Authors' general response

We thank the three anonymous Reviewers for their helpful comments regarding improving our manuscript. We reply to the individual comments in the separate responses. In addition, Reviewers 2 and 3 raised a couple of common questions. These are in turn addressed below.

1. How well does the UMUKCA model simulate the present day Arctic ozone loss?

This will depend both on how well the model's chemistry scheme performs and how well the model reproduces the Arctic meteorology. These two factors are addressed below.

The performance of the UMUKCA CheS+ chemistry scheme can be evaluated using a similar model version but with a so-called specified dynamics set-up, i.e. in which model's temperature and winds are nudged towards meteorological reanalysis data. A comparison between the Arctic/Antarctic mean (65-90°N/S) total ozone columns in this nudged CCMI REFC1 CheS+(SD) integration[1] shows a good correlation between the simulated and observed ozone (Bodeker et al. 2005; Müller et al., 2008) (see Fig. S1). In the Antarctic, there is some overestimation of the ozone column in the model by up to ~15-30 DU (see Fig. S1).

For the cold March 2011, the model shows a positive bias in the zonal mean monthly mean ozone levels in the Arctic lower stratosphere (30-100 hPa) of up to ~0.9 ppb (~41%; for the 70-90°N mean, 50 hPa) compared with MIPAS satellite data (Fisher et al., 2008, Fig. R1). The positive ozone bias is commensurate with a negative bias in the zonal mean monthly mean ClO levels at this altitude (not shown). Note that there is some uncertainty in the observed zonal mean monthly mean ClO, in part due to sparse temporal sampling (twice a day) of the MIPAS instrument.

In general, all models will show some biases with respect to observations. Importantly, as in many studies, we compare the model for the present day and future periods in an internally consistent way; therefore, any biases will become less relevant for our study.

Regarding the NAT PSC formation and removal, as described in Chipperfield et al. (1999), the NAT PSC formation follows the equilibrium expression from Hanson and Mauersberger (1988). Although potentially imperfect, the use of equilibrium NAT scheme is a common technique employed in CCMs (see e.g. Morgenstern et al., 2010). The denitrification scheme assumes a relatively slow NAT sedimentation velocity of ~40 m/day for pure NAT PSCs, and a much faster NAT sedimentation velocity of ~1540 m/day in the presence of ice; the latter assumes coating of NAT PSCs onto ice particles.

Parts of the above information have been added to Sect. 2.1 of the revised manuscript. Figure S1 has also been added to Supplementary Information.

[1]We thank Paul Telford for preparing and running the nudged UMUKCA CCMI REFC1 CheS+(SD) integration discussed above (see also the updated Manuscript for full list of acknowledgements).

