

# On the Role of Dynamical Uncertainties in the Spread of Arctic Ozone Recovery Projections



Natalia Calvo<sup>1,2</sup>, Samuel Benito-Barca<sup>1</sup>, Marta Abalos<sup>1</sup>, Blanca Ayarzagüena<sup>1</sup>, Álvaro de la Cámara<sup>1</sup>, Gabriel Chiodo<sup>2</sup>, H. Akiyoshi, F. Dennison, P. Jöckel, B. Josse, D. Kinnison, O. Morgenstern, D. Plummer, T. Sukhodolov, Y. Yamashita, S. Watanabe

<sup>1</sup> Earth Physics and Astrophysics Department, Universidad Complutense de Madrid, Madrid, Spain, <sup>2</sup> Instituto de Geociencias (IGEO), CSIC-UCM, Madrid, Spain

## MOTIVATION

- Future projections of the **polar vortex** show large uncertainties, with some models featuring a strengthening and others a weakening in response to climate change.
- The deep branch of the **residual circulation** typically shows an acceleration in models under increasing greenhouse gases but also present large uncertainties in their projected evolution.

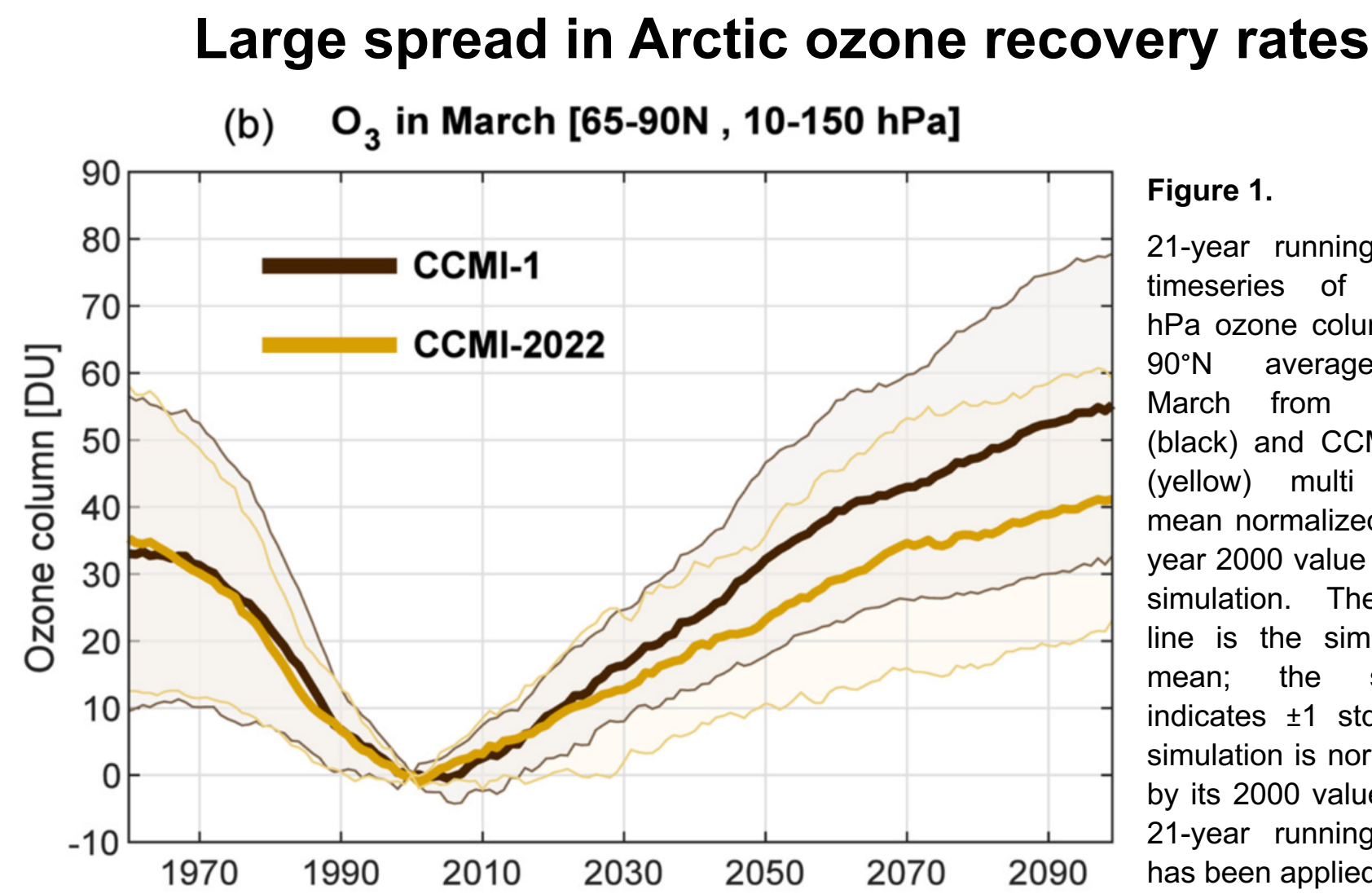


Figure 1. 21-year running mean timeseries of 10-150 hPa ozone column, 65-90°N averaged, in March from CCMI-1 (black) and CCMI-2022 (yellow) multi model mean normalized to the year 2000 value in each simulation. The thick line is the simulations mean; the shading indicates  $\pm 1$  std. Each simulation is normalized by its 2000 value and a 21-year running mean has been applied.

### OUR GOAL

Determine to what extent the **large spread in ozone recovery rates** (Figure 1) is related to uncertainties in the projected evolution of **dynamical features**.

## DATA: CCMI-1 & CCMI-2022 models

| CCMI-1 (ref-C2)   |         |                     |     |      |
|-------------------|---------|---------------------|-----|------|
| Model             | # simul | O <sub>3</sub> ,U,T | TEM | EESC |
