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.

Reply to Referee #1

General Comments This paper examines the future increase/decrease of SSWs due to anthropogenic forcing in a large ensemble of models (12) from the CCMI database. Previous studies have had opposing views on this with some finding an increase in the number of SSWs whilst others have found a decrease. To check the robustness, they use three different commonly-used SSW criteria and conclude that they do not find a significant increase in the future number of SSWs over the course of the 21st century. I find the results to be interesting in that, by using a much larger number of models than previously used, the overall number of SSWs will remain approximately the same. The paper is well-written and the topic is well discussed, hence I suggest only minor corrections which I list below.

Thanks a lot for your comments. Here is our reply to the specific and technical comments in black:

Specific Comments

1) Lines51-52; not just due to anomalously large injections of wave activity from the troposphere, but can also be due to the resonance of wave activity such as that first described in Plumb (1981) and shown by Esler and Scott (2005). I would either cite this second mechanism, or just change the wording in your current sentence to be less definite.
We have modified the sentence to be less definite.

2) Line 53-54; Small point, but not all SSWs can impact the troposphere (e.g., Gerber et al. 2010, GRL and Hitchcock and Simpson 2014). I would instead just add the word 'can' into the sentence to change it from meaning all as it is currently: 'SSWs can also impact the. . .'
Done

3) Line 151; which criteria are absolute and which are relative? Can you somewhere distinguish between the two – from what I can see, the U6090N and WMO are absolute and ZPOL is relative.
It is stated at the end of Section 2.2 (old Line 136) which criteria are absolute and which one is relative. Nevertheless, we have also included a reminder in Section 3.1 (Line 163 in the marked-up manuscript).

4) Line 184-185; at which confidence level do the models simulate statistically significant differences between the SSW duration in the past and in the future? Can you make a comment here on the 90% level? Perhaps just say how many models would become significant if this level was used. My guess is that the HADGEM3-ES and MRIESM-1r1 would be significant at close-to the 95% level as the error bars are nearly separated.
In the case of the multimodel mean, the future change in the duration of SSWs is only statistically significant at the 80% confidence level. When examining each individual model, only HadGEM3-ES shows a statistically significant change in the SSW duration at the 90% confidence level. Apart from HadGEM3-ES, the referee also suggests that the future change for MRI-ESM1r1 might be also statistically significant at the 90% confidence level. However, in that case, this difference would be statistically significant at the 71% confidence level. Probably, the referee got that impression because the error bar of the past extends up to the mean value of the future period and so, it is not easy to identify the end of the first bar.
Following referee's suggestion, we have made a comment on the model that simulates statistically significant differences in the SSW duration between the past and the future at the 90% confidence level (L199-200 in the marked-up manuscript).

5) Line 191; the eddy heat flux (v'T') is what you plot right? This is a proxy for the injection of wave activity. Can you make this clearer? Further, I gather from figure 3 that you use 100hPa (I think this should be included here in the text also), but given the recent paper by de la Camara et

al. (2017) and Birner and Albers (2017), who suggest that 100hPa is not an ideal surface to use as it is already in the bottom of the vortex, how sensitive are you results to the level of choice? Do you get more significant results if you use a slightly lower level?

The referee is correct. Figure 3 shows anomalous eddy heat flux at 100hPa and averaged between 45º-75ºN (aHF100). We have described that in Section 2.3 and included a small comment in new Section 3.4 to make it clearer (L217-218 in the marked-up manuscript).

We acknowledge that these 2 recent papers show that 300hPa is maybe a better level to use than 100hPa. However, 100hPa is the traditional metric and our choice is in line with all previous work. More importantly, we do not have output at 300hPa for some models and so, we cannot do these calculations.

6) Section 2.2 and Line 197; I would be interested to see what the changes between the number of splits and displacements are between the past and the future. From figure 3 it appears that the wave 1 and wave 2 forcing through 100hPa doesn't change too much between each period and so the number of splits and displacements may not change too much either. But given the relatively short length of the paper as it is, this would be an interesting addition.

Thanks for the suggestion. We had indeed started looking at the number of split and displacements SSWs in the past by applying a similar algorithm to Charlton and Polvani (2007). However, the results showed a bias of most models towards an unrealistically high number of displacements events, probably due to a too strong climatological wavenumber 1 wave component in December and January. Thus, given that models could not realistically reproduce the distribution of split and displacements SSWs in the past, we decided not to explore this further. However, figure 3 of the manuscript suggests a null change in the number of splits and displacements as the referee indicates. In the revised version and based on referee's suggestion, we have included a short comment about this when describing figure 3 (L224-225 in the marked-up manuscript).

Technical Comments/Grammatical Errors

1) Line 56; on → at
Done.

2) Line 82; The recent paper by Kim et al. (2017) which you cite later may be a good citation here.
Included!

3) Line 111; Could you clarify this sentence to say whether both reanalyses extend back to 1979, or that both extend back to before 1979 (and if the latter, then which year: 1960?).
They extend back to before 1979, in particular JRA-55 data starts in January 1958 and the ERA-40 reanalysis data is available since September 1957. We have included this information in the manuscript to clarify the mentioned sentence.

4) Line 125; Is the Polar Cap area weighted? I think it should be and it would be good to include a sentence here saying so.
Yes, the polar cap is area-weighted. We have included a comment about that in L134 in the marked-up manuscript.

5) Line 191; 'in the course' → 'during the course'. Also, aHF100 in the text should correspond to the figure title of HF100.
We have modified both things.

6) Line 193; None of the individual models show significantly different results?

We have only found some slight significant changes in two models (GEOS-CCM and EMAC-L47), but only for a few days preceding the SSWs. Thus, we think that it was not worth important to report in the paper.

7) Line 209; 'no statistically significant changes'

Modified!

8) Line 220; Can you give references to the figure which shows this? Figure 1?

Yes, it is Figure 1. We have included the reference to that figure.

9) Line 221; 'across' → 'using'

We prefer using 'across' instead 'using' as the slight future increase in frequency of SSWs is detected in all cases when applying each criterion separately.

10) Line 260; 'in the last years' → 'in recent years'

Changed

11) Line 261; 'metrics' → 'metric'

Changed

References

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

Reply to Referee #2

The paper is easy to read and the main message and methodology are clear. In general I feel positive about the paper and the conclusion but I do think the paper lacks much in-depth analysis above what has been done in previous work, most notably Kim et al. 2017. Some of the figures in the supplementary material might be worth including in the main manuscript (Fig S3 for example). I suggest a major revision to address the points below.

Thanks a lot for your comments. We have addressed all referee's comments. In particular, we have highlighted more clearly how our results compare and extend upon other previous studies, particularly Kim et al. (2017). We have kept the figures in the supplementary material because they are devoted to the analysis of individual models, and these models agree in the main results. Thus, we think showing the multimodel mean values and its robustness across models for some variables is enough and highlights more easily the main conclusions. Nevertheless, we have extended the work and included new analyses such as the deceleration of the polar night jet during SSWs.

Here is our response to your general, specific and technical comments:

General Comments

1) While this study looks at the CCMi models, which is a likely improvement in terms of interactive chemistry and stratospheric processes, it would be nice if this study more clearly explained how its analysis improves or expands upon those of Kim et al. 2017, which considered a large number of stratosphere-resolving (and non-stratosphere resolving) CMIP5 models and two different SSW definitions (and the more extreme RCP8.5 scenario rather than the RCP6.0 scenario used here). From what I can tell, the results were very similar in both studies (an increase in SSWs in future climate scenarios, though not a significant increase), though the message is quite different. While emphasizing the non-significance of the trend does seem important, the results are basically the same. It would be nice if this analysis had included some more in-depth analysis of the CCMi models in particular, maybe of whether models that had different characteristics (prescribed SSTs vs coupled, internal QBO vs nudged, solar variability or no) had different changes in SSWs. The two points below also outline some areas where more analysis could be considered.

First of all, we would like to highlight that the focus of our study and Kim et al's is different. Whereas ours focuses on the effects of projected climate change on the occurrence of SSWs in CCMI runs, the main goal of Kim et al is to search for a new definition of SSWs that is not sensitive to possible model biases. Kim et al perform indeed an in-depth analysis of the new algorithm in the present period in reanalysis data and CMIP5 models. As a secondary task, they apply the new algorithm to RCP8.5 simulations mainly to examine at what extent the application of their new algorithm may affect the conclusions for future frequency of SSWs. In contrast, in our study, we are interested in the future changes in SSWs and so, we do not only investigate the future changes in the mean frequency of occurrence of SSWs by applying different criteria, but we also examine other aspects such as duration of events, deceleration of the polar night jet or the preceding wave activity. Indeed, as far as we know, this is the first study that also compares the sensitivity of these other features to climate change in several models. In all these SSW features, not only the mean frequency, we do not find a statistically significant future change, and so, that would lead us to highlight the null future change. In the revised manuscript, we have indicated more in detail the strengths of our study in the Introduction and the discussion section (L97-100, and L241-243 and L272-275 in the marked-up manuscript, respectively).

Regarding the suggested analysis of the CCMI models, we agree that it would be a nice exercise to further compare the results for models with different characteristics, if we had found a variety of results among models. However, the same conclusion is reached for all CCMI models, a null change of SSWs in the future. It is true that in the case of the mean frequency of SSWs, a few models show a statistically significant change for one or two criteria. However, the number of these models is so low that we cannot derive any conclusions. Thus, it seems that the different characteristics of the models do not play a relevant role in the impact of climate change on SSWs. We thank the reviewer for this suggestion because it has helped us to highlight this extra point concerning the null change of SSWs. Thus, we have added a short comment about that in section 3.1 (L182-184 in the marked-up manuscript) and another bullet to our main conclusions in Section 4 ("The absence of a future change in SSWs is a robust result across all models examined here, regardless of their biases or different representation of the QBO, coupling to the ocean, solar variability, etc..").

2) This study does look at common SSW definitions, but given that the changes in mean zonal winds at 60N in Figure 4 are barely significant, it would be nice to consider zonal wind reversals at a broader range of latitudes. The authors did look at the 60-90N averaged zonal winds, but if that's cosine weighted it will be dominated by winds near 60N. 60N also seems right on the node between significant weakening winds and significant strengthening winds. It would be interesting to explore (and perhaps more clearly quantify) whether those models that showed no increases (or reductions) in SSWs had significant strengthening mid-latitude winds extending further north (seems to be true considering Fig S3). This might beg the question then, if the jet itself is shifting in the future, is maintaining a definition fixed at a particular latitude like 60N the best way to detect changes? I do agree that the polar cap anomaly/U60-90N results suggest it might not matter too much where it's defined, but exploring that sensitivity more methodically might be useful.

