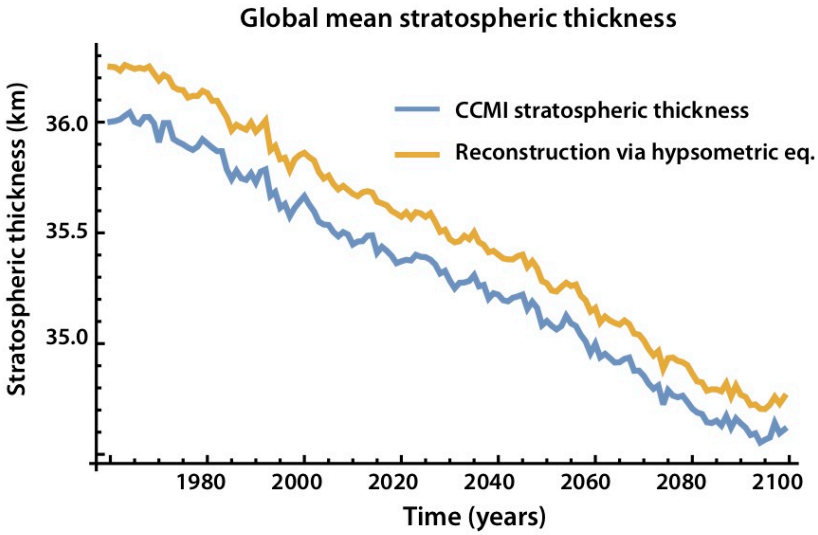
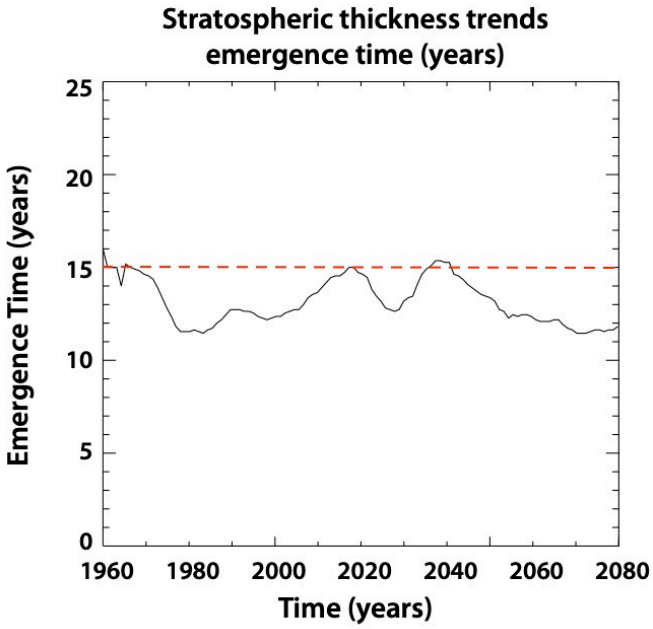