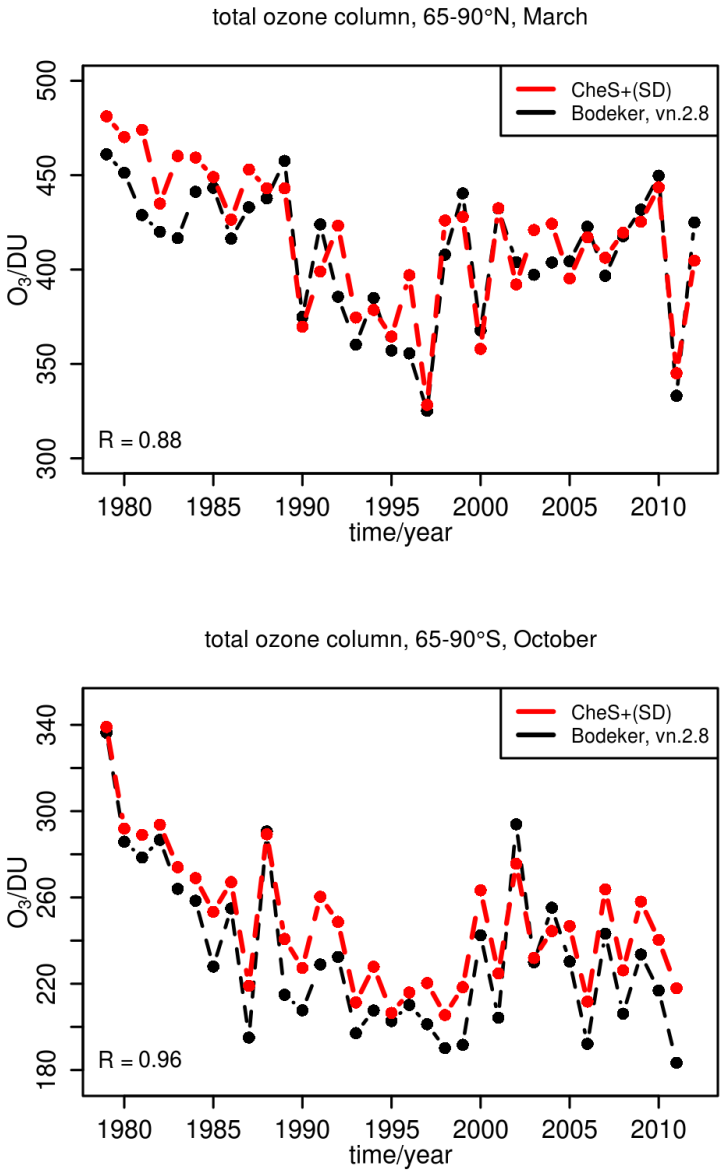

Figure S1. The evolution of 1979-2012 65-90°N March (top) and 1979-2011 65-90°S October (bottom) total ozone column [DU] in the nudged UMUKCA CCMI REFC1 CheS+(SD) integration (red) and observations (black, Bodeker total ozone column dataset: Bodeker et al., 2005; Müller et al., 2008).

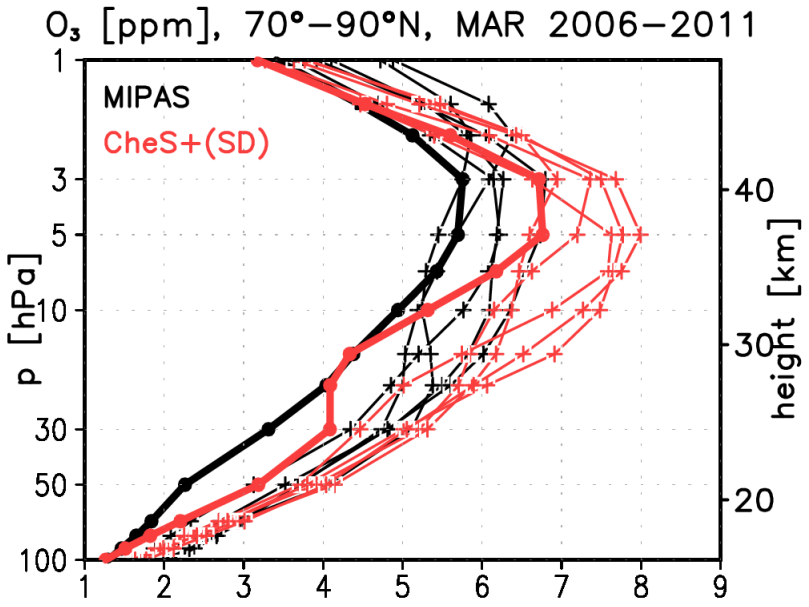

Figure R1. Monthly mean 70-90°N March ozone [ppm] mixing ratios in individual years from 2006 to 2011. Red lines are for the nudged UMUKCA CCMI REFC1 CheS+(SD) simulation and black lines are for MIPAS data (Fisher et al., 2008). Thick lines highlight the year 2011.

Beside chemistry, winter/springtime Arctic ozone levels are also strongly controlled by meteorology; any biases in temperature and winds will therefore impact on the simulated ozone. The UMUKCA REFC2 ensemble integrations described in the manuscript show a somewhat weaker and warmer present day Arctic stratospheric vortex in early/mid-winter, with a slight zonal wind bias of up to ~6 ms^{-1} in the mid-latitude lower/mid- stratosphere in March (see Fig. R2 and R3 of this response).

This information has been included in Sect. 2.2 of the updated manuscript.

As discussed in Sect. 3.2.3 of the updated manuscript, the model captures qualitatively the diagnosed relationship that higher Vpsc is associated with higher halogen induced ozone losses (Rex et al., 2004, 2006). The modelled correlation is R≈0.8 for the individual 20 year periods in the 21st century, demonstrating the coupling between chemistry and meteorology.

