Dear editor,

Please find enclosed our point-by-point response to the referees (they are the same as uploaded as Author Comments (AC1 and AC2)). They contain the referees' comments (in blue) and our replies to their questions and, if appropriate, information on the relevant changes introduced in the revised version the manuscript (in black).

After the point-to-point response, you will find the revised version of the manuscript and the supplementary material with all changes highlighted in blue (added text) and red (deleted text) colors.

Best regards,

Blanca Ayarzagüena and co-authors.

Review of 'On the representation of major stratospheric warmings in reanalyses' by Ayarzagüena et al. (2019)

This paper has examined how different features of SSWs (e.g., magnitude, precursors, surface impact) vary across different reanalysis datasets in both the historical period (1958-1978) ad post-satellite era. The authors have also examined the differences in features between wavenumber 1 and wavenumber 2 SSWs. The paper is overall interesting and is a valuable contribution to the literature; using historical data back before 1979 will be useful for the SSW community and this study suggests that despite the discrepancies between the pre and post satellite era data, the characteristics of SSWs in different reanalyses act fairly similarly. All of my comments below are minor and hence I suggest only minor revisions.

Thanks for your comments. They have been very useful and have improved our manuscript.

One thing to note is that this review was not so convenient to write because of the line numbering. I have included a line number and a page number for each comment as it appears that the numbers ran to 35 before restarting over again continuously!

We apologize for this inconvenience. Before the submission we did not realize that the word template had set up by default the line number restarting at each page. We have fixed this problem.

Specific Comments:
Line 20; Can you just confirm whether by the 'surface fingerprint', you mean either the downward impact following the SSW, or the near-surface precursors?
We mean the downward impact after the SSW. We have replaced "fingerprint" for "response" to clarify it.

Lines 30-32; It is worth mentioning here that SSWs are not always preceded by precursory wave activity in the troposphere (most recently for instance, Birner and Albers 2017, SOLA; White et al. 2019, J.Clim both found that ~30% of SSWs are preceded by lower tropospheric wave activity in observations and in a GCM, respectively). I don't mean for you to go into details regarding this, but it would be good to mention that sometimes the source of the anomalous wave activity is in the stratosphere.
Thanks for the suggestion. First, we would like to indicate that we were not referring to an enhancement of lower tropospheric wave activity in this part, but just tropospheric wave activity at any level, in the upper troposphere too. Nevertheless, we acknowledge that recent studies have shown that the enhancement of wave activity often happens within the stratosphere and/or is related to a preconditioning of the mean stratospheric flow. We have included a comment about this in the introduction section (new Lines 32-34)

Another good citation to add would be Garfinkel et al. (2010), J. Clim who found that a deepened Aleutian Low leads to enhanced upward wave-1 flux. In this part of the text you have only mentioned about blocking highs preceding SSWs, when many SSWs are preceded by such an anomalously-deep Aleutian Low.
Thanks for the suggestion. In the original version (Section 4.2), we already referred to the anomalously deep Aleutian low as a precursor of SSWs and included Garfinkel et al (2010)'s citation. In the revised text, we have also mentioned it in Line 36 of the Introduction.

Line 9, page 2; this line suggests that all SSWs impact the tropospheric circulation when in reality, not all do, and only in the composite mean is there an aggregate impact. It would be better to make this clearer.
We have included some clarifications about the uncertainty about the tropospheric response to SSWs in new lines 45-48.

Lines 9-12, page 4; How are SSWs in each reanalysis determined to be 'common'? What is the time window around the actual SSW date in one reanalysis for which an occurrence of a wind reversal in another reanalysis is deemed to be the same date? You just mention here that four out of seven reanalyses in the common period must show the same SSW event; but, how is the same event determined?
The list of common SSWs has been provided by Amy Butler via the S-RIP initiative (https://www.sparc-climate.org/activities/reanalysis-intercomparison/). For that classification, the events were first individually identified in each reanalysis based on the reversal of the zonal mean zonal wind at 60ºN and 10hPa from November to March, and additional restrictions to ensure the independence between events and the exclusion of stratospheric final warmings (Charlton and Polvani, 2007). Secondly, the number of reanalyses that identify

an event around the same date was determined. It was not necessary to impose any condition to determine whether events detected by different reanalyses were or not the same, because the spread across reanalyses in the dates of SSWs is very small (typically within one or two days). Only an event in the historical period (17 December 1965) showed a difference of more than a week between NCEP/NCAR and the other two historical reanalyses (JRA-55 and ERA-40). In that case, the date of the common event was computed as the average of the dates for the latter reanalyses (those with more vertical levels in the stratosphere) (Chapter 6 of S-RIP initiative). Finally, common SSWs are those identified by at least two of the three reanalyses in the historical period and by at least four out of seven reanalyses in the comparison period. We have clarified this in the new version of the manuscript (lines 116-118).

Line 25, page 4; Can you be clearer here? It is not immediately clear how you chose the common SSWs to be either D or S here. Did you check each common SSW in each renalysis and then determine if the majority of reanalyses showed either a D or an S? Or was there some other way?
Yes, it was exactly done as the reviewer indicated. Again this follows the S-RIP initiative guidelines. We have clarified it in the text (lines 134-137).

Line 27, page 4; how sensitive are the results to different levels and latitudes? A sentence or two would be good to describe the sensitivity. Also, was the 200m difference threshold arbitrarily chosen?
The methodology applied here corresponds to that described by Barriopedro and Calvo (2014), which is based on the algorithm previously presented by Bancalà et al (2012). The latter used data at 10 and 50 hPa, while Barriopedro and Calvo (2014) used the 50 hPa level only because: i) this level is close to that of the maximum amplitude of climatological WN2 and not far from that of WN1; ii) some reanalyses (e.g. NCEP/NCAR) have their model tops at 10 hPa, which may introduce artificial biases. Still, Barriopedro and Calvo (2014) already compared their classification with that by Bancalà et al (2012) and obtained very similar conclusions, suggesting that the method is not too sensitive to the chosen levels. This is also supported by: i) the time evolution of composites of the WN1 and WN2 components of anomalous heat flux for WN1 and WN2 SSWs, which show similar signatures at 10 and 50 hPa (Fig. R1.1); ii) the robustness of the SSW classification across reanalyses (in contrast to most algorithms that classify D and S SSW events).

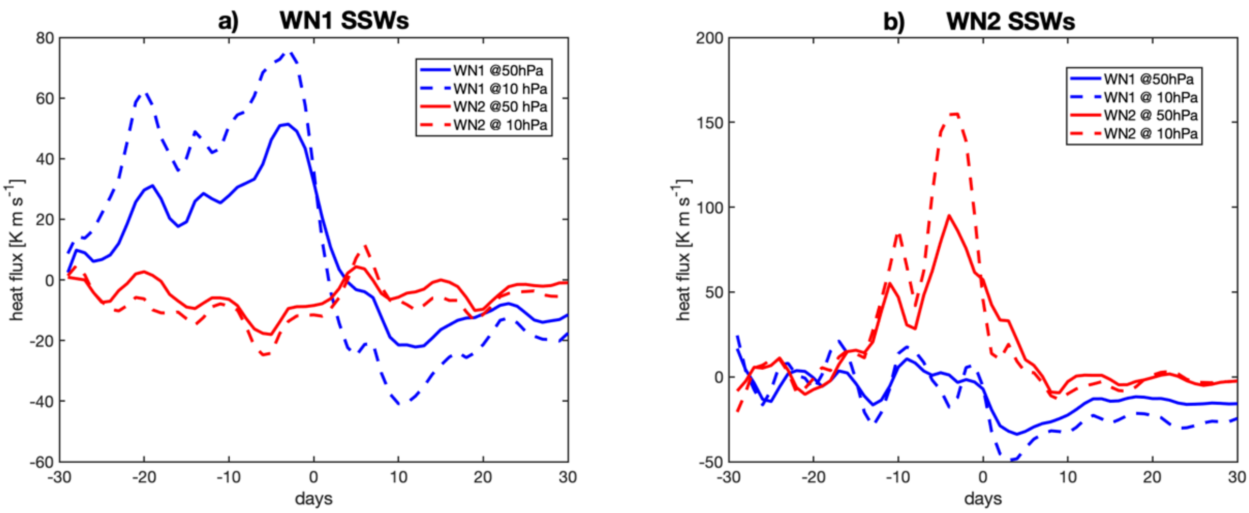

Figure R1. 1. (a) Time evolution of MRM of WN1 (blue) and WN2 (red) component of anomalous heat flux (K m s^{-1}) at 50hPa (solid line) and 10hPa (dash line) from -30 days to 30 days after the occurrence of WN1 SSWs. (**b)** Same as (a) but for WN2 SSWs.

Regarding the sensitivity to different latitudes, both studies used 60ºN for the classification of WN1 and WN2 SSWs. This latitude band is close to the maximum amplitude of both climatological WN1 and WN2 waves (Fig. R1.2), and it is also where the reversal of the zonal mean zonal wind is computed for the identification of SSWs.
As for the threshold of Z_2-Z_1, it was not chosen arbitrarily. The 200 m corresponds to the 90th percentile of the difference of WN2 minus WN1 components of the geopotential height at 50 hPa, as indicated by Barriopedro and Calvo (2014).

Given that this is a published algorithm, and it has also been included in the ongoing S-RIP report, we have decided not to provide more information in our manuscript. Nevertheless, we have now explicitly referred to Barriopedro and Calvo (2014) for more details (lines 142-143).

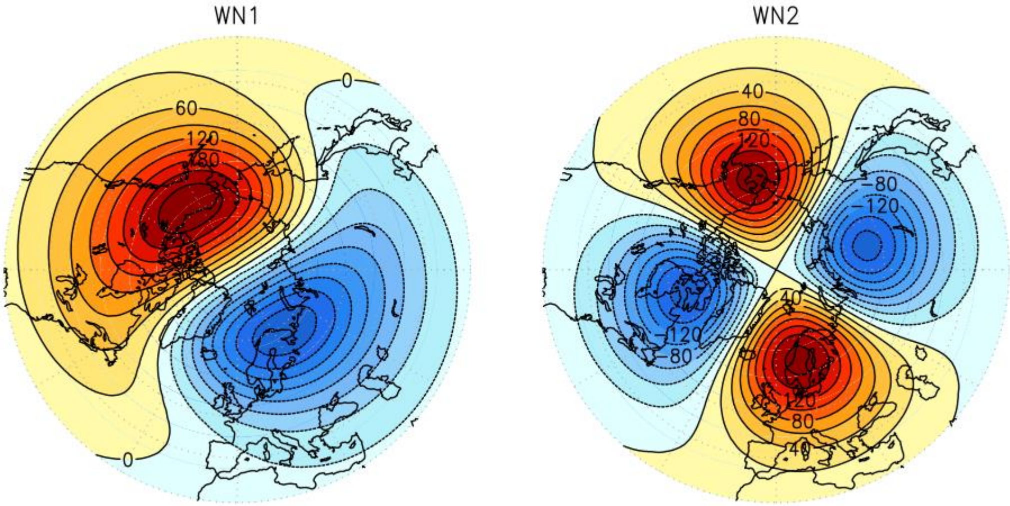

Figure R1. 2: (a) Multi-reanalysis mean of the climatological WN1 component of geopotential height at 50hPa in January and February (Contour interval: 30m). (b) Same as (a) but for the climatological WN2 component (Contour interval: 20m).

Line 1, page 7; can you better explain how these histograms are calculated? It seems to me that for each date on the x-axis you take a 21-day window (centred on that date), and count how many SSWs occurred in that window. You then moved on to the next date and did the same. Is this correct? If so, it seems to me that by doing this, SSWs are counted multiple times and the histogram may not be a fair representation. What happens when this window is shortened from 21 days? Shortening the window length will no doubt be a more accurate way to do this. Just creating bar charts of the #SSWs in each month would be a fairer and less-ambiguous representation and then just compare the distributions.

Yes, the procedure described by the reviewer to create the seasonal distribution of SSWs is correct. Additionally, a 10-day running mean was applied to smooth the distribution. Similar approaches have also been used previously (e.g. Gómez-Escolar et al. 2012). We have explained more carefully the way we computed this seasonal distribution of SSWs (lines 203-205).

We do not totally agree with the reviewer on the use of a monthly histogram of SSWs. The histograms are very useful for giving a brief overview of the monthly frequency of SSWs. However, in our specific case we think that it makes more sense the use of consecutive bins that overlap to build the distribution. The total mean frequency of SSWs has already been shown in Table 2, and in this part of the study we are not interested anymore in the exact number of SSWs but in their distribution along winter. In particular, we would like to know if reanalyses present important differences in their distributions, i.e. if the SSWs captured by each reanalysis correspond to the same events in the other datasets. In this sense, the division per calendar months is somehow arbitrary and might lead to artificial differences between reanalyses. For instance, if a SSW occurred by the turn of a month, it might be detected on the very first days of a month in some reanalyses and on the very last days of the previous month in other datasets. As such, the typical monthly histogram would prevent from knowing if they are the same event or not. This problem is avoided with our approach. Gómez-Escolar et al. (2012) already showed that the bimodal distribution of SSWs could be missed in monthly histograms.

Regarding the sensitivity of results to window width, we have shortened this window as suggested by the reviewer. For instance, Figure R1.3 presents the same distribution but for 11-day windows (± 5 days). We also include in Figure R1.4 the results for a 21-day window to enable the comparison of results herein. We can see that the main conclusions do not change. We still detect the shift of SSWs to a later date in the comparison period, the good agreement between reanalyses in that period and the closer resemblance of distributions between ERA-40 and JRA-55 than between any of these two and the NCEP-NCAR reanalysis in the historical era. Despite the agreement in results, we prefer to keep the 21-day window width (± 10 days), because it is closer to a month and so, it makes easier to identify the main peaks of SSWs in each period than a shorter window.

Please also note that Figure 2 has been slightly modified in the revised manuscript as we now represent the number of SSWs per decade instead of the total number of events. Although the shape of the distribution does not change, it allows a more straight-forward comparison of results between the historical and comparison periods, which have different lengths.

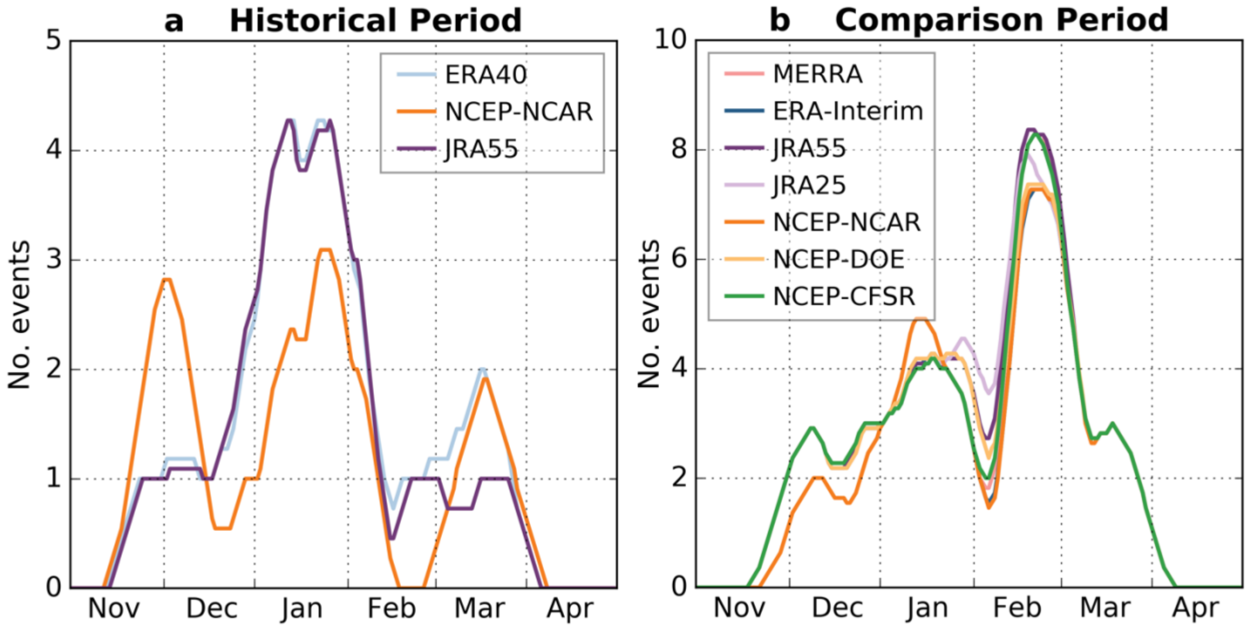

Figure R1. 3: SSW total frequency distribution within ±5 day periods from the date displayed in the x-axis for: (a) the historical period (1958-1978) and (b) the comparison period (1979-2012). Time series are smoothed with a 10-day running mean.

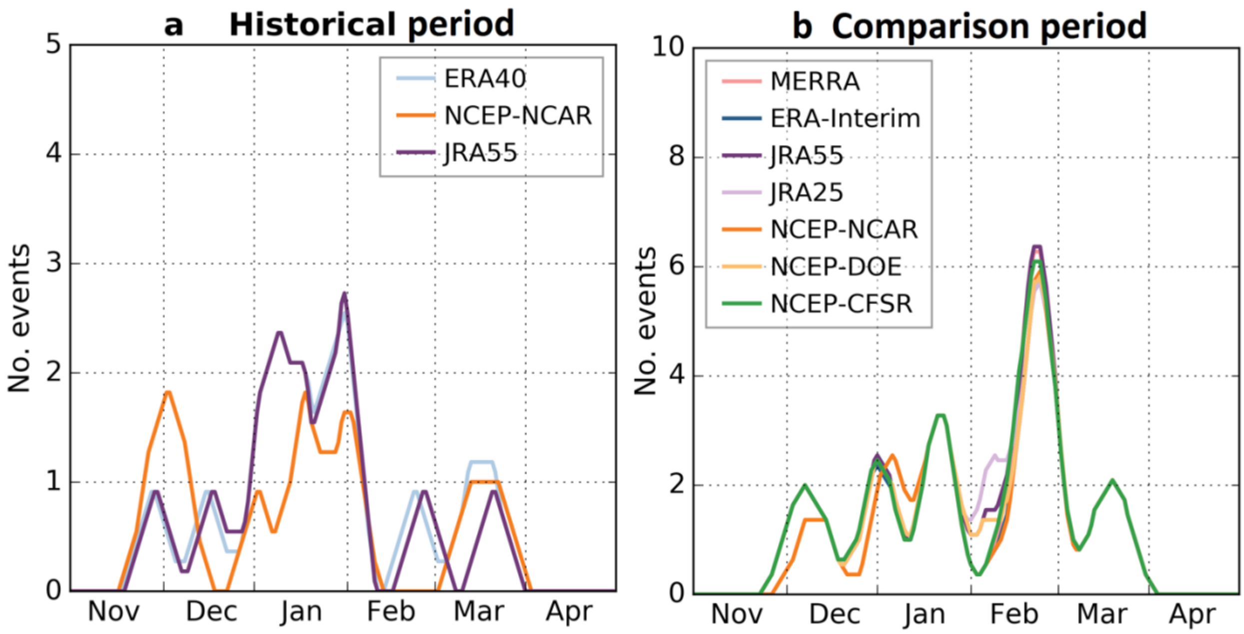

Figure R1. 4. Same as Figure R1.3 but SSW total frequency distribution within ±10 day periods

In terms of the histograms, it would be useful to test the significance between the individual histograms using a Kolgomorov-Smirnov test. My guess is that they are significantly different in (a), but not in (b).
We have applied a two-sample Kolmogorov-Smirnov test. As the reviewer expected, the distributions of SSWs in the comparison period are indistinguishable between each other and statistically significantly different from those in the historical one at the 99% confidence level. In contrast, in the historical period the NCEP-NCAR distribution is significantly different from those of JRA-55 and ERA-40 ($p < 0.01$) according to the same test.

The SSW distribution of JRA-55 and ERA-40 are still indistinguishable in this period. The same results are found when shortening the time window of the distribution to 11 days.
We have included this information in the manuscript (lines 206-209 and 219-220)

Line 14, page 8; how does the HF look below 100hPa? Say down to 300hPa? Are there any significant anomalies? Between 300hPa and 100hPa is the communication region for stratosphere-troposphere coupling that de la Camara et al. (2017) suggested to be particularly important. 100hPa is already in the stratosphere at high latitudes, and hence, 300hPa may be a better measure of the upward propagation of wave activity from the troposphere.
According to the reviewer's suggestion, we have repeated the analysis up to 300hPa. However, our conclusions remain the same given that the region with the strongest signal is above 100hPa. Nevertheless, significant values are also observed between 300 and 100 hPa in most cases supporting a stratosphere-troposphere coupling in the multi-reanalysis mean. In the revised manuscript, we have updated figures 4, 5 and 6 by extending them down to 300hPa.

