

Supplementary Information

Historical total ozone radiative forcing derived from CMIP6 simulations

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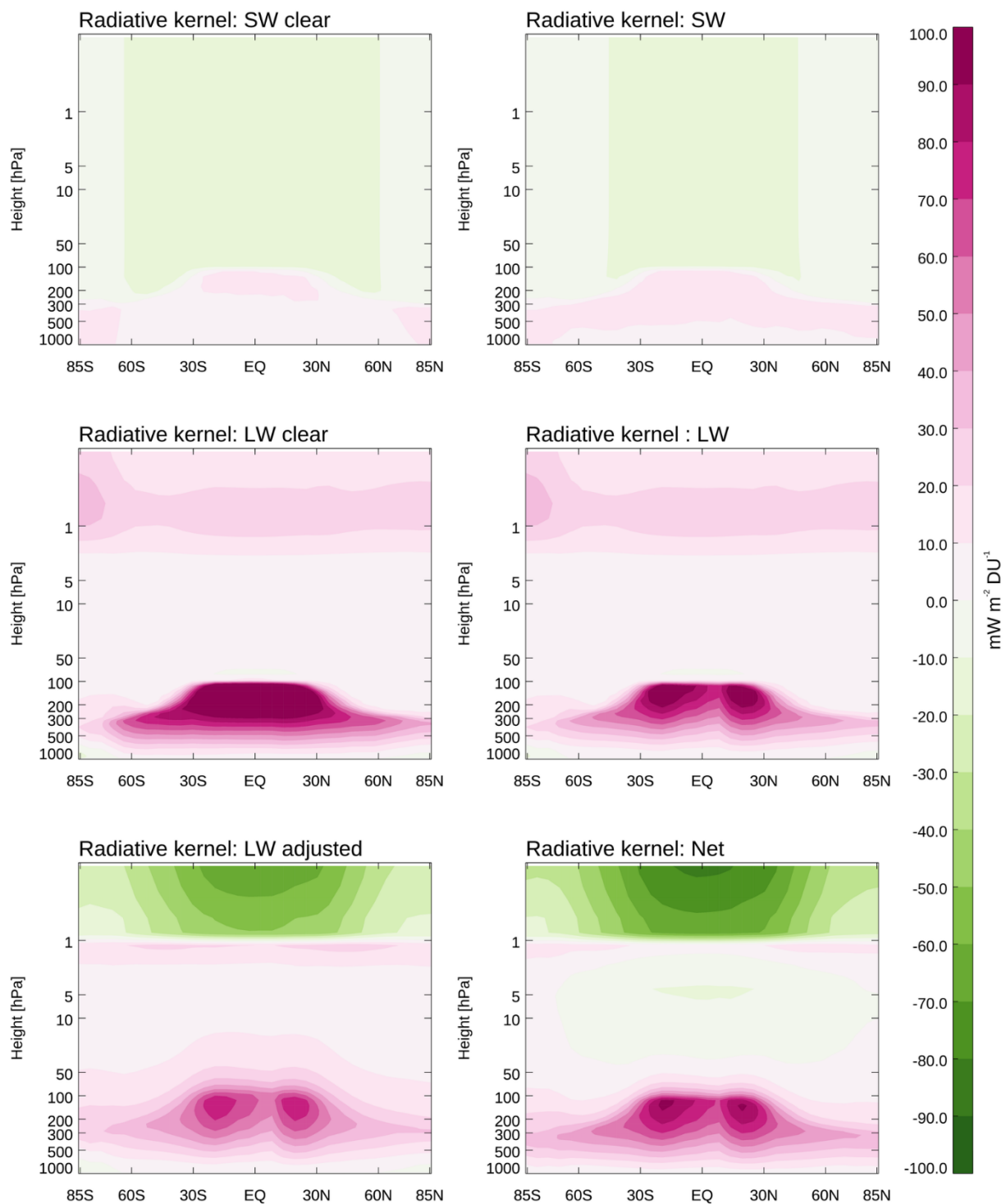


Figure 1 Annual zonal mean values of the radiative kernel (mW m^{-2} per DU) for instantaneous radiative forcing (IRF) shortwave (SW) clear sky, IRF SW all sky, IRF longwave (LW) clear sky, IRF LW all sky, LW all sky with stratospheric adjustment and net forcing (LW adjusted + SW all sky). The vertical coordinates are sigma hybrid-pressure levels. The fields are plotted for the model levels and indicated by an approximate pressure levels on the y-axis.

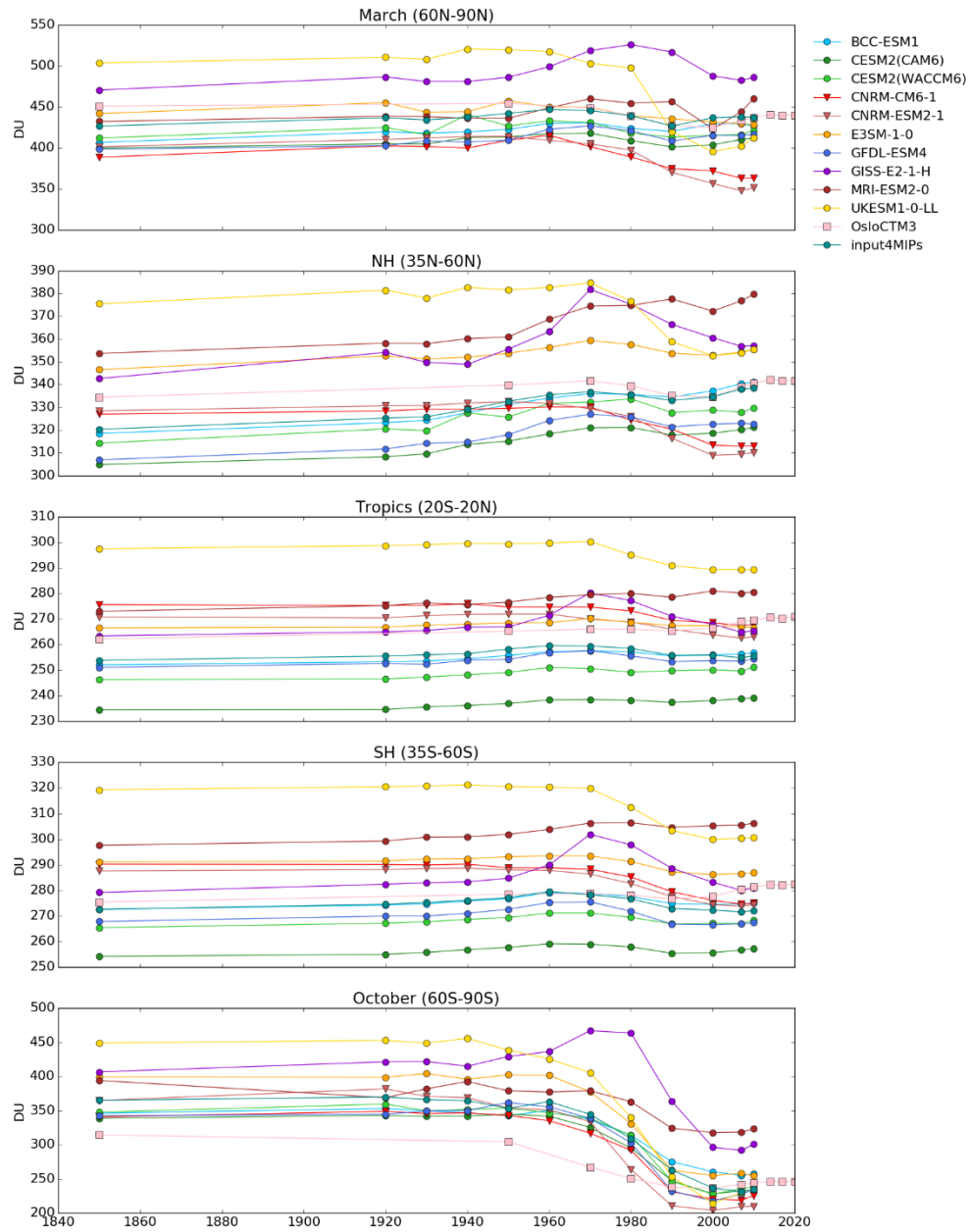


Figure 2 Historical time development of total ozone column (DU) in different latitude bands. In the polar regions spring values are plotted (60N to 90N monthly mean values for March and 60S to 90S monthly mean values for October). For the other regions, annual mean values are plotted. Note that the fields plotted are the averaged and interpolated data as described in the methods section and will differ from what is directly calculated in the individual models. Models without tropospheric chemistry are indicated with a triangle.

