

Impact of SSW frequency uncertainty on future Northern Hemisphere surface temperature extremes

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1 – Motivation

Sudden stratospheric warmings (SSWs) are extreme disruptions of the wintertime polar circulation (polar vortex) that can **alter tropospheric weather for over two months**¹ and potentially influence the occurrence of **surface extreme events**².

Climate models show large **uncertainty** in the future response of the stratospheric polar vortex to CO₂ increase³, and they even disagree on the sign of the response in SSW frequency, with some projecting an increase and others a decrease as a response to CO₂⁴.

**Is the SSWs-troposphere connection going to change in the future?
Are these changes model dependent?**

2 – Data & Methods

12 CMIP6 climate models:

- High top models (9/12)
- Simulations: pre-industrial conditions (piControl) vs quadrupling CO₂ concentrations (abrupt-4xCO₂)

Climate models classification:

Based on the sign of the future change in SSWs frequency

Models with a negative change in SSWs (NEG)

Models with a positive change in SSWs (POS)

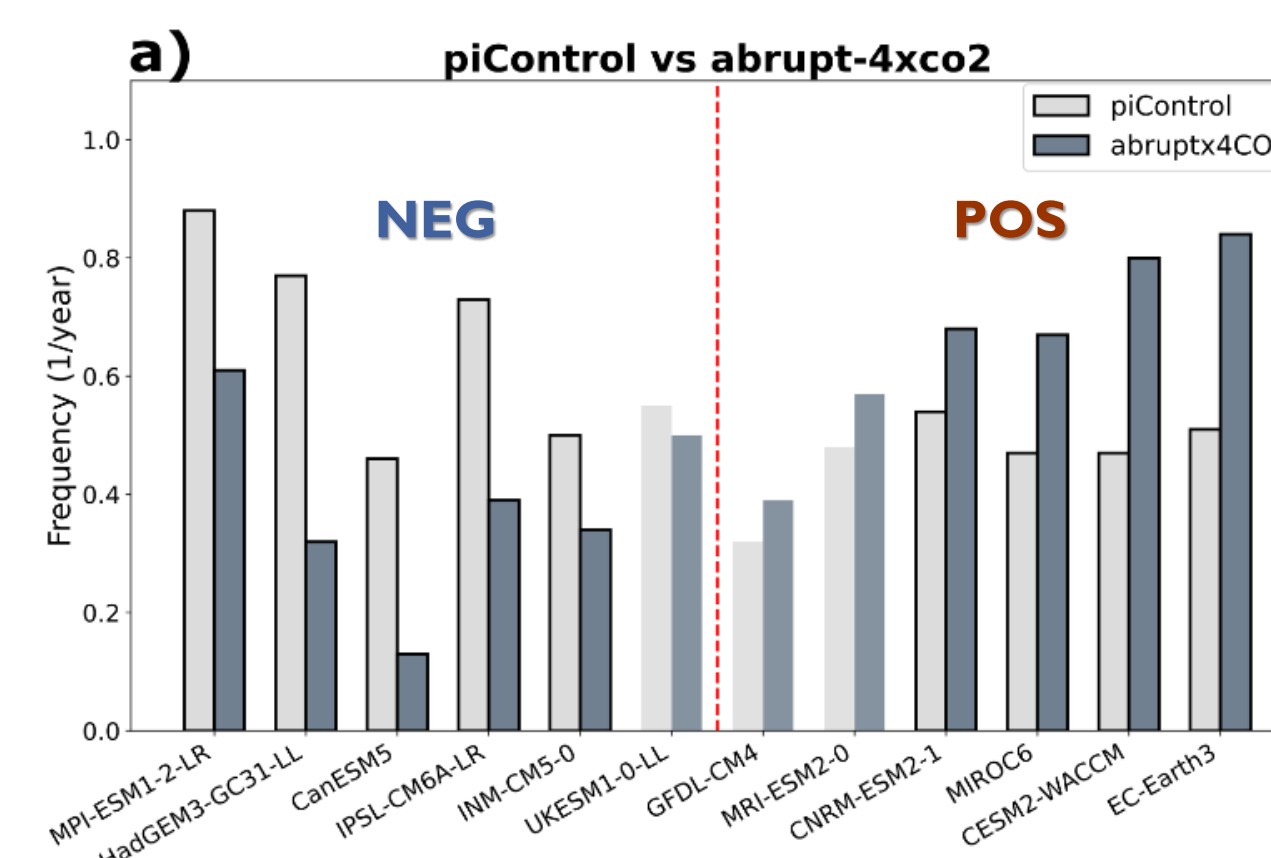


Figure 1: Average annual SSW frequency in the piControl (light grey) and abrupt4xCO₂ (dark grey) simulations. Models with black contours represent significant changes at a 95% confidence level

3 – Stratosphere-troposphere coupling during SSWs

3.1 Polar vortex intensity:

NEG models: strengthening of the polar vortex

POS models: weakening or no change.