Thanks for the suggestion! We have explored the sensitivity of the results to the latitude chosen for the reversal of the wind in the definition of SSWs (Fig. R2.1). To do so we have computed the mean frequency of SSWs based on the WMO but imposing the reversal of the wind at 55°, 65° and 70°N. First of all, we can see that the main conclusion of our study does not change and most of the models do not show a change. It is true that in a few cases, if we change the latitude of reference, the future change becomes statistically significant at a latitude point. However, only one model (EMAC-L47) shows a systematic significant increase in the SSWs frequency for reference latitudes higher than 60°N. EMAC-L47 is one of the models that displays a latitudinal dipole in the future changes of the climatological zonal winds, as suggested by the reviewer, but other models show that dipole (e.g.: SOCOL3 or IPSL) and there is not a systematic change in the significance of results for higher latitudes.

Although performing this extra analysis was a good suggestion, the results are not relevant for our conclusions and we decided not to include it in the revised version. We prefer to keep the main message of our study clear and avoid confusion in the reader.

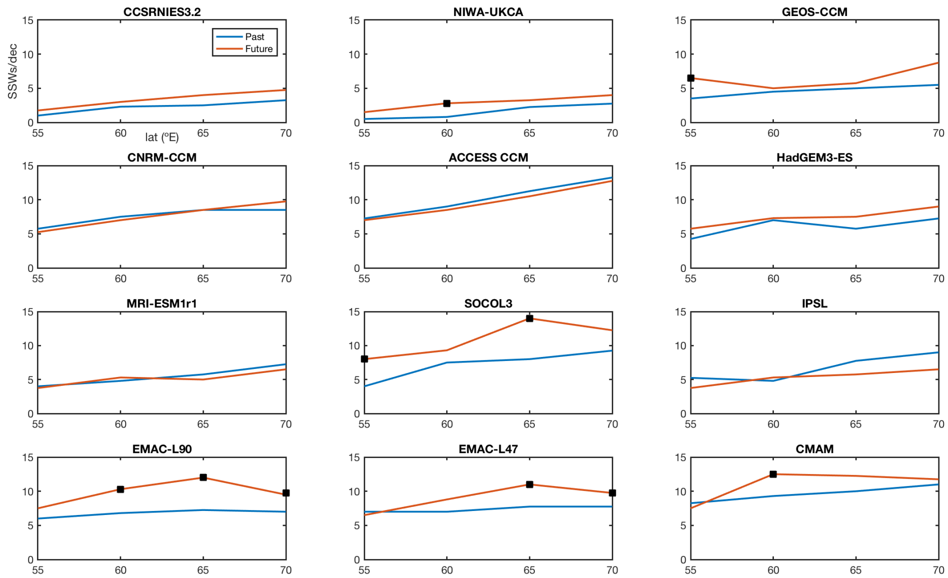

Figure R2.1. Mean frequency of sudden stratospheric warmings per decade for the past (blue line) and the future (orange line) in function of the latitude selected for the reversal of the wind. Black squares indicate that future vales are statistically significantly different from the past ones at the 95% confidence level.

3) While it does seem clear that there is no significant change in the frequency of SSWs in this analysis, the fact that there appears to be a quite robust weakening of the polar vortex (in a mean sense) is only briefly pointed out in the Discussion. It's worth keeping in mind that since the SSWs represent the tail end of the zonal wind distribution, they may be much more sensitive than the mean to small sample size and higher order moments (e.g., changes in skewness). The authors do mention that the "broadness" (variability) of the distribution does not seem to be changing over time- is it possible that the distribution becomes more skewed? I wonder though whether this weakening of the mean state could have potential climate impacts even if the most extreme events (SSWs) are not significantly changing.

As the referee indicates, the variability of the zonal mean zonal wind at 10hPa had been previously examined and compared in the past and future in each model and we did not find statistically significant differences. Following reviewer's suggestion, we have also plotted the pdf of the zonal mean zonal wind at 10hPa and 60°N for the two periods in typical winter months (December, January, and February) to investigate further possible changes in the distribution of this variable (Fig. R2.2). However, we do not find a future change in the probability distribution of the wind in models. Only a slight shift of the mean value in the future towards lower values is detected in a few models (NIWA-UKCA, CCSRNIES3.2, SOCOL3 and EMAC-L90). This result supports our statement of Section 4 about the lack of statistical significance of the weakening of the vortex in most individual models. The shape of the distribution does not change either, particularly when referring to its asymmetry. The skewness is negative in both periods of study, reflecting that westerly winds tend to be of large amplitude in winter, but the asymmetry is not large though, as the values are not smaller than -0.5 (see values in text boxes of Fig. R2.2).

Based on this additional analysis, we have added a short comment about the general null change of the distribution of the wind data in the past and future period in Section 4. The new statement complements the previous sentence where we had already commented that the future weakening of the vortex was not statistically significant in most of the models (L266 in the marked-up manuscript). We have included the figure in the Supplementary material as Fig. S4.

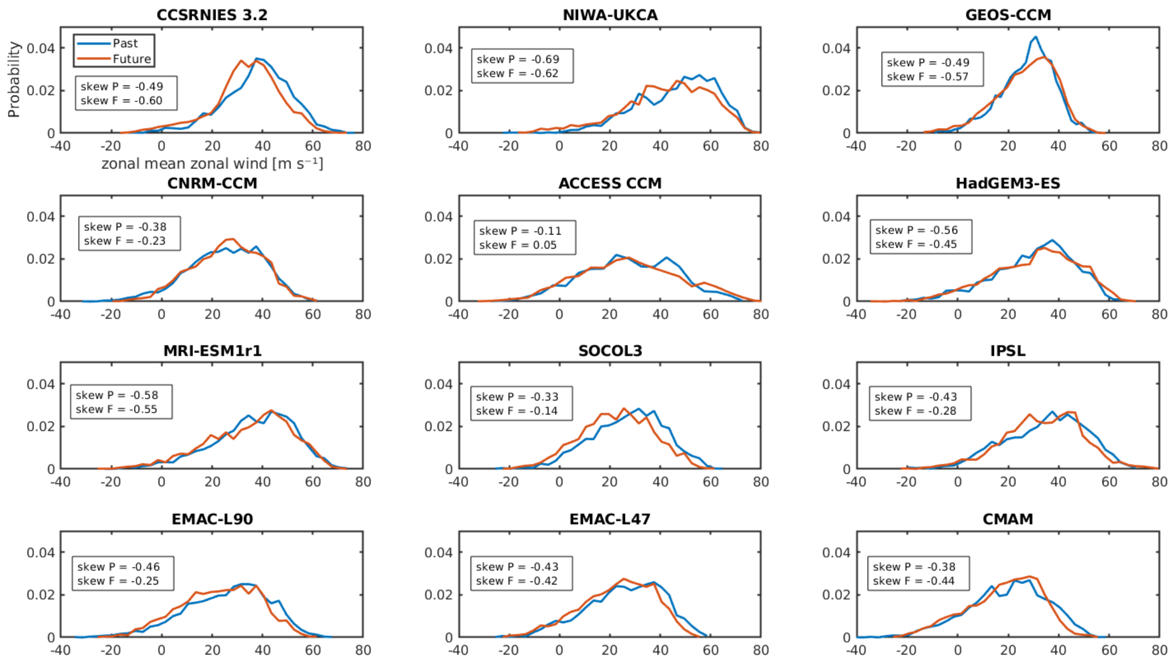

Figure R2.2. Probability distribution function of the daily zonal mean zonal wind at 60ºN and 10hPa in December, January and February in the past (blue line) and future (orange line) for each CCMI model. The skewness of the distribution in each time period is indicated in the text boxes

Specific Comments

Line 63-64: Some of the more recent papers on this topic should be cited here, including Kim et al. 2017 and Manzini et al. 2014, rather than only at the end.

We have included Kim et al. 2017, but not Manzini et al. 2014 because the latter does not examine the future changes in sudden stratospheric warmings.

Line 85: The Kim et al. 2017 results should also perhaps be mentioned here, because they investigated the definition sensitivity as well

Included!

Line 105-107: Would it be possible to consider 40-year blocks from 1960-2100 either by moving the center of the 40 years by ~5-10 years over the full period and getting a distribution that way, or by using a smaller time period (20-30 years) and looking at the change in frequency of consecutive 30-year periods over the entire run? I wonder whether that would give you a better sense for how variable the SSW frequency can be for any given 40 year period (maybe the variability between periods is much larger than the trend between the first and last period).

Thanks for the suggestion! Given that SSWs occur randomly and not very often per decade, we found it difficult to get a distribution just picking-up 40-year block by moving the center of 40 year by ~5-10 years. However, inspired by reviewer's suggestion, we have plotted the evolution of these 40-yr blocks of SSWs computed every 10 years (Fig. R2.3). This procedure allows us to visualize whether there is indeed a trend in the occurrence of SSWs or if in contrast, the multi-decadal variability of SSWs is comparable to the change between the past and future period. Only in a few models, and more specifically in EMAC-L90, do SSWs show a clear increasing trend in the future under climate change conditions. The result agrees well with the statistical analysis performed when just comparing the frequency of SSWs in the past and future periods and applying a Student t-test (Figure 1 of the manuscript). Given the agreement in the results, Figure R2.3 adds little to the study; therefore we have not included it in the revised version of the manuscript

