We would like to sincerely thank the reviewers. Their comments and suggestions significantly improved the paper quality and readability. We have included/addressed all the comments below. Reviewers' comments are written in red (and blue for typos) and our answers in green.

Anonymous Referee #1

GENERAL COMMENTS

This is a relatively straightforward paper that makes use of the SOCOL3-MPIOM chemistry-climate model to simulate changes in climate and ozone under strong and weak grand solar minima. The primary conclusion of the paper is that even a strong grand solar minimum, under a very aggressive GHG emissions reduction scenario (RCP2.6) will not completely offset projected increases in global mean surface temperatures.

I have made some minor suggestions for corrections below. Once these have been addressed, the paper will be suitable for publication in Atmospheric Chemistry and Physics.

SPECIFIC COMMENTS

Page 1, line 11: Replace 'greenhouse gas scenario' with 'greenhouse gas emissions scenario'.

We put "… greenhouse gas concentration scenario RCP4.5" as suggested.

Page 1, line 21: I would suggest replacing 'chlorine-induced' with 'halogen-induced' since it is both chlorine and bromine that drives the depletion.

Fixed. We put "halogen-induced".

Page 1, line 27: Replace 'of greenhouse' with 'of atmospheric greenhouse'.

Fixed. We have done as suggested.

Page 2, line 17: I am not sure that this is true. I don't think that the Montreal Protocol prohibits emissions of ODSs into the atmosphere. I think that it only prohibited their production. I encourage the authors to seek clarification on this.

Yes, the reviewer is right. We changed "emissions" with "production".

Page 2, line 21: Why the specific focus on terrestrial climate here? Is this not an issue for the ocean also?

Good point, "terrestrial and aquatic" would be appropriate, but this phrase usually stands before "ecosystem". We have changed it with "Earth's" instead.

Page 3, line 5: The way in which this is written it is not clear whether the sunspots became rare in 1715, or whether they were rare between 1645 and 1715.

Fixed. Sentence is changed to “A grand solar minimum, which was even more prolonged than the Dalton Minimum was the Maunder Minimum, the period between approximately 1645 and 1715 when sunspots were exceedingly rare.”

Page 3, line 19: I would suggest changing ’cancel global warming’ to ’completely offset GHG-induced global warming’.

Fixed. We have done as suggested.

Page 3, lines 30-31: The statement ’globally cool the surface by around 0.1 K’ suggests that the cooling is spatially uniform. Was this indeed the case?

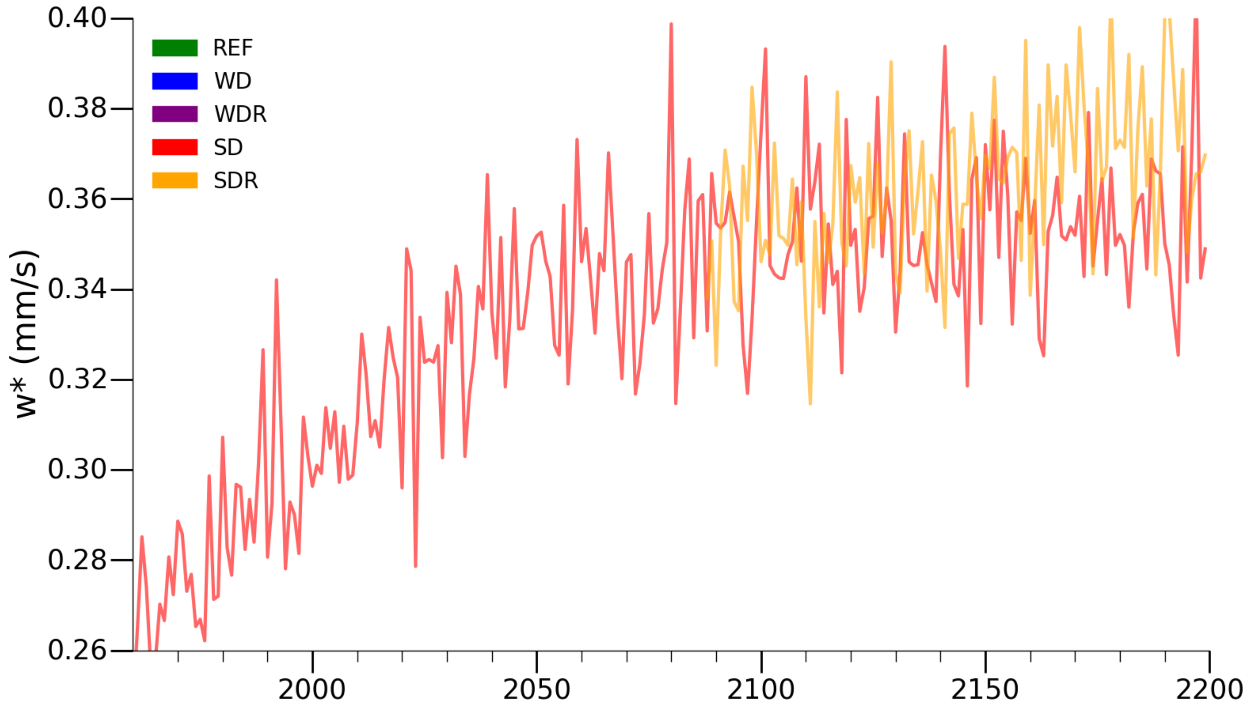
Good point, now this sentence is “…would decrease global mean temperature by around 0.1 K…”

Page 4, line 6: I would suggest ’dissipates’ rather than ’recovers’ since it is not clear what the grand solar minimum is recovering from.

Fixed. We have done as suggested.

Figure 2: Why is there a disconnect between the blue and purple lines in 2090 (and similarly for the red and orange lines)? From figure 1 I thought that WD and WDR would be identical up to 2090 and likewise for SD and SDR?

They are identical up to 2090 but the Savitzky-Golay filter makes this disconnect. Please see the plot below that shows SD and SDR w* without the filter.



Page 7, lines 13 and 14: I am sure that Zubov (2013) was not the first to show that tropospheric warming is mainly caused by the surface warming due to increase of down-welling infrared radiation by GHG, enhanced by latent heat release in the middle troposphere. Why did you specifically choose this reference?

Good point, we have changed this reference to IPCC.

Page 7, line 15: I think you need to be clearer what you mean by ’results from increased cooling rates of GHGs’ and you should provide a citation to support this assertion.

We rewrote the sentence to “The temperature decrease in the stratosphere and mesosphere comes from increased cooling rates due to the GHGs rise (IPCC, 2013)”.

Page 9, line 14: I think that this would be clearer if you replaced ’show lower surface temperatures’ with ’show lower surface temperature reductions’.

Fixed. We have done as suggested.

Page 9, line 28: If I remember correctly, you had two ensemble members for each simulation. I can’t recall that you have said anywhere to this point how they were used. Are the responses shown the average of the ensemble pairs?

They are ensemble means (written in the figure captions). We have added this information for all figures as well.

Page 10, line 2: You state that the increase in upper stratospheric ozone of 15-20% is a result of reduced intensity of the catalytic ozone destruction by reactive chlorine species. How did you do this attribution solely to chlorine chemistry? Is there no component at all that results from upper stratospheric GHG-induced cooling that slows the O+O3 -> 2O2 reaction?

Good point. The ozone increase is due to the reduced rate of ozone depleting cycles – chlorine, NOx, HOx and also O+O3 -> 2O2 reaction. We have rephrased this statement to: "The increase in the upper stratosphere of 15 – 20% is a result of reduced intensity of the ozone destruction cycles." Further discussion describes this in more details.

Page 12, line 9: At this point I am wondering how you are treating N2O emissions in your simulations. N2O was supposed to be the biggest depleter of ozone through the 21st century. There seems to be no discussion of this in the context of your simulations. I understand that N2O emissions are the same in all of your simulations, but this statement that the dominant effect on ozone will be solar activity made me wonder about the relative contribution of N2O.

N2O itself is not threat to ozone, but it reacts with O(1D) and gives NO which is an ozone depleter. We are discussing NOx in a separate chapter. Although we can't distinguish between NOx coming from tropospheric N2O and energetic particle precipitation, NOx coming from N2O is included in the projections and discussions.

The below errors (in blue) in the manuscript have been corrected.

GRAMMAR AND TYPOGRAPHICAL ERRORS

I understand that the authors' first language may not be English. The paper would benefit from a thorough grammar check. I have highlighted just a few of the grammatical errors below.

Page 1, line 25: Replace 'since preindustrial' with 'since the preindustrial'.

Page 1, line 26: Replace 'The mean global' with 'The global mean' or otherwise be specific about which mean you are talking about.

Page 2, line 4: Replace 'RCP8.5' with 'for RCP8.5'.

Page 2, line 6: Replace 'under United' with 'under the United'.

Page 2, line 23: Delete 'basically'.

Page 3, line 30: Replace 'the reduction' with 'a reduction'.

Page 5, line 2: Replace ’assumed previous’ with ’assumed in previous’.

Page 6, line 13: Replace ’increase of GHG concentrations’ with ’rate of increase in GHG concentrations’.

Page 7, line 16: Replace ’ODSs emissions’ with ’ODS emissions’.

Page 8, line 20: Replace ’predict a warming about 2 K’ with ’predict a warming of about 2 K’.

Page 9, line 31: Replace ’in polar lower stratosphere’ with ’in the polar lower stratosphere’.

Page 10, line 18: Replace ’ODSs concentrations’ with ’ODS concentrations’.

Page 12, line 27: Replace ’to conclusion’ with ’to conclude’.

Anonymous Referee #2

Review’s report on Arsenovic et al.

The paper reports on the potential effects of a future solar minimum on climate change projections, according to the SOCOL chemistry-climate model. The sensitivity of future climate (including the evolution of the ozone layer) on the amplitude and duration of the solar minimum are investigated. In agreement with previous studies, it is shown that even a large minimum involving a TSI decrease of up to 6 W/m**2 would only partially (10-20%) ameliorate the warming due to GHG. Moreover, the effects on surface climate are relatively short-lived, as the climate system would quickly bounce back after a "recovery" to present-day solar activity levels. On the other hand, the sensitivity of the evolution of the ozone layer on assumed solar forcing is strikingly large: this is the key and most interesting aspect of this paper. The results presented in the paper are sufficiently supported by the analysis, and the conclusions are of interest to the wider modeling community. Considering this, I think this paper would be suitable for publication. However, the layout of the paper needs some polishing. Also, some claims are not sufficiently justified. I therefore recommend an extensive set of minor revisions, as detailed below.

MINOR POINTS

Abstract

L9 - "Understanding potential interferences with natural forcings". "interference" sounds strange in this context. I would rephrase this to "Understanding the role of natural forcings in modulating global warming"

Fixed. We have done as suggested.

L11 remove "several"

Fixed. We have done as suggested.

L12 "but with different solar forcings" -> a range of different solar forcings

Fixed. We have done as suggested.

L13 "year 2199, whereas the grand solar..." -> ...year 2199. This reference is compared with grand solar minimum simulations, assuming...

Fixed. We have done as suggested.

L14 "different durations" -> specify what durations

"… that last either until 2199 or recover in the 22nd century" is added.

L14 "decreased ... cooling" -> not clear which of the solar minimums is meant here; please be more specific

"by 6.5 W/m^2" is inserted in the text.

L16 "projected to decrease" -> suggest adding this to this sentence: "with respect to a simulation assuming a repeating solar cycle 23"

Fixed. "compared to the reference" is added.

L16 On the global scale the reduced... -> On the global scale, a reduced...

Fixed. We have done as suggested.

L16 The regional effects are predicted to be stronger -> would say "significant" instead of "stronger". It is obvious that regional effects are going to be larger than the global counterpart, so i would just say significant to emphasize the importance of regional changes

Fixed. We have done as suggested.

L19 "In the stratosphere... by up to 8%" it would be good to state the magnitude of the UV forcing (e.g. as W/m2 for the UV spectrum), given the importance of the chemical effect on O3

Good point. We have included information of UV reduction in Abstract: "…reduction of around 15% of…" but also in the Methods: "The drop in the part of the UV spectrum that is most important for ozone production (180 – 250 nm) is about 9% in WD and WDR and about 15% in SD and SDR."

L22 "completion of ... later". Does this mean that a minimum lasting all the way until 2200 is necessary to get the recovery...? not clear here

No, it will recover as soon as the minimum recovers. We have removed “in the 22nd century or later”.

L25 remove "current"

Fixed. We have done as suggested.

L14 p2 "the global ozone depletion" -> the decline in global ozone concentrations

Fixed. We have done as suggested.

L25-29 I would suggest reducing this discussion... since it is not important for the paper

We have reduced the discussion to sentence: “Apart from 11-year solar cycle, the solar activity oscillates in the cycles in the order of hundred years, called “grand solar minima” and “grand solar maxima“.”

L33 The effects of the Dalton minimum on Europe are subject to debate, as the minimum is just too short and weak to significantly affect climate. Moreover, there is a problem of interference with volcanoes. Hence, I would rather limit the discussion to the Maunder Minimum (which is already speculative enough), without the need to discussing weaker (and even more speculative) past solar minima.

It is true that Dalton minimum interferes with volcanoes, but it has been shown that it affected global mean temperature (Anet et al., 2013, ACP). This paragraph serves as motivation to say that the grand solar minima are able to impact global mean temperature.

L3 p3: "computed" -> simulated

Fixed. We have done as suggested.

L15p3 "is important for a realistic representation of ozone" -> of ozone... variability? The (climatological) ozone layer can be well represented even without the EPP forcing (see CCMVal models that don’t include EPP).

Fixed. We have done as suggested.

L16p3: Suggest removing "With respect to surface temperature".

Fixed. We have done as suggested.

L18p3: "estimate" -> assess

Fixed. We have done as suggested.

L19p3: "...would slow or even cancel global warming" -> would lead to possible reduction in the projected warming (I don’t think anybody so far has shown that a solar minimum could cancel GW, but only partially ameliorate it)

Fixed. We have done as suggested.

L22p3: "Meehl..." suggest specifically saying what magnitude and duration for the minimum they chose. There is a bit of spread across different studies in regards to the amplitude and duration of the imposed "idealized" future minima. So, since there is no unified and accepted definition of "grand solar minimum", these details are needed when reporting the results of a specific study

We have included this information in the introduction section: “with total solar irradiance drop of about 3.9 W/m2 (0.25%) in 2024 – 2065 period”.

L24p3: "lower by several tenths..." please always clarify that "lower" is with respect to a reference which is still warming... so we still have a warming even with the minimum, but just smaller in magnitude

Fixed. We put “than the reference” to be more specific.

L25p3: (in between "grand minimum..." and "However...") I think it would be good to add reference to Chiodo et al., 2016 here, since they used the same global model as Meehl et al, but imposed a more conservative minimum and found important regional effects. Hence, I would add the following... "A follow-up study using the same model but a more conservative solar minimum found important regional effects in the Northern high latitudes, suggesting a reduction of the Arctic Amplification (Chiodo et al., 2016)".

Thank you very much for the suggestion. We have added sentence in the manuscript "A follow-up study using the same model but a more conservative solar minimum found important regional effects in the Northern high latitudes, suggesting a reduction of the Arctic Amplification (Chiodo et al., 2016)".

L28p3: "by Meehl et al. (2013)" -> add "Chiodo et al., (2016)" ; they show the same order of magnitude in terms of cooling, at regional level, so they deserve to be cited here, too.

Added. Thank you.

L30p3: "0.13%"... how much is this in W/m**2? Please specifically say it here (e.g. in parenthesis)

We added “… about 1.75 W/m2 (0.13%)…” to be more specific.

L4p4: The novel aspect with respect to Anet et al 2013 is that the minimum is extended in time and the full extent of the response over the 21 and 22 century are analyzed. This should be more clearly stated here... otherwise, there is risk of seeing this paper as a simple "extension of Anet 2013"

Thank you for the suggestion. We have included “The novel aspect with respect to Anet et al 2013 is that the minimum is extended in time and the full extent of the response over the 21st and 22nd century are analysed.”

Sentence “Here we investigate the atmospheric response to a potential grand solar minimum which starts around 2020, reaches full depth by about 2090, and lasts either until 2200 or recovers within the 22nd century.” is removed because the minimum details are discussed later.

L5p4: is there a specific reason as to why this amplitude and duration is chosen? A justification would be nice...

We have removed that sentence (please see the previous comment)

L15p4: "hydrostatic and Bousinnesq": these two are mutually exclusive; adding a bousinnesq assumption implies the model is not necessarily hydrostatic.