Lines 23-24, page 8; This is an interesting result. Is the correct interpretation that prior to lag -5, the wave activity grows in the stratosphere via constructive interference with the climatological planetary waves, whereas from lags -5 to 0, anomalous wave growth occurs? I am wondering if this is indicative of the Plumb (1981), JAS idea of self-tuning resonance? i.e., a standing climatological wave and a transient anomalous wave interact constructively to give a growing-in-amplitude wave in the stratosphere? This wave then grows to very large amplitude and eventually splits the vortex. This is more of a probing statement, as I do not know for sure. But some interpretation as to why the earlier lags are dominated by the interference term and the lags closer to zero are dominated by the anomalous term, would be appreciated here.
We thank the reviewer for this comment. We prefer though not to include this reflection in the mentioned lines. The results that the reviewer is referring to correspond to Figure 5 where all SSWs of the comparison period are considered. However, when separating WN1 and WN2 SSWs (Fig. 6), we can see that their respective peaks of anomalous HF come from different dynamical forcings and occur in different timing. Whereas WN1 SSWs are mainly dominated by persistent but moderate anomalous HF originated from the constructive interference between anomalous and climatological planetary waves during 20 days, WN2 SSWs are preceded by a strong and short pulse of HF due to anomalous waves only in the last five days prior to the SSW onset. Thus, it does not seem that the mechanism suggested by the reviewer is clearly working for none of SSW types. Moreover, it seems that the suggested interpretation should be more likely true for the WN2 events than for the WN1 ones, as most of WN2 SSWs have associated a vortex split. However, in that case, we can only identify a strong anomalous burst of wave activity in the 5 days prior to the SSW occurrence.
Nevertheless, the reviewer's comment was very useful for us and has been used in the following Section 4.2 when discussing the tropospheric circulation anomalies preceding WN2 SSWs. The spatial coincidence of these anomalies and the anti-nodes of the climatological WN2 wave would suggest that the constructive interference in the troposphere is important prior to WN2 SSWs, even if the previous results on heat flux anomalies at higher levels rule out the relevance of the wave interference for these events. In the revised version (lines 312-317), we have tried to solve this apparent contradiction by including the idea of a self-tuning resonance of waves in the stratosphere as a result of a slight enhancement of tropospheric wave activity, probably due to the linear interference of waves. As shown by Albers and Birner (2014), this resonance would be more likely when the polar vortex is preconditioned in an initial structure close to its resonant point as it happens in the case of WN2 events.

Lines 12-13, page 9; How sensitive are the results in this figure to this lag window? I ask because the lag window you have chosen is based on figure 5 which only extends down to 100hPa. In figure 7 you present 500hPa. Do the significant HF anomalies below 100hPa extend further back in time to before lag -10? If so, then this would suggest increasing the length of the lag window.
As the reviewer indicates, the selection of the window (-10, 0) day was based on Figure 5 and in particular, the peak of anomalous eddy heat flux above 100hPa. When extending the new Figure 5 down to 300hPa, we see that the significant HF anomalies below 100hPa do not extend beyond lag -10, supporting our choice. In addition, we have repeated the analysis for two wider time windows: (-20,0) and (-15,0) days (Fig. R1.5 and R1.6, respectively), and the results do not change substantially.
Another point to highlight is that this 10-day window has been very commonly used in previous analyses of the upward branch of the troposphere-stratosphere coupling (e.g.: Martius et al., 2009; Nishii et al., 2011;

Ayarzagüena et al., 2015), as it corresponds to the approximate time that planetary waves take to propagate from the troposphere to the stratosphere (Limpasuvan et al. 2004).

Given that our main results are not sensitive to the width of the time window considered in Figure 7 and based on the previous literature we prefer to keep the (-10, 0) interval. Nevertheless, we have added a short comment justifying more in detail the selection of lag windows in the revised text (lines 297-299).

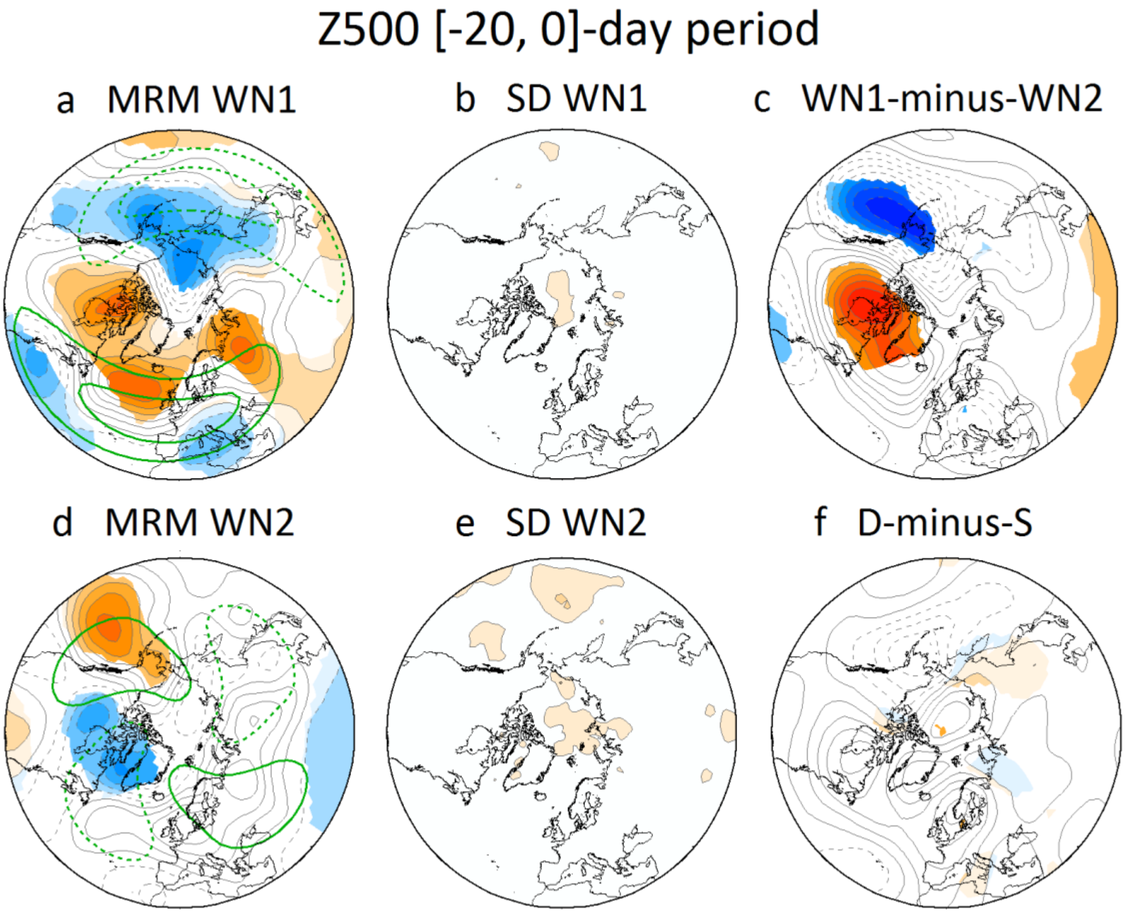

Figure R1. 5. (a) MRM of WN1 SSW-based composites of 500-hPa geopotential height anomalies (contour interval 20 gpm) in the [-20, 0]-day period before events for the comparison (1979-2012) period. Only statistically significant anomalies at the 95% confidence level of the same sign (Monte-Carlo test) in at least 66.7% of all reanalyses are shaded. (b) Standard deviation of the reanalyses with respect to the MRM divided by the square root of the number of reanalyses for WN1 SSWs (contour interval is 1 gpm). (c) Same as (a) but for the WN1 SSWs minus WN2 SSWs differences of MRM composites of 500-hPa geopotential height anomalies. Shading denotes statistically significant differences at the 95% confidence level in at least 66.7% of all reanalyses (Monte-Carlo test). (d) and (e) Same as (a) and (b) but for WN2 SSWs, respectively. (f) Same as (c) but for displacement-minus-split events. Green contours in (a) and (d) show the MRM climatological WN1 and WN2 of 500-hPa geopotential height from November to March, respectively (contours: ±40 and ±80 gpm).

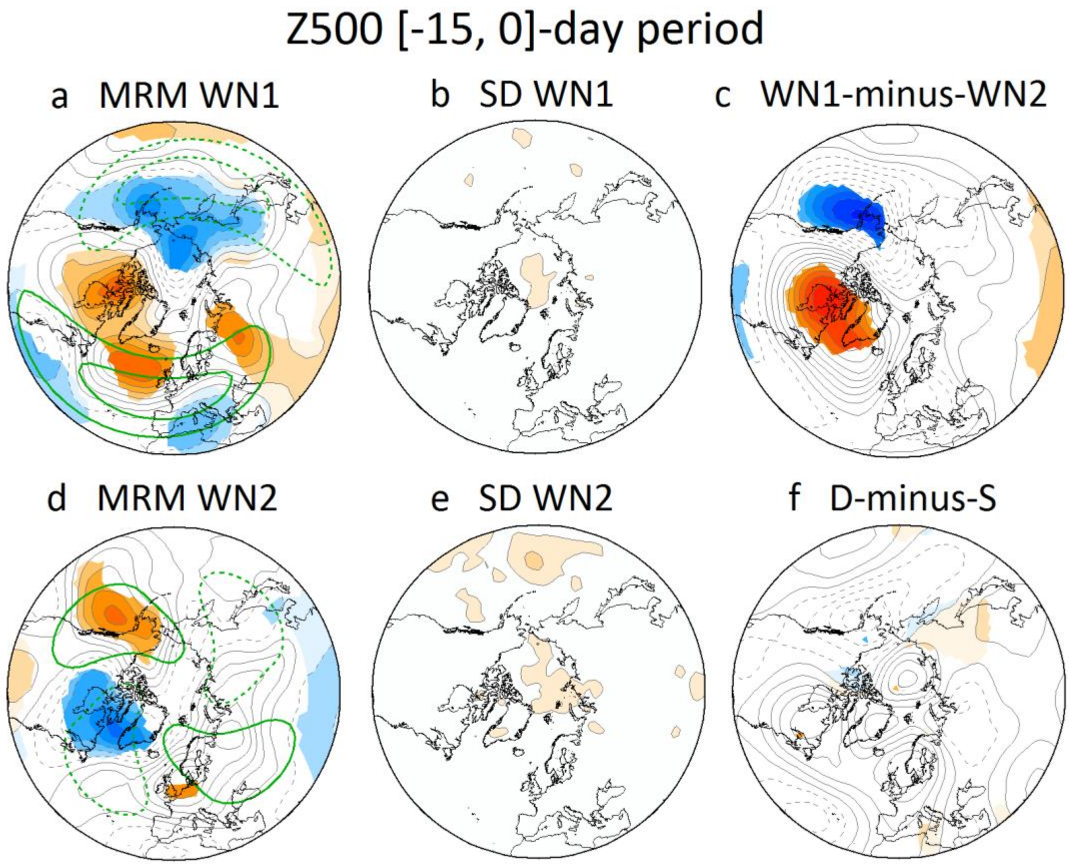

Figure R1. 6: Same as Figure R1.5 but for the period [-15,0]-day period before SSWs.

Technical Comments:
Line 26, page 2; what is the 'second one' here?
The post-satellite period. We have modified it.

Line 32, page 2; Here seems a good place to start a new paragraph when you start talking about the aims/methods of this paper.
It was actually a new paragraph, although it did not look like that. After the inclusion of a new word, the separation between the two paragraphs is clearer.

Lines 3-4, page 3 (top of page); I think you also examined the downward impact of S and D events, right? Unless you are classifying S and D, and WN1 and WN2 events as the same (although I don't think you are)
Yes, we have also examined the downward impact of S and D events. In the revised text, we have listed both classifications (which are independent).

Line 9, page 3; typo. I think you mean: 'The former analyses the momentum budget during SSWs…' or something to this effect!
Yes, we have corrected it.

Line 23, page 3; did you perform the interpolation yourselves? A sentence or two describing the method used would be useful - was it a simple linear interpolation? Or something more complex?
The models of the reanalyses included in the study have different horizontal resolutions and provide output on different grids. If the output on the 2.5ºx2.5º grid was available, we just used it. When this was not possible (only NCEP-CFSR and NASA-MERRA), we used the cdo tool remapcon that performs a first order conservative remapping of the input fields.
Both reanalyses perform very well when comparing with the rest of datasets, and given that we applied the same algorithm in the calculation, we do not think remapping has any effect on the SSW-related computations. We have briefly included all this information in the revised text (new lines 96-97).

Line 32, page 3; Just to clarify, the anomalies are calculated as the departure of the field from the daily climatology for EACH reanalysis? Or do you mean the anomaly from the daily climatology over ALL reanalysis products (i.e., away from the MRM)?
The anomalies are computed as the departure of the field from the daily climatology of each reanalysis. As we are assessing the performance of reanalyses related to anomalous fields, we think it makes more sense to compute the anomalies in each reanalysis as departures from its own climatology. In this case, any bias in the mean flow that does not contribute to the anomalous behavior is removed.
We have now specified "of each reanalysis" to make it clear.

Line 33, page 4; why is the 1981-2010 baseline used instead of the full 1979-2012 period?
This was one of the recommendations of the S-RIP initiative. It also corresponds to the period that NOAA is currently considering for computing the climatology, based on the WMO indications about the computation of climatological values from 30-yr averages (https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/climate-normals/1981-2010-normals-data). Moreover, this 30-yr baseline matches with the full 1979-2012 period, excluding only two years before and after.
Due to the shortness of the historical period, it was not possible to consider any 30-yr period and so, we used the full period as a baseline.
We have not included any clarification in the text since the 1981-2010 baseline is the typical period currently used in many studies.

Line 8, page 4; imposing --> requiring. Also, I think the Charlton and Polvani (2007) paper must be cited here! As this is, as I recall, the definition from their paper exactly.
Modified

Line 24, page 4; Perhaps better would be: '...with respect to the occurrence of an SSW, according to the definition in section 2.2'
Included

Line 4, page 6; 'two-folded' --> 'two fold'
Corrected

Lines 22-24, page 6; somewhere it should be mentioned that only the historical period is considered in figure 1.
We have mentioned it now when referring to the differences between reanalyses in the standard deviation of polar temperature and zonal wind at 10hPa (lines 211).

Line 6, page 7; What is meant here by 'traced back to the PNJ'? You haven't previously explicitly calculated the PNJ (which from section 2.4 I understand to be the difference in wind strength prior to and following the SSW central date). Are you here referring to the PNJ as just the strength of the U at 60N and 10hPa as shown in figure 1c? If so, then the PNJ as defined in section 2.4 needs to be better articulated.
Based on the reviewers' comments, we have modified the expression "traced back to the PNJ". In the revised version, we have only related the different SSW distribution to a different climatological PNJ for NCEP/NCAR and the other two reanalyses in the historical period.
Regarding the issue about the PNJ definition, there must have been a misunderstanding. In Section 2.4 we defined the deceleration of the PNJ during SSWs (decelu) as the difference in the strength of the zonal wind at 60ºN and 10hPa before and after the SSW, but not the PNJ itself, which should therefore be understood as the strength of the zonal wind at 60ºN and 10 hPa. .
To avoid confusion, a reference to the Figure 1c has been included in the text when mentioning the climatology of the PNJ (lines 214). We have also removed the acronym (PNJ) in Section 2.4, where we also mentioned decelu, as it could cause some misunderstanding.

Line 23, page 7; I think you mean to compare Fig 3,b,c with Fig 3,f,g?
Yes, thanks

Line 13, page 8; is this area-averaged? i.e., weighted by the cos(lat)?
Yes. We have included area-averaged.

Lines 23-24, page 8; 'precedent' --> 'preceding'.
Corrected

Line 28, page 8; Change to 'historical period'
Changed

Figures 4-6; Negative contours would be easier to identify if they were dashed rather than solid. This is particularly true if there is no significance (and hence no shading)!
Done

Figure 7, caption; Only gridpoints with stat sig values are shaded right? The contours are the full anomalies? If so, line 4 on page 25 needs to be updated (i.e., change 'plotted' for 'shaded') as it is not clear.
Yes, the reviewer is correct. We have corrected the caption.

Further, the density of anomaly contours is very high, especially considering that much of the plots are insignificant. Seeing as the WN1 and WN2 climatological centres of action are important in your description, it would be useful to put one or two contours (say, in green) for each centre on the plot. Hence, I suggest to reduce the density of anomaly contours and to just put a couple of contours representing the climatology, which should not clog up the plot.
We thank the reviewer for this comment. It has indeed improved the quality of Figure 7. We have realized that the density of anomaly contours in Figure 9 was also too high and have reduced it.

Line 21, page 9; 'MMR' is meant to be MRM?
Yes. Changed

Line 8, page 10; so the bottom row should equal the sum of the top two rows?
Not exactly. The bottom row of Figure 8 corresponds to a "climatology" of the mean blocking frequency prior to SSWs. This was computed as the mean blocking frequency in 1000 Monte Carlo trials of 11-day intervals preceding all SSW dates of the comparison period (note that the date of occurrence varies from case to case). In each trial, a set of 11-day intervals prior to the SSWs dates but with random years is averaged, so that we obtain a pseudo-climatology of the blocking frequency in the same winter periods as when the SSWs took place. This method avoids any effect of the seasonal cycle in blocking activity during the extended winter (NDJFM) that would affect the result. It also provides a fair comparison with the two top rows, which contain the same number and calendar chunks of the winter season as the bottom figure but with the actual SSW dates. The sum of the top two rows is expected to be different to the bottom figure, as there are not SSWs every year. The above description was already included in the caption of Figure 8 in the original version. We still prefer to leave this description in the caption. Inserting it in the main text would make the discussion of the results more tedious. Nevertheless, we have slightly modified the text to avoid the confusion highlighted by the reviewer (lines 331-333). We have also added a reference in the main text to the details given in the figure caption.

Further, are the units of the colorbar percentages?
Yes. We have specified the units in the text (line 328) and the caption of Figure 8.

Line 9, page 10; 'al' --> 'all'
Sorry, we could not find this typo.

Line 19, page 10; 'non-significant' --> 'insignificant'
We do not fully agree with the reviewer in this point. We are just applying a statistical test to determine the significance of results at a given confidence level, but this test does not mean that the result is not statistically significant at another confidence level. Moreover, although the result is not statistically significant, this does not imply that it is negligible or not meaningful in a physical sense. Thus, we prefer "non-significant" rather than "insignificant".

Line 7, page 12; 'but at much less extent' --> 'to less of an extent,'
We thank the reviewer for highlighting the mistake. We have corrected the expression to "to a much less extent".

Line 32, page 12, change to 'pre- and post satellite eras.'
We think it is correct as it is.

References

Albers, J. R. and Birner, T.: Vortex preconditioning due to planetary and gravity waves prior to sudden stratospheric warmings, J. Atmos. Sci., 71, 4028-4054, 2014.

Ayarzagüena, B., Orsolini, Y. J., Langematz, U., Abalichin, J., and Kubin, A.: The relevance of the location of blocking highs for stratospheric variability in a changing climate, J. Climate, 28, 531-549, 2015.

Bancalà, S., Krüger, K., and Giorgetta, M.: The preconditioning of major sudden stratospheric warmings, J. Geophys. Res., 117, D04101, doi :10.1029/2011JD016769, 2012.

Barriopedro, D., and Calvo, N.: On the relationship between ENSO, Stratospheric Sudden Warmings and Blocking, J. Climate, 27, 4704 – 4720, 2014.

Limpasuvan, V., Thompson, D. W. J., and Hartmann, D. L.: The life cycle of the Northern Hemisphere sudden stratospheric warmings, J. Climate, 17, 2584–2596, 2004.

Martius, O., Polvani, L. M., and Davies, H. C.: Blocking precursors to stratospheric sudden warming events. Geophys. Res. Lett., 36, L14806, doi:10.1029/2009GL038776, 2009.

Nishii, K., Nakamura, H., and Orsolini, Y. J.: Geographical dependence observed in blocking high influence on the stratospheric variability through enhancement and suppression of upward planetary-wave propagation, J. Climate, 24, 6408-6423, 2011.

REVIEW of "On the representation of major stratospheric warmings in reanalyses" by Ayarzagüena et al.

SUMMARY: This paper discusses the representation of SSW events in different reanalysis products. This is an important contribution given the increased use of SSWs for long-range prediction of surface quantities, which are often initialized from and compared against different reanalysis products. This is a timely contribution for the S-RIP project of comparing reanalysis products for the stratosphere.

OVERALL ASSESSMENT: The paper is well written and addresses an interesting and worth-while problem. I have some comments that I hope will improve the manuscript, see below.

We thank the reviewer for the useful comments that have contributed to improve the manuscript. Please see below our replies in blue color

SPECIFIC COMMENTS:
Page 1:
Line 22: "surface fingerprint": does this refer to the signature after the SSW event? Please specify.
Yes, it does. We have replaced "fingerprint" for "response" to clarify it.

Line 26: "lead to": this is not a causal effect, but effects that are linked through thermal wind balance
We understand what the reviewer means and it is true that both the vertical shear of zonal wind and the meridional temperature gradient are connected through thermal wind balance, so it is not easy to determine what is causing what. However, in the specific case of SSWs, changes in the meridional heat flux are the forcing that leads to changes in the wind. Moreover, in many SSWs it is the change in the polar temperature that precedes the maximum deceleration of the wind. Thus, we think the "lead to" is justified in this case.

Line 31 – 34: The literature is rather split about this issue, see e.g. Birner & Albers 2017, Sjoberg & Birner, 2014.
We agree with the reviewer that recent studies have already shown that the enhancement of wave activity prior to SSWs tends to happen within the stratosphere and/or is related to a preconditioning of the mean stratospheric flow. We have included a comment about this in the Introduction of the revised manuscript (new lines 32-34).

Page 3:
Line 12: "analyzes the SSWs the momentum budget": unclear
We have slightly modified the sentences to make it clear. The new sentence reads like this: "The former analyzes the momentum budget during SSWs restricted to the post-satellite period"

Page 4:
Lines 24 – 28: since K. Shibata is a co-author, it would help to clarify the algorithm used in the manuscript in case it's not (yet) published.
According to the reviewer's suggestion, the description of the algorithm has been extended in the new version (see new lines 128-134).