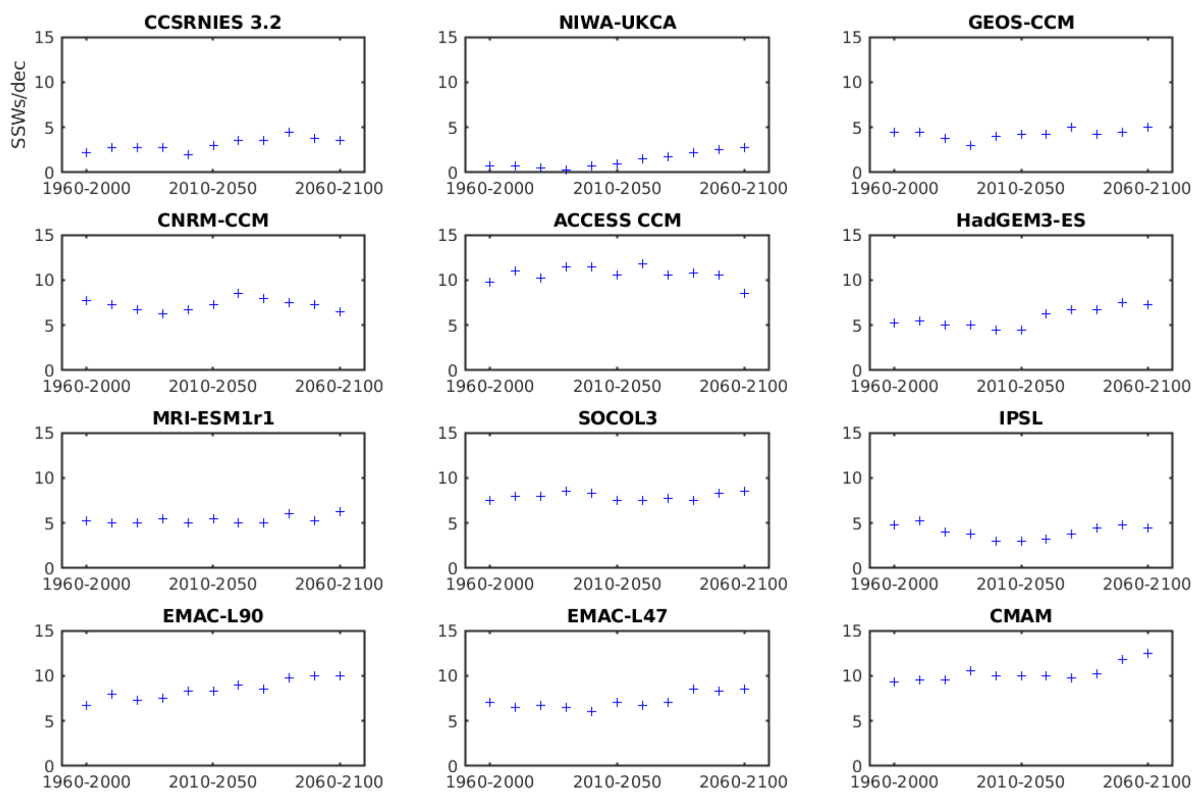

Figure R2.3. 40-yr running-mean frequency of SSWs per decade in each CCMI model.

Line 119-121: How did you deal with the temperature criteria here; was the zonal wind first detected and then the temperature gradient had to reverse within a certain number of days?

We have imposed the simultaneous occurrence of zonal mean easterly winds at 60°N and 10hPa and a positive difference of zonal mean temperature at the same level between the pole and 60°N. We have modified the sentence to clarify it.

Line 137-140: Could any other metrics be considered in addition? These are both interesting features but other metrics like the amplitude or depth of the reversal could also be worth considering (to try to further quantify whether these events will still produce significant surface impacts in the future).

As part of a good characterization of SSWs, we have computed the associated deceleration of the polar night jet at 10hPa and the results are included in the new Section 3.3 and Figure 2b. Similarly to other SSW features, the MM value does not show a statistically significant change at the 95% confidence level and only two out of 12 models do show a reduction. Thus, the results support the null future change of SSWs.

Regarding the possible impacts of SSWs on surface, it is important to remark that there is still not a clear knowledge about the factors that can modulate the amplitude of this signal in the troposphere. The internal tropospheric variability is much larger than the stratospheric contribution and so, often masks the stratospheric fingerprint in the troposphere (Gerber et al., 2009). For instance, specifically looking at the amplitude of the stratospheric anomalies, Runde et al. (2016) found that strong stratospheric perturbations do not obligatory have associated a strong surface signal.

Technical Corrections

1) Line 56: change to "weather forecasts on intraseasonal timescales"

Done!

2) Line 111: ERA-40 and JRA-55 extend further than 1979, is that what you mean? Maybe instead of "back of", change to "beyond"?

Yes, that is what we mean. We have modified the sentence and clarified the paragraph to make it clearer.

3) Line 208: change to "possibly accounts for at least some of the mismatch between"

Changed!

References

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, doi: 10.1029/2009GL04091, 2009.

Runde, T., Dameris, M.,Garny, H., and Kinnison, D. E.: Classification of stratospheric extreme events according to their downward propagation to the troposphere, Geophys. Res. Lett., 43, , 6665–6672, doi:10.1002/2016GL069569, 2016

No Robust Evidence of Future Changes in Major Stratospheric Sudden Warmings: A Multi-model Assessment from CCMI

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Abstract.

Major mid-winter stratospheric sudden warmings (SSWs) are the largest instance of wintertime variability in the Arctic stratosphere. Because SSWs are able to cause significant surface weather anomalies on intra-seasonal time scales, several previous studies have focused on their potential future change, as might be induced by anthropogenic forcings. However, a wide range of results have been reported, from a future increase in the frequency of SSWs to an actual decrease. Several factors might explain these contradictory results, notably the use of different metrics for the identification of SSWs,

and the impact of large climatological biases in single-model studies. To bring some clarity, we here revisit the question of future SSWs changes, using an identical set of metrics applied consistently across 12 different models participating in the Chemistry Climate Model Initiative. Our analysis reveals that no statistically significant change in the frequency of SSWs will occur over the 21st century, irrespective of the metric used for the identification of the event. Changes in other SSWs characteristics, such as their duration, deceleration of the polar night jet and the tropospheric forcing, are also assessed: again, we find no evidence of future changes over the 21st century.

1 Introduction

Stratospheric sudden warmings (SSWs) are the largest manifestation of the internal variability of the wintertime polar stratosphere in the Northern Hemisphere, consisting of a very rapid temperature increase accompanied by a reversal of the westerly wintertime circulation (the polar vortex). In observations, SSWs occur roughly with a frequency of 6 SSWs per decade (e.g., Charlton and Polvani, 2007). However, large variability on intra- and inter-decadal time scales has been reported (Labitzke and Naujokat, 2000; Schimanke et al., 2011).

SSWs also play an important role in the dynamical coupling between the stratosphere and troposphere. Although other mechanisms are possible, ~~-~~SSWs~~They~~ are usually related to ~~known to originate from~~ precursors in the troposphere that lead to ~~, as SSWs are triggered by~~ an anomalously high injection of tropospheric waves that propagate into the stratosphere where they deposit momentum and energy, decelerating the mean flow (Matsuno, 1971; Polvani and Waugh, 2004). More importantly, however, their effects are not restricted to the stratosphere: SSWs can also impact the tropospheric circulation and surface climate for up to two months (e.g., Baldwin and Dunkerton, 2001). Given their importance for seasonal forecasting, SSWs have been studied with great interest, as they are likely to provide a source of improved weather forecasts on~~at~~ intraseasonal scales (Sigmond et al., 2013).

One question of particular relevance is whether SSWs will change in the future, as a consequence of increasing greenhouse gases (GHG) concentrations and ozone recovery. The answer to this question has proven elusive since the first studies over two decades ago. While Mahfouf et al. (1994) found an increase in the frequency of SSWs under doubled CO_2 conditions, Rind et al. (1998) reported a decrease, and Butchart et al. (2000) did not find any change that might be attributed to increasing GHG concentrations. And, in spite of an improved stratospheric representation and more realistic model features in the last decade, a clear consensus as to future SSW changes is still missing (Charlton-Perez et al., 2008; Bell et al., 2010; SPARC CCMVal, 2010; Mitchell et al. 2012a and b; Hansen et al., 2014; Kim et al., 2017).

Several potential reasons that might explain the disparity in the projected SSW changes have been proposed in the literature. One is the combination of different aspects of future climate change with opposing effects on the Arctic stratosphere, such as the projected ozone recovery, increasing GHG concentrations and their induced changes in global sea surface temperatures. These result in a weak polar stratospheric response to climate change (Mitchell et al., 2012a, Ayarzagüena et al., 2013). Consequently, individual models yield different future projections of SSW changes, depending on the relative importance of these competing effects in each model. Hence, any result obtained with a single model needs to be taken with much caution.

Another potential explanation for the discrepancies stems from the criterion chosen for the identification of SSWs. As shown in Butler et al. (2015), the identification of SSWs can be sensitive to the method used. It was found to depend on the meteorological variable chosen for analysis, and also on whether the identification criterion entails total fields and a fixed threshold (absolute criterion), or anomalies relative to a changing climatology (relative criterion). For instance, the traditional criterion of the World Meteorological Criterion (hereafter WMO criterion, McInturff, 1978) requires the reversal of both zonal-mean zonal wind at 60ºN and 10hPa and the meridional gradient of zonal mean temperature between 60ºN and the pole at the same level. This criterion was empirically developed from the observations in the last several decades, and was applied in historical stratospheric analyses (e.g., Labitzke, 1981). Recent studies have continued using the WMO criterion although many of them have only imposed the reversal of the wind for the SSW identification (e.g., Charlton and Polvani, 2007). Because of its simplicity and its dynamical insight, the WMO criterion (and its recent simplified version) is the most commonly used criterion in modelling studies as well. However, such an absolute metric might not always be the best choice to measure the polar stratospheric variability in these studies, as it does not account for potential model biases in the polar vortex climatology, or possible changes in this climatology in the future projections (McLandress and Shepherd, 2009; Mitchell et al., 2012a; Butler et al., 2015; Kim et al., 2017). An analysis with the Canadian Middle Atmosphere Model by McLandress and Shepherd (2009) showed that the frequency of SSWs may or may not change depending on the detection index.

The purpose of this study, therefore, is to revisit the question of possible future SSW changes, taking these issues into consideration. Seeking a robust answer, we employ three different SSW identification criteria (both absolute and relative) and apply them consistently to the output from 12 state-of-the-art climate models (contributing to the Chemistry Climate Model Initiative, CCMI). Interactive stratospheric chemistry, which is present in all the CCMI models, makes them the most realistic in terms of stratospheric processes. In addition, the CCMI models are improved compared to their counterparts which participated in the previous Chemistry Climate Model Validation-2 programme (CCMVal-2). In particular, several CCMI models are coupled to interactive ocean modules, and the vertical resolution of many models has been increased (Morgenstern et al. 2017). Moreover, unlike other previous studies such as Kim et al. (2017), our analysis is not only restricted to the mean frequency of SSWs, but we also examine the possible future changes in other characteristics such as the duration of events, the related deceleration of the ~~vortex~~polar night jet or the wave activity preceding their occurrence. To our knowledge this is the first time that a multi-model assessment of these ~~other~~different SSWs features is ~~also~~ performed. The structure of the paper is as follows: In Section 2 the data and methodology used in the analysis are described. The main results are shown in Section 3, and Section 4 includes the discussion and the most important conclusions derived from the analysis.

