Supplementary information to "Reevaluation of total-column ozone trends and of the Effective Radiative Forcing of ozone-depleting substances"

Olaf Morgenstern[1], Stacey M. Frith[2], Gregory E. Bodeker[3], Vitali Fioletov[4], and Ronald J. van der A[5]

[1]National Institute of Water and Atmospheric Research (NIWA), Wellington, New Zealand
[2]NASA System Science and Applications, Lanham, MD, USA
[3]Bodeker Scientific, Alexandra, New Zealand
[4]Environment Canada, Downsview, ON, Canada
[5]KNMI, De Bilt, Netherlands

1 CMIP6 interactive-ozone models

Model name	Reference	historical sims.	ssp245
CESM2-WACCM	Gettelman et al. (2019)	1, 2, 3	1, 2, 3, 5
CNRM-ESM2-1	Séférian et al. (2019)	1 to 5, 8, 9, 10	1 to 10
GFDL-ESM4	Dunne et al. (2020)	1	1
MRI-ESM2-0	Yukimoto et al. (2019)	1 to 5	1 to 5
UKESM1-0-LL	Sellar et al. (2019)	1 to 4, 8 to 12, 16 to 19	1, 2

Table 1. Models, key references, and CMIP6 "historical" and "ssp245" simulations denoted by their run numbers (Morgenstern et al., 2020).

The five models listed in table 1 are the same as used by Morgenstern et al. (2020) except that one model is excluded here because of a spurious volcanic influence dominating historical trends. "Historical" simulations use best-estimate forcings covering the period 1850-2014 (Eyring et al., 2016); they are complemented with six years (2015-2020) of Shared Socio-Economic Pathway 2-4.5 (ssp245) simulations (Meinshausen et al., 2020).

2 Details of processing applied to the TCO datasets

We here give details on how MSR-2 and SBUV v86 data are used to seamlessly complement and complete the four observational TCO climatologies.

1. Zonal means of all TO datasets are interpolated to a 0.5° latitude grid at monthly resolution. If data are available at fewer than half the gridpoints in the longitudinal direction, the corresponding zonal-mean value is assumed missing.
2. We have experimented with removing a projection onto two indices representing the quasi-biennial oscillation (QBO) from the zonal-mean TCO data, but have decided against using this adjustment as piecewise linear fits do not markedly improve and trends do not substantially change with this additional step of data processing. This small role for the QBO may be due to a cancellation of a QBO-related modification of the TCO field between the tropics and extratropics.

Corresponding author: Olaf Morgenstern, `olaf.morgenstern@niwa.co.nz`

3. For any given latitude λ and month of the year m, we form a linear least-squares regression relating the values of MSR-2 to those of the other climatologies, T_X:

$$T_X(\lambda, m, y) = A(\lambda, m) + B(\lambda, m) T_{\mathrm{MSR2}}(\lambda, m, y) + \xi(\lambda, m, y) \quad (1)$$

   where y stands for the calendar year, A and B are regression coefficient, ξ is the unexplained residual, and T_X are the climatologies. For a perfect fit we would find $A = 0$, $B = 1$, and $\xi = 0$.
4. A and B are extended latitudinally to both poles to achieve complete coverage for all latitudes λ and months of the year m.
5. Where the T_X have data gaps but T_{MSR2} does not, we use equation 1 to fill those gaps, assuming $\xi = 0$. This removes most data gaps for the period 1979-2020.
6. We repeat steps 3, 4, and 5, substituting T_{MSR2} with the SBUV v86 TCO climatology, T_{SBUV}. This means that all climatologies now partially cover 1970-1978.
7. The data gaps remaining for the observational datasets (SBUV, NIWA, MSR-2) are also imposed on the WOUDC groundbased and the CMIP6 TCO datasets and the model data, to retain equivalence of the modelled and observationally derived trends.
8. We have experimented with piecewise linear trends for a variety of different nodes. Here we present trends for nodes at (1970, 1979, 1997, 2020), (1997, 2016), (1979, 2000), and (1979, 2000, 2020). In all cases, we require valid data for at least half the data points in these intervals. For the first case involving a node in 1970, we additionally require at least two data points between 1970 and 1978. Where this is not the case (especially at high latitudes in winter), we revert to nodes in 1979, 1997, and 2020.
9. Due to spatiotemporal cross-correlations of the trends, uncertainty estimates for the derived spatial- and annual-mean trends need to be based on annual- and regional-mean TCO data. For this we use a simple predictor model to produce "educated guesses" for the missing TCO values particularly in the period 1970-1978 when the MSR-2 and SBUV v86 datasets have data gaps. Our model accounts for equivalent effective stratospheric chlorine, Cl_y^{eq} (Newman et al., 2007) and equivalent CO_2^{eq} (Myhre et al., 2013) (representing the total direct radiative forcing of long-lived greenhouse gases) in the same way as Morgenstern (2021):

$$T_X(\lambda, m, y) = T_0(\lambda, m) + C(\lambda, m)\mathrm{Cl}_y^{eq}(y) + D(\lambda, m) CO_2^{eq}(y) + \mu(\lambda, m, y). \quad (2)$$