Page 5:
Line 25: anomalies from climatology?
Yes. We added "daily" to make it clearer.

Page 6:
Line 17: The deviation in the results of NCEP from other reanalysis products is not surprising. There's an artificial trend in the stratosphere – we found it in Badin & Domeisen, 2014 (pages 1498/1499). I could imagine there's also an S-RIP publication that documents this problem?
Thanks for the reference. Unfortunately, most of the S-RIP publications (or even earlier papers) that document the worse performance of NCEP/NCAR in comparison to the other reanalyses are focused on the post-satellite era (e.g.: Manney et al., 2003, Long et al., 2017). In contrast, in this part of the manuscript we are addressing the inter-reanalysis differences in the historical period. We are not aware of other S-RIP publications reporting this issue, and hence we have mentioned the artificial trend in the stratosphere found by Badin & Domeisen

(2014) in the first 50 years of the data record and related that finding to our results by the end of Section 3.1 (lines 214-217) and in the Conclusions (lines 389-390).

Page 6/7: I'm wondering if it would be helpful to list the classification for all events, not just the ones that are common

Thanks for the suggestion. However, we think it is not necessary for different reasons. First, as indicated in the text, most of the differences are more likely due to specific thresholds or methodological issues rather than relevant biases in the reanalyses. In addition, we are using this information in Table 2, as a brief overview of the reanalyses' performance when different events are considered based on fixed criteria. The remaining analyses in the manuscript are based on the events shown in Table 1. As the classification requested by the reviewer is a result of the SRIP initiative (to be included in Chapter 6 of the SRIP report), we have just added an additional reference to that chapter in Section 2 when talking about the classification of SSWs.

Page 7:
Line 8: "can be traced back to the PNJ": this does not sound like an explanation, rather a symptom

We have modified the sentence to avoid confusion. In particular, we have only related the NCEP/NCAR peak of SSWs in early winter to a weaker climatological PNJ in this reanalysis than in the other two.

Lines 15/16: given the large uncertainties in the pre-satellite period this is difficult to state. However, there are indeed changes in decadal variability of SSW frequency in Domeisen, 2019, JGR, maybe this is helpful?

Yes, it certainly helps. We have included the reviewer's comment and some references to previous studies that reported a multi-decadal variability of SSW frequency (including Domeisen 2019). Multi-decadal changes in SSW frequency could also translate to the intra-seasonal distribution of SSWs. Indeed, in the new version of the manuscript, we have confirmed that the SSW distributions of the historical and satellite periods are statistically significant, according to a Kolmogorov-Smirnov test.

Page 8:
Lines 1-6: maybe it would be helpful to indicate the changes in stratospheric representation between the different NCEP reanalysis tools, or maybe refer to the Hitchcock, 2019 paper?

NCEP/NCAR and NCEP-DOE reanalyses are using basically the same model although with different versions, 1995 and 1998, respectively. Most of the improvements made in NCEP-DOE from NCEP/NCAR are related to changes in the lower levels (troposphere), except for the prescription of a new climatology of ozone (Kanamitsu et al., 2002; Long et al., 2017). Other differences in the concentrations of CO_2 or radiation schemes might also explain the small differences in results between both NCEP reanalyses.

In the revised manuscript, we have briefly extended the description of differences in the setup and models of both NCEP/NCAR and NCEP-DOE based on Kanamitsu et al. (2002), Fujiwara et al. (2017) and Long et al. (2017) (new lines 245-254).

Page 9:
Lines 24 – 26: yes, indeed, this is why it is so difficult to trace waves from the troposphere to the stratosphere. This is not so counterintuitive given the literature on the stratospheric contribution to SSWs.

Following the recommendations of Reviewer#1, in the revised text we have extended the discussion and inserted references to the recent literature on this topic (lines 312-318). In particular, we have stressed the special importance of the initial state of the polar vortex for the occurrence of WN2 SSWs (e.g. Albers and Birner 2014), the type of events discussed in this part of the study. In those cases, an initial vortex structure close to its resonant point is prone to lead to the split of SSWs with a small increase of tropospheric wave forcing.

Line 29: at which level?

We first checked at 10 and 20hPa, where we found the largest values of anomalous heat flux. However, they are probably not the best levels if we are trying to connect those changes with tropospheric structures. We have removed this sentence from the discussion.

Page 11 / Figure 7 / Page 23, line 31: are these differences significantly different from each other? i.e. not just significantly different from climatology?

Yes, they are. Panel c shows WN1-minus-WN2 differences and the shading indicates that these differences are statistically significantly different from each other. We have corrected the figure caption.

MINOR COMMENTS:
Page 1:
Line 30: I would suggest using Charlton et al (2007) as the authoritative reference here.
Modified

Page 2:
Line 8: Martius et al (2009) seems like the perfect reference here, it's already included in a different place in the manuscript
Included

Lines 10 – 16: would it make sense to include the classification into reflective and absorptive events here (Kodera et al, 2016)?
We prefer to keep it as it is, because we are not referring to these events later on.

Line 18: given the very limited number of studies of stratospheric effects on the ocean I would not call the assessment of oceanic phenomena based on the stratosphere a "common metric"
We just meant just the other way, i.e. oceanic effects on the stratospheric variability. Actually, we were mainly referring to the ENSO effects on the polar stratosphere or other phenomena that have also been recently explored such as PDO or MJO. We have slightly modified the sentence to clarify it.

Line 21: leave out "interestingly", and "largely"
Done

Line 22: "assimilation data sources": do you mean the data used for the assimilation of observational data into the reanalysis products?
Yes. This has been modified

Line 27: "than in the second one". Do you mean "than during the satellite era"?
Yes. We have changed it

Page 3:
Line 6: is made on > is given to
Changed.

Line 26: do you mean "across different reanalysis products"?
We meant across different reanalyses, not products. It has been corrected and clarified.

Page 4:
Line 29: "similarly": do you mean the identification was similar or it was also included in the table?
We meant that the identification was carried out in a similar way as for the common dates. We have clarified it.

Page 5:
Line 28: I'm not sure what is meant by "discrepancies" (also: page 6, line 14)
In the first case we have clarified that it means to the lack of consensus on the precursor role of blockings in SSWs. As for page 6 (now line 184), we have just replaced discrepancies for reanalyses results.

Page 8:
Line 9: ones -> SSWs
Corrected

line 19: "reanalysis deviation": not clear what this means
Differences across reanalyses.

Lines 23 – 26: be more clear which terms this corresponds to in the equation
Done

References

Albers, J. R. and Birner, T.: Vortex preconditioning due to planetary and gravity waves prior to sudden stratospheric warmings, J. Atmos. Sci., 71, 4028-4054, 2014.

Badin, G. and Domeisen, D. I. V.: A search for chaotic behavior in Northern Hemisphere stratospheric variability, J. Atmos. Sci., 71, 1494-1507, 2014.

Fujiwara, M. and coauthors: Introduction to the SPARC Reanalysis Intercomparison Project (S-RIP) and overview of the reanalysis systems, Atmos. Chem. Phys., 17, 1417–1452, 2017.

Kanamitsu, M. and coauthors: NCEP-DOE AMIP II reanalysis (R-2), Bull. Amer. Meteor. Soc., 83, 1631-1643, 2002.

Long, C. S., Fujiwara, M., Davis, S., Mitchell D. M., and Wright, C. J.: Climatology and interannual variability of dynamic variables in multiple reanalyses evaluated by the SPARC Reanalysis Intercomparison Project (S-RIP), Atmos. Chem. Phys., 17, 14593–14629, 2017.

Manney, G. L. et al.: Lower stratospheric temperature differences between meteorological analyses in two cold Arctic winters and their impact on polar processing studies, J. Geophys. Res., 108, 8328, doi: 10.1029/2001JD001149, 2003.

On the representation of major stratospheric warmings in reanalyses

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Abstract. Major sudden stratospheric warmings (SSWs) represent one of the most abrupt phenomena of the boreal wintertime stratospheric variability, and constitute the clearest example of coupling between the stratosphere and the troposphere. A good representation of SSWs in climate models is required to reduce their biases and uncertainties in future projections of stratospheric variability. The ability of models to reproduce these phenomena is usually assessed with just one reanalysis. However, the number of reanalyses has increased in the last decade and their own biases may affect the model evaluation.
Here we compare the representation of the main aspects of SSWs across reanalyses. The examination of their main characteristics in the pre- and post-satellite periods reveals that reanalyses behave very similarly in both periods. However, discrepancies are larger in the pre-satellite period than afterwards, particularly for the NCEP/NCAR reanalysis. All datasets reproduce similarly the specific features of wavenumber-1 and wavenumber-2 SSWs. A good agreement among reanalyses is also found for triggering mechanisms, tropospheric precursors and surface ~~fingerprint~~response. In particular, differences in blocking precursor activity of SSWs across reanalyses are much smaller than between blocking definitions.

1 Introduction

Major sudden stratospheric warmings (SSWs) constitute the most important phenomena of the Northern Hemisphere polar stratospheric variability in wintertime. They are abrupt warmings of the polar stratosphere that lead to a deceleration of the polar vortex and a reversal of the typical westerly circulation (Andrews et al., 1987). SSWs can be classified into two different types according to the structure of the polar vortex during the event. Accordingly, the polar vortex is either displaced from the polar cap (vortex displacement, D SSWs) or split into two parts of similar size (vortex split, S SSWs) (~~Labitzke and Naujokat, 2000~~Charlton and Polvani, 2007).
SSWs represent a clear example of stratosphere-troposphere coupling in both directions. First, they are usually preceded by an enhancement of ~~upward-propagating~~ wave activity (e.g. Matsuno, 1971). Although this enhancement can take place in the

lower troposphere, recent studies have shown that it often happens within the stratosphere or tropopause region and depends on the stratospheric mean flow conditions (Sjoberg and Birner, 2014; Birner and Albers, 2017; de la Cámara et al., 2017; White et al., 2019). The sources of ~~this~~ upward-propagating ~~anomalous~~ wave activity are mainly located in the mid-to-upper troposphere and correspond to anomalous circulation events such as a deepened Aleutian low (e.g.: Garfinkel et al., 2010) or blocking highs, among others (e.g. Martius et al., 2009; Nishii et al., 2011; Ayarzagüena et al., 2011; Barriopedro and Calvo, 2014). Based on the wave activity preceding SSWs, they are commonly classified into wavenumber 1 (WN1) or wavenumber 2 (WN2) events (e.g. Bancalà et al., 2012; Barriopedro and Calvo, 2014). This classification produces subsets of events similar to the D/S catalogue. However, there are differences since the former is based on the precursory wave activity while the D/S classification accounts for the shape of the polar vortex during the post-warming phase (Bancalà et al., 2012). Depending on the type of SSWs, the tropospheric precursors are different and/or located in different geographical locations (Martius et al., 2009; Cohen and Jones, 2011; Bancalà et al., 2012). In particular, differences in blocking precursors are larger when SSWs are classified into WN1/WN2 than D/S (Barriopedro and Calvo 2014).

In terms of downward coupling, the SSWs signal propagates downward and reaches the troposphere as revealed from composite analyses ~~are known to impact the tropospheric circulation in the subsequent weeks~~ (Baldwin and Dunkerton, 2001), although there is still uncertainty about this tropospheric response when analyzing individual events (e.g.: Gerber et al. 2009). One of the suggested factors that may contribute to the spread of ~~As in the case of the precursors,~~ the surface signature of ~~these events~~SSWs ~~has recently been suggested to~~is the ~~depend on the~~ type of event. However, while s~~S~~ome studies have shown that only S SSWs have large effects on surface climate (Mitchell et al., 2012, Seviour et al., 2013), ~~while~~ others have not found consistent differences between S and D SSWs in its significant surface impact (Charlton and Polvani, 2007; Cohen and Jones, 2011). Thus, there is not yet a consensus in this regard, probably due to the differences in the algorithms used to identify S and D SSWs (Maycock and Hitchcock, 2015). As for WN1 and WN2 SSW, their surface signature has not yet been explored.

SSWs are a key element when analyzing stratospheric variability. The frequency and seasonality of SSWs are common metrics to assess the effects of tropospheric and oceanic phenomena on ~~stratospheric variability~~the polar night jet (PNJ). These metrics are also used to evaluate ~~or~~ the stratospheric response to climate change (e.g.: Taguchi and Hartmann, 2006; Charlton-Perez et al., 2008; Ayarzagüena et al., 2018). Indeed, in modeling studies most of them use simulations that are previously validated by comparing their results with reanalysis datasets (e.g.: Charlton et al., 2007; McLandress and Shepherd, 2009; Kim et al., 2017). However,~~Interestingly,~~ the number of reanalyses has ~~largely~~ increased in the last decade, and although the observational data used in the assimilation process is~~assimilation data sources are~~ the same, the reanalysis models are different, and so may the final products be (Fujiwara et al., 2017). As it happens with other atmospheric models, reanalyses also have biases and this can affect the model evaluation (Fujiwara et al., 2017).

Due to quality improvements associated with the assimilation of satellite data, modern reanalyses, such as ERA-Interim, NASA-MERRA, and NCEP-CFSR, only cover the post-satellite period since 1979. This means that the number of available reanalyses to assess the model performance in the pre-satellite era is smaller than in the ~~second one~~post-satellite period. In addition, the amount of data to assimilate is also limited in the former~~is~~ period. All this might produce artificial differences in results before and after the inclusion of satellite data. Gómez-Escolar et al. (2012) documented a change of some SSW features from the pre-satellite to the post-satellite era in NCEP-NCAR and ERA-40 reanalyses. For instance, the intra-seasonal distribution and the amplitude of the SSW-associated warming showed differences between both periods, potentially due to a change in the type of the assimilated data. With the availability of the new JRA-55 reanalysis, which is the only one that applies an advanced data assimilation scheme to upper-air data during the pre-satellite era, revisiting this topic seems appropriate.

In this study, we aim to assess the performance of the most widely used reanalyses in representing SSWs. To do so, first, the main characteristics of SSWs are examined for all datasets to quantify the degree of agreement across reanalyses. Both pre- and post-satellite periods are compared to investigate whether discrepancies among reanalyses in the representation of the main SSW characteristics depend on the examined period. Secondly, we address the dynamical forcing of SSWs in all datasets, including precursors such as blockings. Finally, the surface impact of SSWs retrieved from the different reanalyses is analyzed. Special emphasis is ~~made on~~given to the assessment and robustness of the potential differences in the forcing and surface impact of WN1 and WN2 SSWs, as well as S and D events.

Our work is a contribution to the Chapter 6 of the Stratosphere-troposphere Processes And their Role in Climate (SPARC) Reanalysis Intercomparison Project (S-RIP) initiative, which aims to assess stratosphere-troposphere coupling in reanalyses. In the framework of this initiative, a few recent studies have addressed some aspects of the representation of polar stratospheric variability in reanalyses. In particular, Martineau et al. (2018) and Hitchcock (2019) also investigate SSWs-related aspects. The former analyzes ~~the SSWs~~ the momentum budget during SSWs restricted to the post-satellite period, while Hitchcock (2019) compares the representation of stratosphere-troposphere coupling in both pre and post-satellite period, with the emphasis on the impact of including pre-1979 data. Different from these studies, our work provides a comprehensive inter-reanalyses comparison of the most important and typical aspects and processes associated with SSWs in both pre- and post-satellite eras. Additionally, we explore further the characteristics of WN1 and WN2 SSWs that have not yet been investigated ~~yet~~.

The structure of the paper is as follows. The data used and methodology applied are described in Section 2. Section 3 compares the performance of the main characteristics of SSWs across reanalyses. Section 4 focuses on the dynamical forcing of the events and Section 5 addresses the performance of reanalyses in representing the surface impact of SSWs. The main conclusions are summarized in Section 6.

2 Data and methodology

2.1 Data

We have used daily data from the following reanalyses: ERA-40 (Uppala et al., 2005), ERA-Interim (Dee et al., 2011), JRA-25 (Onogi et al., 2007), JRA-55 (Kobayashi et al., 2015), NASA-MERRA (Rienecker et al., 2011), NCEP-CFSR (Saha et al., 2010), NCEP-DOE (Kanamitsu et al., 2002), and NCEP-NCAR reanalysis (Kalnay et al., 1996). More details about the different reanalyses can be found in Fujiwara et al. (2017). For the comparison across different reanalyse~~i~~s, all data was used at the ~~have been interpolated to a~~ common regular grid of 2.5° lon x 2.5° lat. When not directly available from the reanalysis centers, a first order conservative remapping was applied.

The methodology for the intercomparison follows the S-RIP specifications. As such, the analysis has been carried out for two different periods: historical (1958-1978) and comparison (1979-2012). Given the periods covered by each reanalysis, only ERA-40, NCEP-NCAR, and JRA-55 are employed in the historical period. In contrast, all the above listed reanalyses are used in the comparison period with the exception of ERA-40, because it ends in 2002. The performance of each reanalysis is evaluated against a multi-reanalysis mean (MRM), herein considered as an "unbiased" reference. In the historical period, the MRM refers to the average of the three reanalyses that cover that period, while in the comparison period, the MRM is defined as the average of the most recent reanalyses of each center (ERA-Interim, NCEP-CFSR, JRA-55 and NASA-MERRA). Hereafter, anomalies for each reanalysis are defined as the departure of the field from the daily climatology of each reanalysis. In the historical period, the climatology covers the whole period (i.e. 1958-1978), whereas the comparison period uses the 1981-2010 baseline. Unless otherwise stated, statistical significance of the results is computed with a Monte-Carlo test of 1000 permutations, each one containing the same number of cases and dates as the SSWs of each composite but with random years of occurrence.

2.2 Criteria for the identification of SSWs

W~~Unless otherwise stated, w~~e have used the list of SSWs and common dates identified in Butler et al. (2017) and provided for the S-RIP initiative (Chapter 6), unless otherwise indicated. First, for each reanalysis, SSWs are identified based on the reversal of the zonal mean zonal wind at 60ºN and 10hPa between November and March, with at least 20 days of separation between events. Stratospheric final warmings are excluded by ~~imposing~~ requiring at least 10 consecutive days of westerly winds before the end of April (Charlton and Polvani, 2007). The first day of reversal of winds determines the date of occurrence of the SSW (the so-called central date). Common SSWs are those identified by at least two of the three reanalyses in the historical period and by at least four out of seven reanalyses in the comparison period around the same date (usually within one or two days). The central date of these common events is computed as the ~~average~~ median of the central dates from the SSWs detected for each reanalysis. Thus, with this approach, the same events and central dates apply for all reanalyses even if the reversal of the winds does not occur in all of them. This is useful to ensure that the differences between datasets are not due to the selection of different events or dates. The common SSWs are listed in Table 1 for the comparison period.

Nevertheless, in the very first part of our study, we have addressed the opposite question and quantified the possible discrepancies in the frequency of SSWs among reanalyses when the same criterion is applied to all datasets. In that case, we have imposed the WMO definition for the identification of SSWs in each reanalysis. The definition is based on the ~~simultaneous~~ reversal, within ±5 days) ~~-~~of zonal-mean zonal wind at 10hPa and 60ºN and zonal-mean temperature difference between 90ºN and 60ºN at the same level (Labitzke, 1981).

2.3 Types of SSWs

SSWs are classified following two definitions: D vs S SSWs, and WN1 vs WN2 events. In this study, D and S SSWs were identified according to the algorithm by K. Shibata ~~(personal communication)~~, which is similar to that of Charlton and Polvani (2007). It is based on the identification of cyclonic vortices and their relative sizes by means of the non-zonal absolute vorticity at 10hPa from 5 days before to 10 days after (i.e. [-5,10]-day) with respect to the occurrence of an SSW, according to the definition of Section 2.2. More specifically, S SSWs are identified when two local maxima of the absolute vorticity are located diametrically opposed and the size ratio of the sectors around those maxima is larger than 0.5 during at least one of the 16-day period surrounding the SSW. Otherwise the SSW is defined as D. The events were classified individually in each reanalysis. The classification into S/D events of common SSWs in the comparison period (used in Sections 4 and 5) was based on the predominant type of each single event across the different reanalyses ~~across reanalyses~~, ~~similarly~~ following a similar procedure to that employed for ~~to~~ the identification of the common dates (Table 1).

WN1 and WN2 SSWs were selected by applying a zonal Fourier decomposition of the daily 50hPa geopotential height data at 60ºN into WN1 (Z_1) and WN2 (Z_2) amplitudes for the [-10,0]-day period before each SSW (Barriopedro and Calvo, 2014). An SSW was defined as a WN2 event if $[Z_2] \geq [Z_1]$ (brackets denote the averaged amplitude for the [-10,0]-day period before the SSW) or if $Z_2 - Z_1 \geq 200$ m at least for one day within the [-10,0]-day period before the SSW. Otherwise, the SSW was defined as a WN1 event. See the list of events of each type in Table 1 and Barriopedro and Calvo (2014) for more details on the algorithm.~~.~~

2.4 Dynamical benchmarks

We have applied the following diagnostics proposed by Charlton and Polvani (2007) to evaluate the dynamical signatures associated with the occurrence and development of SSWs:

- Amplitude of the SSW in the middle stratosphere (hereafter *amp010*) computed as the area-weighted mean 10hPa temperature anomaly over the polar cap (50°N-90°N) and averaged for the [-5,5]-day period with respect to the central date of the event.
- Amplitude of the SSW in the lower stratosphere (hereafter *amp100*), defined as *amp010* but at 100hPa. It provides a measure of the coupling between the middle and lower stratosphere around the occurrence of SSWs.
- Deceleration of the ~~polar night jet (~~PNJ~~)~~ (hereafter *decelu*), corresponding to the difference of the 10hPa zonal-mean zonal wind at 60°N between the [-15, -5]-day period prior to the central date and the [0, 5]-day period after the central date.
- Wave activity prior to SSW (hereafter *actwav*), computed as the area-weighted mean 100hPa meridional eddy heat flux (HF) anomaly averaged over 45°N-75°N for the [-20,0]-day period before the occurrence of the event.