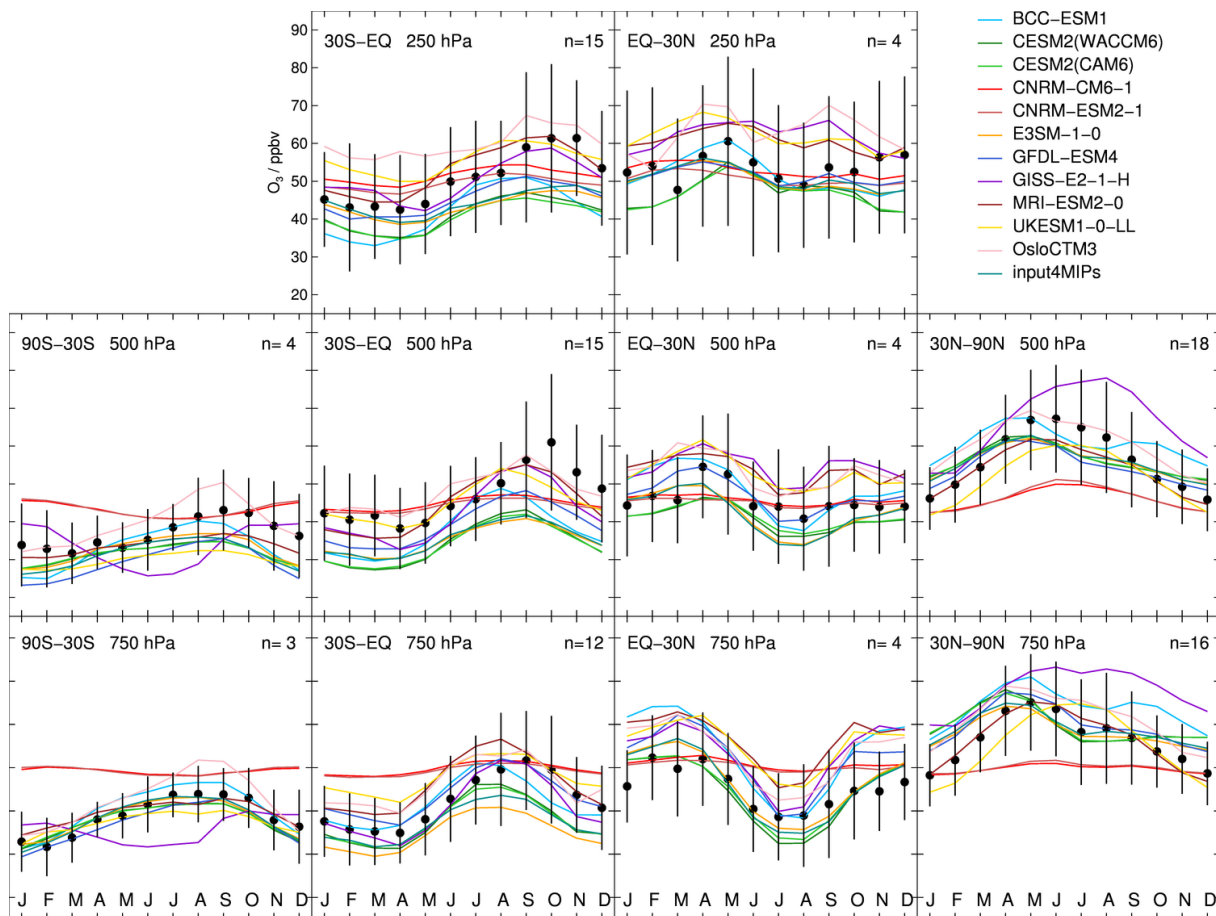


Figure 3 Comparison of the annual cycle of ozone observations (black dots) and monthly mean O_3 for the year 2000 for the different models at different latitude bands and at different pressure levels (750 hPa, 500 hPa and 250 hPa). Ozone sonde data are from Logan (1999), Thompson et al. (2003a) and Thompson et al. (2003b). The number of sites is given in the top right corner of each plot. The figure is adapted from Stevenson et al. (2006).

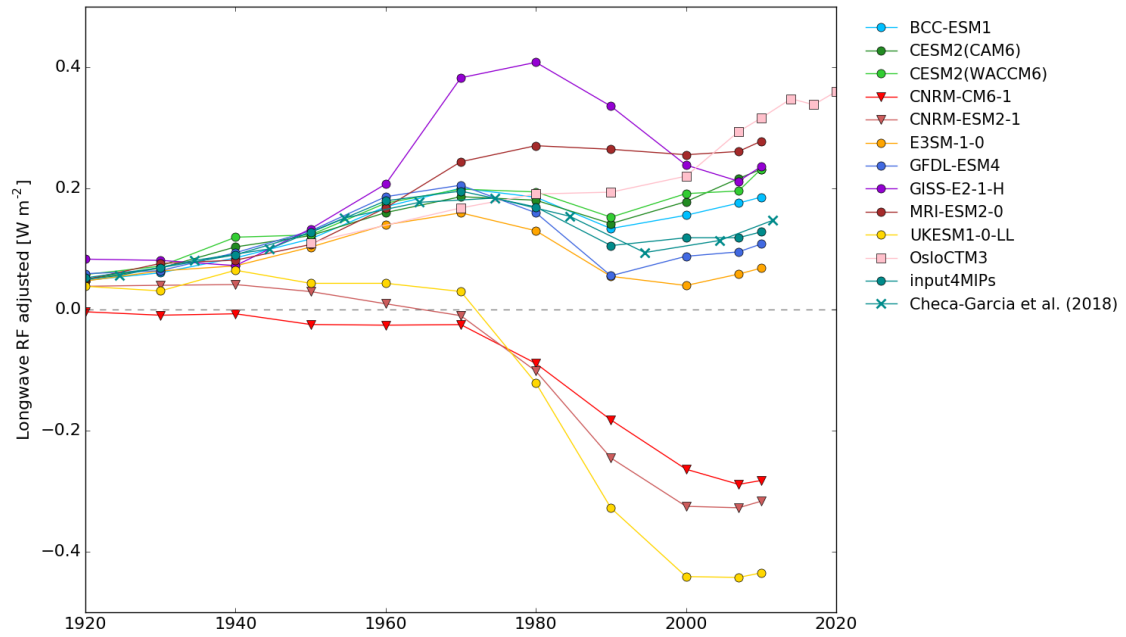


Figure 4 Longwave adjusted RF relative to 1850s calculated using the radiative kernel. Also shown in the figure is the forcing time development calculated by Checa-Garcia et al. (2018) on the input4MIPs data. Models without tropospheric chemistry are indicated with a triangle.

