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A Large Ozone-Circulation Feedback & Its Implications for Global Warming Assessments

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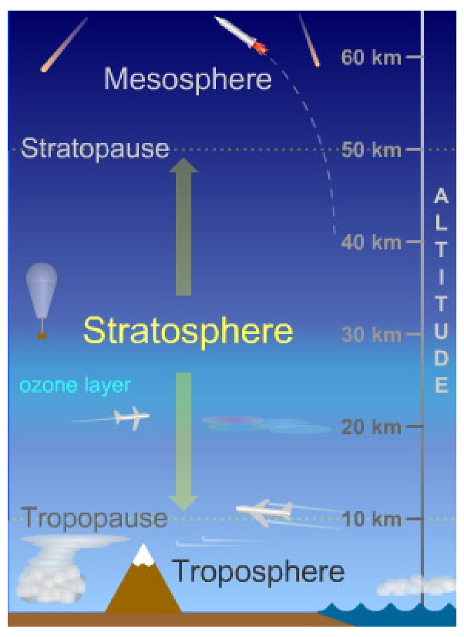
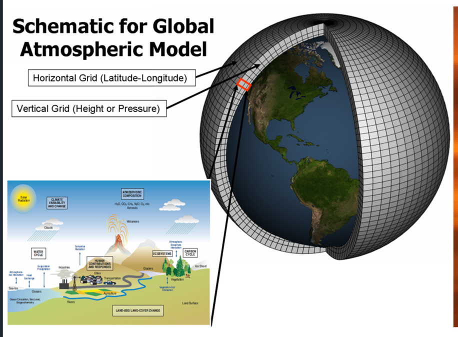
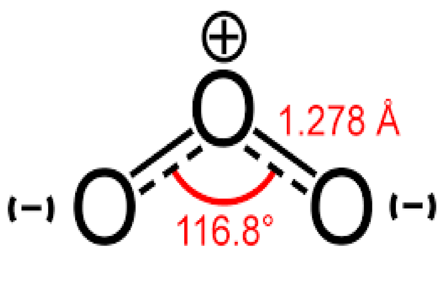
1. BACKGROUND

- Climate change is one of the greatest challenges that human civilisation will face in the 21st century
  → realistic model projections are crucial for an informed climate policy.
- Climate models become more and more sophisticated
  → by incorporating an ↑ number of earth system processes
  → due to ↑ scientific understanding
  → due to ↑ model resolutions
- In spite of steadily ↑ computing power, many processes can still not be considered in climate change simulations.
- **Stratospheric chemistry-climate interactions are a classic example of processes which are commonly *not* treated interactively**, i.e. are not allowed to adapt consistently to the modelled changes of the environment (to avoid high computational costs).







Aim: To isolate the impact of neglecting changes in stratospheric O_3 in a state-of-the-art climate model.

2. MODEL CONFIGURATION

- HadGEM3 model (UMUKCA-AO configuration)[1,2].
- **Atmosphere/land-surface** = Unified Model @ vn7.3 from the UK Met Office, resolution: 3.75°lon x 2.5°lat, 60 vert levs ≤ 84 km.
- **Chemistry** scheme = Chemistry for the Stratosphere (CheS) developed in the UK Chemistry and Aerosol (UKCA) project[3].
- Interactive **ocean** (NEMO[4], ≲2° resolution, 31 vert levs > -5km) and **sea-ice** (CICE[5]) models.

3. MODEL SIMULATIONS

- **piControl**: $[CO_2]$ = 285 ppmv.
- **Abrupt 4xCO_2**: $[CO_2]$ abruptly ↑ to 1140 ppmv.
- **Interactive** and **non-interactive** versions
  → Non-interactive runs using prescribed monthly-mean climatologies of O_3, CH_4, N_2O.
- **3D/2D climatologies (X)** = non-interactive runs using full 3D or zonal mean (2D) chemical climatologies from interactive run X.