We removed "hydrostatic and Bousinnesq" and connected this sentence with the following:

“The oceanic component is MPIOM, a primitive equation model which includes a dynamic/thermodynamic sea-ice module and uses a curvilinear orthogonal grid which allows for various setups.”

L21p4 applied -> imposed

Fixed. We have done as suggested.

L22p4 Figure 1: please att W/m2 values to your plot, e.g. as a Y axis on the right hand side

We have added the change in TSI in W/m2 as left axis and percentage axis as right.

L23p4: "weak drop" : would not call 0.25% a "weak drop", since it is much larger than the 11-yr solar cycle and any current version of TSI reconstructions back to MM... it is weak in the context of the other experiments of this paper though... so I would add "relatively" before "weak" to emphasize this

Fixed. We have added “relatively”.

L3p5 "Ineson et al., 2015..." Chiodo et al., 2016 missing in this load of citations

We have added Chiodo reference as suggested.

L3p5: "As described by Meehl et al., 2013" -> Meehl does not really discuss this aspect, so i would drop this citation

We have removed Meehl reference and added Schrijver et al (2011) and Foukal et al (2011). The sentence now is: “Previous estimates regarding the TSI decrease during the Maunder Minimum compared to present-day values range from somewhere close to present 11-year solar minima (Schrijver et al., 2011), to reductions of 0.15% to 0.3% below present solar minima (Foukal et al., 2011) all the way to more than 0.4% below present solar minima derived by Shapiro et al. (2011) and applied here in the SD and SDR scenarios."

L11p5: "In agreement with M2013" -> I would drop this citation. " In agreement" is for results, not for an assumption.... so i would either drop it, or rephrase it to "As in Meehl et al 2013, we emphasize..."

Fixed. The sentence construction is changed to "As in…"

L11p5: "an actual" -> a hypothetical. We are not certain a minimum is actually going to happen to would use "hypothetical" here

Fixed. We have done as suggested.

L17p5: "solar minimum values." Indicate by which year this recovery is reached

Fixed. We have added "…about 2170 – 2180"

L18p5 "identically to" -> as in

Fixed. We have done as suggested.

L24p5 "CMIP4" -> there is no CMIP4... either CMIP3 or CMIP5

Fixed. We changed CMIP4 to CCSM3.

L4p6: "to elucidate the role of solar forcing" -> to elucidate the role of solar forcing in modulating GHG driven temperature trends

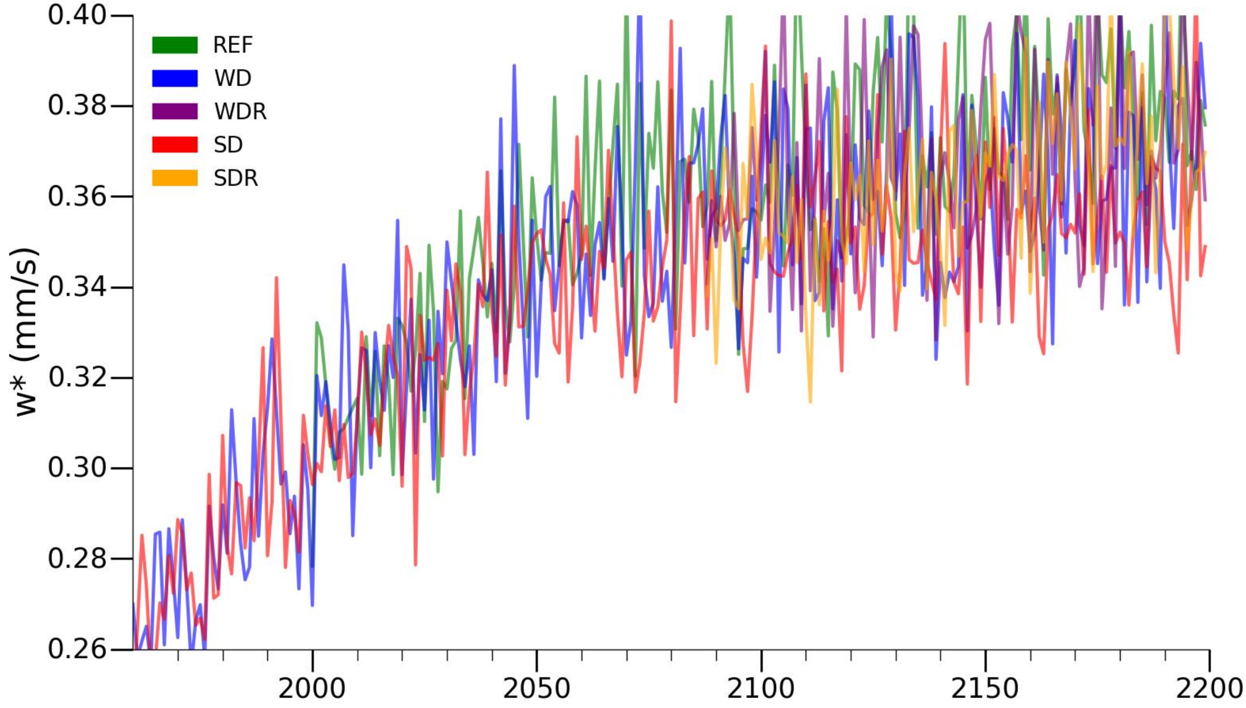
Fixed. We have included "… in modulating GHG driven temperature trends"

GENERAL COMMENT ON THE RESULTS SECTION: I recommend swapping the order of sections 3.1 and 3.3. I suggest moving 3.3 to 3.1, and moving the BDC section to 3.2, then NOx in 3.3 and ozone in 3.4. Temperature is generally the first variable we look at, and then go back in the causality chain (WSTAR could explain T trends, and then CHEMISTRY)

We have changed the order of the chapters as suggested by reviewer.

L9p6: is this filter really needed? What does the t-series look like without such filter?

Please see the plot below (yearly means). The filter makes the differences in w* in scenarios more obvious, especially when there are 5 scenarios shown.



L14p6: "however... strength, but statistically significant" -> at a reduced rate, although still statistically significant

Fixed. We have done as suggested.

L16p6 BDC -> the BDC

Fixed. We have done as suggested.

p19 p6 applied -> imposed

Fixed. We have done as suggested.

L19p6 " are decreasing and... 21st century" -> are projected to decrease, and N2O will increase during the 21st century.

Fixed. We have changed this sentence to "… surface emissions of NOx are projected to decrease and concentrations of N2O will increase during the 21st century…"

L29p6: well visible -> clearly visible

Fixed. We have done as suggested.

L12p7: in the future -> would remove this; REF already implies this is "future projection"

Fixed. We have done as suggested.

L13p7: "Zubov... middle troposphere". I think this is a generally accepted explanation, based on complex and also simpler (moist GCMs / acquaplanet) models, so I don’t think Zubov is the first one giving this explanation. You could perhaps cite the IPCC instead

We have changed Zubov et al reference to IPCC, 2013

L15p7 rates of GHGs -> arising from increased GHG

We changed this sentence to “The temperature decrease in the stratosphere and mesosphere comes from increased cooling rates due to the GHGs rise”

L15p7 "the secondary maximum" -> Please specify what location you mean here; i.e. the warming at 100 hPa at 70-90S.

We included “… around 100 hPa”. It is already said that it is around Antarctica.

L22p7 "has relatively" -> has a relatively

Fixed. We have done as suggested.

L1p8 "The temperature anomaly... REF" -> suggest rephrasing to: The impact of SD forcing relative to GHG is quantified as the difference between SD and REF: this is shown in Fig.4c

We changed the manuscript as suggested.

L3p8 "As expected... magnitude". As expected, based on the UV forcing in WD being 50% smaller than SD? If so, please specifically say it here...

We put “… due to the lower UV forcing…”. It is not exactly 50% - it is 9% in WD and 15% in SD.

L6-L12p8 would put all this at the beginning of the results section

Thank you for the suggestion. We followed the advice, this paragraph is in the beginning of the chapter.

L14p8 "of the minimum" -> from a solar minimum

Fixed. We have done as suggested.

L15-L19p8 but what is the impact of SDR over the 21st century? Does it make sense to look at the effects 30 years after the recovery...?

SD and SDR are very similar in the 21st century (identical up until 2087). Therefore, we don't discuss SDR in the 21st century. We look into the effects after the recovery to see if the minimum would slow down warming and ozone layer recovery before the sun goes back to present values.

L25p8 "reproduces the polar amplificiation well" I would not use the word "reproduce... well" since this is a projection, not a validation against OBS data. Recommend rewording this to "...simulates a polar amplification too".

We have changed the manuscript accordingly.

The below points (in blue) are all included as suggested:

L32p8 "see Figure .... SD scenario" -> In this scenario, the model suggests a...

L3p9 "Beyond the scope..., this" rephrase to -> However, this phenomenon needs to be investigated in more detail....

L10p9 "previous century" -> 21st century

L15p9 "see Fig.7a... scenario" -> as shown in Figure 7a for the strong reduction (SD) scenario

L16p9 "but to a smaller magnitude" -> but to a smaller extent

L17p9 "amounting to around" -> and is around

L18p9 "simulating a solar anomaly" -> assuming a future solar minimum

L19p9 "Considering... Asia" -> In the SD scenario, the largest cooling during boreal winter (DJF) is seen over the Barents Sea and northern Asia,

L21p9 Similar cooling areas appear -> Similar cooling appears...

L22p9 "the boreal winter projection" ->boreal winter

L25p9 "Chiodo et al 2016 -> Similarly, Chiodo et al., (2016) reported...

L26p9 "This cooling..." -> In their model, this cooling...

GENERAL COMMENT ON SECTION 3.4 This section on the O_3 should follow the NO_x analysis (3.2). The sequence of surface temp. BDC, NO_x and O_3 would also follow more "naturally", as you start off with the pure thermodynamical response, then look at the dynamics, and then looking into the chemistry.

Good idea, we agree and change the order as suggested.

L7p10: is there a paper showing this point? if there is, please include a citation to it.

These lines are: “Conversely, the future decline of NOx surface emissions will result in less tropospheric ozone with a maximum in the northern hemisphere of up to 20%.” We are not aware of any other study showing this claim.

L17p10: "low level of solar UV" -> by decreased UV input

Fixed. We have done as suggested.

L22p10 "Together with the NOx" -> the link to NOx is further evidence that this section would naturally follow immediately after the one on NOx (3.2)

We have changed the order of paragraphs as suggested.

L27-L28p10 -> isn’t this a repetition of L20-22 one paragraph above...?

It is not a repetition: L20-22 refer to future decrease of HOx and lines L27-28 to decrease of HOx in case of solar minimum. Both result in ozone increase.

L29p10 suggest adding ", consistent with the smaller (by a factor of 2) UV forcing."

We have changed the manuscript as suggested.

L10p11 "Reduction of... future" -> A future reduction in solar activity

Fixed. We have done as suggested.

L23-24p11: is this effect statistically significant? The impact of solar irradiance on the polar vortex is generally small and not really significant in models...

We found the significant zonal wind change (please see the plot below).

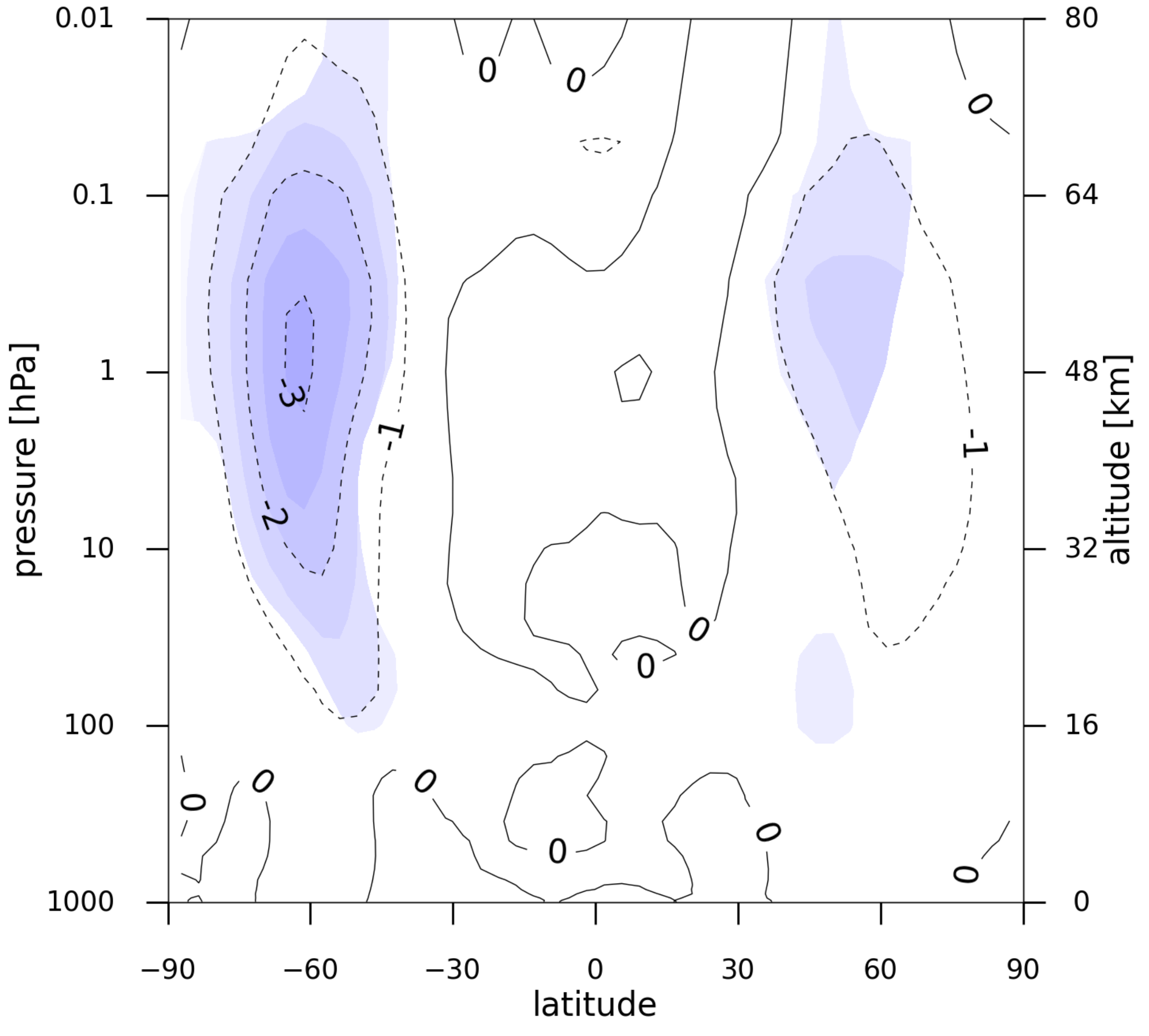


Figure. Annual zonal mean zonal wind difference in m/s of SD minus REF under future conditions (2090 – 2099)

The below lines (in blue) are all included as suggested by reviewer:

L4p12 by several years (Anet et al., 2013).

L5p12: :" we show annual..." -> we show the annual

L8p12 "the dominant ... activity" -> solar activity turns into the the dominant driver of ozone changes.

L18p12 ", but would still be" -> . However, it would still be

L20p12 "While... the year 2100" -> A solar minimum, assuming a very large drop in solar irradiance (SD scenario) is predicted to compensate about 15% of the GHG induced warming by 2100. However, this fraction could increase to about...

