Robust polar amplification in ice-free climates relies on ocean heat transport and cloud radiative effects

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Polar amplification is a robust feature of climate change in the modern-day climate. However, previous climate modelling studies fundamentally do not agree on whether polar amplification occurs in ice-free climates. In this study, we find in a state-of-the-art climate model that, if ocean heat transport is neglected, the response to an increase in CO_2 is not polar amplified, whereas robust polar amplification occurs if ocean heat transport is included. Using targeted model experiments, we diagnose cloud radiative effects as the driver of this divergent behaviour. We conclude that polar amplification is a robust feature of the atmosphere-ocean system. Our results have important implications for interpreting past warm climates and future projections under high emissions scenarios.

In the absence of sea ice loss, does polar amplification occur?

It is well established that sea ice loss is a major contributor to polar amplification (whereby the polar surface warms more than the rest of the globe under increased radiative forcing)[1]. However, a number of recent modelling studies have disagreed on whether polar amplification is also a robust feature of ice-free climates.

✓ Refs 2, 3, and 4 conclude that polar amplification is <u>an inherent and ubiquitous response of a moist atmosphere</u>, and does not rely on the presence of sea ice.

✗ Refs 5, 6, 7 and 8 suggest that <u>polar amplification does not occur in ice-free climates</u>.

How can we reconcile this discrepancy and further our understanding of the drivers of polar amplification? There was one consistent difference between the two sets of slab ocean aquaplanet based studies: polar amplification is present in simulations with prescribed climatological q-fluxes and is lacking in simulations with zero climatological q-fluxes.

Hence, we were motivated to investigate the role of climatological OHT in enabling polar amplification in ice-free climates.

Slab ocean aquaplanet simulations in CESM2-CAM6 and CESM1-CAM5

- 30m mixed layer depth
- Symmetrised, zonally-averaged ozone and aerosol input
- No representation of sea ice
- Each simulation run for 120 years, averaging over years 21-120
- For each q-flux profile, we performed a 1xCO_2 and a 4xCO_2 simulation

Four experiments (see Fig 1):

1. Zero q-flux (i.e. no OHT)
2. Annual-mean q-flux taken from CESM2 1850 control run
3. Annual-mean q-flux taken from last 500 years of 4xCO2 CESM2 run which have near-zero ice cover
4. As in (2) but with full seasonal cycle

Note that prescribed q-flux is identical for 1xCO_2 and 4xCO_2 simulations: we are investigating the role of climatological OHT, not the role of OHT changes.