2 Data and methodology

2.1. Data description

Our study is based on the analysis of the transient REF-C2 simulation of 12 CCMI models (cf. Table 1; for more details see Morgenstern et al., 2017). The REF-C2 runs extend from 1960 to 2099 or 2100 for most models (except for the IPSL-LMDZ-REPROBUS model that terminates the run in 2095), and include natural and anthropogenic forcings following the CCMI specifications (Eyring et al., 2013). In particular, GHG concentrations and surface mixing ratios of ozone depleting substances (ODS) are based on observations until 2000, and on the Representative Concentration Pathway 6.0 (RCP6.0, Meinshausen et al., 2011) and A1 (WMO, 2011) scenarios, respectively, from 2000 to 2100. Solar variability is included in most of the models. Depending on the characteristics and performance of the models, sea surface temperatures (SSTs) and the quasi-biennial oscillation (QBO) are prescribed or internally generated. Future changes in frequency and other features of SSWs are obtained by comparing the last 40 winters of each run (denoted as “the future”) to the first 40 winters (denoted as “the past”). Unless otherwise stated, anomalies are calculated from the climatology of the corresponding 40-year period. A Student’s t-test is applied to determine if the future changes are statistically significant in all cases except for the duration of SSWs where we applied a Wilcoxon ranked-sum test. The performance of the models in reproducing SSWs characteristics for the past period (1960-2000) is assessed by comparing the models to the ERA-40 and JRA-55 reanalyses (Uppala et al., 2005; Kobayashi et al., 2015). Both reanalyses extend back to before~~of~~ 1979;~~,~~ ERA-40 data starts in September 1957 and JRA-55 begins in January 1958. Thus, they cover~~ing~~ the past period of our study. Among the few reanalyses that have available data in the pre-satellite era, ERA-40 and JRA-55 are the most suitable for middle atmosphere analyses because they have a higher top level and vertical resolution (Fujiwara et al., 2017).

2.2 Criteria for the detection of SSWs

As the detection of SSWs is somewhat sensitive to the chosen criterion, we use three different criteria to ensure that the conclusions regarding future changes are the same irrespective of the metric. The criteria we use are described in Butler et al. (2015) and as follows.

1) WMO (World Meteorological Organization) criterion

SSWs are identified when the zonal-mean zonal wind at 10 hPa and 60°N and the zonal-mean temperature difference between 60°N and the pole at the same level ~~reverse~~are simultaneously reversed. Two events must be separated by at least 20 consecutive days of westerly winds. Only events from November to March are considered. Stratospheric final warmings are excluded by imposing at least 10 days with westerly winds after the occurrence of a SSW and before 30 April, to ensure the recovery of the polar vortex before its final breakup. The onset date of the event corresponds to the first day of the wind reversal.

2) Polar cap zonal wind reversal (u6090N)

SSWs are identified when the area-weighted zonal wind at 10 hPa averaged over the polar cap (60°N-90°N) reverses. The separation of events and the exclusion of stratospheric final warmings are done in the same way as for the WMO criterion.

3) Polar cap 10hPa geopotential (ZPOL)

SSWs are identified based on the polar cap standardized anomalies of 10 hPa geopotential height. The anomalies are detrended and computed following Gerber et al. (2010). A SSW is detected if the anomalies exceed three standard deviations of the climatological January to March geopotential height (Thompson et al. 2002).

Note that WMO and u6090N are absolute SSWs criteria, whereas ZPOL is a relative SSW one.

2.3 Other SSW characteristics

Beyond their frequency, we also study if the other key characteristics of SSWs, such as duration and tropospheric forcing, will change in the future. The considered events in all features are those identified by the WMO criterion, because it is a popular criterion and, as will be shown later, the conclusions relative to the frequency results are not different from those obtained for the other two criteria. These are the metrics/diagnostics applied:

1. *Duration:*

The duration of the events is computed by the number of consecutive days of easterly wind regime at 60°N and 10 hPa as in Charlton et al. (2007).

2. Deceleration of the polar night jet

The deceleration of the polar night jet associated with the occurrence of SSWs is defined as the difference in the zonal-mean zonal wind at 60ºN and 10hPa, 15-5 days before the SSWs minus 0-5 days after the SSW as in Charlton and Polvani (2007).

~~2.~~3. *Tropospheric forcing*

The analysis of the tropospheric forcing is based on the evolution of the anomalous eddy heat flux at 100 hPa averaged between 45° and 75°N (aHF100) before and after the occurrence of SSWs. aHF100 is a measure of the injection of tropospheric wave activity into the stratosphere (Hu and Tung, 2003).

3. Future changes in the main characteristics of SSWs

3.1 Mean frequency

We start by considering the frequency of SSWs, and whether it is projected to change as a consequence of anthropogenic forcings. For this purpose, we have identified SSWs in the 12 models listed in Table 1, for the past and future periods, according to the three criteria presented in Section 2.2. Figure 1 shows the mean frequency of SSWs for each case.

In spite of some differences among the criteria, there appears to be a suggestion of a small increase in frequency in the multimodel mean (hereafter MM), but this tendency is not statistically significant at the 95% confidence level for any of the criteria, either absolute (WMO, U6090N) or relative (ZPOL). Also, while most models show a small increase in the frequency of SSWs in the future (10 of 12 models for the WMO criterion; 9 of 12 in the u6090N criterion; and 7 of 12 for the

ZPOL), most of those changes are not statistically significant. Specifically, none of the models displays a statistically significant future change for the relative criterion (ZPOL) (Fig. 1c), only 3 out of 12 models show a significant increase for the WMO criterion (NIWA-UKCA, EMAC-L90 and CMAM) (Fig. 1a), and only 2 out of 12 models for the u6090N criterion (SOCOL3, EMAC-L90) (Fig. 1b). It is, however, important to note that the NIWA-UKCA and CMAM models do not simulate a realistic frequency of SSWs when compared to reanalyses for the current climate, so they may not be a reliable indicator of possible future changes. Additionally, none of the four models (NIWA-UKCA, SOCOL3, EMAC-L90 and CMAM) shows an increase in SSWs for the three criteria simultaneously, indicating the lack of consistency for those models across the different methods. This confirms the absence of a robust future signal regarding changes in the frequency of SSWs.

A further comparison of the results for the different criteria for the past period confirms the findings of previous studies (e.g. McLandress and Shepherd, 2009) which showed that models' biases in mean state and variability affect the frequency values for the absolute criteria, since the different models show a wide range of SSW frequency values in the past period (see Fig. S1). For instance, CCSRNIES-MIROC3.2 and NIWA-UKCA show very low SSW frequencies in agreement with the fact that the polar vortex in these models is much stronger than in the reanalyses, and the opposite is seen for ACCESS CCM, CMAM and CNRM-CCM (Fig S2). Note the good agreement between the JRA-55 and ERA-40 reanalyses. Conversely, SSW frequencies computed with the relative ZPOL criterion are more similar across the models, as they are less affected by climatological model biases. Interestingly, note how the values for the relative criterion are somewhat lower in models than in the reanalyses. Since the threshold for selecting events is based on the latter, this suggests that models may be underestimating the variability of the Arctic polar stratosphere. Nevertheless, regardless of the biases of models and their different representations of the underlying processes, the null future change in the frequency of SSWs is a robust result across all examined models.

Finally, it is worth highlighting that nearly identical results to the ones obtained with the WMO criterion are found, for both past and future periods, when only the reversal of the wind at 60°N and 10hPa (Charlton and Polvani, 2007) is used as the identification criterion. It is reassuring to report that the additional temperature constraint imposed in the WMO criterion does not significantly alter the frequency of SSWs, even for the future climates. This means that most recent studies, which have used the simpler method and considered the reversal of the wind as the sole quantity for identifying SSWs, would have likely reached the same conclusions had they used the more precise WMO criterion, and can thus be considered valid.

3.2 Duration

Next, we turn to the duration of SSWs, for which the results are shown in Fig. 2a, for the past and future. In each period, we notice a considerable spread across the models; nonetheless, the MM value for the past period falls within the interval of reanalyses values ±1.5 standard error. Note, however, the variability within each model is larger than that across the models. This is particularly true for the NIWA-UKCA and CCSRNIES-MIROC3.2 models, possibly as a consequence of the low number of SSWs simulated by these two models. MRI-ESM1r1 also shows a large variability in SSW duration, but only in the past period.

The key message from Fig. 2a is that the duration of SSWs does not change in the future, using the canonical 95% confidence level for each individual model. In fact, even at 90% confidence SSWs show a statistically significant change in only one model (HadGEM3-ES). Nevertheless, as in the case of the mean frequency, more than half of the models (7 out of 12) agree on the sign of the future change in the SSW duration (they indicate that it will be slightly shorter), but this change in the MM is not statistically significant at the 95% confidence level.

3.3 Deceleration of the polar night jet

The next step is the assessment of future changes in the deceleration of the polar night jet (PNJ) associated with SSWs (Fig. 2b). Similar~~ly~~ to the duration and mean frequency, the MM value of the PNJ deceleration does not change in the future at the 95% confidence level, with only two models (EMAC-L90 and CMAM) showing a significant future reduction of the PNJ. These are the same models ~~who~~that show a significant though small increase in SSWs in the future with the WMO criterion (an absolute criterion), but at least, in one of these models (CMAM) the climatological polar vortex is unrealistically weak.

It is also worth noting that the MM value for the past period falls out of the interval of reanalys~~e~~is values ±1.5 standard error. Thus, one could question the reliability of the future projections of the deceleration of the polar night jet during SSWs. Half of the models show values included in the reanalysis interval, and only two of these six models display a statistical change in the future. Thus, we are quite confident in concluding that the PNJ deceleration during SSWs does not change in the future.