| ACCESS-CCM        | 2       | ✓                   | ✓   |      |
| CCSRNIES-MIROC3.2 | 2       | ✓                   | ✓   | ✓    |
| CHASER-MIROC      | 1       | ✓                   |     | ✓    |
| CMAM              | 1       | ✓                   | ✓   | ✓    |
| EMAC-L47          | 2       | ✓                   | ✓   | ✓    |
| EMAC-L90          | 1       | ✓                   | ✓   | ✓    |
| GEOSCCM           | 1       | ✓                   | ✓   | ✓    |
| HadGEM3-ES        | 1       | ✓                   |     |      |
| MRI-ESM           | 1       | ✓                   | ✓   | ✓    |
| NIWA-UKCA         | 5       | ✓                   | ✓   |      |
| SOCOL3            | 1       | ✓                   | ✓   | ✓    |
| UMSLIMCAT         | 1       | ✓                   |     | ✓    |
| UMUKCA-UCAM       | 2       | ✓                   |     |      |
| WACCM             | 3       | ✓                   | ✓   |      |

| CCMI-2022 (ref-D2) |         |                     |     |      |
|--------------------|---------|---------------------|-----|------|
| Model              | # simul | O <sub>3</sub> ,U,T | TEM | EESC |
| ACCESS-CM2-Chem    | 1       | ✓                   | ✓   |      |
| CCSRNIES-MIROC3.2  | 1       | ✓                   | ✓   | ✓    |
| CESM2-WACCM        | 3       | ✓                   | ✓   | ✓    |
| CMAM               | 3       | ✓                   | ✓   | ✓    |
| CNRM-MOCAGE        | 4       | ✓                   |     | ✓    |
| EMAC               | 3       | ✓                   | ✓   | ✓    |
| MIROC-ES2H         | 3       | ✓                   | ✓   | ✓    |
| NIWA-UKCA2         | 3       | ✓                   |     |      |
| SOCOL*             | 3       | ✓                   |     |      |