L32p12 "period" -> season

L9p13 cause -> causes

L11-L13p13 : GENERAL COMMENT: well, the effects of UV vs EPP have not really been separated, as they are lumped together in the forcing imposed in these runs. Hence, it cannot be really stated that this study "improves our understanding of the effect of EPP"... so either rephrase it, or remove this sentence

We have rephrased the sentence to: "… While this study includes the effect of energetic particle precipitation…"

The below lines (in blue) are all included as suggested by reviewer:

L19p13 "it faces us with" -> it poses

L20p13 "The accelleration... dynamics" -> there is no "accelleration of atmospheric dynamics", but of the BDC... so rephrase this to "The accelleration of the BDC"

L3p14 "lets more UV reach the ground" -> allows more UV to reach the ground

Implications of potential future grand solar minimum for ozone layer and climate

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Abstract. Continued anthropogenic greenhouse gas (GHG) emissions are expected to cause further global warming throughout the 21st century. Understanding the role of natural forcings ~~in modulating~~ and their influence on global warming ~~Understanding potential interferences with natural forcings~~ is thus of great interest. Here we investigate the impact of a recently proposed 21st century grand solar minimum on atmospheric chemistry and climate using the SOCOL3-MPIOM chemistry-climate model with interactive ocean. We examine ~~several~~ five model simulations for the period ~~2000~~ 2000 ~~–~~ – 2199, following the greenhouse gas concentration scenario RCP4.5~~,~~ and ~~but with~~a range of ~~-~~different solar forcings~~:~~. ~~the~~ The ~~reference~~ reference simulation is forced by perpetual repetition of solar cycle 23 until the year 2199. This reference is compared with grand solar minimum simulations, assuming ~~year 2199, whereas the grand solar minimum simulations assume a~~ strong declines in solar activity of 3.5 and 6.5 W/m^2 , respectively, ~~with different durations~~that last either until 2199 or recover in the 22nd century. Decreased solar activity by 6.5 W/m^2 is found to yield up to a doubling of the GHG induced stratospheric and mesospheric cooling. Under the grand solar minimum scenario tropospheric temperatures are also projected to decrease compared to the reference. On the global scale ~~the~~ a reduced solar forcing compensates at most 15% of the expected greenhouse warming at the end of 21st and around 25% at the end of 22nd century. The regional effects are predicted to be ~~stronger~~significant, in particular in northern high latitude winter. In the stratosphere, the ~~reduced~~ reduction of around 15% of incoming ultraviolet radiation leads to ~~less~~ a decrease in ozone production by up to 8%, which overcompensates the anticipated ozone increase due to reduced stratospheric temperatures and an acceleration of the Brewer-Dobson circulation. This, in turn, leads to a delay in total ozone column recovery from anthropogenic ~~chlorine~~halogen-induced depletion, with a global ozone recovery to the pre-ozone hole values happening only upon completion of the grand solar minimum~~ in the 22nd century or later~~.

1 Introduction

Global warming is one of the main ~~current~~ societal problems. The observed global warming since the preindustrial period (1850 – 1900) until the end of 20th century (1986 – 2005) is estimated to be around 0.6 °C (IPCC, 2013). The ~~mean~~ global mean surface temperature is expected to continue to rise in the 21st century due to human activity and an associated increase of atmospheric greenhouse gas (GHG) concentrations. In its fifth assessment report (AR5), the Intergovernmental Panel on Climate Change (IPCC) examined four Representative Concentration Pathways (RCPs) of GHG concentration trajectories (IPCC, 2013). The projected warming (2081-2100 mean minus 1986-2005 mean) is 1±0.4 °C for RCP2.6, 1.8±0.5 °C for RCP4.5, 2.2±0.5 °C for RCP6.0, and 3.7±0.7 °C for RCP8.5, given as multi-model mean ± standard deviation of the various IPCC models. In December 2015, many countries agreed to make an effort to reduce their emissions of GHG into the atmosphere in order to keep the global surface temperature rise below 2 °C above pre-industrial levels. This agreement was adopted under the United Nations Framework Convention on Climate Change (UNFCCC), and it is now known as The Paris climate agreement. RCP2.6 is the only GHG concentration scenario that limits the global mean surface temperature increase at 2 °C at the end of 21st century (van Vuuren et al., 2011b).

A second major anthropogenic influence on the atmosphere results from the release of ozone depleting substances (ODSs). Rowland and Molina (1974) warned against human-produced chemicals which ~~playing~~ play an important role in stratospheric ozone depletion, leading to a thinning of the ozone layer, thereby increasing the incidents of skin cancer and eye cataracts, but also affecting plants, crops and the oceanic ecosystem (e.g.~~,~~ Hegglin et al., 2015). Observations confirmed the decline in global ozone ~~depletion~~concentrations, and revealed that the maximum ozone depletion occurred in the springtime Antarctic stratosphere, a phenomenon commonly known as the “ozone hole”. As a response to ozone depletion, the Montreal Protocol was established in 1987, which prohibited ~~emissions~~ production of certain ODSs into the atmosphere. In their latest report on the ozone layer, the World Meteorological Organization (WMO) and United Nations Environmental Programme (UNEP) projected that the reduction of ODSs will lead to ozone increase in the 21st century, reaching pre-1980 levels in the second half of the century, with detailed recovery times depending on latitude (WMO, 2014).

The projections of ~~terrestrial~~ Earth’s climate by the IPCC and of the ozone layer by WMO/UNEP assume solar irradiance to remain ~~basically~~ constant with respect to both incoming integrated power (total solar irradiance, TSI) and spectral distribution of the power (spectral solar irradiance, SSI). However, the Sun is a variable star and its output varies over vast time scales. Apart from 11-year solar cycle, the solar activity oscillates in the cycles in the order of hundred years, called “grand solar minima” and “grand solar ~~maxima“~~maxima“. ~~The decadal-scale solar variability was discovered in the middle of the 19th century (Schwabe, 1852; Wolf, 1861). This cycle is today known as the 11-year solar cycle and is characterized by a change in TSI between maximum and minimum of approximately 1 W/m^2 at Earth distance (Fröhlich, 2006), corresponding to about 0.07% of the average TSI of 1366 W/m^2 (Gray et al., 2010). Solar activity on longer time scales can be reconstructed using cosmogenic radionuclides, whose atmospheric production rate is modulated by solar activity. The reconstructions reveal cycles in the order of hundreds of years, called “grand solar minima” and “grand solar maxima”.~~ Several recent publications suggest a new grand solar minimum to occur in the 21st century (Abreu et al., 2010; Lockwood et al., 2011; Roth and Joos, 2013) and to last even until the end of 22nd century (Steinhilber and Beer, 2013). Such events might have a significant impact on climate and on the ozone layer. As an example, the Dalton minimum (1790 – 1830) is thought to have contributed to significant cooling in Europe (Brugnara et al., 2013; Luterbacher et al., 2004).~~–~~ It was characterized by reduced solar irradiation (Hoyt and Schatten, 1998), estimated to range between a moderate ~1 W/m^2 (Kopp, 2016) and as much as ~5 W/m^2 (Shapiro et al., 2011) below present values. Anet et al. (2013b) applied the forcing derived by Shapiro et al. (2011) to modulate the solar input in a climate model and found that, among other natural factors (e.g. volcanic activity), the ~~computed~~ simulated cooling was to a large degree caused by low solar activity. A grand solar minimum, which was even more prolonged than the Dalton Minimum was the Maunder Minimum, the period ~~starting around~~between approximately 1645 ~~and continuing to~~and ~~around~~ 1715 when sunspots ~~became~~ were exceedingly rare.

Energetic particle precipitation (EPP) is closely related to solar activity. Energetic particles have the ability to produce odd nitrogen and odd hydrogen species, NO_x ([N] + [NO] + [NO_2]) and HO_x ([H] + [OH] + [HO_2]), which are known to catalytically deplete ozone. Amongst all energetic particles, galactic cosmic rays (GCR) are the most energetic (1 MeV to $5 \cdot 10^{13}$ MeV; Dorman, 2004), so that they penetrate deep into the atmosphere. Their influence is ~~most important~~largest in the polar lower stratosphere and upper troposphere (Calisto et al., 2011; Jackman et al., 2016; Mironova et al., 2015). Their intensity is anticorrelated with the solar activity (Bazilevskaya et al., 2008). Conversely, low energy electrons (LEE) are stopped already in the upper atmosphere and produce NO_x in thermosphere, above 80 km altitude. During polar night, NO_x created by LEE is then transported downwards and affects mesospheric and stratospheric ozone (Rozanov et al., 2012). Therefore, inclusion of these processes in chemistry-climate models is important for a realistic representation of ozone variability.

~~With respect to surface temperature, r~~Reductions in solar activity may lead to a partial compensation of the radiative forcing stemming from increased anthropogenic emissions of GHGs. A number of studies were conducted to ~~estimate~~ assess if a potential future grand solar minimum would ~~slow or even cancel~~ lead to a possible reduction in the projected global warming. Mokhov et al. (2008) performed 21st century simulations with different solar, volcanic and anthropogenic forcings. Their analysis of the response of global mean near-surface temperature to various solar scenarios showed that solar activity variations of up to 2 W/m^2 impose only small changes in the surface temperature. Meehl et al. (2013) used the climate model CESM1 WACCM to investigate whether a future Maunder-like minimum could stop global warming. They found that such a potential grand solar minimum with ~~total solar irradiance~~TSI drop of about 3.9 W/m^2 (0.25%) ~~in the middle of 21st century~~~~in~~from 2024 to~~—~~ 2065 ~~period~~ would slow down and delay anthropogenic global warming, such that surface temperatures would be lower than the reference by several tenths of a degree by the end of the grand minimum. However, their study focused on surface temperature, whereas chemical effects and stratospheric changes caused by a grand solar minimum were not investigated. A follow-up study using the same model but a more conservative solar minimum found important regional effects in the Northern high latitudes, suggesting a reduction of the Arctic amplification (Chiodo et al., 2016). Another modelling study was performed by Anet et al. (2013a) using the SOCOL3-MPIOM model. Their work also showed a reduction of surface temperatures of the same order of magnitude as shown by Meehl et al. (2013) and ~~(~~Chiodo et al.~~,~~ ~~(~~2016) and a delay of the ozone recovery back to the "pre-ozone hole" conditions. Ineson et al. (2015) used the HadGEM2-CC climate model to evaluate possible impacts of a grand solar minimum on climate. They found that ~~the~~ a reduction of solar irradiance of about 1.75 W/m^2 (0.13%) would decrease global mean temperature ~~globally cool the surface~~ by ~~around~~ approximately 0.1 K for the second half of 21st century. Maycock et al. (2015) used the same model and applied a decrease in ~~total solar irradiance~~TSI and UV over the second half of 21st century of 0.12% (1.63 W/m^2) and 0.85% respectively, compared to present values. They found that the decrease in solar activity would reduce global annual near surface temperature by around 0.1 K and cool the stratopause region by around 1.2 K. However, their climate model lacked interactive chemistry, hence change in ozone and the influence of the EPP were neglected.

The present work is a continuation and extension of the study of Anet et al. (2013a).-. The novel aspect with respect to Anet et al. (2013a) is that the minimum is extended in time and the full extent of the response over the 21st and 22nd century are analysedHere we investigate the atmospheric response to a potential grand solar minimum which starts around 2020, reaches full depth by about 2090, and lasts either until 2200 or recovers within the 22nd century.

2 Methods

We use the coupled chemistry-climate model SOCOL3-MPIOM (Stenke et al., 2013; Muthers et al., 2014), which consists of the atmospheric model coupled to the chemistry module and the ocean model. The atmospheric component is a general circulation model ECHAM5.4, a spectral model based on primitive equations with temperature, vorticity, divergence, the surface pressure, humidity and cloud water as prognostic variables (Manzini et al., 2006; Roeckner, 2003; Roeckner et al., 2006). Here it was applied in a configuration with T31 spectral horizontal truncation (approximately 3.75° x 3.75° horizontal resolution) and 39 vertical levels from the ground to 0.01 hPa (~80 km). The chemistry module is MEZON (Egorova et al., 2003; Rozanov et al., 1999), which computes the tendencies of 41 gas species, taking into account 200 gas-phase, 16 heterogeneous and 35 photolytical reactions. The oceanic component is MPIOM, a primitive equation model with the hydrostatic and Boussinesq assumptions made. Itwhich includes a dynamic/thermodynamic sea-ice module and uses a curvilinear orthogonal grid which allows for various setups. In our study it was used with a nominal horizontal resolution of 3°, divided vertically into 40 levels from the ocean surface to the bottom (for more details see Muthers et al., 2014).

We simulated five different scenarios, each with two ensemble members, with the only difference between these experiments being the applied imposed solar forcing: four experiments with grand solar minima of two different strengths and two different durations, plus a reference simulation (see Figure 1). The reference simulation (hereafter termed REF) is forced by a perpetual repetition of the solar cycle 23 until the year 2199. Two experiments assume a relatively weak drop (termed WD or WDR) in the solar forcing with total solar irradiance (TSI) approximately 3.5 W/m^2 lower than in REF (0.2526% reduction). The assumed solar minimum either continues throughout the 22nd century (WD) or starts to recover (WDR) soon after reaching the minimum of -3.5 W/m^2 around the year 2087. Two further experiments assume a strong drop (termed SD or SDR) with TSI about 6.5 W/m^2 lower (0.48% reduction) than in REF, again either continuing throughout the 22nd century (SD) or recovering (SDR) soon after reaching the minimum (Figure 1). Since this is a continuation of the study of Anet et al. (2013a), we are using the same solar forcing as they did. It is calculated using the method developed by Shapiro et al. (2011) based on the solar modulation potential (Φ). The drop in the part of the UV spectrum that is most important for ozone production (180 – 250 nm) is about 9% in WD and WDR and about 15% in SD and SDR. The complete description of applied spectral solar irradiance (SSI) is describedcan be found in Anet et al. (2013a, Figure S3). The prolonged grand solar minimum scenarios (WD and SD) are based on the same Φ: WD represents the upper envelope of the uncertainty range of the solar forcing reconstruction, while

SD represents the mean of solar forcing. The same applies to WDR and SDR, but the Φ follows the recovery of grand solar minimum. We call the scenarios "weak" and "strong" for clear distinction, though it must be noted that both scenarios actually represent stronger irradiance reductions than those generally assumed in previous studies (Chiodo et al., 2016; Ineson et al., 2015; IPCC, 2013; Maycock et al., 2015; Meehl et al., 2013; Mokhov et al., 2008)~~ and by the IPCC~~. ~~As described by Meehl et al. (2013), p~~Previous estimates regarding the TSI decrease during the Maunder Minimum compared to present-day values range from somewhere close to present 11-year solar minima (Schrijver et al., 2011), to reductions of 0.15% to 0.3% below present solar minima (Foukal et al., 2011) all the way to more than 0.4% below present solar minima derived by Shapiro et al. (2011) and applied here in the SD and SDR scenarios. The stronger reductions in TSI have been criticized as being too large (Feulner, 2011), but here we regard these estimates as an absolute lower bound in TSI. Judge et al. (2012) found the Shapiro et al. (2011) estimates to be within ~~bounds~~ the limits set by current stellar data, however, likely have over-estimated quiet-Sun irradiance variations by about a factor of two, based upon a re-analysis of sub-mm data from the James Clerk Maxwell telescope. This is the basis for the WD and WDR scenarios employed here. ~~In agreement with~~As in Meehl et al. (2013) we emphasize that the caveat for the present study is that an ~~actual~~ hypothetical future Maunder Minimum-type event could feature a smaller reduction of TSI and an even lower climate system response. We therefore want to stress that the results from our study represent the uppermost possible global climate reactions to a very strong solar forcing reduction.

To extend the simulations to the 22nd century, we repeated the last solar cycle for WD and SD simulated by Anet et al. (2013a) for the year 2090 (Figure 1) until the year 2199 as was suggested by Steinhilber and Beer (2013). For WDR and SDR we mirrored SSI values backwards from 2088 into the future. This way we constructed ~~the~~ that ~~recovery of~~ solar activity recovers to pre-grand solar minimum values about 2170 – 2180. The parameterizations of galactic cosmic rays (GCR), solar energetic protons and low energy electrons (LEE) were introduced ~~identically~~ as in ~~to~~ Rozanov et al. (2012). Apart from solar irradiance, Φ is used to parametrize GCR (based on Usoskin et al., 2010) and also to develop the geomagnetic activity (A_p) index needed for the LEE parameterization. As mentioned above, since "weak" and "strong" scenarios are developed from the same Φ, the EPP forcing is identical in WD and SD and in WDR and SDR scenarios.

Tropospheric aerosols are adapted from NCAR Community Atmospheric Model (CAM3.5) simulations with a bulk aerosol model forced with the Community Climate System Model 3 (~~CMIP4~~ CCSM3) sea surface temperatures and the 2000 – 2100 CMIP5 emissions. For the 22nd century simulations, they are fixed at 2090 levels. Stratospheric aerosols are kept at background levels except for the following four randomly chosen volcanic eruptions in the 21st century: A Fuego-like eruption in 2024, a smaller eruption in 2033, an Agung-like eruption in 2060 and again a smaller eruption in 2073 (Anet et al., 2013a; 2013b). For the 22nd century we assume four identical small eruptions (with a magnitude between the eruptions in 2033 and 2073) in the years 2115, 2137, 2166 and 2187. The concentrations of GHGs and ODSs follow the CMIP5 RCP4.5 scenario (Meinshausen et al., 2011; van Vuuren et al., 2011a), while the quasi-biennial oscillation (QBO) wind fields are nudged (for more details on the experimental set-up see Anet et al., 2013a).