3.4 Tropospheric forcing

Since SSWs are usually triggered by anomalously high tropospheric wave activity entering the stratosphere in the weeks preceding the events (Matsuno, 1971; Polvani and Waugh 2004), we have analyzed the possible future changes in the injection of wave activity ~~(aHF100)~~ ~~in~~ during the course of the occurrence of these events for the MM. Thus, as indicated in Section 2.3, ~~(~~Fig. ~~.~~3 displays the anomalous eddy heat flux at 100hPa averaged between 45º-75ºN (aHF100) ~~)~~. The results do not show a statistically significant change in any aspect of the anomalous wave activity preceding SSWs in the MM and in the individual models (not shown). In particular, neither the strong peak of aHF100 of the MM in the 10 days prior to the occurrence of events nor the general time evolution of the aHF100 are projected to change in the future (Fig.3a). Hence the common, but not statistically significant, trend of models towards shorter future SSWs mentioned above cannot be explained by changes in tropospheric forcing. Additionally, when examining the two first zonal wavenumber components of the anomalous HF100, no significant future changes are found either (Fig.3b). This would also imply little change in the distribution of split and displacement SSWs.

Model projections of future aHF100 are reliable because models are able to simulate the tropospheric forcing of these events reasonably well (Fig.3). Only a few discrepancies can be seen between the MM and the mean of JRA-55 and ERA-40 reanalyses (Reanalyses Mean, RM, black curve). Note that we include the average of JRA-55 and ERA-40 because they show very similar results and we avoid confusion by including too many lines in the same plot. One of the discrepancies between

MM and RM is that the strong peak in aHF100 in the 5 days prior to the occurrence of SSWs is weaker in the models than in observations. The reanalyses also show a secondary peak of aHF100 between -20 and -10 days that does not appear in the MM. Additionally, the contribution of the wavenumber 1 (WN1) component to the strongest wave pulse is similar or even stronger than in the reanalyses (Fig.3b), but the wavenumber 2 (WN2) in the models is much weaker than in the RM. This explains the weaker total value of aHF100 in the MM than in the RM. Nevertheless, the RM is only one realization averaged over 40 years and the MM corresponds to the average over many more realizations. Thus, the multi-model/individual realization spread possibly accounts for at least some of ~~partially~~ the~~se two~~ mismatch~~es~~ between MM and RM. In any case, the models show no statistically significant changes between the past and the future.

4. Discussion and conclusions

We have revisited the question of whether SSWs will change in the future, analysing 12 state-of-the-art stratosphere resolving models that participated in CCMI. To obtain robust results, we have used three different identification criteria (two absolute and one relative) and have applied them consistently across all 12 models. Moreover, unlike most previous multi-model comparison studies, we have not ~~only~~ restricted our analysis to the mean frequency of SSWs, but we have also analysed other SSWs characteristics that are important for the stratosphere-troposphere coupling. In summary, our analysis reveals that:

- No statistically significant changes in the frequency of occurrence of SSWs are to be expected in the coming decades and until the end of the 21st century. This result is robust, as it is obtained with three different identification criteria.
- Other features of SSWs, such as their duration, deceleration of the polar night jet and the tropospheric precursor wave fluxes, do not change in the future either in the model simulations, in agreement with other studies such as McLandress and Shepherd (2009) or Bell et al. (2010).
- The absence of a future change in SSWs is a robust result across all models examined here, regardless of their biases or different representation of the QBO, coupling to the ocean, solar variability, etc..

Despite the lack of statistical significant changes in the frequency of SSWs, both the MM and the majority of the models analysed show a slight increase in frequency across all criteria (Fig. 1). A similar result was reported by Kim et al. (2017), who analysed the change in SSW frequency in some CMIP5 models by identifying the events based either on the reversal of the wind or the vortex deceleration. Looking at changes in the daily climatology of the zonal mean zonal wind at 10 hPa (Figs. 4a and S3), the MM and individual model simulations also provide a consistent picture, with a robust weakening of the polar night jet (PNJ) from mid-December until mid-March, the deceleration being particularly strong between mid-December and mid-February; this is in agreement with previous CMIP5 results (Manzini et al., 2014). This deceleration is, however, only statistically significant in less than half of the models (Fig. S3), explaining why we do not find a significant change in the tropospheric forcing of SSWs (Fig. 3). To determine whether these changes in the climatology of wintertime PNJ might be associated with changes in SSWs frequency, the future-minus-past difference plots of the climatological wind are shown separately for winters with and without SSWs (Fig. 4b and c, respectively). We find a weakening of the PNJ in midwinter in both cases: this allows us to conclude that the future deceleration of the PNJ is not a consequence of a higher frequency of SSWs. This deceleration might be related to a general increase in the total stratospheric variability that, in the case of winters without SSWs, would correspond to a higher frequency of minor warmings. However, this possibility is unlikely because we do not find a robust future increase in the standard deviation of zonal-mean zonal wind at 10hPa across the models or a change in the shape of the distribution of the zonal-mean wind ~~(not shown)~~as shown in Fig. S4. Perhaps the future deceleration of the PNJ might explain the statistically significant increase in SSWs in a few models, using the absolute criteria in agreement with McLandress and Shepherd (2009). In any case, these signals are small and it is nearly impossible to untangle the cause and the effect, as these changes occur simultaneously.

More importantly our findings dispel, to a large degree, the confusion in the literature regarding future SSW changes, and suggest that previous reports of significant changes are likely to be artefacts, caused by biases associated with individual models, or by flaws in the identification methods used (or both). In addition, the analysis of other features of SSWs besides the mean frequency supports the key finding of our study, i.e. that anthropogenic forcings will not affect SSWs over the 21st century. Our results confirm and expand the findings of Kim et al. (2017) ~~that~~who did not find a statistically significant future change in the frequency of SSWs in CMIP5 models. Note that although th~~e~~e key finding~~g of our study – i.e. that anthropogenic forcings will not affect SSWs over the 21st century –~~ of our study is a null result, it is by no means uninteresting. Just to offer one example: Kang and Tziperman (2017) have recently proposed that future changes in the Madden Julian Oscillation (which are expected to occur with increased levels of CO_2 in the atmosphere) will cause an increased occurrence of SSWs. While their conclusion may be correct, our findings indicate that it can be misleading to project changes in the SSWs on the basis of a single mechanism: the complexity of the climate system is such that multiple mechanisms may be at play, with likely opposite effects which may result in net changes that are not statistically significant.

One may argue that the lack of a statistically significant future change in our study could be explained, at least partially, by the high interannual variability of the boreal polar stratosphere in 40-year periods (e.g., Langematz and Kunze, 2006), or perhaps by the natural variability on longer time-scales coming from other subcomponents of the climate system (e.g.: Schimanke et al., 2011). As shown in a recent paper, 10 identically forced model simulations, over the 50-year period 1952-2003, exhibit great differences in the number of SSWs, and these differences are solely due to internal variability (Polvani et al, 2017). This means that the 40 years of observations at our disposal may not represent the mean of a distribution, but could happen to be an outlier. Needless to say, we have no means of determining whether this is the case, as we do not have long enough observations.

One might also object that the forcing in the scenario used of our runs (RCP6.0) is not extreme enough to produce a significant signal in the frequency and duration of SSWs, but that a significant change would occur with stronger forcing~~. For instance, one may think that this signal might become significant~~, such as the ~~under the~~ RCP8.5 scenario. Although we cannot rule out this possibility, it seems improbable based on a similar lack of significance in the results documented for that very extreme scenario by several previous studies (Mitchell et al. 2012a; Ayarzagüena et al. 2013, Hansen et al. 2014; Kim et al.

2017). Nevertheless, it would be hard to verify the hypothesis because of the low number of CCMI RCP8.5 simulations available.

Finally, in recent ~~the last~~ years much activity has been devoted to search for novel criteria for the identification of SSWs (Butler et al., 2015). One of the reasons given to justify the implementation of a new metric~~s~~ was that the traditional WMO criterion was not appropriate for modelling studies, as it was based on observationally chosen parameters, such as the location of the polar night jet. However, our results show that this criterion performs well under a changing climate, provided models are able to reproduce correctly the past stratospheric variability. Thus, considering the good agreement among the three criteria used here on the lack of change in future SSWs, and given the dynamical implications for the propagation of planetary waves into the stratosphere, we suggest that the WMO criterion is appropriate for the study of SSWs in the future if the model can represent well the stratospheric variability. Furthermore, since the simplest (and most commonly used) criterion, involving only the zonal winds (Charlton and Polvani, 2007), yields identical results as the WMO criterion, one could argue that the simplest method may suffice in most cases for the study of SSWs, and that more complex criteria might not be worth the trouble. A similar conclusion was reached, independently, by Butler and Gerber (2018) who methodically assessed different metrics and concluded that the simplest algorithm is within the optimal range.

Data availability. Data of this manuscript has been mostly downloaded from the Centre for Environmental Data Analysis (CEDA, 2017; http://catalogue.ceda.ac.uk/uuid/9cc6b94df0f4469d8066d69b5df879d5) or supplied directly by the co-authors. For instructions for access to this archive see http://blogs.reading.ac.uk/ccmi/badc-data-access. The data supplied by the co-authors will in due course be uploaded to the CEDA archive.

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Tables

Table 1. Main characteristics relative to the models and their REF-C2 simulations used in this study.

