen flexibly and there is no need to select the same resolution as provided by the meteorology, it was here indeed chosen to be 1 x 1 degree.

p. 821, l. 23: Can you expect to identify air masses transported to Jungfraujoch by convection in summer although convection is neglected in the trajectory model (p. 820, l. 7)? Please comment.

Convective transport can not adequately be represented by a trajectory model relying on fields from a global hydrostatic model. Nevertheless, convective areas are usually associated with (grid scale) low level convergence and mid-level upward motion which also affects the transport of the trajectories. The trajectories thus “feel” convection to some extent but they will never rise to the upper troposphere at the time scale observed in a convective updraft. The more organized and the more persistent the convection, the larger will be the influence of convection on the vertical trajectory paths. Transport from the PBL to the upper troposphere in the warm conveyor belts of cold fronts, for example, is well captured by trajectories. Our experience shows that trajectories show much more vertical motion in summer than in winter which reflects the fact that convective activity has an impact on grid-scale winds which in turn affects the trajectory paths. We have appended the following sentence on line 26 on the limitations of the trajectories: “It should be noted, however, that trajectories based on relatively coarse wind fields as used here can not resolve the many small scale and mesoscale processes which are particularly relevant for vertical transport to Jungfraujoch during summer. They should rather be considered as representing the large-scale flow patterns and their reliability will be limited under particularly convective situations.”

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p. 823, l. 19-21: What are background data, how are they determined? The definition is only given later in the manuscript. Please consider to rearange the sections describing the way in which trend, seasonal cycle and short term variations were separated in the time series. Otherwise the statement at p. 824, l. 9-10 seems contradictory.

We agree that the term “background” should be explained earlier. We rearranged the paragraphs such that we appende the first four sentences of paragraph 3.2 to the end of 3.1. Then 3.2 would be the Background corrected data, 3.3. the Seasonal cycle (previously included in paragraph 3.1) which and 3.4. Long term and short term variations.

p. 824, l. 18-23: Does this background include the seasonal variations? Is this the same background as mentioned in p. 823, l. 21?

Yes it is the same background which includes the seasonal variations. This approach guarantees the characterization of regional emissions.

p. 827, l. 17: Explain the color scale of the relative footprint map.

The colors in the legend (see figures 7, 8 left and from 10 to 15) correspond directly to the ratio of residence times over specific grid-cells (which therefore has no units). A value of 10 e.g. denotes a residence time of the selected trajectories 10 times larger than the average of all trajectories. Hence, the trajectories corresponding to the specific selection have a 10 times higher probability to have passed over particular grid cell than any arbitrary trajectory released from JFJ.

p. 827, l. 6: Explain briefly what South Foehn events are, what is the meteorological situation.

South Foehn is a typical Alpine meteorological phenomenon characterized by south to north advection which is caused by a strong pressure gradient across the Alps leading to a descending air stream north of the Alps [Brinkmann, 1971; Hoinka, 1980; Seibert, 1990]. South Foehn usually occurs when a cyclone approaching from the west induces

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a synoptic-scale southerly or southwesterly flow over the Alpine region. South Foehn situations are typically associated with orographic precipitation on the Southern side of the Alps thereby releasing latent heat that causes the descending air stream north of the Alps to be particularly warm [Zängl and Hornsteiner, 2007].

p. 828, l. 16-20: The argument why it is better to use CO2 vs. APO instead of CO2 vs. O2 is difficult to follow, needs clarification, give a more physical explanation.

APO is defined in such a way that its value is not influenced by photosynthesis and respiration from the terrestrial biosphere. Therefore, using CO2 vs. APO allows for a better distinction between ocean and terrestrial biosphere influences on CO2 than CO2 vs. O2. We replaced : Note that the advantage of using APO instead of O2 is that no rotation of the corresponding selection boxes is required. In a scatter plot of O2 versus CO2 a rotation would be necessary to align the boxes with the general negative slope of the O2 versus CO2 correlation (see Fig. 6, left panel). With : Note that the advantage of using APO instead of O2 is due to the definition of APO that guarantees a subtraction of a mean terrestrial biosphere influence and therefore allows a better distinction of ocean and terrestrial biosphere influences on CO2 than CO2 vs. O2.

Section 4.2: The terms ‘negative CO2’ and ’negative APO’ are not fully correct. ’Negative _CO2’ or ’negative _APO’ would be better terms to denote a negative deviation from the background. As this might be confused with the nomenclature in the definition of APO in the introduction, the term ‘low CO2’ could also be considered. In any case, use low/high and negative/positive consistently in text and figures.

Yes, true. We changed “negative” and “positive” to “low” and “high”

p. 829, l. 5-6: The seasonal cycle indicated in Fig. 9 is contradictory to the description of subset 5 (winter and spring) and subset 6 (winter). It seems that there is not such clear seasonal cycle as suggested with Fig. 9.