3 Results

In order to understand the influence of a future grand solar minimum on climate and ozone layer evolutions, we first investigate the future evolution for the individual solar forcing scenarios. Subsequently we calculate differences in various quantities between the applied solar scenarios and REF for the future (2090 – 2099) to elucidate the role of the solar forcing in modulating GHG driven temperature trends.

3.~~3~~ 1 Temperature response

The global mean surface temperature evolution is displayed in Figure ~~5~~2. As shown by Anet et al. (2013a), the global mean surface temperature rises in the 21st century in all three scenarios (REF, WD, SD). The difference of global surface temperature between REF and SD, averaged over the last 20 years of the 21st century, is about 0.3 K (as also found by Anet et al. (2013a)). Should the grand solar minimum persist until the end of the 22nd century, the difference between REF and SD would increase to about 0.6 K (averaged over 2180 – 2199), which is about 25% of projected global warming of 2.3 K at the end of the 22nd century compared to the base period (1986 – 2005). The continued temperature increase after 2100 is supported by the thermal inertia of the ocean, as all forcings are kept constant in the 22nd century.

In case of a recovery ~~of the~~from a solar minimum within the 22nd century, the difference of global surface temperature between REF and SDR, averaged over the last 20 years of the 22nd century, is computed to be only about 0.1K. This temperature response would compensate just ~4% of the anthropogenic temperature increase at the end of 22nd (2180 – 2199) century. In other words, an occurrence of the grand solar minimum in 21st century followed by its recovery would only slightly reduce global surface temperature.

In REF, anthropogenic forcings according to RCP4.5 lead to a warming of the troposphere and a cooling of the stratosphere and mesosphere ~~in the future~~ as indicated in Figure ~~4a~~3a. The tropospheric warming reaches a maximum of around 3 K in the tropical upper troposphere. ~~Zubov et al. (2013) showed that t~~Tropospheric warming is mainly caused by the surface warming due to increase of down-welling infrared radiation by GHG, enhanced by latent heat release in the middle troposphere. The temperature decrease in the stratosphere and mesosphere ~~results~~ comes from increased cooling rates ~~of~~ due to the GHG concentration~~s~~ rise (IPCC, 2013). The secondary maximum in the Antarctic lower stratosphere around 100 hPa is explained by the ozone recovery following the limitation of ODS~~s~~ emissions. Li et al. (2009) used the Goddard Earth Observing System chemistry climate model to evaluate temperature and ozone response to GHG increases and ODS declines. They found a warming of the troposphere in the second half of the 21st century of up to ~~4~~ 4 K compared to the mean 1975 – 1984 values, accompanied by a cooling of stratosphere of up to 8 K. Our results for the same period (not shown) agree very well with their study. In the SD scenario the warming of the whole troposphere continues into the 22nd century relative to the end of 21st, with an additional warming peaking at around 1 K in tropics (not shown), while stratospheric temperatures do not further change during that century. The latter is expected, as the stratosphere has a relatively short thermal relaxation time of less than a month (Newman and Rosenfield, 1997).

Figure ~~4b~~ 3b shows the temperature difference between future and present for the SD scenario. Relative to REF in Figure ~~4a~~3a, the temperature response pattern shows a reduced warming by up to 1 K in the troposphere, but a more intensive cooling in the stratosphere and mesosphere. The analysis of the zonal annual mean temperature presented by Maycock et al. (2015) showed the most intense cooling around the stratopause of up to 1.5 K for the 2050 – 2099 period. Our results for the same period suggest a similar temperature pattern (not shown). However, the magnitude is larger: the most pronounced cooling is located above the stratopause and amounts to around 2 K in the WD and 3 K in the SD scenario. The difference in magnitude is related to a smaller decrease of the solar UV irradiance in their study.

The impact of SD forcing relative to GHG is quantified as the difference between SD and REF (~~The temperature anomaly in SD compared to REF is shown in~~ Figure ~~4c~~3c). The temperature difference increases from the tropopause to the mesopause up to -7 K. Cooling in the troposphere of around 0.5 K is also found, but this can compensate less than 20% of the warming caused by anthropogenic GHG emissions. As expected, due to the lower UV forcing, the WD scenario (Figure ~~4d~~3d) shows a similar difference pattern, but with a smaller magnitude.

For the RCP4.5 scenario, climate models also predict a warming of about 2 K at the end of 21st century (2081 – 2100) compared to the 1986 – 2005 reference period (Figure 12.8, IPCC, 2013). As the ocean has a larger heat capacity and thermal inertia than the land surface and the atmosphere, the warming over land is more pronounced. The increase is most prominent near the poles of both northern (up to 5 K) and southern hemisphere (up to 3 K) (Figure 12.11, IPCC, 2013), a feature known as polar amplification (Serreze and Barry, 2011). Comparing the end of the 21st century (2090 – 2099) to its beginning (2000 – 2009), our model ~~reproduces~~ simulates the polar amplification as well: REF yields an increase of up to 4 K in North America and of up to 2 K in Antarctica (Figure ~~6a~~4a). The other continental regions warm up by around 2 K, while the sea surface temperature increases by 1 – 1.5 K. Recent studies (~~IPCC, 2013;~~ Bakker et al., 2016; IPCC, 2013) suggest that the Atlantic Meridional Overturning Circulation (AMOC) could weaken in the 21st century resulting in a temperature reduction in the North Atlantic. Our simulations reproduce this characteristic cooling of 1 K in the northern Atlantic that could be caused by a weakening of the AMOC in the 21st century.

A pronounced global warming would persist even if a strong irradiance drop, scenario SD, occurred in the near future (Figure 4b)~~,~~. In this scenario, t~~see Figure 6b. T~~he model suggests a reduction of the warming in northern high latitudes, i.e. the damping of the polar amplification~~ in the SD scenario~~. The surface temperature increase is also damped over continental Africa, Asia and North America, but amplified around Antarctica. The sea surface temperature, although still increasing, shows a smaller warming compared to REF. A study by Menary and Scaife (2014) suggests that the low solar irradiance might cause a strengthening of the AMOC through stratosphere-troposphere coupling. Our results confirm the disappearance of the cooling in the northern Atlantic, likely caused by a recovering AMOC in the grand solar minimum (Muthers et al., 2016). ~~Beyond the scope of our paper~~However, this phenomenon needs to be investigated in more detail as it might have an impact on global, and especially on the European climate (Jackson et al., 2015).

The surface temperature continues to rise in 22nd century (Figure ~~6c~~ 4c and ~~6d~~4d) in both the REF and SD scenarios. REF shows that the further increase is located mostly on the continents, but also in the Pacific, Kamchatka, Alaska and Greenland. The warming patterns in the 22nd century show similar locations of maxima as at the end of the 21st, but with a smaller magnitude. The warming during the 22nd century is less pronounced than in the ~~previous~~ 21st century, especially in the SD case. The maximum warming of 1 K is located in the high latitudes.

The reduction of the annual mean surface temperatures due to the reduced solar activity at the end of 21st century is pronounced in the Arctic, and generally continental areas show lower surface ~~temperatures~~temperature reductions, except for Australia and Europe, ~~see~~ as shown in Figure ~~7a~~ 5a for the strong reduction (SD) scenario. The sea surface temperatures decrease by up to 0.5 K. The weaker WD scenario also shows a reduced warming, but to a smaller ~~magnitude~~ extent (Figure ~~7b~~5b). The cooling is most prominent in Russia and North America, ~~amounting~~ and is~~to~~ around 1 K. The temperature decrease over sea is confined to the Indian Ocean and does not exceed 0.5 K. In both scenarios ~~simulating~~ assuming a solar anomaly, a temperature increase of up to 1 K in SD and 0.75 K in WD, is predicted over the North Atlantic, likely due to a partial recovery of AMOC (Muthers et al., 2016). ~~Considering~~ In the SD scenario, the largest cooling during boreal winter (DJF) ~~analysis of surface temperature response~~ is seen over the Barents Sea and northern Asia (Figure ~~7c~~ 5c and ~~7d~~5d)~~ shows the largest temperature reduction in winter over the Barents Sea and northern Asia~~. Similar cooling ~~areas~~ appears also in the WD case. The warming in the North Atlantic and in Greenland is present in ~~the~~ boreal winter ~~projection~~ as well as in the annual mean. Ineson et al. (2015) showed wintertime cooling in northern Eurasia and eastern North America with minima of -1.5 K in the 2050 – 2099 period. Our simulations show a similar, but more pronounced pattern for the same period (not shown), possibly due to our applied drop in UV forcing being stronger than the one used by Ineson et al. (2015). Similarly, Chiodo et al. (2016) reported significant cooling in their model simulations in boreal winter in continental Asia and the Bering Sea with peaks of -1.2 K for 2005 – 2065. In their results, ~~This~~ this cooling is accompanied by a warming in North America and off the coast of Japan. Our results for WD suggest a slight warming at the east coast of North America and Europe, albeit not statistically significant (not shown).

3.~~1~~ 2 Brewer-Dobson Circulation (BDC)

The transformed Eulerian mean vertical residual velocity (w^*; Hardiman et al., 2010) can be used as a measure of intensity of the Brewer-Dobson circulation. Figure ~~2~~ 6 shows annual mean w^* slightly above tropopause (70 hPa) averaged over 20° N – 20° S, since its maximum is around 15° – 20° on both hemispheres (Eyring et al., 2010). To reduce variability, the curves are smoothed with Savitzky and Golay (1964) filter.

The BDC accelerates in all experiments. From 1960 throughout the 21st century, the increase is 2 – 3% per decade, which agrees with SPARC multi-model mean (Eyring et al., 2010) and study of Butchart et al. (2006). The intensification is most evident in the first half of 21st century, when the rate of increase of GHG concentrations is highest (van Vuuren et al., 2011, Figure 9). The second half of 21st century and the 22nd century show a continued acceleration of the BDC~~, however~~ at a reduced rate, although ~~with a reduced strength, but~~still statistically significant (at 95% confidence level using Mann-Kendall significance test). The intensification is highest in REF simulation and lower in WD and SD scenarios. However, in WDR and SDR scenarios, after the recovery of solar activity, the BDC quickly adjusts to match the REF scenario at the end of 22nd century.

3.~~2~~ 3 NO_x response

According to the ~~applied~~ imposed RCP4.5 scenario, surface emissions of NO_x are projected to ~~decreasing~~ decrease and concentrations of N_2O ~~are~~ will ~~increasing~~ increase during the 21st century. Decreasing NO_x emissions in the troposphere lead to lower NO_x concentrations in REF by up to 80% by the end of 21st century throughout the northern and of up to 40% throughout the southern troposphere (Figure ~~3a~~7a). In contrast, increasing N_2O concentrations lead to increasing NO_x levels in the upper stratosphere due to N_2O conversion to reactive nitrogen oxides through the reaction with $O(^1D)$ (Brasseur and Solomon, 2005). By the end of the 21st century stratospheric NO_x is projected to increase by about 10%. The NO_x decrease by 20% in the tropical upper troposphere most likely comes from decreasing tropospheric NO_x and therefore less NO_x transport from the troposphere into the stratosphere.

Figure ~~3b~~ 7b shows the simulated future change in NO_x volume mixing ratio changes for the SD scenario. The different solar forcing leaves NO_x levels unchanged in the troposphere, where NO_x is dominated by anthropogenic influence. In the stratosphere, however, the effect of the solar irradiance decrease is ~~well~~ clearly visible. Reduced NO photolysis limits NO_x removal in the stratosphere via the reaction $N + NO \rightarrow N_2 + O$, leading to a more pronounced stratospheric NO_x increase under SD than under REF conditions. Furthermore, the GCR intensity is stronger during grand solar minima leading to enhanced NO_x production in the lower polar stratosphere. This effect, together with faster transport to the polar regions via the BDC, yield around 50% more NO_x the in southern and 20% in the northern hemisphere. During the grand solar minimum, the precipitation of LEE is decreased, leading to 60% reduced production of NO_x in the polar mesosphere.

At the end of the 21st century, the lower photolysis rates in SD relative to REF would yield around 10% more stratospheric NO_x (Figure ~~3c~~7c). In contrast, t~~T~~he WD scenario would only lead to a 5% more stratospheric NO_x, i.e. about half the effect of SD (Figure ~~3d~~7d). As the applied LEE forcing in the model is the same for WD and SD, there is a similar reduction of NO_x of around 80% in the polar mesosphere.

3.4 Ozone response

~~Due to~~ T~~t~~he Montreal Protocol ODSs' concentrations are projected to further decrease in future, which is expected to lead to a recovery of stratospheric ozone, mainly in the polar lower stratosphere and globally in the upper stratosphere (Figure 8a). The decrease in concentrations of chlorine species strongly affects polar lower stratospheric ozone (exceeding +30%), mainly due to a ~~slowing~~ ~~decceleration~~deceleration of heterogeneous chlorine chemistry in the polar winter stratosphere, which is also responsible for the Antarctic "ozone hole" (Solomon et al., 1986). The increase in the upper stratosphere of 15 – 20% is a result of reduced intensity of the ~~catalytic~~ ozone destruction ~~by reactive chlorine species (Molina and Rowland, 1974)~~cycles. In particular in the tropical stratosphere, the increase in ozone is also due to the GHG~~-~~-induced cooling, which slows the catalytic ozone destruction cycles as well as the reaction $O + O_3 \rightarrow 2\ O_2$. In the mesosphere the reaction $O + O_2 + M \rightarrow O_3 + M$ also becomes important as its reaction rate coefficient increases with cooling (Jonsson et al., 2004), leading to ozone increase of around 5%. Conversely, the future decline of NO_x surface emissions will result in less tropospheric ozone with a maximum in the northern hemisphere of up to 20%.

Besides chemical processes, which depend on ODS concentrations and on temperature, the circulation changes expected to result from GHG-induced radiative changes, are also important for ozone. The acceleration of the BDC causes faster transport of ozone from the tropics to high latitudes causing ozone decrease in the tropical lower stratosphere exceeding 10% around 100 hPa (Figure 8a). The ~~further~~ continued acceleration of the BDC during the 22nd century leads to a further reduction of tropical ozone by 5% (years 2190 – 2199 relative to 2090 – 2099, not shown) and an increase in polar regions of 5%.

The strong solar minimum scenario SD shows a similar ozone pattern (Figure 8b). The increase of ozone in the lower polar stratosphere is the same as in REF as the impact by ODSs does not seem to depend much on the solar activity. However, in the upper stratosphere the ozone increase is smaller than in the reference case, as its production is supressed by ~~low level of~~decreased ~~solar~~ UV input. Regardless, decreasing ODS~~s~~ concentrations dominate over a decrease of the solar activity, therefore stratospheric ozone mixing ratios increase. The ozone decrease in the troposphere and in the tropical stratosphere is very similar as in REF, as it is a result of anthropogenic activities. The most pronounced future differences between ozone in the SD scenario and REF occur in the mesosphere. Reduced photolysis of water vapour results in future decreases of HO_x of 40% in the mesosphere (not shown), which contribute to the ozone increase at these altitudes. Together with the NO_x decline due to the LEE weakening in the grand solar minimum and the GHG-induced cooling, it leads to an increase of ozone in the mesosphere of up to 35%.

The comparison between SD and REF at the end of 21st century is depicted in Figure 8c. Due to the weaker solar UV irradiance in the grand solar minimum, stratospheric ozone is reduced ~~of~~ by up to 8% in nearly the entire stratosphere in SD compared to REF scenario. Less mesospheric NO_x and HO_x, and colder temperature in the grand solar minimum impacts ozone at these altitudes, leading to an increase of up to 30%. The results are similar in case of WD, consistent with the smaller ~~but changes are smaller (~~by approximately a factor of 2) UV forcing drop (Figure 8d).