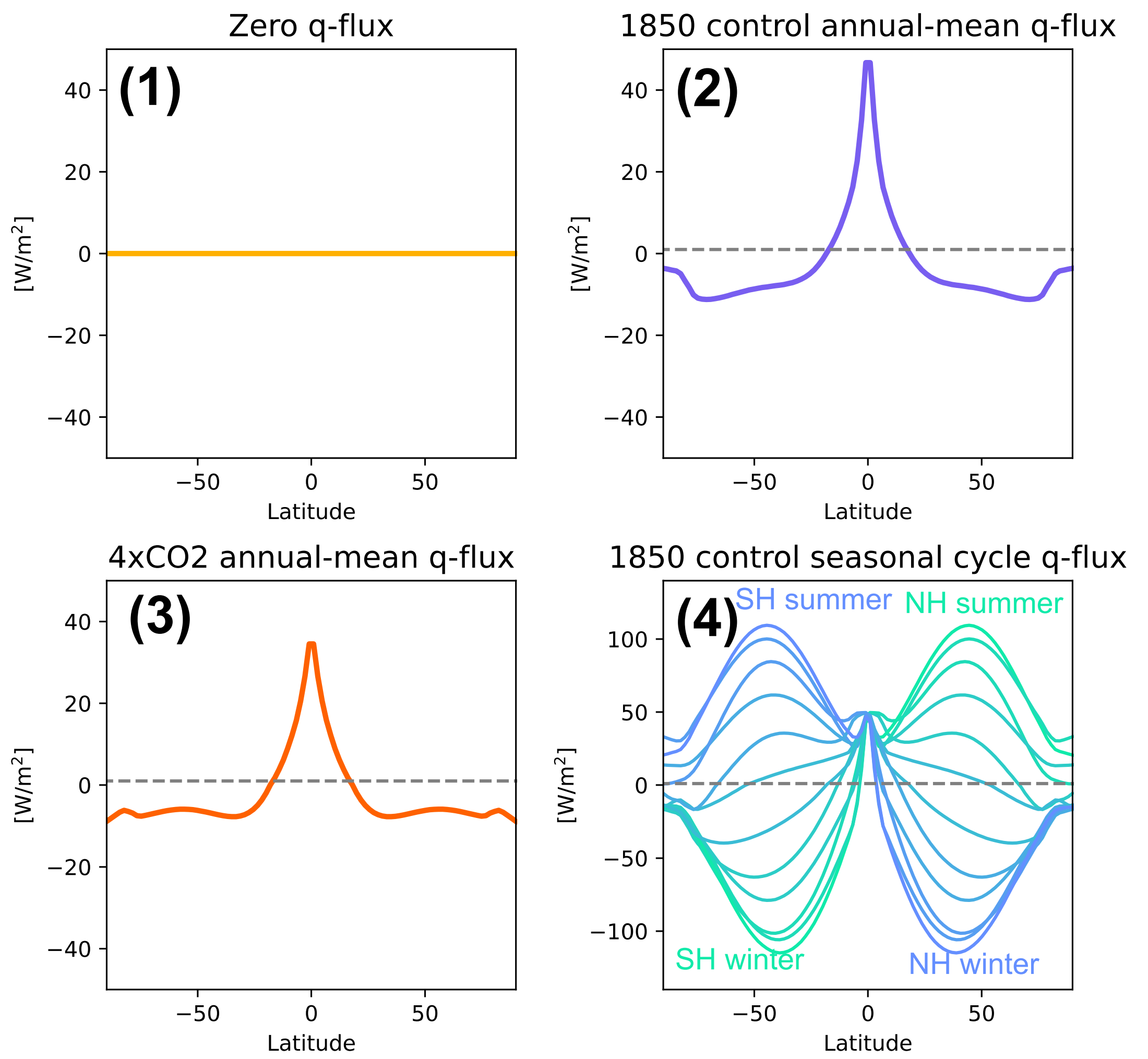


Figure 1: Q-flux profile used in CAM6 and CAM5 slab ocean simulations experiments 1-4. Note the extended vertical axis scale for experiment 4. Here positive values denote a heat sink from the atmosphere to the ocean and negative values denote a heat source from the ocean to the atmosphere.

1. Screen and Simmonds (2010), The central role of diminishing sea ice in recent Arctic temperature amplification, *Nature*. **2. Russotto and Biasutti (2020),** Polar Amplification as an Inherent Response of a Circulating Atmosphere: Results From the TRACMIP Aquaplanets, *GRL*. **3. Langen et al (2012),** Separation of Contributions from Radiative Feedbacks to Polar Amplification on an Aquaplanet, *J. Clim*. **4. Armour et al (2019),** Meridional Atmospheric Heat Transport Constrained by Energetics and Mediated by Large-Scale Diffusion, *J. Clim*. **5. Shaw and Smith (2022),** The Midlatitude Response to Polar Sea Ice Loss: Idealized Slab-Ocean Aquaplanet Experiments with Thermodynamic Sea Ice, *J. Clim*. **6. Kim et al (2018),** Sensitivity of Polar Amplification to Varying Insolation Conditions, *J. Clim*. **7. Feldl et al (2017),** Coupled high-latitude climate feedbacks and their impact on atmospheric heat transport, *J. Clim*. **8. Dai et al (2019),** Arctic amplification is caused by sea-ice loss under increasing CO_2, *Nat Comms*. **9. Middlemas et al (2020)**, *GRL*.

Occurrence of polar amplification in CESM2 aquaplanet predetermined by climatological ocean heat transport (OHT)

- With zero climatological q-flux, the response to 4xCO_2 is in fact polar stabilised (Fig 2b) with less warming at the poles than the rest of the globe (—). This effect is largest in the summer, suggesting a role for shortwave feedbacks.
- After implementing a realistic representation of OHT (— , — , —), robust polar amplification occurs under 4xCO_2.
- Including the full seasonal cycle of 1850 Control OHT (compare — and —), does not change the magnitude of polar amplification (Fig 2b and 2c).

