

## ***Interactive comment on “Implications of potential future grand solar minimum for ozone layer and climate” by Pavle Arsenovic et al.***

**Anonymous Referee #2**

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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  $6 \text{ W/m}^2$  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

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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"

L11 remove "several"

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

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

L14 "different durations" -> specify what durations

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

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

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

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

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L19 "In the stratosphere... by up to 8%" it would be good to state the magnitude of the UV forcing (e.g. as W/m<sup>2</sup> for the UV spectrum), given the importance of the chemical effect on O<sub>3</sub>

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

L25 remove "current"

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

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

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.

L3 p3: "computed" -> simulated

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).

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

L18p3: "estimate" -> assess

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)

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

### C3

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

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

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)".

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.

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

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"

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

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

L21p4 applied -> imposed

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L22p4 Figure 1: please add W/m<sup>2</sup> values to your plot, e.g. as a Y axis on the right hand side

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

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

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

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..."

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

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

L18p5 "identically to" -> as in

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

L4p6: "to elucidate the role of solar forcing" -> to elucidate the role of solar forcing 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 NO<sub>x</sub> 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)

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

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

L16p6 BDC -> the BDC

p19 p6 applied -> imposed

L19p6 "are decreasing and... 21st century" -> are projected to decrease, and N<sub>2</sub>O will increase during the 21st century.

L29p6: well visible -> clearly visible

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

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

L15p7 rates of GHGs -> arising from increased GHG

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

L22p7 "has relatively" -> has a relatively

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

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...

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

C6

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

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...?

L25p8 "reproduces the polar amplification 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".

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 O3 should follow the NOx analysis (3.2). The sequence of surface temp. BDC, NOx and O3 would also follow

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more "naturally", as you start off with the pure thermodynamical response, then look at the dynamics, and then looking into the chemistry.

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

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

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)

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

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

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

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...

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.

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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

L19p13 "it faces us with" -> it poses

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

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

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Interactive comment on Atmos. Chem. Phys. Discuss., <https://doi.org/10.5194/acp-2017-818>, 2017.