

Evaluation of stratospheric transport in Chemistry Climate Models

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Abstract

Accurate representation of stratospheric transport in Chemistry–Climate Models (CCMs) is essential for simulating the ozone layer and other climate-relevant trace gases. We assess transport performance across three generations of CCM intercomparison projects (CCMVal-2, CCMI-1, and CCMI-2022) using recent satellite observations and reanalyses. Results show that several persistent biases remain across model generations, with limited improvement in the latest simulations. In particular, models continue to simulate excessively fast global mean transport by the Brewer–Dobson circulation and a delayed vortex breakup. In the SH, the newest models produce overly deep ozone spring minima. Long-term trends in stratospheric transport are broadly consistent across generations and confirm the important role of ozone depletion in strengthening the Brewer–Dobson circulation and delaying the breakdown of the Antarctic polar vortex.

Mean age of air

Mean age of air is **underestimated in the three generations of models** (Fig. 1). Based on current satellite estimates (Garny et al. 2024), the median of the newest model group CCMI-2022 underestimates approximately one year the stratospheric mean age globally. This implies that air and tracers are transported too fast from the tropical tropopause. Note that different generations include different models.

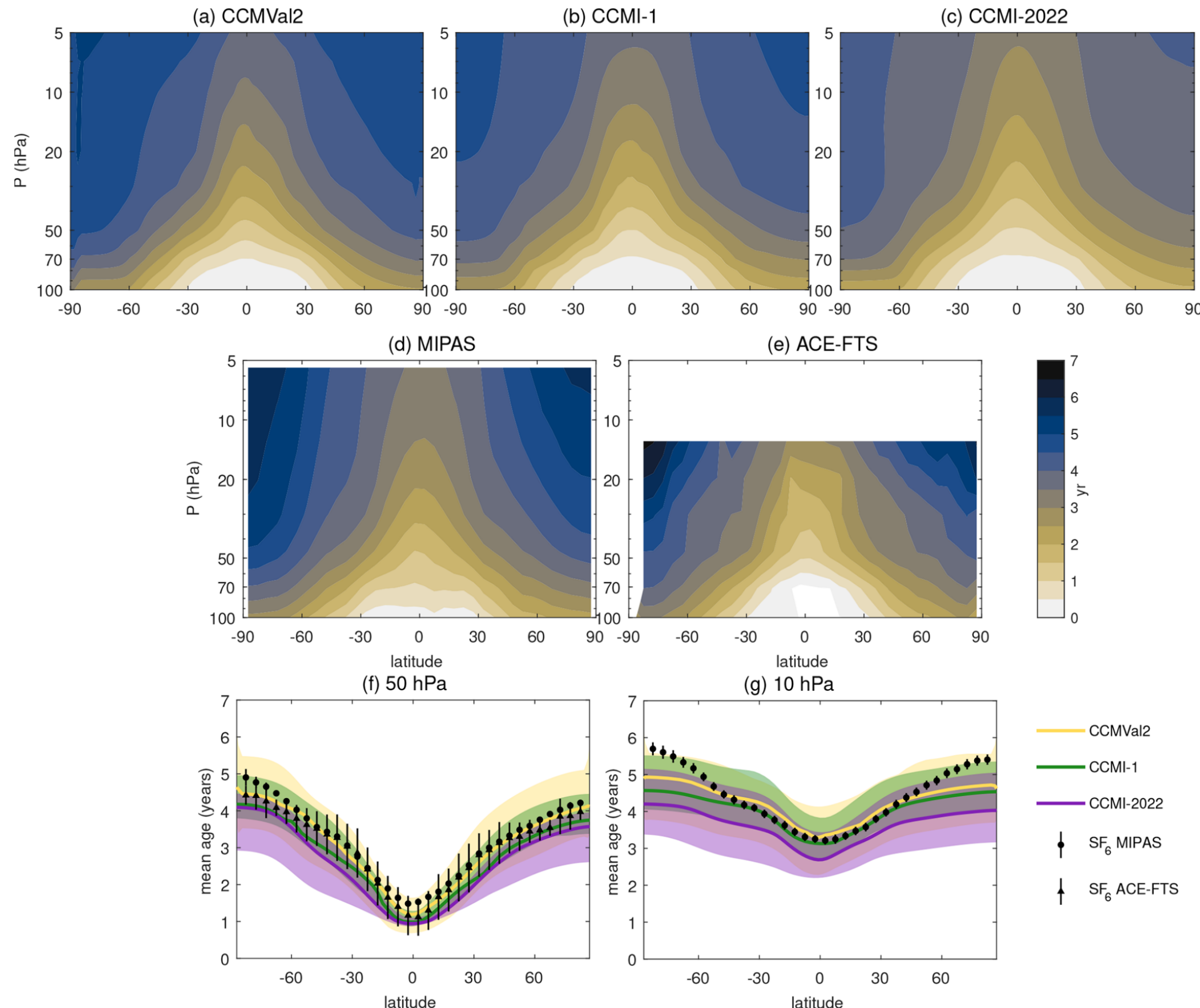


Figure 1. (a–e) Cross sections (latitude–pressure) of annual mean AoA multimodel median for CCMVal-2, CCMI-1, and CCMI-2022, and for the observational dataset from MIPAS and ACE-FTS. (f–g) Latitudinal section of the mean age of air from the three generations of models and the satellite estimates at 50 hPa (left) and 10 hPa (right). In all panels the mean age is corrected by removing the value at the equator and 100 hPa of the corresponding dataset.

Tropical upwelling

Tropical upwelling is overestimated in the tropical lower stratosphere (Fig. 2). This magnitude is not measured directly, but is estimated as the vertical component of the residual circulation net upward mass flux from three modern reanalyses (Fig. 2, left panel; Martineau et al. 2018, Fujiwara et al. 2024), and independently from the water vapor tape recorder from SWOOSH measurements. While the strong residual circulation contributes to the excessively fast net transport seen in Fig. 1 in the models, the differences in mixing efficiency dominate the intermodel spread in mean age (not shown, see Fig. 2 in Abalos et al. 2026).

