

The lower stratospheric ozone conundrum updated: a Bayesian DLM assessment using satellite and model data through 2025

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1. BACKGROUND AND MOTIVATION

Ozone recovery — a mixed picture

- The Montreal Protocol and its amendments have reduced stratospheric chlorine and bromine loading since the late 1990s.
- Upper-stratospheric (US) ozone recovery, driven by decreasing declining halogen loading and decreasing temperatures, is now well established.
- In contrast, satellite composites indicate a continued post-1997 decline in lower-stratospheric (LS) ozone (Ball et al., 2018).

An unresolved model–observation gap

- Chemistry-climate models and reanalysis-driven chemical transport models (CTMs) do not reproduce the observed LS decline (Chipperfield et al., 2018; Petropavlovskikh et al., 2019; WMO, 2022) — pointing to missing dynamical or chemical processes.
- Recent extreme events — the 2019/2020 Australian wildfires, the 2022 Hunga Tonga eruption, and anomalous QBO behaviour — further complicate trend attribution (Salawitch et al., 2025).

This study applies a Bayesian Dynamic Linear Model (DLM; Laine et al., 2014, Ball et al., 2018) to four datasets — GOZCARDS, SWOOSH, ERA5 TOMCAT and ML-TOMCAT — all extended through 2025, to resolve time-varying LS ozone trends and quantify their statistical robustness.

2. DATA AND METHODS

Observations & models

- GOZCARDS (Froidevaux et al., 2015) and SWOOSH (Davis et al., 2016) merged satellite ozone composites
- ERA5-driven TOMCAT 3-D chemical transport model (CTM) – Chipperfield et al., 2025, Chrysanthou et al., 2025.
- ML-TOMCAT (Dhomse et al., 2021): TOMCAT output corrected using machine learning and satellite-based data
- Yields a chemically self-consistent, gap-free record — an independent benchmark separating model deficiencies from observational uncertainty.

Bayesian Dynamic Linear Modelling (DLM)

- Framework of Ball et al. (2018), applied consistently to all four datasets through 2025.
- Captures time-varying, nonlinear trends rather than a single fixed linear trend.
- Use of forced regressors (ENSO, Solar, QBO30/50, AO, AAO and stratospheric aerosol loading)
- Returns posterior probabilities of ozone recovery or continued decline, for each dataset and region via Markov chain Monte Carlo (MCMC) sampling