This is closely related with the initial state of the winds at 70hPa 45-55°N (UNECK).

Positive correlation: **UNECK (pi) vs ΔU_{10hPa}** (Figure 2)

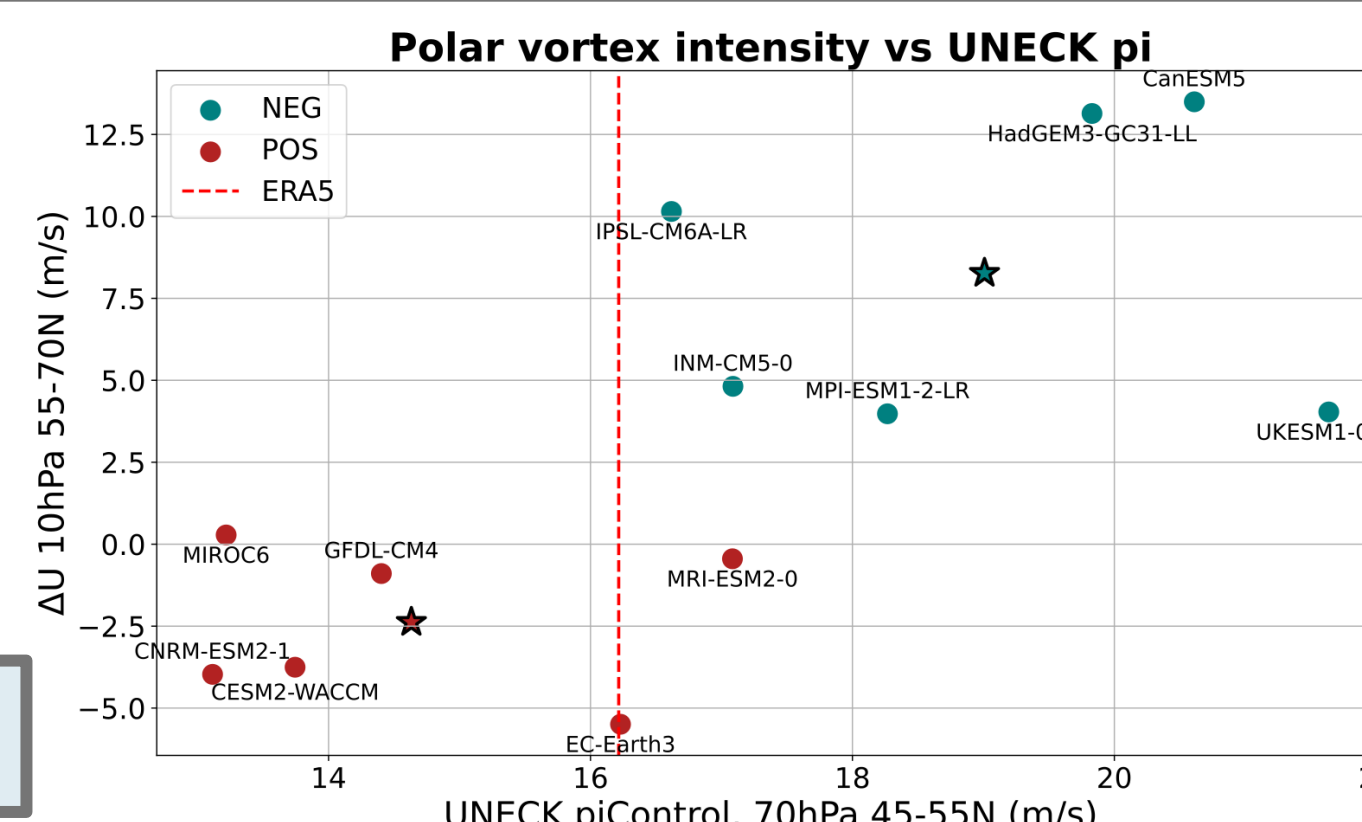


Figure 2: Scatter plot of the UNECK at 70 hPa, 45°N-55°N vs ΔU_{10hPa} . Models with decreasing SSWs frequencies (NEG) are marked in blue and models with increasing SSWs frequencies (POS) in red. Red dotted line represents ERA5 climatological value.