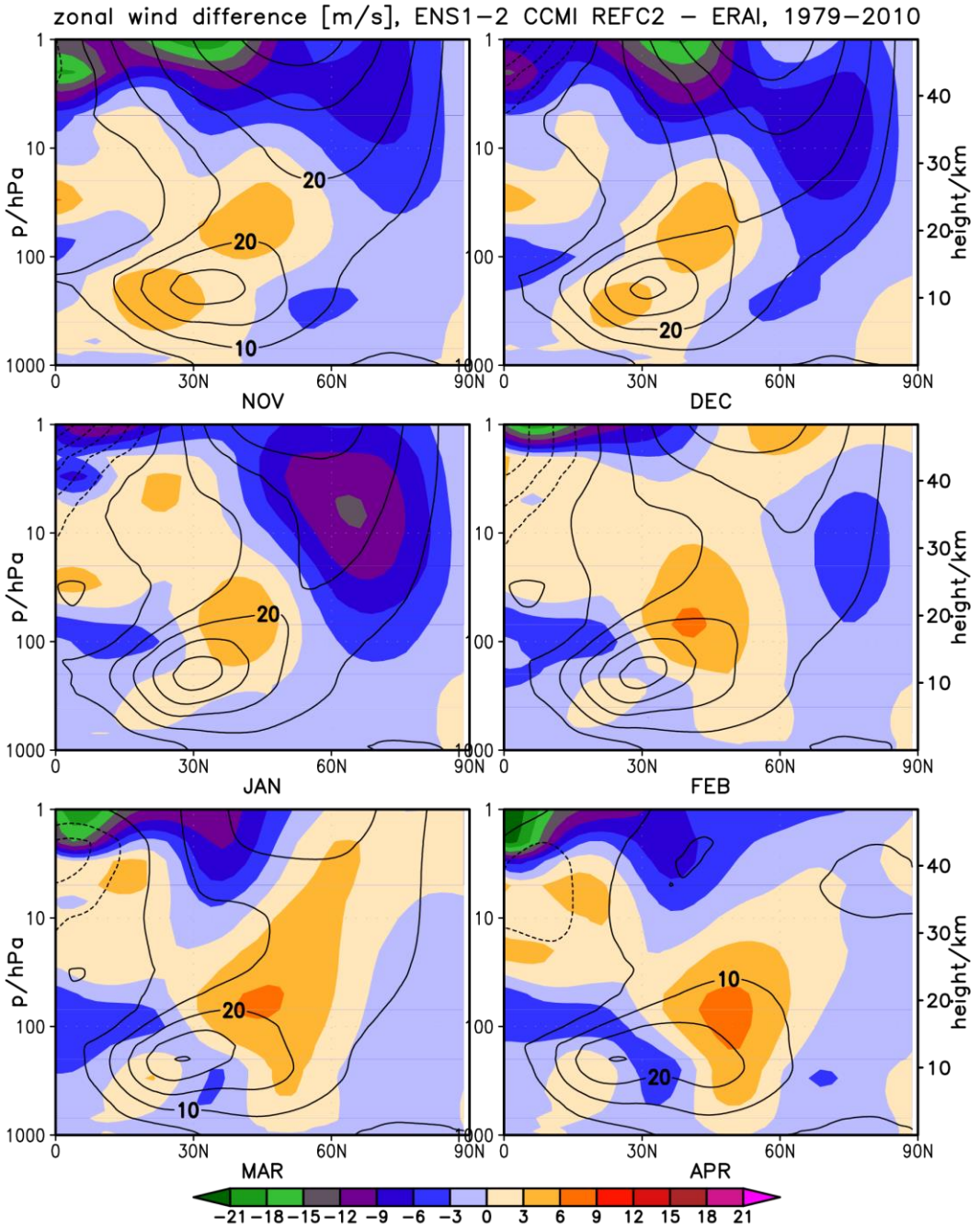

Figure R2. Contours: November to April monthly mean zonal mean zonal wind [m/s] climatology over 1979-2010 in the mean of ensemble members 1 and 2. Shading: the difference [m/s] between the model and the ERAI reanalysis (Dee et al., 2011).