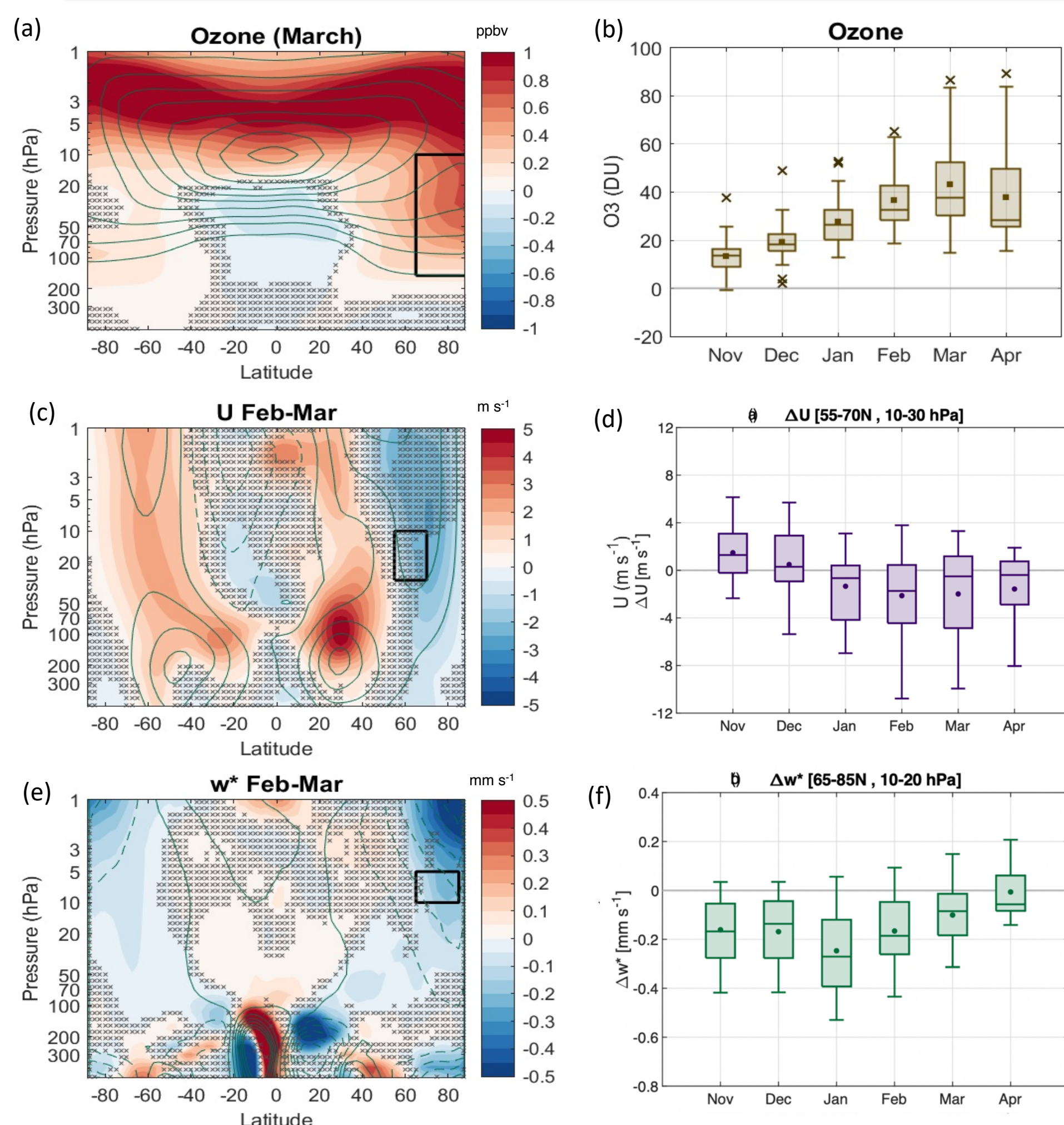
\* Only available for 1980-2099

- 140 years** of simulation (1960-2099)
- Scenarios:** ref-C2 → RCP6.0  
ref-D2 → ssp2-4.5
- Changes between 1991-2020 and 2070-2099** are analyzed.