3.3 SSWs Surface impacts:

Sea level pressure (SLP): Near-surface circulation anomalies intensify due to increased CO₂ in the North Atlantic region particularly in **NEG models**.

Surface temperature (TAS): SSW impacts on TAS do not change except for Barent-Kara Sea where sea ice loss could be heavily affected.

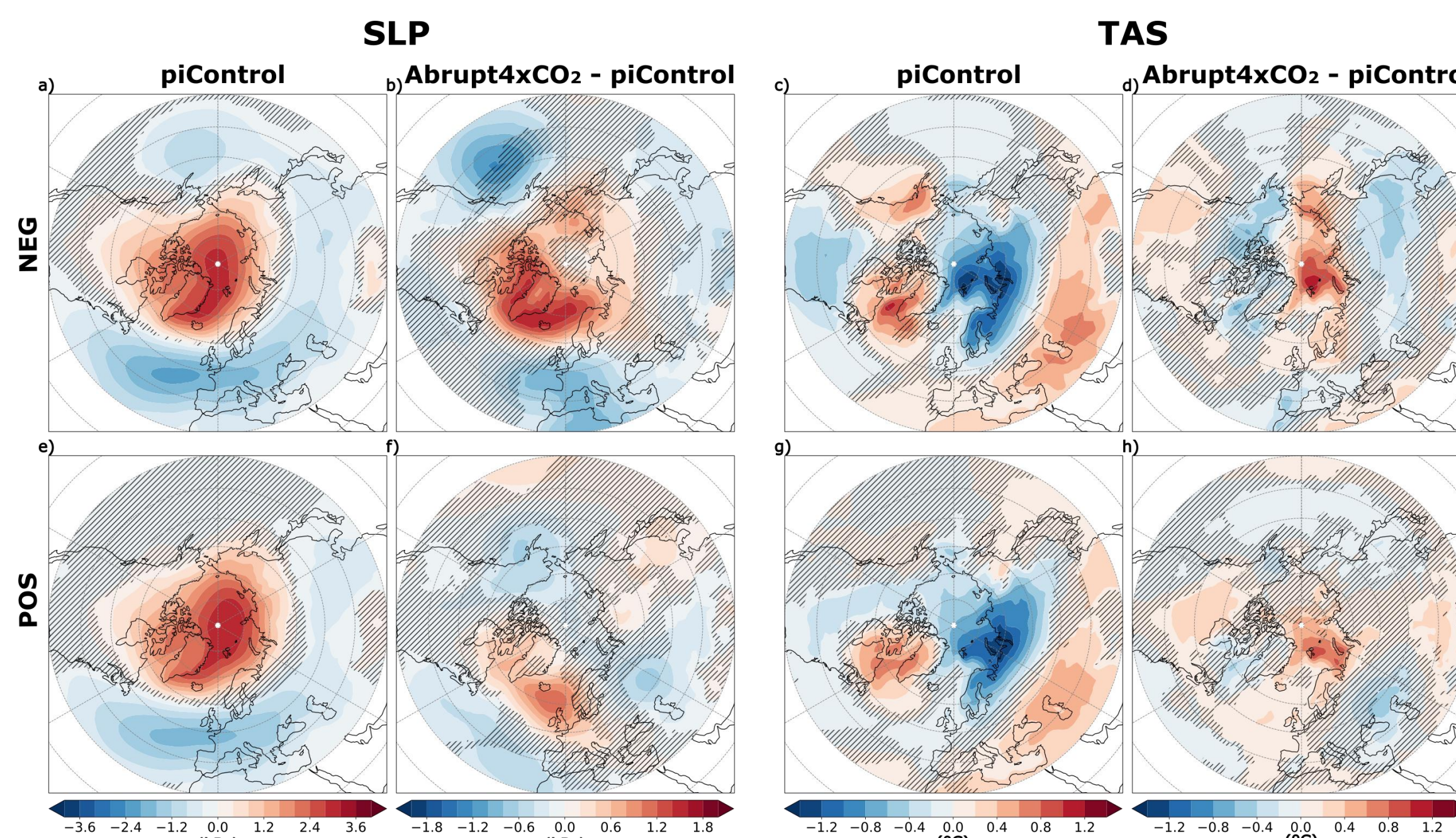


Figure 4: Composites of averaged SLP anomalies (shading, hPa) over days (0,60) relative to the SSWs onset for the multimodel mean for piControl simulation for (Top row) NEG models and (Bottom row) POS models and Differences abrupt4xCO₂ minus piControl. Stripes represent non-significant values at a 95% confidence level.