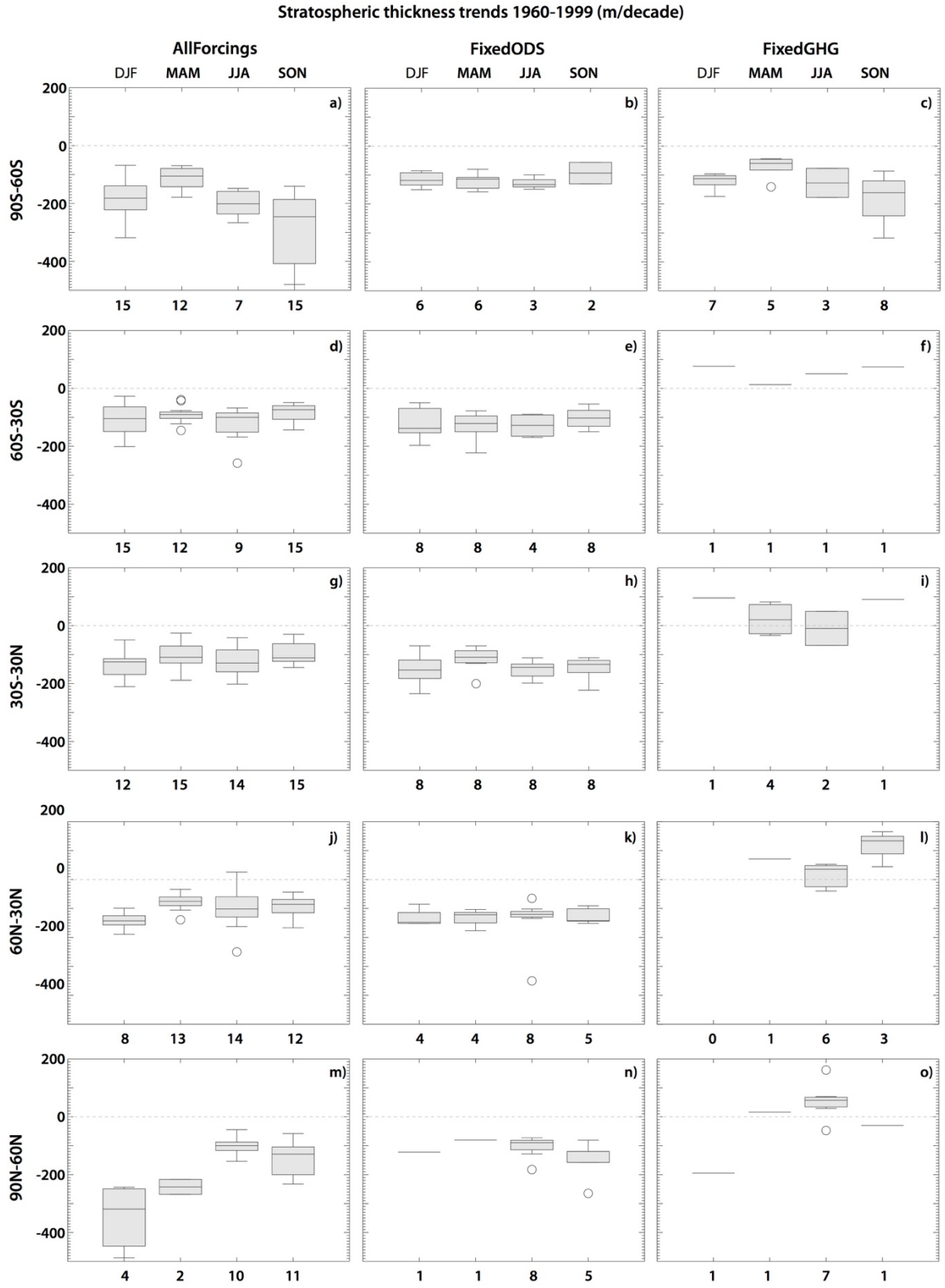
Supplementary material