Figure 9a shows the future increase in the annual mean total ozone column (TOC) over the middle to high latitudes in REF, which is attributed to reduced emissions of ODSs and an enhanced BDC in the warmer climate (Zubov et al., 2013). This future increase reaches 40 (60) Dobson units in the Northern (Southern) Hemisphere~~s~~, which corresponds to about 10 – 20% of TOC increase. Acceleration of the BDC is expected to transport more ozone from the tropics to mid-latitudes fostering extra-tropical ozone recovery, but delaying ozone recovery in the tropics (Austin and Wilson, 2006; Shepherd, 2008; Waugh, 2009). Because of this effect, future tropical ozone levels even show further decline at the end of 21st century compared to near present values. The slowing of photochemical ozone loss reactions caused by the cooling in the stratosphere (Barnett et al., 1975; Jonsson et al., 2004) contributes to a smaller degree to the overall TOC evolution (Zubov et al., 2013). Li et al. (2009) showed that the BDC acceleration plays a crucial role in future ozone recovery and spatial distribution. They found recovery of extratropical ozone in year 2060 to 1975-1984 levels, but the tropical TOC did not recover. A study performed by Shepherd (2008) also showed this so-called "super-recovery" of extra-tropical and "sub-recovery" of tropical ozone by the end of the 21st century with respect to 1960 values.

Figure 9b illustrates future TOC changes for the SD scenario. ~~Reduction~~ A future reduction ~~of the~~in solar activity ~~in the future~~ changes the situation dramatically. Weaker solar UV reduces oxygen photolysis leading to lower ozone production rate and pronounced TOC depletion in the entire tropical area by around 15 – 20 DU (≙ 5 – 6%). On the other hand, cooler ocean surface due to less solar activity (see Figure ~~7a~~5a) slightly reduces the BDC relative to REF (see Figure ~~2~~6). These two processes cancel about 30 – 50% of the TOC increase in the Northern hemisphere obtained for REF. Over the Southern hemisphere the TOC changes are dominated by the reduction in ODSs (Zubov et al., 2013), therefore the implications of the potential solar minimum are not as dramatic.

The effect of a decrease of the solar activity on the TOC is illustrated in Figure 10a and 10b. Both of the grand solar minimum scenarios predict a reduction in TOC, which would be stronger in the SD than in the WD scenario. An ozone reduction of around 10 DU in the tropics in SD and 5 DU in WD is mostly a result of reduced production, and to a lesser degree because of a very small difference in BDC between the experiments. The most affected areas are mid-latitudes with maximum around

20 DU in the SD case (up to 4%). Since the polar vortex prevents mixing of ozone-rich air with polar air, ozone-rich air accumulates in the mid-latitudes. We found that drop in solar activity deaccelerates polar vortices on both hemispheres (not shown) and due to the weaker polar vortex, more ozone is able to reach polar areas. Also, during the grand solar minimum, less ozone is produced in the tropical lower stratosphere. These two factors lead to less accumulation of the ozone-rich air in the mid-latitudes, creating a TOC minimum.

The amount of UV radiation that reaches the surface depends on incoming UV as well as on ozone layer thickness. Although the solar UV input is reduced in grand solar minimum, we showed that the ozone layer is thinning in the tropical areas. The increase in tropospheric $O(^1D)$ in the grand solar minimum (not shown) suggests that ozone photolysis by UV (λ<320 nm) is enhanced through reaction $O_3 + h\nu \rightarrow O_2 + O(^1D)$ (Brasseur and Solomon, 2005). The increase of UV radiation at ground level can have potential positive and negative effects on human health (Reichrath, 2006). UV radiation is important for the production of vitamin D and therefore for human health (Hart et al., 2011), but can also cause skin cancer (Armstrong and Kricker, 2001). Furthermore, UV radiation was shown to be harmful to plants as well, damaging DNA, proteins, lipids and membranes (Hollosy, 2002).

A future grand solar minimum could delay the recovery of the ozone layer by several years (Anet et al., 2013) ~~by several years~~. In Figure 11 we show the annual global mean ~~total ozone column~~TOC evolution until the end of the 22nd century. The first decline in 1960 – 1990 period of total ozone is caused by the emission of ODSs before the Montreal Protocol coming into force. In the beginning of the 21st century, with the Montreal Protocol being effective, total ozone is increasing in all three solar scenarios. In the second half of the century, after a substantial reduction of reactive halogen containing species, solar activity turns into the dominant driver of ozone changes. ~~the dominant effect on ozone will be solar activity.~~ In the reference scenario (REF), the total global ozone recovers to the 1960 – 1980 values and even exceeds them. However, neither the weak nor the strong solar minimum scenario (WD and SD) show a recovery within the simulated period. If the grand solar minimum persists during the 22nd century, as the stratospheric temperatures and solar UV irradiance stay unchanged, so does the global mean of TOC. However, since the BDC continues to accelerate, it will continue to redistribute ozone from the tropics to the polar regions, which lead to the absence of strong trends in the global mean value. When the grand minimum recovers, TOC recovers to REF values readily.

4 Conclusions and Outlook

In this paper we investigated the influence of a potential future grand solar minimum on atmospheric chemistry and climate. Such an event, should it occur with the extreme intensity assumed here, could temporarily partly counteract the anthropogenic climate change caused by ongoing emissions of greenhouse gases that follow RCP4.5 scenario, ~~but~~ However, it would still be by far too weak to fully compensate it. Even if the grand solar minimum were fully developed by the year 2090 and then lasted until the end of the 22nd century, global mean surface temperatures would continue to rise. ~~While the~~A solar ~~effect~~minimum, ~~when~~ assuming ~~the said~~a very large ~~strong~~ drop in solar irradiance (~~the~~ SD scenario)~~,~~ is predicted to compensate about 15% of GHG-induced warming by ~~the year~~ 2100~~, ~~. However, this fraction could increase to about 25% during the 22nd century, suggesting that the Earth system is still equilibrating to the increased GHG concentrations (which stay approximately constant during the 22nd century within RCP4.5). For the lowest GHG concentration scenario, RCP2.6, IPCC (2013) multi-model mean projects global warming at the end of 21st century of 1±0.4 °C. Our results show that even in this case, the extreme drop in solar activity would only reduce the projected increase in surface temperature by around 20 – 50%. As expected, for the higher RCPs 6.0 and 8.5 the grand solar minimum would result in only very minor reduction of the warming. This ~~leads~~ let us ~~to conclusion~~ conclude that a strong drop in solar forcing would help ~~us~~ the global community to reach the Paris agreement goal for RCP2.6 and increase the chance of reaching it for RCP4.5. Nevertheless, the multi-model mean of RCP4.5 (IPCC, 2013) would still be above 2 °C threshold, and~~.~~ other problems like ocean acidification due to higher atmospheric CO_2 concentrations would still lead to significant damages to global ecosystems.

Areas with the highest partial compensation of global warming are located in high northern latitudes especially in the winter ~~period~~season. Our results suggest that a grand solar minimum could lead to a recovery of AMOC, which might cancel the cooling in North Atlantic in the 21st century (Muthers et al., 2016). More research should be done to address the uncertainty of the solar influence on the AMOC response.

A cooling caused by the weaker solar activity occurs throughout the middle atmosphere, with a prominent maximum in the mesosphere. Our results indicate an increase in stratospheric NO_x via decreased UV radiation and decrease of mesospheric NO_x as the EPP becomes weaker in a grand solar minimum. Water vapour photolysis is also decreased ~~in~~ during the grand solar minimum leading to reduced HO_x concentrations. The declines of NO_x and HO_x, together with the reduced UV heating, result in an ozone increase in the mesosphere. In the stratosphere, although the ozone production is reduced here as well due to the decrease in solar UV, the reduction of ODSs causes an increase in ozone.

While this study ~~enhances our understanding of~~includes the effect of energetic particle precipitation for high and low energetic particles (such as GCRs and LEEs, respectively), future work should also concentrate on energetic electrons of higher energies (Matthes et al., 2016) and thus evaluate more precisely their effect on future climate. The flux of energetic electrons is dependent on solar activity (e.g. Sinnhuber et al., 2012) and in the grand solar minimum its intensity is diminished. By including these particles in climate models, we can expect an amplification of our results in the grand solar minimum – less NO_x produced and more stratospheric ozone preserved in polar regions, followed by further changes in dynamics and temperature (Arsenovic et al., 2016).

While the future grand solar minimum reduces surface temperature to some degree, it ~~faces us with~~poses another problem: thinning of the tropical ozone layer. The acceleration of ~~atmospheric dynamics~~the BDC caused by the warming of tropospheric climate due to the GHGs transports the freshly formed ozone more quickly away from the tropical into extratropical areas and give catalytic chemical cycles less time to deplete ozone. As a consequence, the extratropical areas will reach a "super-recovery" of ozone, while the tropical areas display negative anomalies. Even if the grand solar minimum does not occur, the total ozone in the tropics will be reduced compared to present values. Since the probability of the grand solar minimum to happen in 21st century is rather high (Steinhilber and Beer, 2013), this will compromise the ozone recovery even after a low level of active halogens will be reached. The tropical regions would suffer a loss of up to 6% of the column ozone compared to present values, and tropical ozone would not reach the recovery to the pre-ozone hole (1960-1980) levels. Therefore, all efforts to reduce GHG emissions and the fulfilment of Paris agreement are absolutely crucial. The possibility of failing the Paris climate agreement also brings the risk of thinning of tropical ozone layer.

In the strong and weak solar scenarios, SD and WD, the acceleration of atmospheric dynamics persists throughout the 22nd century, leading to an ozone redistribution from the tropics to the poles, but the global total ozone would stay at the similar levels as at the end of the 21st century. In the SDR and WDR scenarios, when the solar minimum recovers during the 22nd century, global total ozone would increase rapidly and recover (or super-recover).

Stratospheric ozone plays a key role for terrestrial life as it absorbs UV radiation. Although during grand solar minimum UV radiation is decreased, the fact that ozone layer is thinning ~~lets~~ allows more UV to reach the ground. The increase of UV radiation at the ground in grand solar minimum could have implications on terrestrial ecosystem and needs to be investigated in future studies.

Acknowledgements

This work has been supported by the Swiss National Science Foundation under Grant CRSII2-147659 (FUPSOL II) and it is a part of ROSMIC WG1 activity within the SCOSTEP VarSITI program. We would like to sincerely thank the co-editor, Dr. Hoyle from PSI, Switzerland, and two anonymous reviewers whose comments significantly improved the manuscript.

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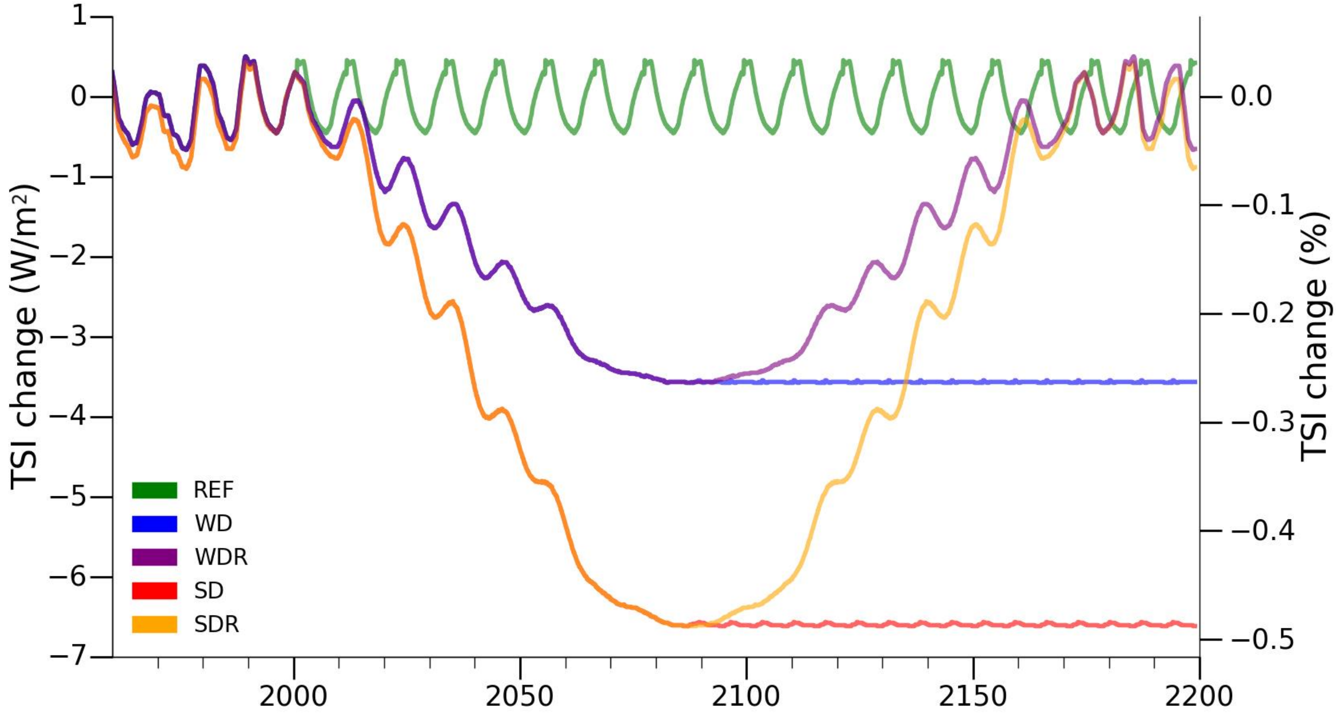
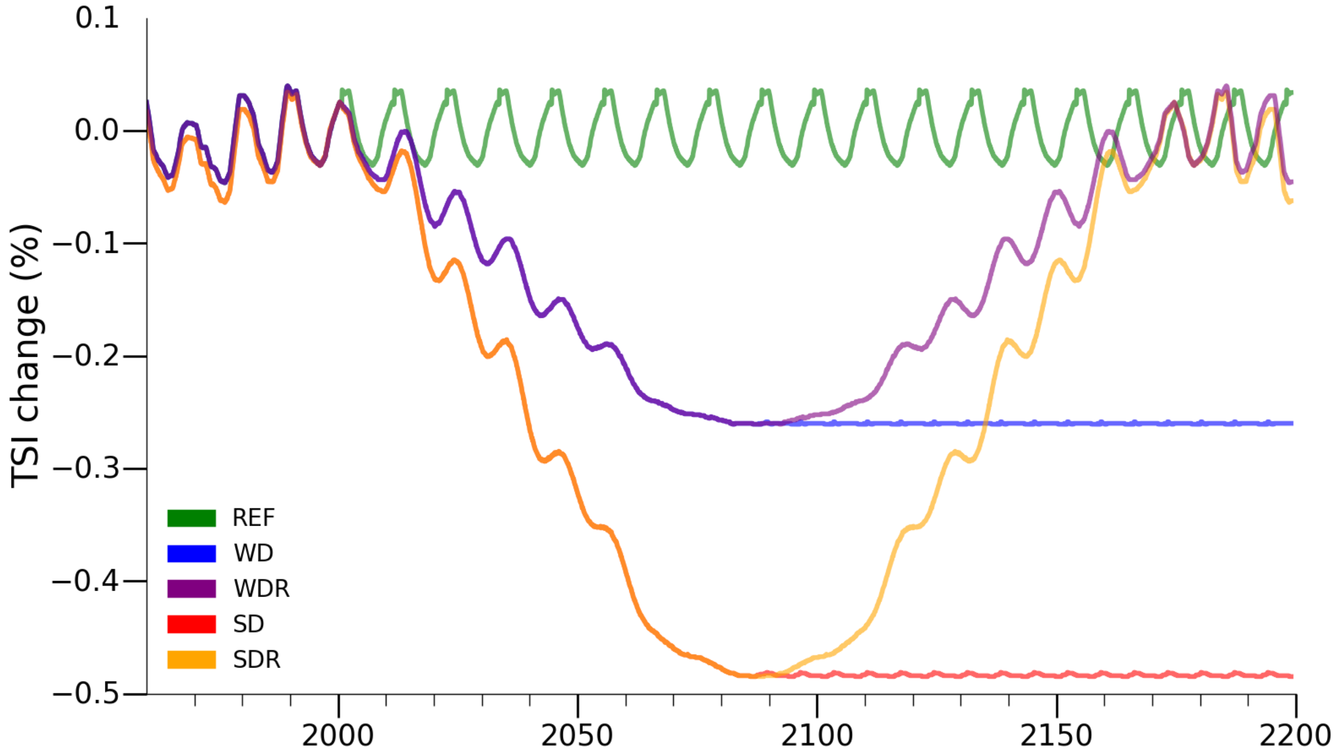


TSI change (W/m²)
TSI change (%)
REF
WD
WDR
SD
SDR



TSI change (%)
REF
WD
WDR
SD
SDR

Figure 1: Total solar irradiance c-hange change relative to the mean of the REF scenario (green line) in W/m^2 (left axis) and % (right axis) used in the simulations. Weak drop (WD) in blue, weak drop with recovery (WDR) in purple, strong drop (SD) in red and strong drop with recovery (SDR) in orange.