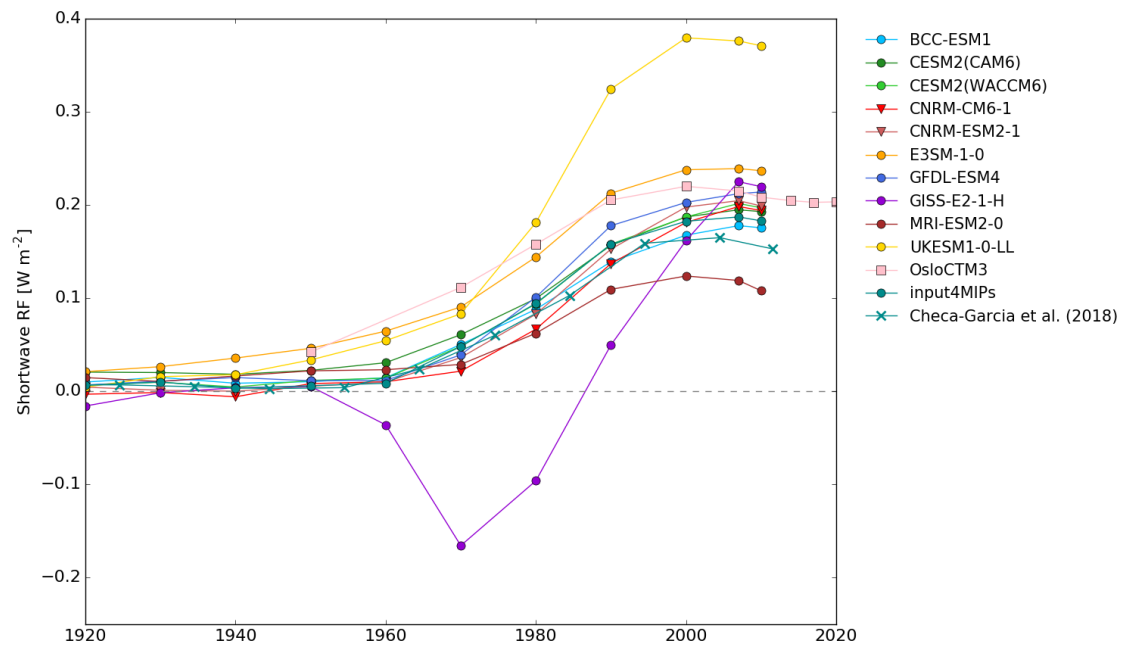


Figure 5 Short-wave RF relative to 1850s calculated using the radiative kernel. Also shown in the figure is the forcing time development calculated by Checa-Garcia et al. (2018) on the input4MIPs data. Models without tropospheric chemistry are indicated with a triangle.

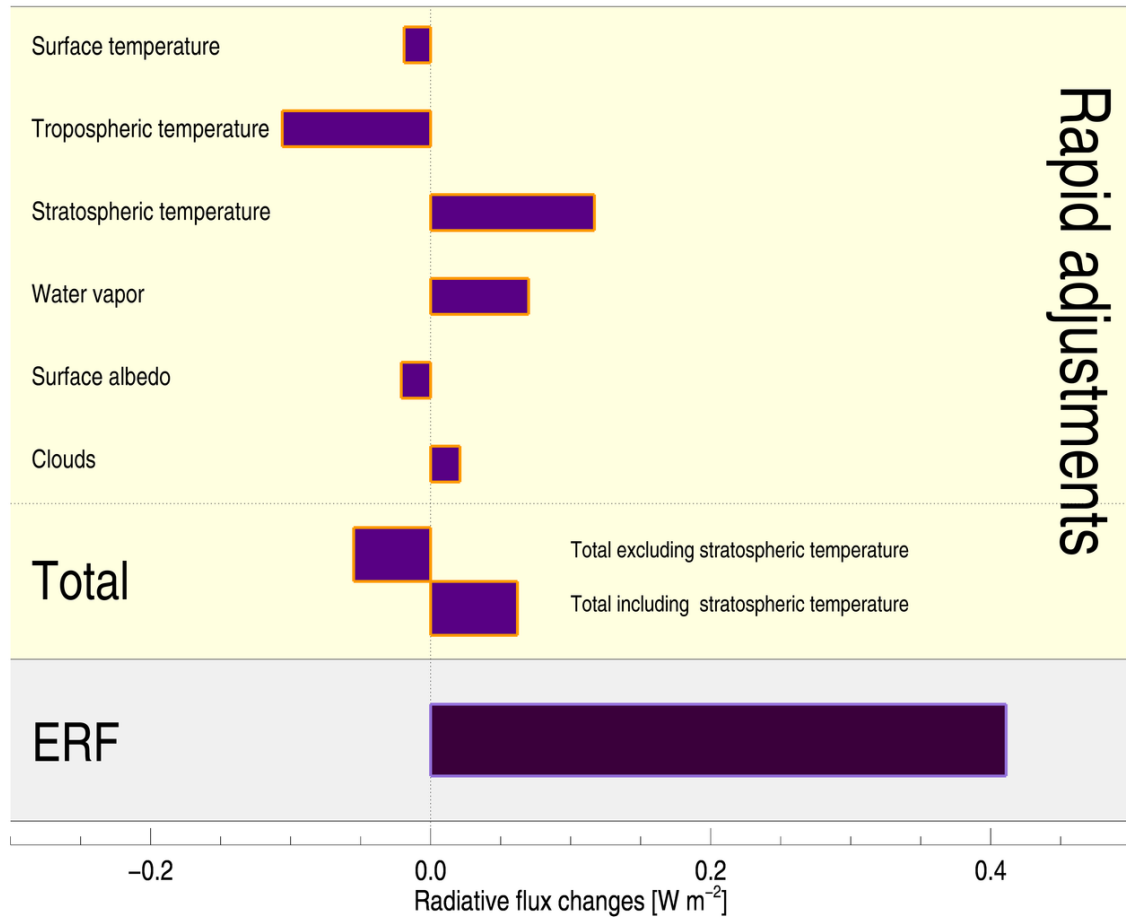


Figure 6 Effective Radiative Forcing (ERF) and rapid adjustments (total and individual terms) for industrial era ozone change (1850 to 2014) derived from GFDL-AM4 as an additional simulation using setup as in the RFMIP experiment (Pincus et al., 2016) and the two models MIROC-SPRINTARS and NorESM1 within the PDRMIP experiment (Myhre et al., 2017). Results are shown as mean of the three models. A mean of five radiative kernels, see description in Myhre et al. (2018); Smith et al. (2018), are applied in the calculations of rapid adjustments in the two PDRMIP models and off-line radiative transfer calculations in the GFDL-AM4 model. The rapid adjustment from stratospheric temperature change is taken into account in RF of ozone change. Therefore, total rapid adjustment is shown both when stratospheric temperature adjustment is excluded and included.