Label	Description	Chemistry
A	piControl	Interactive
A1	piControl	3D climatologies (A)
A2	piControl	2D climatologies (A)
B	Abrupt 4xCO_2	Interactive
B1	Abrupt 4xCO_2	3D climatologies (B)
B2	Abrupt 4xCO_2	2D climatologies (B)
C1	Abrupt 4xCO_2	3D climatologies (A)
C2	Abrupt 4xCO_2	2D climatologies (A)

6. OZONE & WATER VAPOUR CHANGES

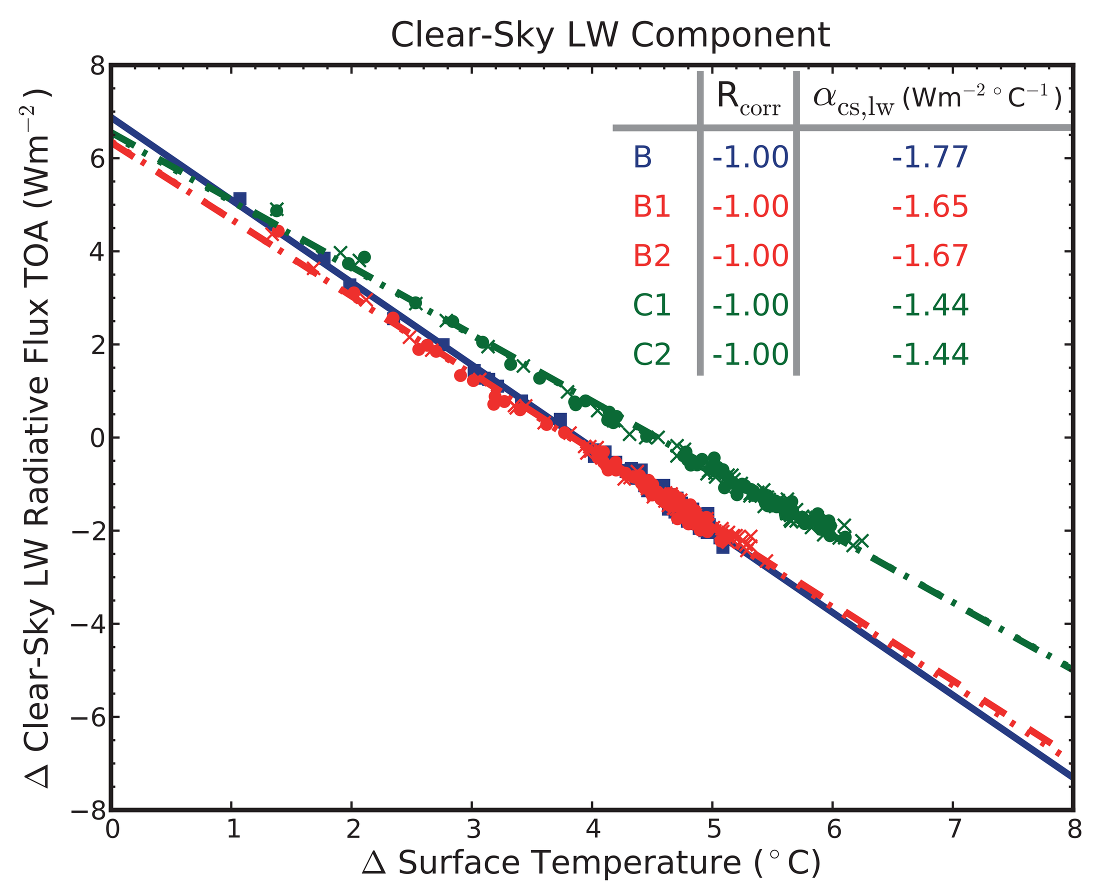
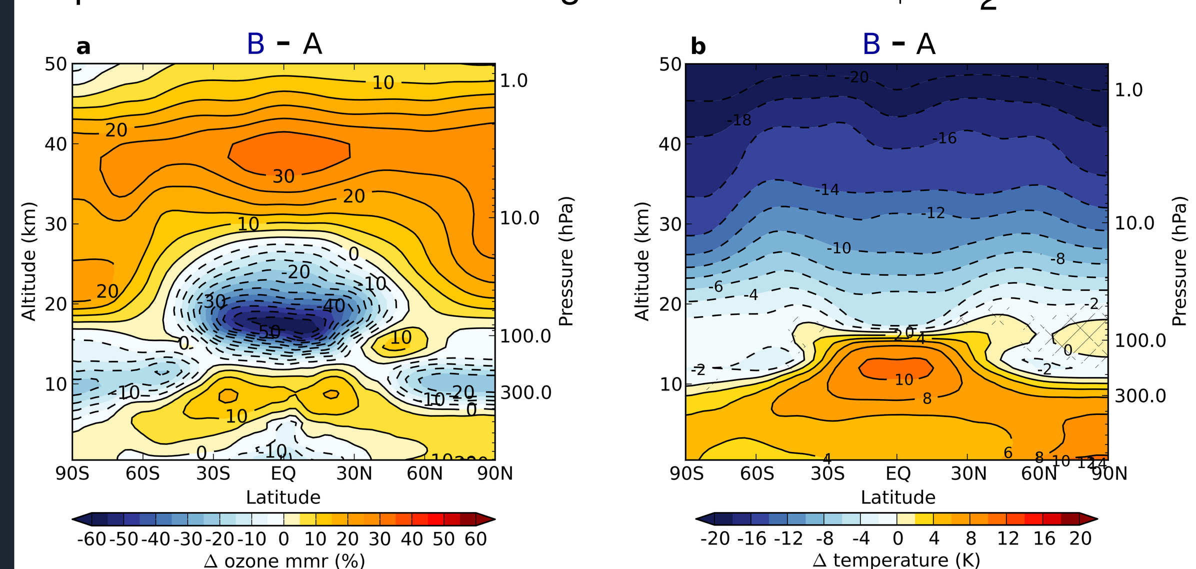