## RESULTS

### 1. Projected changes and spread across CCMI models

Large spread in projected changes in CCMI models for both ozone recovery and dynamical features

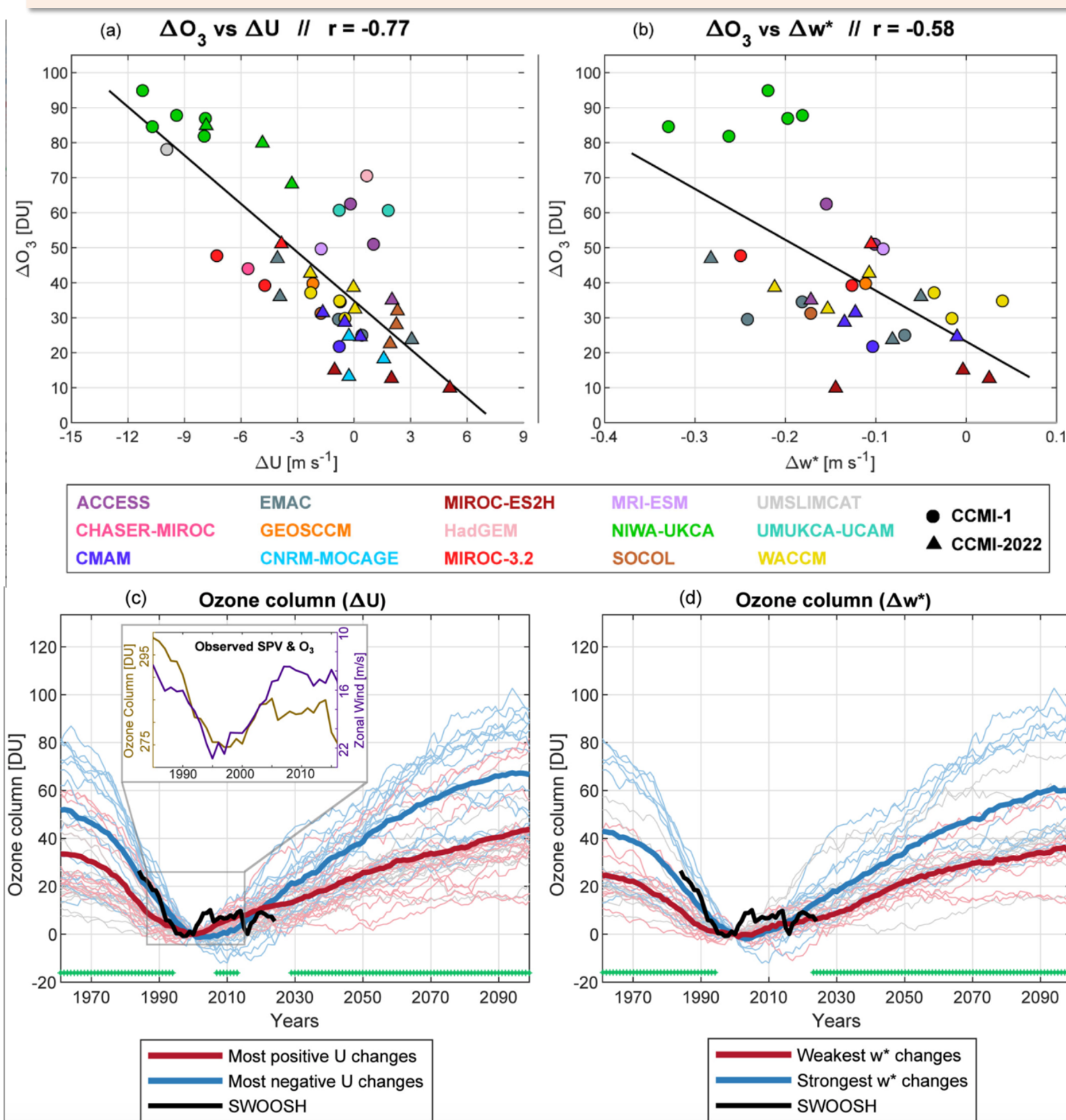


- The largest **spread** in the **ozone recovery** is in **March** (b)
- The spread in the **stratospheric polar vortex (SPV)** evolution is largest in **February-March**, with approximately 2/3 of the simulations projecting a weakening and the other third a strengthening (d).
- The largest changes and uncertainties in downwelling ( $w^*$ ) appear in December-January (f), but the spread in ozone recovery in March is **best explained by  $w^*$  in February-March** (Section 2).

Figure 2. (Left column) Projected changes between 1991-2020 and 2070-2099; CCMI-1 and CCMI-2022 all simulations mean. Black crosses represent regions where less than 75% of the simulations agree on the sign of the change. Black boxes illustrate selected regions for Arctic ozone, polar vortex, and residual circulation. (Right column) Boxplots showing the distribution of changes between 1991-2020 and 2070-2099 in CCMI-1 and CCMI-2022 simulations in the regions indicated by the black boxes in the left column.