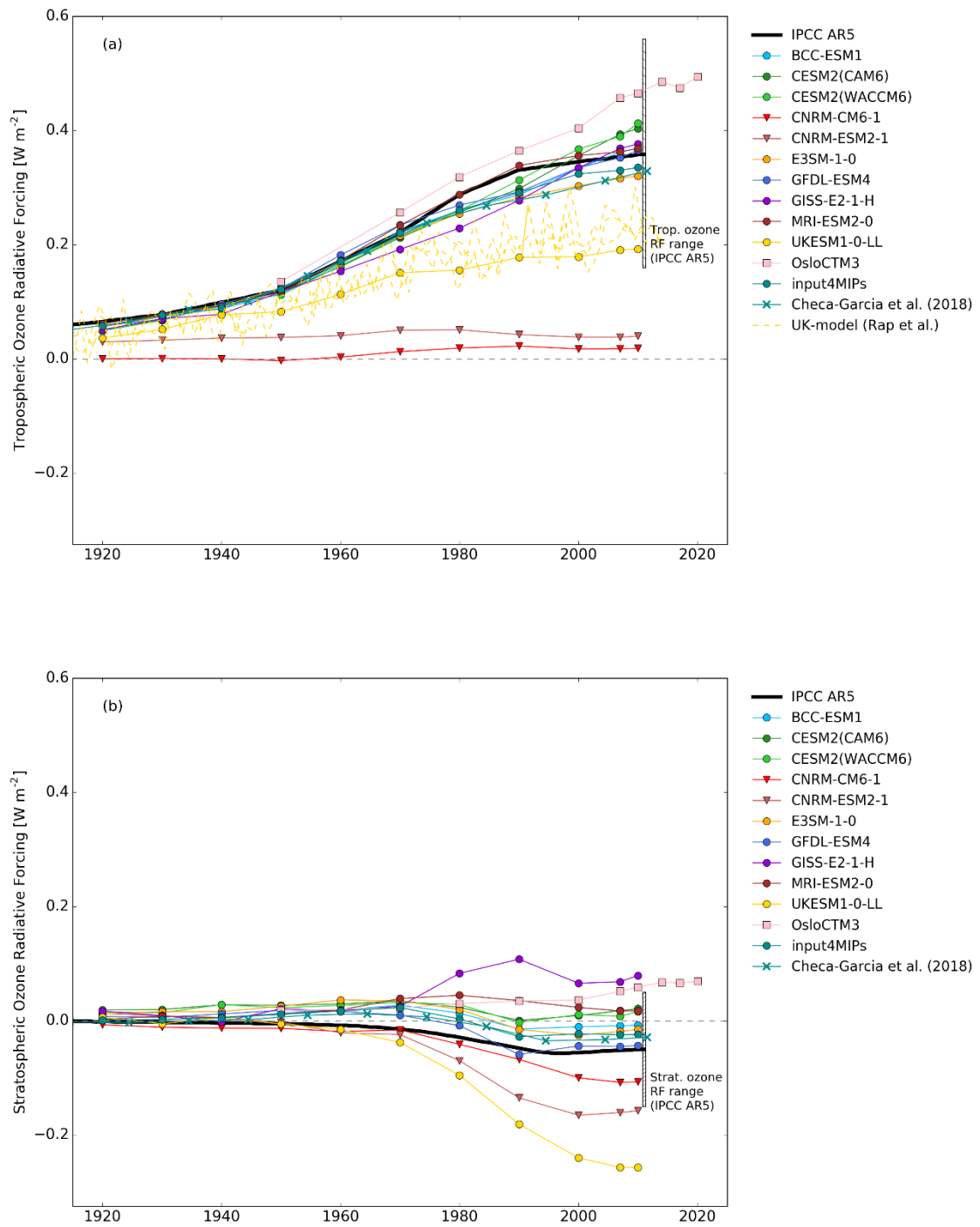


Figure 7 Tropospheric (a) and stratospheric (b) ozone RF calculated using the radiative kernel for ozone changes below and above the tropopause. Tropopause used here is where ozone mixing ratio is greater than 150 ppbv in 1850 for the individual models (similar definition as in e.g. Stevenson et al. (2006)). The results of Checa-Garcia et al. (2018) are based on a different definition of the tropopause used by Hansen et al. (2005). IPCC RF timeseries and the 90% confidence range for 2011 are adjusted to have 1850 as base period. Also shown in (a) are the tropospheric ozone RF (baseline 1850-59) for three ensemble members of the UKESM1-0-LL model using the radiative kernel by Rap et al. (2015) and the 150ppbv tropopause.

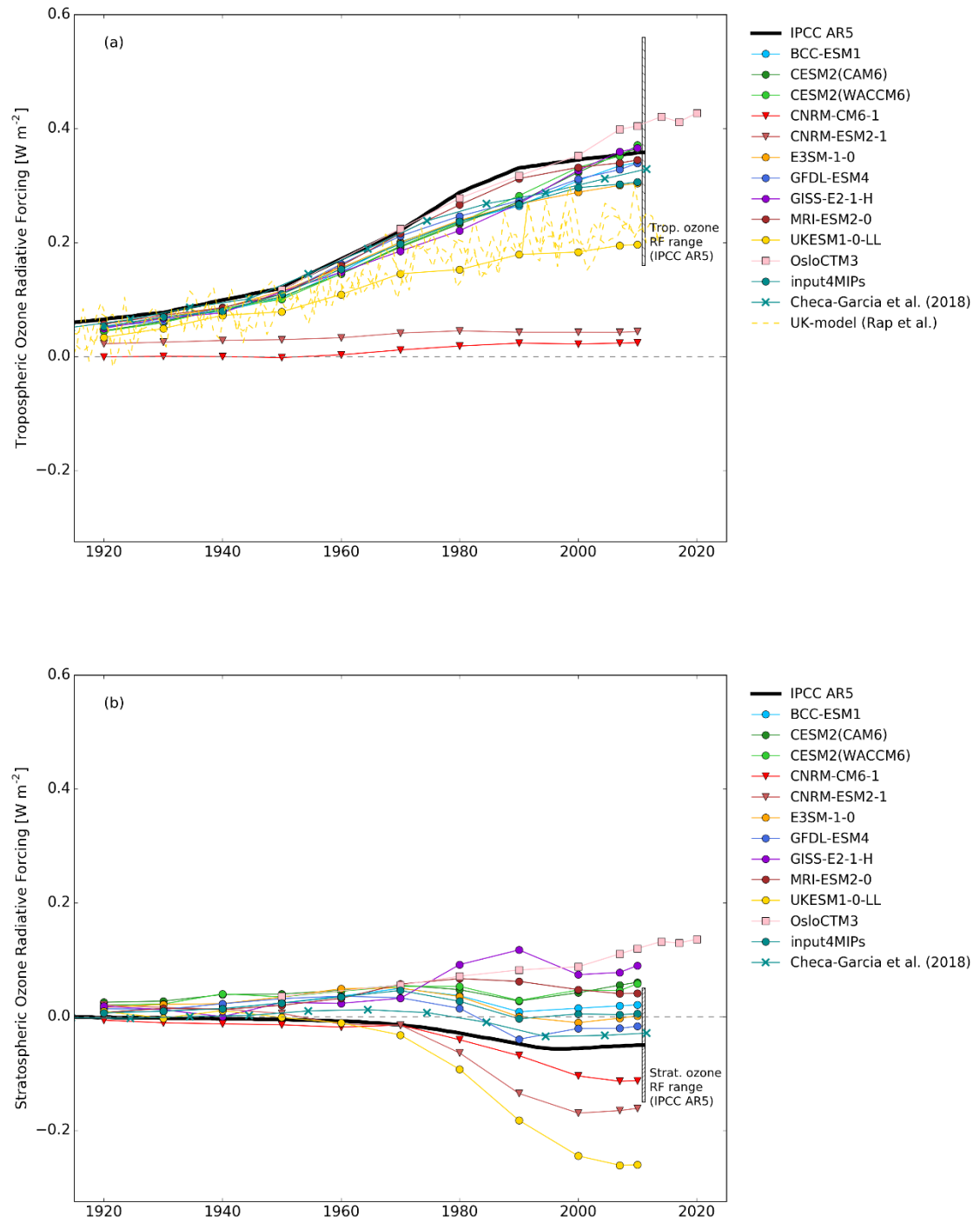


Figure 8 Similar to Fig. 7, but with a different tropopause. Tropopause used here is the tropopause of the OsloCTM3 model with year 2010 meteorology.