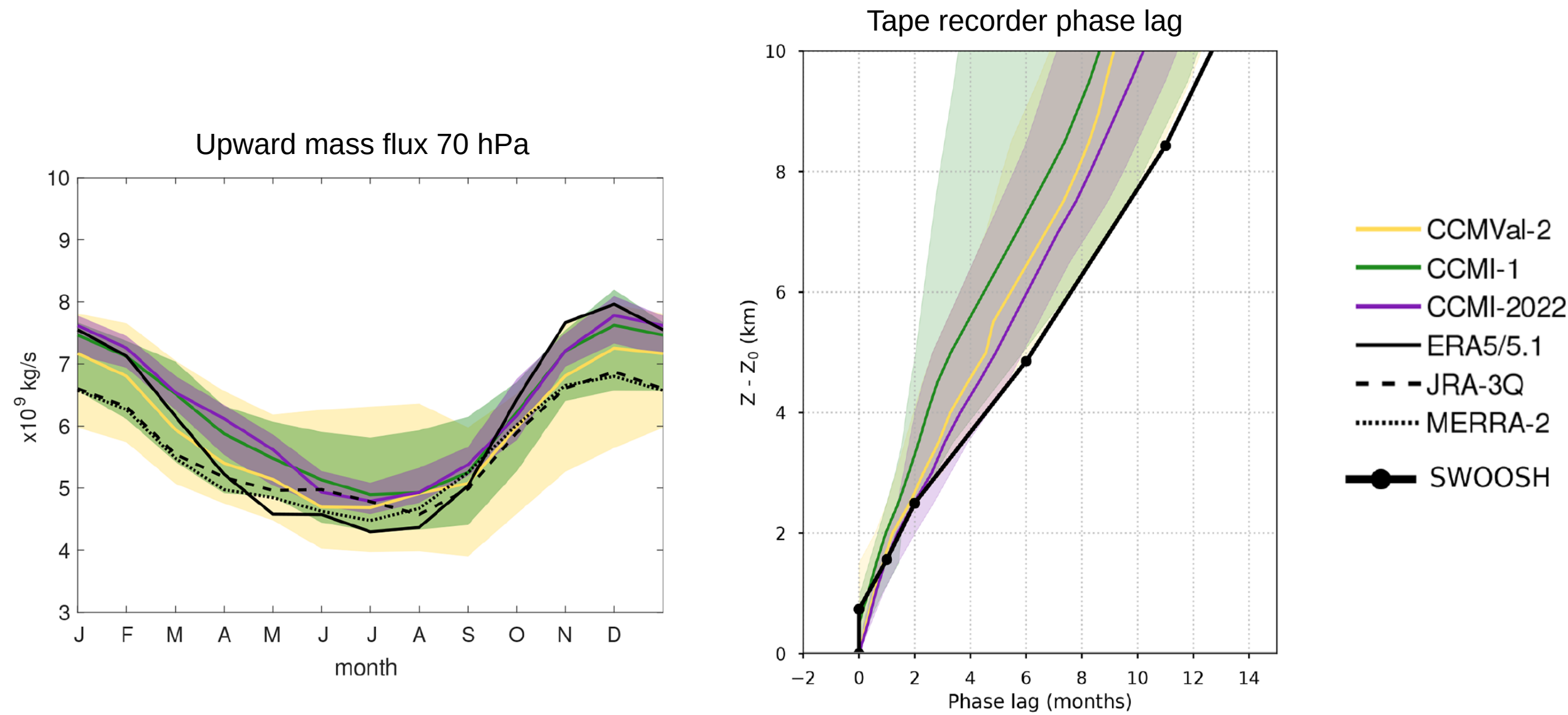


Figure 2. (left) Net upward mass flux in the three model generations (MMMed and 15th/85th percentiles) and three reanalyses (ERA5, JRA-3Q, MERRA-2) seasonal cycle at 70 hPa. (right) Water vapor tape recorder phase lag as a function of distance from the level of peak tape recorder amplitude (20° S–20° N) in CCMVal-2, CCMI-1, and CCMI-2022 multi-model medians and SWOOSH. The time period over which the tape recorder is computed starts in 1992 for all datasets and ends in 2005 for CCMVal-2, 2012 for CCMI-1, and 2018 for CCMI-2022 and SWOOSH.

Final warming date and ozone hole

The **transition from the winter polar vortex to the summer circulation happens too late in all model generations, with up to 3 weeks delay** for the multi-model median of the newest generation. This delayed final warming is related to the longstanding cold-pole bias and misrepresentation of wave driving. Connected with the particularly long-lived and cold polar vortex in the newest generation of CCMs is an excessively deep ozone hole (Fig. 4 right).