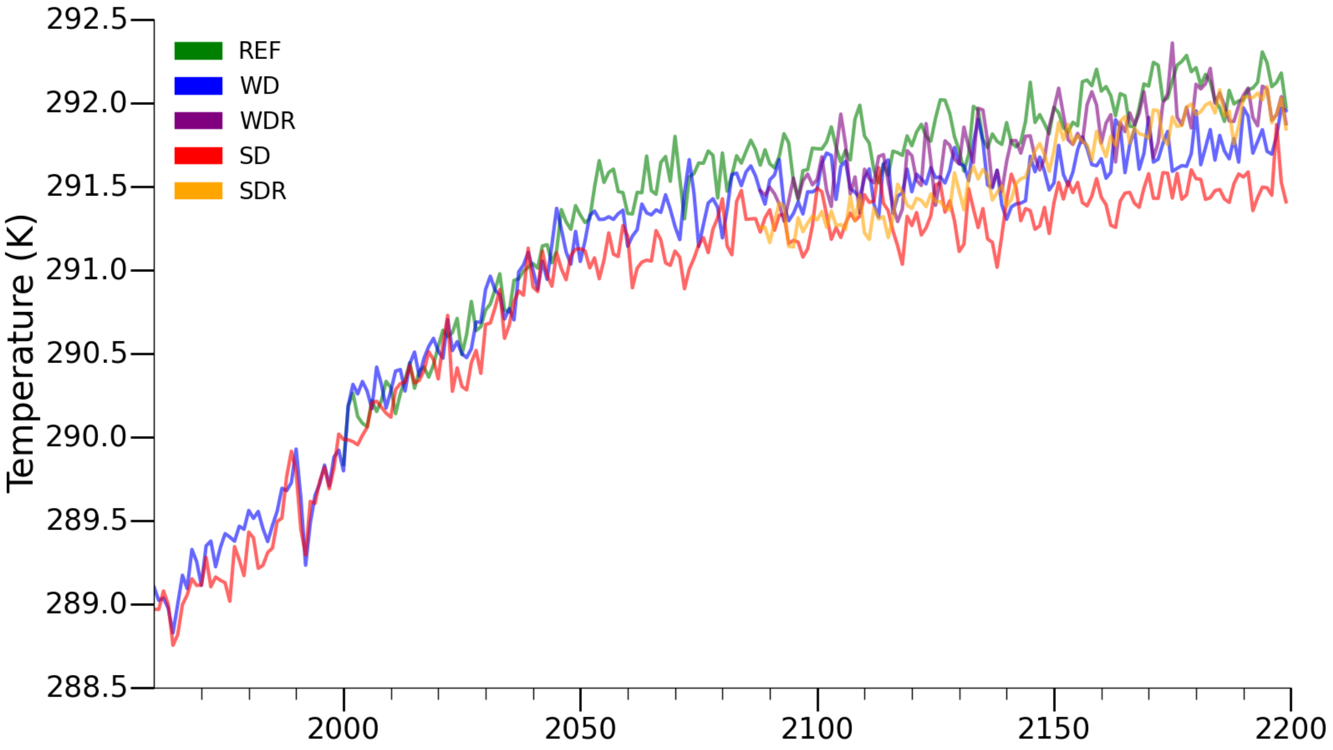


Figure 2: Annual global mean surface temperature in K of ensemble means from 1960 to 2199.

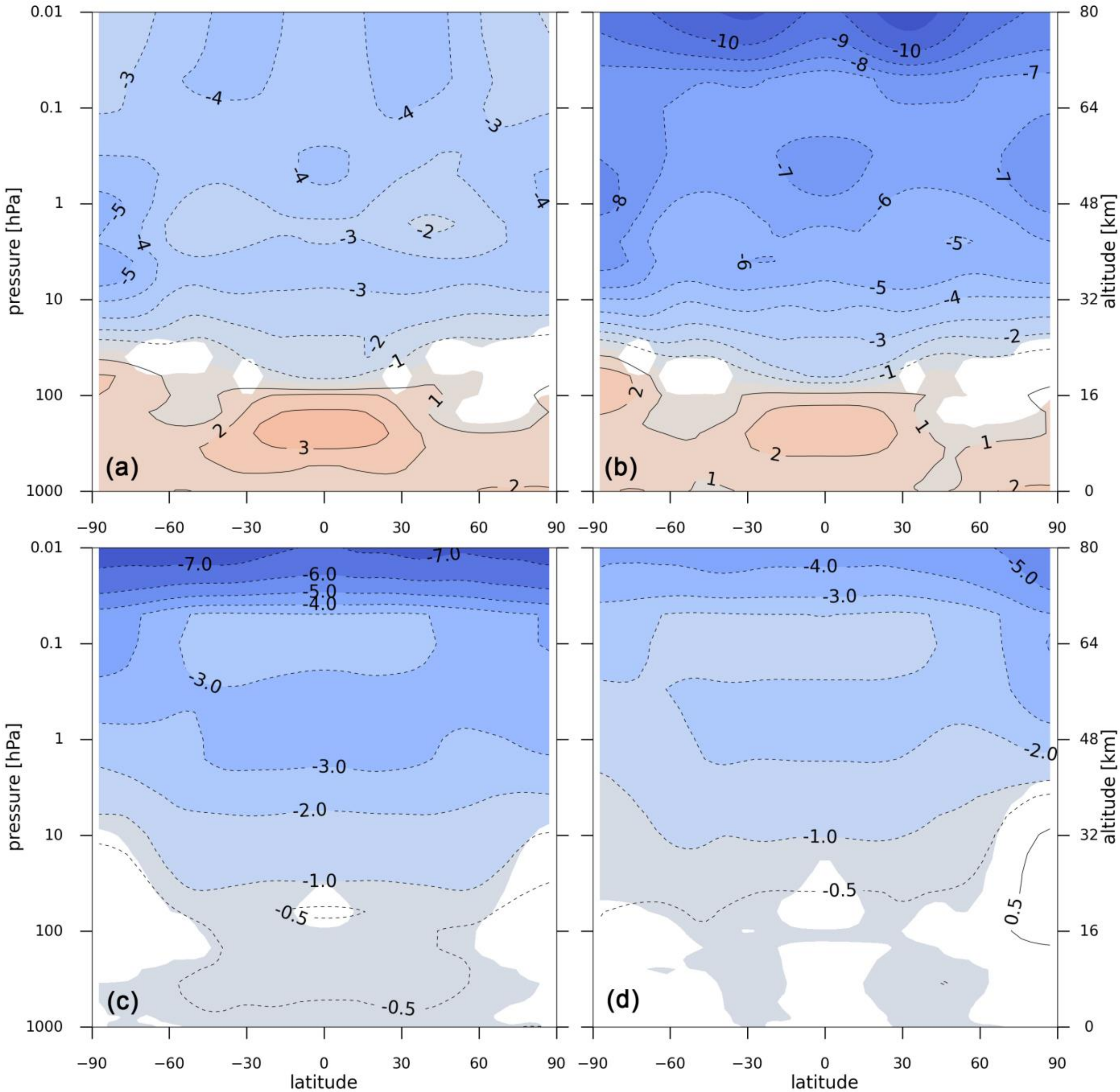


Figure 3: Annual zonal mean temperature difference in K of ensemble means of future (2090 – 2099) minus near present (2000 – 2009) for REF (a) and SD (b). The lower two plots show absolute differences of , and difference SD –minus REF (c) and WD minus– REF (d) under future conditions (2090 – 2099). Coloured regions are significant at the 95% confidence level (calculated using a Student t-test). Colour interval is 1 K.

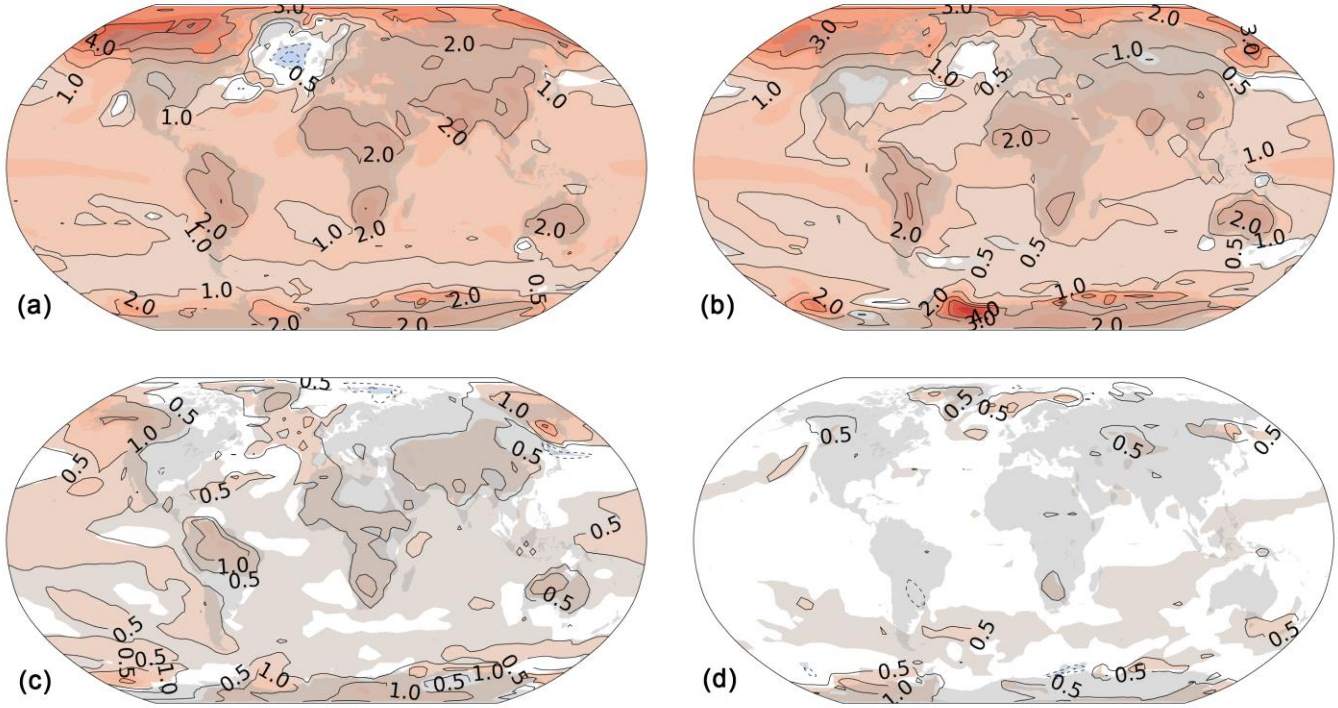


Figure 4: Spatial distribution of surface temperature difference in K of ensemble means of future (2090 – 2099) minus near present (2000 – 2009) for REF (a) and SD (b), and of far future (2190 – 2199) minus intermediate future (2090 – 2099) for REF (c) and SD (d). Coloured regions are significant at the 95% confidence level (calculated using a Student t-test). Colour interval is 0.5 K.

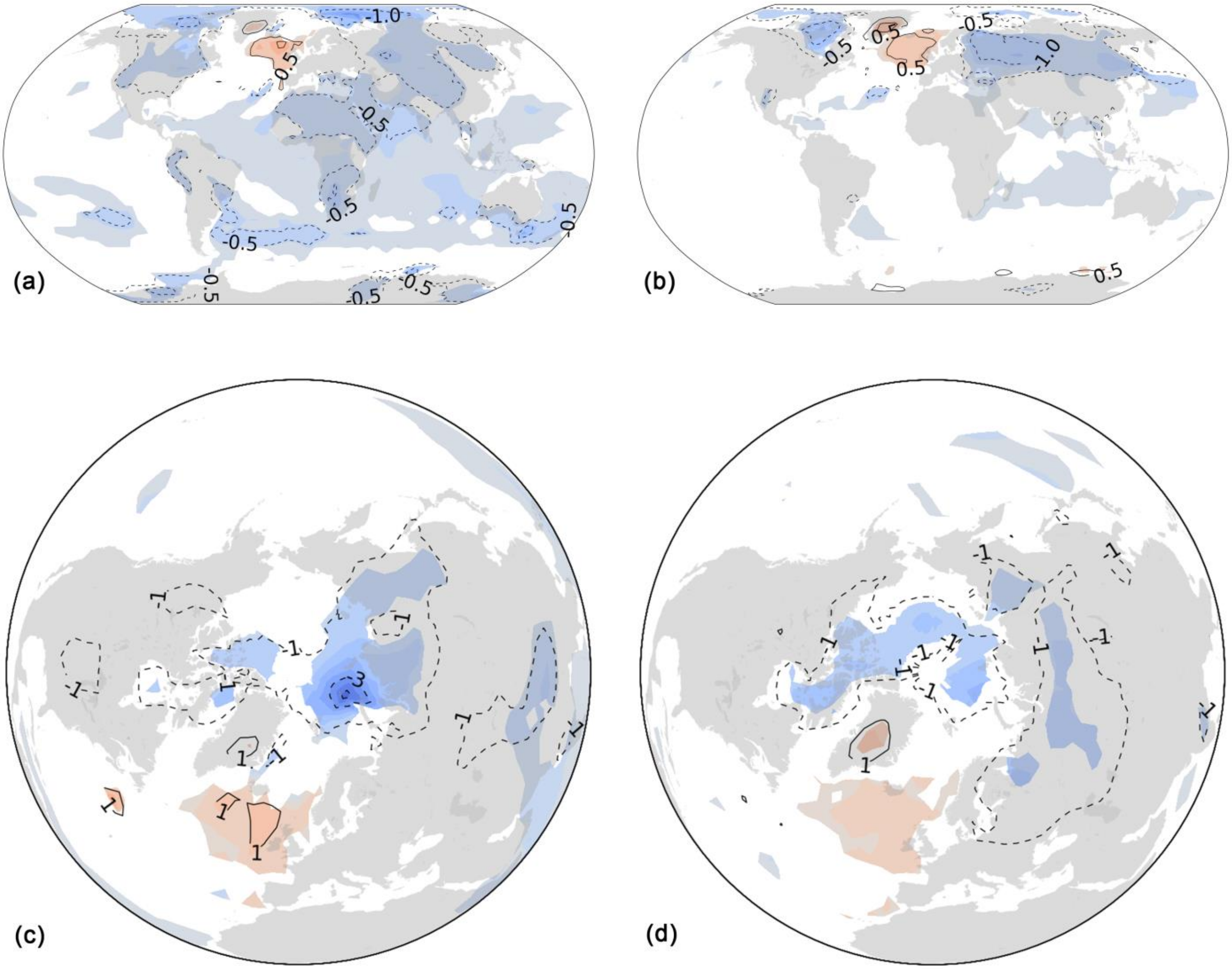


Figure 5: Global projections of spatial distributions of annual mean surface temperature differences in K of ensemble means of SD minus REF (a) and WD minus REF (b) in the late 21st century (2090 – 2099). Polar projections of boreal winter (DJF) mean surface temperature differences in K of SD minus REF (c) and WD minus REF (d) in the late 21st century (2090 – 2099). Coloured regions are significant at the 95% confidence level (calculated using a Student t-test). Colour intervals are 0.5 K in (a) and (b) and 2 K in (c) and (d).