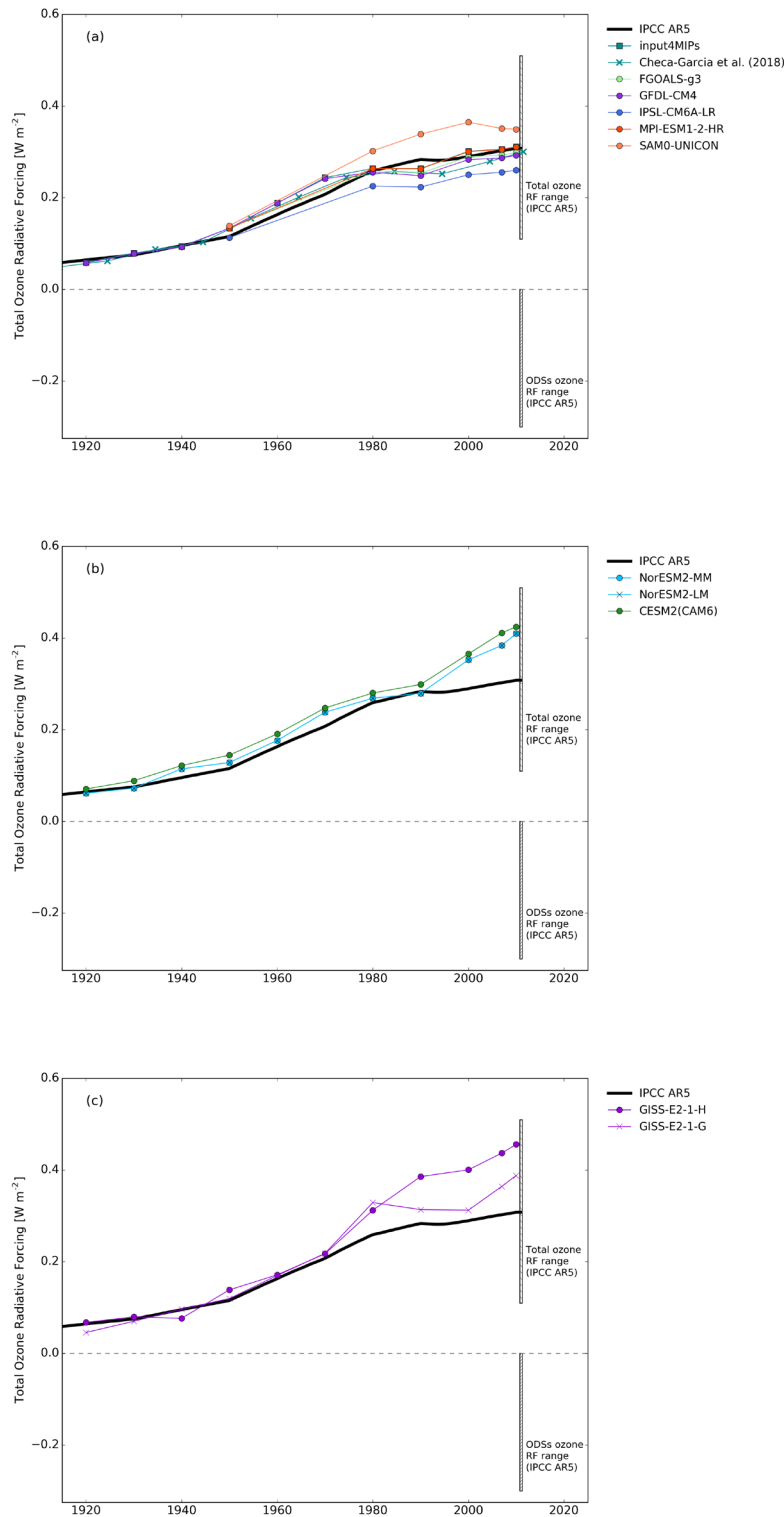


Figure 9 Same as Fig. 4, but for model results not included in this study. In a) the total ozone RF for the models using prescribed ozone fields from input4MIPs compared to the kernel results using input4MIPs ozone fields as well as Checa-Garcia et al. (2018) total ozone RF timeseries. In b), the NorESM models that use the same input fields as in CESM2(CAM6) compared to the results from CESM2(CAM6). In c) the GISS-E2-1-G model compared to the results from GISS-E2-1-H. These two models are identical, except for different ocean models. Differences in the Southern Ocean between the G and H models are likely to lead to different behavior in the stratosphere. The H model is quite consistent with temperature trends in the lower stratosphere over the past three decades based on retrievals from the Microwave Sounding Unit, whereas there is too much cooling in the G model, indicative of too much ozone loss.

Table 1: Overview of CMIP6 models and other data used in this study. This is an extended version of table 1 in the main manuscript. Indicated in the table is if the model includes a chemistry scheme in the troposphere and/or stratosphere (Y: yes, N: no, P: prescribed), ensemble member, table ID, number of vertical levels in the model as well as model top. For Amon fields, the indicated vertical levels and top level are presented for the Amon fields that are interpolated to a specified grid rather than the model levels and model top.

Model:	Institution:	Description:	Trop:	Strat:	Ensemble member:	Table ID:	Vertical resolution of model output (top level):	References:
CMIP6 models:								
BCC-ESM1	BCC	The tropospheric chemistry is MOZART2 (Horowitz et al., 2003). No stratospheric chemistry scheme, but the concentration of ozone at the top two model levels are zonally and monthly values from input4MIPs.	Y	P	r1i1p1f1	AERmon	26 (2.917 hPa)	Wu et al. (2020)
CESM2(CAM6)	NCAR	Ozone fields prescribed using results from a CESM2(WACCM6)simulation.	P	P	r1i1p1f1	AERmon	32 (3.6 hPa)	Danabasoglu et al. (2020)
CESM2(WACCM6)	NCAR	Interactive chemistry in the whole atmosphere with TSM1.1 scheme (Emmons et al., 2020) which includes VBS-SOA (Tilmes et al., 2019)	Y	Y	r1i1p1f1	AERmon	70 (6E-6 hPa)	Gettelman et al. (2019)
CNRM-CM6-1	CNRM	A simple parameterization of the ozone production rate as a linear function of the ozone mixing ratio. Monthly coefficients of the function computed using the interactive chemistry scheme of CNRM-ESM2-1. The ozone concentrations of CNRM-CM6-1 should be close to those of CNRM ESM2-1.	N	Y	r1i1p1f2	AERmon	91 (0.01 hPa)	Volodire et al. (2019), Michou et al. (2019)
CNRM-ESM2-1	CNRM	The atmospheric chemistry scheme is the Reactive Processes Ruling the Ozone Budget in the Stratosphere version 2 (REPROBUS-C_v2). No tropospheric chemistry scheme. Concentrations of O ₃ below the 560 hPa level are relaxed towards the 560 hPa value.	N	Y	r1i1p1f2	AERmon	91 (0.01 hPa)	S��f��rian et al. (2019), Michou et al. (2019)
E3SM-1-0	DOE E3SM-Project	Linearized ozone photochemistry to predict stratospheric ozone changes (Linoz v2)(Hsu and Prather, 2009). In the troposphere the ozone concentrations are prescribed using input4MIPs.	P	Y	r2i1p1f1	Amon	19 (1 hPa)	Rasch et al. (2019), Golaz et al. (2019)
GFDL-ESM4	NOAA-GFDL	Includes interactive tropospheric (Schnell et al., 2018) and stratospheric (Austin et al., 2012) gas-phase chemistry.	Y	Y	r1i1p1f1	AERmon	49 (0.02 hPa)	Dunne et al. (2019), Horowitz et al. (2019), Krasting et al. (2018)

MRI-ESM2-0	MRI	Interactive chemistry in the troposphere and middle atmosphere with the MRI Chemistry Climate Model version 2.1 (MRI-CCM2.1) model (Yukimoto et al., 2019).	Y	Y	r1i1p1f1	Amon	19 (1hPa)	Yukimoto et al. (2019)
UKESM1-0-LL	MOHC/NERC	Interactive chemistry covering troposphere and stratosphere.	Y	Y	r1i1p1f2	AERmon	85 (85 km)	Sellar et al. (2019), Archibald et al. (2020)
GISS-E2-1-H	NASA-GISS	Interactive chemistry covering troposphere and stratosphere.	Y	Y	r1i1p3f1	AERmon	40 (0.16 hPa)	Shindell et al. (2013)
Other:								
input4MIPs	University of Reading	CCMI v1.0: a merged ozone product based on WACCM1-CESM (simulation CCMI tag3) and CMAM (simulation 964). Ozone precursor emissions follow the CCMI data protocol (Eyring et al., 2013) and are based on a combination of emissions from Lamarque et al. (2010) and RCP8.5 before and after 2005, respectively.	Y	Y			66 (0.0001 hPa)	Hegglin et al. (2016)
OsloCTM3	CICERO	Chemical transport model, chemistry scheme for both stratosphere and troposphere.	Y	Y			60 (0.1 hPa)	Søvde et al. (2012)

Table 2: Total ozone RF relative to 1850 (W m^{-2}). The underlying numbers of Fig. 4.