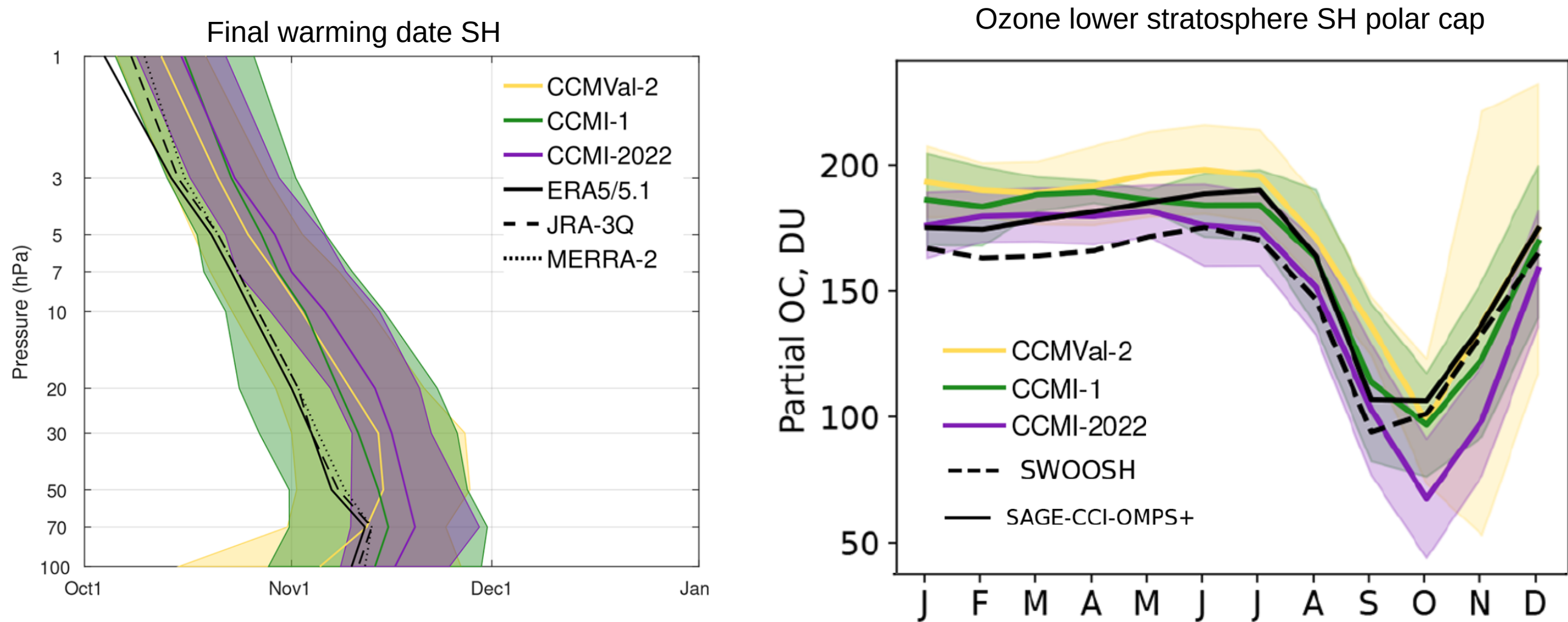


Figure 4. (left) Descent of the final warming date in the SH, computed as the day when the zonal-mean zonal wind at 60° S crosses the 30 m s−1 line in the SH. Based on monthly mean output interpolated to daily values for the period 1980–2000. (right) Seasonal cycle of lower stratospheric ozone column averaged over 90S–60S. The lower stratospheric column is defined over 150–20 hPa.

Polar downwelling

The **polar downwelling is underestimated in the SH winter-spring** (Fig. 3 left). This results in too weak downward transport of tracers, as demonstrated by the tendency of N₂O concentrations derived from satellite measurements (Fig. 3 right).