2.5 Upward-propagating wave activity

The anomalous meridional eddy HF averaged over 45°N-75°N at different pressure levels was used as a metric to measure the upward ~~vertical~~ propagation of wave activity. This latitudinal band corresponds to the climatological area with the strongest vertical wave propagation from the troposphere to the stratosphere (Hu and Tung, 2003).

As a second step, the methodology by Nishii et al. (2009) was applied to analyze the role of different forcing processes in the occurrence of SSWs. This methodology is based on the decomposition of daily anomalous eddy HF into two components, which correspond to the interaction between climatological waves and anomalous waves (second and third right hand terms of Eq. 1) and the inherent contribution of anomalous waves (first right hand term of Eq. 1):

$$[v^*T^*]_a = [v_a^*T_a^*]_a + [v_c^*T_a^*] + [v_a^*T_c^*] \qquad (1)$$

where brackets and asterisks indicate zonal mean and deviation from it, respectively, v is meridional wind, T is temperature and the a and c subscripts denote daily anomalies and climatological values, respectively. Eq. 1 has been applied to each pressure level.

2.6 Blocking definitions

The precursor role of blocking in SSWs has been discussed ~~with discrepancies~~ across studies (see e.g., Castanheira and Barriopedro (2010) for an overview ~~on this topic~~), although there is not a clear consensus on this topic. The divergent results of previous studies may partially be attributed to different methodologies of blocking detection (e.g., Woollings et al., 2008). In this study, three different blocking definitions have been used to address this question. The three methodologies use daily geopotential height at 500 hPa (Z500) and span almost all approaches to blocking definition. The first method is based on the occurrence of regional and persistent meridional Z500 gradient reversals (the absolute method, ABS; e.g., Scherrer et al., 2006). The second metric involves the detection of persistent and quasi-stationary Z500 anomalies, computed with respect to the local climatological field (the anomaly method, ANO; e.g., Sausen et al., 1995). Finally, a combined method of absolute and anomaly Z500 fields (the mixed method, MIX) is used, providing a two-fold~~ed~~ perspective of blocking (Barriopedro et al., 2010). Several criteria are imposed to ensure that the detected episodes represent large-scale, quasi-stationary, and persistent high-pressure systems. See Woollings et al. (2018) for more details about blocking definitions.

3 Main SSW characteristics

In this section, the main signatures of SSWs (frequency, type of events and process-based diagnostics) are analyzed for each period and compared among the different datasets.

3.1 Frequency, seasonality and type of events

First, we have analyzed the ~~discrepancies~~ results ~~in~~ for the frequency and type of events ~~across reanalyses~~ when the same criterion is applied to each dataset. Table 2 shows the mean frequency of events and the ratio of D to S SSWs for each period and reanalysis. The main differences are found in the historical period when the reanalyses show a large spread in both frequency and type of events. In particular, the NCEP/NCAR reanalysis displays the results that deviate the most from the other two datasets, although the differences are not statistically significant at the 95% confidence level (Student's t-test). The short period of analysis and hence the reduced sample might explain part of these discrepancies. More importantly~~,~~ the unavailability of satellite data in the pre-satellite era leads to a strong dependency of the reanalysis data in the stratosphere on the characteristics of each reanalysis model. Note that NCEP/NCAR reanalysis is the only reanalysis with a low-top model and a lid in the stratosphere (3hPa), whereas JRA-55 and ERA-40 have the top in the mesosphere (0.1hPa). The low top typically dampens variability close to the top and so, reduces the probability of the occurrence of an SSW (Charlton-Pérez et al., 2013). In fact, the standard deviation of daily polar temperature and zonal wind at 10 hPa in December and January of the historical period is much lower in NCEP/NCAR than in the other two reanalyses, although the differences are not statistically significant at the 95% confidence level (F-Fisher test) (Figure 1a, c). In contrast, at lower levels, we do not find such discrepancies (see 100 hPa temperature in Fig. 1b, d), supporting that the occurrence of SSWs during this period is strongly influenced by the model performance and hence should be considered reanalysis-dependent.

Conversely, in the comparison period, there is a good agreement in both the frequency and ratio of D/S SSWs. Small differences are found, particularly, in the D/S ratio, but this might be due to the specific thresholds or other methodological issues of the applied criterion, since such deviation does not appear when classifying SSWs into WN1 and WN2 events (Barriopedro and Calvo, 2014). More details about these classifications of SSWs can be found in the Chapter 6 of S-RIP.

Regarding SSWs seasonality, Figure 2 shows the smoothed seasonal distribution~~the~~ of SSW per decade~~total frequency distribution within ±10-day periods~~. This distribution has been computed by counting the number of SSWs within the ±10-day periods centered on each winter days. Additionally, the distribution has been smoothed with a 10-day running mean. Similar~~ly~~ to the winter mean frequency of SSWs, historical reanalyses show the largest spread in the seasonal distribution. A substantial part of this spread is due to the NCEP/NCAR reanalysis whose distribution is ~~,~~statistically significantly different from that of the other two reanalyses at a 99% confidence level (two-samples Kolmogorov-Smirnov test). In contrast, ERA- 40 and JRA-55 distributions display similar (statistically undistinguishable) distributions. In particular, they ~~ERA-40 and JRA-55~~ show an~~display~~ increasing SSW occurrence from early winter that maximizes in January and decreases by late winter (Fig. 2a), in agreement with the temporal evolution of the standard deviation of the zonal-mean zonal wind at 60ºN and 10 hPa in the historical period (Fig. 1c). In contrast, SSWs for NCEP/NCAR are more uniformly distributed with three sharp maxima in early, mid and late winter. The early winter peak of SSWs in NCEP/NCAR ~~can be traced back to~~agrees well with the climatological polar stratospheric state~~the PNJ~~, which shows a weaker ~~values~~ PNJ and a warmer polar stratosphere than the other two reanalyses (Fig. 1a and c). These~~is~~ NCEP/NCAR ~~-~~differences in the PNJ are only~~is not~~ statistically significant for the polar stratospheric temperature and ERA-40~~,~~ though, likely due to the short sample and the general large interannual variability of the winter polar stratosphere. However, they agree with an artificial positive temperature trend of 8ºC at 10 hPa for 1948-1998 in the NCEP/NCAR reanalysis, as documented by Badin and Domeisen (2014)~~ (Fig. 1c)~~. On the other hand, the lower wind variability in January in NCEP/NCAR would agree with the reduced frequency of SSWs in that month and reanalysis, as compared to the other datasets. In the comparison period the results are similar across reanalyses, which show statistically indistinguishable distributions (Kolmogorov-Smirnov test, Fig. 2b). In this period, the maximum occurrence shifts to late winter in all datasets compared to the distributions of ERA-40 and JRA-55 in the historical period. Similar differences in the intra-seasonal distribution of events were already documented by Gómez-Escolar et al. (2012) between the pre- and post- 1979 periods. Despite the large uncertainty of the earlier period, their distributions are statistically significantly different at the 99% confidence level and this result~~This~~ ~~adds~~ supports ~~to~~ the hypothesis of multi-decadal ~~variability~~ variations in the intra-seasonal occurrence of SSWs, which adds to the reported variability in the total winter frequency of SSWs~~.~~ (Schimanke et al. 2011; Reichler et al. 2012; Domeisen 2019).

3.2 Process-based diagnostics

The processes involved in the occurrence of SSWs have been compared across reanalyses by using the diagnostics defined in Section 2d. In this case, and in the rest of the paper, we have used the common dates of SSWs to make sure the differences found across reanalyses are not due to the inclusion of different events.

Figure 3 shows the statistics (mean, median and interquartile range) of the dynamical benchmarks for all reanalyses in the two periods. A quick comparison of the MRM of these benchmarks for both periods reveals that SSWs are preceded by a similar anomalous strengthening of wave activity at 100hPa, are associated with a comparable deceleration of the PNJ and have a similar amplitude in the middle and lower stratosphere in both periods. Only slight differences are found in the median of *decelu* and *amp100* (compare Fig. 3b,c with Fig.3~~e,~~f,g). However, given that the median and mean of these magnitudes for one period are included within the interquartile range of the other, we can conclude that SSWs characteristics are similar in both periods of study.

The comparison period shows good agreement among all reanalyses as all datasets are characterized by similar median, mean and spread values (Fig. 3e-h). Nevertheless, slight deviations can be found for NCEP/NCAR in the distribution of *decelu*, which is shifted towards lower values and shows a reduced spread among events, as compared to the rest of the datasets (Fig. 3g). These deficiencies are even clearer in the historical period, when a similar discrepancy is detected in *amp010* (Fig. 3a), consistent with the reduced strength and variability of the PNJ in NCEP/NCAR reanalysis (Figs. 1c). As the deviation of *decelu* in the NCEP-NCAR reanalysis is common for both periods, this might point to a bias of the model, whose effects are amplified in the first period by the lower amount of assimilated data. As mentioned before, this bias is very likely linked to the low top of the model and the low vertical resolution in the stratosphere, provided that the SSW characteristics at lower levels (i.e. *amp100*, *actwav*) do not differ much from those of other reanalyses. Note that these differences are still noticeable in NCEP-DOE, in agreement with Long et al. (2017) that identified similar biases in the climatology and interannual variability of temperature and zonal winds for both NCEP reanalyses. The model of NCEP-DOE is basically the same as that of NCEP/NCAR reanalysis although with an updated version (1995 vs 1998) (Fujiwara et al. 2017). This implies that both reanalyses use a model with a low resolution in the stratosphere and with assimilated temperature data instead of direct radiances that reduce their ability to represent the stratosphere (Fujiwara et al. 2017). Despite their similarities, ~~but~~the NCEP-DOE performs better with respect to the MRM~~they are minimized~~, particularly for *decelu*,~~,~~ arguably due to improvements introduced in the ~~new~~ updated version of ~~this reanalysis~~the reanalysis model. Primarily, NCEP-DOE was run with ~~such as~~ a new ozone climatology (Kanamitsu et al., 2002). Other differences in the concentration of CO_2 or the radiation scheme between both reanalyses might also explain the differences between both NCEP reanalyses (Fujiwara et al., 2017).

A similar analysis has been carried out separately for WN1 and WN2 SSWs in the comparison period (Fig. S1). All datasets reproduce a similar behavior for both types of events and all diagnostics, with the exception of the associated deceleration of the PNJ in the middle stratosphere: WN2 SSWs are related to larger decelerations of the PNJ, probably because they are usually preceded by a stronger polar vortex than WN1 ~~ones~~ SSWs (Albers and Birner, 2014; Díaz-Durán et al., 2017). These results also confirm the overall good agreement across reanalyses except for the deficiency of NCEP/NCAR concerning *decelu*. Unfortunately, these findings cannot be confirmed in the historical reanalyses due to the very low frequency of WN2 events in that period (not shown).

4 Dynamical forcing

4.1 Upward-propagating wave activity

Figures 4 and 5 show the composited anomalous eddy HF, area-averaged between 45° N and 75°N, at different levels around the SSWs onset date for the historical and comparison period, respectively. Only results from 3~~1~~00 to 10 hPa are presented, as the [300-100] hPa layer corresponds to the communication region for the stratosphere-troposphere coupling (de la Cámara et al. 2017), and the ~~these~~ levels above this layer typically ~~are the levels with~~show the strongest HF anomalies. The MRM shows a strong anomalous peak of HF around the central date of SSWs in both periods. This strong peak is preceded by a weak pulse around [-20, -15] days in the middle stratosphere in the comparison period but not in the historical one. The largest ~~reanalyses deviation~~differences across reanalyses are~~is~~ detected in the middle stratosphere in agreement with Martineau et al. (2018), and they are more pronounced for the historical than for the comparison period.

By applying the methodology by Nishii et al. (2009) we have analyzed the contributing role of the different HF terms to the occurrence of SSWs. The MRM decomposition of the HF in the comparison period shows that the strongest peak ([-5,0]-day interval) is mainly due to the action of anomalous waves (first right hand term of Eq. 1), albeit with a relevant contribution of the constructive interaction between climatological and anomalous waves (second and third right hand terms of Eq. 1, Figs. 4c, e and 5c, e). Conversely, the preceding~~ent~~ weaker pulses of the comparison period seem to be more dominated by the interaction term. The agreement among reanalyses concerning the relative roles of these terms is higher for the comparison period, mainly in the middle stratosphere, than for the historical ~~one~~ period (compare Fig. 4d, f vs Fig. 5d, f).

Given the documented differences in the dynamical forcing of different types of SSWs (e.g. Smith and Kushner, 2012; Barriopedro and Calvo, 2014), we have repeated the analysis separately for WN1 and WN2 SSWs (Fig. 6). It has only been done for the comparison period, due to the low sample size of WN2 events for the historical one. Although there is not a univocal relationship between D and S SSWs and WN1 and WN2 events (Waugh, 1997), our results for WN1 and WN2 events agree well with those of Smith and Kushner (2012) for D and S SSWs. WN1 events are mainly triggered by persistent but moderately intense anomalies of HF during different periods ([-20, -15] and [-10, 0] days), which are associated with the constructive interference of climatological and anomalous waves (Figs. 6e and i). In contrast, WN2 events are related to intense but short pulses of eddy HF in the five days prior to the central date. These pulses are predominantly due to the anomalous term (Figs. 6g and k), consistent with Smith and Kushner's finding for S SSWs. The recovery of the polar vortex after WN2 SSWs is due to a reduction of wave activity in the interaction term, while only the anomalous term has a statistically significant contribution to this reduction after WN1 SSWs (Figs. 6e, g, i and k).

The comparison among reanalyses reveals that all datasets can reproduce the above differences between WN1 and WN2 SSWs. The spread is higher for WN2 SSWs than for WN1 SSWs (Figs. 6b, d, f, h, j, and l), particularly for the anomalous HF term (Fig. 6l). However, considering the differences in HF values between WN1 and WN2 SSWs (i.e., by dividing the standard deviation by the MRM), the resulting spread becomes comparable for both types of SSWs (not shown).

4.2 Tropospheric circulation anomalies associated with SSWs

To investigate the tropospheric patterns preceding SSWs we have analyzed the averaged Z500 anomalies in the 10 days prior to the central date of each type of SSW (Fig. 7). As in the previous section, we have focused on the differences between WN1 and WN2 events in the comparison period only. The chosen time window corresponds to the peak of the strongest anomalies of HF in Fig. 5a. It is also the approximate time that planetary waves take to propagate from the troposphere to the stratosphere (Limpasuvan et al., 2004). The results reveal statistically significant differences between the precursors of WN1 and WN2 SSWs (Fig. 7c). The precursor signal for WN1 SSWs shows a predominant WN1-like structure, with negative anomalies of Z500 over the North Pacific and eastern Asia, and positive anomalies over northern Canada, the North Atlantic and western Siberia (Fig.7a). This agrees with the pattern identified by previous studies such as Limpasuvan et al (2004) and Garfinkel et al. (2012) for all SSWs. Most of these centers of action project onto the climatological WN1 of the MRM, especially the one over the North Pacific (e.g., Garfinkel and Hartmann, 2008), explaining the high positive values of the interaction term of HF (e.g., Martius et al., 2009; Nishii et al., 2011). Differently, the precursor signal of WN2 SSWs shows strong negative Z500 anomalies over Canada and Greenland and positive anomalies over the northeastern Pacific (Fig. 7d). The main anomalous centers coincide geographically and in sign with the antinodes of the climatological WN2 of the M~~M~~RM (e.g., Garfinkel and Hartmann, 2008). Although this pattern agrees with the preferred blocking precursors of WN2 SSWs (Barriopedro and Calvo, 2014), it seems counterintuitive with the predominant role of the anomalous waves found in Fig. 6 for these events, although we are looking at very different levels in the two figures. The same apparent contradiction was already highlighted by Smith and Kushner (2012). ~~However, additional analyses revealed that, despite the projection of Z500 anomalies onto the stationary~~

~~WN2, the interaction HF term is weak due to the low amplitude of WN2 climatological v^* and T^* with respect to that of anomalous WN2 waves. Consequently, a considerable part of the WN2 HF anomalies is explained by the large amplitude of the anomalous WN2 wave preceding these events (not shown).~~ Nevertheless, the tropospheric and stratospheric results might not be so contradictory as suggested at the first sight. As indicated in the Introduction Section, recent studies have given evidences of the importance of the stratospheric contribution in the amplification of anomalous wave activity prior to an SSW (e.g.: Sjoberg and Birner, 2014; Birner and Albers, 2017; de la Cámara et al., 2017). This contribution seems particularly relevant in the case of WN2 SSWs, when an initial vortex structure close to its resonant point can split the vortex with only a small increase of tropospheric wave forcing (Plumb, 1981; Albers and Birner, 2014). Based on our results, this tropospheric wave forcing probably might result from the constructive interference of anomalous and climatological waves.

The agreement among reanalyses is very good (Fig.7b and e). Only very small differences appear in the tropospheric pattern over the North Pacific, which are larger for WN2 than for WN1 SSWs, in agreement with the comparison of wave activity (Fig.6). We stress that the largest differences in wave activity among reanalyses are found in the middle stratosphere and hence the Z500 deviations from the MRM are smaller than those in the HF composites. The lower spread among reanalyses in tropospheric fields compared to that in the stratosphere is expected based on the larger number of assimilated data.

4.3 Blocking

The positive Z500 anomalies identified in the previous section may imply an increased blocking frequency over those locations prior to the occurrence of each type of SSW. Similarly, a below-normal activity of blocking before SSWs might translate into negative Z500 anomalies. Here, we identify blocking precursors of WN1 and WN2 SSWs by performing 2-D composites of the blocking frequency (in % of winter days) for the [-10,0]-day period before the central day of SSWs (same window as in Fig. 7). We have employed the three different algorithms described in Section 2f. Upper and middle rows of Figure 8 show the MRM of blocking precursor frequencies for WN1 and WN2 SSWs in the comparison period, respectively. Bottom row of Figure 8 displays the MRM of a pseudo-climatology of the ~~the mean~~ blocking frequency prior to all SSWs (~~a pseudo-climatology~~see the figure caption for details on its computation). In general, in all methods there is a spatial preference for specific blocking precursors depending on the main wave activity preceding SSWs. For WN1 SSWs, enhanced (above climatology) blocking frequencies are detected over the western Atlantic and east of Scandinavia, and reduced (below climatology) blocking activity occurs over the eastern Pacific (compare upper and bottom rows of Figure 8). Nearly opposite patterns are identified for WN2 SSWs (compare middle and bottom rows of Figure 8) except for an increased blocking frequency over east of Scandinavia. These results also agree well with the Z500 pattern preceding each type of SSWs in Fig. 7. They are also consistent with previous studies that identified the preferred location of blockings for the intensification of WN1 and WN2 wave activity (e.g., Castanheira and Barriopedro, 2010; Nishii et al., 2011; Barriopedro and Calvo, 2014; Ayarzagüena et al., 2015).

This blocking signal is reproduced by all methods and reanalyses (not shown), although the intensity, significance and spatial extension of the anomalies vary with the blocking definition. For example, the precursor signal of SSWs in ABS is confined to smaller regions than in ANO and MIX, eventually becoming non-significant. These differences between methods do not only refer to the blocking signal prior to SSWs but also to the climatology (Figs. 8g-i), which can be explained by the different aspects captured by each blocking indicator (Barriopedro et al. 2010). Reanalyses show a reasonable agreement in the blocking frequency results, and they even agree on the statistical significance of changes in the blocking frequency for the ANO and MIX methods, which show a noticeable deviation from the climatology prior to SSWs. Thus, the disagreement between previous studies regarding the precursor role of blocking in SSWs is better explained by the blocking definition than the chosen reanalysis.

5 Surface signal of SSWs

Finally, the surface signal after the occurrence of SSWs was explored by compositing the mean sea-level pressure (MSLP) anomalies of the [5, 35]-day period for all events. The time interval was selected following Palmeiro et al. (2015), who identified the strongest negative values of the Northern Annular Mode (NAM) index in this period. We found a general good agreement in the surface signal of all SSWs across reanalyses in both historical and comparison periods (not shown). Similar to the previous sections, we present here only the MSLP composites for WN1 and WN2 SSWs and the comparison period (Figs. 9a and d). WN1 and WN2 SSWs show a significant negative NAM-like pattern response, with positive anomalies over the polar cap in both cases. However, some slight differences between WN1 and WN2 events are found. Over the northeastern Pacific, MSLP anomalies of different sign (positive for WN2 SSWs and negative for WN1 SSWs) were also detected prior to the occurrence of SSWs (see Fig. 7 and also in MSLP maps (not shown)). Thus, they may be a remainder of the tropospheric precursors, as also suggested by Charlton and Polvani (2007). In the Euro-Atlantic sector, negative anomalies after WN1 SSWs extend over the whole Atlantic Ocean and western and central Europe (Fig. 9a), while those related to WN2 SSWs are shifted towards Eurasia (Fig. 9d). Nevertheless, these differences are only statistically significant in western-central Europe and the Mediterranean region, where the response to SSWs is significantly stronger in WN2 than in WN1 SSWs (Fig. 9c). Interestingly, despite their small extension, the different surface responses for WN1 and WN2 SSWs reported here show very good agreement across reanalyses (Figs. 9b and e). Note that the deviations from the MRM are very low for both types of SSWs. Additionally, the regions with the highest disagreement across reanalyses do not correspond to the areas with the largest differences in the surface fingerprint of WN1 and WN2 SSWs. Thus, although small, the differences in surface responses detected between both types of events are robust across reanalyses.

