

## ***Interactive comment on “First description and classification of the ozone hole over the Arctic in boreal spring 2020” by Martin Dameris et al.***

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### **Important remark**

There is a joint special issue of JGR and GRL on the 2019/2020 winter. Several of the papers submitted to the special issue show a considerable overlap to your study and are relevant for your manuscript.

These studies have been publicly available as preprints since several weeks (on ESSOAR, the equivalent of the discussions stage of ACP for the AGU journals) and a list of the planned and submitted papers has been publicly available for several months. The first study relevant for your paper (Manney et al.) has already been accepted and

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published.

The call for the special issue has been widely circulated in the community. I would have assumed that you are aware of it, but your manuscript does not make this impression. I think it is mandatory that you discuss, cite and acknowledge the relevant papers from the special issue. Some of them are still under review, but will very probably appear before acceptance of your paper.

The list of planned and submitted papers and the current status of the special issue are available at [https://docs.google.com/document/d/1QqGblz\\_CXZ2eQRtv0-KY4f4XcGjTCIDkhVWLx8e4uTM/edit](https://docs.google.com/document/d/1QqGblz_CXZ2eQRtv0-KY4f4XcGjTCIDkhVWLx8e4uTM/edit)

Here are the links to the preprints of the studies relevant for your manuscript:

- Manney et al.: <https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020GL089063>
- Lawrence et al.: <https://www.essoar.org/doi/10.1002/essoar.10503356.1>
- Wohltmann et al.: <https://www.essoar.org/doi/abs/10.1002/essoar.10503518.1>
- Groß et al.: <https://www.essoar.org/doi/abs/10.1002/essoar.10503569.1>

I make some suggestions in the specific comments where to cite these papers, but this is certainly not a complete list. Please cite them where necessary.

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## General

In general, I found most parts of the manuscript to be scientifically sound and would recommend publication. While there are some issues (see specific comments), I don't think that there is anything which cannot not be resolved.

I have to admit that I had more of a problem with the wording and readability in some places. On the positive side, I did not find a single typo. But on the other hand, wording was quite awkward in some places, and sometimes the text could have been less confusing and better organized, it felt a little bit rushed in places. I have the impression that asking a native speaker to go through the text would help in many places.

## Major comment

Unfortunately, however, I have a major comment on a less scientific issue. The general wording and tone of the paper are quite sensationalist in title, abstract and conclusions (or as a colleague who is a native speaker put it: "attention-grabbing"). I don't find the wording appropriate in several places. I don't think that you do yourself or the stratospheric community a favor with that. You need to phrase your manuscript more carefully. In addition, things are sometimes not put into perspective, which may lead the reader to draw the wrong conclusions.

If you imply conclusions here that are at least debatable and at the same time choose a manuscript title that will attract the interest of the public or press, I think this could be problematic. In particular:

- Remove "first" from the title. This is not a contest, but a scientific paper. In addition, it is just not correct. There are papers under review in the upcoming GRL/JGR special issue that have overlap in content to what you write here, and

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the first paper has already been accepted.

- I find the repeated and prominent use of the phrase "ozone hole" highly problematic. In the abstract and title alone, it appears 7 times. This raises expectations and may imply conclusions for some readers which are not really backed by the facts or are at least debatable. Given that the phrase "ozone hole" has played a prominent role in the public discussion in the last decades, many people will have a certain understanding of the phrase which sticks in their minds, and we as a community should be careful what we write (in our own interest).

I feel obliged to go a little bit more into detail why I think that prominently stating that the winter 2019/2020 showed an "ozone hole" is problematic. I think we probably agree that the winter 2019/2020 was exceptional. It was the coldest stratospheric Arctic winter on record and showed the lowest ozone columns and concentrations ever observed in the Arctic, which were comparable to typical values in the Antarctic ozone hole locally and for limited time periods.

Having said this, it still was far removed from the usual conditions in the Antarctic ozone hole.

- First, the area with Dobson values below 220 DU was much, much smaller than the typical area of the Antarctic ozone hole. First of all, the area of the Arctic vortex is typically smaller than the area of the Antarctic vortex (Manney et al., 2011, gives a number of 60% for 2011). Then, the area with values below 220 DU covers only a small part of the vortex. This can easily be seen in your Figure 1. According to the numbers you give in the conclusions, even at maximum, the area was less than 5% of the Antarctic ozone hole (0.9 million km<sup>2</sup> compared to 20 million km<sup>2</sup>).