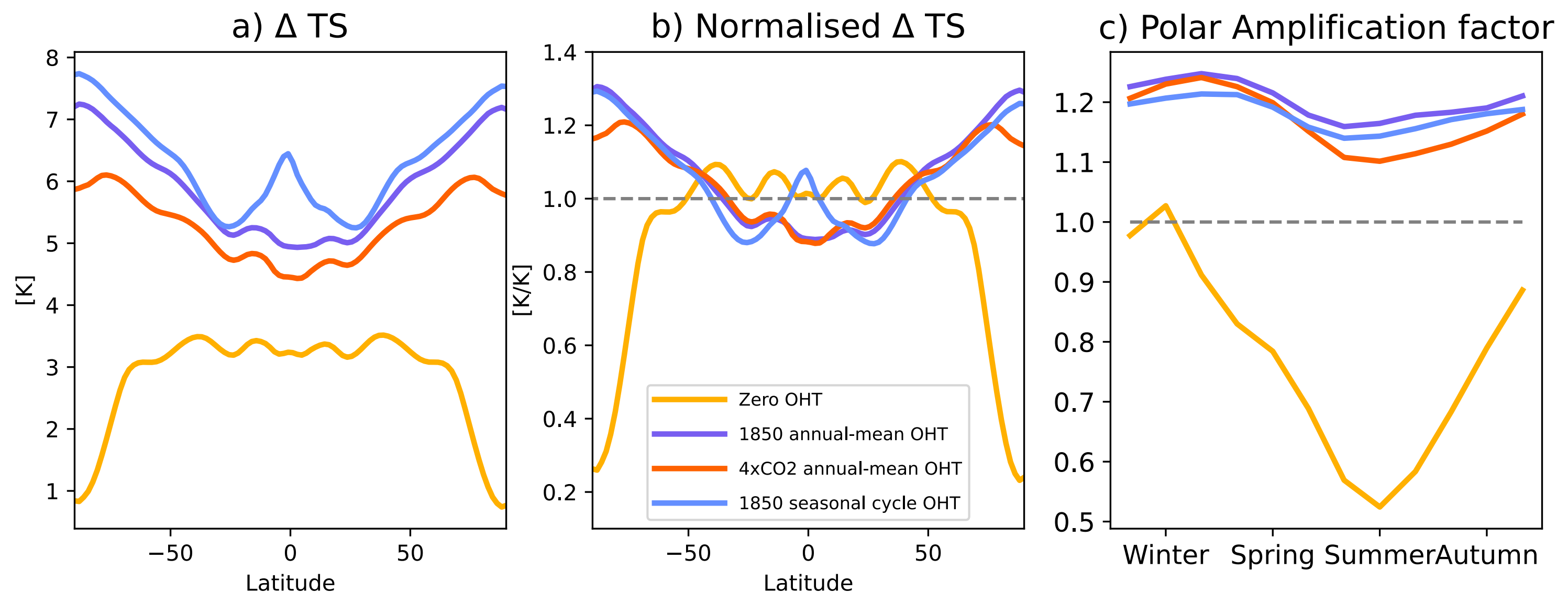


Figure 2: a) Annual mean, zonal mean surface temperature response to 4xCO_2. b) Same as panel a but each response is normalised by the annual mean global mean surface temperature response, with the dashed grey line denoting a ratio of 1. c) The monthly polar amplification factor under 4xCO_2, calculated as the ratio of polar (60-90°) warming in each hemisphere to annual mean global warming, with values greater than the dashed grey line showing a polar amplified response.

Introducing OHT enhances polar amplification because of shortwave cloud radiative effects

- Differences in the shortwave CRE account for the majority of the difference in higher latitude total CRE response between the OHT and zero OHT experiments and differences in the longwave CRE are small.
- This is consistent with the finding from Fig. 2c that the largest seasonal difference in surface temperature response is in the summer.
- We next examine the <u>cloud fraction and cloud liquid water.</u>

