Interactive comment on “Analysis of 24 years of mesopause region OH rotational temperature observations at Davis, Antarctica. Part 2: Evidence of a quasi-quadrennial oscillation (QQO) in the polar mesosphere” by W. John R. French et al.

Anonymous Referee #1

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Reviewer Report on the manuscript acp-2019-1097

Analysis of 24 years of mesopause region rotational temperature observations at Davis, Antarctica. Part 2: Evidence of quasi-quadrennial oscillation (QQO) in the polar mesosphere

By W.J.R.French, A.R.Klekociuk, and F.J.Mulligan

General Remarks

1) The paper studies multi-annual variability in the lower and middle atmosphere up to the mesopause which is an interesting objective. 2) Emphasis is on quasi-quadrennial oscillations (QQO) observed in mesopause hydroxyl temperatures in a 24 year time series. 3) The variability signal is also seen in many other parameters as temperature, winds , geopotential, trace gas mixing ratios, SST, sea ice. These are obtained from various sources as satellites (MLS, SABER), ground based radar, ERA 5, etc.. 4) The analysis concerns vertical as well as meridional and zonal structures of the middle at- mopsphere. This is very interesting and worth publishing! 5) However: More than half of the paper (pictures) deals with these parameters, only, and not with the Davis temperatures! The title of the paper is, therefore, inappropriate and misleading. It should be changed to something more general, and the manuscript should be rearranged accordingly. I know that this is not an easy task, as the interannual variability of the middle atmosphere is a very extended topic, and the data shown in the paper form only part of it. Nevertheles I recommend rewriting the paper in this direction, rather than turning it down. (To make it clear: I do not recommend that the authors write a review of middle atmosphere interannual variability, but that they state that their work forms an essential part of such a larger overview.) 6) The paper is well written, but many of the figures need improvement. 7) The paper is recommended for publication after major changes have been made.

We thank the reviewer for the comments. As a general response to item 5), thank you for the suggestion regarding the title. This work forms part 2 of a two part series reporting on the long-term measurements of OH rotational temperatures at Davis. In part 1 (acp-2019-1001; “Analysis of 24 years of mesopause region OH rotational temperature observations at Davis, Antarctica. Part 1: Long-term trends.”) we focus on the solar cycle response and long term trend components. In this part, we focus on the residual variability observed in those data (the QQO). We decided to separate these sections as they deal with distinctly separate aspects of the long-term measurements..

The principle and foremost observation in both these reports are the trends and variability in the OH rotational temperature data set from Davis. We use many different (publicly available) data-sets in this part to put the Davis observations in global context and use correlation and composite analyses to understand the source and mechanism of the apparent QQO in Davis OH residual temperatures. We provide evidence of the feature by comparisons with Aura/MLS and SABER temperatures and search for clues to its origin in wind, pressure and sea surface temperature data. We therefore do not think the title is inappropriate or misleading.

Major Comments

1) Fig.1: a) The period of 4.2 years is not very convincing! In the years before 2006 the agreement of Davis-T, Saber-T, and the 4.2 yr oscillation curve is marginal! Please give an error bar for the 4.2 yr period value (see for instance Kalicinsky et al., ACP 16, 15033, 2016; Kalicinsky et al., JASTP 178, 7, 2018). b) How did you detrend solar cycle and long-term trend? Simultaneously or in an iteration?

a) The period of 4.2 years is obtained with a simple sinusoid fit to the residuals. The period and error estimate is 4.18 ± 0.10 years. Coefficients and errors for all model fit coefficients are provided below. The curve is provided as a guide. It is clearly not a simple sinusoid of 4.2 years which is why the term *quasi*-quadrennial oscillation is used (in much the same way that the *quasi*-biennial oscillation (QBO) is not strictly a 2-year periodicity) .

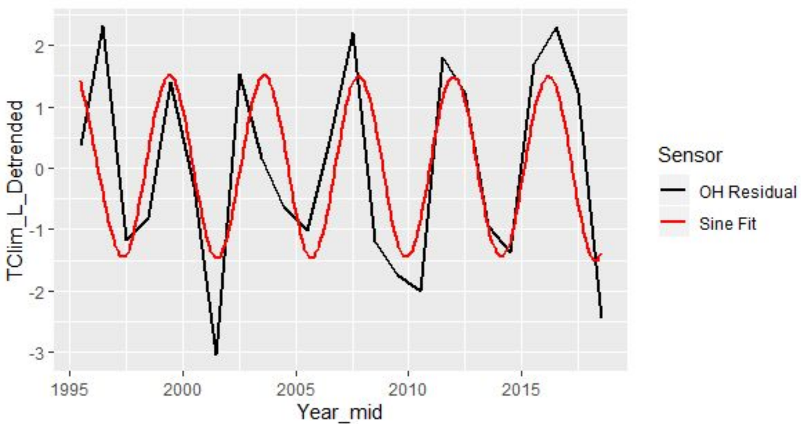
Formula: y ~ Offset + Amp * sin(2 * pi * (Phase - x)/Period)

Parameters:

	Estimate	Std. Error	t value	Pr(>|t|)
Offset(K)	0.02455	0.25801	0.095	0.925137
Amp(K)	1.49255	0.35868	4.161	0.000483 ***
Phase(year)	1994.20367	0.35537	5611.601	< 2e-16 ***
Period(years)	4.18158	0.10287	40.647	< 2e-16 ***

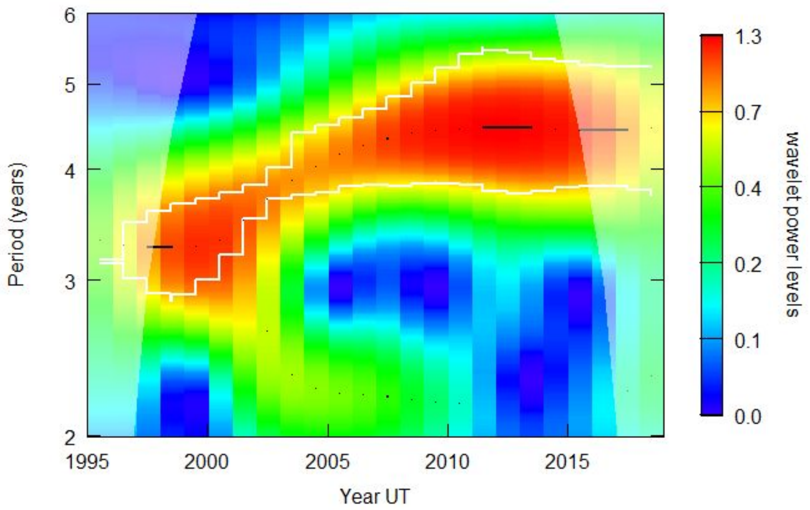
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.26 on 20 degrees of freedom



The comparison with SABER is limited as we cannot compare the same winter data interval due to SABERs yaw cycle. As described in the text ‘only days 106-140 and 196-259 are comparable between SABER and Davis-OH over the winter interval and days 141 - 195 (21 May to 14 July) are excluded. We note that the comparison is not as good an agreement as Aura/MLS but still indicates the presence of a QQO feature.

Another version of the wavelet analysis is shown below with 95% confidence contour in white and the ridge as black points, (cone of influence shaded). The ridge varies between 3.29 and 4.46 years.



b) The solar-cycle and long-term trends are detrended simultaneously with a multiple linear regression model. This is described in detail in part 1 of this work (acp-2019-1001)

2) Fig. 1 and related text: Figure 10 might be moved to this part of the paper to illustrate that the interannual variability is fairly different in summer, winter, North and South.

Thank you for the suggestion. Figure 1 is specifically the Davis QQO observation. It is the source of our identification of the QQO variation, describes the characteristics of the feature, and provides corroborating evidence of the variation from satellite observations specific to the location of Davis.