CCMI models	Model resolution	QBO	Solar variability	SSTs
GEOS-CCM	2.5° x 2°, L72 (top:0.01hPa)	Internally generated	Yes~~No~~	Prescribed (CESM1)
CNRM-CCM	T42L60 (top: 0.07 hPa)	Internally generated	Yes	Prescribed (CNRM)
NIWA-UKCA	3.75° x 2.5°, L60 (top: 84 km)	Internally generated	No	Coupled to ocean model
CCSRNIES-MIROC 3.2	T42L34 (top: 0.012 hPa)	Nudged	Yes	Prescribed (MIROC 3.2)
IPSL-LMDZ-REPROBUS	3.75° x 2.5°, L39 (top: 70 km)	Nudged	Yes	Prescribed (SRES A1b IPSL)
ACCESS CCM	3.75° x 2.5°, L60 (top: 84 km)	Internally generated	No	Prescribed (HadGEM2-ES~~2~~)
HadGEM3-ES	1.875°x1.25°, L85 (top: 85 km)	Internally generated	Yes	Coupled to ocean model
SOCOL3	T42L39 (top: 0.01hPa)	Nudged	Yes	Prescribed (CESM1(CAM5))
MRI-ESM1r1	TL159L80 (top: 0.01hPa)	Internally generated	Yes	Coupled to ocean model
EMAC-L47	T42L47 (top: 0.01hPa)	Nudged	Yes	Prescribed (HadGEM2-ES)
EMAC-L90	T42L90 (top: 0.01hPa)	Internally generated (slightly nudged)	Yes	Prescribed (HadGEM2-ES)
CMAM	T47L71 (top: 0.0575 hPa)	No	No	Prescribed (CanCM4)

Figures

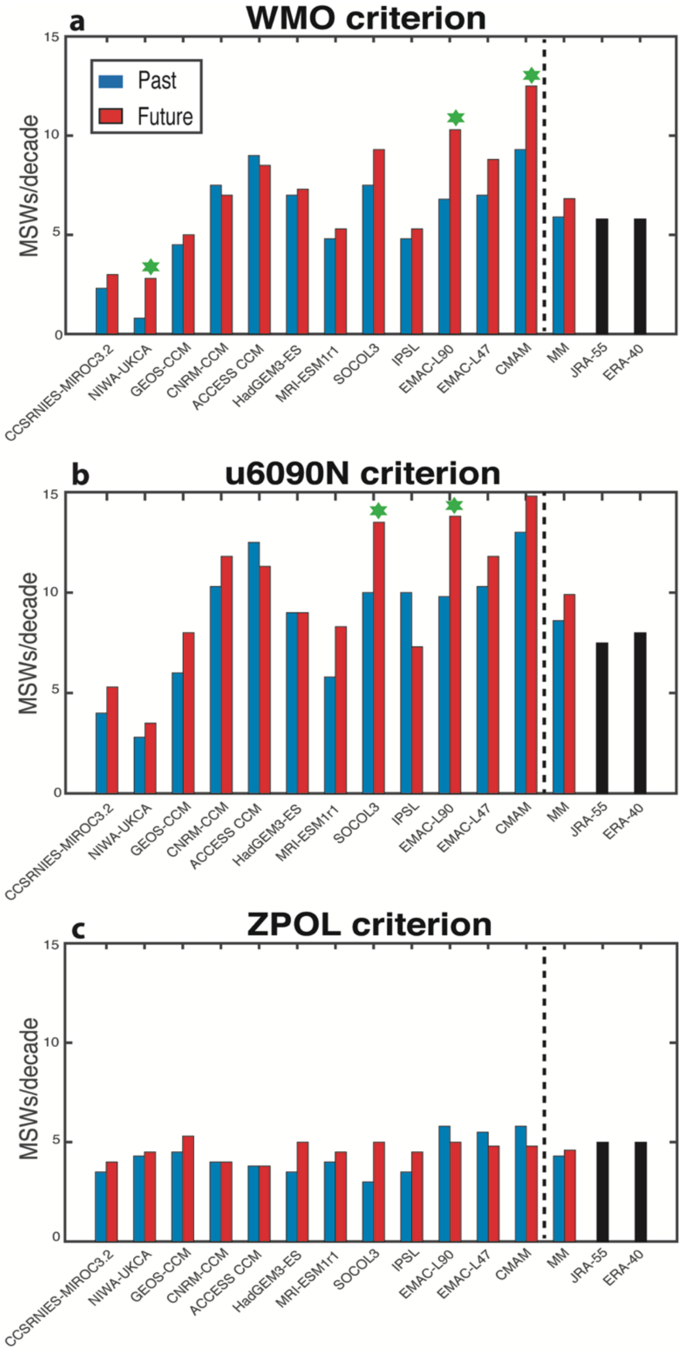
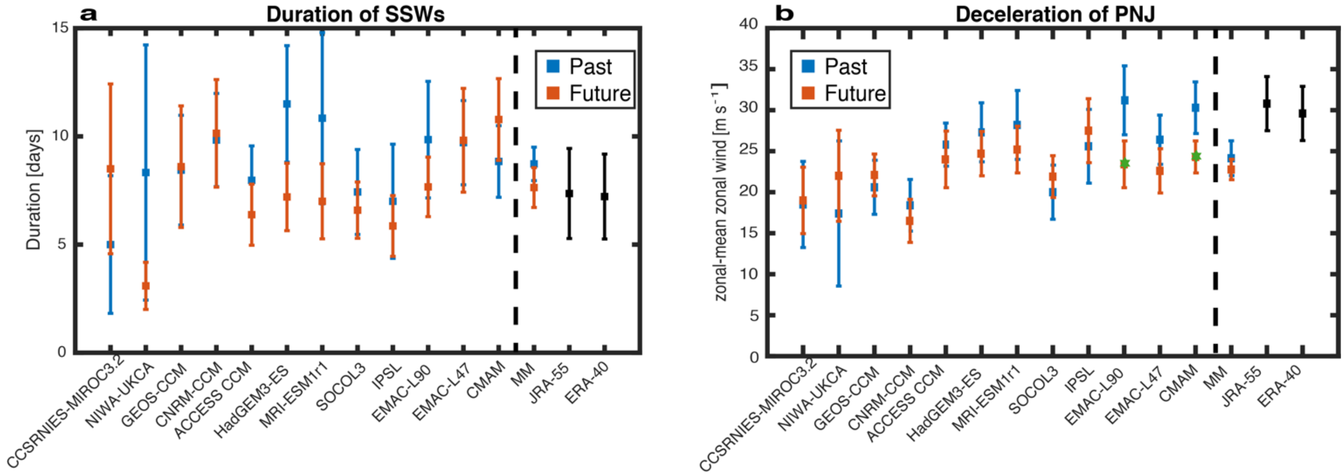


Figure 1: (a) Mean frequency of ~~major~~ stratospheric sudden warmings per decade for the past (blue bars) and the future (red bars) for all models, the multimodel mean (MM) and JRA-55 and ERA-40 reanalyses (black bars) according to the WMO criterion. (b) – (c) Same as (a) but for the u6090N and ZPOL, respectively. Green stars on top of the future bar denote a statistically significant change in the frequency of SSWs in the future at the 95% confidence level.



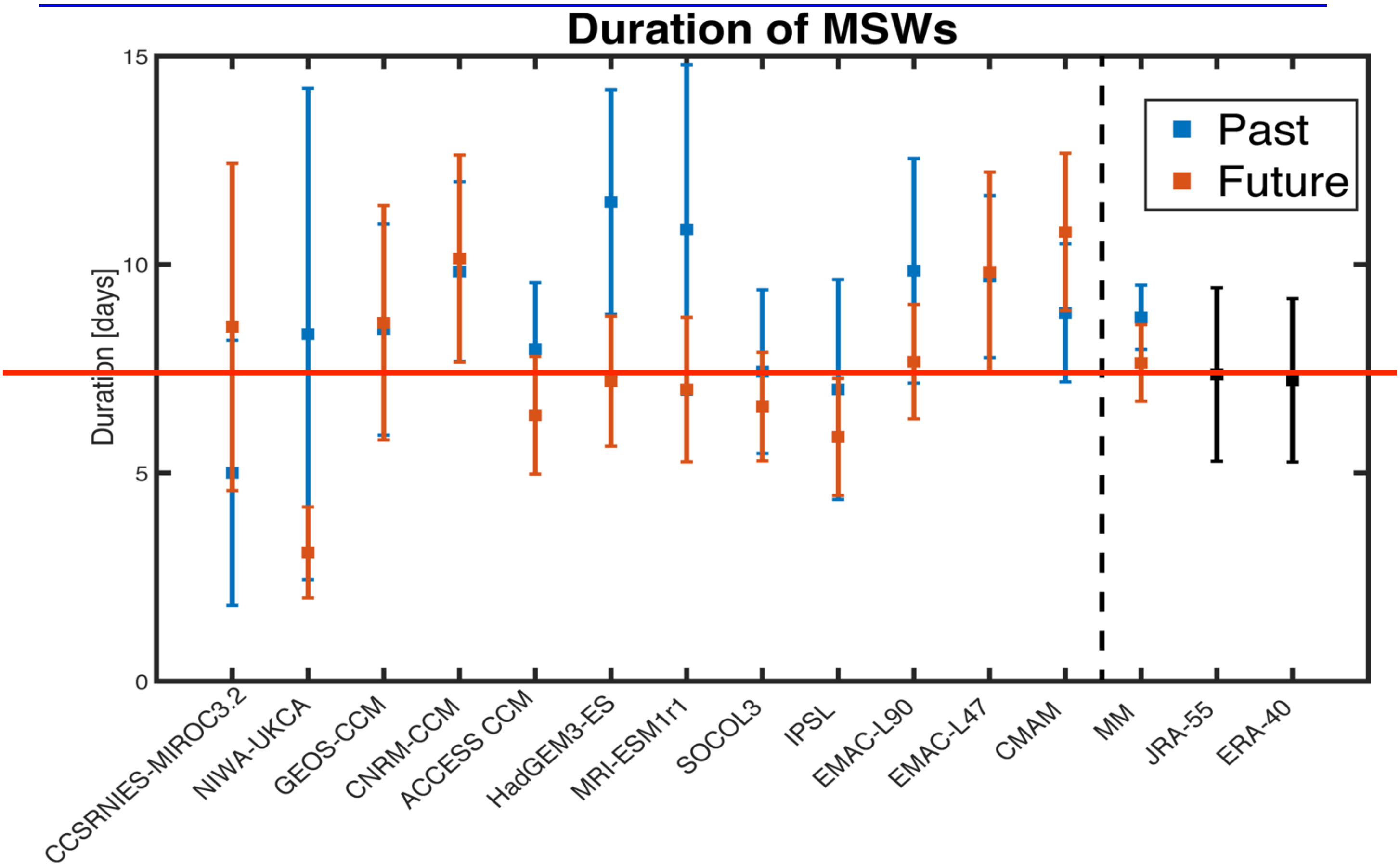


Figure 2. (a) Duration of SSWs (in days) and (b) deceleration of the PNJ associated with SSWs (in m s^{-1}) in each model for both periods of study. Bars denote ±1.5 standard error and green stars would indicate future values that are statistically significantly different from the past ones at the 95% confidence level ~~(but they are absent as there are not statistically significant changes).~~

