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Investigating the role of stratospheric ozone as a driver of inter-model spread in CO_2 effective radiative forcing

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Text S1 – NorESM2-MM model configuration

The Norwegian Earth System Model version 2 (NorESM2) is the latest generation of Earth system models developed by the Norwegian Climate Center (Seland et al., 2020). Here, we use the "medium-resolution" version of NorESM2 (hence named NorESM2-MM) which has a horizontal resolution of 0.9° latitude by 1.25° longitude in the atmosphere-land components and a tripolar irregular ocean grid, with a 1° latitude by 0.25° longitude resolution at the equator that progresses towards more isotropic grid boxes at higher latitudes (with sea-ice discretised on the same horizontal grid). NorESM2 is based on the Community Earth System Model version 2 (CESM2; Danabasoglu et al., 2020) and shares many Earth system features along with the same computer code infrastructure. However, the ocean and ocean biogeochemistry components are completely different and the atmospheric component of the model (CAM6-Nor) employs a different module for aerosol physics and chemistry, including cloud and radiation interactions. Radiative fluxes and heating rates are computed by the Rapid Radiative Transfer Model for General circulation models code (RRTMG; Iacono et al., 2008). RRTMG utilizes the correlated k-distribution method to calculate radiative transfer across longwave and shortwave spectral intervals from 3.1 to 1000 µm and 0.2 to 12.2 µm, respectively. CAM6-Nor has 32 vertical levels with a model top at about 2.26 hPa (40 km). Note that NorESM2-MM output used in this study uses the model top layer midpoint as it's uppermost level at 3.64 hPa and the stratospheric vertical resolution of CAM6-Nor is relatively coarse. CAM6-Nor has no prognostic chemistry module for ozone and other stratospheric species, therefore ozone fields are prescribed using output from previous CESM-Whole Atmosphere Community Climate Model version 6 (WACCM6) simulations as zonally-averaged 5 day fields (see Supplementary Figure 1). WACCM6 is configured identically to CAM6-Nor albeit with 70 vertical levels and a model top at 4.5×10^{-6} hPa. Hence, WACCM offers a much higher stratospheric vertical resolution and includes comprehensive interactive chemistry. For use in NorESM2-MM, these ozone fields are interpolated from the 70 WACCM6 vertical levels onto the 32 CAM6-Nor vertical levels by an internal model subroutine. Note that CAM6-Nor and WACCM6 share the same vertical level structure from the surface up to 87 hPa. Further NorESM2 model description is given by Seland et al., 2020.

NorESM2-MM					
Horizontal resolution	**Vertical resolution**	**Radiative transfer code**	**Atmospheric component**	**O_3 dataset**	**Reference**
0.9°x1.25°	32 levels (uppermost level at 3.64 hPa)	RRTMG Iacono et al., 2008	CAM6-Nor	Zonal-mean 5-day fields from CESM2-WACCM6	Seland et al., 2020