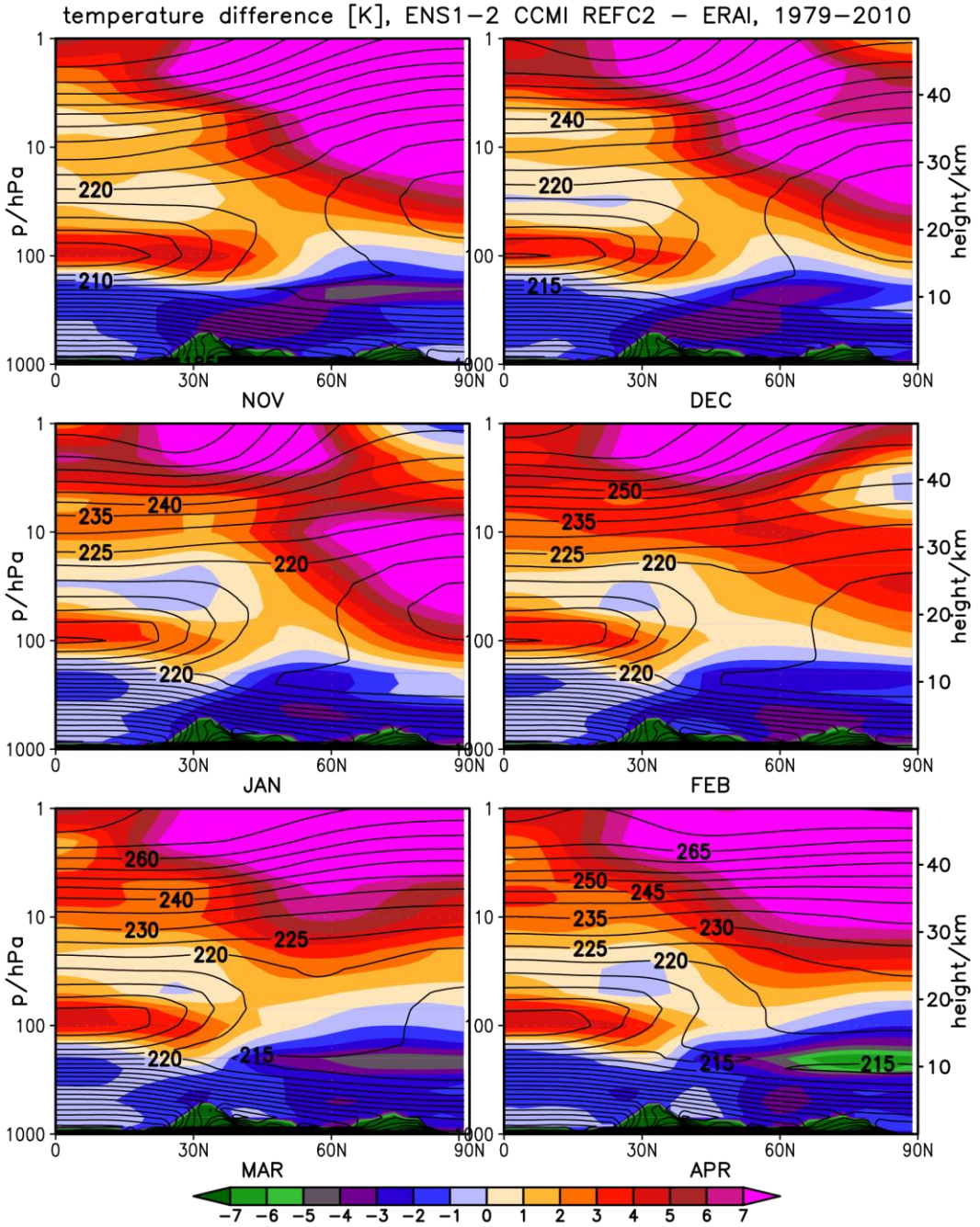

Figure R3. As in Fig. R2 but for temperature [K].

2. Chemical losses inside and outside polar vortex.

As stated in the manuscript, the model's passive ozone tracer does not participate in any chemical processing, and not just that due to halogen chemistry. This includes gas phase chemistry that is particularly important outside the polar vortex, as well as heterogeneous and gas phase chemistry inside and at the edge of the polar vortex. To avoid confusion with the interpretation of the passive ozone tracer diagnostic, we have replaced the Arctic mean passive ozone tracer with the vortex-averaged tracer in Fig. 8(a) of the revised manuscript. In addition, we have removed the last two sentences of Sect. 2.3 and the polar cap quantity from the last but one paragraph of Sect. 3.3. Lastly, we have reformulated the passive ozone paragraph in Sect. 3.3., including a cautionary sentence regarding the interpretation of the difference between the passive and full ozone column as resulting of a complex balance between chemical loss and production cycles as well as their interaction with transport throughout the winter.

In comparison, the halogen induced ozone loss diagnostic (Sect. 2.3) inside the polar vortex (calculated using various definitions of the polar vortex edge) lower atmosphere shows that the losses for model years 2063/2060 are mostly similar or even somewhat higher than those calculated for the Arctic mean (See Table 1 as well as Fig. R4-R5 below). This supports the use and interpretation of the Arctic mean diagnostic for analysing the long-term trends and variability in the halogen induced ozone loss for the full ensemble (Sect. 3.2.1).