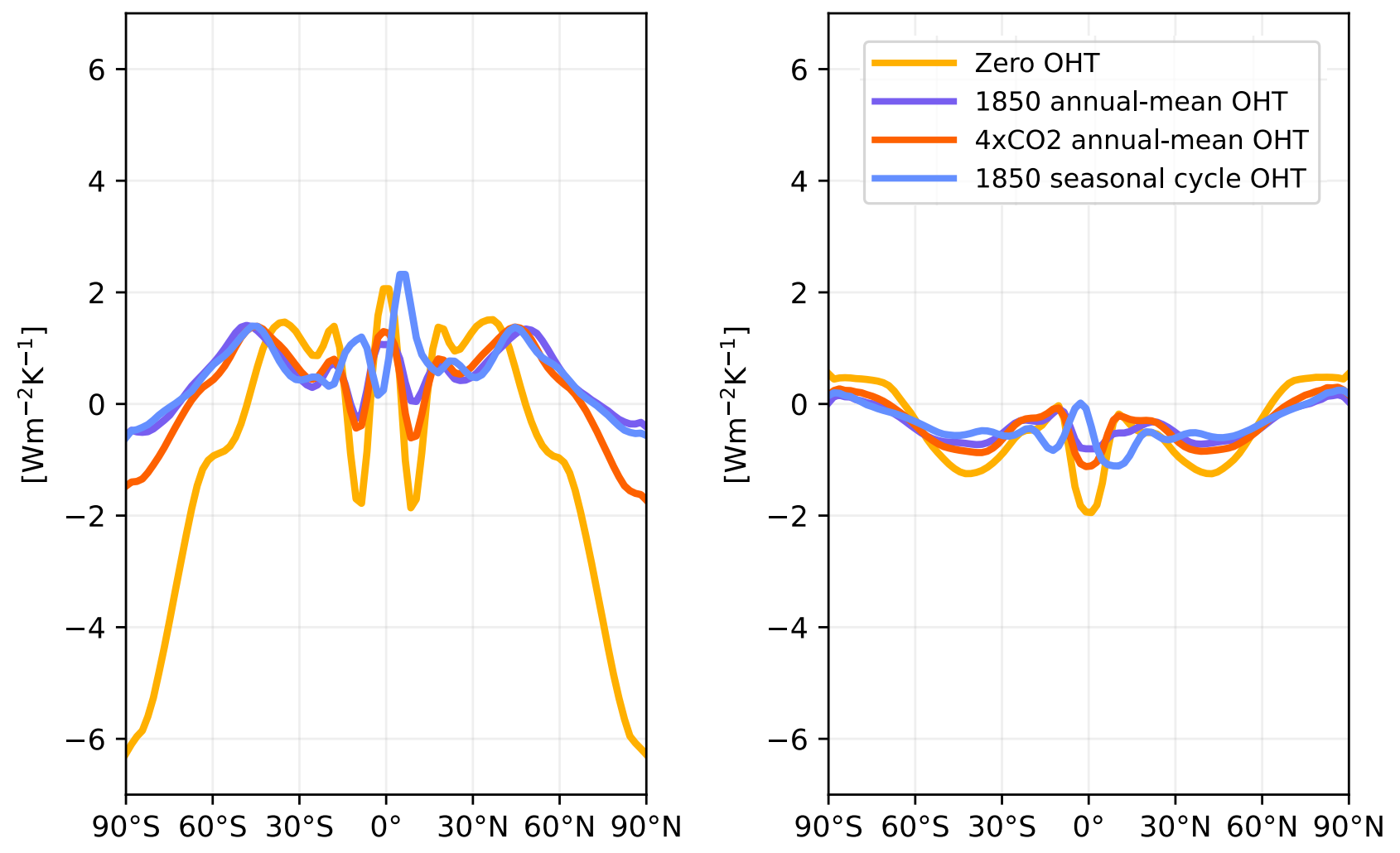