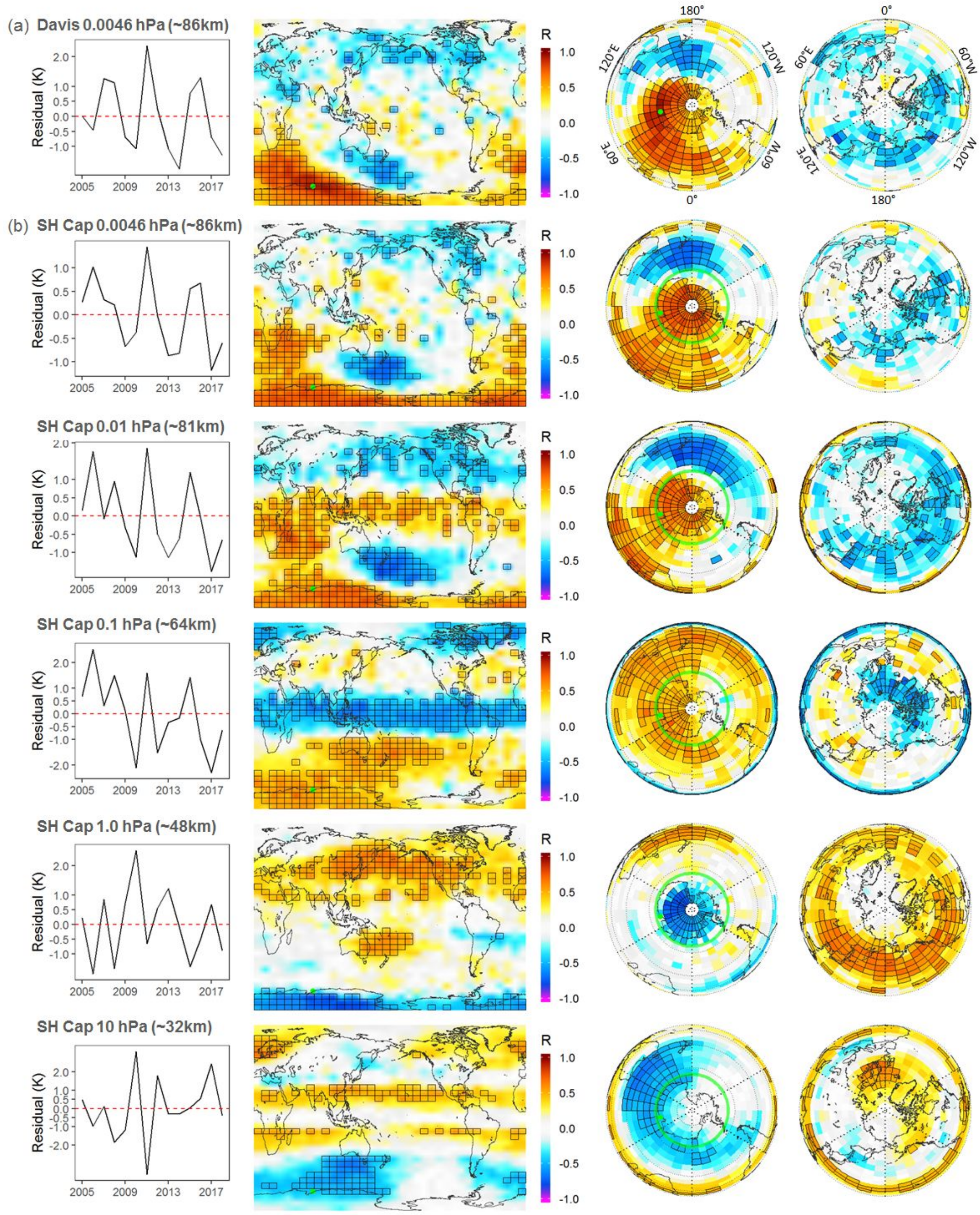
Figure 10, on the other hand, is polar cap averages (65-85° North and South) of the MLS 0.00464 hPa pressure level and the summer and winter months (AMJJAS and ONDJFM) in each hemisphere.

Our focus is primarily on the SH and we prefer to keep discussion of the hemispheric and seasonal comparison separate in section 4.5

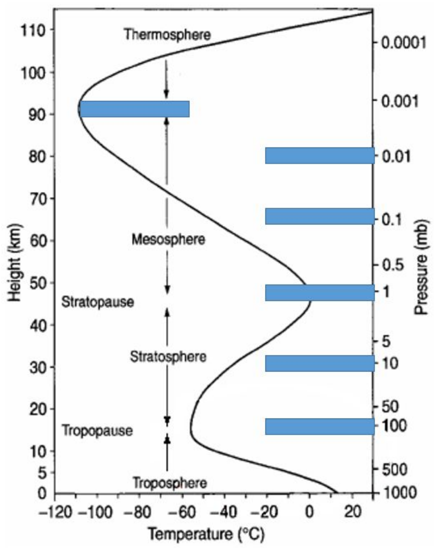
3) Fig.2: a) This is mostly a global analysis, and only a small part is from OH temperatures. Hence, my General Remark #5 applies. This is also the case in Fig.3 and many other places of the paper, especially for most of Section 4. My suggestions in the following assume a paper version in which title and text have been modified already. b) The “hashed areas” are indicated by crosses. These are difficult to discern! This also applies to the following figures, especially if the background colour is blue! The paper would become much more readable if this was improved! c) Fig.2b shows the vertical structure of the interannual variability, which is very interesting. However, the altitude resolution is poor: it only shows that the mesosphere differs from the stratosphere. As described in Section 2.2 there are more altitude levels available. Therefore please complement the left hand column of Fig. 2 by the altitude levels missing. This should show whether the vertical phase distribution is continuous or steplike (as the ones of Offermann et al., 2015).

a) As stated above, the key result, the new observational data, and the focus of the investigation reported here is to explain the QQO feature observed in the Davis OH temperatures. We would argue that explanation of the QQO variability in the OH temperatures are the whole reason for the study. We have examined the temporal and spatial extent of the QQO signal with available global data sets to place the observation in context and to attempt to identify its source. We believe this is a reasonable title.

b) We have made appreciable efforts to re-work the figures to improve the hashed/stippled areas which indicate significance. Perhaps this option of applying a border to grid cells that pass the significance criterion improves visibility and clarity? We are happy to defer to editorial and publication recommendations on this.