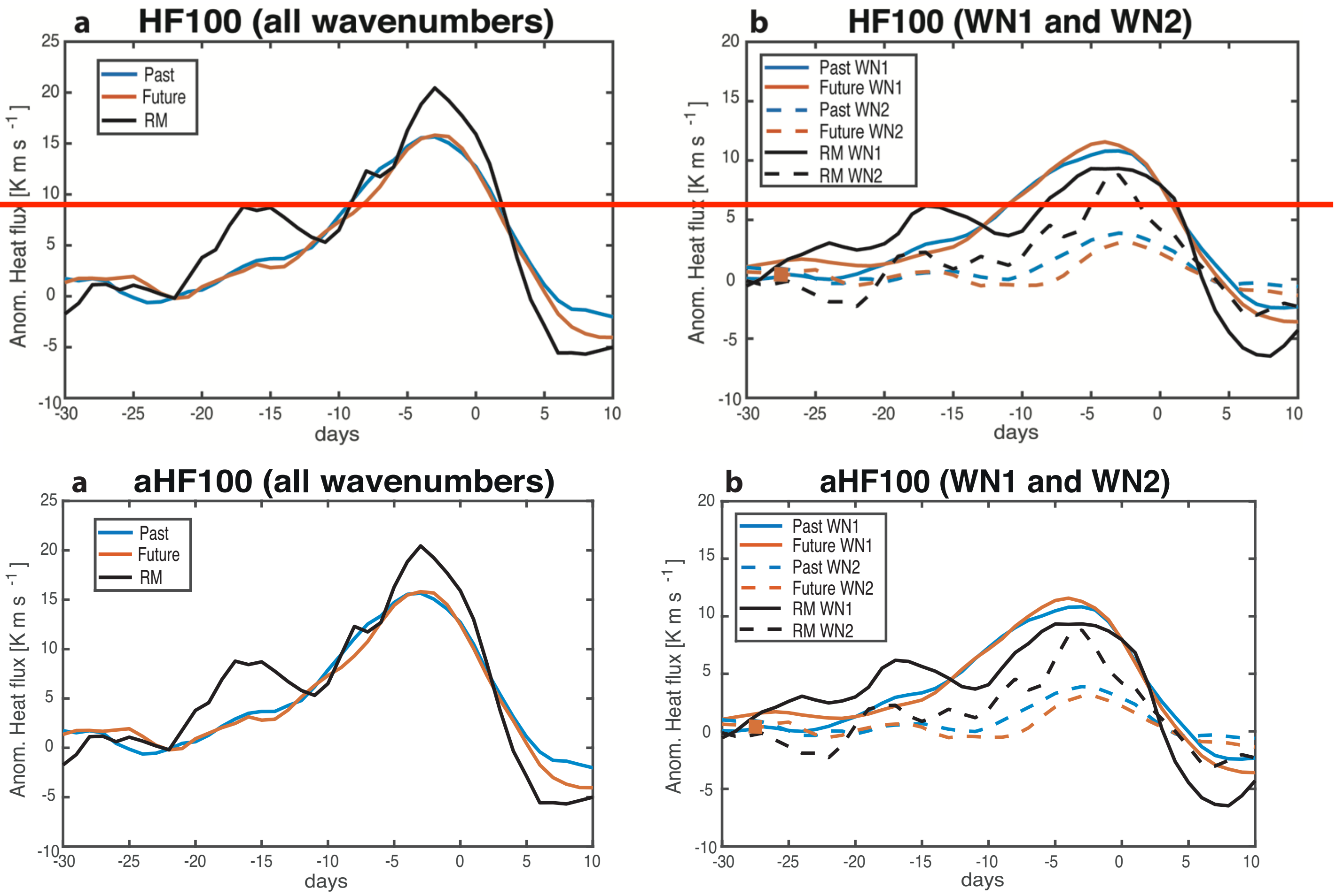


Figure 3. (a) Multimodel mean of anomalous heat flux (K m s^{-1}) at 100hPa averaged over 45°N-75°N from 30 days before until 10 days after the occurrence of SSWs. (b) Same as (a) but for WN1 (solid lines) and WN2 (dashed lines) wave components. Thick lines denote statistically significant future values different from the past ones at the 95% confidence level. RM stands for the Reanalyses (JRA-55 and ERA-40) Mean.

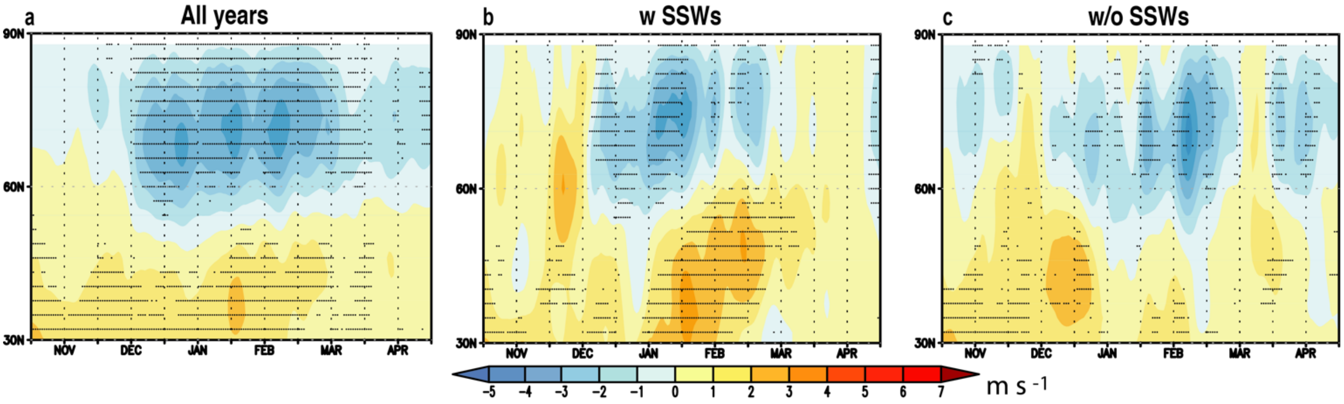


Figure 4. (a) Multimodel mean of future-minus-past differences in the daily climatology of 5-day running mean of zonal mean zonal wind at 10 hPa. (b) Same as (a) but only for winters with SSWs. (c) Same as (a) but for winters without SSWs. Shading interval: 1 m s^{-1}. Dots indicate where at least 75% of the models coincide in sign with the multimodel mean.

Supplementary material of the manuscript "No Robust Evidence of Future Changes in Major Stratospheric Sudden Warmings: A Multi-model Assessment from CCMI" by B. Ayarzagüena et al.

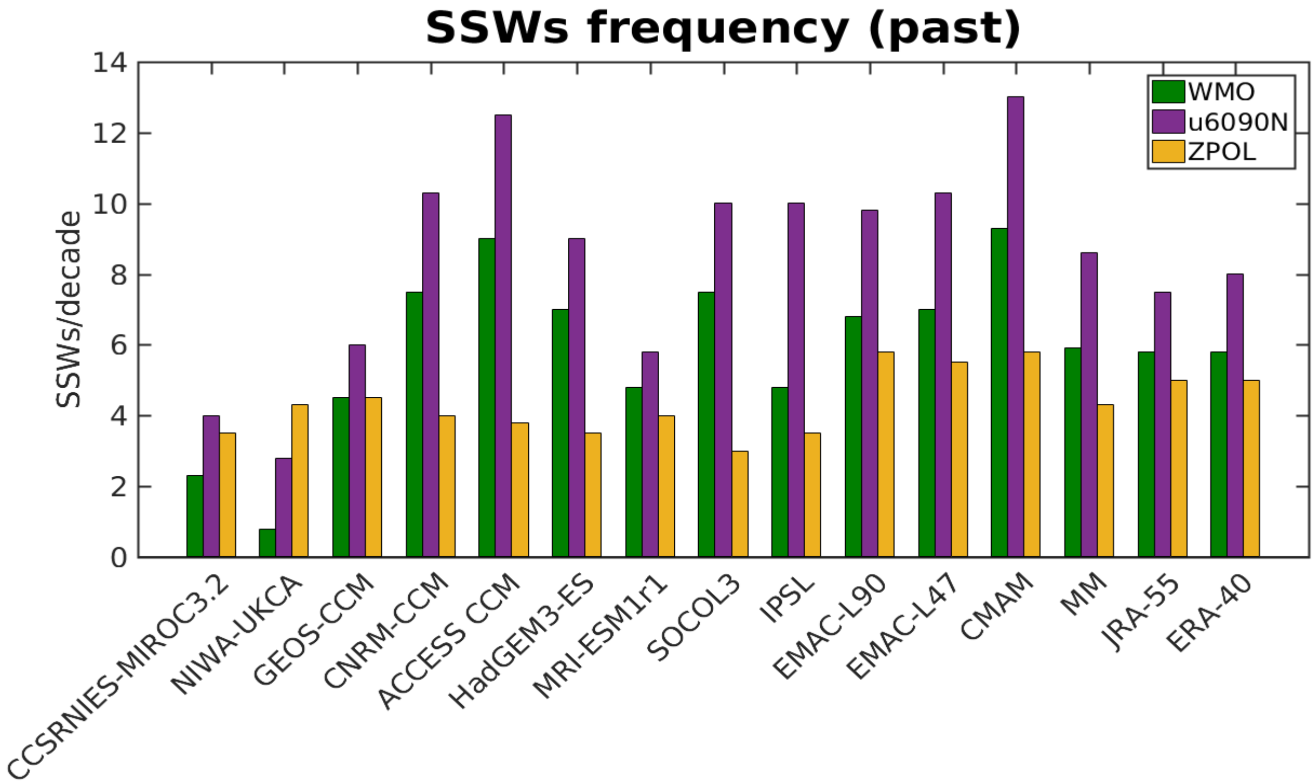


Figure S1. Mean frequency of stratospheric sudden warmings per decade identified with the WMO (green), u6090N (purple) and ZPOL (yellow) criteria in all models, the multimodel mean (MM), JRA-55 and ERA-40 in the past period.