3. RESULTS

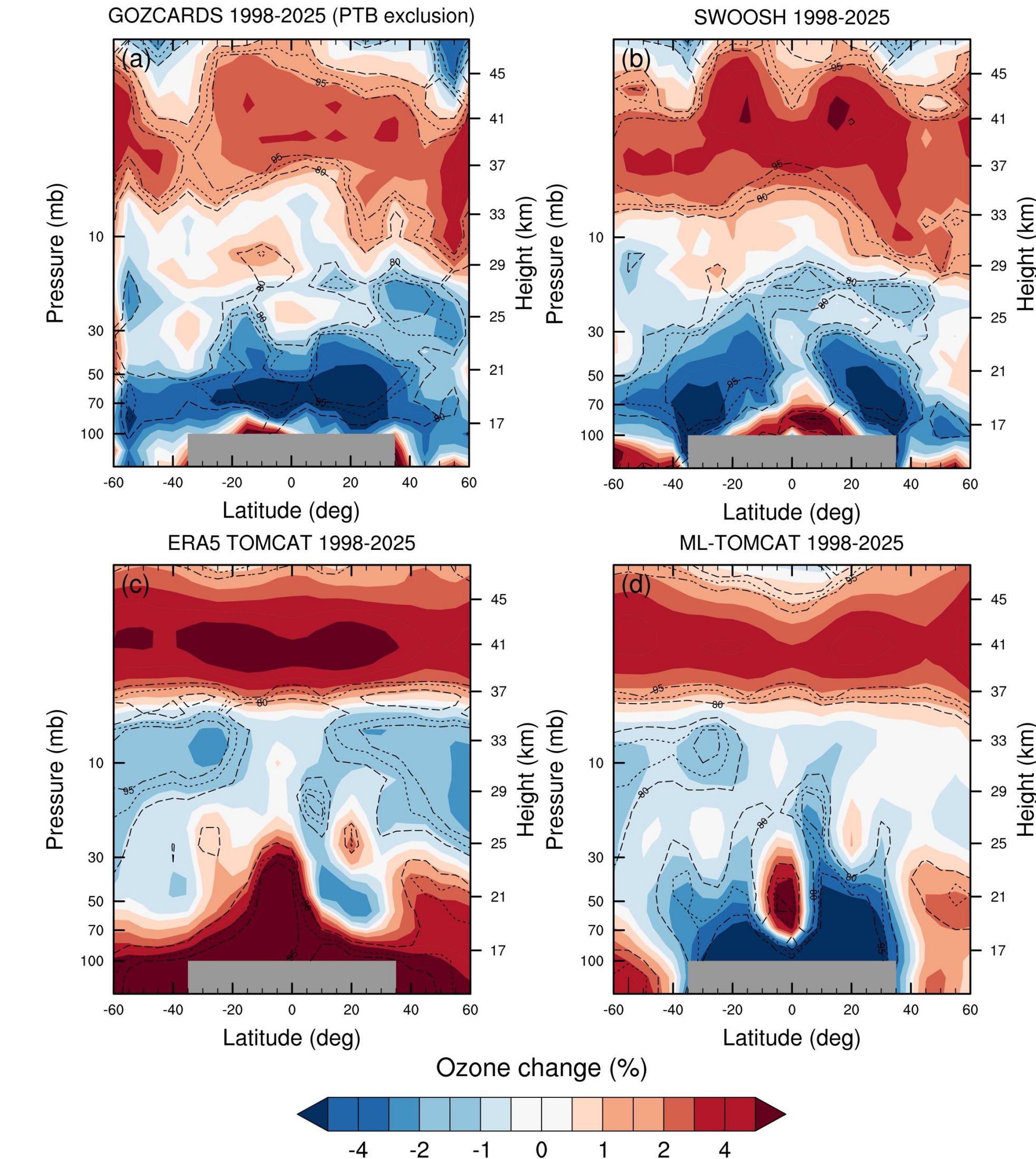


Figure 1. Zonally averaged change in ozone between 1998 through 2025 for (a) GOZCARDS, (b) SWOOSH observational datasets, (c) ERA5 TOMCAT, (d) ML-TOMCAT model simulations. Coloured contours represent the percentage change of ozone between January 1998 through December 2025 while black dashed line contours denote the probability level of a given change at 80%, 90% and 95%. Gray filled areas represent missing data for all datasets and are not considered part of the lower stratosphere in the partial column ozone calculations in this study.

Key points

A coherent vertical dipole

- Both satellite composites show the same pattern: robust upper-stratospheric (US) recovery alongside a persistent LS decline, across all latitude bands (Fig. 1a–b).
- A sign reversal in the model simulations**
- ERA5-TOMCAT captures the US recovery but simulates the opposite sign of LS O₃ change over 1998–2025 (Fig. 1c) showing an almost uniform O₃ increase maximising in the tropics.