   Here C and D are regression coefficients. Using equation 2 we fill remaining data gaps, almost all in 1970-1978 (figure 1).
10. We then form annual and regional means of the TCO datasets and calculate piecewise linear regression on these averages, weighting years of data with their respective coverage before apply equation 2. This ensures that years with extensive "guessed" fill-in receive an appropriately reduced weight in the piecewise regression. The regression fit then comes with standard uncertainty estimates for the resultant trends.
11. To assess the role of the filled-in data according to equation 2, for the model data we repeat the process, this time replacing data generated by applying equation 2 with the original model data. We find essentially unchanged error estimates for the model data, allowing us to conjecture that also for the observational climatologies, the regression-based fill-in according to equation 2 does not unduly influence the uncertainty estimates.

References

Dunne, J. P., Horowitz, L. W., Adcroft, A. J., Ginoux, P., Held, I. M., John, J. G., . . . Zhao, M. (2020). The GFDL Earth System Model version 4.1 (GFDL-ESM4.1): Overall coupled model description and simulation characteristics.

Journal of Advances in Modeling Earth Systems, *12*, e2019MS002015. Retrieved from https://doi.org/10.1029/2019MS002015

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958. Retrieved from https://www.geosci-model-dev.net/9/1937/2016/ doi: 10.5194/gmd-9-1937-2016

Gettelman, A., Mills, M. J., Kinnison, D. E., Garcia, R. R., Smith, A. K., Marsh, D. R., … Randel, W. J. (2019). The Whole Atmosphere Community Climate Model version 6 (WACCM6). *Journal of Geophysical Research: Atmospheres*, *124*(23), 12380-12403. Retrieved from https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JD030943 doi: 10.1029/2019JD030943

Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., … Wang, R. H. J. (2020). The Shared Socio-economic Pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, *13*(8), 3571–3605. Retrieved from https://gmd.copernicus.org/articles/13/3571/2020/ doi: 10.5194/gmd-13-3571-2020

Morgenstern, O. (2021). The Southern Annular Mode in 6th Coupled Model Intercomparison Project models. *Journal of Geophysical Research: Atmospheres*, *126*(5), e2020JD034161. Retrieved from https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020JD034161 (e2020JD034161 2020JD034161) doi: https://doi.org/10.1029/2020JD034161

Morgenstern, O., O'Connor, F. M., Johnson, B. T., Zeng, G., Mulcahy, J. P., Williams, J., … Kinnison, D. E. (2020). Reappraisal of the climate impacts of ozone-depleting substances. *Geophysical Research Letters*, *47*(20), e2020GL088295. Retrieved from https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020GL088295 (e2020GL088295 10.1029/2020GL088295) doi: https://doi.org/10.1029/2020GL088295

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., … Zhang, H. (2013). Anthropogenic and Natural Radiative Forcing. In *Climate Change 2013 - The Physical Science Basis* (chap. 8). Geneva, Switzerland: Intergovernmental Panel on Climate Change (IPCC). Retrieved from https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf

Newman, P. A., Daniel, J. S., Waugh, D. W., & Nash, E. R. (2007). A new formulation of equivalent effective stratospheric chlorine (EESC). *Atmospheric Chemistry and Physics*, *7*(17), 4537–4552. Retrieved from https://acp.copernicus.org/articles/7/4537/2007/ doi: 10.5194/acp-7-4537-2007

Sellar, A. A., Jones, C. G., Mulcahy, J. P., Tang, Y., Yool, A., Wiltshire, A., … Zerroukat, M. (2019). UKESM1: Description and evaluation of the U.K. Earth System Model. *Journal of Advances in Modeling Earth Systems*, *11*(12), 4513-4558. Retrieved from https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019MS001739 doi: 10.1029/2019MS001739

Séférian, R., Nabat, P., Michou, M., Saint-Martin, D., Voldoire, A., Colin, J., … Madec, G. (2019). Evaluation of CNRM Earth System Model, CNRM-ESM2-1: Role of earth system processes in present-day and future climate. *Journal of Advances in Modeling Earth Systems*, *11*(12), 4182-4227. Retrieved from https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019MS001791 doi: 10.1029/2019MS001791

Yukimoto, S., Kawai, H., Koshiro, T., Oshima, N., Yoshida, K., Urakawa, S., … ISHII, M. (2019). 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*. doi: 10.2151/jmsj.2019-051