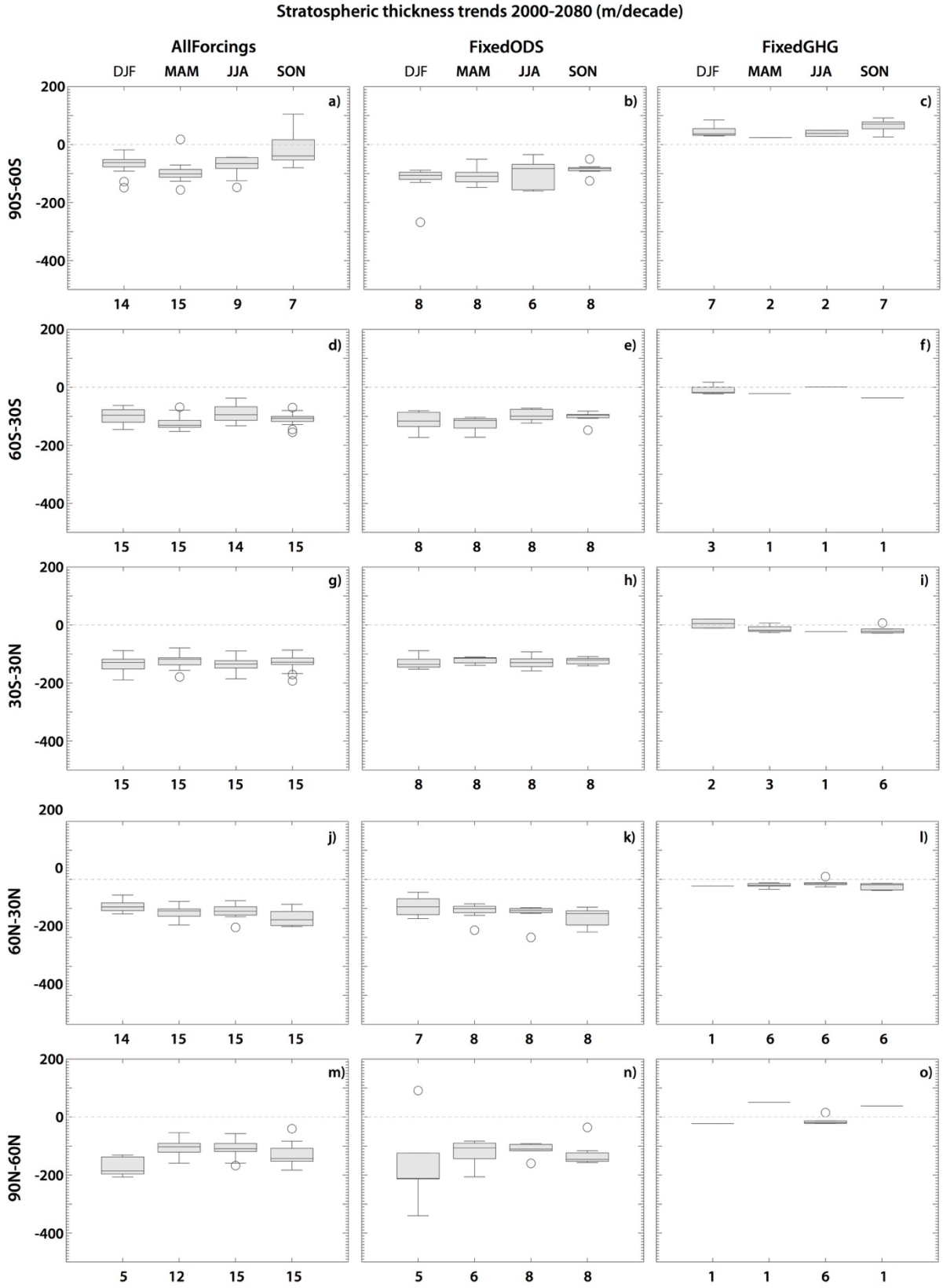
Supplemental Figure 1. Global mean stratospheric thickness as diagnosed using CCMI ensemble in comparison with the hypsometric equation estimate.