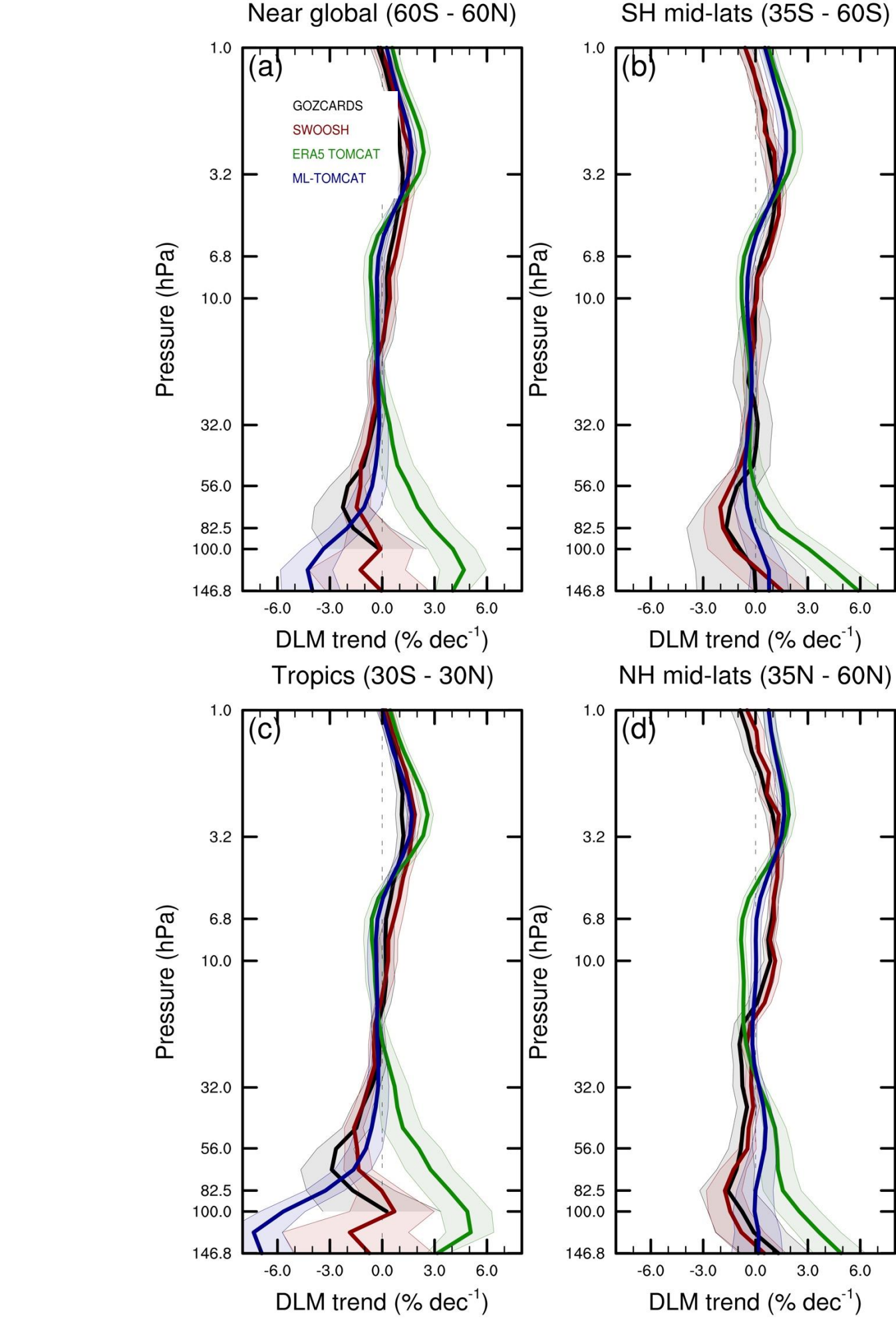


Figure 2. Vertical profiles of the stratospheric O₃ DLM trends between 1998 through 2025 for (a) near-global (60°S - 60°N), (b) SH mid-latitudes (35°S - 60°S), (c) Tropics (30°S - 30°N) and (d) NH mid-latitudes (35°N - 60°N). Coloured solid lines represent the mean DLM non-linear trend expressed in % dec⁻¹ while the shaded coloured regions denote the envelope of ±2σ uncertainty of the DLM trend estimate as denoted by the boundaries in coloured solid lines for GOZCARDS (black), SWOOSH (red), ERA5 TOMCAT (green) and ML-TOMCAT (blue), respectively.

Key points

- **All four datasets agree in the US**, with positive trends of roughly +1 to +2% dec⁻¹ near 3 hPa (halogen-driven recovery signal).
- **Divergence below ~50 hPa.** GOZCARDS, SWOOSH and ML-TOMCAT show –ve trends, with ML-TOMCAT the most negative in the tropics (100–147 hPa). ERA5-TOMCAT goes strongly +ve, (≤ 5% dec⁻¹).
- **The middle stratospheric trends (~10–32 hPa) are close to zero in all datasets.**