Figure 3 | Gregory regression plot for the CS-LW component.

- $\Delta\alpha_{CS,LW}$ must be due to Δ in greenhouse gases other than CO_2.
- Under 4xCO_2: O_3 ↑ in the upper stratosphere (~30-50km) and ↓ in the lower tropical stratosphere (~20 km, 30N-30S, Figure 4a).
- Explanation for the O_3 ↑: T-dependency of O_3 depletion cycles

$$X + O_3 \rightarrow XO + O_2$$
$$XO + O \rightarrow X + O_2$$

  with the catalytic radical species X (e.g. NO, OH, Cl), which slow down with stratospheric cooling under 4xCO_2 (Figure 4b)[7].
- Explanation for the O_3 ↓: acceleration of the wave-driven stratospheric meridional overturning circulation under ↑ CO_2[8].



- 30N-30S: ΔO_3 → ΔT due to SW/LW absorption/emission (Fig. 4c)
  → important due to trop. to strat. air transport in this region.
- Cooling effect of ΔO_3 in the lower strat. = regulating factor for entry of water vapour into the strat. (Clausius-Clapeyron, Figure 4c/4d).
- O_3 and water vapour = greenhouse gases → greenhouse effect ↓
  → RF of -0.68Wm^{-2} (O_3)/-0.78Wm^{-2} (water vapour) → ΔCS-LW.