In the last decades, many studies have focused on the surface signal of D and S SSWs (e.g.: Charlton and Polvani, 2007; Mitchell et al., 2013; Lehtonen and Karpechko, 2016). However, this classification is difficult to predict before the SSW onset, since it is strongly based on the evolution of the polar vortex during the post-warming phase. Here, we have rather investigated the surface signal of WN1 and WN2 SSWs, whose typification is dictated by their precursors. Indeed, whereas the Z500 patterns preceding SSWs show statistically significant differences ~~for~~ between WN1 and WN2 events (Fig. 7c), the areas with statistical significance of the differences between D and S events ~~is~~ are more limited (Fig. 7f). In the case of the surface signal, both classifications (WN1/WN2 or S/D) show areas of statistically significant differences between the two types of events ~~,~~ ~~being stronger for WN1/WN2 than for D/S SSWs~~ (compare Figs. 9c and 9f). Our results agree well with previous studies that also found a surface signal for D and S SSWs (e.g., Charlton and Polvani, 2007; Maycock and Hitchcock, 2015). Maycock and Hitchcock (2015) indicated that the absence of a surface fingerprint for D SSWs reported by previous studies is more probably due to the sampling of events rather than a physical reason. The reported differences between the surface impacts of WN1 and WN2 SSWs may also be influenced by this issue, particularly ~~taking into account~~considering the small sampling size of WN2 events. Still, our results confirm a detectable surface fingerprint for all types of SSWs independently of the classification chosen.

6 Summary and conclusions

In this study, we have compared the representation of the main features, triggering processes and surface fingerprint of SSWs in different generations of reanalyses. Apart from a direct assessment of the SSW characteristics in the pre- and post-satellite period, questions concerning the representation of SSWs by reanalyses have been addressed thanks to the larger number of datasets available for the post-1979 period. Unlike most studies that focus on D versus S SSWs, a separate analysis of WN1 and WN2 events has also been performed. The main conclusions are summarized as follows:

- An overall good agreement across reanalyses is found in the representation of the main features of SSWs. However, there are differences across reanalyses, particularly in the historical period, concerning the characteristics of SSWs in the middle stratosphere such as amplitude or deceleration of the PNJ. Some of the discrepancies also extend to climatological fields and their variability and are more pronounced for the NCEP/NCAR reanalysis, in agreement with Badin and Domeisen (2014). Arguably, the characteristics of the reanalysis models, including the location of their upper lid, play an important role in that period, when the performance of the reanalysis is preferentially determined by the characteristics of the underlying model. These limitations also affect the comparison period, but to a~~at~~ much less extent, due to the availability of satellite data in the upper levels.
- In general, SSWs (frequency, type and dynamical benchmarks) do not substantially differ between the historical and comparison periods. Only the seasonal distribution of SSWs reveals robust differences between both periods with a shift towards a later occurrence in the satellite period, in agreement with Gómez-Escolar et al. (2012) and Hitchcock (2019).
- SSWs are mainly associated with anomalous wave packets immediately before their onset. However, the interference with climatological stationary waves plays a predominant role several days before the SSW onset. This behavior is robust across reanalyses during the comparison period, but subject to considerable uncertainties during the historical period concerning the wave activity in the middle stratosphere.
- WN1 and WN2 SSWs and their tropospheric precursors display differences in the comparison period that are robustly captured by all reanalyses. WN1 events are mainly triggered by the interaction between climatological and anomalous

waves during long-lasting and moderately intense peaks of HF anomalies. Conversely, WN2 events are related to intense but short-lived pulses of HF arising from anomalous wave packets. The results resemble those by Smith and Kushner (2012) for D and S events, respectively, despite the lack of a one-to-one correspondence between WN1 (WN2) and D (S) SSWs.

- The tropospheric precursor signal for WN1 and WN2 SSWs shows a predominant WN1-like and WN2-like structure, respectively. This is consistent with the spatial distribution of blockings preceding both types of SSWs. For WN1 SSWs, there is an enhanced activity over the western Atlantic and below normal frequencies over the eastern Pacific, with nearly opposite patterns for WN2 SSWs. A robust pattern emerges for all reanalyses, but there are substantial differences among blocking definitions.
- Both WN1 and WN2 SSWs have significant impacts on surface weather characterized by a negative NAM pattern, but with some differences in southern and central Europe. These differences are significantly different between WN1 and WN2 events and robust across reanalyses during the comparison period.

In summary, we conclude that the representation of SSWs is, in general, robust in both periods of study for the available reanalyses, and overall not different between the pre- and post-satellite eras. This would agree with Hitchcock (2019) who recommended the consideration of using data prior to 1979 in dynamical studies for stratosphere-troposphere coupling, as it might be advantageous for reducing the sampling uncertainty for many purposes. However, in our study some discrepancies in the historical period were identified, particularly for the NCEP/NCAR reanalysis, which limit its use for this period in model evaluation initiatives. Furthermore, this work provides some guidelines, highlighting discrepancies among reanalyses concerning SSWs and identifying related aspects that may be sensitive to the chosen reanalysis. Although robust, some reanalyses results (such as the differences between types of SSWs) should be taken with caution in this period, due to the limited sampling.

Author contribution

BA, FMP, DB, NC and UL designed the analysis and wrote the paper. BA, FMP and DB carried out the analysis of the renalyses data and drafted the figures. KS provided the algorithm for identification of S and D SSWs and helped with its implementation.

Data availability

NCEP/NCAR and NCEP-DOE reanalyses data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. JRA-25 data were provided from the cooperative research project of the JRA-25 long-term reanalysis by the Japan Meteorological Agency (JMA) and the Central Research Institute of Electric Power Industry (CRIEPI). Japanese 55-year Reanalysis (JRA-55) project was carried out by the Japan Meteorological Agency (JMA).

JRA-25, JRA-55 and NCEP-CFSR data were accessed through NCAR/UCAR Research Data Archive (https://rda.ucar.edu). The NASA-MERRA data were disseminated by the Global Modeling and Assimilation Office (GMAO) and the GES DISC. ERA-Interim and ERA-40 are available online (http://apps.ecmwf.int/datasets/data/).

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References

Albers, J. R. and Birner, T.: Vortex preconditioning due to planetary and gravity waves prior to sudden stratospheric warmings, J. Atmos. Sci., 71, 4028-4054, 2014.

Andrews, D. G., Holton, J. R., and Leovy, C. B.: Middle Atmosphere Dynamics, Academic Press, 489pp, 1987.

Ayarzagüena, B, Langematz U., and Serrano, E.: Tropospheric forcing of the stratosphere: A comparative study of the two different major stratospheric warmings in 2009 and 2010, J. Geophys. Res., 116, D18114, 2011.

Ayarzagüena, B., Orsolini, Y. J., Langematz, U., Abalichin, J., and Kubin, A.: The relevance of the location of blocking highs for stratospheric variability in a changing climate, J. Climate, 28, 531-549, 2015.

Ayarzagüena, B., and coauthors: No robust evidence of future changes in major stratospheric sudden warmings: a multi-model assessment from CCMI models, Atmos. Chem. Phys., 18, 11277–11287, 2018.

Badin, G. and Domeisen, D. I. V.: A search for chaotic behavior in Northern Hemisphere stratospheric variability, J. Atmos. Sci., 71, 1494-1507, 2014.

Baldwin, M. P. and Dunkerton, T. J.: Stratospheric harbingers of anomalous weather regimes, Science, 294, 581–584, 2001.

Bancalà, S., Krüger, K., and Giorgetta, M.: The preconditioning of major sudden stratospheric warmings, J. Geophys. Res., 117, D04101, doi :10.1029/2011JD016769, 2012.

Barriopedro, D., García-Herrera, R. and Trigo, R. M.: Application of blocking diagnosis methods to General Circulation Models. Part I: a novel detection scheme, Clim. Dyn., 35, 7-8, 1373-1391, 2010.

Barriopedro, D., and Calvo, N.: On the relationship between ENSO, Stratospheric Sudden Warmings and Blocking, J. Climate, 27, 4704 – 4720, 2014.

Birner, T., and Albers, J. R.: Sudden stratospheric warmings and anomalous upward wave activity flux, SOLA, 13A, 8-12, doi: 10.2151/sola.13A-002, 2017.

Butler, A. H., Sjoberg, J. P., Seidel, D. J. and Rosenlof, K. H.: A sudden stratospheric warming compendium, Earth. Syst. Sci. Data, 9, 63-76, 2017.

Castanheira, J. M. and Barriopedro, D.: Dynamical connection between tropospheric blockings and stratospheric polar vortex, Geophys. Res. Lett., 37, L13809, doi:10.1029/2010GL043819, 2010.

Charlton, A. J. and Polvani, L. M.: A new look at stratospheric sudden warmings. Part I: Climatology and modeling benchmarks, J. Climate, 20, 449-469, 2007.

Charlton, A. J., Polvani, L. M., Perlwitz, J., Sassi, F., Manzini, E., Shibata, K., Pawson, S., Nielsen, J. E., and Rind, D.: A new look at stratospheric sudden warmings. Part II: Evaluation of numerical model simulations, J. Climate, 20, 470-488, 2007.

Charlton-Pérez, A. J., Polvani, L. M., Austin, J., and Li, F.: The frequency and dynamics of stratospheric sudden warmings in the 21st century, J. Geophys. Res., 113, D16116, doi:10.1029/2007JD009571, 2008.

Charlton-Pérez, A. J. and coauthors: On the lack of stratospheric dynamical variability in low-top versions of the CMIP5 models, J. Geophys. Res., 118, 2494–2505, doi:10.1002/jgrd.50125, 2013.

Cohen, J. and Jones, J.: Tropospheric precursors and stratospheric warmings, J. Climate, 24, 6562-6572, 2011.

Davini, P., Cagnazzo, C., Gualdi, S., and Navarra, A.: Bidimensional diagnostics, variability, and trends of Northern Hemisphere blocking, J. Climate, 25, 6496-6509, 2012.

Dee, D. P. and coauthors: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. R. Meteorol. Soc., 137, 553-597, 2011.

De la Cámara, A., Albers, J. R., Birner, T., García, R. R., Hitchcock, P., Kinnison, D. E. and Smith, A. K.: Sensitivity of sudden stratospheric warmings to previous stratospheric conditions. J. Atmos. Sci., 74, 2857-2877, 2017.

Díaz-Durán, A., Serrano, E., Ayarzagüena, B., Ábalos, M., and de la Cámara, A.: Intra-seasonal variability of extreme boreal stratospheric polar vortex events and their precursors, Clim. Dyn., 49, 3473–349, doi: 10.1007/s00382-017-3524-1, 2017.

Domeisen, D. I. V.: Estimating the frequency of sudden stratospheric warming events from surface observations of the North Atlantic Oscillation, J. Geophy. Res., 124, 3180-3194.

Fujiwara, M. and coauthors: Introduction to the SPARC Reanalysis Intercomparison Project (S-RIP) and overview of the reanalysis systems, Atmos. Chem. Phys., 17, 1417–1452, 2017.

Garfinkel, C. I. and Hartmann, D. L.: Different ENSO teleconnections and their effects on the stratospheric polar vortex, J. Geophys. Res., 113, D18114, doi: 10.1029/2008JD009920, 2008.

Garfinkel, C. I., Hartmann, D. L., and Sassi, F.: Tropospheric precursors of anomalous Northern Hemisphere stratospheric polar vortices, J. Climate, 23, 3282-3299, 2010.

Garfinkel, C. I., Butler, A. H., Waugh, D. W., Hurwitz, M. M., and Polvani, L. M.: Why might stratospheric sudden warmings occur with similar frequency in El Niño and La Niña winters? J. Geophys. Res., 117, F19106, doi:10.1029/2012JD017777, 2012.

Gerber, E. P., Orbe, C., and Polvani, L. M.: Stratospheric influence on the tropospheric circulation revealed by idealized ensemble forecasts. Geophys. Res. Lett., 36, L24801, https://doi.org/10.1029/2009GL04091, 2009.

Gómez-Escolar, M., Fueglistaler, S., Calvo, N. and Barriopedro, D.: Changes in polar stratospheric temperature climatology in relation to stratospheric sudden warming occurrence, Geophys. Res. Lett., 39, doi:10.1029/2012GL053632, 2012.

Hitchcock, P.: On the value of reanalyses prior to 1979 for dynamical studies. Atmos. Chem. Phys. 19, 2749-2764, https://doi.org/10.5194/acp-2018-879, 2019.

Hu, Y. and Tung, K. K.: Possible ozone-induced long-term changes in planetary wave activity in late winter, J. Climate, 16, 3027-3038, 2003.

Kalnay, E. and coauthors: The NCEP/NCAR40-year reanalysis project, Bull. Amer. Meteor. Soc., 77, 437-471, 1996.

Kanamitsu, M. and coauthors: NCEP-DOE AMIP II reanalysis (R-2), Bull. Amer. Meteor. Soc., 83, 1631-1643, 2002.

Kim, J., Son, S.-W., Gerber, E., and Park, H. –S.: Defining sudden stratospheric warming in climate models: Accounting for biases in model climatologies, J. Climate, 30, 5529-5546, 2017.

Kobayashi, S. and coauthors: The JRA-55 reanalysis: General specifications and basic characteristics, J. Meteor. Soc. Japan, 93, 5-48, 2015.

~~Labitzke, K. and Naujokat, B.: The lower arctic stratosphere in winter since 1952, SPARC Newsl., 15, 11-14, 2000.~~

Lehtonen, I. and A. Y. Karpechko: Observed and modeled tropospheric cold anomalies associated with sudden stratospheric warmings, J. Geophys. Res., 121, 1591-1610, doi:10.1002/2015JD023860, 2013.

Limpasuvan, V., Thompson, D. W. J., and Hartmann, D. L.: The life cycle of the Northern Hemisphere sudden stratospheric warmings, J. Climate, 17, 2584-2596, 2004.

Long, C. S., Fujiwara, M., Davis, S., Mitchell D. M., and Wright, C. J.: Climatology and interannual variability of dynamic variables in multiple reanalyses evaluated by the SPARC Reanalysis Intercomparison Project (S-RIP), Atmos. Chem. Phys., 17, 14593–14629, 2017.

Martineau, P., Son, S-W, Taguchi, M., and Butler, A. H.: A comparison of the momentum budget in reanalysis datasets during sudden stratospheric warming events, Atmos. Chem. Phys., 18, 7169-7187, 2018.

Martius, O., Polvani, L. M., and Davies, H. C.: Blocking precursors to stratospheric sudden warming events. Geophys. Res. Lett., 36, L14806, doi:10.1029/2009GL038776, 2009.

Matsuno, T.: A dynamical model of stratospheric sudden warming, J. Atmos. Sci., 28, 1479–1494, 1971.

Maycock, A. C. and Hitchcock, P.: Do split and displacement sudden stratospheric warmings have different annular mode signatures? Geophys. Res. Lett., 42, 10943-10951, 2015.

McLandress, C., and Shepherd, T. G.: Impact of climate change on stratospheric sudden warmings as simulated by the Canadian Middle Atmosphere Model, J. Climate, 22, 5449-5463, 2009.

Mitchell, D. M., Gray, L. J., Anstey, J., Baldwin, M. P., and Charlton-Perez, A. J.: The influence of stratospheric vortex displacements and splits on surface climate, J. Climate, 26, 2668–2682, 2013.

Nakagawa, K. I. and Yamazaki, K.: What kind of stratospheric sudden warming propagates to the troposphere? Geophys. Res. Lett, 33, L04801, doi: 10.1029/2005GL024784, 2006.

Nishii, K., Nakamura, H., and Miyasaka, T.: Modulations in the planetary wave field induced by upward-propagating Rossby wave packets prior to stratospheric sudden warming events: A case-study, Q. J. R. Meteorol. Soc., 135, 39-52, 2009.

Nishii, K., Nakamura, H., and Orsolini, Y. J.: Geographical dependence observed in blocking high influence on the stratospheric variability through enhancement and suppression of upward planetary-wave propagation, J. Climate, 24, 6408-6423, 2011.

Onogi, K. and coauthors: The JRA-25 reanalysis, J. Meteor. Soc. Japan, 85, 369-432, 2007.

Palmeiro, F. M., Barriopedro, D., García-Herrera R., and Calvo, N.: Comparing sudden stratospheric warming definitions in reanalysis data, J. Climate, 28, 6823-6840, 2015.

Plumb, R. A.: Instability of the distorted polar night vortex: A theory of stratospheric warmings, J. Atmos. Sci., 38, 2514–2531, 1981.

Reichler, T., Kim, J., Manzini, E., and Kröger, J.: A stratospheric connection to Atlantic climate variability, Nat. Geosci., 5, 783-787, 2012.

Rex, D. F.: Blocking action in the middle troposphere and its effect upon regional climate. Tellus, 2, 196–211, doi:10.1111/j.2153-3490.1950.tb00331.x, 1950.

Rienecker, M. M. and coauthors: MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications, J. Climate, 24, 3624-3648, 2011.

Saha, S. and coauthors: The NCEP climate forecast system reanalysis, Bull. Amer. Meteor. Soc., 91, 1015-1057, 2010.

Sausen, R., König, W., and Sielmann, F.: Analysis of blocking events from observations and ECHAM model simulations, Tellus, 47A, 421–438, 1995.

Scherrer, S. C., Croci-Maspoli, M., Schwierz, C., and Appenzeller, C.: Two-dimensional indices of atmospheric blocking and their statistical relationship with winter climate patterns in the Euro-Atlantic region, Int. J. Climatol., 26, 233-249, 2006.

Schimanke, S., Körper, J., Spangehl, T., and Cubasch, U.: Multi-decadal variability of sudden stratospheric warmings in an AOGCM, Geophys. Res. Lett., 38, L01801, oi:10.1029/2010GL045756, 2011.

Seviour, W. J. M., Mitchell, D. M., and Gray, L. J.: A practical method to identify displaced and split stratospheric polar vortex events, Geophys. Res. Lett., 40, 5268–5273, doi:10.1002/grl.50927, 2013.

Sjoberg, J. P., and Birner, T.: Stratospheric wave-mean flow feedbacks and sudden stratospheric warmings in a simple model forced by upward wave activity flux. J. Atmos. Sci., 71, 4055-4071, 2014.

Smith, K. L. and Kushner, P. J.: Linear interference and the initiation of extratropical stratosphere–troposphere interactions. J. Geophys. Res., 117, D13107, doi: 10.1029/2012JD017587, 2012.

Taguchi, M. and Hartmann, D. L.: Increased occurrence of stratospheric sudden warmings during El Niño as simulated by WACCM, J. Climate, 19, 324-332, 2006.

Taguchi, M.: Is there a statistical connection between stratospheric sudden warming and tropospheric blocking events? J. Atmos. Sci., 65, 1442-1454, 2008.

Treidl, R. A., Birch, E.C., and Sajecki, P.: Blocking action in the Northern Hemisphere: A Climatological study, Atmosphere-Ocean, 19, 1-23, 1981.

Tripathi, O. P. and coauthors: Examining the predictability of the stratospheric sudden warming of January 2013 using multiple NWP systems, Mon. Wea. Rev., 144, 1935–1960, 2016.

Uppala S. M. and coauthors: The ERA-40 re-analysis, Q. J. R. Meteorol. Soc., 131, 2961-3012, 2005.

Waugh, D. W.: Elliptical diagnostics of stratospheric polar vortices, Q. J. R. Meteorol. Soc., 123, 1725-1748, 1997.

White, I., Garfinkel, C. I., Gerber, E. P., Jucker, M., Aquila, V., Oman, L. D.: The downward influence of sudden stratospheric warmings: Association with tropospheric precursors, J. Climate, 32, 85-108, 2019.

Wiedenmann, J. M., Lupo, A. R., Mokhov, I. I., and Tikhonova, E. A.: The climatology of blocking anticyclones for the Northern and Southern Hemispheres: Block intensity as a diagnostic, J. Climate, 15, 3459-3473, 2002.

Woollings, T.J., Hoskins, B. J., Blackburn, M., and Berrisford, P.: A new Rossby wave-breaking interpretation of the North Atlantic Oscillation. J. Atmos. Sci., 65, 609–626, 2008.

Woollings, T., Charlton-Perez, A., Ineson, S., Marshall, A. G., and Masato, G.: Associations between stratospheric variability and tropospheric blocking, J. Geophys. Res., 115, D06108, doi:10.1029/2009JD012742, 2010.

Woollings, T., Barriopedro, D., Methven, J., Son, S-W., Martius, O., Harvey, B., Sillmann, J., Lupo, A. R., and Seneviratne, S.: Blocking and its response to climate change. Curr. Clim. Change Rep., 4, 287-300, 2018.