Larger differences in SLP and TAS in **NEG models**. They show **stronger significant SSWs surface impacts (intensified NAM-)** as a response to the CO₂ increase (Figure 4).

3.2 SSWs precursors and downward propagation of the stratospheric signal:

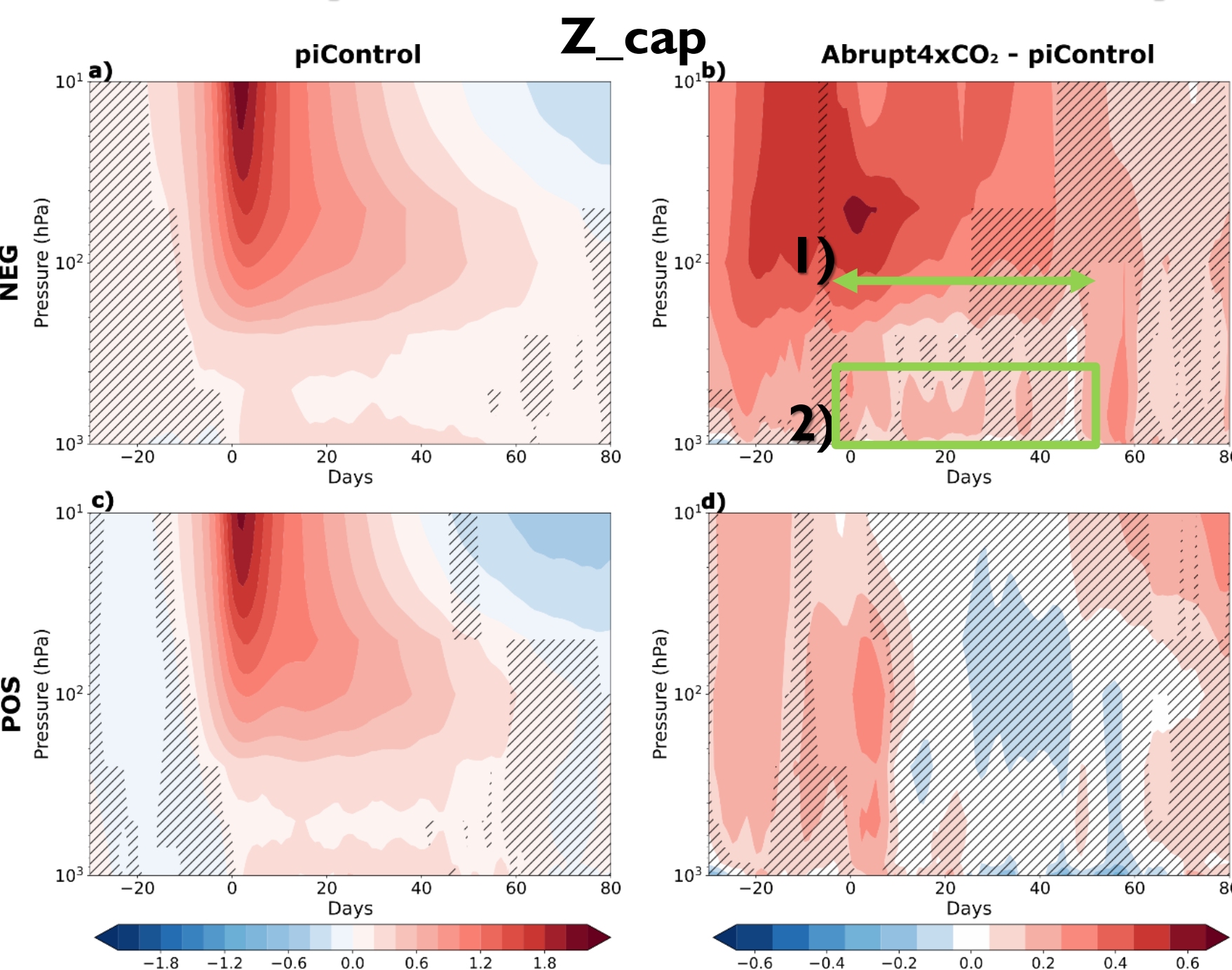


Figure 3: Standardized geopotential height anomalies for the polar cap (65°-90°) for SSWs composites from (-30, 80) days relative to the onset: (a,c) piControl simulation for multimodel mean NEG and POS models respectively, (b,d) abrupt4xCO₂ - piControl simulation for multimodel mean NEG and POS models. Stripes represent non-significant values at a 95% confidence level.