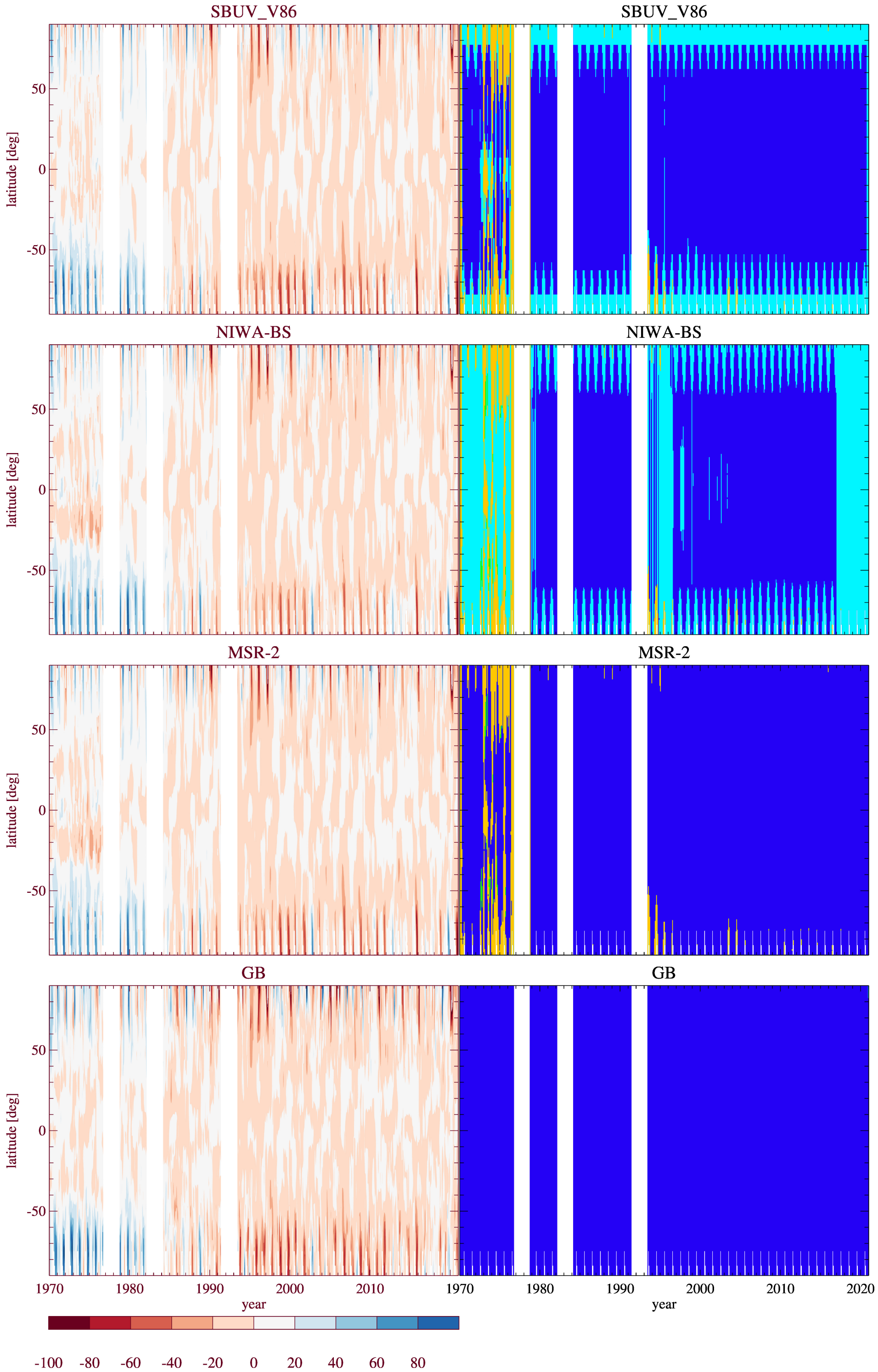

Figure 1. (left) Zonal-mean TCO (Dobson Units) in four of the climatologies as used here (SBUV, NIWA-BS v3.4, MSR-2, and WOUDC ground-based), with the mean annual cycle over 1970-2020 removed. (right) Provenance of the data. White: data gap. Dark blue: original data. Light blue: filled in using MSR-2 data. Green: filled in using SBUV v86 data. Orange: filled in using regression. The filling pattern for NIWA-BS v3.5.1 is identical to v3.4 except for 2017-2019 when NIWA-BS v3.5.1 only requires fill-in for the polar winter situation. The filling pattern applied to the ground-based climatology (which is originally gap-free) is also used for all five modelled TCO fields used here and the CMIP6 ozone forcing dataset.