The vortex-averaged halogen induced ozone losses for the two case study years have now been added to the manuscript (Sect. 3.3). We stress that we use a simple definition of the polar vortex edge, based on a rough estimate of a characteristic PV value for the maximum PV gradient.

CUMULATIVE HALOGEN-INDUCED OZONE LOSS [DU]

	65-90°N	$PV_{850K} \geq 600$ PVU	$PV_{450K} \geq 30$ PVU	$PV_{450K} \geq 35$ PVU
2063	39	44	46	43
2060	18	23	23	6

Table 1. Cumulative halogen induced ozone loss (1 Nov-30 Mar, 1-25 km) for the two case study years 2063 and 2060, calculated for the 65-90°N mean and a number of polar vortex edge definitions.

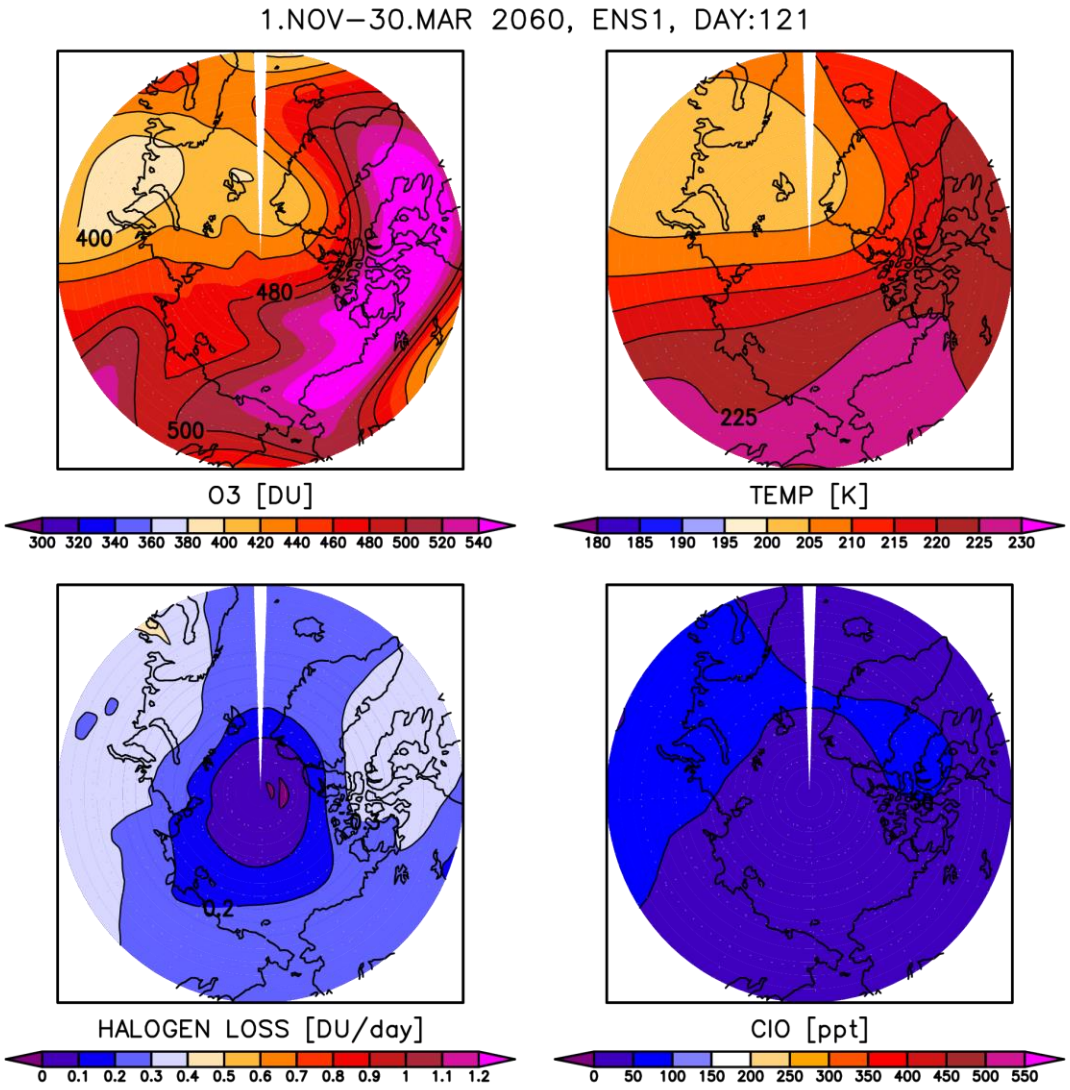

Figure R4. Daily mean total ozone column [DU] (top left), temperature at 21.5 km [K] (top right), halogen induced ozone loss in the 1-25 km layer [DU/day] (bottom left) and ClO [ppt] (bottom right) at 21.5 km simulated on 1 March in the case study year 2060.