Model number	Year	1920	1930	1940	1950	1960	1970	1980	1990	2000	2007	2010
1	BCC-ESM1	0.06	0.08	0.09	0.13	0.18	0.25	0.27	0.27	0.32	0.35	0.36
2	CESM2(CAM6)	0.07	0.09	0.12	0.14	0.19	0.25	0.28	0.30	0.37	0.41	0.42
3	CESM2(WACCM6)	0.06	0.08	0.12	0.13	0.19	0.25	0.29	0.31	0.38	0.40	0.43
4	CNRM-CM6-1	-0.01	-0.01	-0.01	-0.02	-0.02	0.00	-0.02	-0.05	-0.08	-0.09	-0.09
5	CNRM-ESM2-1	0.04	0.04	0.04	0.04	0.02	0.03	-0.02	-0.09	-0.13	-0.12	-0.12
6	E3SM-1-0	0.07	0.09	0.11	0.15	0.20	0.25	0.27	0.27	0.28	0.30	0.31
7	GFDL-ESM4	0.07	0.08	0.11	0.14	0.20	0.24	0.26	0.23	0.29	0.31	0.32
8	GISS-E2-1-H	0.07	0.08	0.08	0.14	0.17	0.22	0.31	0.39	0.40	0.44	0.46
9	MRI-ESM2-0	0.06	0.09	0.10	0.13	0.19	0.27	0.33	0.37	0.38	0.38	0.39
10	UKESM1-0-LL	0.04	0.05	0.08	0.08	0.10	0.11	0.06	0.00	-0.06	-0.07	-0.06
11	OsloCTM3				0.15		0.28	0.35	0.40	0.44	0.51	0.52
12	input4MIPs	0.06	0.08	0.09	0.13	0.19	0.24	0.26	0.26	0.30	0.31	0.31

For year 2010:

All models excluding 4 and 5:	Standard deviation: 0.16,	Mean value: 0.35,	90 % confidence interval: [0.08, 0.61]
All models excluding 4, 5 and 10:	Standard deviation: 0.07,	Mean value: 0.39,	90 % confidence interval: [0.27, 0.51]
All models excluding 2, 4, 5 and 6:	Standard deviation: 0.18,	Mean value: 0.34,	90 % confidence interval: [0.05, 0.63]
All models excluding 2, 4, 5, 6 and 12:	Standard deviation: 0.19,	Mean value: 0.34,	90 % confidence interval: [0.03, 0.66]
All models excluding 2, 4, 5, 6, 10 and 12:	Standard deviation: 0.07,	Mean value: 0.41,	90 % confidence interval: [0.29, 0.53]

Supplementary References

Archibald, A. T., O'Connor, F. M., Abraham, N. L., Archer-Nicholls, S., Chipperfield, M. P., Dalvi, M., Folberth, G. A., Dennison, F., Dhomse, S. S., Griffiths, P. T., Hardacre, C., Hewitt, A. J., Hill, R. S., Johnson, C. E., Keeble, J., Köhler, M. O., Morgenstern, O., Mulcahy, J. P., Ordóñez, C., Pope, R. J., Rumbold, S. T., Russo, M. R., Savage, N. H., Sellar, A., Stringer, M., Turnock, S. T., Wild, O., and Zeng, G.: Description and evaluation of the UKCA stratosphere–troposphere chemistry scheme (StratTrop v1.0) implemented in UKESM1, *Geosci. Model Dev.*, 13,1223-1266, 10.5194/gmd-13-1223-2020, 2020.

Austin, J., Horowitz, L. W., Schwarzkopf, M. D., Wilson, R. J., and Levy, H.: Stratospheric Ozone and Temperature Simulated from the Preindustrial Era to the Present Day, *J. Clim.*, 26,3528-3543, 10.1175/JCLI-D-12-00162.1, 2012.

Checa-Garcia, R., Hegglin, M. I., Kinnison, D., Plummer, D. A., and Shine, K. P.: Historical Tropospheric and Stratospheric Ozone Radiative Forcing Using the CMIP6 Database, *Geophys. Res. Lett.*, 45,3264-3273, doi:10.1002/2017GL076770, 2018.

Danabasoglu, G., Lamarque, J. F., Bacmeister, J., Bailey, D. A., DuVivier, A. K., Edwards, J., Emmons, L. K., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C., Holland, M. M., Large, W. G., Lauritzen, P. H., Lawrence, D. M., Lenaerts, J. T. M., Lindsay, K., Lipscomb, W. H., Mills, M. J., Neale, R., Oleson, K. W., Otto-Bliesner, B., Phillips, A. S., Sacks, W., Tilmes, S., van Kampenhout, L., Vertenstein, M., Bertini, A., Dennis, J., Deser, C., Fischer, C., Fox-Kemper, B., Kay, J. E., Kinnison, D., Kushner, P. J., Larson, V. E., Long, M. C., Mickelson, S., Moore, J. K., Nienhouse, E., Polvani, L., Rasch, P. J., and Strand, W. G.: The Community Earth System Model Version 2 (CESM2), *J. Adv. Model. Earth Syst.*, 12,e2019MS001916, 10.1029/2019MS001916, 2020.

Dunne, J. P., L. W. Horowitz, A. J. Adcroft, P. Ginoux, I. M. Held, J. G. John, J. P. Krasting, S. Malyshev, V. Naik, F. Paulot, E. Shevliakova, C. A. Stock, N. Zadeh, V. Balaji, C. Blanton, K. A. Dunne, C. Dupuis, J.

Durachta, R. Dussin, P. P. G. Gauthier, S. M. Griffies, H. Guo, R. W. Hallberg, M. Harrison, J. He, W. Hurlin, C. McHugh, R. Menzel, P. C. D. Milly, S. Nikonov, D. J. Paynter, J. Ploshay, A. Radhakrishnan, K. Rand, B. G. Reichl, T. Robinson, D. M. Schwarzkopf, L. A. Sentman, S. Underwood, H. Vahlenkamp, M. Winton, A. T. Wittenberg, B. Wyman, Y. Zeng, and Zhao, M.: (submitted) The GFDL Earth System Model version 4.1 (GFDL-ESM4.1): Model description and simulation characteristics, *J. Adv. Model. Earth Syst.*, 2019MS002008, 2019.

Emmons, L. K., Schwantes, R. H., Orlando, J. J., Tyndall, G., Kinnison, D., Lamarque, J.-F., Marsh, D., Mills, M. J., Tilmes, S., Bardeen, C., Buchholz, R. R., Conley, A., Gettelman, A., Garcia, R., Simpson, I., Blake, D. R., Meinardi, S., and Pétron, G.: The Chemistry Mechanism in the Community Earth System Model Version 2 (CESM2), *J. Adv. Model. Earth Syst.*, 12,e2019MS001882, 10.1029/2019MS001882, 2020.

Eyring, V., J.-F. Lamarque, P. Hess, F. Arfeuille, K. Bowman, M. P. Chipperfield, B. Duncan, A. Fiore, A. Gettelman, M. A. Giorgetta, C. Granier, M. Hegglin, D. Kinnison, M. Kunze, U. Langematz, B. Luo, R. Martin, K. Matthes, P. A. Newman, T. Peter, A. Robock, T. Ryerson, A. Saiz-Lopez, R. Salawitch, M. Schultz, T. G. Shepherd, D. Shindell, J. Stähelin, S. Tegtmeier, L. Thomason, S. Tilmes, J.-P. Vernier, Waugh, D. W., and Young, P. J.: Overview of IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) Community Simulations in Support of Upcoming Ozone and Climate Assessments, http://www.sparc-climate.org/fileadmin/customer/6_Publications/Newsletter_PDF/40_SPARCnewsletter_Jan2013_web.pdf, SPARC Newsletter 40,48-66, 2013.

Gettelman, A., Mills, M. J., Kinnison, D. E., Garcia, R. R., Smith, A. K., Marsh, D. R., Tilmes, S., Vitt, F., Bardeen, C. G., McInerney, J., Liu, H. L., Solomon, S. C., Polvani, L. M., Emmons, L. K., Lamarque, J. F., Richter, J. H., Glanville, A. S., Bacmeister, J. T., Phillips, A. S., Neale, R. B., Simpson, I. R., DuVivier, A. K., Hodzic, A., and Randel, W. J.: The Whole Atmosphere Community Climate Model Version 6 (WACCM6), *J. Geophys. Res.*, 124,12380– 12403, 10.1029/2019JD030943, 2019.