In the end, this is a little bit of a problem with the standard definition of the ozone hole as the area below 220 DU. This definition does not take into account the area covered by the hole at all. But certainly nobody would call

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it an ozone hole if the area of the hole would be only one square meter.

- Then, the vertical extent of the layer almost completely depleted in ozone in the Antarctic is much larger than the vertical extent of the depleted layer seen in 2019/2020 in the Arctic. Usually, ozone is depleted to near zero values in a large altitude range from about 350 K to more than 500 K in the Antarctic (e.g. Kuttippurath et al., doi:10.1038/s41612-018-0052-6). While the ozone profiles of 2020 show a pronounced minimum, very low values (below, say, 0.2–0.3 ppm) were restricted to a layer of a few 10 K depth around 450 K (see plot of a sonde measurement in Ny-Alesund on 27 March, measurement is the blue line).

This also is a weakness of the 220 DU definition. In the Antarctic, values will usually fall far below 220 DU, while they only scratch 220 DU in the Arctic in 2020 (please see my comment to Figure 7 how to improve on this).

- While the lowest mixing ratios reached in 2019/2020 were comparable to mixing ratios that can often be observed in the Antarctic ozone hole (0.1–0.2 ppm), they did not reach the near zero minimum values (0.01 ppm) that are typical for the Antarctic ozone hole.
- And last but not least, it is also the time period. The Antarctic ozone hole lasts several months, while the time period with very low ozone values in 2019/2020 was at most 5 weeks or so.

Thus, I really would suggest to phrase things more carefully, e.g. to speak of an "ozone minimum" or "values comparable to values observed in the Antarctic ozone hole" and so on. Please see the specific comments for the places where I think you have to phrase things more carefully.

- Sometimes, it seems that you would like to push the reader into a certain direction by omitting information in strategical places. While this means that you don't write anything scientifically wrong formally, you may push the reader to draw con-

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clusions that are not correct. In particular, it would have been very easy to include Antarctic data in figures like Figure 1, 5, 6 and 7, and to discuss this data in the text to put things into perspective. I think it is really mandatory that you change the manuscript to be more balanced and to put things better into perspective.

### Specific comments

- Page 1, lines 11–12: Please rephrase to something like "record low ozone column" or similar and avoid the term "ozone hole".
- Page 1, lines 12–14: The sentence would work equally well when you omit "A persistent ozone hole pattern". Just start with: "Minimum total ozone column values. . .". To make the "for the first time" in the sentence work better, maybe you could write "for more than 5 weeks" (or 4 weeks?) instead of "about 5 weeks".
- Page 1, line 14 (next sentence): Suggestion: "Usually such low total ozone column values have only been observed in the ozone hole in the polar Southern hemisphere (Antarctic) in spring over the last 4 decades, but not over the Arctic." Slight change in text, but larger change in meaning. But please state here in addition that column values will go far below 220 DU in the Antarctic to put things into perspective. It would also make sense to state the other differences which I have outlined in my general comment here (smaller area, vertical extent and time period).
- Page 1, line 16: Change to "The record low values were caused. . ."
- Page 1, line 16: A stable vortex does not enable a cold stratosphere. This confuses cause and effect, when there is no wave activity. When there is wave activity, it is a little bit more complicated, please see my comment to page 5, line 3 (sorry, wrote that comment first. . .). Please phrase that correctly.

