

Supplementary information: Stratospheric water vapor affecting atmospheric circulation

Edward Charlesworth^{1*†}, Felix Plöger^{1,2†}, Thomas Birner³,
Rasul Baikhadzhaev¹, Marta Abalos⁴, Nathan Luke Abraham^{5,6},
Hideharu Akiyoshi⁷, Slimane Bekki⁸, Fraser Dennison⁹,
Patrick Jöckel¹⁰, James Keeble^{5,6}, Doug Kinnison¹¹,
Olaf Morgenstern¹², David Plummer¹³, Eugene Rozanov¹⁴,
Sarah Strode^{15,16}, Guang Zeng¹², Tatiana Egorova¹⁴, Martin Riese¹

^{1*}Institute for Energy and Climate Research: Stratosphere (IEK-7),
Research Center Jülich, Jülich, Germany.

²Institute for Atmospheric and Environmental Research, University of
Wuppertal, Wuppertal, Germany.

³Meteorological Institute Munich, Ludwig Maximilians University of
Munich, Munich, Germany.

⁴Earth Physics and Astrophysics Department, Universidad Complutense
de Madrid, Madrid, Spain.

⁵National Centre for Atmospheric Science (NCAS), University of
Cambridge, Cambridge, UK.

⁶Yusuf Hamied Department of Chemistry, University of Cambridge,
Cambridge, UK.

⁷National Institute for Environmental Studies, Tsukuba, Japan.

⁸Laboratoire de Météorologie Dynamique (LMD/IPSL), Palaiseau,
France.

⁹Commonwealth Scientific and Industrial Research Organization
(CSIRO) Environment, Aspendale, Vic. 3195, Australia.

¹⁰Institut für Physik der Atmosphäre, Deutsches Zentrum für Luft- und
Raumfahrt (DLR), Oberpfaffenhofen, Germany.

¹¹Atmospheric Chemistry Observations and Modeling Laboratory,
National Center for Atmospheric Research, Boulder, CO 80301, USA.

¹²National Institute of Water and Atmospheric Research, Wellington,
New Zealand.

¹³Climate Research Branch, Environment and Climate Change Canada,
Montreal, Canada.

¹⁴Physikalisch-Meteorologisches Observatorium, Davos World Radiation
Center, Davos Dorf, Switzerland.

¹⁵Goddard Earth Sciences Technology and Research (GESTAR-II),
Morgan State University, Baltimore, MD, 21251, USA.

¹⁶NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

*Corresponding author(s). E-mail(s): e.charlesworth@fz-juelich.de;

Contributing authors: f.ploeger@fz-juelich.de;

thomas.birner@physik.uni-muenchen.de; r.baikhadzhaev@fz-juelich.de;

mabalosa@ucm.es; N.Luke.Abraham@ncas.ac.uk; hakiyosi@nies.go.jp;

Slimane.Bekki@latmos.ipsl.fr; fraser.dennison@csiro.au;

Patrick.Joeckel@dlr.de; james.keeble@atm.ch.cam.ac.uk; dkin@ucar.edu;

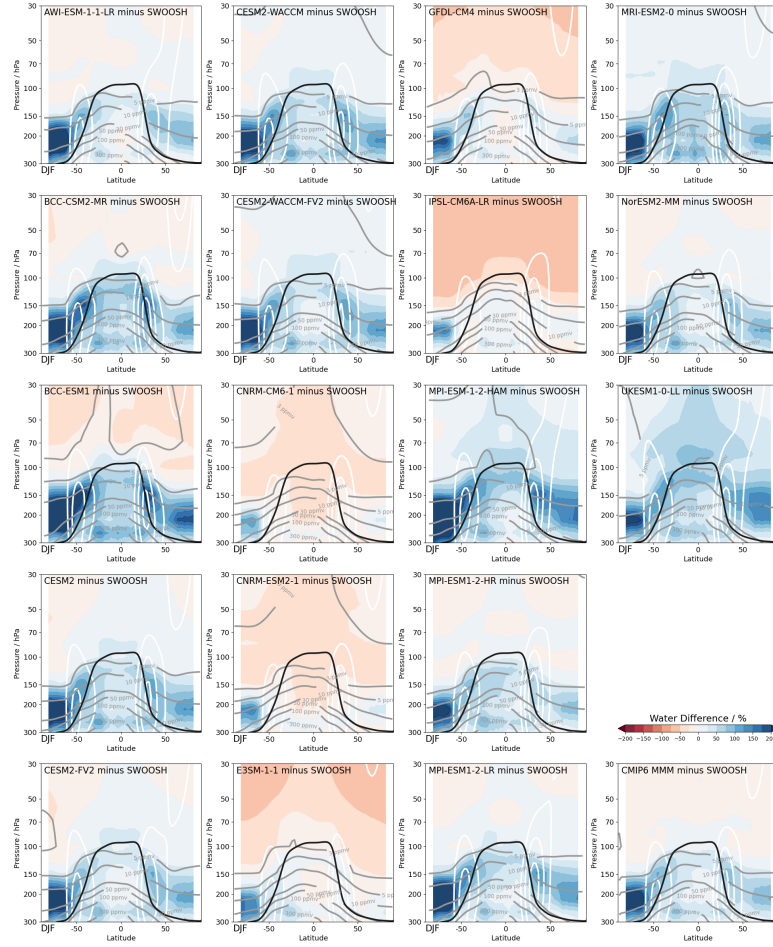
olaf.morgenstern@niwa.co.nz; david.plummer@ec.gc.ca;