SSWs precursors:

NEG models show a **significant increase** in anomalous extratropical eddy heat flux at 100 hPa during the 5 days preceding the SSW onset in the abrupt-4xCO₂

Downward propagation:

Stronger SSWs precursors lead to a **stronger** downward propagation in **NEG models** in the abrupt4xCO₂ (Figure 3):

- 1) More persistence at 100hPa
- 2) Stronger signal reaching surface
- 3) Increased percentage of Downward (DW) propagating events

4 – SSW and surface temperature extreme events

Scandinavian cold spells:

Cold spells over Scandinavia are the most affected by SSWs influence (~1/3 of cold spells are preceded by an SSW).

The canonical SLP response to SSWs resembles the atmospheric circulation associated with cold spells over the Scandinavia region (Figure 5).

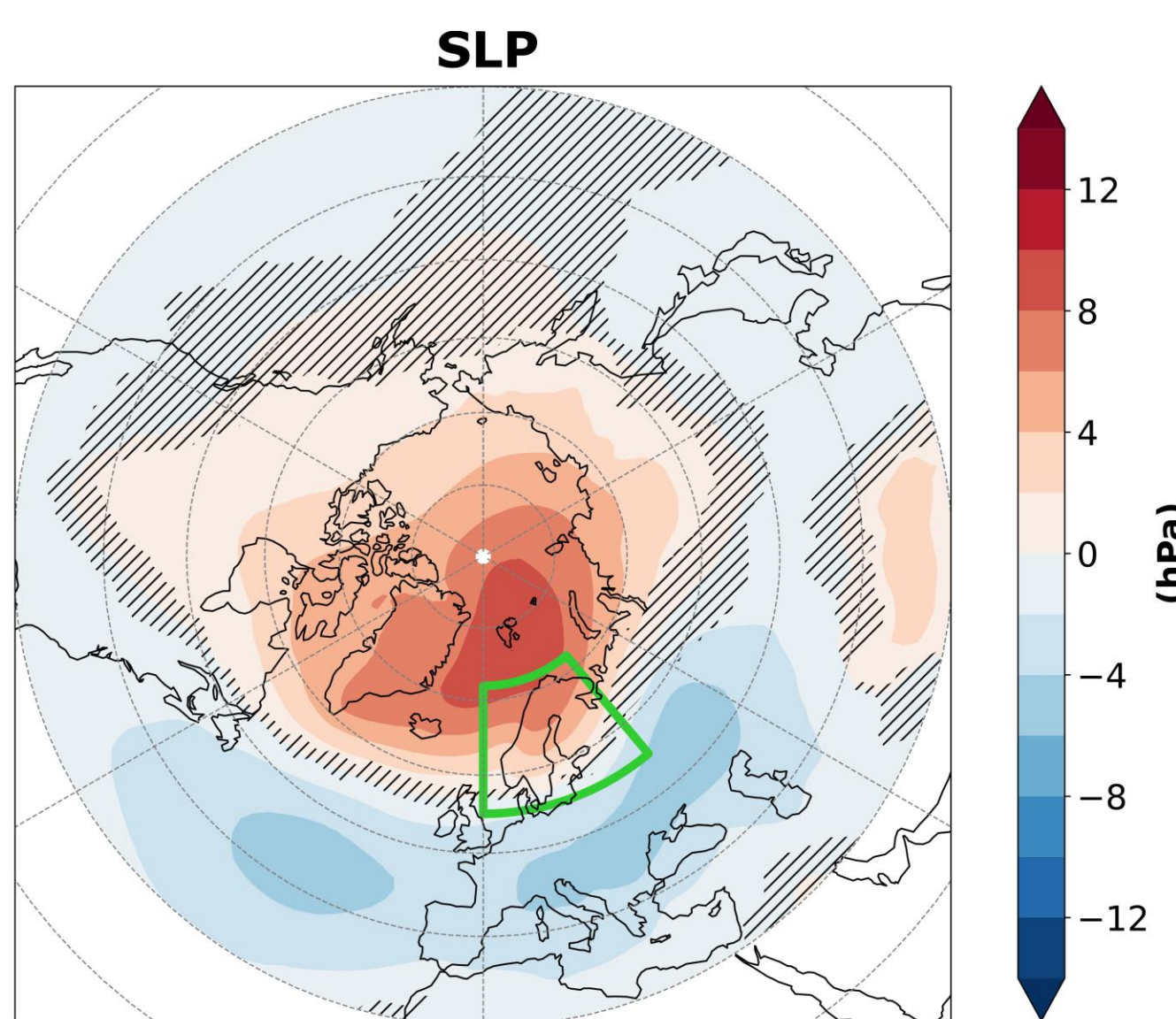
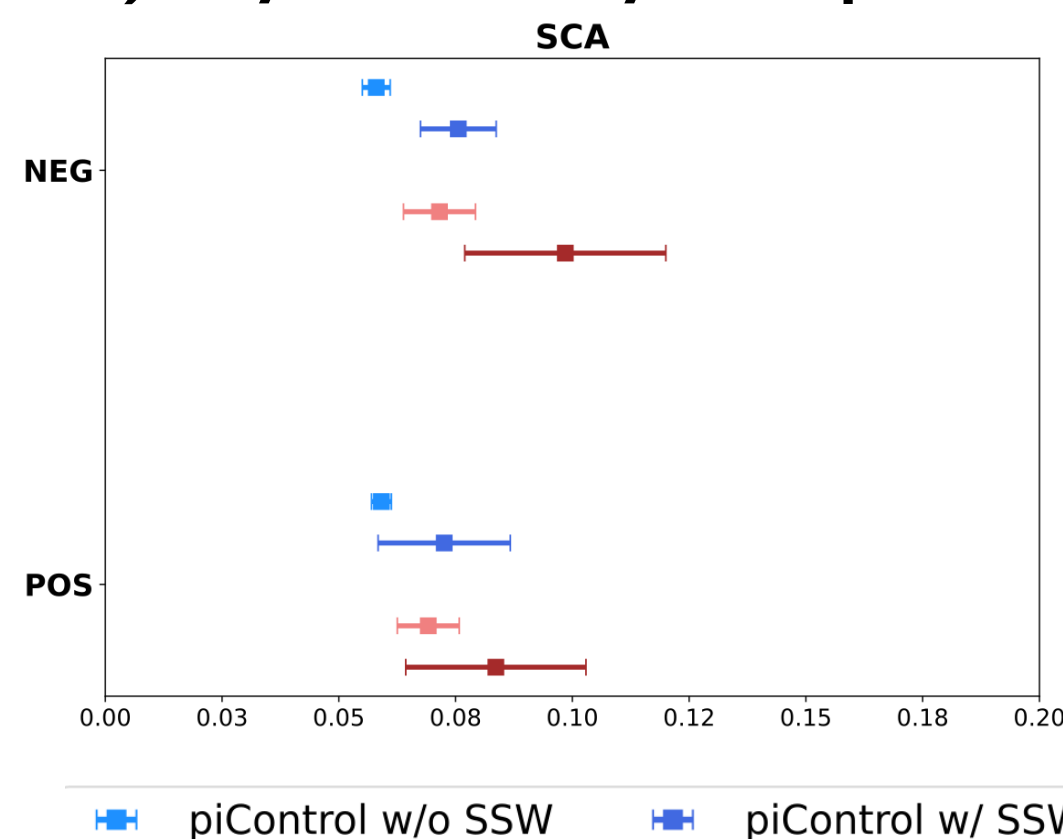