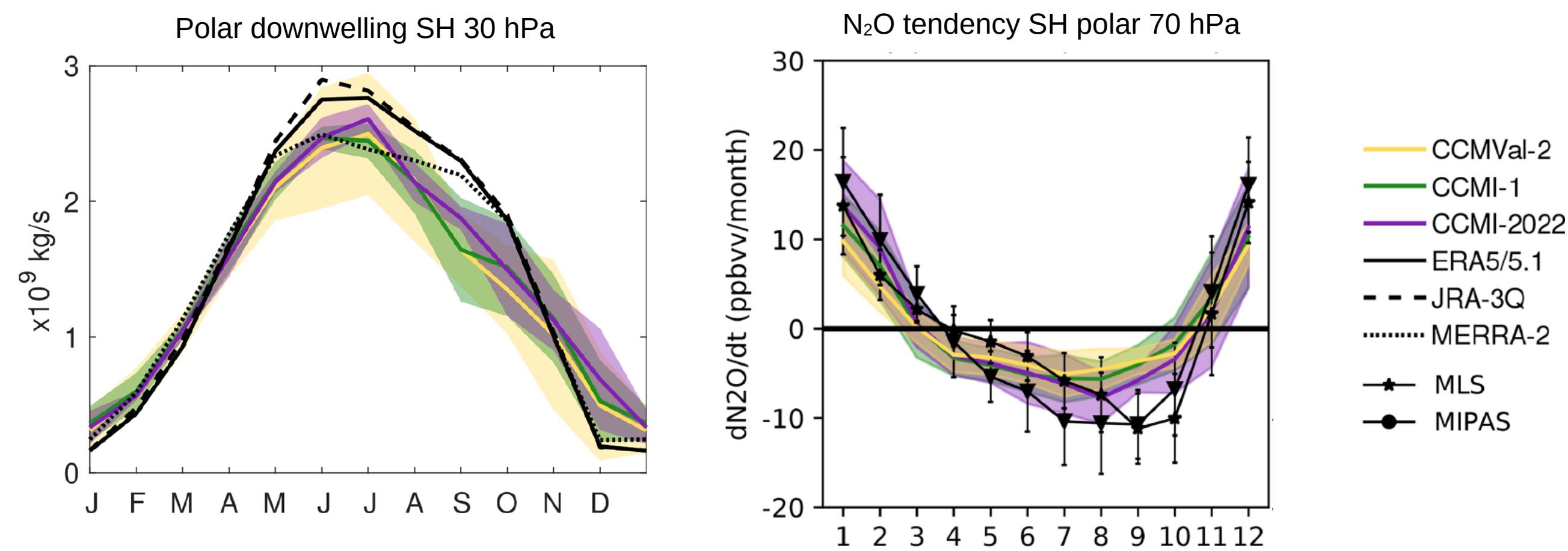


Figure 3. (left) Seasonal cycle of the SH (a) and NH (b) polar downward mass flux in the three generations together with reanalyses estimates (ERA5/5.1, JRA-3Q, MERRA-2). Shading shows the 15th and 85th percentiles. (right) Climatological seasonal cycles of the N₂O tendency (ppbv per month) at 70 hPa for the southern extratropics (a; 89–50° S), and the northern extratropics (b; 50–89° N). MLS and MIPAS use their respective complete periods. All models show 20 years: 1980–2000 for CCMVal-2, 1990–2010 for CCMI-1 and 1998–2018 for CCMI-2022.