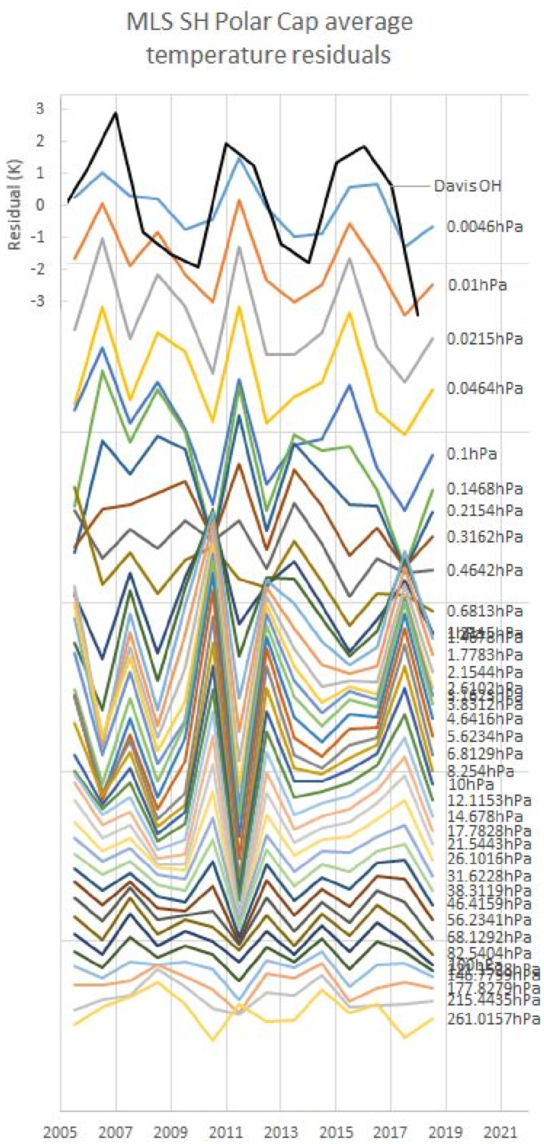


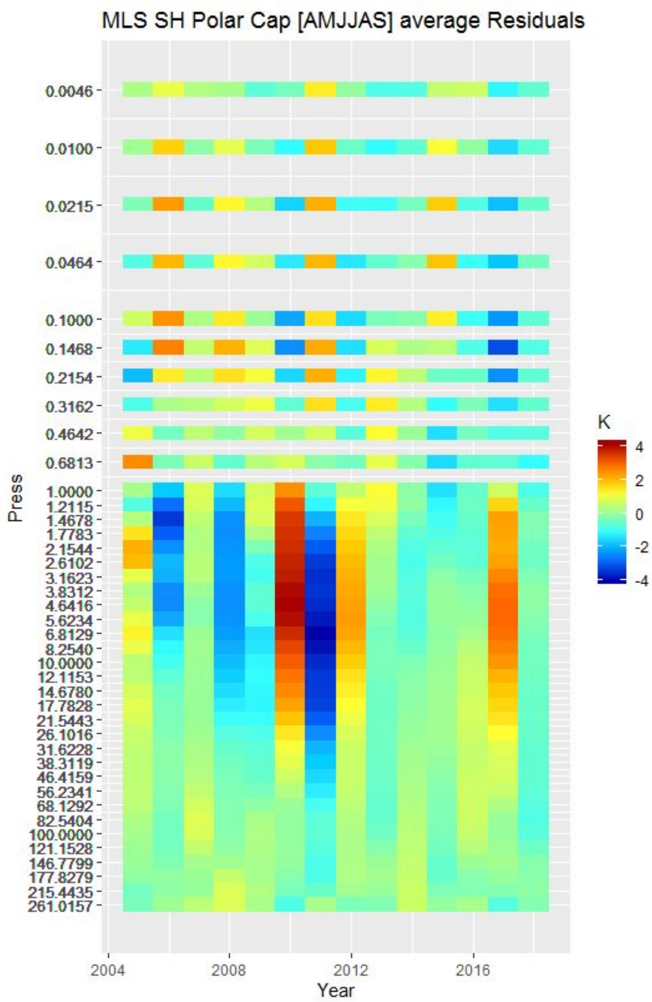
c) Indeed, 55 pressure levels are available in the Aura\MLS data set but we have selected levels which are representative of the stratosphere, stratopause region, mesosphere and mesopause region (see fig right).



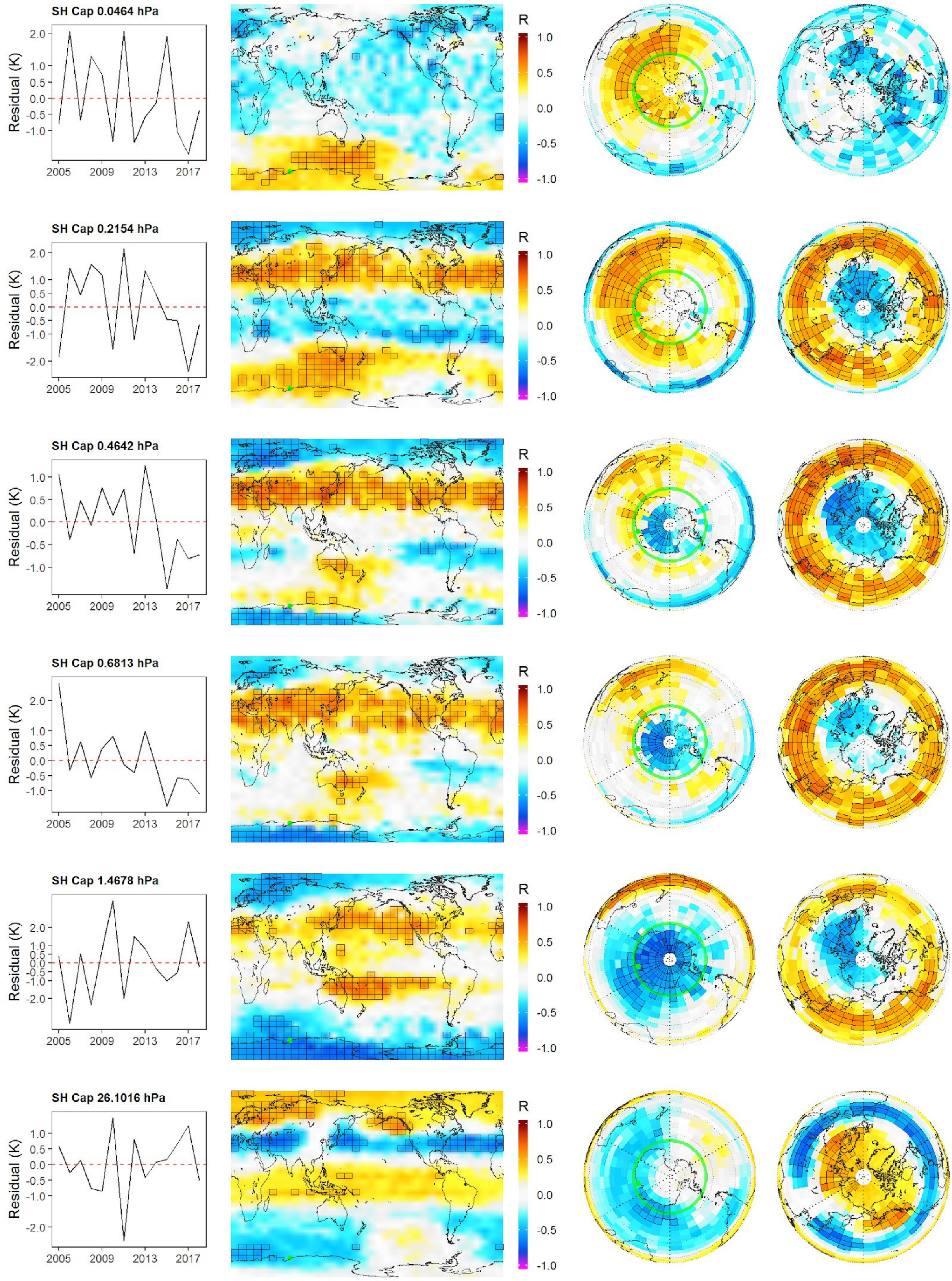
Plotted below are the additional time series of Aura/MLS [AMJJAS] polar cap (65-85°S) averages at each of the MLS native pressure levels compared to the Davis OH time series. The y-axis temperature scale is common to all series, but they are offset by the pressure (log scale) indicated by the labels.

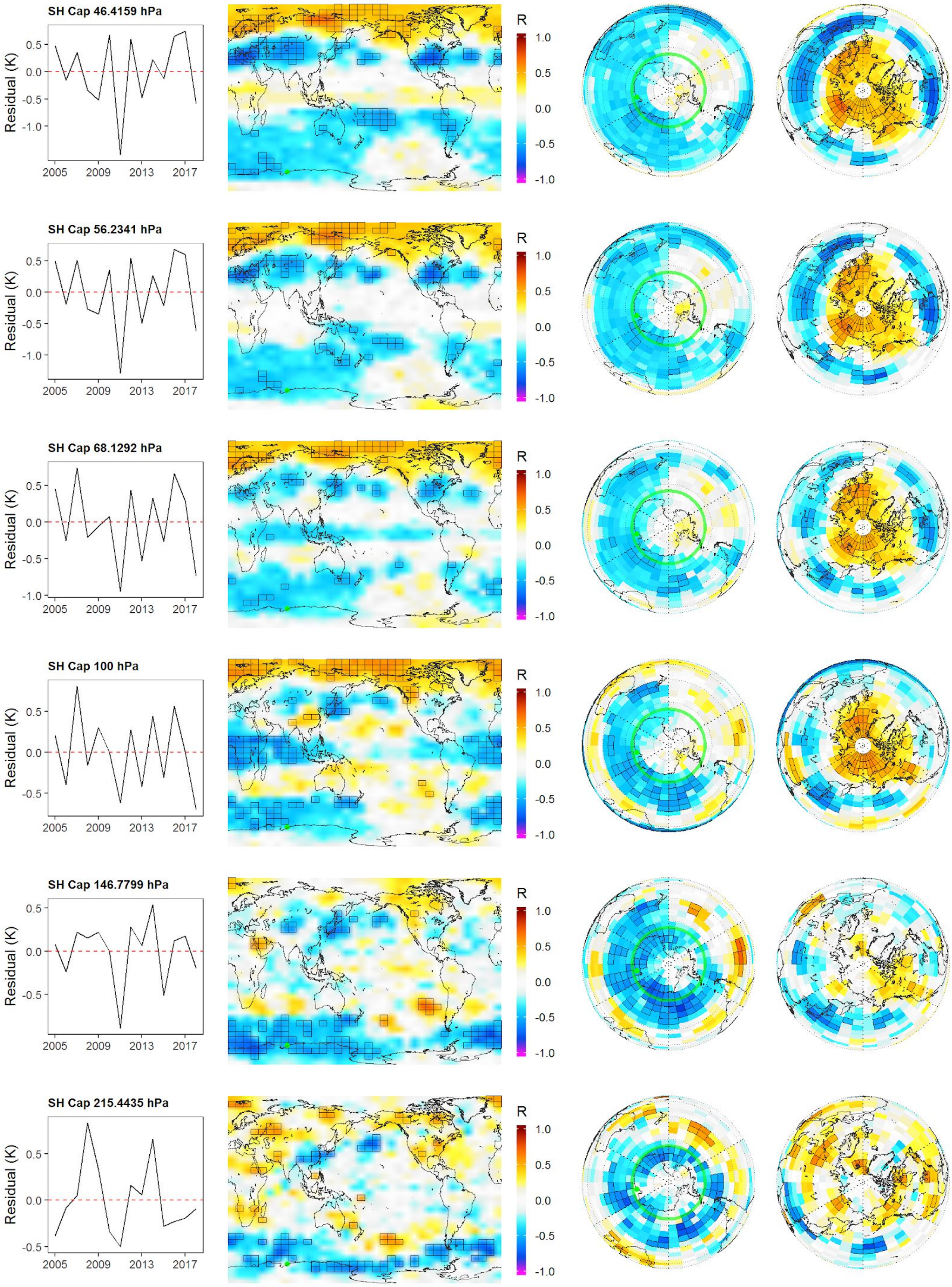
These plots show the QQO feature is common through the range 0.0046 - 0.1 hPa, (represented by the 0.0046, 0.01 and 0.1 hPa panels in our figure) then there is a transition between 0.1 and ~1hPa (1hPa is shown) followed by a reasonably consistent pattern to the time series below 1hPa (10hPa is shown). The selected levels of fig 2 thus reasonably encompass the range of variability shown over the polar cap and are representative of the 3 different regimes. This figure is added to the supplementary material as figure 2S.