Supplemental Figure 2. Evolution of the minimum length of the stratospheric thickness time series in years to detect a statistically significant trend. Calculated for AllForcings simulations.



Supplemental Figure 3. Trends (m/decade) of the stratospheric thickness for the 1960-1999 period and various latitudinal belts, seasons, and scenarios. The open circles mark the outliers (defined as exceeding 1.5 times the inter-quartile range). The numbers on the x axis denote the number of models included (i.e., models with significant trends).



Supplemental Figure 4. Trends (m/decade) of the stratospheric thickness for the 2000-2080 period and various latitudinal belts, seasons, and scenarios. The open circles mark the outliers (defined as exceeding 1.5 times the inter- quartile range). The numbers on the x axis denote the number of models included (i.e., models with significant trends).

Model/Experiment	AllForcings	FixedGHG	FixedODS	Reference(s)
ACCESS-CCM	X	X	X	(Morgenstern *et al.*, 2009; Morgenstern *et al.*, 2013)
CCSRNIES- MIROC3.2	X	X	X	(Akiyoshi *et al.*, 2016; Imai *et al.*, 2013)
CESM1-WACCM	X	X	X	(Garcia *et al.*, 2017; Marsh *et al.*, 2013; Solomon *et al.*, 2015)
CMAM	X	X	X	(Jonsson *et al.*, 2004; Scinocca *et al.*, 2008)
CNRM-CM5-3	X			(Michou *et al.*, 2011; Voldoire *et al.*, 2013)
EMAC-L47MA	X			(Jockel *et al.*, 2010; Jockel *et al.*, 2016)
EMAC-L90MA	X	X		(Jockel *et al.*, 2010; Jockel *et al.*, 2016)
GEOSCCM	X			(Molod *et al.*, 2015; Molod *et al.*, 2012; Oman *et al.*, 2013; Oman *et al.*, 2011)
HadGEM3-ES	X			(Madec, 2008; Walters *et al.*, 2014)
MRI-ESM1r1	X			(Deushi and Shibata, 2011; Yukimoto *et al.*, 2012)
NIWA-UKCA	X	X	X	(Stone *et al.*, 2016)
SOCOL3	X			(Revell *et al.*, 2015; Stenke *et al.*, 2013)
UMUKCA-UCAM	X			(Morgenstern *et al.*, 2009; Bednarz *et al.*, 2016)
UMSLIMCAT	X		X	(Tian and Chipperfield, 2005)

Supplemental Table 1. List of the experiments performed by individual CCMI models, which have been included in the analysis of the stratospheric contraction. Full information about model specific references can be found in Morgenstern *et al.* (2017).

Contribution by changes in	1960-1999 (refC2/FixedODS/FixedGHG) %	2000-2080 (refC2/FixedODS/FixedGHG) %
Stratospheric temperature	83.7 / 57.5 / 237.1	52.7 / 58.3 / -314.9
Tropopause pressure	36.9 / 20.4 / 209.3	25.9 / 37.1 / -313.4
Stratopause pressure	-20.6 / 22.1 / -345.4	21.4 / 4.7 / 722.6

Supplemental Table 2. Contributions to the stratospheric contraction in %. Contribution of changes in stratospheric temperature, tropopause pressure, and stratopause pressure to the change in stratospheric thickness (derived from the hypsometric equation) expressed as % over the corresponding time period for the AllForcings, FixedODS, and FixedGHG simulations.

Supplementary references

Akiyoshi H, Nakamura T, Miyasaka T, Shiotani M and Suzuki M 2016 A nudged chemistry-climate model simulation of chemical constituent distribution at northern high-latitude stratosphere observed by SMILES and MLS during the 2009/2010 stratospheric sudden warming *Journal of Geophysical Research-Atmospheres* **121** 1361-80

Bednarz E M, Maycock A C, Abraham N L, Braesicke P, Dessens O and Pyle J A 2016 Future Arctic ozone recovery: the importance of chemistry and dynamics *Atmospheric Chemistry and Physics* **16** 12159-76

Deushi M and Shibata K 2011 Development of a Meteorological Research Institute chemistry-climate model version 2 for the study of tropospheric and stratospheric chemistry *Papers in Meteorology and Geophysics* **62** 1-46

Garcia R R, Smith A K, Kinnison D E, de la Camara A and Murphy D J 2017 Modification of the Gravity Wave Parameterization in the Whole Atmosphere Community Climate Model: Motivation and Results *Journal of the Atmospheric Sciences* **74** 275-91