### 2. Role of U and $w^*$ changes in Arctic ozone recovery

Significant separation in Arctic ozone recovery between simulations with negative and positive stratospheric polar vortex (SPV) changes and between strong and weak acceleration of the residual circulation.



- ~60% of the inter-model **spread** in Arctic **ozone recovery** in **March** can be explained by uncertainties in the future evolution of the **SPV (Feb-Mar)**
- ~33% of the variance can be explained by changes in **polar downwelling (Feb-Mar)**
- When both changes in zonal mean zonal winds (U) and  $w^*$  are used together as predictors in a MLR model, the explained ozone recovery variance is 75%.
- Simulations with the **largest change in future ozone** (and in polar vortex or polar downwelling) also simulate the largest ozone loss in the past and agree very well with observations in the 90s but not in the 2000's (observed decadal variability not reproduced in models)

Figure 3. (Top) Scatterplot of changes (2070-2099 minus 1991-2020) in Arctic ozone versus (a) polar vortex and (b) polar downwelling. (bottom): time series of March Arctic ozone (65-90N, 10-150hPa) normalized to year 2000 value for each simulation. In panel c) the blue (red) lines represent the third of simulations with the most negative (positive) changes in the polar vortex from panel (a), and (panel d) the third of simulations with strongest (weakest) increase in polar downwelling from panel (b). The embedded figure in panel c) shows the SWOOSH observations of Arctic ozone in light brown and ERA5 polar vortex strength (Feb-Mar) in purple. Thick lines are the mean of each group. Black line for SWOOSH observations. Green dots in c-d indicate when the two groups of simulations are significantly different at 95% using a t-test.

### 3. Contribution of ODSs and GHGs to the spread of Arctic ozone recovery rates

$$O_3(t) = \alpha \cdot GW(t) + \beta \cdot ODS(t) + \varepsilon(t)$$

Global mean surface air temperature ("Global Warming")

Equivalent effective stratospheric chlorine (ODS) over the polar cap at 50 hPa

Both ODSs and GHGs contribute significantly to the spread in ozone recovery rates in both CCMI-1 and CCMI-2022.