e.rozanov@pmodwrc.ch; sarah.a.strode@nasa.gov;

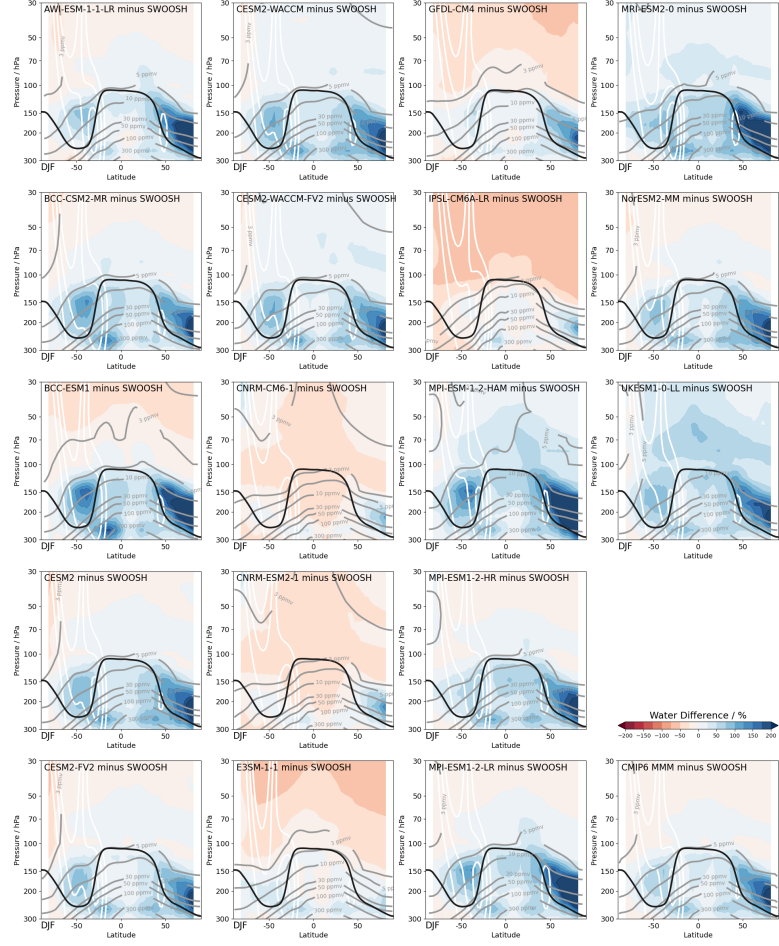
Guang.Zeng@niwa.co.nz; tatiana.egorova@pmodwrc.ch;

m.riese@fz-juelich.de;