Trends in the Brewer-Dobson circulation

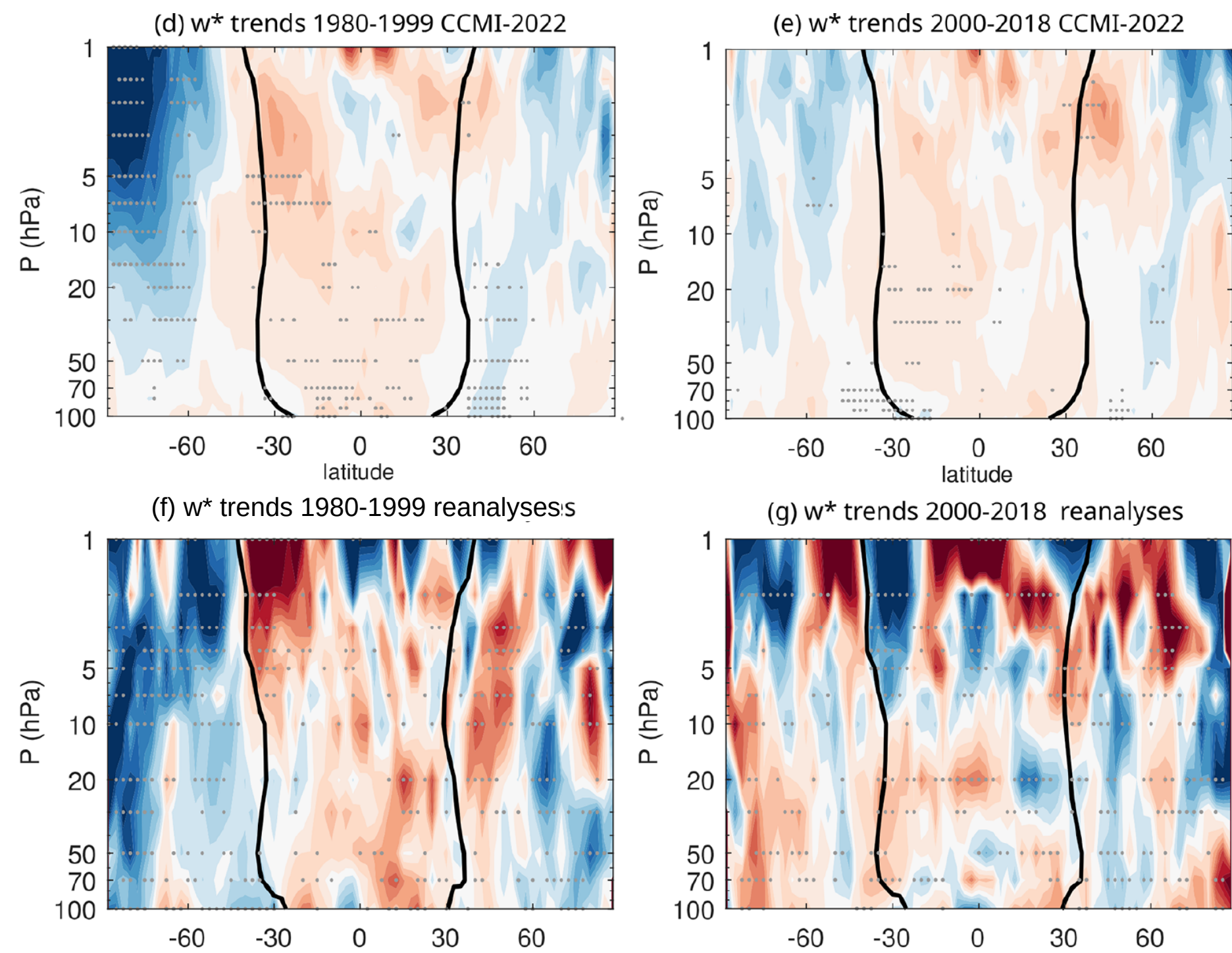


Figure 5. Trends in vertical component of the residual circulation for the CCMI-2022 MMed (top) and the multi-reanalysis mean (bottom) for the ozone depletion (left) and recovery (right) periods. Stippling indicates where all the models (d, e) or all the reanalyses (f, g) agree in the sign of the trends.

The residual circulation accelerates more in the ozone depletion (pre-2000) than in the ozone recovery (post-2000) period. Despite very noisy trends from the reanalyses, this result holds, and the main difference is the SH polar region, linked to the ozone hole-induced downwelling (Polvani et al. 2018).

Trends in FWD

The delay of the final warming date during the ozone depletion period 1980–1999 is consistent with reanalyses for the multi-model median of the three generations. However, there is a very large intermodel spread, which is reduced in the newer model generation.