Full correlation plots for some additional levels are also provided below for your reference, but note that the selected levels do in general capture the correlation patterns throughout the atmosphere profile.

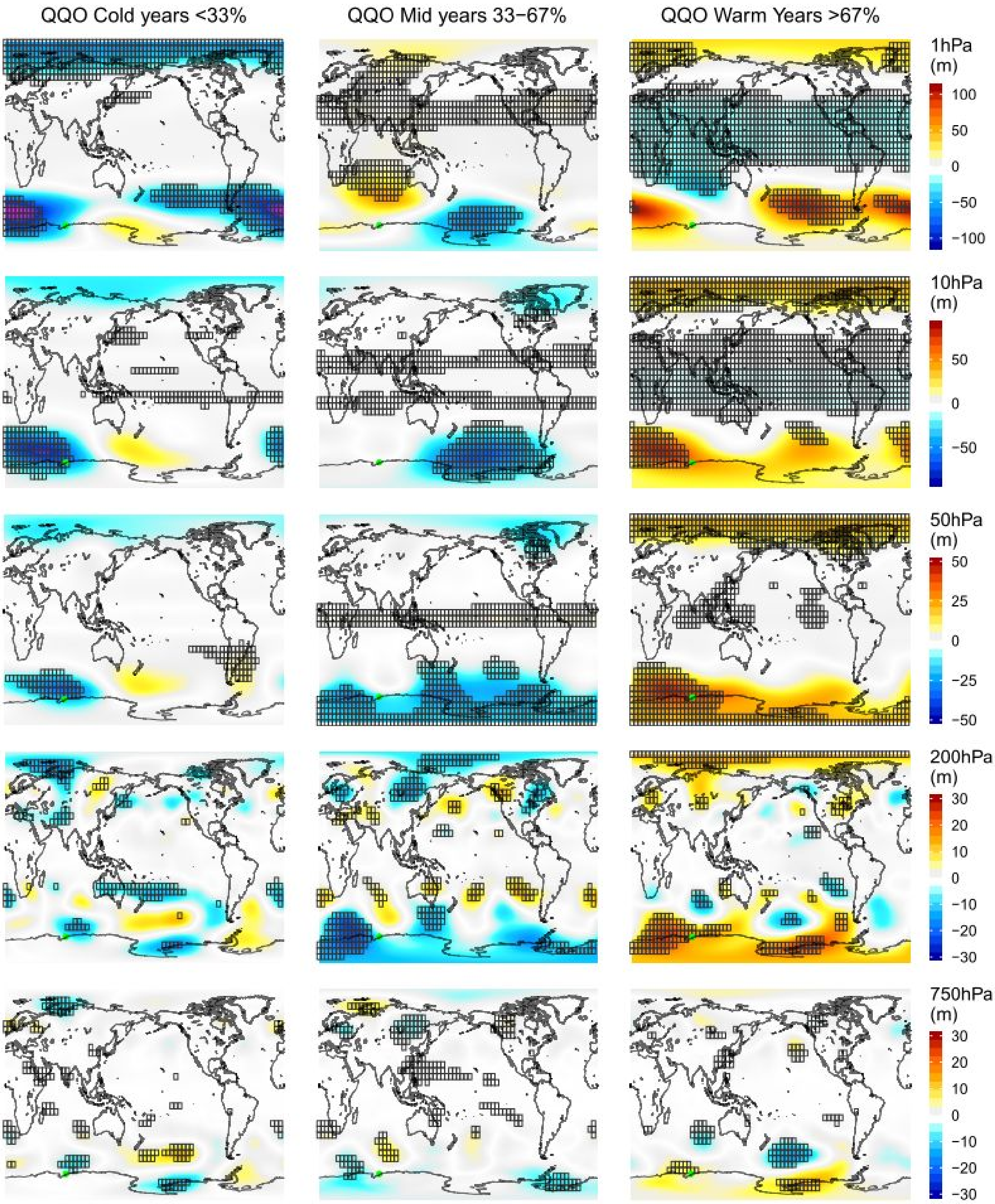


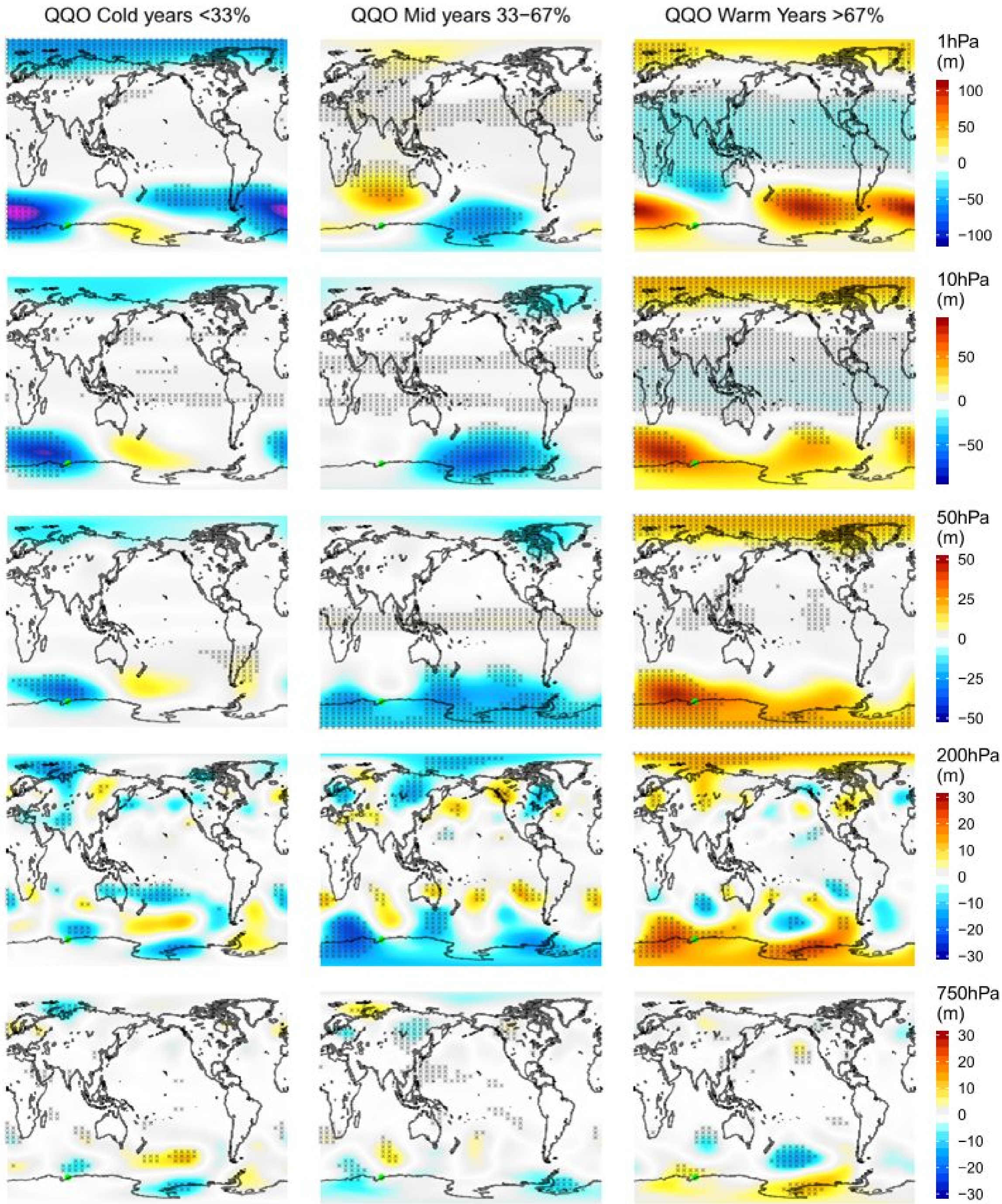

SH Cap 46.4159 hPa
SH Cap 56.2341 hPa
SH Cap 68.1292 hPa
SH Cap 100 hPa
SH Cap 146.7799 hPa
SH Cap 215.4435 hPa
Residual (K)
2005
2009
2013
2017
R
1.0
0.5
0.0
-0.5
-1.0

4) Fig.3 and Fig.4: Please give time series as in the left hand panel in Fig.2.