Table 1: Classification of the common SSWs into WN1 and WN2 events in the comparison period. (In brackets the S/D classification).

WN1 SSWs		WN2 SSWs
29 02 1980 (D)	11 02 2001 (D)	22 02 1979 (S)
04 03 1981 (D)	31 12 2001 (D)	01 01 1985 (S)
04 12 1981 (D)	18 01 2003 (S)	21 02 1989 (S)
24 02 1984 (D)	05 01 2004 (D)	20 03 2000 (D)
23 01 1987 (D)	21 01 2006 (D)	22 02 2008 (D)
08 12 1987 (S)	24 02 2007 (D)	24 01 2009 (S)
14 03 1988 (S)	09 02 2010 (S)	
15 12 1998 (S)	24 03 2010 (D)	
26 02 1999 (S)		

Table 2: Frequency of SSWs per decade and ratio of vortex displacement (D) vs vortex split (S) SSWs for each reanalysis and period of study.

	Historical period (1958-1978)		Comparison period (1979-2012)	
Reanalyses	**Frequency (SSWs/dec)**	**Ratio D/S**	**Frequency (SSWs/dec)**	**Ratio D/S**
ERA-40	6.2	1.6		
NCEP-NCAR	4.8~~3~~	0.7~~5~~	6.2	1.6
JRA-55	5.7~~2~~	1.0~~.8~~	6.8	1.2
ERA-Interim			6.2	1.6
JRA-25			6.5	1.8
NCEP-CFSR			6.5	1.4
NCEP-DOE			6.5	1.4
NASA-MERRA			6.5	1.2

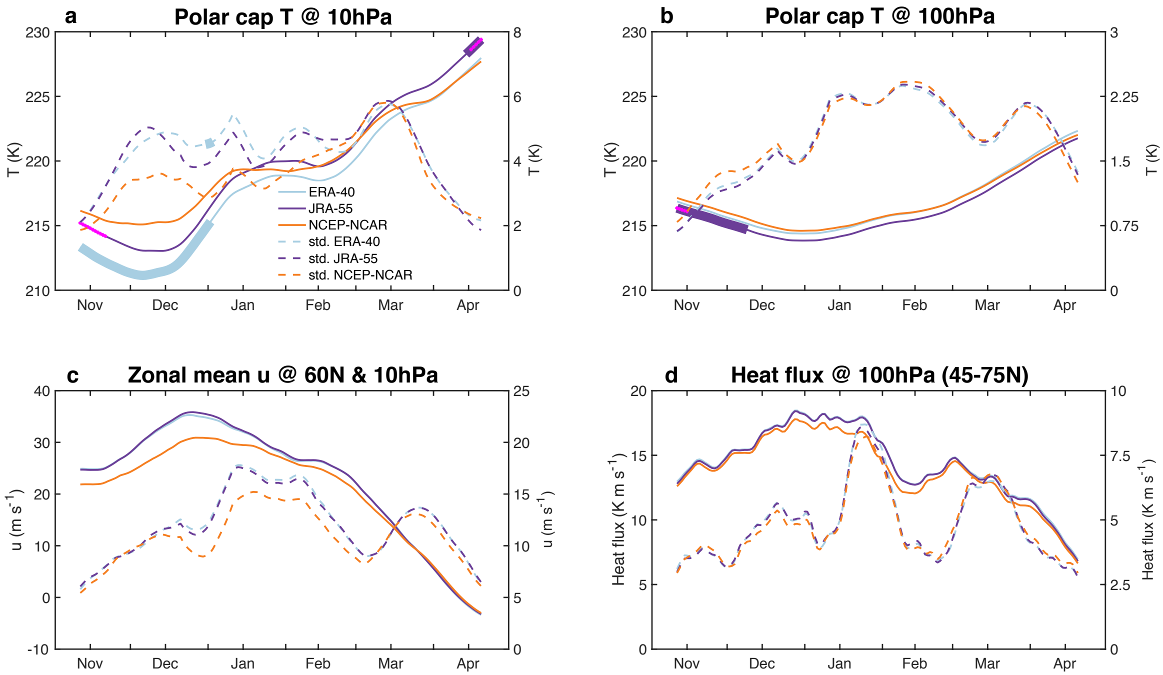
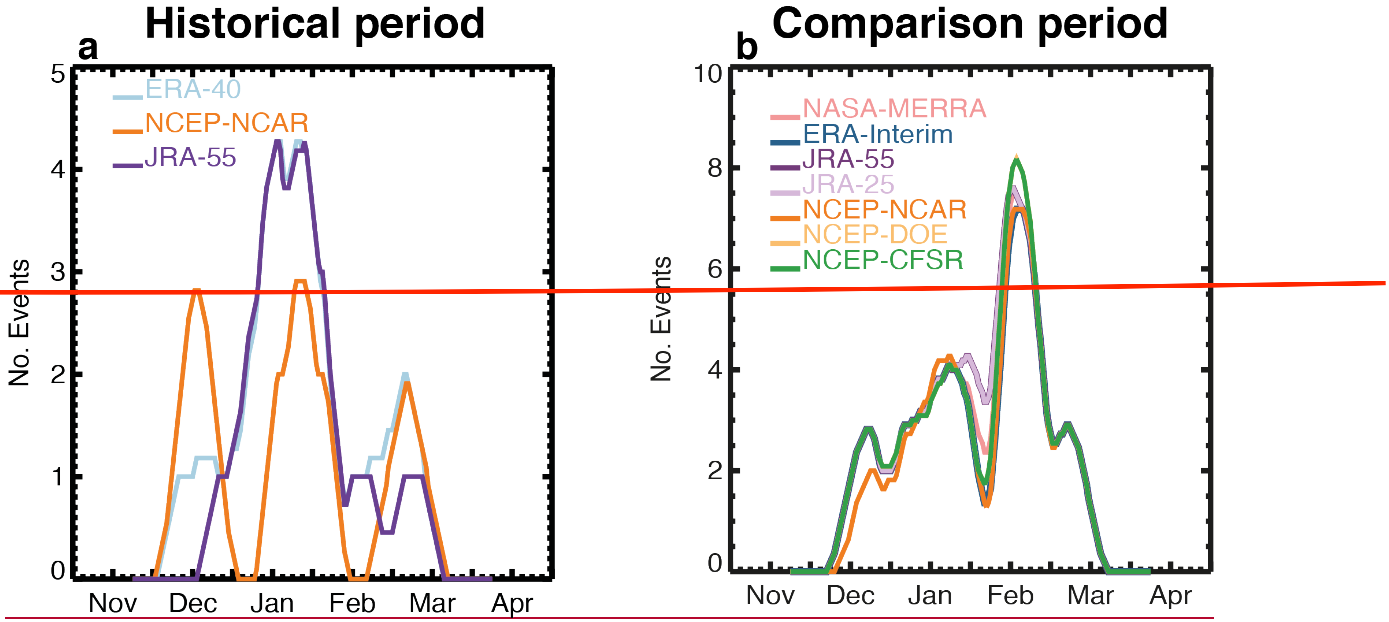


Figure 1: 21-day running mean of the daily climatology (solid line) and standard deviation (dashed line) in the historical period (1958-1978) of: (a) polar-cap (50ºN -90ºN) averaged temperature at 10 hPa, (b) polar-cap (50ºN -90ºN) averaged temperature at 100 hPa, (c) zonal mean zonal wind at 60°N and 10 hPa and (d) heat flux at 100 hPa averaged over 45ºN -75°N. The left (right) y-axis refers to the mean (standard deviation) in each plot. Thick lines indicate values of ERA-40 or JRA-55 that are significantly different from those of NCEP-NCAR reanalysis at the 95% confidence level. Magenta crosses correspond to JRA-55 values that are significantly different from ERA-40 ones at the 95% confidence level (Student's t-test).



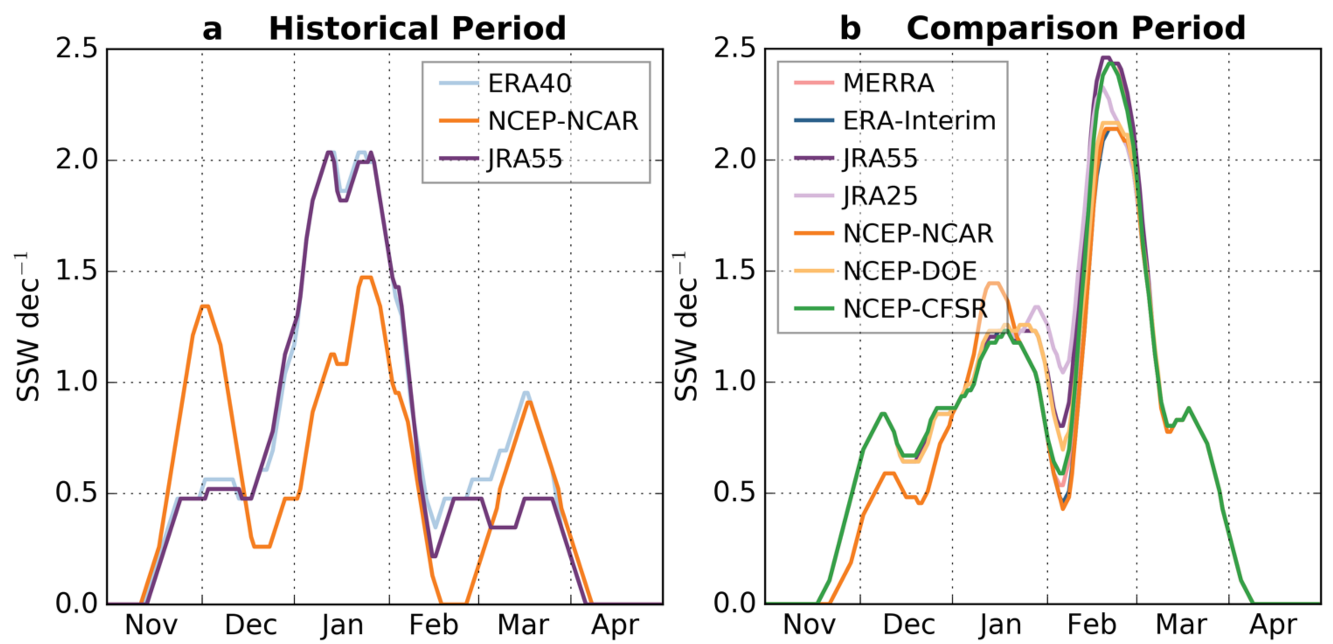


Figure 2. SSW total frequency distribution within ±10 day periods from the date displayed in the x-axis for: (a) the historical period (1958-1978) and (b) the comparison period (1979-2012).

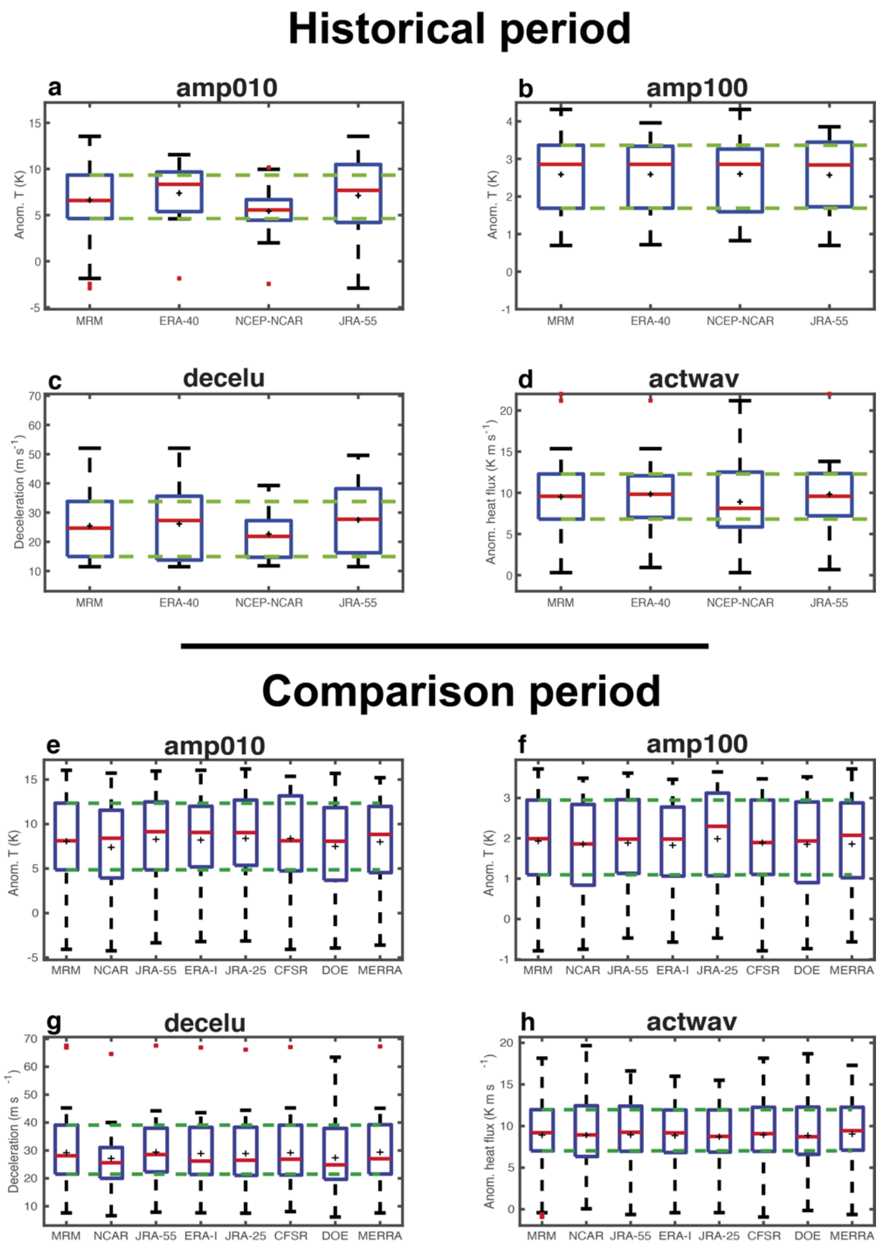
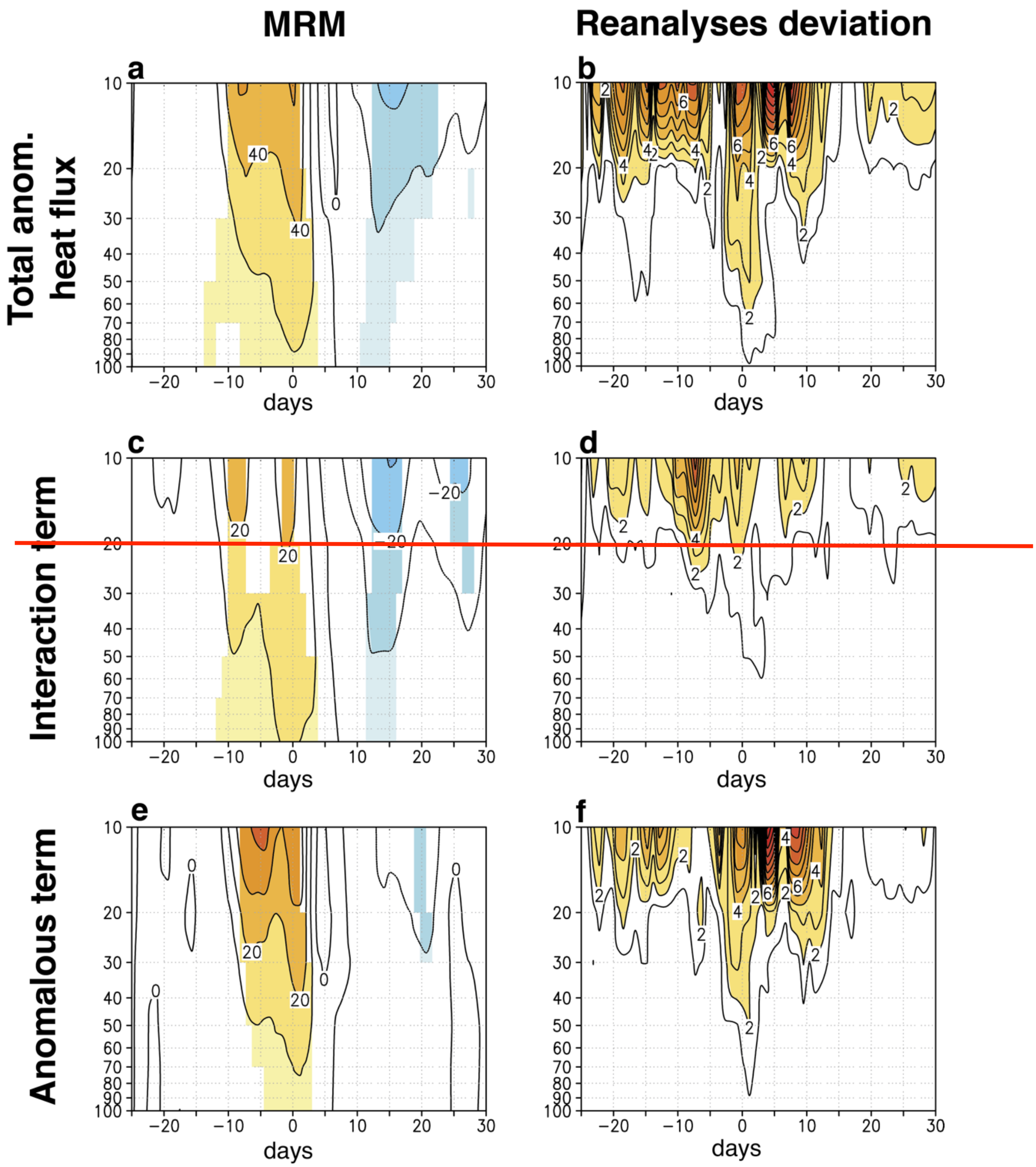


Figure 3. Box plots showing the distribution of the dynamical benchmarks of SSWs (amp010, amp100, decelu and actwav) in the historical (1958-1978) and comparison (1979-2012) periods. The interquartile range is represented by the size of the box and the red line (black cross) corresponds to the median (mean). Whiskers indicate the maximum and minimum points in the distribution that are not outliers. Outliers (red crosses) are defined as points with values greater than 3/2 times the interquartile range from the ends of the box. See text for the definition of dynamical benchmarks.