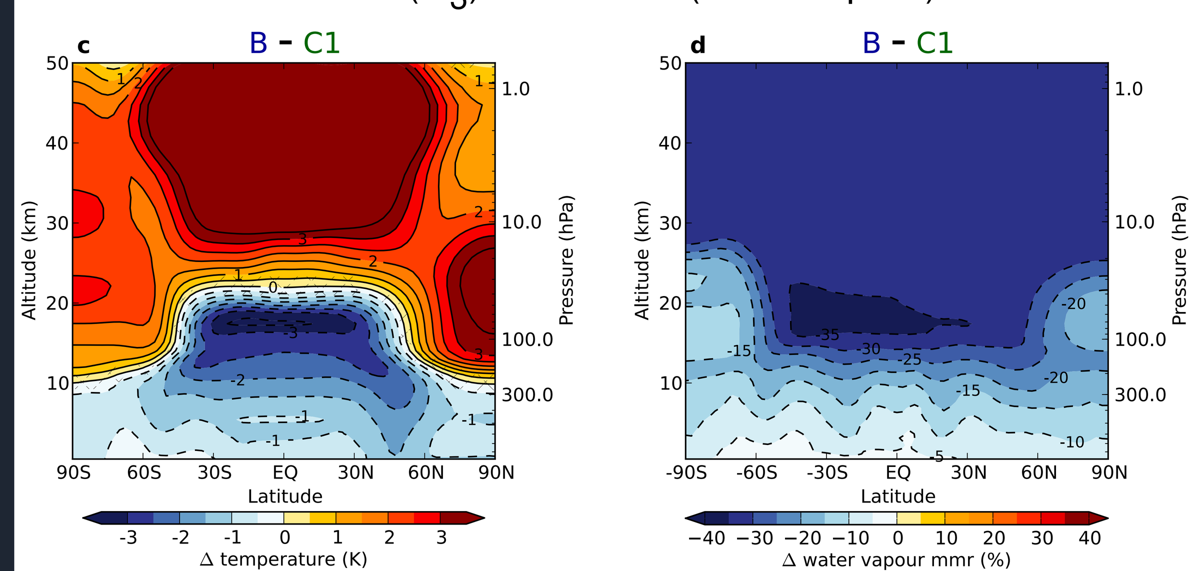


Figure 4 | Annual, zonal mean differences. Runs as labelled. **a** ΔO_3 by 4xCO_2, **b** ΔT by 4xCO_2, **c** ΔT by ΔO_3 and **d** Δwater vapour by ΔO_3.