Figures 3 and 4 are *composites* of 5° x 10° (latitude x longitude) or 36 x 36 grid cells corresponding to the cold, mid and warm years of the Davis detrended QQO signal shown in Fig 1(b). As composites the series are accumulated by the Davis detrended temperature, not by time.

We have tried several variants of the significance hatching on these plots to the boxing applied on Fig 2 but this is too heavy with the smaller grid cells in ERA5. We prefer the original although we have modified the point density (see examples below). Again, we will work with editors to optimise this.

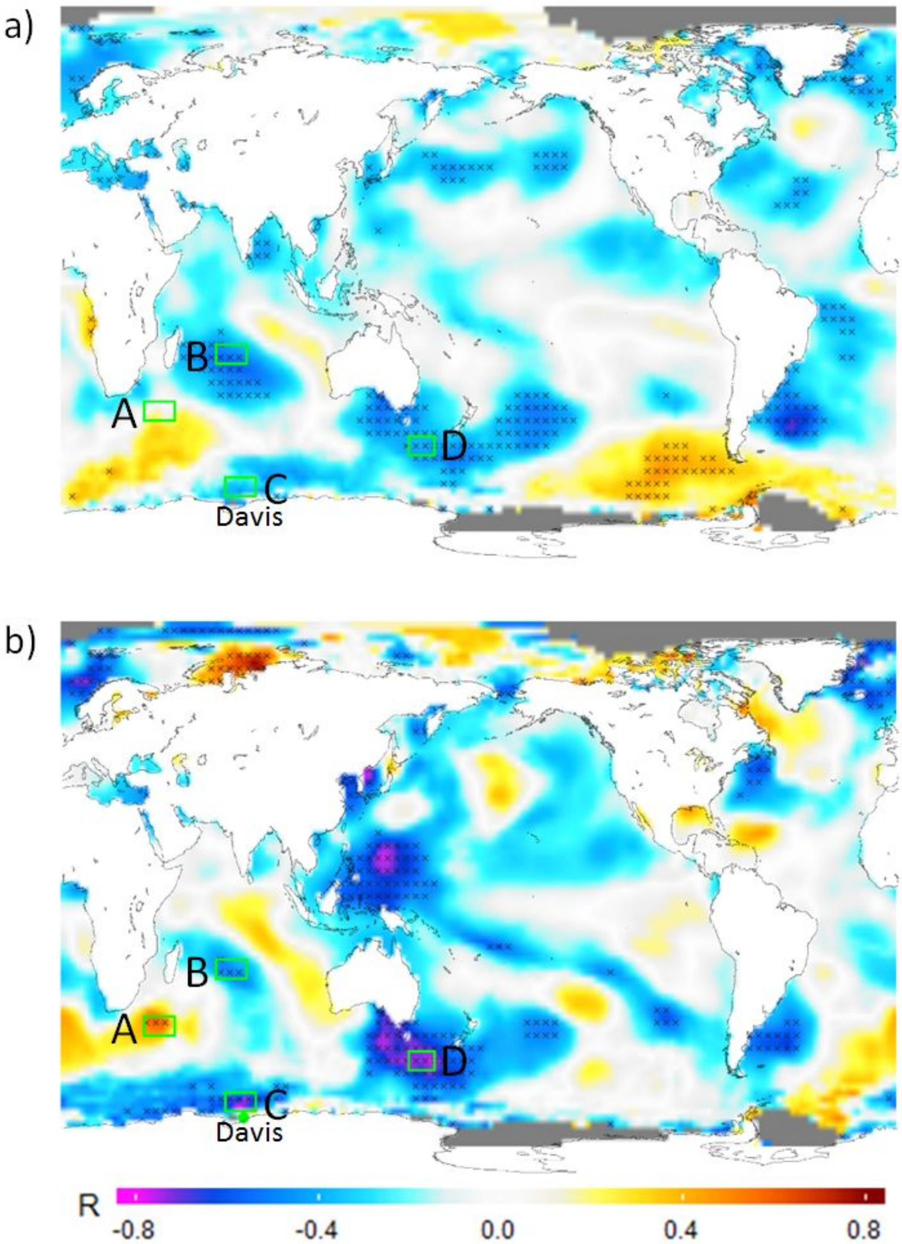




QQO Cold years <33%
QQO Mid years 33−67%
QQO Warm Years >67%
1hPa
(m)
100
50
0
−50
−100
10hPa
(m)
50
0
−50
50hPa
(m)
50
25
0
−25
−50
200hPa
(m)
30
20
10
0
−10
−20
−30
750hPa
(m)
30
20
10
0
−10
−20
−30

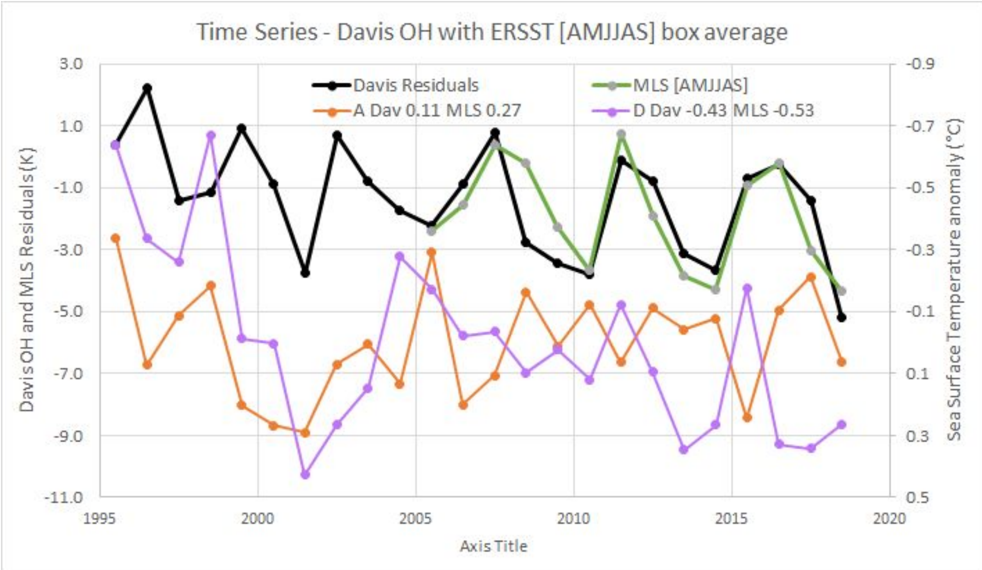
5) Fig.5: Please give a time series for SST (near to Davis)!

The correlation analysis in Fig 5a does not show, and we do not claim, a significant correlation of the Davis OH QQO signal with SST in the vicinity of Davis (region C). Instead, we note in the text that the “strongest and most consistent patterns of anti-correlation (QQO warmest for below average SST) for the two epochs occur at mid-latitudes in the south-western Pacific Ocean (to the south of Australia and New Zealand, region D), in the south-western Atlantic Ocean (near the east coast of South America), and in the west-central Indian Ocean (to the west of Madagascar, region B). Significant positive correlation is also seen at mid-latitudes south of Africa (region A), and for the longer-term Davis data set, in the south-eastern Pacific Ocean.”