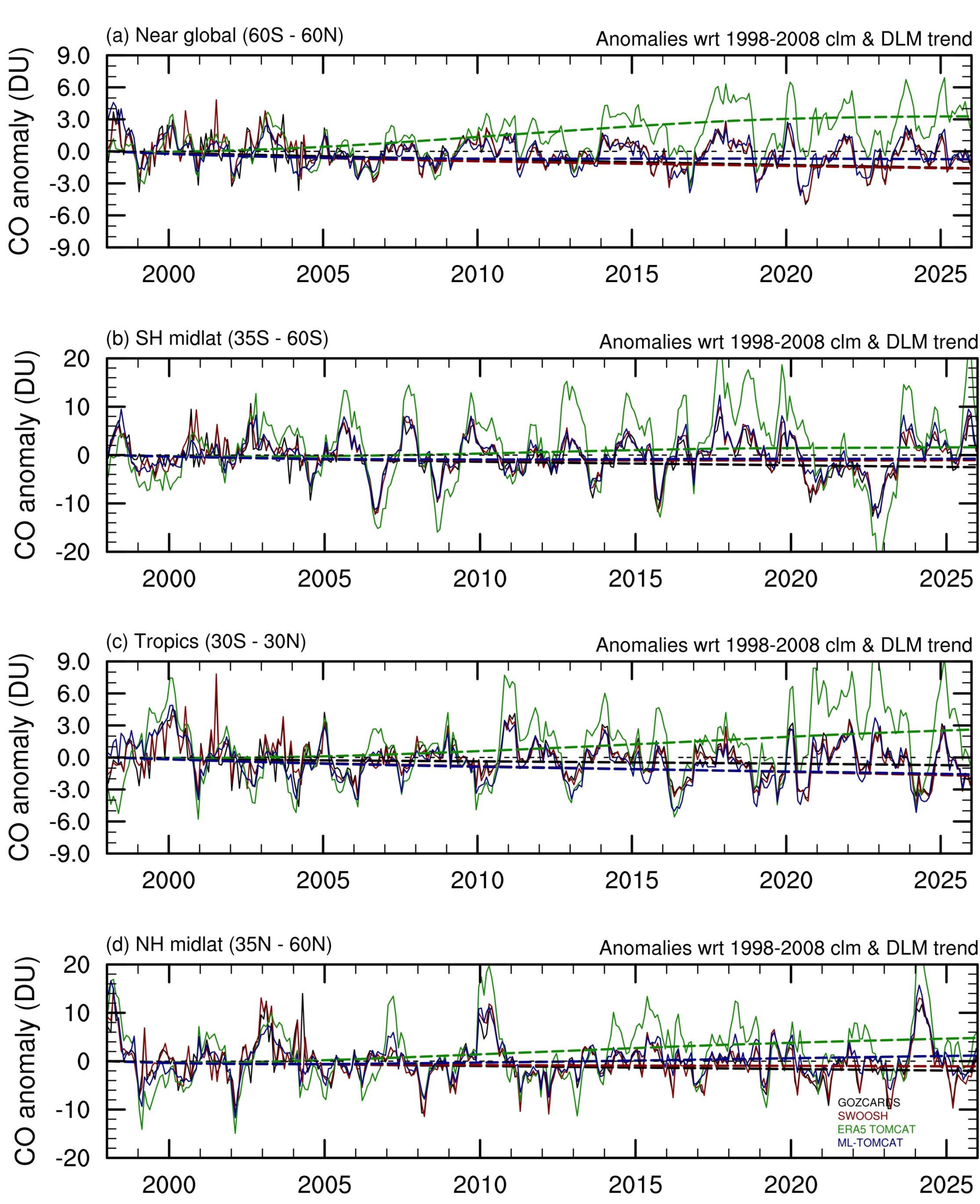


Figure 3. Timeseries of the LS (147/100 - 32 hPa) PCO anomalies wrt the 1998 - 2008 climatology for 4 separate latitude bands as in Figure 2. Coloured solid lines represent the PCO anomalies for the different datasets used in this study as in Figure 2. Coloured dashed lines represent the smooth, non-linear mean trend estimates as calculated with the DLM.

Key points

- **Diverging long-term trends for the extrapolar region:** the DLM trends are declining for GOZCARDS, SWOOSH and ML-TOMCAT, while ERA5-TOMCAT shows a strong upward trend in every region.
- **ML-TOMCAT shows remarkable agreement with observational datasets tracking each other closely.** Their interannual variability agrees, e.g. the NH mid-lat peaks around 2010 and 2024.
- **ERA5-TOMCAT captures the variability but has a larger anomaly amplitude**, especially in mid-lats. It also diverges from the others after about 2010.