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- Page 1, line 20: "in the context of" is probably better.
- Page 1, line 20: Replace "ozone-hole like features" simply by "cold winters"
- Page 1, lines 27–28: I would delete this sentence. This is exactly what I would call "attention-grabbing", but it doesn't really transport information.
- Introduction: In a later comment (page 5, line 3–30), I suggest to add a short overview on how ozone depletion works somewhere in the introduction (PSCs, cold temperatures, chlorine activation, return of sunlight, ...) to be able to streamline the text in the later sections a bit.
- Introduction: In some places, I find the references a bit odd, while I miss others. E.g. Langematz, 2019 and Loyola et al., 2009, would not be the first ones that come to my mind. I would expect the review paper of Susan Solomon from 1999 somewhere (Rev. Geophys. 37, 275–316, 1999). A paper that is mandatory to cite in a study like this is in my opinion Solomon et al., "Fundamental differences between Arctic and Antarctic ozone depletion", 2014, doi:10.1073/pnas.1319307111 (it is by chance that it is Susan again). This is a review paper about exactly the topic you are talking about here, and it also contains some very critical remarks about using the term "ozone hole" for the Arctic.
- Page 2, lines 5–10: You don't need to explain the meaning of the term "ozone column". This is basic textbook knowledge.
- Page 2, line 7: Delete "so-called"
- Page 2, line 11: You need a citation for the 220 DU threshold (it is for example defined in the WMO report 2018, along with further references). This is more or less an "official" definition which most people agree on, and you will need some references for that. All of your following discussion depends on this definition.

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- Page 2, line 14: This is misleading. Changes of ozone column by transport and changes of the column by chemistry are correlated (e.g. Tegtmeier et al., 2008, which you may want to cite here). A more dynamically active winter means both more transport of ozone into the vortex and less ozone depletion because of higher temperatures. Your sentence reads as if the difference between 450 DU and 220 DU would mainly be caused by chemistry. In fact, one of the fundamental differences between the Arctic and the Antarctic is that transport plays a large role in determining the Arctic ozone columns.
- Page 3, line 3: Perhaps replace "with respect to low TOC" by "in reaching low ozone columns"?
- Page 3, line 4–5: Some references from the paragraph starting page 10, line 27 would also fit, and see also my comment to this paragraph for even more references.
- Page 3, line 11: It would probably be good to mention the official databases for ozone sondes here, i.e. WOUDC and NDACC.
- Page 3, line 13: You need to phrase that more carefully: "which led for the first time to ozone values below 220 DU in larger parts of the vortex for an extended time period".
- Page 3, line 25: As far as I know, the nominal resolution of ERA5 is 0.28125 degrees. It does not really make sense to sample the data at a higher resolution (but does not hurt either).
- Page 3, line 24–28: You don't need to go into detail how you do a daily average. I trust you that you are able to do this correctly :-). In fact, you can replace anything between "For our investigations..." and the end of line 28 by "We use daily and monthly averages in the following". This is totally sufficient.

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- Page 4, line 3 and line 8: Delete "first". This is really not relevant in the context of this paper. Again, this is no contest.
- Why is Figure 2 the first plot that you discuss in the paper? You should change the order of the plots, so that Figure 2 becomes Figure 1.
- Figure 2 and accompanying discussion: Lawrence et al. from the special issue contains similar figures and discussion. Please cite and discuss Lawrence et al. here.
- Page 4, line 25 and Figure 2: At first, I was a little bit confused by the plot because I didn't realize that the dots are monthly mean values and the lines are daily values, causing the colored dots not to lie exactly on the lines. Maybe there is some information overkill in the plot. One could replace the dots by a grey area showing the range of the daily values in all years for every day.
- Page 4, lines 26–28: I would suggest to delete the part in parentheses. Either discuss this explicitly in the paper, or leave it at "caused by planetary wave activity".
- Page 4, lines 28: Would be good to use the established terminology here (major warming, minor warming, sudden stratospheric warming...)
- Page 4, lines 29: The wording is a little bit awkward and hard to understand. I would try wording like "stable and undisturbed vortex", "circular shape", "not displaced from the pole" etc. "deteriorated" is not the correct word.
- Page 5, line 2: Figure 3 does not add any relevant information which is not contained in Figure 2. You could delete this figure without loss of information.
- Page 5, line 3: You confuse cause and effect here. First, in the absence of wave activity, the polar region gets colder than mid-latitudes in winter due to a lack of

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sunlight and because of radiative cooling. Then, a pressure difference develops compared to mid-latitudes, which causes a geostrophic wind as response.

For a correct discussion, you would need to explain the mechanisms of the Brewer-Dobson circulation in more detail. Interannual differences in polar temperatures or vortex strength are caused by differences in momentum deposition by breaking waves (mainly in the mid-latitude stratosphere) which drive the BDC.