NorESM2-MM model configuration details

Figure S1: CESM2-WACCM6 zonal 5-day mean O_3 field

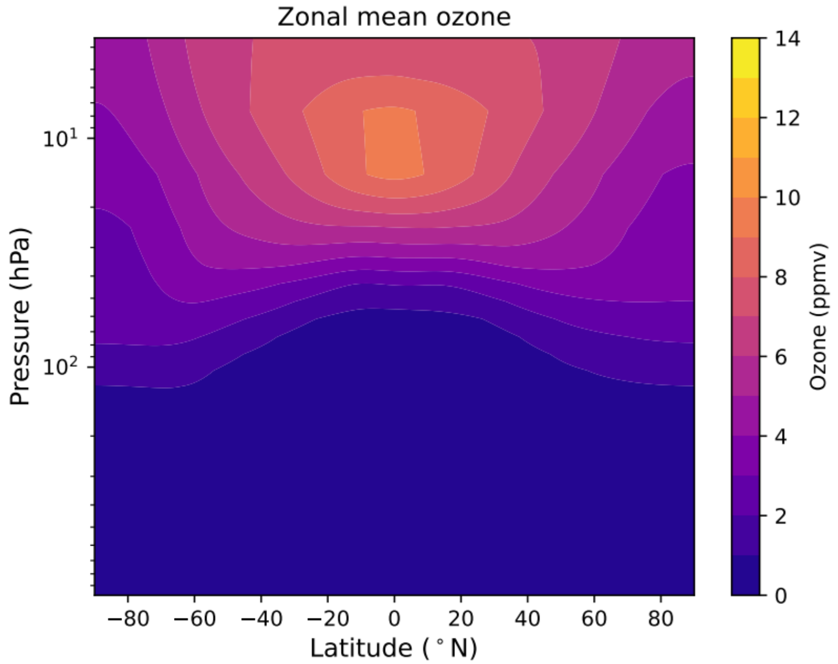


Table S1: Model experiments

Experiment name	**Baseline integration**	**Perturbed integration**	**Integration length**
'Standard' $4xCO_2$	Pre-industrial	$4xCO_2$	30 years
Strat O_3x1.5	Pre-industrial with stratospheric O_3 increased by 50%	$4xCO_2$ with stratospheric O_3 increased by 50%	15 years
Strat O_3x0.5	Pre-industrial with stratospheric O_3 decreased by 50%	$4xCO_2$ with stratospheric O_3 decreased by 50%	15 years

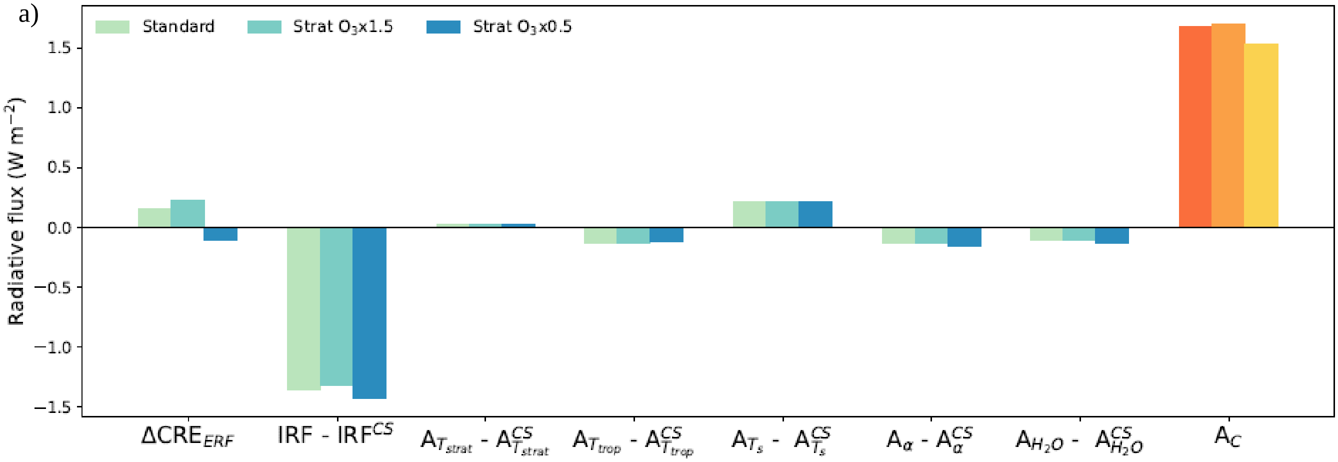
Table S2: The impact of ozone increases/decreases on forcing components

Component	Difference between ‘StratO3x1.5’ and ‘standard’	Difference between ‘StratO3x0.5’ and ‘standard’
IRF	-0.319	0.444
$A_{T_{Strat}}$	-0.060	0.072
$A_{T_{Trop}}$	0.055	0.016
A_{T_S}	-0.001	0.011
A_{α}	-0.007	0.070
A_{H_2O}	-0.029	0.110
A_c	0.028	-0.138
ϵ	0.318	-0.362
ERF	-0.012	0.227