MRM
Reanalyses deviation
Total anom. heat flux
Interaction term
Anomalous term
a
b
c
d
e
f
days

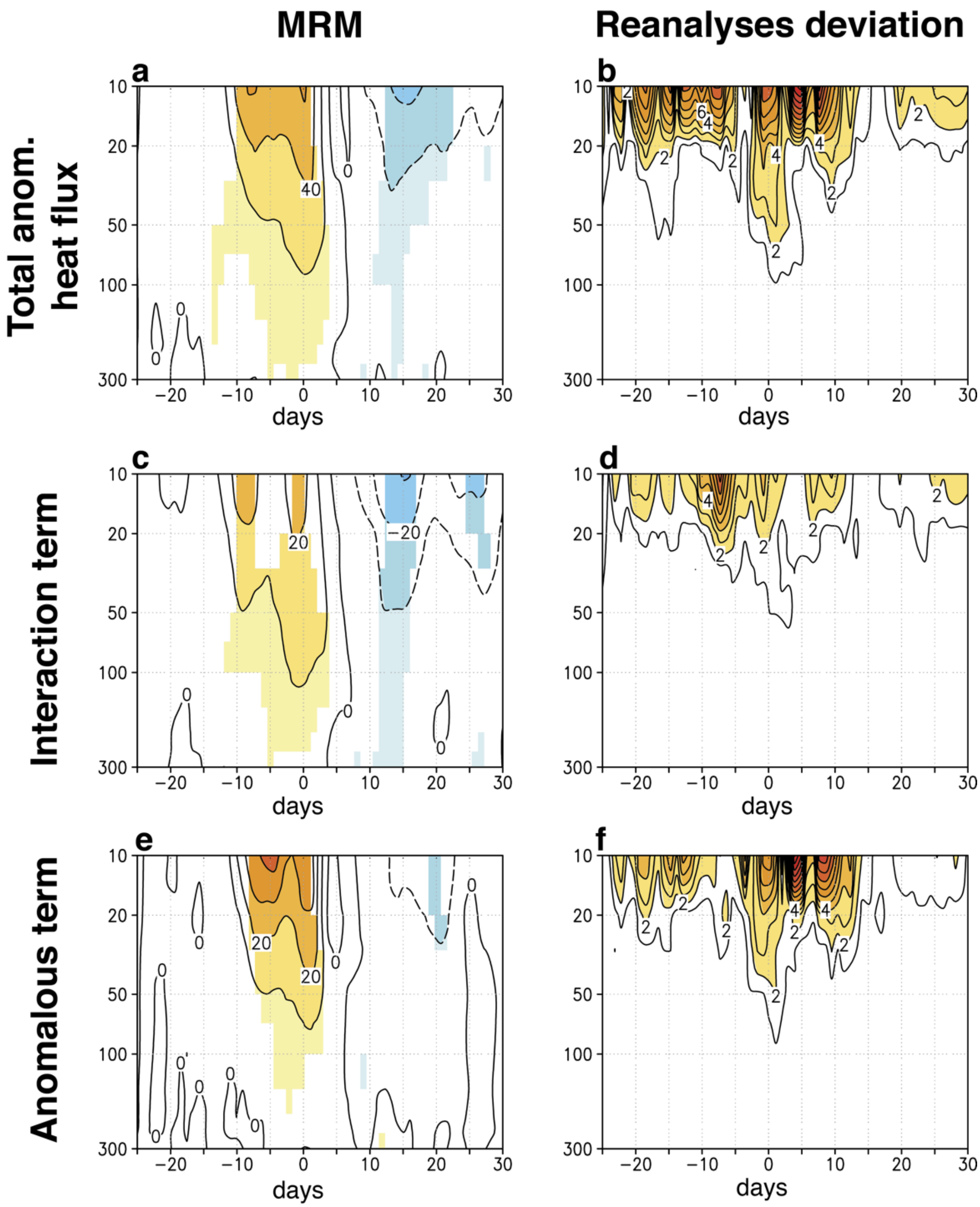
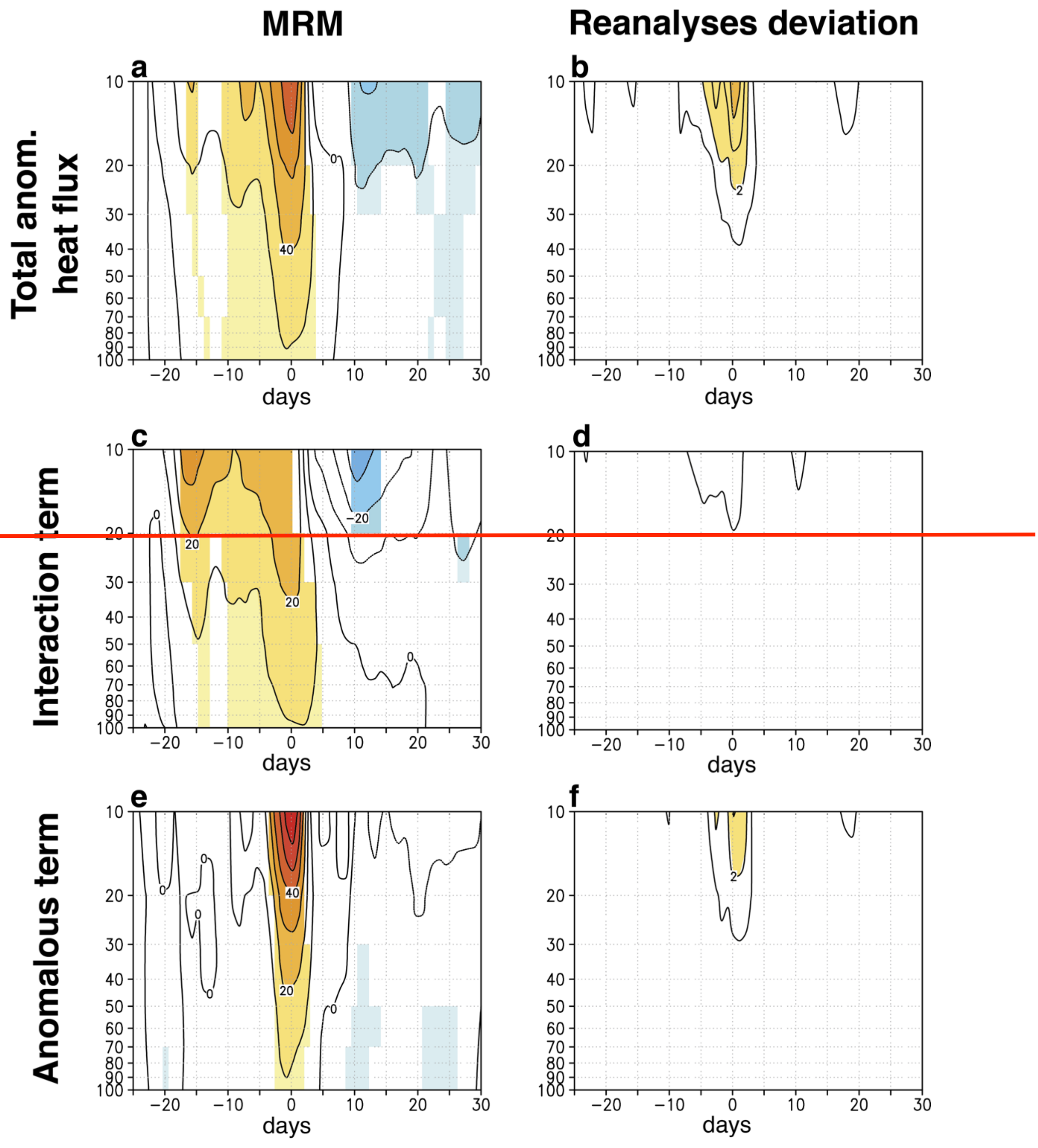


Figure 4. (a) Composited time evolution of the total anomalous heat flux averaged over 45°N-75°N (K m s^{-1}) at different pressure levels from 29 days before to 30 days after the occurrence of SSWs in the historical (1958-1978) period. Contour interval is 20 K m s^{-1}. (b) Same as (a) but for the standard deviation of the reanalyses with respect to the MRM divided by the square root of the number of reanalyses. Contour interval is 1 K m s^{-1}. (c) and (d) Same as (a) and (b) but for the interaction between climatological and anomalous waves. Contour intervals are 10 K m s^{-1} and 2 K m s^{-1}, respectively. (e) and (f) Same as (a) and (b) but for the contribution of the anomalous waves to the total anomalous heat flux. Contour intervals are 10 K m s^{-1} and 2 K m s^{-1}, respectively. Shading in (a), (c) and (e) denotes statistically significant anomalies at the 95% confidence level of the same sign in at least 66.7% of all reanalyses (Monte-Carlo test).


MRM
Reanalyses deviation
Total anom. heat flux
Interaction term
Anomalous term
a
b
c
d
e
f
days

635

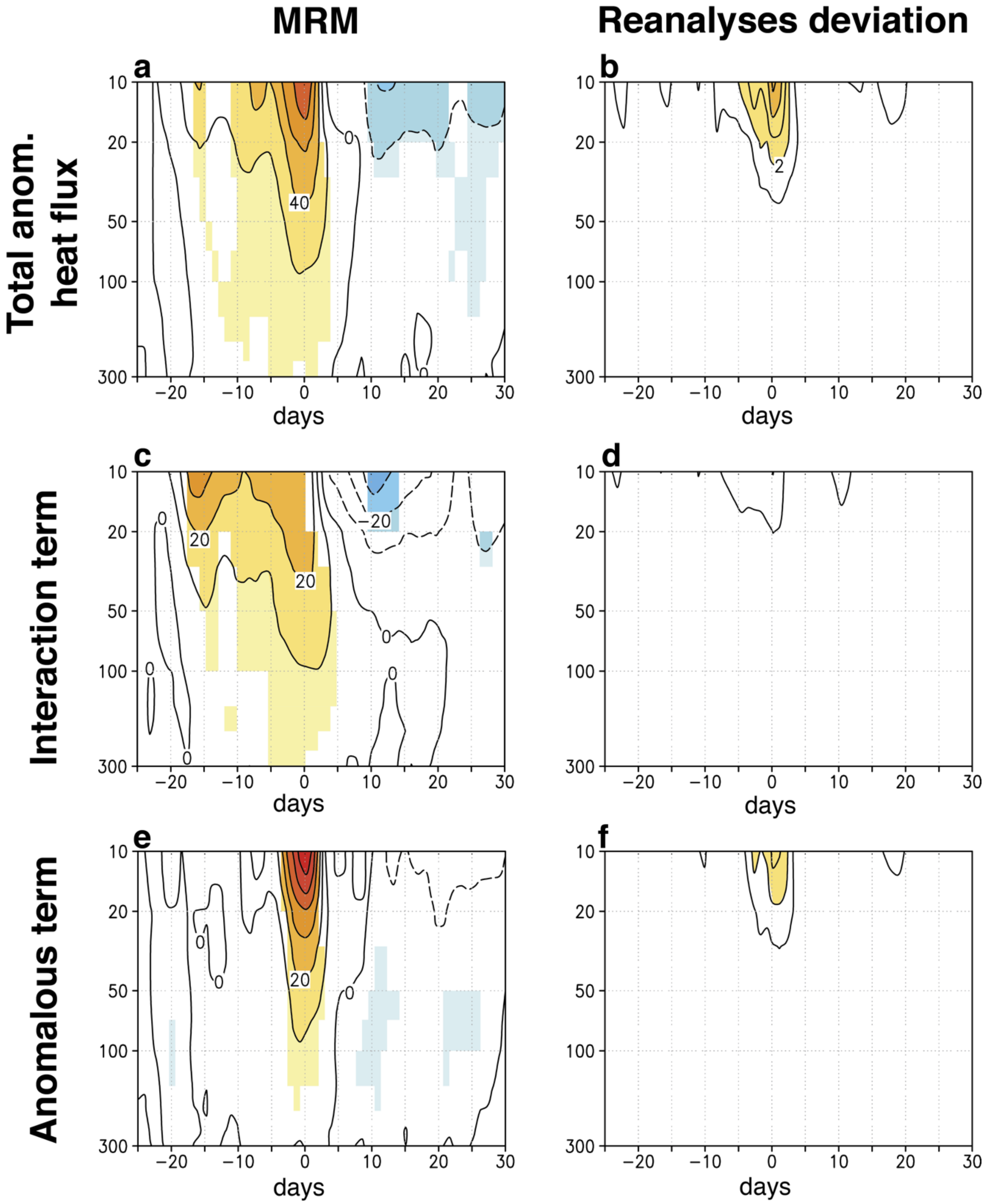
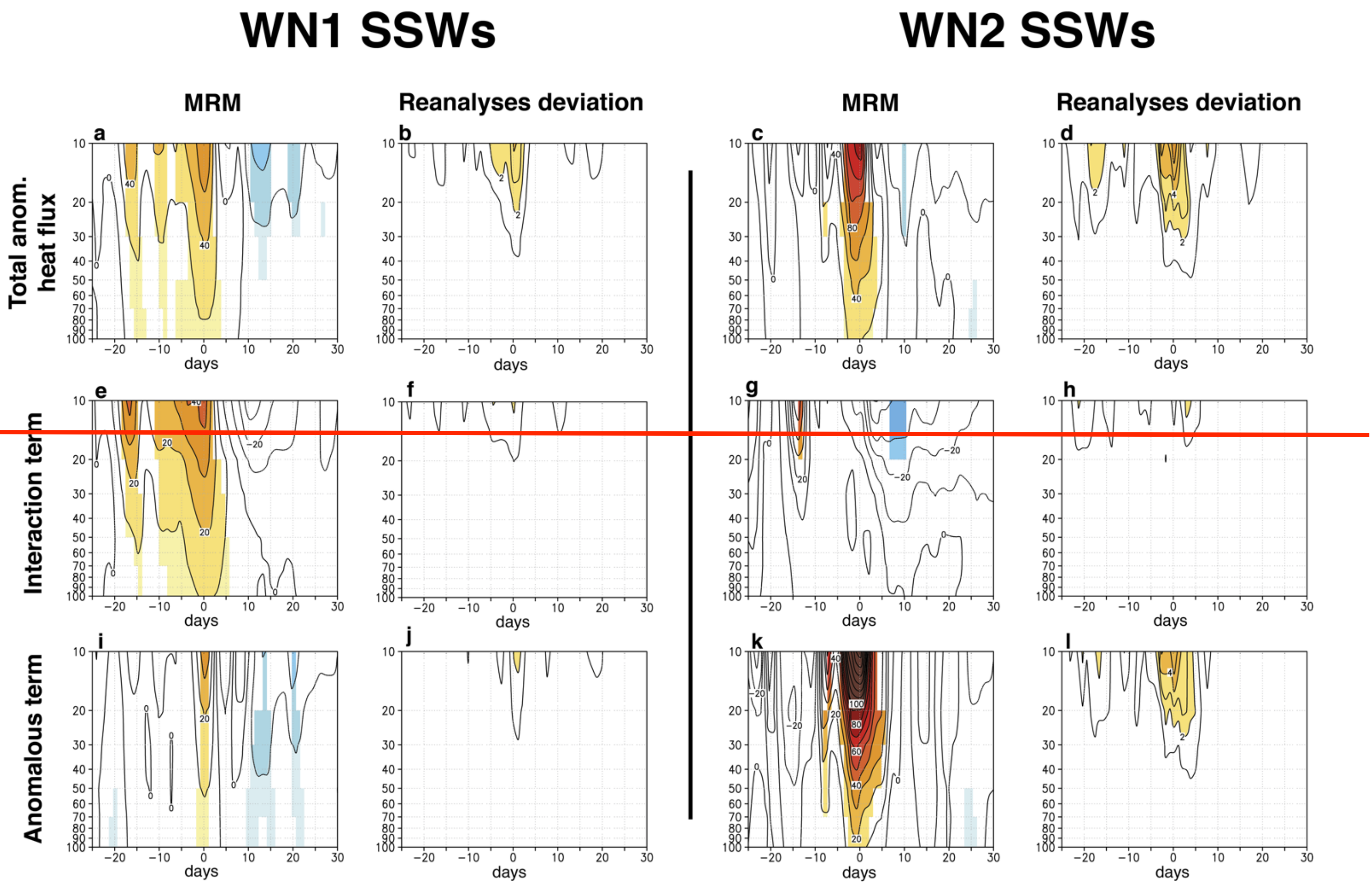


Figure 5. Same as Fig. 4 but for the comparison (1979-2012) period.


WN1 SSWs
WN2 SSWs
MRM
Reanalyses deviation
MRM
Reanalyses deviation
Total anom. heat flux
Interaction term
Anomalous term
a
b
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d
e
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i
j
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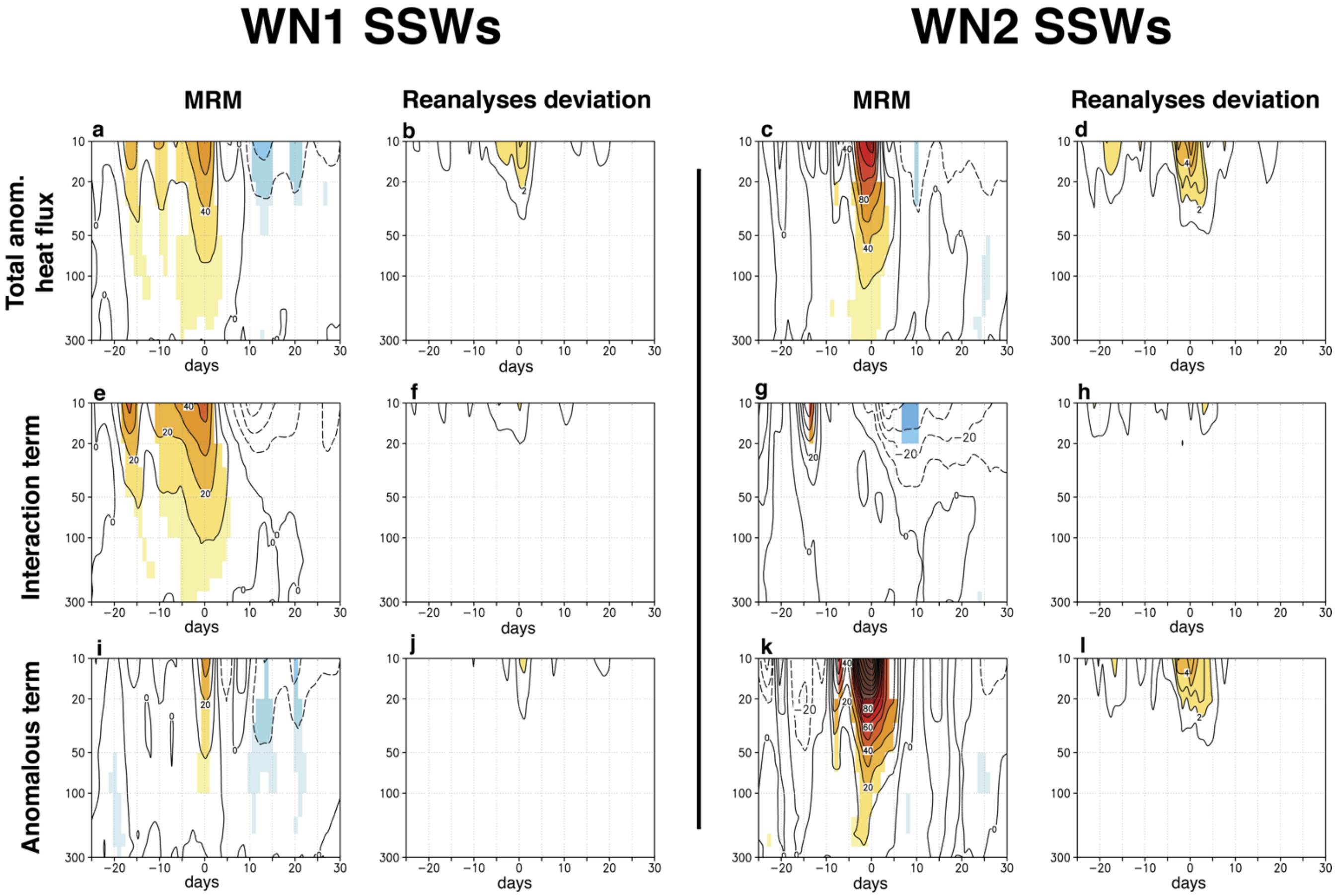
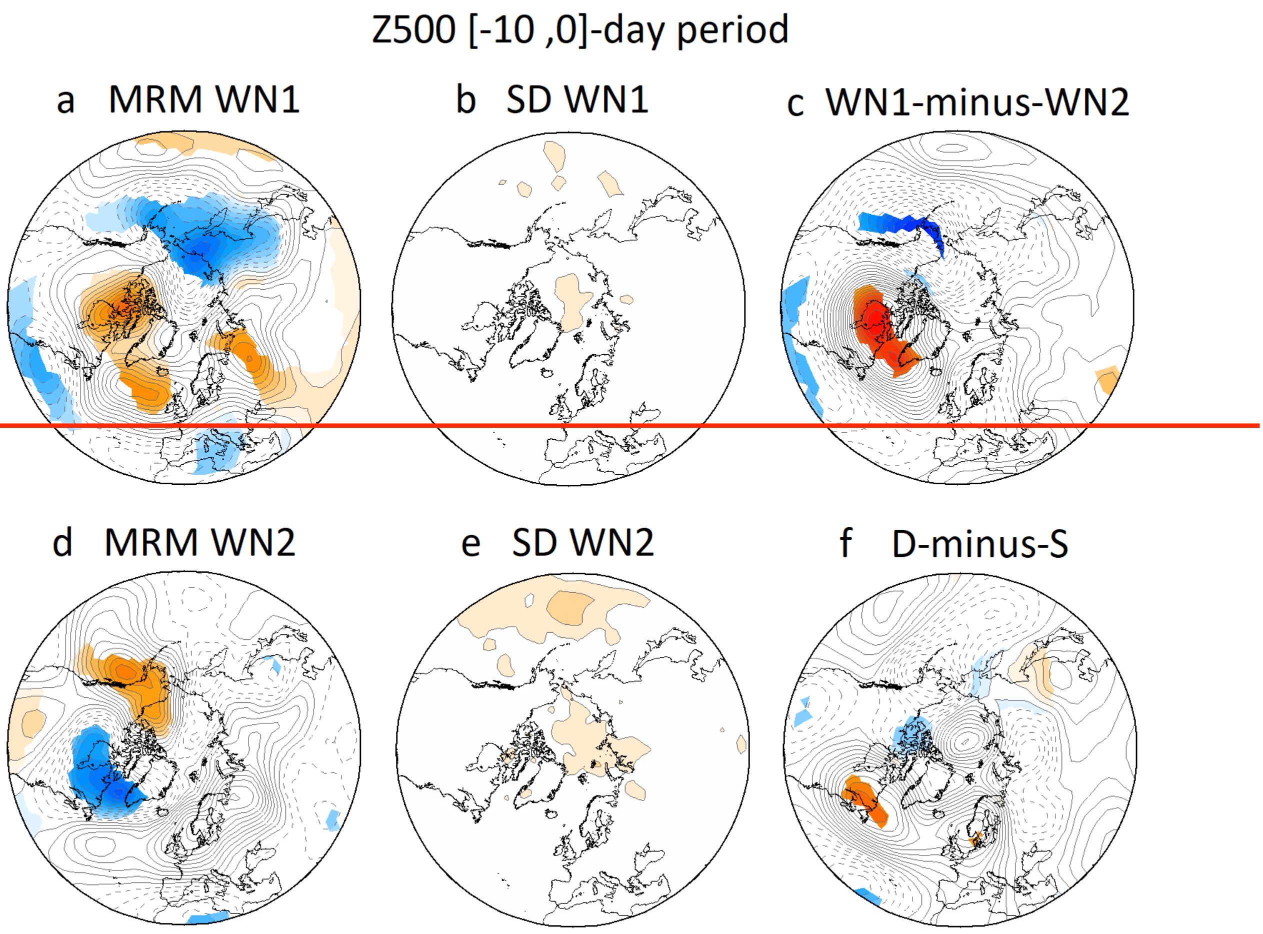
days



640 **Figure 6. Same as Fig. 5 but for WN1 SSWs (left) and WN2 SSWs (right).**


Z500 [-10 ,0]-day period
a MRM WN1
b SD WN1
c WN1-minus-WN2
d MRM WN2
e SD WN2
f D-minus-S