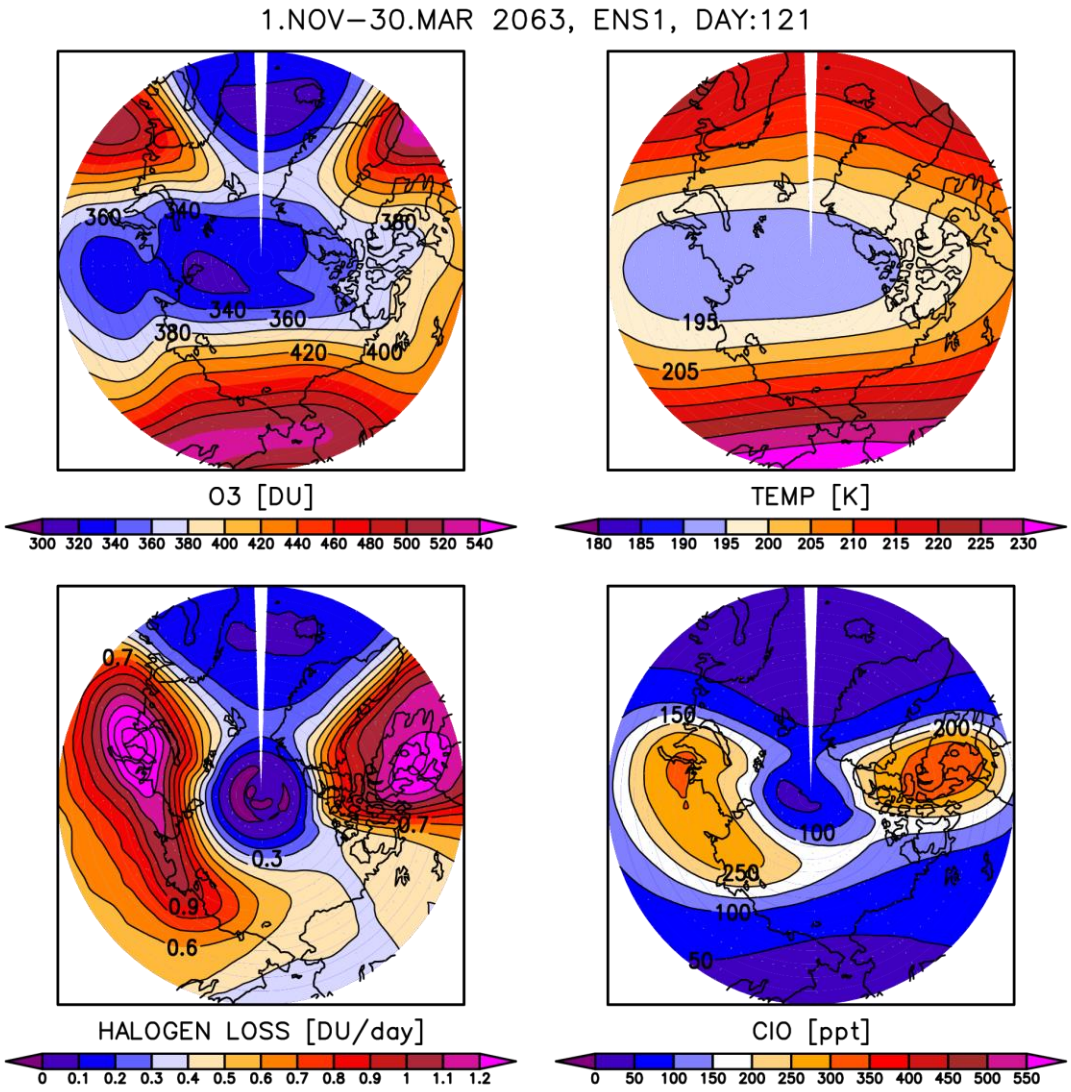

Figure R5. As in Fig. R4 but for the case study model year 2063.

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