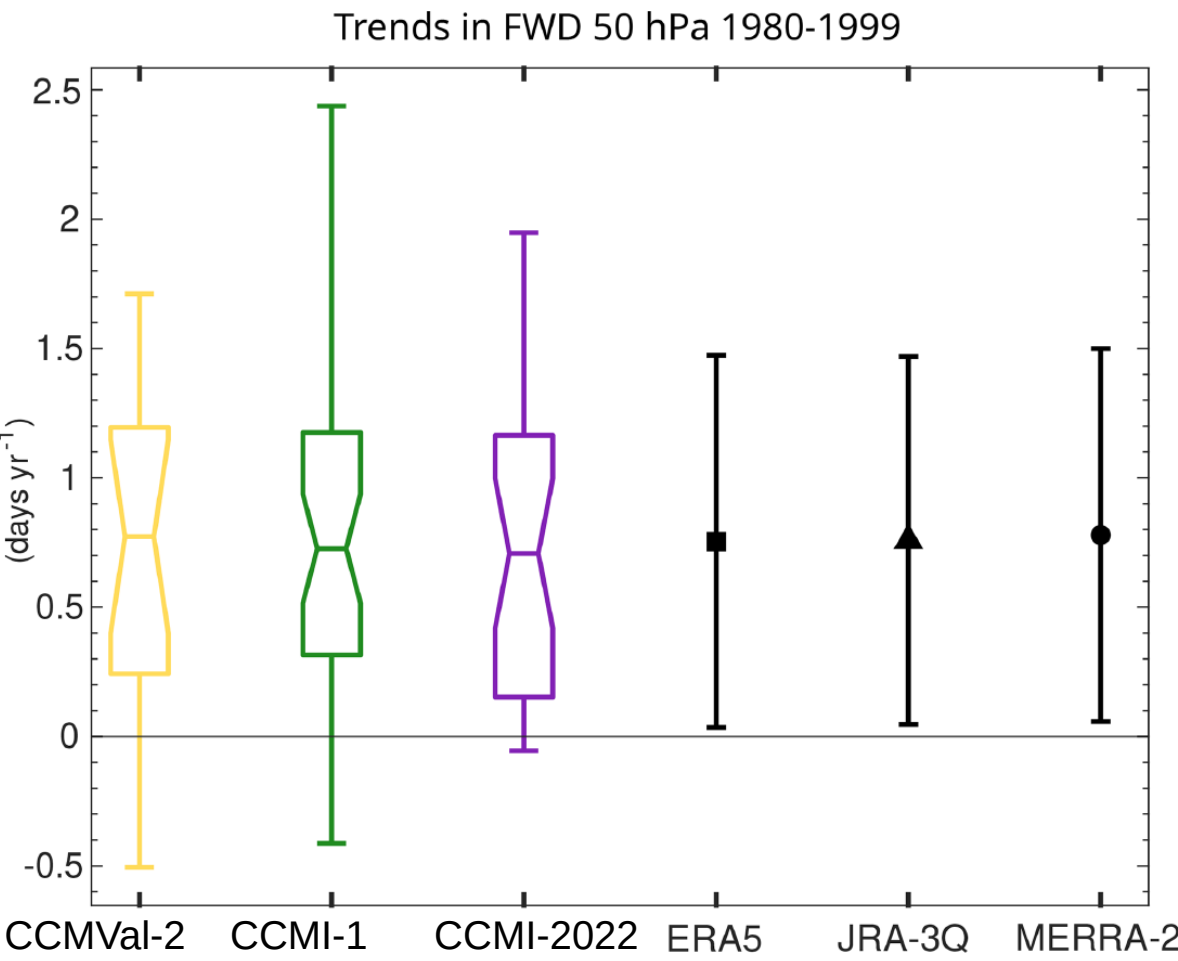


Figure 6. Trends of FWD in the SH over the period 1980–1999. The horizontal lines in the boxes show the MMed, the height of the boxes represents the interquartile (25th–75th percentile) range, and the whiskers extend from the minimum to the maximum values. The error bars for the reanalyses show the 95 % confidence interval based on a Student's t-test distribution for the linear trend.

References Abalos et al. (2026 ACP) <https://doi.org/10.5194/acp-26-5249-2026>; Garny et al. (2024 RoG) <https://doi.org/10.1029/2023RG000832>, Polvani et al. (2018 GRL) <https://doi.org/10.1002/2017GL075345>; Fujiwara et al. (2024 ACP) <https://doi.org/10.5194/acp-24-7873-2024>; Martineau et al. (2018 ESSD) <https://doi.org/10.5194/essd-10-1925-2018>

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