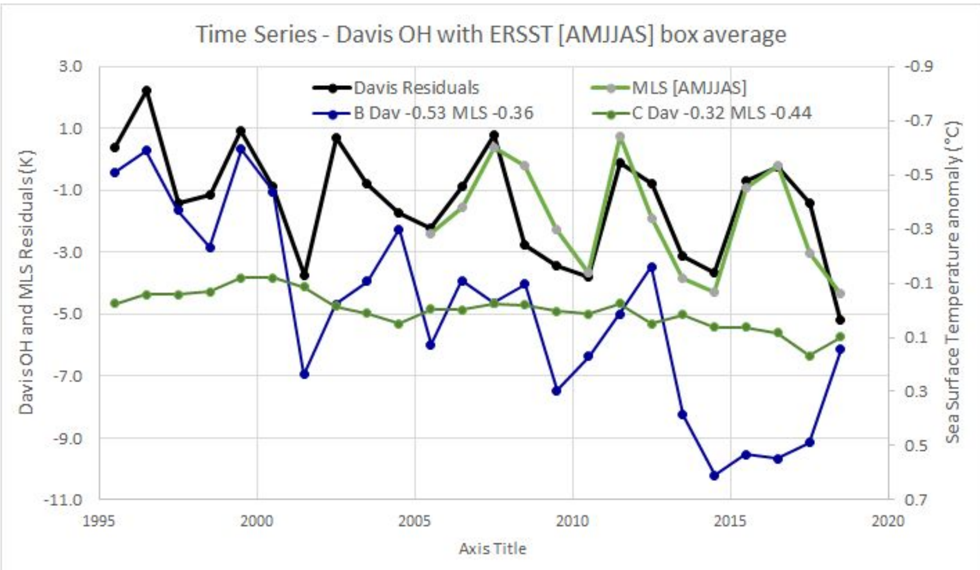


We have plotted below timeseries of SST anomaly compared to the Davis OH residuals and Aura/MLS residuals for the mean within the green bounding boxes A,B,C, and D above.

Correlation coefficients for Davis (Dav) and Aura/MLS (MLS) are provided in the legend text. This figure shows the positive correlation with region A and the negative correlation with region D

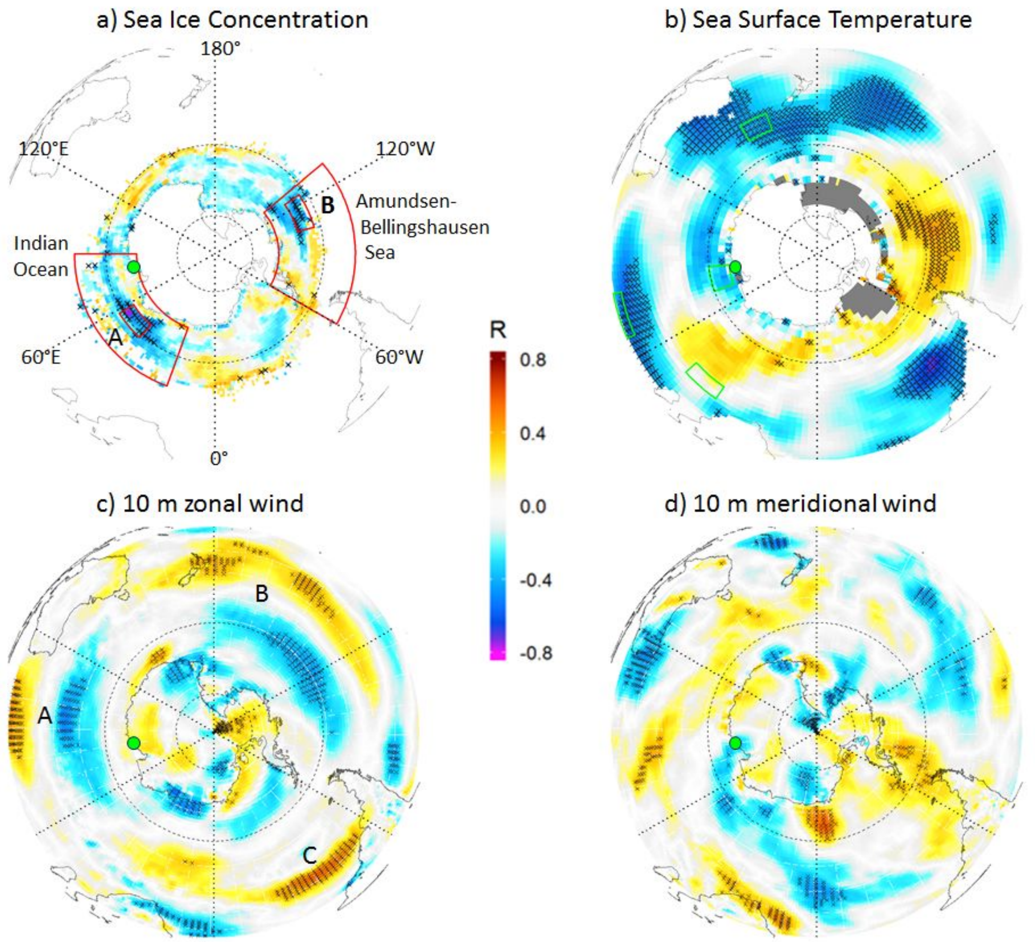


This figure shows the negative correlations with regions B and the vicinity of Davis region C. Note that the latter is largely sea-ice during the AMJJAS months.

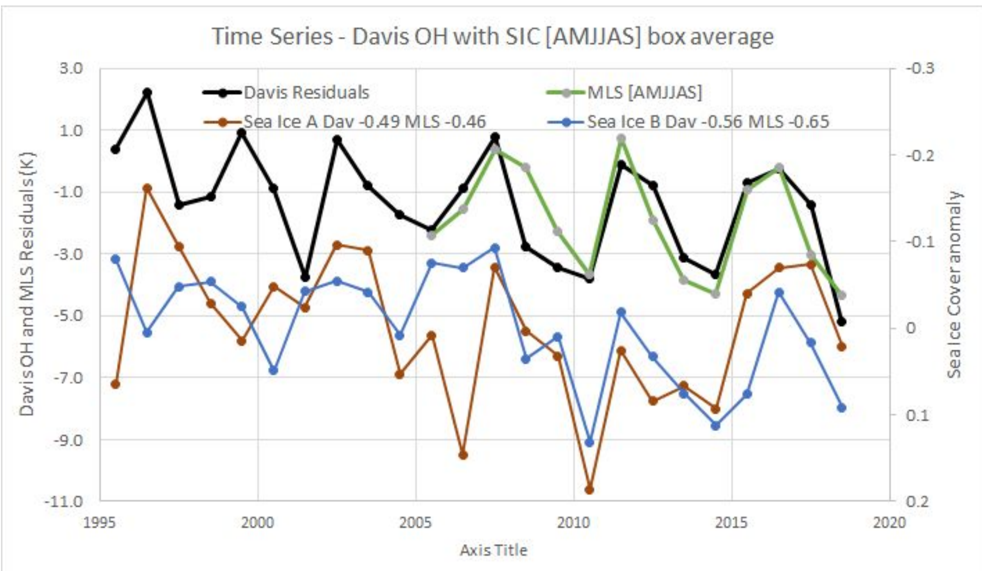


6) Fig. 6: Please give time series!

Figure 6 has been modified to improve significance plotting and time-series of the two regions of significant correlation (identified as A and B in figure 6a have been provided below.



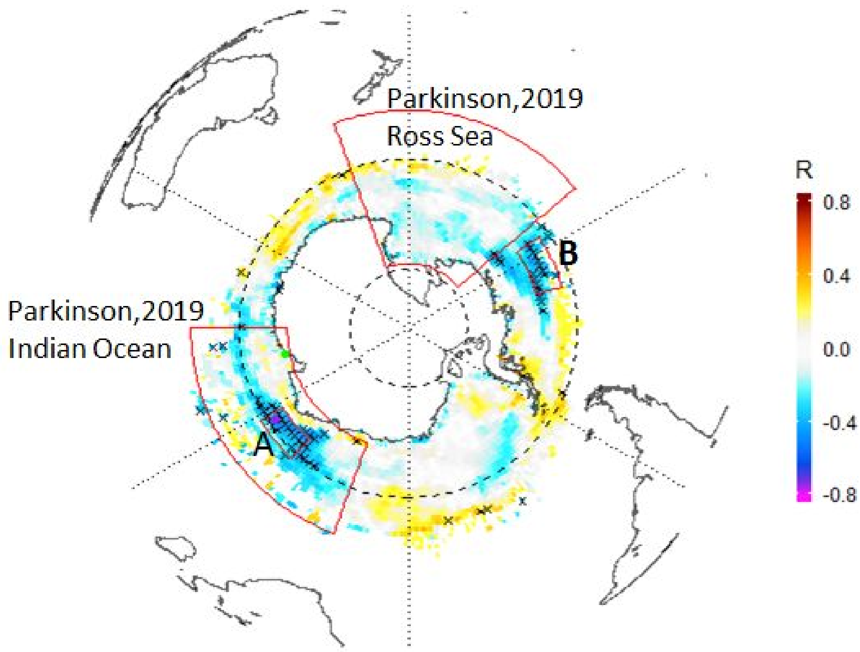
Time series for A and B regions of maximum anticorrelation are provided below (correlation coefficients provided in the legend). Note the inverse sea ice cover axis.