Figure 5: Composites of the averaged SLP anomalies for SSWs-related cold spells in Scandinavia in the piControl simulation for the multimodel mean. Stripes represent non-significant values at a 95% confidence level.

a) Days affected by cold spells



b) Duration of cold spells

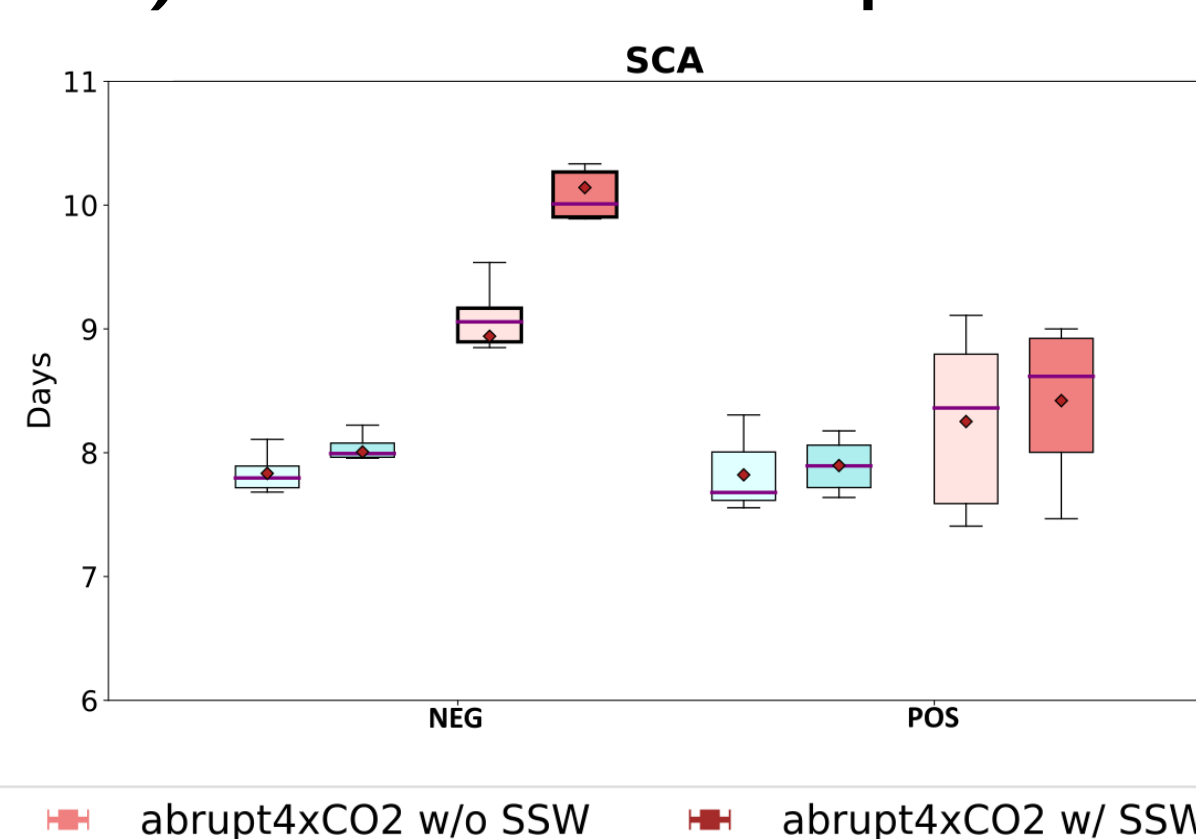


Figure 6: a) Probability of days affected by a surface extreme event in Scandinavia. Bars represent ± 1 standard deviation. b) Boxplots of the multimodel distribution of surface extreme event duration. Black contours represent significant changes at a 95% confidence level.

Pre-Industrial:

- There is an **increased risk (~25%)** in the probability of occurrence of days affected by cold spells after an SSW
- Cold spells following SSWs **tend to be more persistent**, but the difference is not statistically significant

Response to 4xCO₂:

- The probability of days affected by cold spells increases even more in **NEG models**
- Cold spells are more persistent after an SSW specially in **NEG models** where the duration is up to **10 days**