4. GLOBAL WARMING RESPONSE

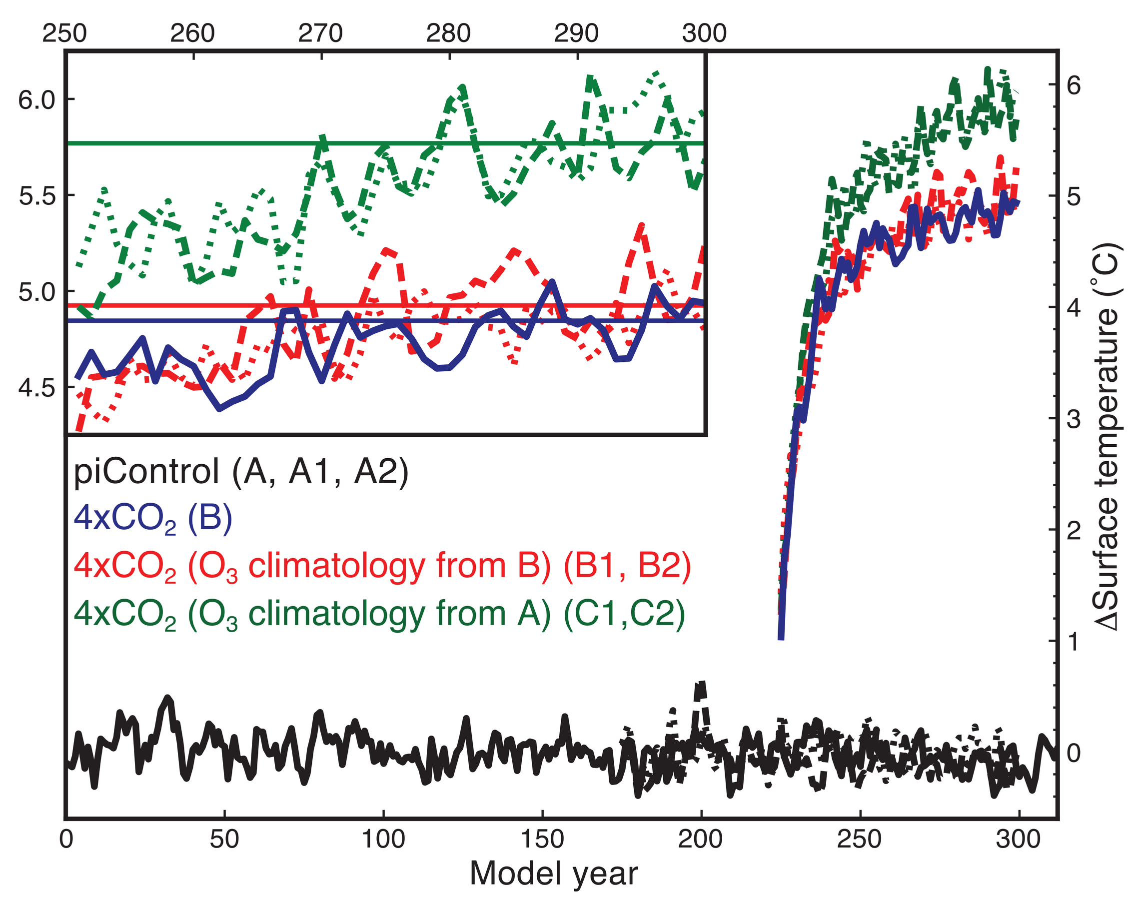


Figure 1 | Temporal evolution of the annual and global mean surface temperature anomalies. Interactive chemistry runs are given in solid lines, dashed/dotted lines show 3D/2D non-interactive experiments.

Ignoring O_3 feedback → ~20% greater warming!

5. ENERGY BUDGET ANALYSIS

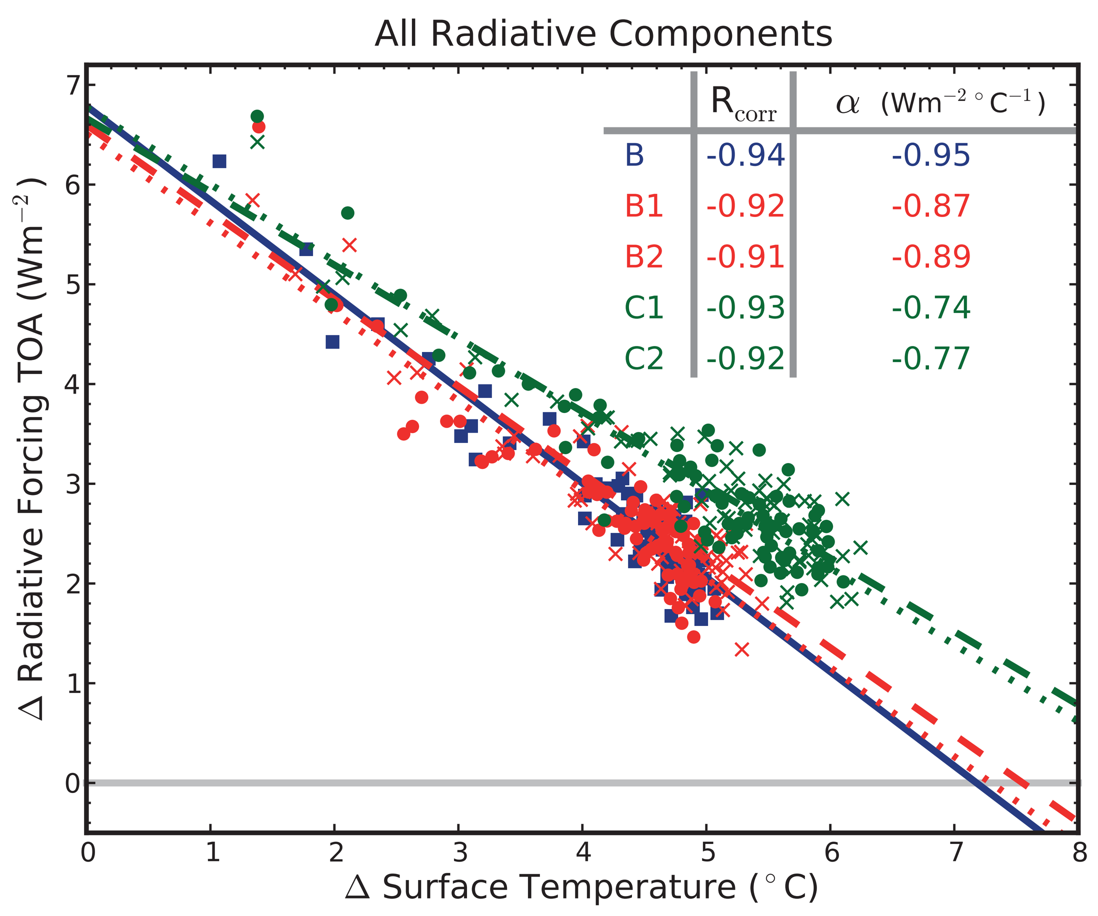


Figure 2 | Gregory regression plot for the net change in TOA radiative fluxes. The Δ in the slopes (α) are consistent with the ΔT (~20%).