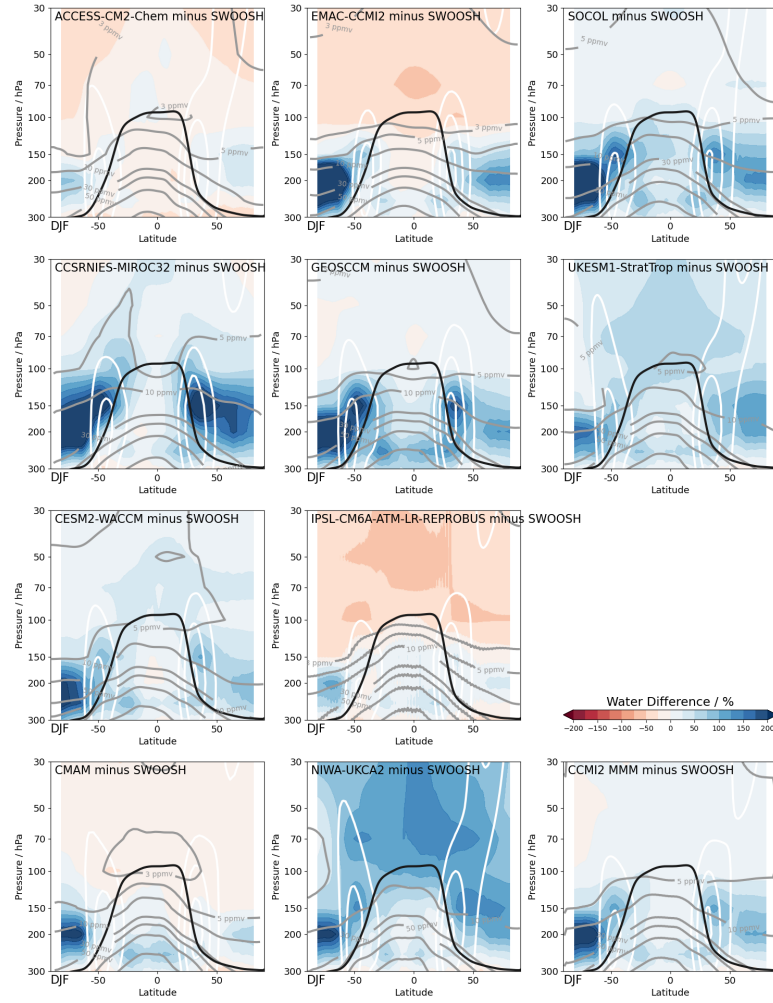
[†]These authors contributed equally to this work.



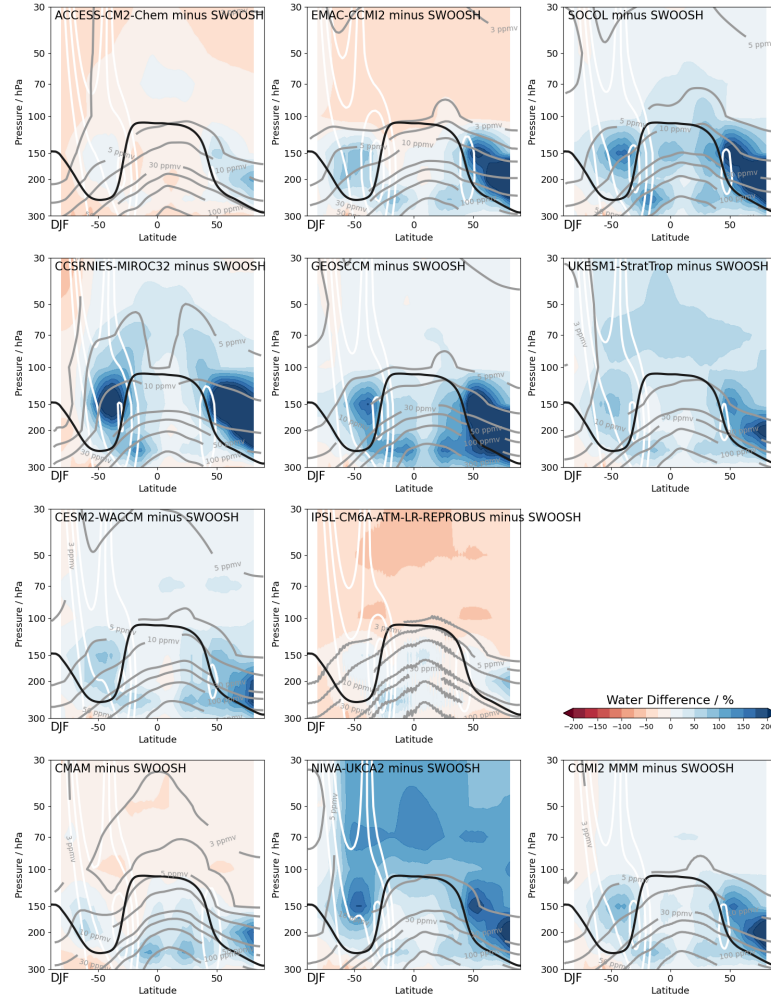
Supplementary Figure 1 Lowermost stratosphere moist bias in individual CMIP6 climate model simulations. Relative differences in water vapor distributions compared to SWOOSH merged satellite observations for CMIP6 multi model mean (lower right) and individual CMIP6 models (all other panels) for boreal winter (December–February). Relative differences are calculated by the relevant distribution minus SWOOSH as a percentage of local SWOOSH values. Only data from 2000–2014 were used. The SWOOSH water vapor distribution is shown in light grey solid contours, the 20, 30, and 40 m/s zonal wind contours are shown in white, and the tropopause as thick black line.