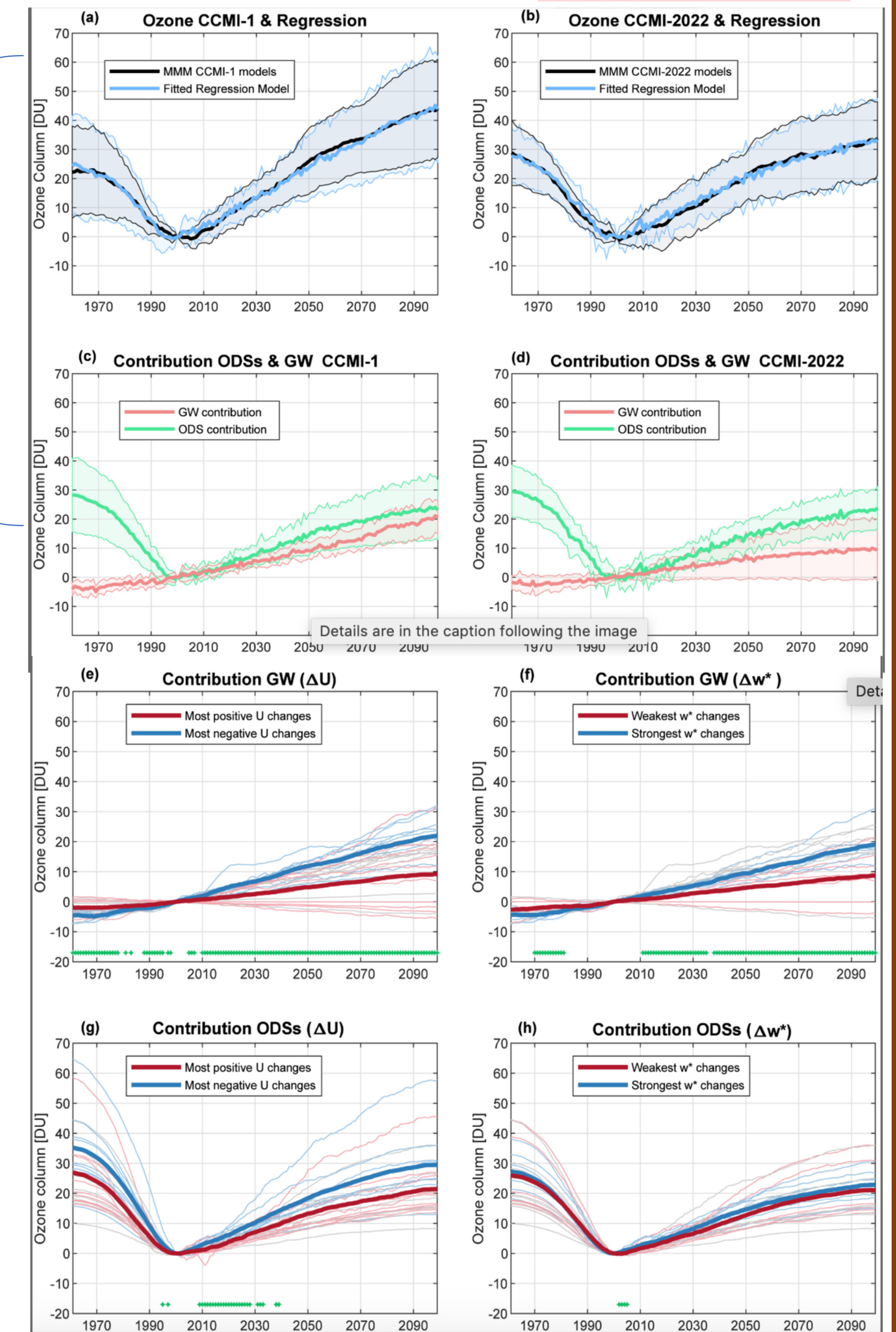


Figure 4. (a,b) Black line represents the MMM original time series of March Arctic ozone normalized to year 2000, with a 21-year running mean applied, while the light blue line displays the linear fit from the regression model for a subset of a) CCMI-1 and b) CCMI-2022 simulations. (c,d) Contributions of ozone-depleting substances (ODS, green line) and global warming (GW, in red) to the Arctic ozone evolution in c) CCMI-1 and d) CCMI-2022 simulations. In panels a-d, the light envelopes indicate the multimodel standard deviation. (e-h) Same as (a,b) but for (e,f) GW contribution and (g,h) ODS contribution. Green dots in (e-h) indicate when the two simulation groups (blue and red) are significantly different at 95% using a t-test.

- The **GW contribution to ozone recovery** (Fig.4 e,f) is significantly different between simulations with extreme change in both SPV and downwelling. This means that simulations with the largest weakening of the SPV and/or the strongest acceleration of polar downwelling simulate a faster ozone recovery associated with GW.
- The **ODS contribution to ozone recovery** (Fig.4 g,h) shows non-significant differences between subsets of simulations that project strong/weak SPV at the end of the century. Thus, the contribution of ODS decline to ozone recovery does not occur through changes in dynamics (i.e. wind changes and downwelling).

## CONCLUSIONS ( Benito-Barca et al. GRL 2026; doi: 10.1029/2025GL120212)

- 70% of the intermodal spread in the Arctic ozone recovery in March can be attributed to uncertainties in dynamical trends in late winter. 60% is related to uncertainties in the Stratospheric polar vortex (SPV) trends, and 33% to uncertainties in polar downwelling trends. The larger the weakening of the SPV and/or strengthening of the polar downwelling, the faster the recovery of Arctic ozone.
- The simulated ozone recovery can be clearly separated into distinct groups based on dynamical changes in the polar stratosphere. However, the large decadal variability of the Arctic stratosphere in NH late winter, particularly of the SPV during the 90s and 2000s, prevents the identification of an observational constraint on future ozone recovery.
- Contributions of the projected decline in Ozone Depleting Substances and GHG-driven Global Warming are important drivers to explain the uncertainty in Arctic ozone recovery rates. Global Warming only affects the ozone recovery spread via its effects on uncertainty in stratospheric circulation trends.