That means that both temperatures and vortex strength are correlated, but that this has a common underlying cause, and not that one causes the other.

- Figure 5 and 6 and accompanying discussion: Lawrence et al. and Wohltmann et al. from the special issue contain similar figures and discussion (e.g. Figure 1 Wohltmann et al. and Figure 11 Lawrence et al.). Please cite and discuss Lawrence et al. and Wohltmann et al.
- Figure 5 and 6: Please add typical Antarctic values in the figures and discuss them in the text. This will help very much to put things into perspective and I think this is mandatory.
- Figure 5: It is a little bit confusing that you use a polar cap area and not the vortex area here as the area where you look for the minimum. That only gives the desired result because of the comparatively high temperatures outside of the vortex. You are interested in the minimum temperatures inside the vortex here, because these are relevant for ozone depletion. It would be more consistent to base the plot on the vortex area (the plot would look almost identical probably).
- Figure 5: Can you really learn something from the minima of the monthly mean values? These will by definition always be higher than the daily minima. I don't really see that they provide any insight. I would suggest to remove them and to replace them by some grey area showing the range of the daily values over all years.

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- Page 5, lines 11–12: The numbers for the vortex area are a little bit unintuitive. At least I don't have a really good judgement of them. An alternative would be to divide the values by the vortex area, which gives a value in percent, which is more easy to grasp. In addition, the unit for the cumulative area can't be correct. There must be some time unit missing (probably "days").
- Page 5, line 14: The citation seems odd. An obvious citation would have been the original study of Solomon et al., *Nature*, 321, 755, 1986. Or the WMO report or the 1999 Solomon review paper.
- Page 5, line 16–20: Discussion on "ozone hole". Please phrase that more carefully. You could state here that record low values have been reached and that their temporal extent and the covered area were unrivalled in other years (but please check that, this is just what I suppose is correct).  
It is certainly also ok to mention the 220 DU definition of the Antarctic ozone hole here, but I think it is mandatory here to discuss the smaller area, the limited vertical extent and the limited time period compared to the Antarctic ozone hole to put things into perspective.
- Page 5, line 20: As far as I can see, this is the first time you mention Figure 1. Please correct the order of the figures.
- Figure 1: Add contours for the 220 DU contour and the vortex edge. These are things that are really hard to see in a coloured contour plot. And the 220 DU contour is really central for the discussion in your paper.
- Page 5, paragraph lines 3–30: The readability of this paragraph suffers because of two issues in my opinion:  
First, you introduce 5 figures in this short paragraph, but only by mentioning them in parentheses. It would help immensely to insert a few sentences starting with "Figure xxx shows. . ." in this paragraph.

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In addition, you try to explain how ozone depletion works in some half-sentences and in parentheses here and introduce things like CI activation and NAT clouds. I think you could improve your manuscript a lot by adding a short paragraph in the introduction explaining the basics of ozone depletion in a few sentences (cold temperatures, PSCs, return of sunlight, chlorine activation, CFCs, ...). Then, you could refer to that later, and the text would read much more fluently.

You have tried to explain even more basic things in this manuscript, like the definition of ozone column or the averaging, so it seems odd that you don't explain some things in the introduction which would really help to streamline the text in your paper.

- Figure 6: To make things more consistent, you could show the range of values of all other years in grey, as in Figure 2, 5 and 7.
- Page 6, line 9: Why is this expected from January on, and why is this expected with values above 220 DU? I don't understand your reasoning here. Maybe it would be better to simply write "is observed"?
- Page 6, line 12: See comment page 3, line 11.
- Page 6, line 21: Please compare the area below 220 DU to the area of the vortex here. This would really be important and interesting information which helps to put things into perspective.
- Page 6, line 22: Again, the units are not quite correct (at least formally). A unit of "days" is missing.
- Figure 7 (and accompanying text): What really would add a lot of value to your paper with relatively small effort would be to show typical values from the Antarctic in the same plot and to discuss the differences between Arctic and Antarctic in the text. Please add Antarctic values to the figure to put things into perspective.