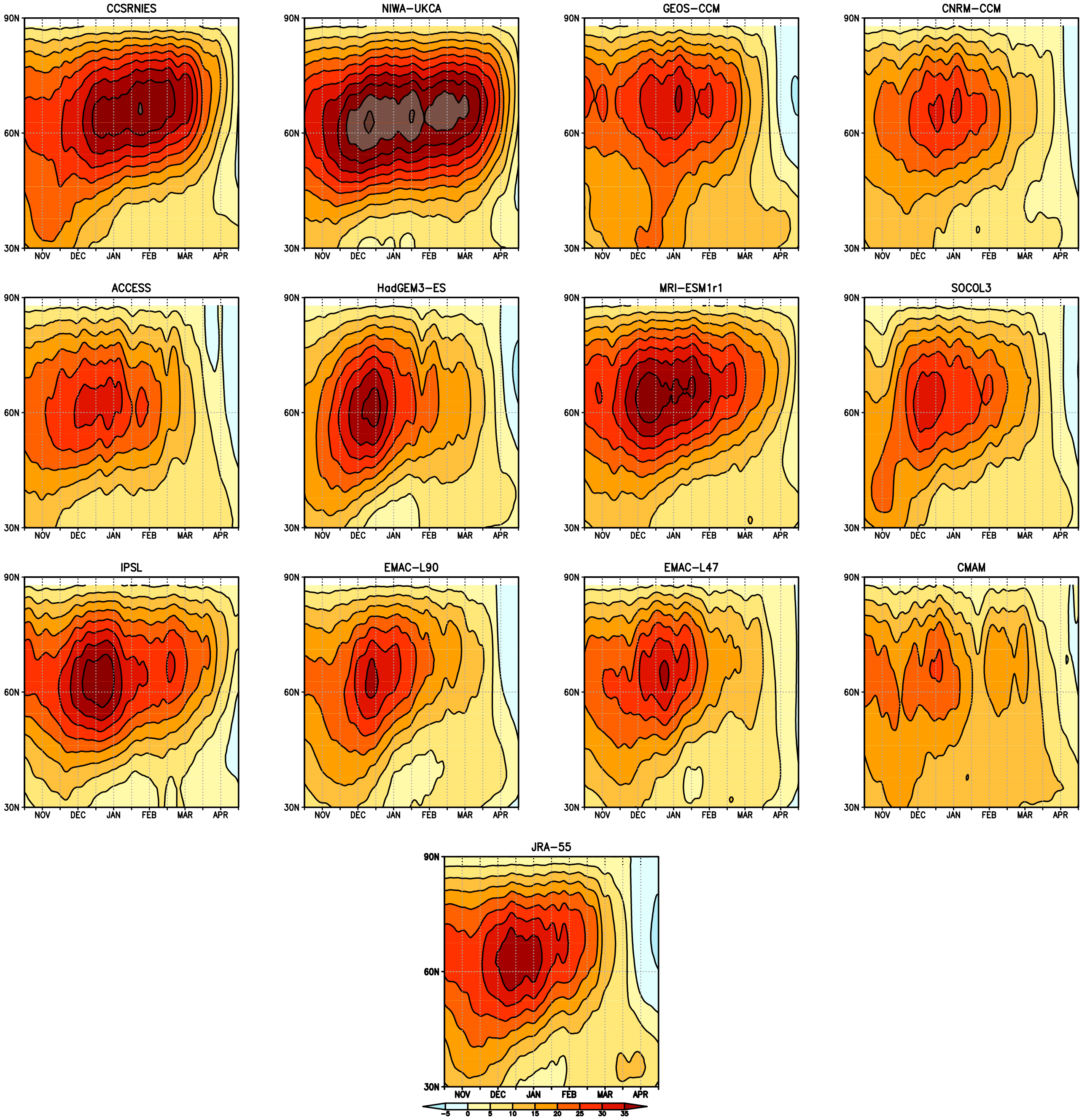


Figure S2. Climatology of 5-day running mean of zonal mean zonal wind at 10 hPa in the past period (1960/61-1999/2000). Shading interval: 5 m s^{-1}.

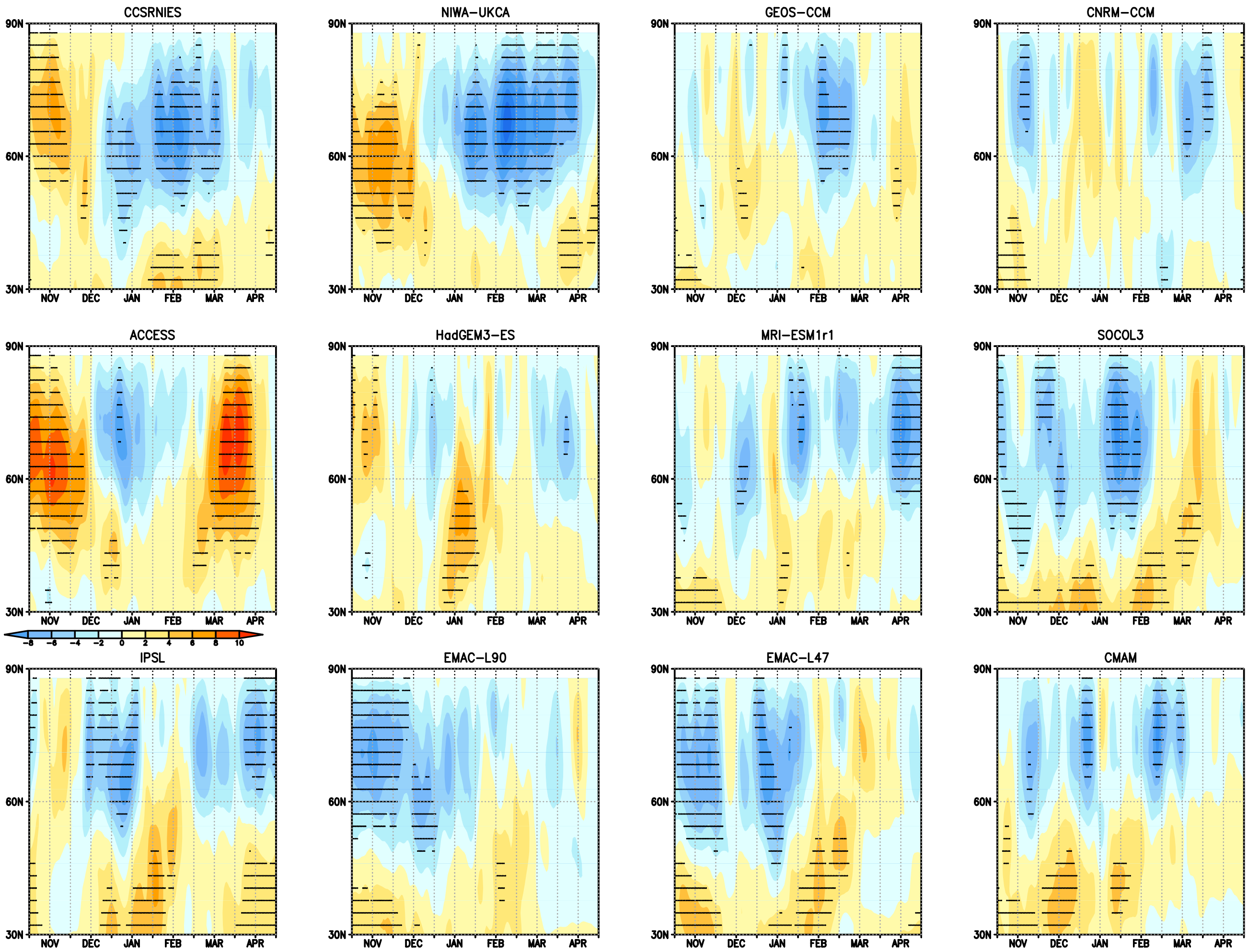


Figure S3. Future-minus-past differences in the climatology of 5-day running mean of zonal mean zonal wind at 10hPa. Shading interval: 2 m s^{-1}. Dots indicate statistically significant differences at a 95% confidence level.

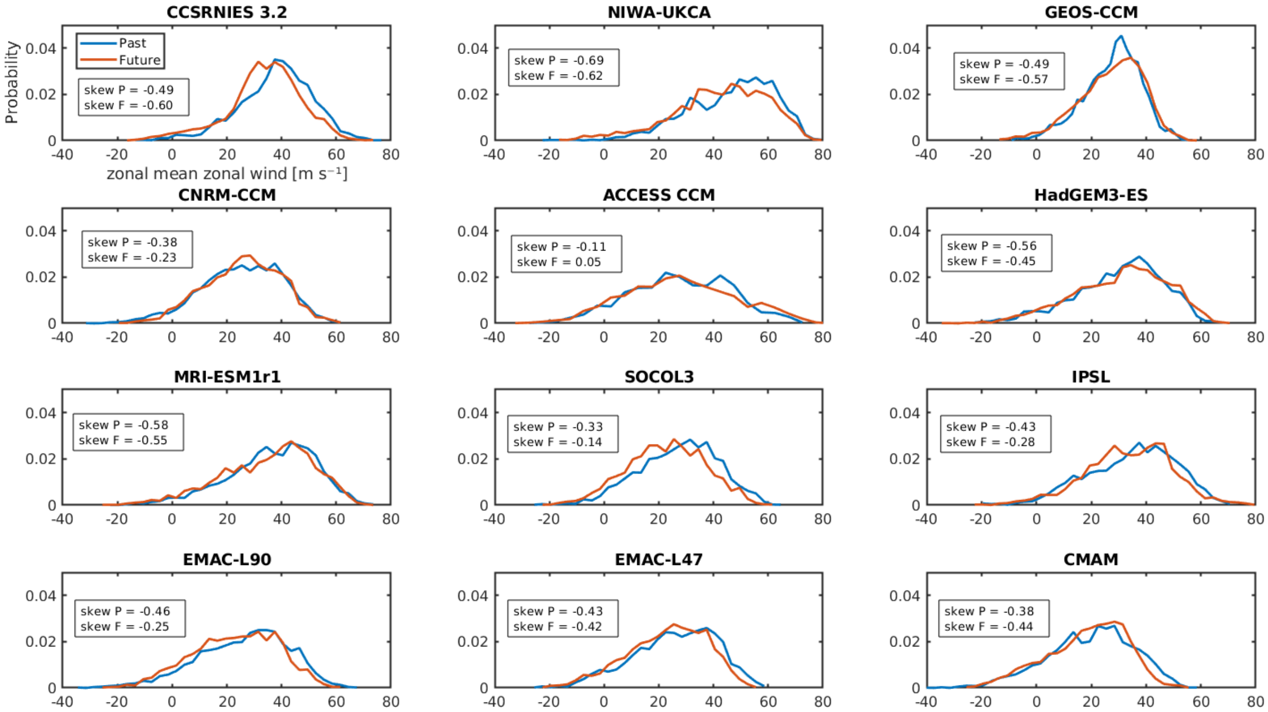


Figure S4. Probability distribution function of the daily zonal mean zonal wind at 60ºN and 10hPa in December, January and February in the past (blue line) and future (orange line) for each CCMI model. The skewness of the distribution in each time period is indicated in the text boxes

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