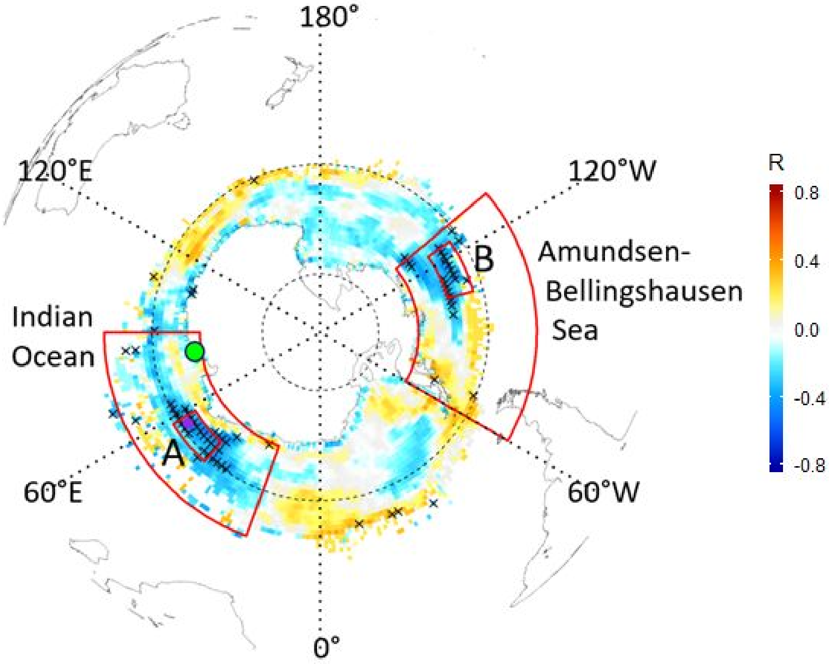


7) Section 4.1: I understand that the authors are interested in showing a conection between SST and sea ice, and the upper atmosphere QQO. However, Sect.4.1 is not really suitable for this. The correlations discussed are marginal or non-existent (L387: R = -0.09 is not a correlation). The text refers to many literature papers that one would need to read in order to understand the text. Finally, correlation of a parameter below the tropopause with one above the tropopause is generally a delicate business, as is, for instance, indicated by Fig.3, 4. Altogether, a much mor extended analysis would be needed, as the authors state by themselves. As this is beyond the scope of this paper, I recommend to summarize this Section in a few sentences or omit it, at all.

We have moved this section to Section 4.4 to provide better flow in the discussion. We have also added text to better describe the motivation for this section. It is not that we are interested in showing a connection but rather, we note that there are regions in the sea ice zone that are significantly correlated with the Davis QQO variation (regions A and B below) that appear to have a wave-2 structure. We propose that both the upper mesosphere and sea ice may be responding to a common driver and suggest that possibly the meridional winds could drive both observations ie “a persistent northward (southward) flow on one side of a circulation anomaly could increase (decrease) sea ice due to the associated flow of relatively cold (warm) air from higher (lower) latitudes and expansion compaction) of the ice edge.

As shown in Fig 6a, specific regions of significant correlation between the Davis OH temperature record and sea ice concentration occur (regions A and B below). On this map, we have added values for the local maxima and minima of the correlation coefficient where these values are significant. ie region A -0.49 and region B -0.56 (see response to item 6 above) The maximum anti-correlation is -0.61 at 55.5°E, 61.5°S (within region A, marked with purple dot)



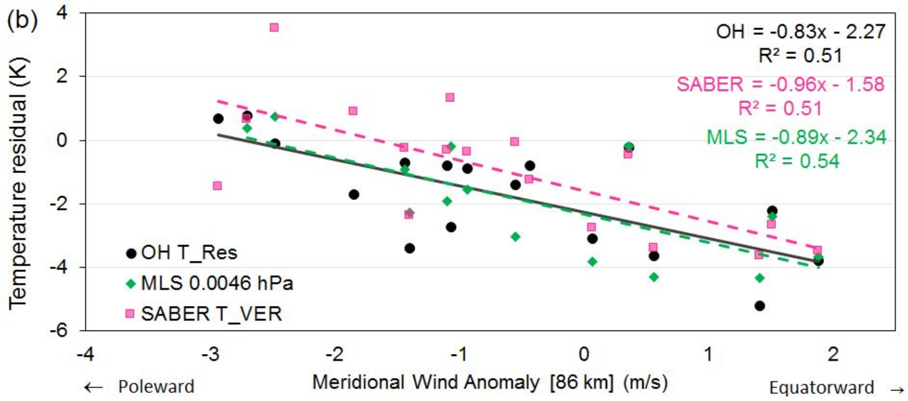


The correlation given at L387 the reviewer is referring to (R = -0.09), is the coefficient of the correlation between the time series of sea ice anomaly for a large sector of the Ross Sea region from Parkinson et al. (2019) and the Davis OH residual. We have compared with Parkinson et al (2019) because this reference provides a recent assessment of sea ice trends in various sectors of Antarctica.From the plot above it is clear that the Ross Sea region is not well correlated compared to regions A and B. Instead of the Ross Sea region, we now compare with the Amundsen-Bellingshausen sea region used by Parkinson (2019). The correlation is more negative (R=-0.24) but not significant. We have restated the sentence starting at L386 to better convey that there is no significant correlation for this particular region.

8) Section 4.3, L444pp: Obviously, the data of Dyrland and of Espy are Northern Hemisphere data. How does this compare to your SH results? Can you give a picture?

The table below shows a comparison of the Dyrland et al. (2010), and Espy et al. (2003) values to the results obtained here. As noted in the comment, the data in Dyrland et al. (2010) are from the NH (78 N), but the data in Espy et al. (2003) are from the SH (~68 S). Northward wind is positive; at both poles, poleward flow results in warmer temperatures. Figure 3 in Espy et al. (2003) and Figure 3 in Dryland et al (2010) show correlation plots similar to Figure 7(b) in this work. A reference to earlier work by Garcia and Solomon (1985) has been added in response to a comment from referee 2.

Reference	Location	Cofficient of linear regression (temperature to meridional wind) (K/m·s^{-1}) (Northward wind is positive; at both poles, poleward flow results in warmer temperatures)	Correlation coefficient
Espy *et al*. (2003) (Fig. 3)	Rothera (67.6°S, 61.8°W)	-0.71	-0.61
Dyrland *et al*. (2010) (Fig. 3)	Longyearbyen(78°N, 16°E)	+0.50	0.71
This work			
OH(6-2) T_Residual	Davis (68°S, 16°E)	-0.70 ± 0.25	-0.56
MLS T(0.0464 Pa) Residual	Davis (68°S, 16°E)	-0.89 ± 0.24	-0.73
SABER T_VER Residual	Davis (68°S, 16°E)	-0.96 ± 0.24	-0.71



9) Section 4.4: CO is an important parameter, and its analysis is interesting. However, the correlation R^2 = 0.13 at 14 datapoints is barely significant.

The square of the correlation coefficient was incorrectly stated as 0.13; it should be 0.19 (as rounded to 2 significant figures) and thus explaining 19% of the variance.

10) L483: Do you mean concentrations or mixing ratios in the text and figures?

As noted at L473 and the caption to Figure 8 and 9, we use CO mixing ratios, with units in ppmv (parts per million by volume). We have clarified the reference to CO at L483 in terms of mixing ratio.

11) Fig.9a, L493pp: I could detect the “crosses of significance” only if I used a strong magnifying glas.

We have improved Fig 9 so that a magnifying glass is no longer required to detect the crosses of significance. The correlation scale is common and applies to all panels so only one scale is now shown.