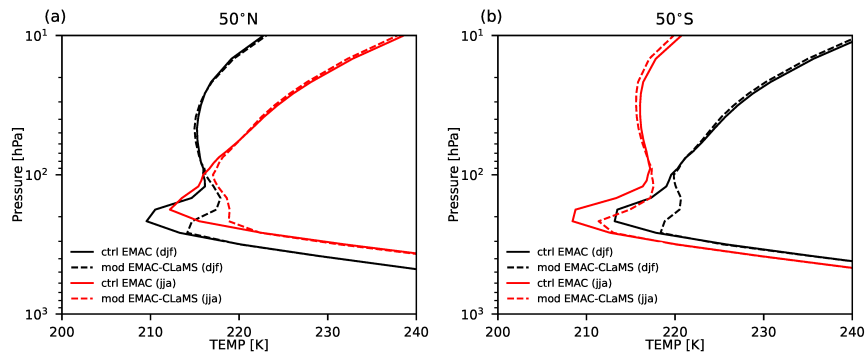
Supplementary Figure 2 Lowermost stratosphere moist bias in CMIP6 model simulations, boreal summer. Same as Figure ??, but for boreal summer (June–August).



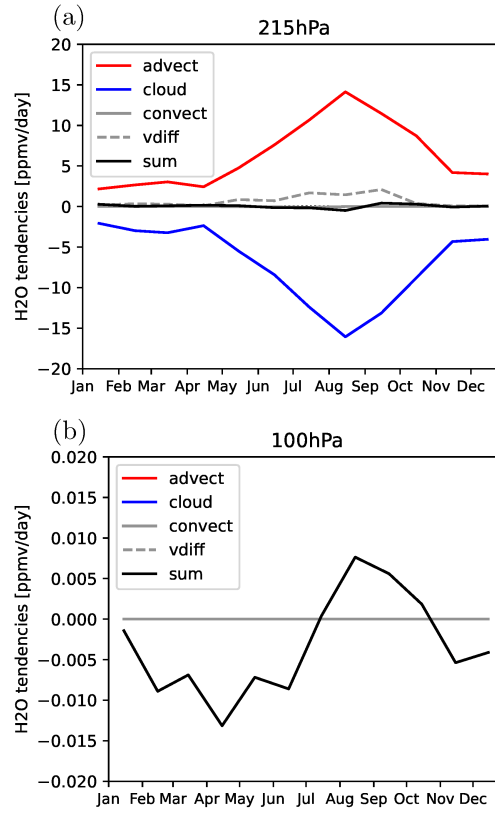
Supplementary Figure 3 Lowermost stratosphere moist bias in individual CCM2 climate model simulations. Relative differences in water vapor distributions compared to SWOOSH merged satellite observations for CCM2 multi model mean (lower right) and individual CCM2 models (all other panels) for boreal winter (December–February). Relative differences are calculated by the relevant distribution minus SWOOSH as a percentage of local SWOOSH values. Only data from 2000–2018 were used. The SWOOSH water vapor distribution is shown in light grey solid contours, the 20, 30, and 40 m/s zonal wind contours from the relevant distributions are shown in white, and the tropopause as thick black line.



Supplementary Figure 4 Lowermost stratosphere moist bias in CCM12 model simulations, boreal summer. Same as Figure ??, but for boreal summer (June–August).



Supplementary Figure 5 Changes in tropopause height induced by lowermost stratospheric water vapor. (a) Climatological temperature profiles at 50°N are shown for boreal winter (December–February, black) and summer (June–August, red) from control (solid lines) and Lagrangian modified (dashed) EMAC simulations. (b) Shows the same, but at 50°S.



Supplementary Figure 6 Tendency contributions to lowermost stratospheric water vapor. Tendencies for control EMAC simulated water vapour at (a) 215 hPa and (b) 100 hPa averaged over the middle latitude region (50°-70°N). Shown is the seasonal cycle of tendencies for advection, cloud processes (including e.g. dehydration, evaporation, ice sublimation), convection, parameterized vertical diffusion, and the sum of all these individual contributions. At 100 hPa, the tendencies due to convection, clouds and vertical diffusion overlie the zero line.