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- Figure 7: The same comment as for Figure 5 applies: It would be better to base the figure on the vortex area and not on a polar cap area.
- Page 6, line 27: There is a lot of literature on the 2010/2011 winter. Maybe it wouldn't hurt to cite one or two studies more here. Suggestions: Sinnhuber et al., 2011, doi:10.1029/2011GL049784, Hommel et al., 2014, doi:10.5194/acp-14-3247-2014, Strahan et al., 2013, doi:10.1002/jgrd.50181, Kuttippurath et al., 2012, doi:10.5194/acp-12-7073-2012, ...
- Table 1: I could live well without the table. The information can already be found in the plots.
- Page 8, line 9: The wording is awkward. Suggestion: "The winter 2019/2020 showed a larger volume below the formation temperature of PSCs than other winters for an extended period of time."
- Page 8, line 11–15: This is visible in the HNO<sub>3</sub> measurements of MLS. Please cite the Manney et al. paper from the special issue here. You don't need to speculate.
- Page 9, line 12–14: Can you get a little bit more quantitative here? What is the quantity you are looking at here? Vortex mean temperatures at some level? In the moment, these sentences do not convey enough information to be useful (I am well aware that the uncertainties are large and will only allow a qualitative statement).
- Page 9, line 25–32: And of course, there is the ozone hole split of 2002.
- Page 10, paragraph 1–6: The statements in this paragraph are problematic and don't really tell the truth because you omit information. You don't mention that the temperatures in the Antarctic are considerably lower than in the Arctic (even for 2019/2020) and that the period of low temperatures is much longer in the

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Antarctic. If you would have added this information to your plots (e.g. Figure 5 and 6), this would be quite obvious.

It is also not true that this would result in ozone depletion rates that are comparatively strong. The depletion rates will also depend on the amount of ClO<sub>x</sub>, which in turn e.g. depends on the amount of descent in the vortex. In fact, this is a rather complicated topic. The crucial difference between the Arctic and the Antarctic which leads to very low ozone values is the much longer time period with ozone depletion. Since ozone loss is usually in saturation in the southern hemisphere, some details on the path to zero ozone don't really matter here.

- Page 10, line 10: Please give numbers for the chlorine content. This would show that the differences are not that large (I assume 10% to 20% difference?) and that it is not too surprising that differences in temperature are the main driving factor. But in principle, you are right, this is worth mentioning. Maybe some additional discussion along the lines above is appropriate.
- Page 10, line 17: In fact, a dehydration event can clearly be seen in the MLS H<sub>2</sub>O measurements. Please cite Manney et al. from the special issue here.
- Page 10, lines 18–22: You repeat what you already have said on page 8. Please delete. See also the comment to page 8, lines 11–15.
- Page 10, line 24: See comment page 10, line 10.
- Page 10, line 27. Please rephrase "atypical ozone hole" to something like "record low ozone values".
- Page 10, line 29 and line 32: I totally agree that you never can tell climate change from a single year and that you have to look how this evolves in the future in the context of a longer time series. On the other hand, you can have a look into the winters observed so far and don't need to wait for the future to have a

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long timeseries. And the year 2019/2020 does add information to this timeseries, since it was the coldest Arctic winter observed so far and the coldest winters have become colder in the last years quite consistently, at least according to some metrics and meteorological data sets. You could cite Wohltmann et al., Figure 1, from the special issue for a figure illustrating this quite well. But in general, I agree with you.

- Paragraph Page 10, line 27 to page 11, line 10: Some additional recent relevant studies on this topic: Ivy et al., 2016, doi:10.1175/jcli-d-15-0503.1, Rieder and Polvani, 2013, doi:10.1002/grl.50835, Butchart et al., 2010, doi:10.1175/2010JCLI3404.1, Bednarz et al., 2016, doi:10.5194/acp-16-12159-2016. These contain a lot of interesting discussion on this somewhat controversial topic (Are coldest winters getting colder etc.), which you may want to add here.
- Page 11, line 2: I think an important point to mention here is that the other important driver of changes in stratospheric temperature (apart from changes in radiative cooling by greenhouse gases) are changes in the strength of the Brewer-Dobson circulation (e.g. Langematz et al., 2014 and many more), and the BDC in turn is affected by climate change.
- Page 11, line 11–14: This paragraph seems a little bit out of context.
- Page 11, line 16–17: The sentence seems overly complicated and wording is a little bit awkward. Suggestion: "This study presents a description of the Northern winter and spring season 2019/2020 considering the..." ("regarding" seems not to be the correct English word to me, I think "considering" is what you mean).
- Page 11, line 17–19, 23–26: Please phrase more carefully. It is ok to discuss that the observations were below the 220 DU threshold for a longer period of time, but please also discuss the differences to the Antarctic ozone hole in area, vertical