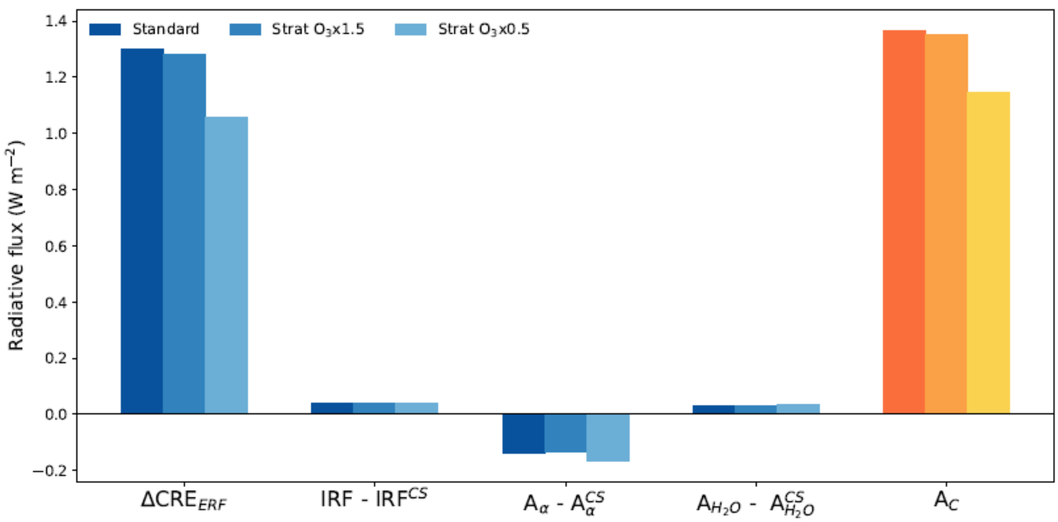
Table S2: The difference (in W m^{-2}) between each O_3 experiment and the ‘standard’ $4xCO_2$ case for each term in Equation 1 of the main text.

Figure S2: LW, SW and net components of A_c

a)



b)



Cont.

c)