Imai K, Manago N, Mitsuda C, Naito Y, Nishimoto E, Sakazaki T, Fujiwara M, Froidevaux L, von Clarmann T, Stiller G P, Murtagh D P, Rong P P, Mlynczak M G, Walker K A, Kinnison D E, Akiyoshi H, Nakamura T, Miyasaka T, Nishibori T, Mizobuchi S, Kikuchi K, Ozeki H, Takahashi C, Hayashi H, Sano T, Suzuki M, Takayanagi M and Shiotani M 2013 Validation of ozone data from the Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) *Journal of Geophysical Research-Atmospheres* **118** 5750-69

Jockel P, Kerkweg A, Pozzer A, Sander R, Tost H, Riede H, Baumgaertner A, Gromov S and Kern B 2010 Development cycle 2 of the Modular Earth Submodel System (MESSy2) *Geoscientific Model Development* **3** 717-52

Jockel P, Tost H, Pozzer A, Kunze M, Kirner O, Brenninkmeijer C A M, Brinkop S, Cai D S, Dyroff C, Eckstein J, Frank F, Garny H, Gottschaldt K D, Graf P, Grewe V, Kerkweg A, Kern B, Matthes S, Mertens M, Meul S, Neumaier M, Nutzel M, Oberlander-Hayn S, Ruhnke R, Runde T, Sander R, Scharffe D and Zahn A 2016 Earth System Chemistry integrated Modelling (ESCiMo) with the Modular Earth Submodel System (MESSy) version 2.51 *Geoscientific Model Development* **9** 1153-200

Jonsson A I, de Grandpre J, Fomichev V I, McConnell J C and Beagley S R 2004 Doubled CO2-induced cooling in the middle atmosphere: Photochemical analysis of the ozone radiative feedback *Journal of Geophysical Research-Atmospheres* **109**

Madec G 2008 NEMO ocean engine. Institut Pierre-Simon Laplace (IPSL), Paris)

Marsh D R, Mills M J, Kinnison D E, Lamarque J F, Calvo N and Polvani L M 2013 Climate Change from 1850 to 2005 Simulated in CESM1(WACCM) *Journal of Climate* **26** 7372-91

Michou M, Saint-Martin D, Teyssedre H, Alias A, Karcher F, Olivie D, Voldoire A, Josse B, Peuch V H, Clark H, Lee J N and Cheroux F 2011 A new version of the CNRM Chemistry-Climate Model, CNRM-CCM: description and improvements from the CCMVal-2 simulations *Geoscientific Model Development* **4** 873-900

Molod A, Takacs L, Suarez M and Bacmeister J 2015 Development of the GEOS-5 atmospheric general circulation model: evolution from MERRA to MERRA2 *Geoscientific Model Development* **8** 1339-56

Molod A, Takacs L, Suarez M, Bacmeister J x, Song I and Eichmann A 2012 The GEOS-5 Atmospheric General Circulation Model: Mean Climate and Development from MERRA to Fortuna. In: *Technical Report Series on Global Modeling and Data Assimilation,* p 124

Morgenstern O, Braesicke P, O'Connor F M, Bushell A C, Johnson C E, Osprey S M and Pyle J A 2009 Evaluation of the new UKCA climate-composition model - Part 1: The stratosphere *Geoscientific Model Development* **2** 43-57

Morgenstern O, Hegglin M I, Rozanov E, O'Connor F M, Abraham N L, Akiyoshi H, Archibald A T, Bekki S, Butchart N, Chipperfield M P, Deushi M, Dhomse S S, Garcia R R, Hardiman S C, Horowitz L W, Jockel P, Josse B, Kinnison D, Lin M Y, Mancini E, Manyin M E, Marchand M, Marecal V, Michou M, Oman L D, Pitari G, Plummer D A, Revell L E, Saint-Martin D, Schofield R, Stenke A, Stone K, Sudo K, Tanaka T Y, Tilmes S, Yamashita Y, Yoshida K and Zeng G 2017 Review of the global models used within phase 1 of the Chemistry-Climate Model Initiative (CCMI) *Geoscientific Model Development* **10** 639-71