Golaz, J.-C., Caldwell, P. M., Van Roekel, L. P., Petersen, M. R., Tang, Q., Wolfe, J. D., Abeshu, G., Anantharaj, V., Asay-Davis, X. S., Bader, D. C., Baldwin, S. A., Bisht, G., Bogenschutz, P. A., Branstetter, M., Brunke, M. A., Brus, S. R., Burrows, S. M., Cameron-Smith, P. J., Donahue, A. S., Deakin, M., Easter, R. C., Evans, K. J., Feng, Y., Flanner, M., Foucar, J. G., Fyke, J. G., Griffin, B. M., Hannay, C., Harrop, B. E., Hoffman, M. J., Hunke, E. C., Jacob, R. L., Jacobsen, D. W., Jeffery, N., Jones, P. W., Keen, N. D., Klein, S. A., Larson, V. E., Leung, L. R., Li, H.-Y., Lin, W., Lipscomb, W. H., Ma, P.-L., Mahajan, S., Maltrud, M. E., Mametjanov, A., McClean, J. L., McCoy, R. B., Neale, R. B., Price, S. F., Qian, Y., Rasch, P. J., Reeves Eyre, J. E. J., Riley, W. J., Ringler, T. D., Roberts, A. F., Roesler, E. L., Salinger, A. G., Shaheen, Z., Shi, X., Singh, B., Tang, J., Taylor, M. A., Thornton, P. E., Turner, A. K., Veneziani, M., Wan, H., Wang, H., Wang, S., Williams, D. N., Wolfram, P. J., Worley, P. H., Xie, S., Yang, Y., Yoon, J.-H., Zelinka, M. D., Zender, C. S., Zeng, X., Zhang, C., Zhang, K., Zhang, Y., Zheng, X., Zhou, T., and Zhu, Q.: The DOE E3SM Coupled Model Version 1: Overview and Evaluation at Standard Resolution, *J. Adv. Model. Earth Syst.*, 11,2089-2129, 10.1029/2018MS001603, 2019.

Hansen, J., Sato, M., Ruedy, R., Nazarenko, L., Lacis, A., Schmidt, G. A., Russell, G., Aleinov, I., Bauer, M., Bauer, S., Bell, N., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Del Genio, A., Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, C., Kelley, M., Kiang, N., Koch, D., Lean, J., Lerner, J., Lo, K., Menon, S., Miller, R., Minnis, P., Novakov, T., Oinas, V., Perlwitz, J., Rind, D., Romanou, A., Shindell, D., Stone, P., Sun, S., Tausnev, N., Thresher, D., Wielicki, B., Wong, T., Yao, M., and Zhang, S.: Efficacy of climate forcings, *J. Geophys. Res.*, 110,D18104, 10.1029/2005JD005776 2005.

Hegglin, M. I., D. Kinnison, J.-F. Lamarque, and Plummer, D. CCMI ozone in support of CMIP6 - version 1.0,<http://dx.doi.org/10.22033/ESGF/INPUT4MIPS.1115> (2016).

Horowitz, L. W., Walters, S., Mauzerall, D. L., Emmons, L. K., Rasch, P. J., Granier, C., Tie, X., Lamarque, J.-F., Schultz, M. G., Tyndall, G. S., Orlando, J. J., and Brasseur, G. P.: A global simulation of tropospheric ozone and related tracers: Description and evaluation of MOZART, version 2, *J. Geophys. Res.*, 108, 10.1029/2002JD002853, 2003.

Horowitz, L. W., V, N., F. Paulot, P. A. Ginoux, J. P. Dunne, J. Mao, J. Schnell, Xi Chen, M. Lin, P. Lin, S. Malyshev, D. Paynter, E. Shevliakova, and Zhao, M.: (submitted) The GFDL Global Atmospheric Chemistry-Climate Model AM4.1: Model Description and Simulation Characteristics, *J. Adv. Model. Earth Syst.*, 2019.

Hsu, J., and Prather, M. J.: Stratospheric variability and tropospheric ozone, *J. Geophys. Res.*, 114, 10.1029/2008JD010942, 2009.

Krasting, J. P., John, J. G., Blanton, C., McHugh, C., Nikonov, S., Radhakrishnan, A., Rand, K., Zadeh, N. T., Balaji, V., Durachta, J., Dupuis, C., Menzel, R., Robinson, T., Underwood, S., Vahlenkamp, H., Dunne, K. A., Gauthier, P. P. G., Ginoux, P., Griffies, S. M., Hallberg, R., Harrison, M., Hurlin, W., Malyshev, S., Naik, V., Paulot, F., Paynter, D. J., Ploshay, J., Schwarzkopf, D. M., Seman, C. J., Silvers, L., Wyman, B., Zeng, Y., Adcroft, A., Dunne, J. P., Guo, H., Held, I. M., Horowitz, L. W., Milly, P. C. D., Shevliakova, E., Stock, C., Winton, M., and Zhao, M. NOAA-GFDL GFDL-ESM4 model output prepared for CMIP6 CMIP,10.22033/ESGF/CMIP6.1407 (2018).

Lamarque, J. F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., and van Vuuren, D. P.: Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, *Atmos. Chem. Phys.*, 10,7017–7039, 10.5194/acp-10-7017-2010, 2010.

Logan, J. A.: An analysis of ozonesonde data for the troposphere: Recommendations for testing 3-D models and development of a gridded climatology for tropospheric ozone, *J. Geophys. Res.*, 104,16115–16149, 1999.

Michou, M., Nabat, P., Saint-Martin, D., Bock, J., Decharme, B., Mallet, M., Roehrig, R., Séférian, R., Sénéci, S., and Voldoire, A.: Present-day and historical aerosol and ozone characteristics in CNRM CMIP6 simulations, *J. Adv. Model. Earth Syst.*, 12, 10.1029/2019MS001816, 2019.

Myhre, G., Forster, P. M., Samset, B. H., Hodnebrog, Ø., Sillmann, J., Aalberg, S. G., Andrews, T., Boucher, O., Faluvegi, G., Fläschner, D., Iversen, T., Kasoar, M., Kharin, V., Kirkevåg, A., Lamarque, J.-F., Olivié, D., Richardson, T. B., Shindell, D., Shine, K. P., Stjern, C. W., Takemura, T., Voulgarakis, A., and Zwiers, F.: PDRMIP: A Precipitation Driver and Response Model Intercomparison Project—Protocol and Preliminary Results, *Bull. Am. Meteorol. Soc.*, 98,1185–1198, 10.1175/bams-d-16-0019.1, 2017.

Myhre, G., Kramer, R. J., Smith, C. J., Hodnebrog, Ø., Forster, P., Soden, B. J., Samset, B. H., Stjern, C. W., Andrews, T., Boucher, O., Faluvegi, G., Fläschner, D., Kasoar, M., Kirkevåg, A., Lamarque, J.-F., Olivié, D., Richardson, T., Shindell, D., Stier, P., Takemura, T., Voulgarakis, A., and Watson-Parris, D.: Quantifying the Importance of Rapid Adjustments for Global Precipitation Changes, *Geophys. Res. Lett.*, 45,11,399–311,405, doi:10.1029/2018GL079474, 2018.

Pincus, R., Forster, P. M., and Stevens, B.: The Radiative Forcing Model Intercomparison Project (RFMIP): experimental protocol for CMIP6, *Geosci. Model Dev.*, 9,3447–3460, 10.5194/gmd-9-3447-2016, 2016.

Rap, A., Richards, N. A. D., Forster, P. M., Monks, S. A., Arnold, S. R., and Chipperfield, M. P.: Satellite constraint on the tropospheric ozone radiative effect, *Geophys. Res. Lett.*, 42,5074-5081, 10.1002/2015GL064037, 2015.

Rasch, P. J., Xie, S., Ma, P. L., Lin, W., Wang, H., Tang, Q., Burrows, S. M., Caldwell, P., Zhang, K., Easter, R. C., Cameron-Smith, P., Singh, B., Wan, H., Golaz, J. C., Harrop, B. E., Roesler, E., Bacmeister, J., Larson, V. E., Evans, K. J., Qian, Y., Taylor, M., Leung, L. R., Zhang, Y., Brent, L., Branstetter, M., Hannay, C., Mahajan, S., Mametjanov, A., Neale, R., Richter, J. H., Yoon, J. H., Zender, C. S., Bader, D., Flanner, M., Foucar, J. G., Jacob, R., Keen, N., Klein, S. A., Liu, X., Salinger, A. G., Shrivastava, M., and Yang, Y.: An Overview of the Atmospheric Component of the Energy Exascale Earth System Model, *J. Adv. Model. Earth Syst.*, 11,2377-2411, 10.1029/2019MS001629, 2019.

Schnell, J. L., Naik, V., Horowitz, L. W., Paulot, F., Mao, J., Ginoux, P., Zhao, M., and Ram, K.: Exploring the relationship between surface PM_{2.5} and meteorology in Northern India, *Atmos. Chem. Phys.*, 18,10157-10175, 10.5194/acp-18-10157-2018, 2018.