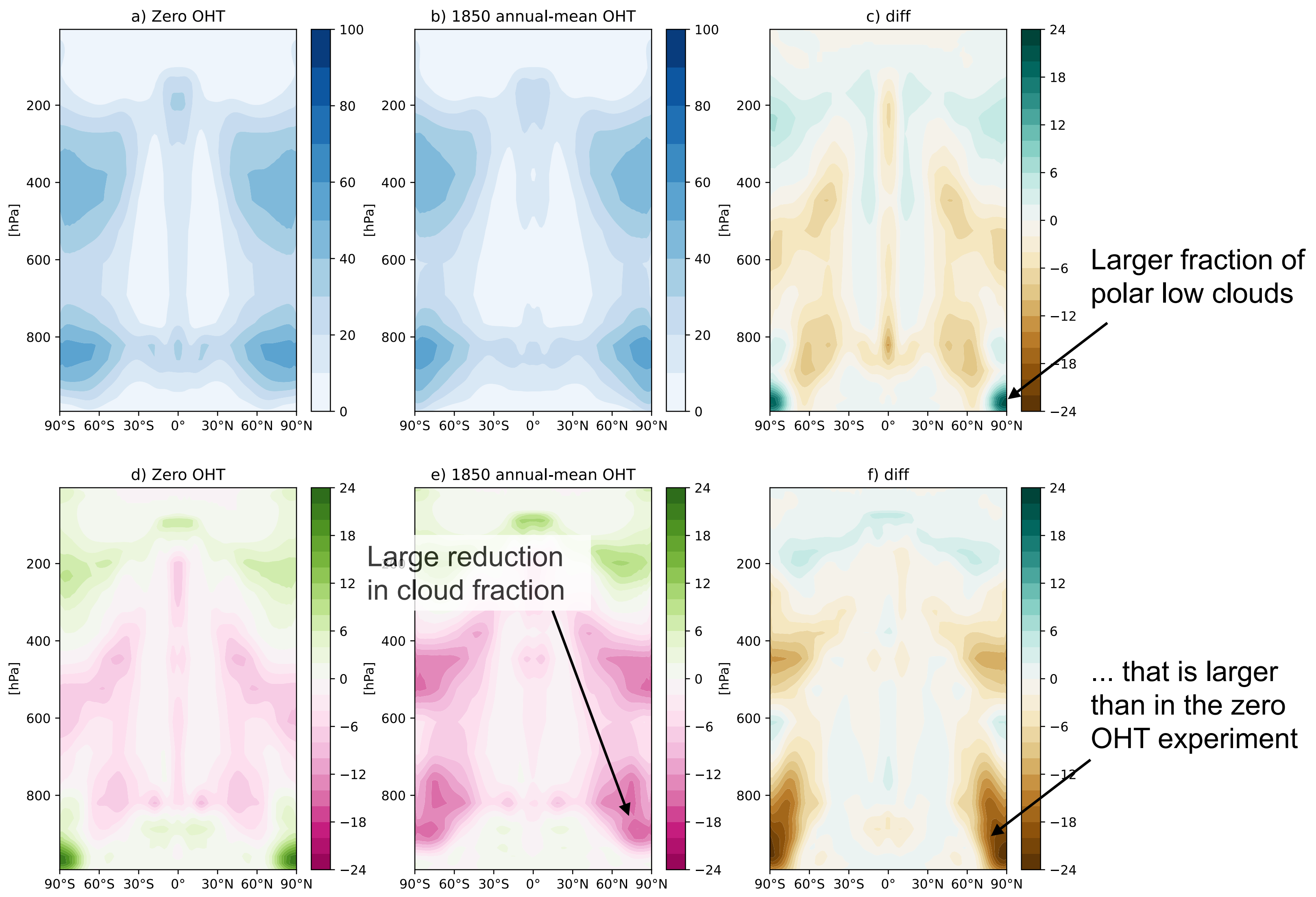