Indeed, the seasonal cycle suggested by Fig. 9 is better represented by the subsets 3

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and 4 (spring to summer) than by subsets 5 and 6 (autumn to spring). Nevertheless, the basic structure still holds considering the statistical information about the number of trajectories represented by each subset. We changed the description of the two subsets 5 and 6 such that this statistical information is represented: The subset with regular CO2 and high APO values (corresponding also to high O2 values, subset 5) is associated with air masses advected from the Western North Atlantic Ocean, in particular during late autumn, winter to early spring (from November to April). Most of the events associated with regular CO2 and low O2 (low APO) concentrations were observed in winter to spring.

p. 829, l. 26: Is really more O2 used in respiration or less O2 produced by photosynthesis?

The high CO2 and low O2 concentrations recorded at Jungfraujoch occur generally in wintertime which is in line with the fact that respiration, which produces CO2 and consumes O2, is more important in winter than photosynthesis and with higher anthropogenic CO2 emissions in Europe due to the burning of fossil fuels (solid, liquid or gas) (Rotty, 1987) for heating, thus enhancing the decrease of atmospheric oxygen.

p. 830, l. 17-20: Some more explanation is needed why the patterns suggest a cyclonic path.

We have extended the sentence to "typically followed a cyclonic path (patterns have a cyclonic, i.e. anticlockwise curvature) .."

p. 830, l. 20-21: That the upward transport was connected with fronts in the case studies should be explained in detail already in 4.1.1 and 4.1.2

This is a good point since frontal activity was key in both case studies. The last line in Section 4.1.1 will be changed to "This persistent weather situation appears to have induced large accumulation of trace gases in these air masses as they moved from the north passing over heavily industrialized countries before they were lifted by the fronts

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and finally transported to Jungfraujoch." In section 4.1.2 the role of frontal activity was already mentioned.

p. 832, l. 16: This is not consistent with Fig. 9

Refer to answer of comment p. 829, l. 5-6: above.

Figures: Please indicate in all maps the location of Jungfraujoch. Please indicate subset number in the legends of Figures 10-15.

Yes, done

Fig. 1: EDGAR 3.2 Fast Track emissions are for 2000 not 2005.

Edgar 3.2 is indeed the version including data from 2000. We used the version 4.0 which provides data for 2005.

Fig. 8: 'South Foehn situation drawn by Meteo Swiss' Please give a proper reference for the meteorological map.

The sentence in the figure legend will be changed to: "South Foehn situation on 21 November as represented in the daily surface weather analysis chart of MeteoSwiss (available from http://www.meteoschweiz.admin.ch/web/de/wetter/wetterrueckblick.html) (right). "

Fig. 10-15: Add explanation of the histograms in the legend.

The following explanation will be added: The lower panels show the number of trajectories in the different months of the year (left) and in the different hours of the day (right) used to create the footprint map. We will add this sentence only for the first figure of this type.

Fig. 11-15: Use high/low or positive/negative consistent with text.

Yes, done.

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Fig. 2, 7-15: Better use the original grid instead of color-filled contours, which produce artificial diamond shaped structures.

The diamond shaped structures are indeed an artefact of the plotting method. However, the overall smooth contours generated in this way are better guiding the eye than would be the case for e.g. filled rectangles. Moreover, the original output grid has little meaning here since its resolution can be chosen arbitrarily and the specific choice has little impact on the figure.

Technical corrections:

p. 815, l. 12 : Do you mean d(O2/N2) or (dO2)/N2 ?

d(O2/N2)

p. 815, l. 15: Van der Laan-Luijkx

Corrected r

p. 816, l. 11: you probably mean 'consumption'

Corrected

p. 817, l. 11: Balzani Lööv

Corrected

p. 819, l. 7: acronym SIO needs to be explained

After several measurements of three standard air cylinders (CA07043, CA07045, CA07047) that were filled and analysed for CO2 and O2 at the Scripps Institution of Oceanography of California, La Jolla (SIO), the difference between the Bern internal scale and SIO scale for oxygen was set to -556 per meg.

p. 827, l. 14: concentrations...were also...

Corrected

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p. 829, l. 25:...because of CO_2 increases due...

Corrected

p. 831, l. 3: There is something missing in this sentence.

Yes there is an “and” missing: carbon exchange is low and its influence on the oxygen budget

p. 832, l. 6:...are consistent....

yes corrected are instead of is

p. 833, l. 4:...relatively high...

yes corrected a relative high with relatively high

p. 833, l. 10: Van der Laan-Luijkx

yes corrected der instead of Der

p. 838, l. 26: Balzani Lööv

yes corrected Lööv instead of Loov

Fig. 6: ‘All’ instead of ‘Both’ records.

yes corrected

Fig. 7: According to the text this is not the south foehn situation.

Indeed this was a mistake. In case 2 the extremely high CO_2 concentration is associated with air mass transport from the north with high residence time over eastern European and central European countries.

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