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extent and duration that I have mentioned in my general comment right after lines 17–19. I am very happy that you finally discuss some of this in lines 23–26, but please move it a few lines up and discuss a little more. I.e. put things into perspective. Please don't call it an "ozone hole". And don't claim that this year was the first occurrence of an "ozone hole". This was already claimed by some people in 2011, and it didn't help in the discussion back then, too. In general, I don't find this chase for superlatives very helpful, and it does not help to advance our scientific understanding.

- Page 11, line 23–26: I am very happy that you finally discuss this here, but I hope you agree that it would have been necessary to mention this much much earlier (and more often) in your manuscript.

### Technical corrections

- Page 3, line 18: You can delete "It must be noted that".
- Page 6, line 16: I don't think "outstanding" is the right word here. Maybe "prominent" or "remarkable"?
- Page 8, line 1 and 3: I would write "ice PSC" and not "ICE-PSC" (ice is not an abbreviation).
- Page 8, line 28: "Discussion" and not "Discussions"
- Page 9, line 17: "recall" is not the right word. Suggestion: "We note"
- Page 11, line 19: You very probably mean "compared" and not "confronted"?
- Page 11, line 20: I would say "which show" and not "which are showing"
- Page 11, line 20: I would say "the most recent datasets"

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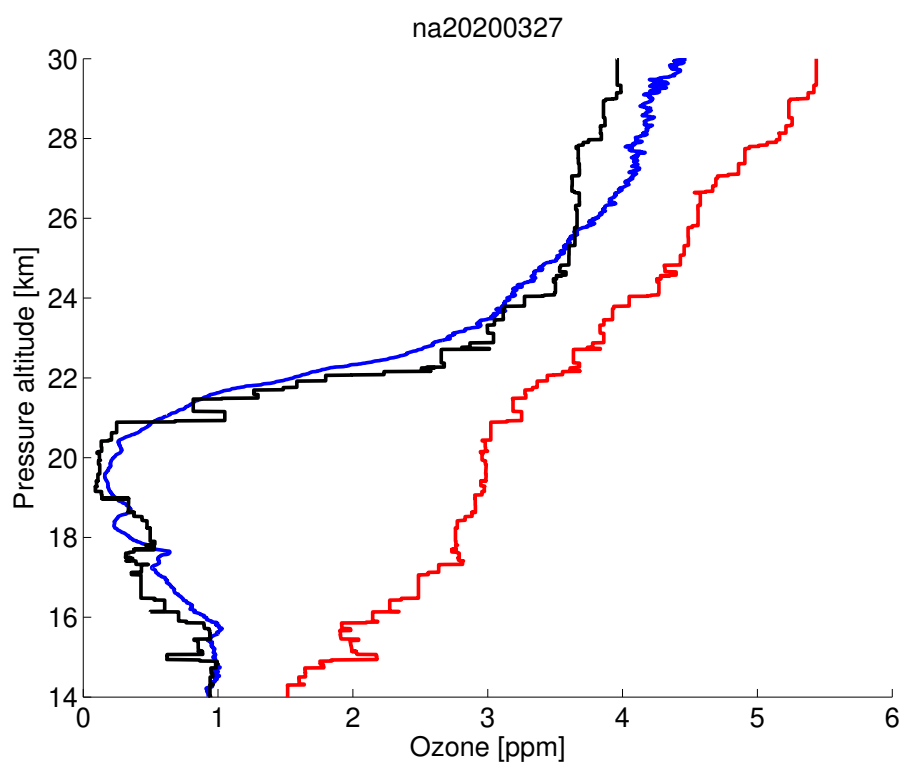


Fig. 1. Sonde measurement in Ny-Alesund on 27 March, measurement is the blue line

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