Morgenstern O, Zeng G, Abraham N L, Telford P J, Braesicke P, Pyle J A, Hardiman S C, O'Connor F M and Johnson C E 2013 Impacts of climate change, ozone recovery, and increasing methane on surface ozone and the tropospheric oxidizing capacity *Journal of Geophysical Research-Atmospheres* **118** 1028-41

Oman L D, Douglass A R, Ziemke J R, Rodriguez J M, Waugh D W and Nielsen J E 2013 The ozone response to ENSO in Aura satellite measurements and a chemistry-climate simulation *Journal of Geophysical Research-Atmospheres* **118** 965-76

Oman L D, Ziemke J R, Douglass A R, Waugh D W, Lang C, Rodriguez J M and Nielsen J E 2011 The response of tropical tropospheric ozone to ENSO *Geophysical Research Letters* **38**

Revell L E, Tummon F, Stenke A, Sukhodolov T, Coulon A, Rozanov E, Garny H, Grewe V and Peter T 2015 Drivers of the tropospheric ozone budget throughout the 21st century under the medium-high climate scenario RCP 6.0 *Atmospheric Chemistry and Physics* **15** 5887-902

Scinocca J F, McFarlane N A, Lazare M, Li J and Plummer D 2008 Technical Note: The CCCma third generation AGCM and its extension into the middle atmosphere *Atmospheric Chemistry and Physics* **8** 7055-74

Solomon S, Kinnison D, Bandoro J and Garcia R 2015 Simulation of polar ozone depletion: An update *Journal of Geophysical Research-Atmospheres* **120** 7958-74

Stenke A, Schraner M, Rozanov E, Egorova T, Luo B and Peter T 2013 The SOCOL version 3.0 chemistry-climate model: description, evaluation, and implications from an advanced transport algorithm *Geoscientific Model Development* **6** 1407-27

Stone K A, Morgenstern O, Karoly D J, Klekociuk A R, French W J, Abraham N L and Schofield R 2016 Evaluation of the ACCESS - chemistry-climate model for the Southern Hemisphere *Atmospheric Chemistry and Physics* **16** 2401-15

Tian W S and Chipperfield M P 2005 A new coupled chemistry-climate model for the stratosphere: The importance of coupling for future O-3-climate predictions *Quarterly Journal of the Royal Meteorological Society* **131** 281-303

Voldoire A, Sanchez-Gomez E, Melia D S Y, Decharme B, Cassou C, Senesi S, Valcke S, Beau I, Alias A, Chevallier M, Deque M, Deshayes J, Douville H, Fernandez E, Madec G, Maisonnave E, Moine M P, Planton S, Saint-Martin D, Szopa S, Tyteca S, Alkama R, Belamari S, Braun A, Coquart L and Chauvin F 2013 The CNRM-CM5.1 global climate model: description and basic evaluation *Climate Dynamics* **40** 2091-121

Walters D N, Williams K D, Boutle I A, Bushell A C, Edwards J M, Field P R, Lock A P, Morcrette C J, Stratton R A, Wilkinson J M, Willett M R, Bellouin N, Bodas-Salcedo A, Brooks M E, Copsey D, Earnshaw P D, Hardiman S C, Harris C M, Levine R C, MacLachlan C, Manners J C, Martin G M, Milton S F, Palmer M D, Roberts M J, Rodriguez J M, Tennant W J and Vidale P L 2014 The Met Office Unified Model Global Atmosphere 4.0 and JULES Global Land 4.0 configurations *Geoscientific Model Development* **7** 361-86

Yukimoto S, Adachi Y, Hosaka M, Sakami T, Yoshimura H, Hirabara M, Tanaka T Y, Shindo E, Tsujino H, Deushi M, Mizuta R, Yabu S, Obata A, Nakano H, Koshiro T, Ose T and Kitoh A 2012 A New Global Climate Model of the Meteorological Research Institute: MRI-CGCM3-Model Description and Basic Performance *Journal of the Meteorological Society of Japan* **90A** 23-64