The linear regression methodology for diagnosing climate forcing and feedbacks established by Gregory *et al.*[6] uses a nearly linear relationship between the change in the Top of the Atmosphere (TOA) radiative imbalance *N* and global mean $\Delta T_{surface}$

$$N = F + \alpha \Delta T_{surface}$$

with the parameters *F*=effective radiative forcing (Wm^{-2}) and α (Wm^{-2}K^{-1}), a measure for the linear superposition of all feedback processes → decomposition into shortwave (SW) and longwave (LW) clear-sky (CS) and cloud radiative effect (CRE)

$$\alpha = \alpha_{CS} + \alpha_{CRE} = \alpha_{CS,SW} + \alpha_{CS,LW} + \alpha_{CRE,SW} + \alpha_{CRE,LW}$$

→ can be calculated from analogous regressions (Figures 3 & 5).

7. CLOUD CHANGES

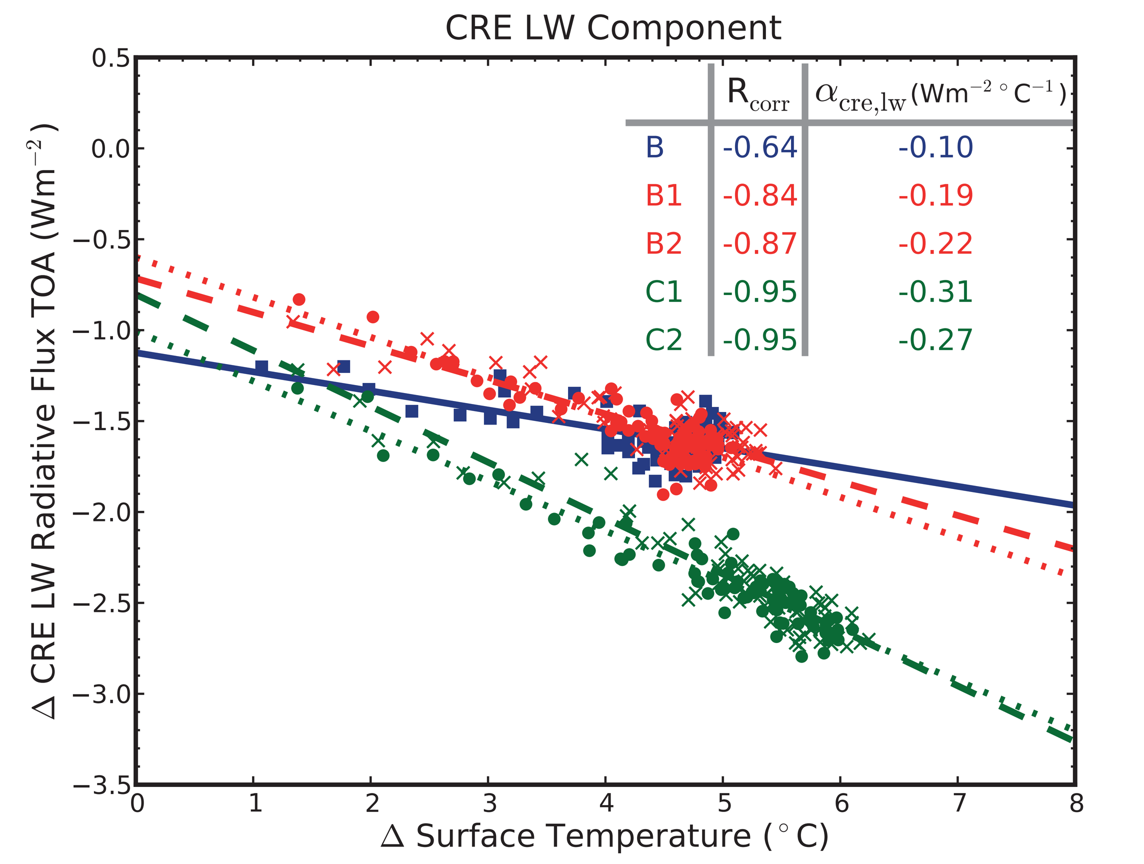


Figure 5 | Gregory regression plot for the CRE-LW component.