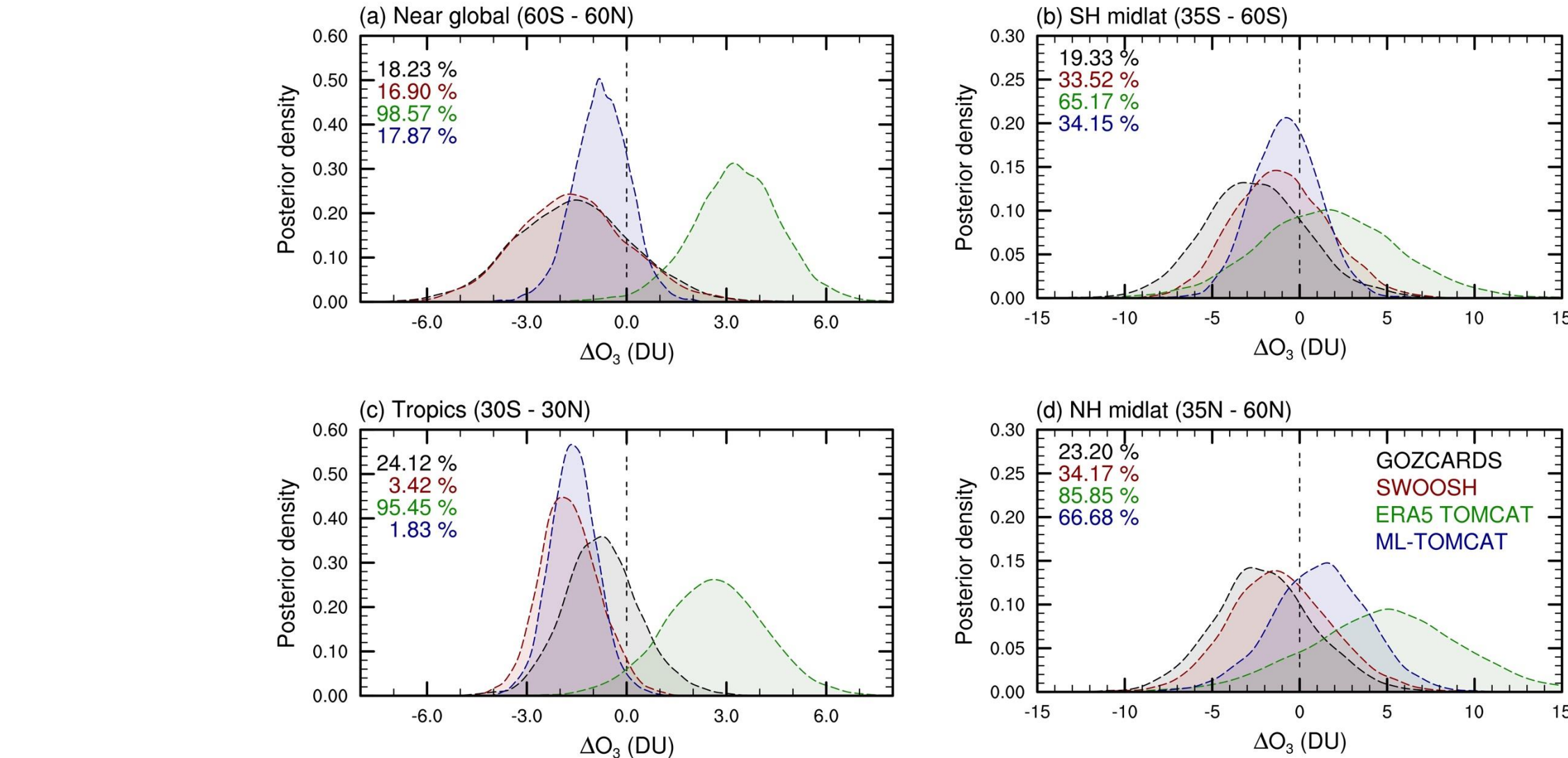


Figure 4. Posterior distributions (shaded) for the net ozone change in the LS PCO between 1998 through 2025, from the MCMC samples of each dataset for 4 separate latitude bands as in Figure 2 following the same colour code introduced above. The numbers at the top-left corner of each panel denote the percentage of the distribution that is positive (i.e. ozone recovery).

Key points

- **Near-global and tropics:** GOZCARDS, SWOOSH and ML-TOMCAT lean toward decline (probabilities of 24% or less;). ERA5-TOMCAT shows very probable increases (> 95 %).
- **Mid-lats:** in observational datasets show a more probable O₃ decline than ERA5 TOMCAT and ML-TOMCAT – overlap is better in the SH mid-lats, NH mid-lats most uncertain.
- **ERA5 TOMCAT** shows the most discrepancies relative to the other three datasets with a very positive ΔO₃ overall but its probability is most uncertain in the SH mid-lats.

4. SUMMARY

- **Extending the Bayesian DLM analysis through 2025 confirms a persistent, coherent decline in LS O₃ in both GOZCARDS and SWOOSH satellite composites, across all latitude bands — uncertainty is increasing with time (arising mostly from the tropics).**
- **Agreement in the overall magnitude of the US O₃ recovery across all datasets.**
- **ERA5 TOMCAT continues to simulate a strong O₃ recovery trend over the same period— despite tracking the interannual variability with fidelity. The divergence post 2010 is potentially associated with underlying circulation trends in ERA5 reanalysis.**
- **ML-TOMCAT shows an improvement in the LS O₃ changes – aligning much closer to the observational dataset trends.**
- **Posterior probabilities show the model–observation sign disagreement remains robust in the near-global and tropical LS while in the mid-latitudes, NH especially, remain too uncertain to differentiate.**
- **Next steps include exploring the attribution of the trends to transport and chemical processes**

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THE PROJECT WAS FUNDED BY ESA
CONTRACT NO. 4000137112/22/I-AG
(OREGANO)
<https://www.iup.uni-bremen.de/OREGANO/>