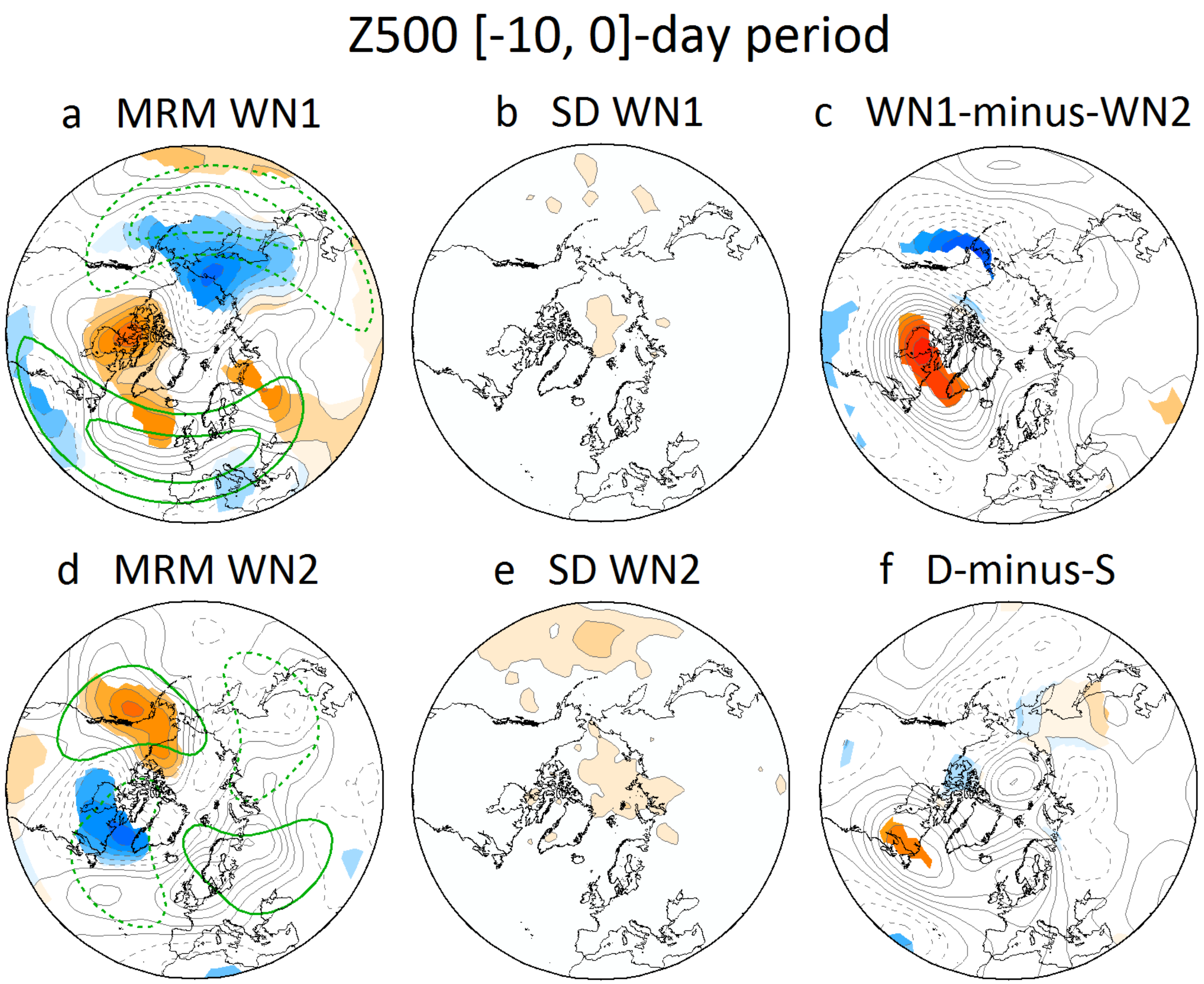


Figure 7. **(a) MRM of WN1 SSW-based composites of 500-hPa geopotential height anomalies (contour interval 20~~10~~ gpm) in the [-10, 0]-day period before events for the comparison (1979-2012) period. Only statistically significant anomalies at the 95% confidence level of the same sign (Monte-Carlo test) in at least 66.7% of all reanalyses are ~~plotted~~shaded. (b) Standard deviation of the reanalyses with respect to the MRM divided by the square root of the number of reanalyses for WN1 SSWs (contour interval is 1 gpm). (c) Same as (a) but for the WN1 SSWs minus WN2 SSWs differences of MRM composites of 500-hPa geopotential height anomalies. Shading denotes statistically significant differences at the 95% confidence level in at least 66.7% of all reanalyses (Monte-Carlo test). (d) and (e) Same as (a) and (b) but for WN2 SSWs, respectively. (f) Same as (c) but for displacement-minus-split events. Green contours in (a) and (d) show the MRM climatological WN1 and WN2 of 500-hPa geopotential height from November to March, respectively (contours: ±40 and ±80 gpm).**

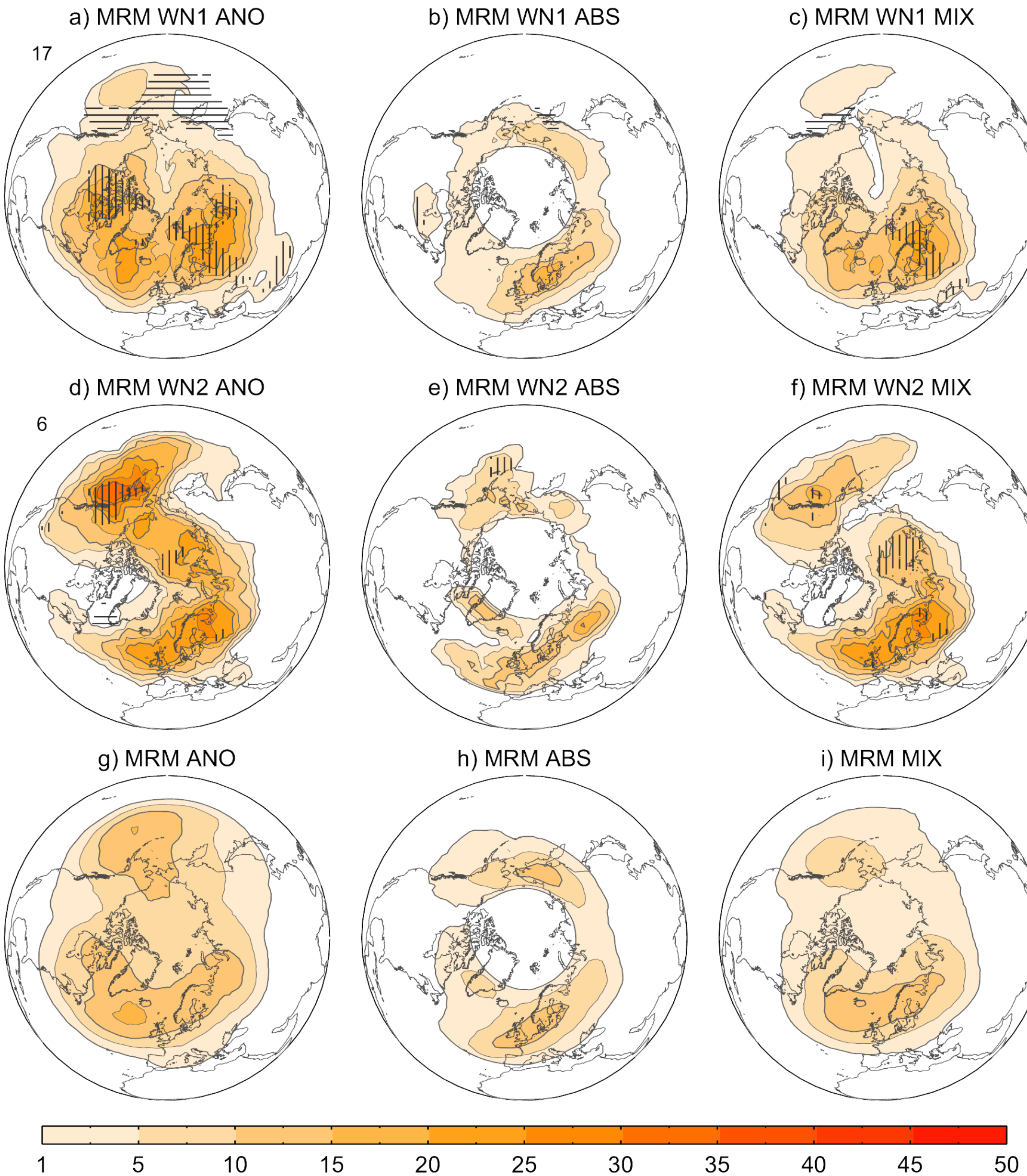
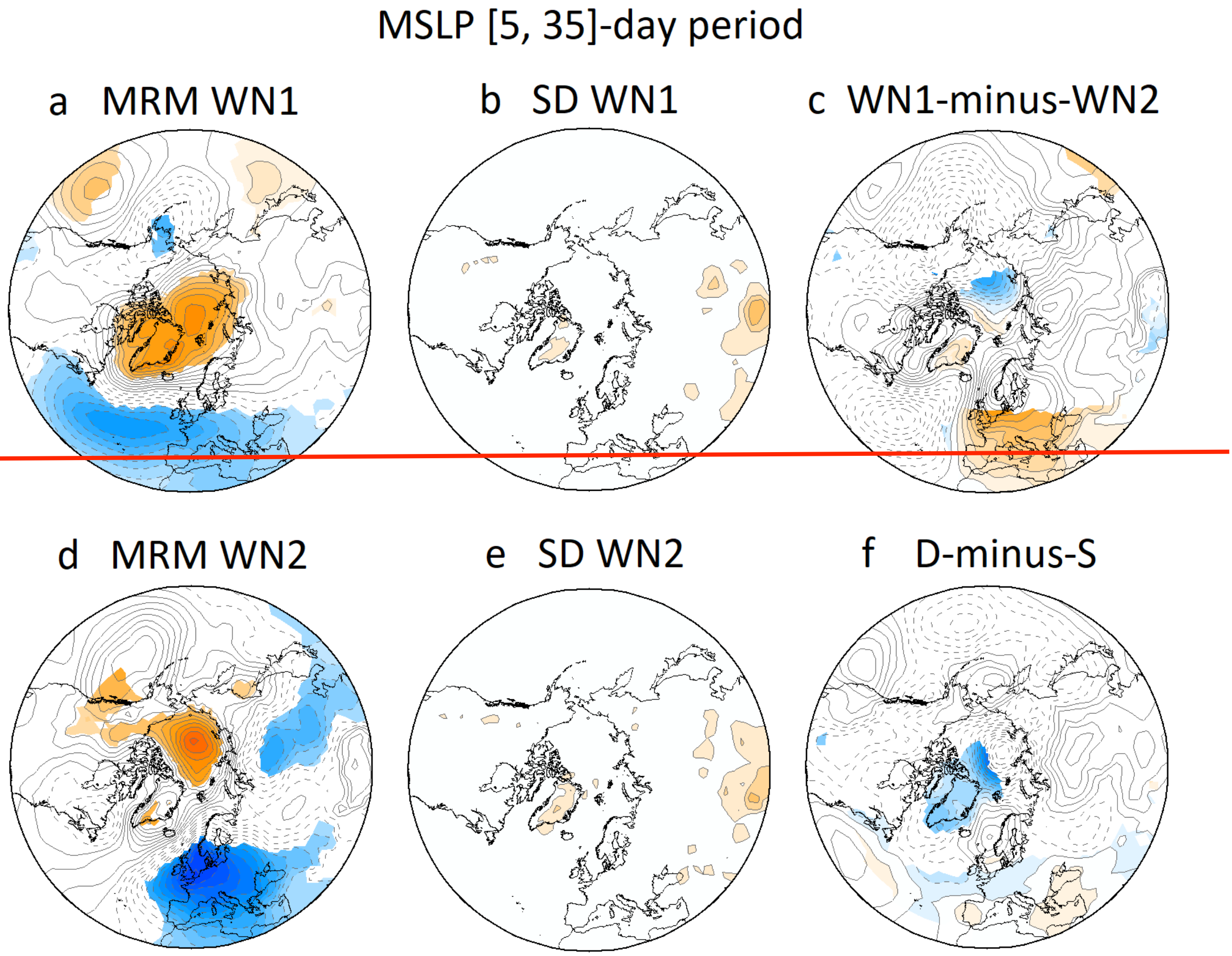


Figure 8. (a-c) MRM of blocking frequency (% of winter days) for the [-10, 0]-day period before the central date of WN1 SSWs of the comparison period (1979-2012) for the: (a) anomaly, (b) absolute, (c) mixed method. The blocking frequency is expressed as the percentage of time (over the 11-day period) during which a blocking was detected at each grid point. Vertical (horizontal) hatching denotes regions where at least 66.7% of the reanalyses show a significant increase (decrease) of the frequency with respect to the climatology at the 90% confidence level. (d-f) Same as (a-c) but for WN2 SSWs. (g-i) MRM of the mean blocking frequency in 1000 Monte Carlo trials of 11-day intervals preceding all SSWs dates of the comparison period. In each trial, a set of 11-day intervals prior to the SSWs dates of random years is averaged, so that we obtain a pseudo-climatology of the blocking frequency in the same winter moments as when the SSWs took place. This method avoids any effects of the seasonal cycle of the blocking activity during the extended winter (NDJFM) that would affect the result if we averaged directly the blocking activity during that season.


MSLP [5, 35]-day period
a MRM WN1
b SD WN1
c WN1-minus-WN2
d MRM WN2
e SD WN2
f D-minus-S

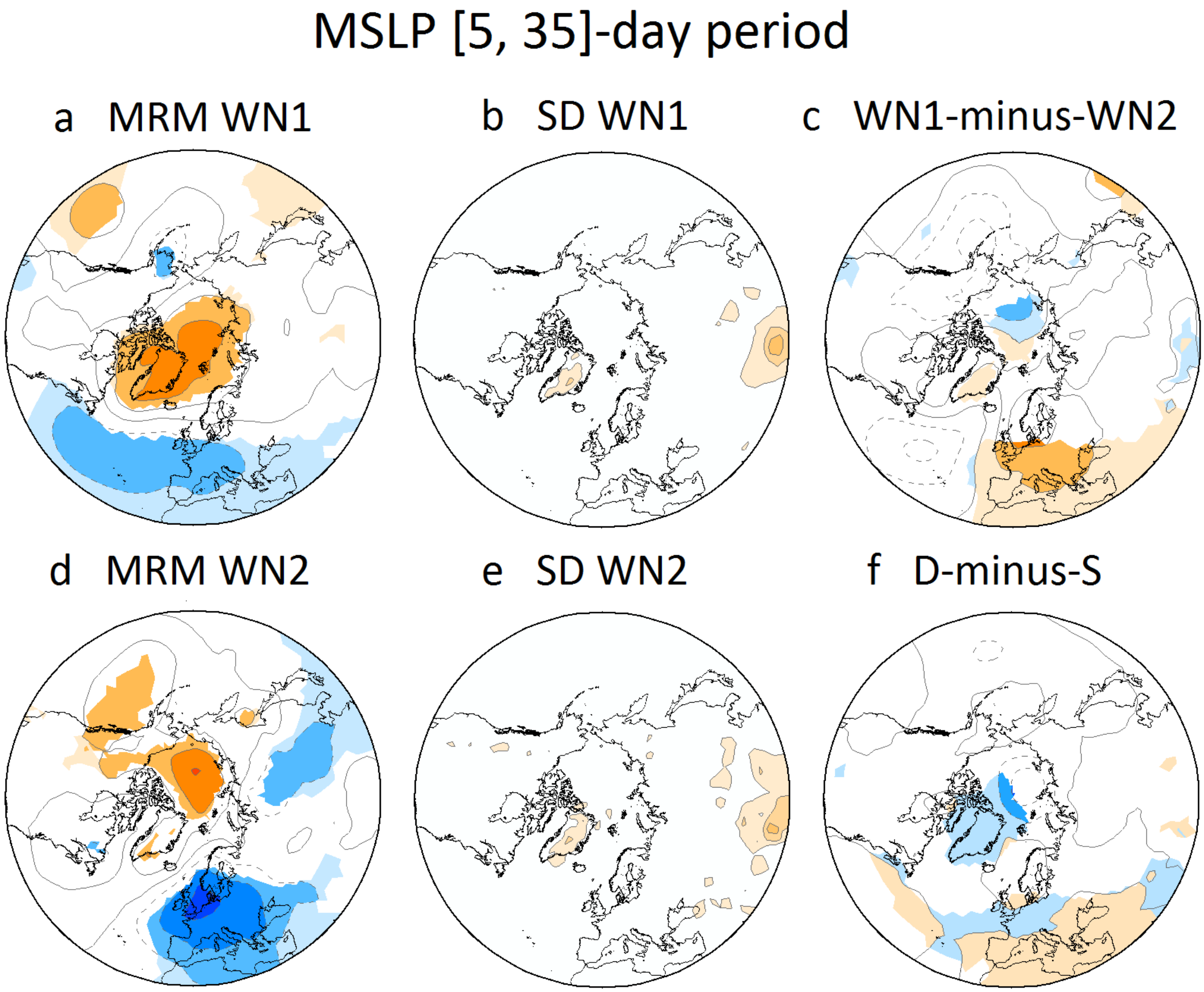


Figure 9. Same as Fig. 7 but for MSLP and the [5,35]-day period after SSWs. Contour interval is 2~~0.5~~ hPa for MRM composites and differences and 0.1 hPa for the standard deviation of the reanalyses.

Supplementary material

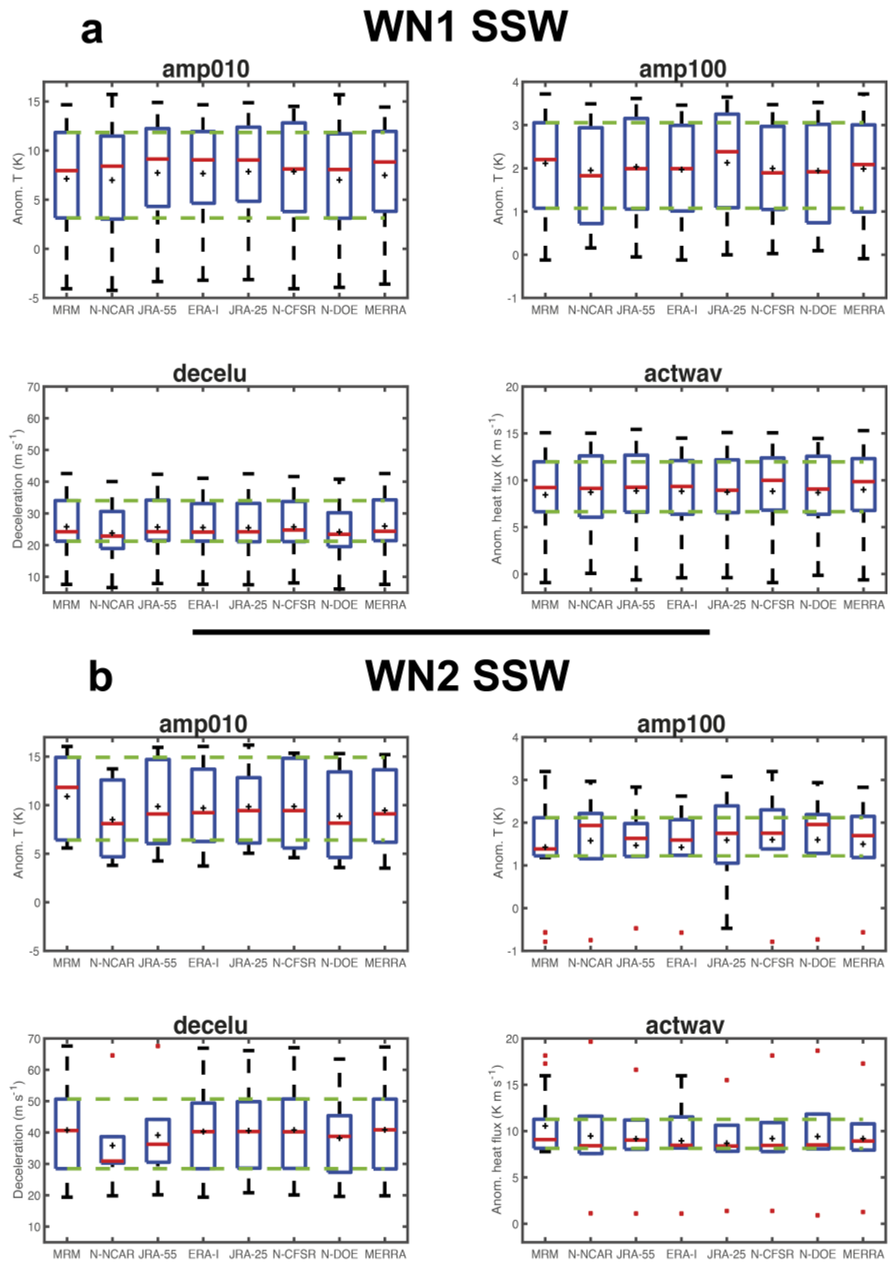


Figure S1. Box plots showing the distribution of the dynamical benchmarks of (a) WN1 SSWs and (b) WN2 SSWs in the comparison periods. The interquartile range is represented by the size of the box and the red line (black cross) corresponds to the median (mean). Whiskers indicate the maximum and minimum points in the distribution that are not outliers. Outliers (red crosses) are defined as points with values greater than 3/2 times the interquartile range from the ends of the box.