- Cloud feedbacks = great uncertainty factor in global warming[9].
- $\Delta\alpha_{CRE,LW}$ between C1/C2 and B is of opposite sign to $\Delta\alpha_{CS,LW}$
  → more positive feedback → reduces the overall effect!
- $\alpha_{CRE,LW}$ range of -0.3 to -0.1Wm^{-2}K^{-1} only due to ΔO_3 → large compared to -0.3 to 0.4Wm^{-2}K^{-1} found in 15 state-of-the-art models[10].

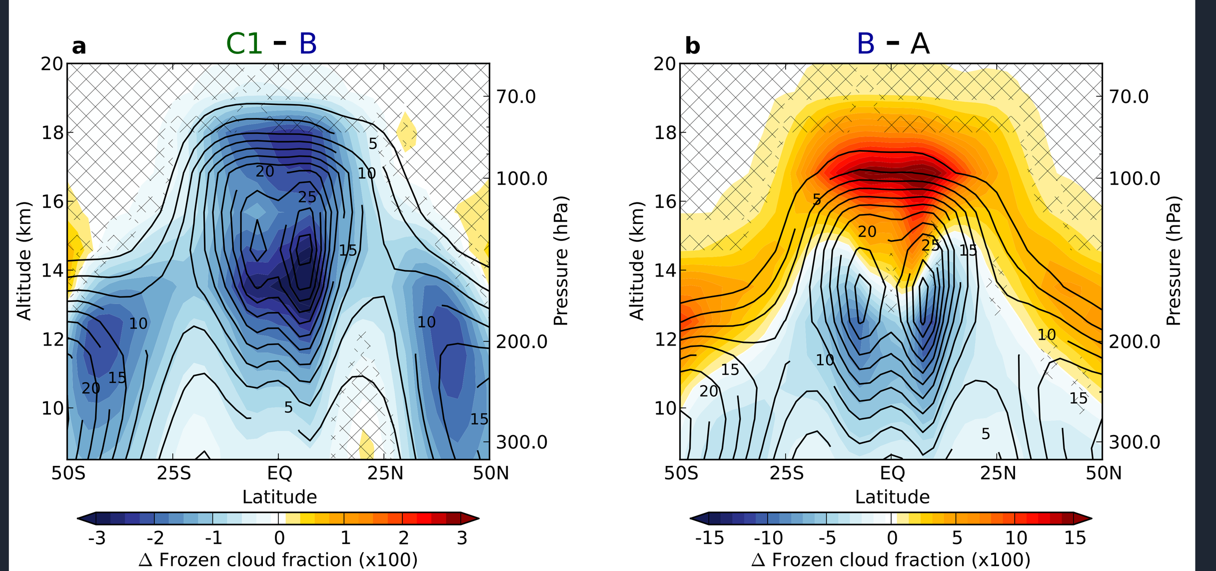


Figure 6 | Δ Annual, zonal mean frozen cloud fraction. Runs as labelled. Non-significant Δ are crossed out (95% confidence level Student's t-test).

- $\Delta\alpha_{CRE,LW}$ can be explained by changes in upper tropospheric to lower stratospheric ice clouds (greater LW than SW impact).
- Ice cloud formation = function(T, vertical T-gradient)[11]
  → more ice clouds formed in B (additional cooling due to ΔO_3).

8. CONCLUSIONS

- The large impact of changes in ozone on the here estimated effective climate sensitivity implies a need for model- and scenario-specific treatment of ozone in global warming assessments.
- Future work has to assess this often neglected factor in a range of state-of-the-art climate models.

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