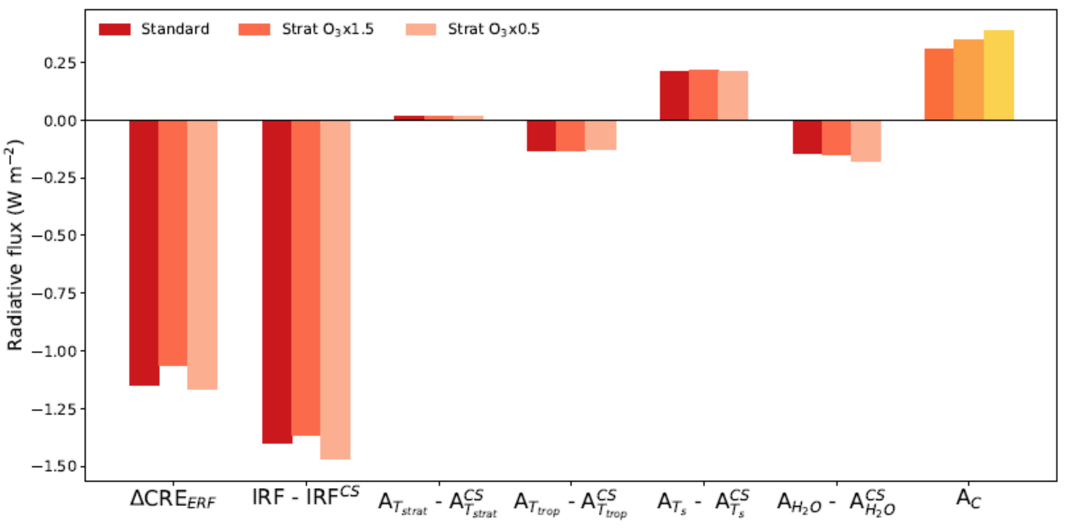


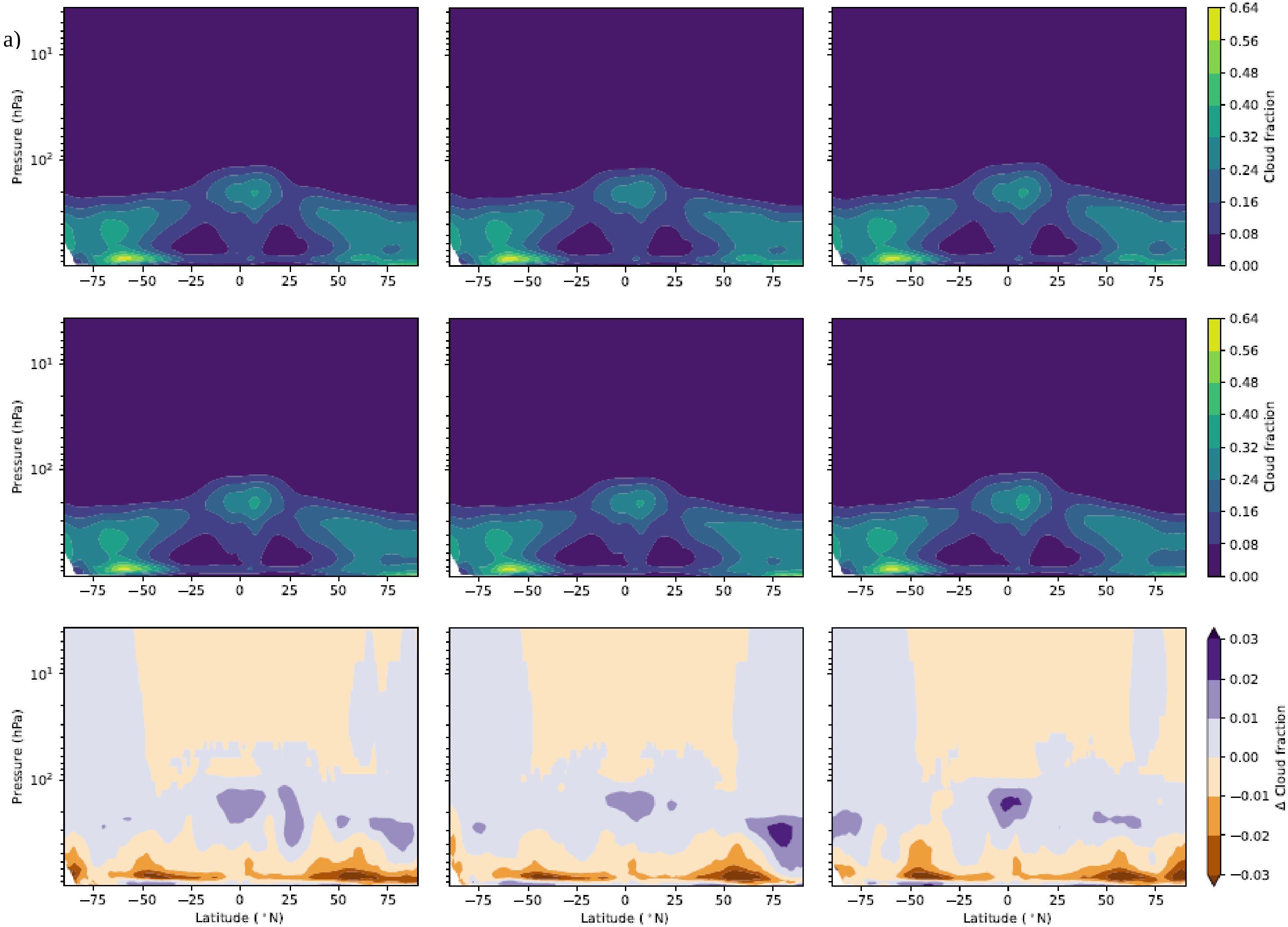
Figure S2: Components of the A_c term (orange bars) for the 'standard', 'Strat O_3x1.5' and 'Strat O_3x0.5' cases for a) net (LW+SW) fluxes, b) SW fluxes and c) LW fluxes. As noted in the main text A_c is composed of the ΔCRE minus the impact of cloud masking of the IRF and each adjustment term in Eq. 1. For each experiment, A_c = ΔCRE_{ERF} – $(IRF\text{-}IRF^{CS})\text{-}(A_{T_{Strat}}\text{-}A_{T_{Strat}}{}^{CS})\text{-}(A_{T_{Trop}}\text{-}A_{T_{Trop}}{}^{CS})\text{-}(A_{T_S}\text{-}A_{T_S}{}^{CS})\text{-}(A_{\alpha}\text{-}A_{\alpha}{}^{CS})\text{-}(A_{H_20}\text{-}A_{H_20}{}^{CS})$, where the superscript 'CS' refers to each component under clear-sky conditions.