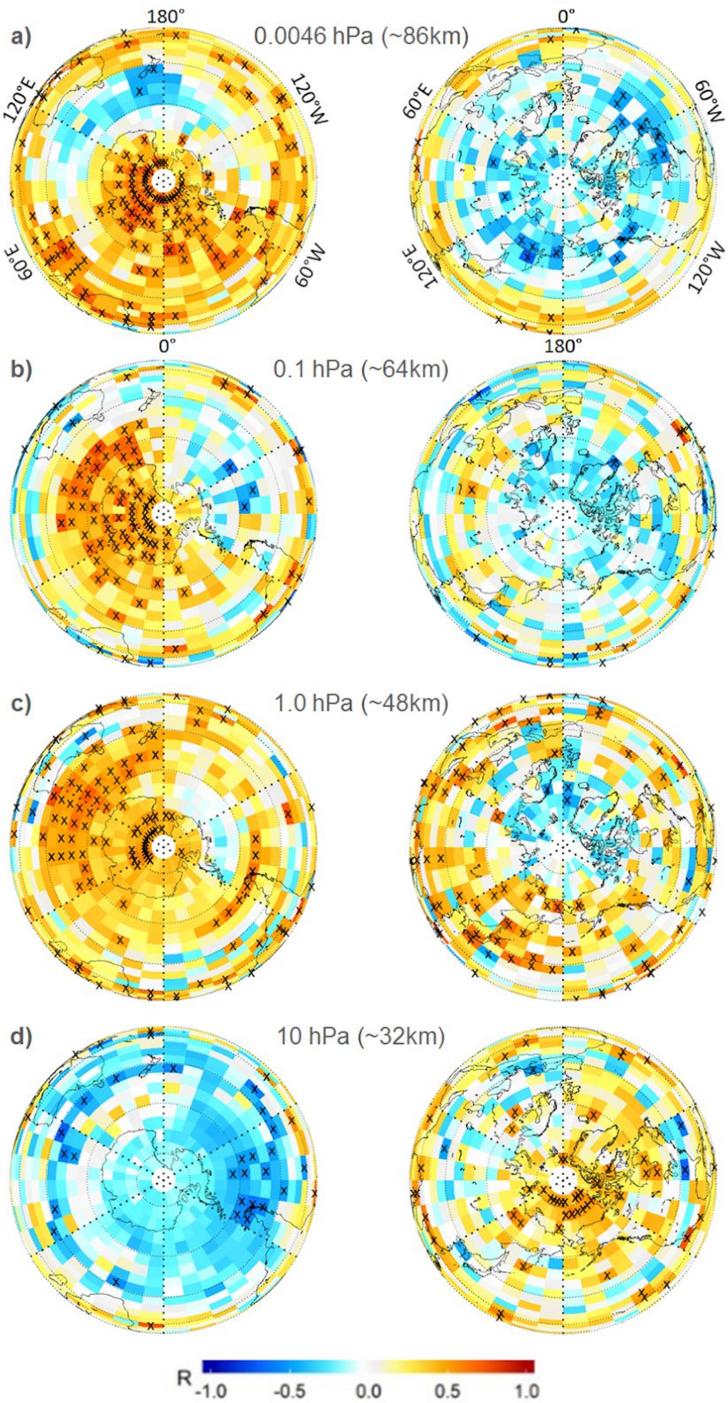


Figure 9

12) Sect.4.5; Lines 507, 510: If you omit two or four data points from a series of fourteen, the resulting conclusions are very dubious. Please phrase more cautiously!

Section 4.5 has been substantially modified to *'suggest'* the phase and amplitude relationships between summer and winter NH and SH QQO variation given the data set only spans 14 years. We can only base our interpretation on the data available but believe it is worthwhile examining the SH/NH and winter/summer seasonal comparison. The observations drawn from this comparison that the QQO amplitude appears to be larger in summer than in winter (in both hemispheres), and that the NH (summer) is the opposite phase to the SH we dont believe are overly dubious.

13) Lines 529, 530: Apparently, WACCM does not detect your QQO, either! Why then show this Section 4.6?

As we state in section 4.6 “Our interest here is to see if the model physics produces a QQO response in the mesosphere” and have added “particularly as Offermann et al. (2015) had noted that the CESM-WACCM model showed low-frequency variability in temperatures on 3-6 year timescales over Middle Europe”

If WACCM did show a statistically significant QQO it could be explored and understood through the model mechanism. The fact that it shows a sporadic or not statistically significant response implies a limitation of the model. We have added further text to refer to time-period spectra for each ensemble at three pressure levels - these spectra are shown as Fig. S8 in the Supplementary Material.

14) L 610-612: This is a misunderstanding: The periods cited are from the Duffin oscil- lator which is a non-linear oscillator in the ocean. However,the oscillations discussed by Offermann et al., 2015, are intrinsic in the atmosphere! These authors state that their results are not in contradiction to other authors who reported solar cycle harmon- ics. They note, however, that it is difficult to disentangle these two types (Section 6.2, last paragraph in that paper).

Lines 610-612 refer to the association by Offermann et al (2015) of the periods they found in their data with similar periods found in GLOTI data and the NAO index. The only point we wish to make here is that the QQO found in the Davis data has similarity to the periods reported by Offermann et al (2015). We have rephrased the sentences referring to Offermann et al.(2015) in an attempt to clarify the point.

15) Summary, L 626pp: Please state clearly, that the Davis data are winter data, and that summer values are lacking. Fig.10 shows that there may be large differences!

We have specified ‘winter average’ throughout the summary and conclusions section to make this point clear. In general, the fact that the Davis data are winter measurements is stated explicitly in the Abstract, Introduction, Data sets (section 2.1) and with reference to the months [AMJJAS] for comparison with Aura/MLS, SABER and other data sets. Section 3 and in the discussion in section 4.

Minor Comments

1) Line 38: relationship is suggesting

Changed to ‘suggests’

2) L 50: French et al., 2020

Corrected all occurrences referring to Part 1 of the paper.

3) L 80 : including high

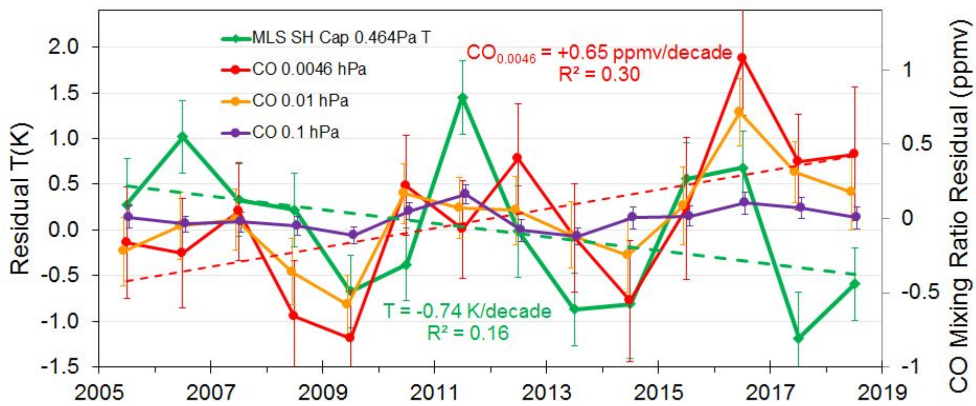
removed ‘at’ as suggested

4) Fig.3 – 5 : Please indicate location of Davis.

Davis location has been added to Figs 3-5

5) Fig.8: Please give error bars.

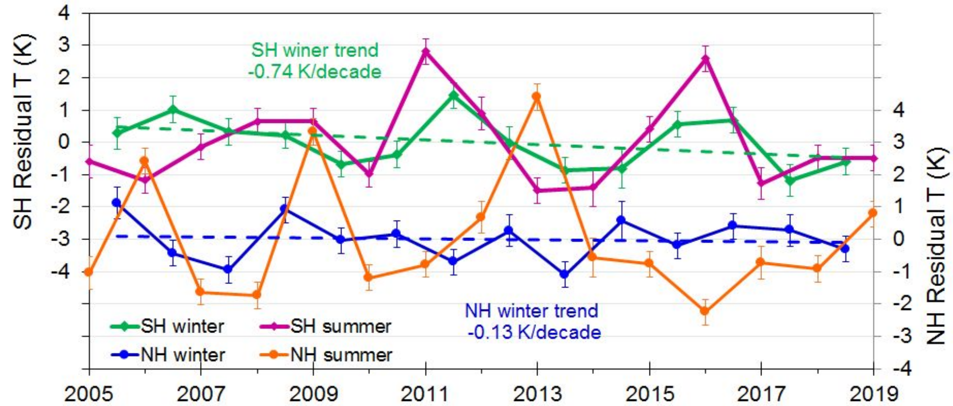
Error bars have been added to Fig 8



6) Fig. 10: Please give error bars. Orange and red lines difficult to distinguish!

Added error bars, modified trend line colors and separated SH from NH to improve visibility. Corrected NH winter trend value.

New



Old