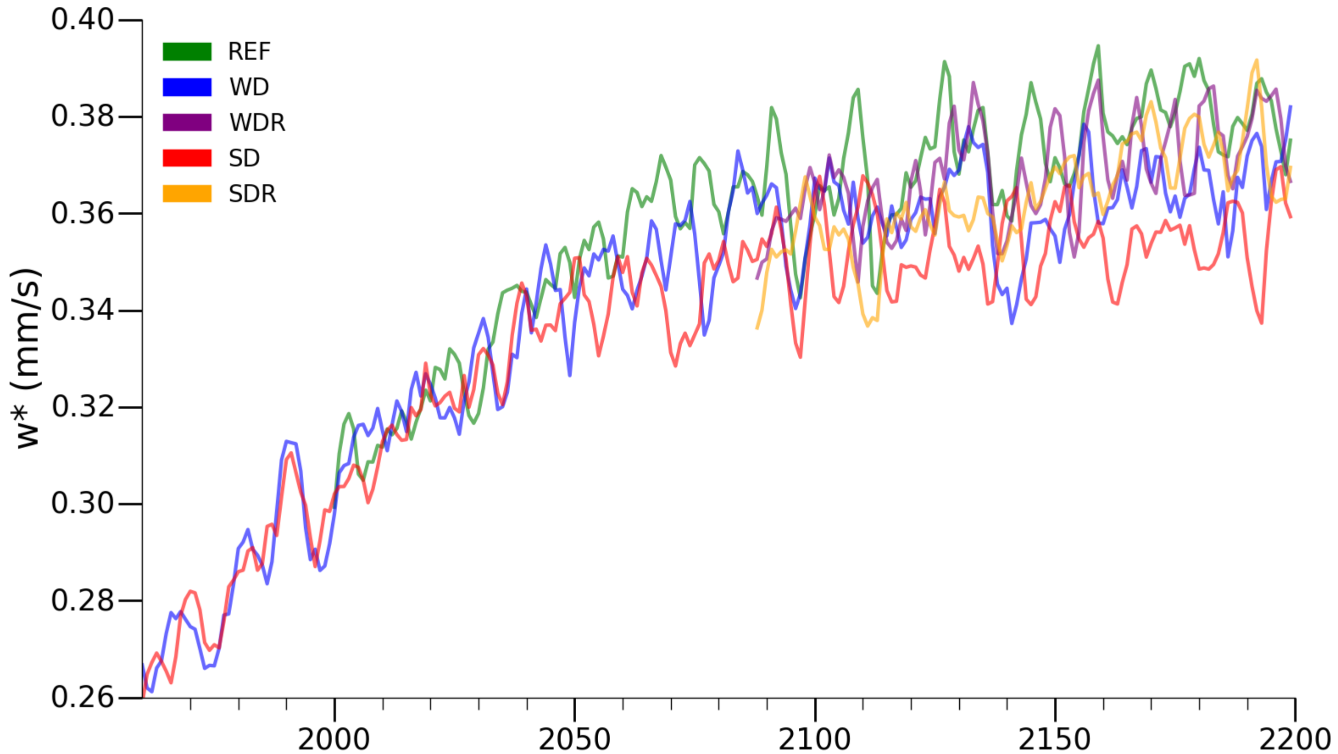


Figure ~~2~~6: Annual mean residual vertical velocities (w*) of ensemble means at 70 hPa averaged over 20° N – 20° S latitudes and smoothed with Savitzky-Golay filter. Weak drop (WD) in blue, weak drop with recovery (WDR) in purple, strong drop (SD) in red and strong drop with recovery (SDR) in orange.

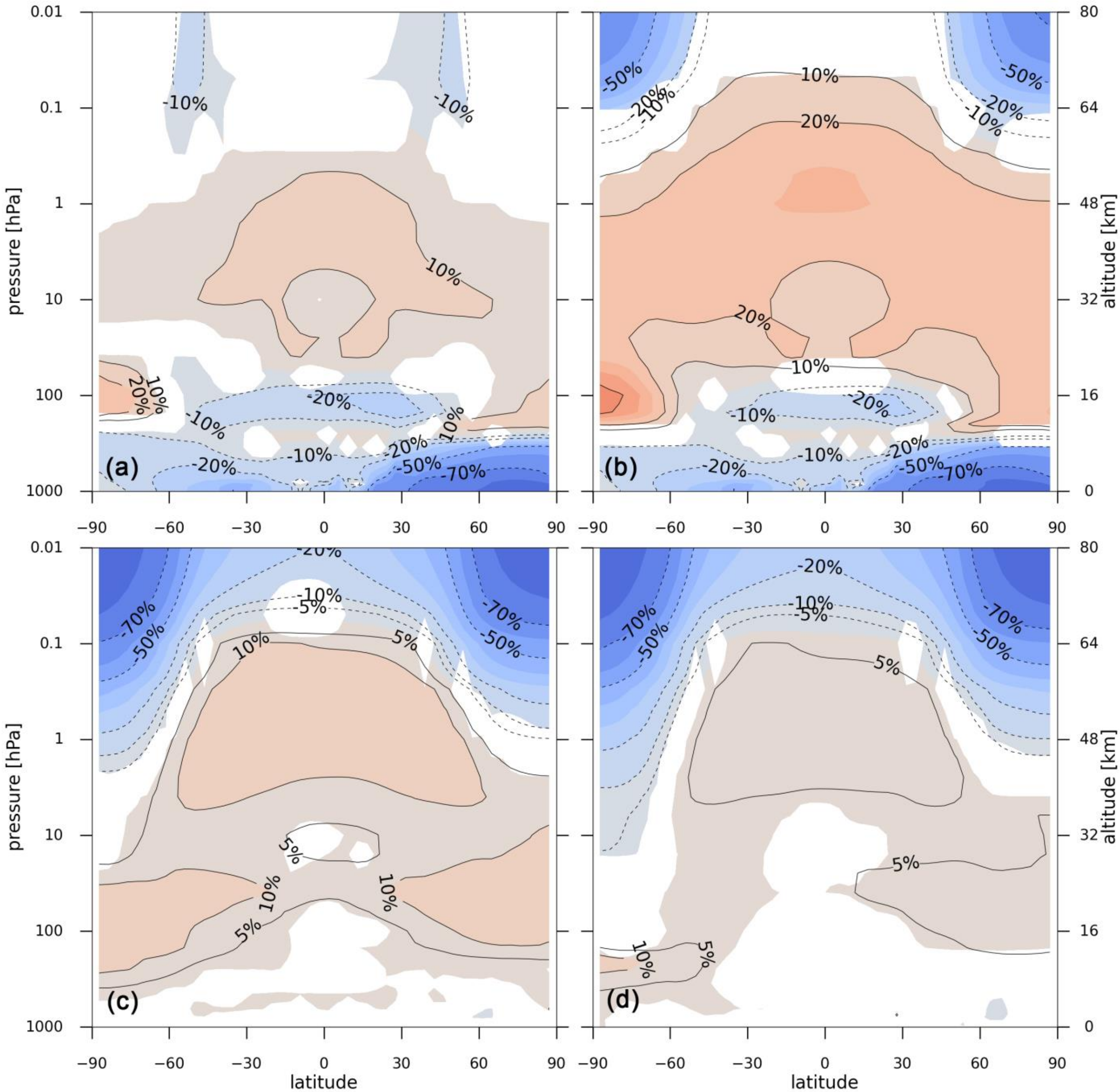


Figure ~~3~~7: Annual zonal mean NO_x difference in % of ensemble means of future (2090 – 2099) minus near present (2000 – 2009) for REF (a) and SD (b), and the difference SD – REF (c) and WD – REF (d) under future conditions (2090 – 2099). Coloured regions are significant at the 95% confidence level (calculated using a Student t-test). Colour interval is 10%.

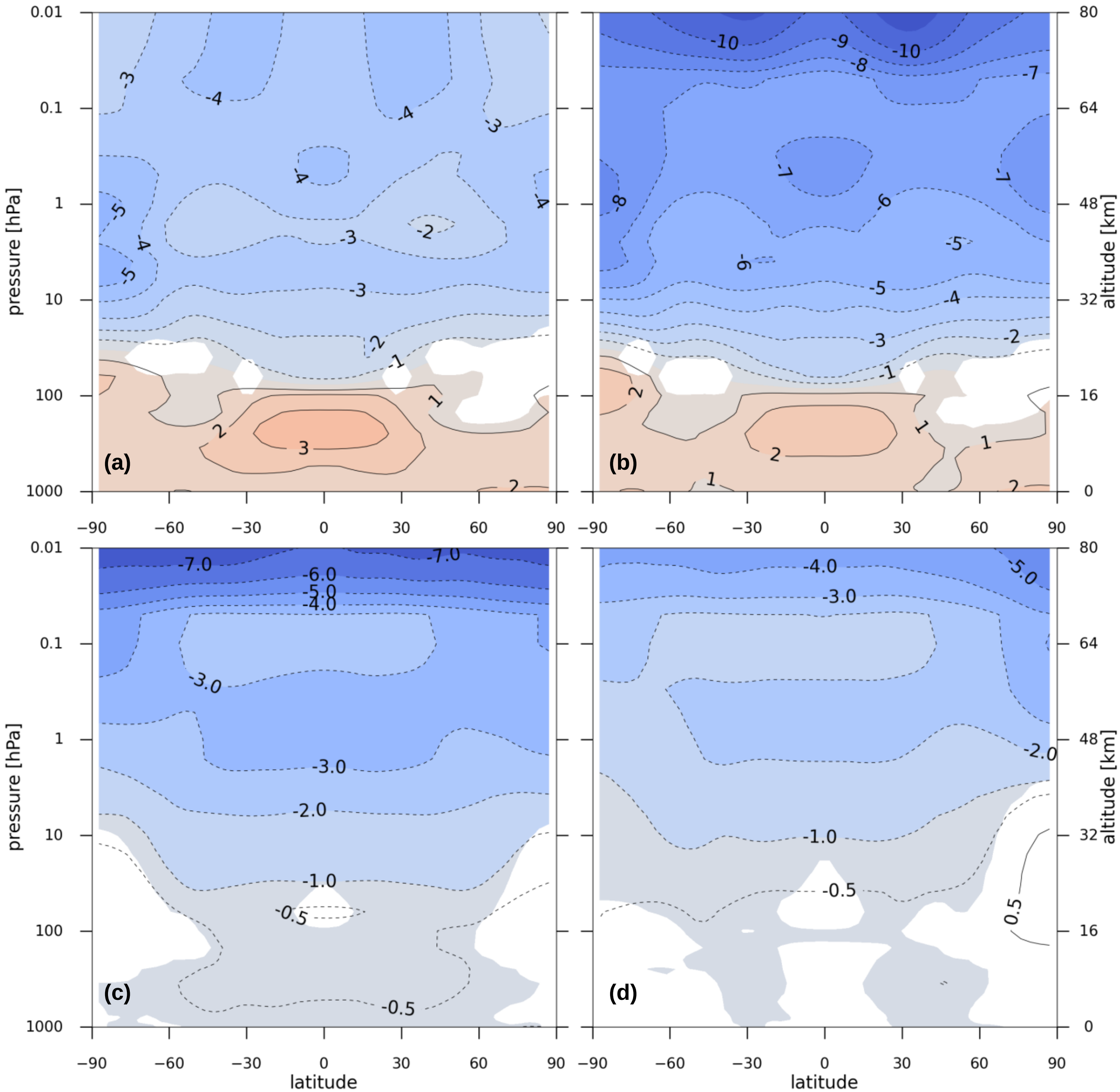
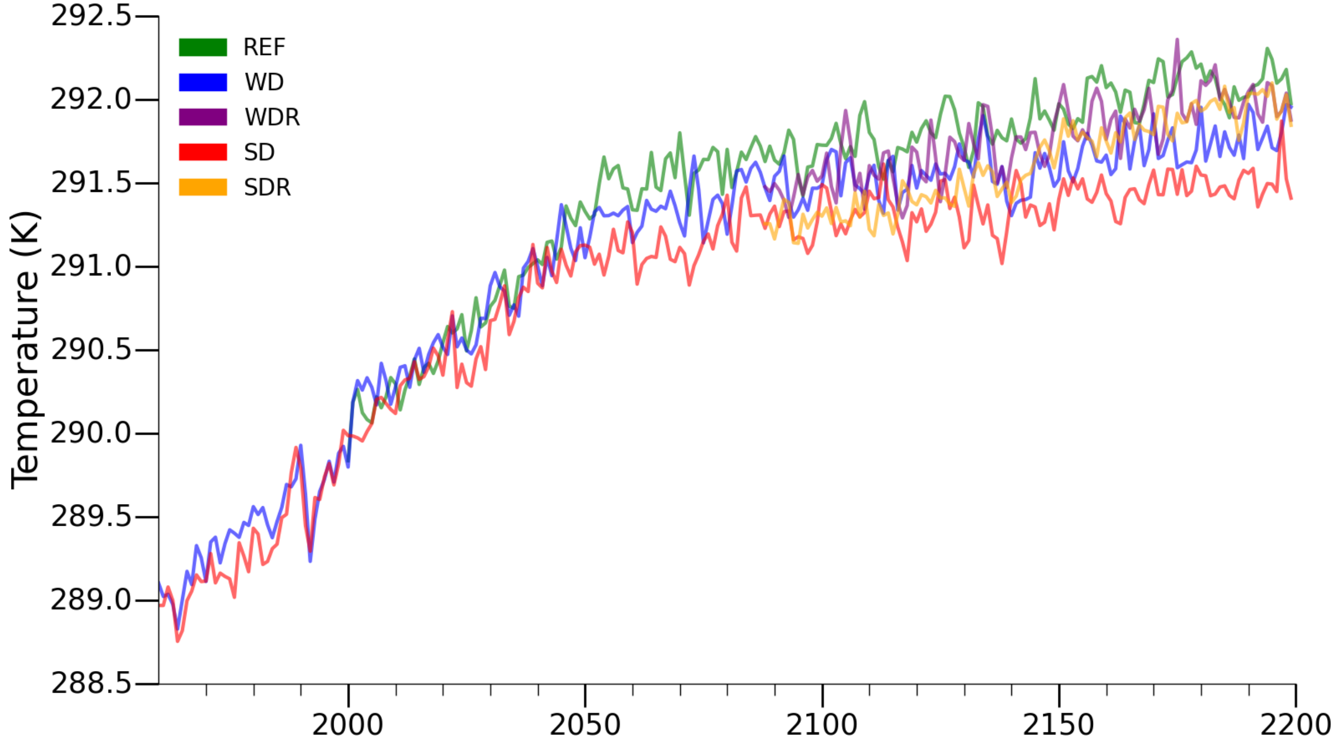


Figure 4: Annual zonal mean temperature difference in K of future (2090 – 2099) minus near present (2000 – 2009) for REF (a) and SD (b), and difference SD – REF (c) and WD – REF (d) under future conditions (2090 – 2099). Coloured regions are significant at the 95% confidence level (calculated using a Student t-test). Colour interval is 1 K.



~~Figure 5: Annual global mean surface temperature in K of ensemble means from 1960 to 2199.~~

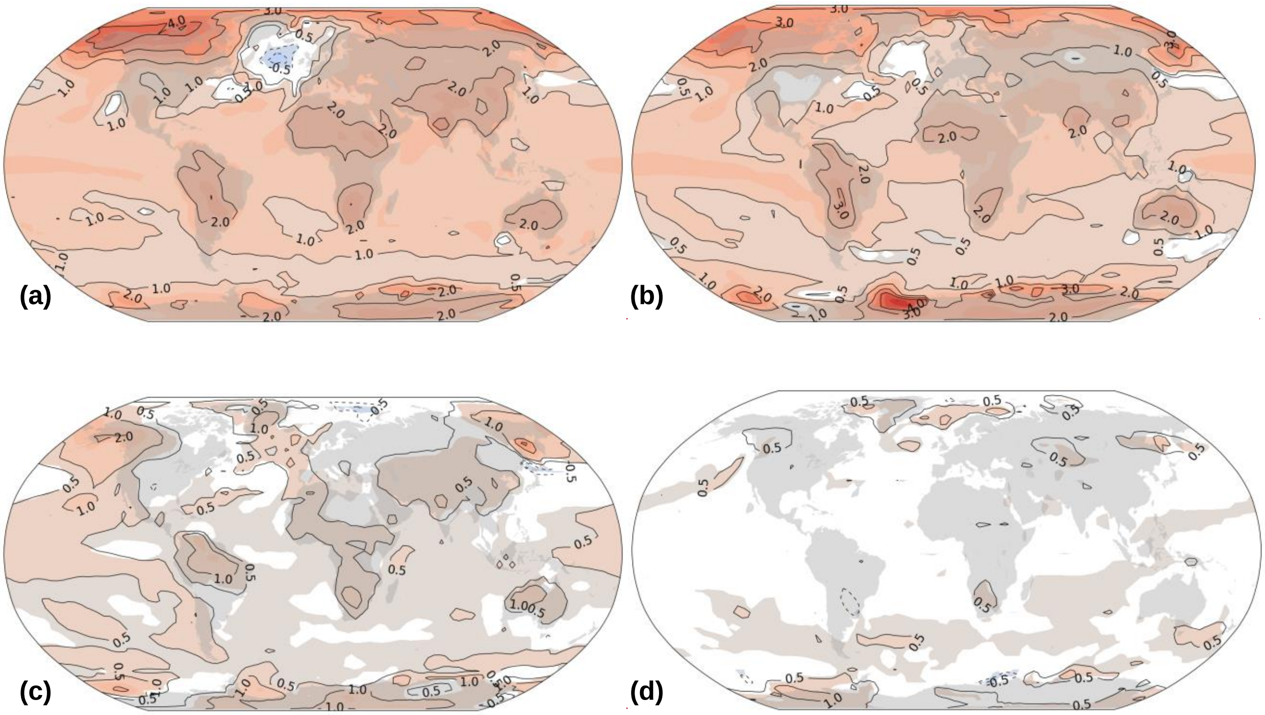


Figure 6: Spatial distribution of surface temperature difference in K of future (2090 – 2099) minus near present (2000 – 2009) for REF (a) and SD (b), and of far future (2190 – 2199) minus intermediate future (2090 – 2099) for REF (c) and SD (d). Coloured regions are significant at the 95% confidence level (calculated using a Student t-test). Colour interval is 0.5 K.