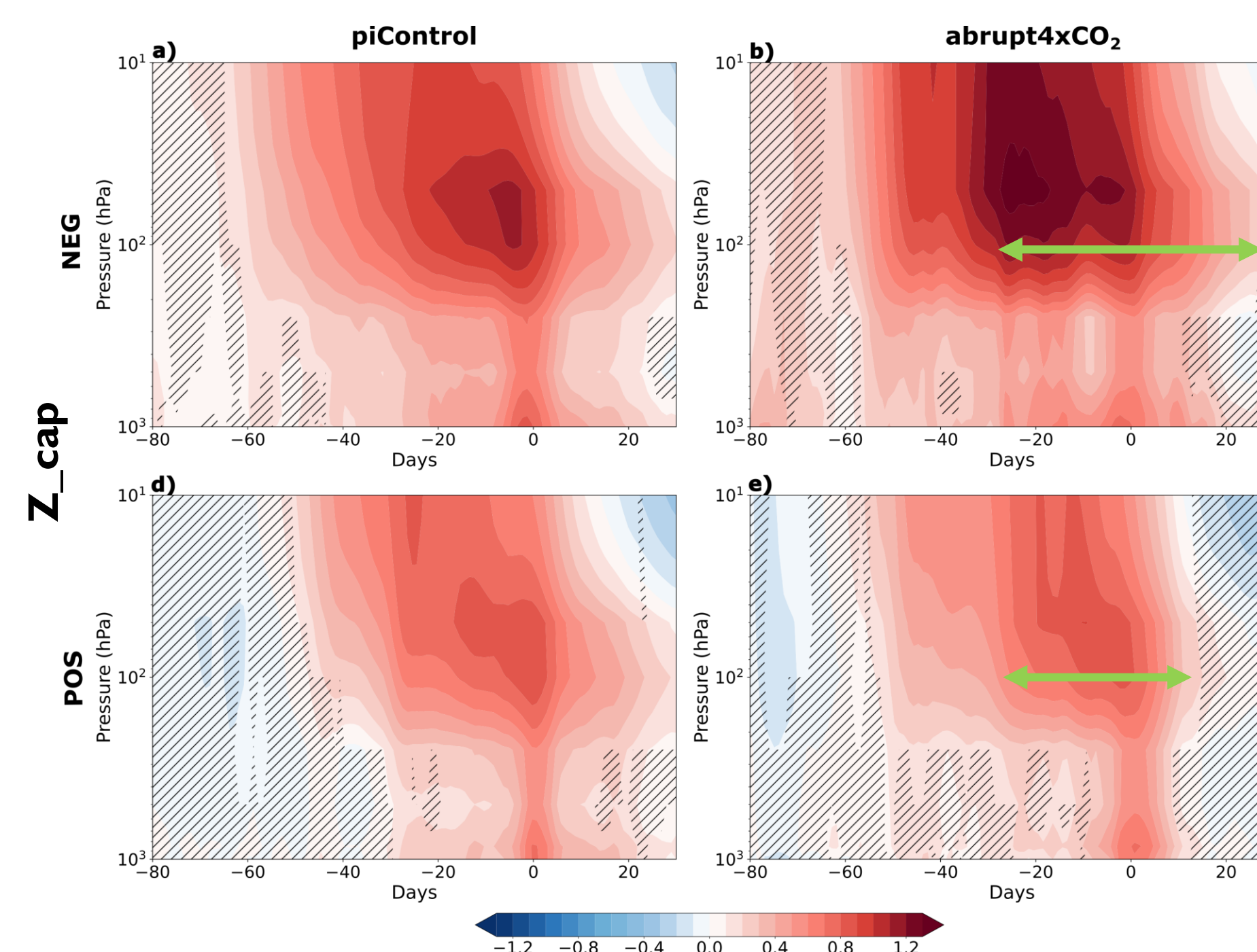


Figure 7: Composite maps of standardized geopotential height anomalies for the polar cap (65°-90°N) for SSWs-related cold spells in Scandinavia from (-80, 30) days relative to the onset of the extremes. Panels (a, d) show results from the piControl simulation and (b, e) for abrupt4xCO₂ simulation for the multimodel mean of NEG and POS models, respectively. Stripes represent non-significant values at a 95% confidence level.

The favorable conditions for cold spells following SSWs are intensified due to CO₂ increase, especially in **NEG models** where the downward propagation is stronger (Figure 7).

5 – Conclusions

- The sign of the change in the SSW frequency also affects the downward propagation of their signal under increased CO₂ concentrations. **NEG models** simulate a longer persistence of the SSW anomalies in the lower stratosphere in the abrupt4xCO₂ run compared to the piControl, leading to a stronger signal reaching the surface.

- SSWs favor the occurrence of days affected by cold spells over the Scandinavian region. They also tend to prolong the duration of these extremes. These impacts are larger for **NEG models** in the abrupt4xCO₂ simulation where there is a stronger downward propagation of the SSW signal caused by the larger persistence in the lower stratosphere.



¹ Baldwin, M. P., Ayarzagüena, B., Birner, T., Butchart, N., Butler, A. H., Charlton-Perez, A. J., et al. (2021). 809 Sudden Stratospheric Warmings. *Reviews of Geophysics*, 59(1).

² Domeisen, D. I. V., & Butler, A. H. (2020). Stratospheric drivers of extreme events at the Earth's surface. 841 *Communications Earth and Environment*. Nature Publishing Group.

³ Karpechko, A. Y., Afargan-Gerstman, H., Butler, A. H., Domeisen, D. I. V., Kretschmer, M., Lawrence, Z., et al. 911 al. (2022). Northern Hemisphere Stratosphere-Troposphere Circulation Change in CMIP6 Models: 1. Inter-912 Model Spread and Scenario Sensitivity. *Journal of Geophysical Research: Atmospheres*, 127(18).

⁴ Ayarzagüena, B., Charlton-Perez, A. J., Butler, A. H., Hitchcock, P., Simpson, I. R., Polvani, L. M., et al. 796 (2020). Uncertainty in the Response of Sudden Stratospheric Warmings and Stratosphere-Troposphere 797 Coupling to Quadrupled CO₂ Concentrations in CMIP6 Models. *Journal of Geophysical Research: 798 Atmospheres*, 125(6).