Table S3: Clear-sky and all-sky IRF and ERF values

	SW IRF		LW IRF	
	Clear-sky	**All-sky**	**Clear-sky**	**All-sky**
'standard'	0.007	0.046	6.65	5.25
'Strat O_3x1.5'	0.006	0.046	6.30	4.94
'Strat O_3x0.5'	0.008	0.048	7.17	5.70
	SW ERF		**LW ERF**	
	Clear-sky	**All-sky**	**Clear-sky**	**All-sky**
'standard'	0.19	1.49	8.13	6.99
'Strat O_3x1.5'	0.18	1.47	8.07	7.00
'Strat O_3x0.5'	0.38	1.44	8.43	7.27

Table S3: Clear-sky and all-sky SW and LW IRF and ERF for each experiment (units: W m^{-2})

Figure S3



Cont.

b)

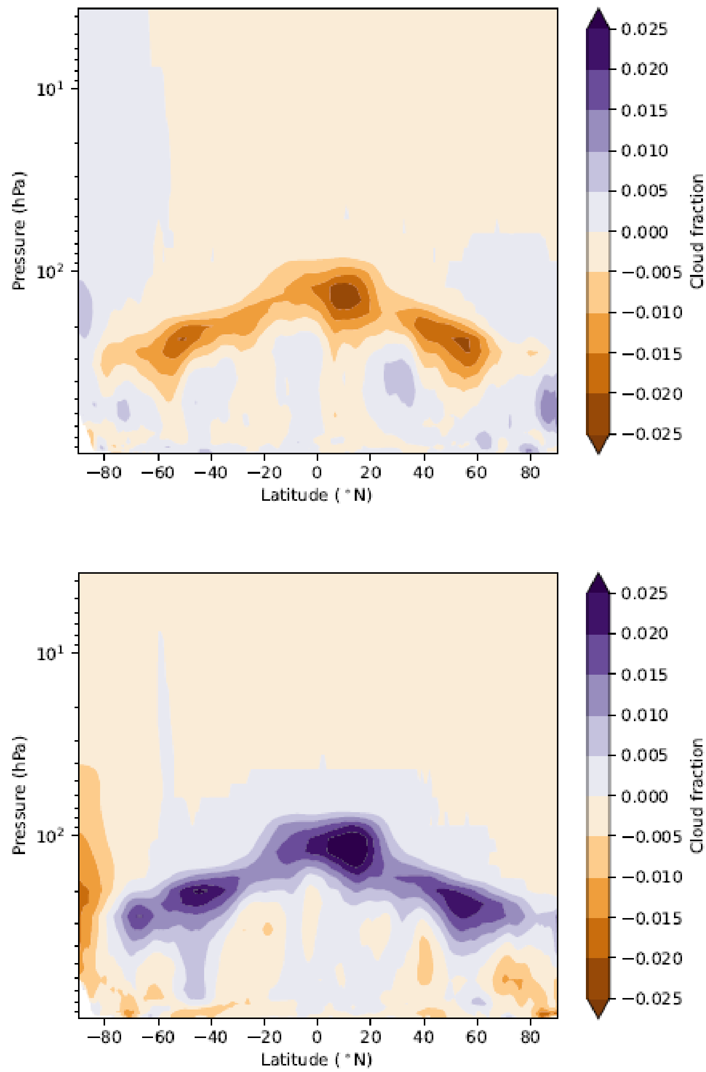


Figure S3: a) Zonal-mean cloud fraction for the base-state (upper row) and 4xCO_2 (middle row) atmosphere for the 'standard' (left-most column), 'Strat O_3x1.5' (middle column) and 'Strat O_3x0.5' (right-most column) cases. The lower row shows the change in cloud fraction between the base-state and 4xCO_2 simulation for each case. b) Difference in zonal-mean base-state cloud fraction between 'Strat O_3x1.5' and the 'standard' case (upper) and 'Strat O_3x0.5' and the 'standard' case (lower), derived from the upper row of plot a). Note that for display purposes model output on hybrid-sigma levels has been interpolated onto global-mean NorESM2-MM pressure levels. Note also that cloud fraction values range between 0 and 1.

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