Séférian, R., Nabat, P., Michou, M., Saint-Martin, D., Voltaire, A., Colin, J., Decharme, B., Delire, C., Berthet, S., Chevallier, M., Sénéci, S., Franchisteguy, L., Vial, J., Mallet, M., Joetzjer, E., Geoffroy, O., Guérémy, J. F., Moine, M. P., Msadek, R., Ribes, A., Rocher, M., Roehrig, R., Salas-y-Méla, D., Sanchez, E., Terray, L., Valcke, S., Waldman, R., Aumont, O., Bopp, L., Deshayes, J., Éthé, C., and Madec, G.: Evaluation of CNRM Earth-System model, CNRM-ESM 2-1: role of Earth system processes in present-day and future climate, *J. Adv. Model. Earth Syst.*, 11,4182– 4227, 10.1029/2019MS001791, 2019.

Sellar, A. A., Jones, C. G., Mulcahy, J., Tang, Y., Yool, A., Wiltshire, A., O'Connor, F. M., Stringer, M., Hill, R., Palmieri, J., Woodward, S., de Mora, L., Kuhlbrodt, T., Rumbold, S., Kelley, D. I., Ellis, R., Johnson, C. E., Walton, J., Abraham, N. L., Andrews, M. B., Andrews, T., Archibald, A. T., Berthou, S., Burke, E., Blockley, E., Carslaw, K., Dalvi, M., Edwards, J., Folberth, G. A., Gedney, N., Griffiths, P. T., Harper, A. B., Hendry, M. A., Hewitt, A. J., Johnson, B., Jones, A., Jones, C. D., Keeble, J., Liddicoat, S., Morgenstern, O., Parker, R. J., Predoi, V., Robertson, E., Siahann, A., Smith, R. S., Swaminathan, R., Woodhouse, M. T., Zeng, G., and Zerroukat, M.: UKESM1: Description and evaluation of the UK Earth System Model, *J. Adv. Model. Earth Syst.*, 11,4513– 4558, 10.1029/2019MS001739, 2019.

Shindell, D. T., Pechony, O., Voulgarakis, A., Faluvegi, G., Nazarenko, L., Lamarque, J. F., Bowman, K., Milly, G., Kovari, B., Ruedy, R., and Schmidt, G. A.: Interactive ozone and methane chemistry in GISS-E2 historical and future climate simulations, *Atmos. Chem. Phys.*, 13,2653-2689, 10.5194/acp-13-2653-2013, 2013.

Smith, C. J., Kramer, R. J., Myhre, G., Forster, P. M., Soden, B. J., Andrews, T., Boucher, O., Faluvegi, G., Fläschner, D., Hodnebrog, Ø., Kassoar, M., Kharin, V., Kirkevåg, A., Lamarque, J.-F., Mülmenstädt, J., Olivié, D., Richardson, T., Samset, B. H., Shindell, D., Stier, P., Takemura, T., Voulgarakis, A., and Watson-Parris, D.: Understanding Rapid Adjustments to Diverse Forcing Agents, *Geophys. Res. Lett.*, 45,12,023-012,031, 10.1029/2018gl079826, 2018.

Stevenson, D. S., Dentener, F. J., Schultz, M. G., Ellingsen, K., van Noije, T. P. C., Wild, O., Zeng, G., Amann, M., Atherton, C. S., Bell, N., Bergmann, D. J., Bey, I., Butler, T., Cofala, J., Collins, W. J., Derwent, R. G., Doherty, R. M., Drevet, J., Eskes, H. J., Fiore, A. M., Gauss, M., Hauglustaine, D. A., Horowitz, L. W., Isaksen, I. S. A., Krol, M. C., Lamarque, J. F., Lawrence, M. G., Montanaro, V., Muller, J. F., Pitari, G., Prather, M. J., Pyle, J. A., Rast, S., Rodriguez, J. M., Sanderson, M. G., Savage, N. H., Shindell, D. T., Strahan, S. E., Sudo, K., and Szopa, S.: Multimodel ensemble simulations of present-day and near-future tropospheric ozone, *J. Geophys. Res.*, 111,D08301, 10.1029/2005JD006338, 2006.

Søvde, O. A., Prather, M. J., Isaksen, I. S. A., Berntsen, T. K., Stordal, F., Zhu, X., Holmes, C. D., and Hsu, J.: The chemical transport model Oslo CTM3, *Geosci. Model Dev.*, 5,1441-1469, 10.5194/gmd-5-1441-2012, 2012.

Thompson, A. M., Witte, J. C., McPeters, R. D., Oltmans, S. J., Schmidlin, F. J., Logan, J. A., Fujiwara, M., Kirchhoff, V., Posny, F., Coetzee, G. J. R., Hoegger, B., Kawakami, S., Ogawa, T., Johnson, B. J., Vomel, H., and Labow, G.: Southern Hemisphere Additional Ozonesondes (SHADOZ) 1998-2000 tropical ozone climatology - 1. Comparison with Total Ozone Mapping Spectrometer (TOMS) and ground-based measurements, *J. Geophys. Res.*, 108,8238, 10.1029/2001jd000967, 2003a.

Thompson, A. M., Witte, J. C., Oltmans, S. J., Schmidlin, F. J., Logan, J. A., Fujiwara, M., Kirchhoff, V., Posny, F., Coetzee, G. J. R., Hoegger, B., Kawakami, S. J., Ogawa, T., Fortuin, J. P. F., and Kelder, H. M.: Southern Hemisphere Additional Ozonesondes (SHADOZ) 1998-2000 tropical ozone climatology - 2. Tropospheric variability and the zonal wave-one, *J. Geophys. Res.*, 108,8241, 10.1029/2002jd002241, 2003b.

Tilmes, S., Hodzic, A., Emmons, L. K., Mills, M. J., Gettelman, A., Kinnison, D. E., Park, M., Lamarque, J. F., Vitt, F., Shrivastava, M., Campuzano-Jost, P., Jimenez, J. L., and Liu, X.: Climate Forcing and Trends of Organic Aerosols in the Community Earth System Model (CESM2), *J. Adv. Model. Earth Syst.*, 11,4323– 4351, 10.1029/2019MS001827, 2019.

Voldoire, A., Saint-Martin, D., Sénési, S., Decharme, B., Alias, A., Chevallier, M., Colin, J., Guérémy, J. F., Michou, M., Moine, M. P., Nabat, P., Roehrig, R., Salas y Mélia, D., Séférian, R., Valcke, S., Beau, I., Belamari, S., Berthet, S., Cassou, C., Cattiaux, J., Deshayes, J., Douville, H., Ethé, C., Franchistéguy, L., Geoffroy, O., Lévy, C., Madec, G., Meurdesoif, Y., Msadek, R., Ribes, A., Sanchez-Gomez, E., Terray, L., and Waldman, R.: Evaluation of CMIP6 DECK Experiments With CNRM-CM6-1, *J. Adv. Model. Earth Syst.*, 11,2177-2213, 10.1029/2019MS001683, 2019.

Wu, T., Zhang, F., Zhang, J., Jie, W., Zhang, Y., Wu, F., Li, L., Yan, J., Liu, X., Lu, X., Tan, H., Zhang, L., Wang, J., and Hu, A.: Beijing Climate Center Earth System Model version 1 (BCC-ESM1): model description and evaluation of aerosol simulations, *Geosci. Model Dev.*, 13,977-1005, 10.5194/gmd-13-977-2020, 2020.

Yukimoto, S., Kawai, H., Koshiro, T., Oshima, N., Yoshida, K., Urakawa, S., Tsujino, H., Deushi, M., Tanaka, T., Hosaka, M., Yabu, S., Yoshimura, H., Shindo, E., Mizuta, R., Obata, A., Adachi, Y., and Ishii, M.: The Meteorological Research Institute Earth System Model Version 2.0, MRI-ESM2.0: Description and Basic Evaluation of the Physical Component, *Journal of the Meteorological Society of Japan. Ser. II*, 97,931-965, 10.2151/jmsj.2019-051, 2019.