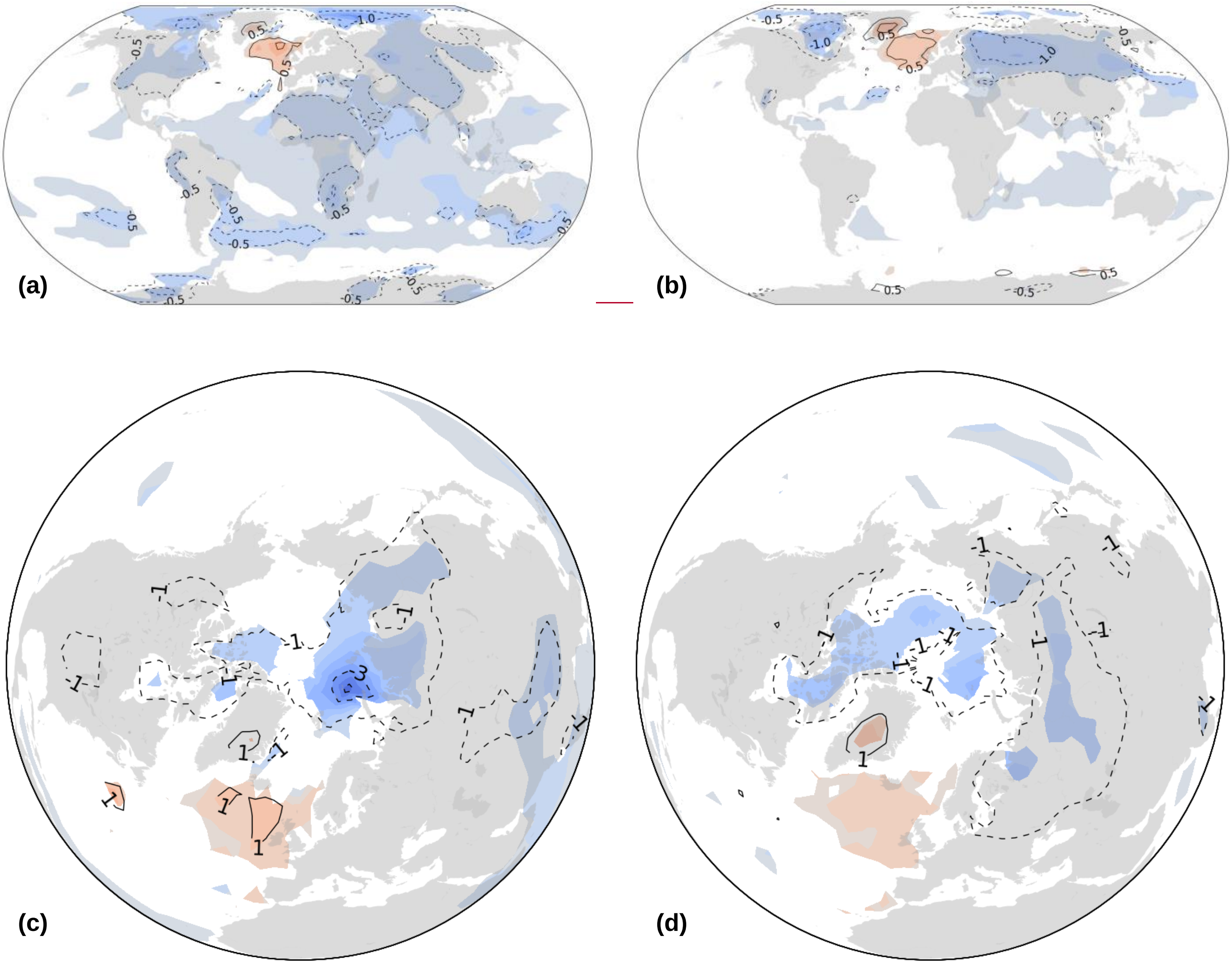


Figure 7: Global projections of spatial distributions of annual mean surface temperature differences in K of SD minus REF (a) and WD minus REF (b) in the late 21st century (2090 – 2099). Polar projections of boreal winter (DJF) mean surface temperature differences in K of SD minus REF (c) and WD minus REF (d) in the late 21st century (2090 – 2099). Coloured regions are significant at the 95% confidence level (calculated using a Student t-test). Colour intervals are 0.5 K in (a) and (b) and 2 K in (c) and (d).

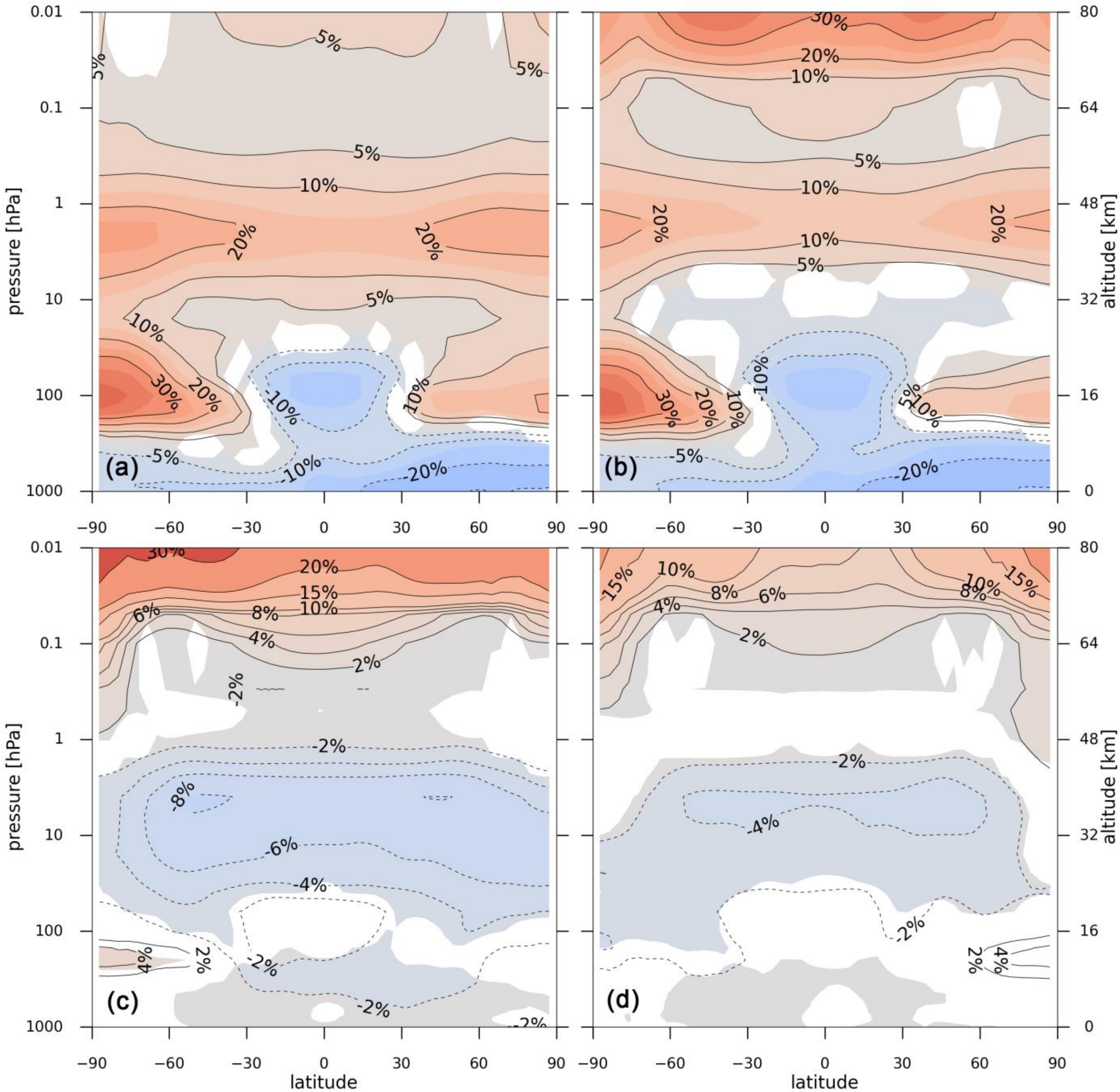


Figure 8: Annual zonal mean ozone difference of ensemble means of future (2090 – 2099) minus near present (2000 – 2009) for REF (a) and SD (b), and difference of SD minus REF (c) and WD minus REF (d) for the late 21st century (2090 – 2099). Coloured regions are significant at the 95% confidence level (calculated using a Student t-test). Colour interval is 5% in (a) and (b) and 2% in (c) and (d).

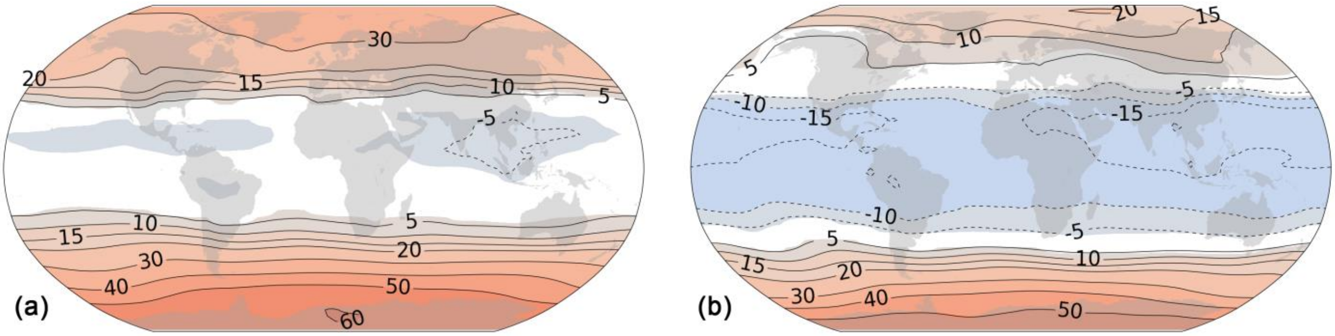


Figure 9: Spatial distribution of total-column ozone difference in Dobson units of ensemble means of future (2090 – 2099) minus near present (2000 – 2009) conditions for REF (a) and SD (b). Coloured regions are significant at the 95% confidence level (calculated using a Student t-test). Colour interval is 10 Dobson units.

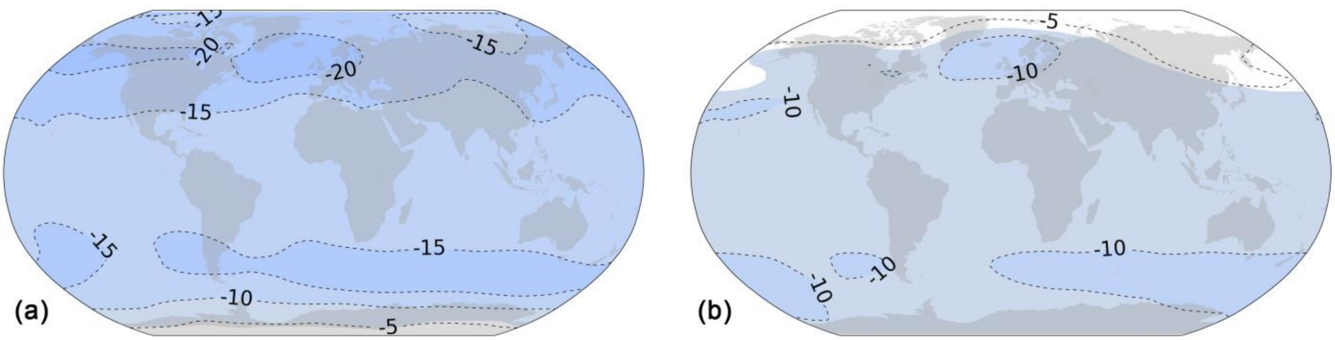


Figure 10: Spatial distribution of total-column ozone difference in Dobson units of ensemble means of SD minus REF (a) and WD minus REF (b) for the late 21st century (2090 – 2099). Coloured regions are significant at the 95% confidence level (calculated using a Student t-test). Colour interval is 5 Dobson units.

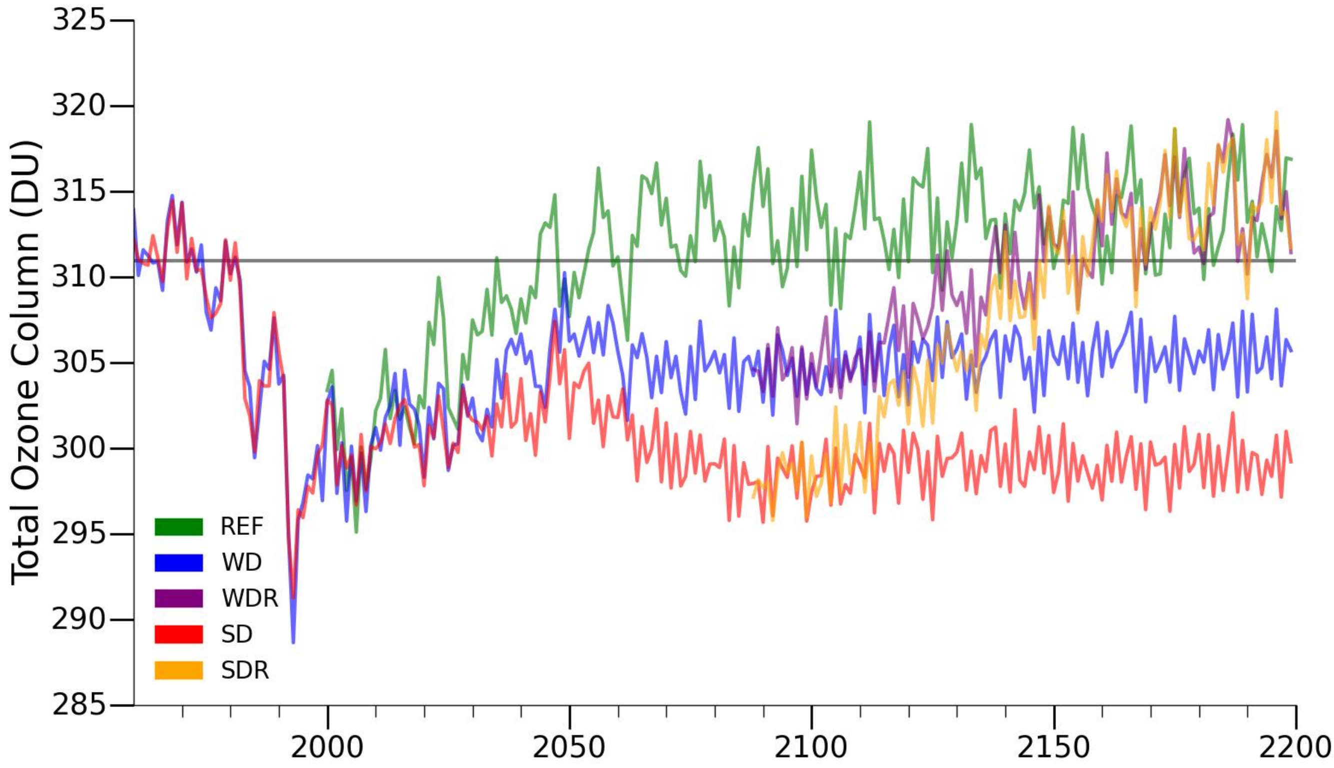


Figure 11: Annual global mean total-column ozone in Dobson units of ensemble mean values for the 1960 to– 2199 period. The horizontal grey line presents the 1960 – 1980 period mean value.