Figure 3: Zonal-mean annual-mean (a) shortwave CRE, (b) longwave CRE and (c) total CRE response to a quadrupling of CO2 in CESM2-CAM6 normalized by the global-mean annual-mean surface warming response for the four experiments.

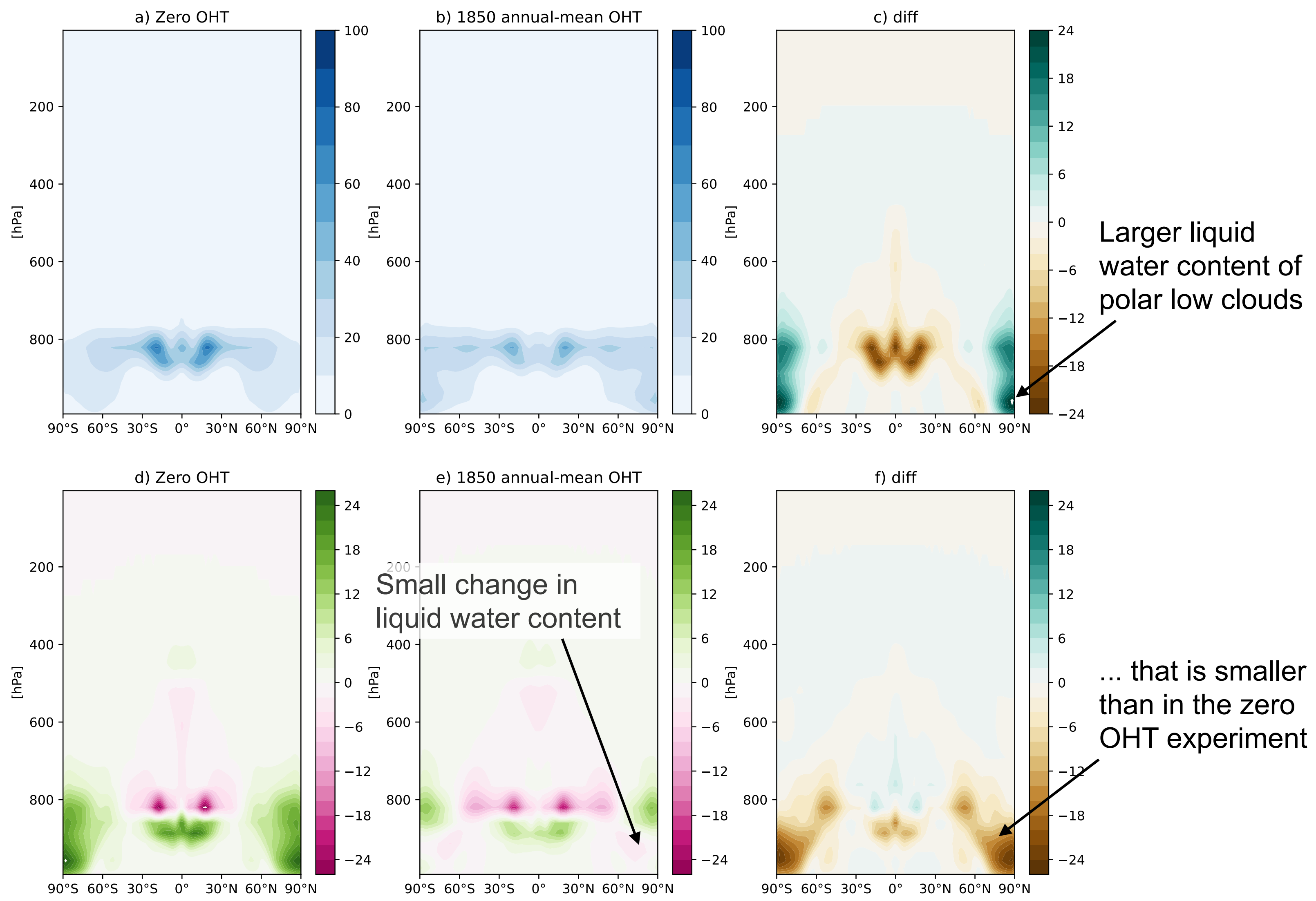


Larger fraction of polar low clouds

Large reduction in cloud fraction

... that is larger than in the zero OHT experiment

Figure 4: Zonal-mean annual-mean cloud fraction [%] in 1xCO2 climate for (a) zero OHT experiment, (b) 1850 annual-mean OHT experiment, and (c) the difference (b)-(a). Panels (d-f) are the same as (a-c) except showing the 4xCO2 - 1xCO2 response.



Larger liquid water content of polar low clouds

Small change in liquid water content

... that is smaller than in the zero OHT experiment

Figure 5: Same as in Figure 4 except for zonal-mean annual-mean liquid water content [x10^{-7} kg/kg].

- Adding climatological OHT produces a 1xCO2 climate which has warmer polar regions, a higher fraction of near-surface polar clouds, and, particularly in the summer, moister lower tropospheric polar clouds (Fig. 4 and 5, a-c).
- From this initially moist, cloudy state, there is less cloud gain near the surface (rather, the troposphere is characterized by cloud loss) and less cloud moisture gain as the climate warms in response to a quadrupling of CO2 (Fig. 4 and 5, d-f).
- In essence, adding climatological OHT inhibits the strong negative high latitude shortwave CRE change present in the zero OHT experiment.

Cloud locking simulations confirm key role of cloud radiative feedbacks

In this method, the CRE is prescribed to a desired state, while cloud fraction and microphysics are unconstrained[9]. Given the same change in high latitude CRE as the 1850 annual-mean OHT experiment, will we be able to replicate the polar amplification simulated by that experiment but with zero OHT?

- 1xCO2 1850 OHT clouds polewards of 45° → 1xCO2 zero OHT climate
- 4xCO2 1850 OHT clouds polewards of 45°→ 4xCO2 zero OHT climate

The magnitude and seasonal characteristics of the polar-amplified climate response to increases in radiative forcing are reproduced solely by altering the CRE (Fig 6b and 6c).

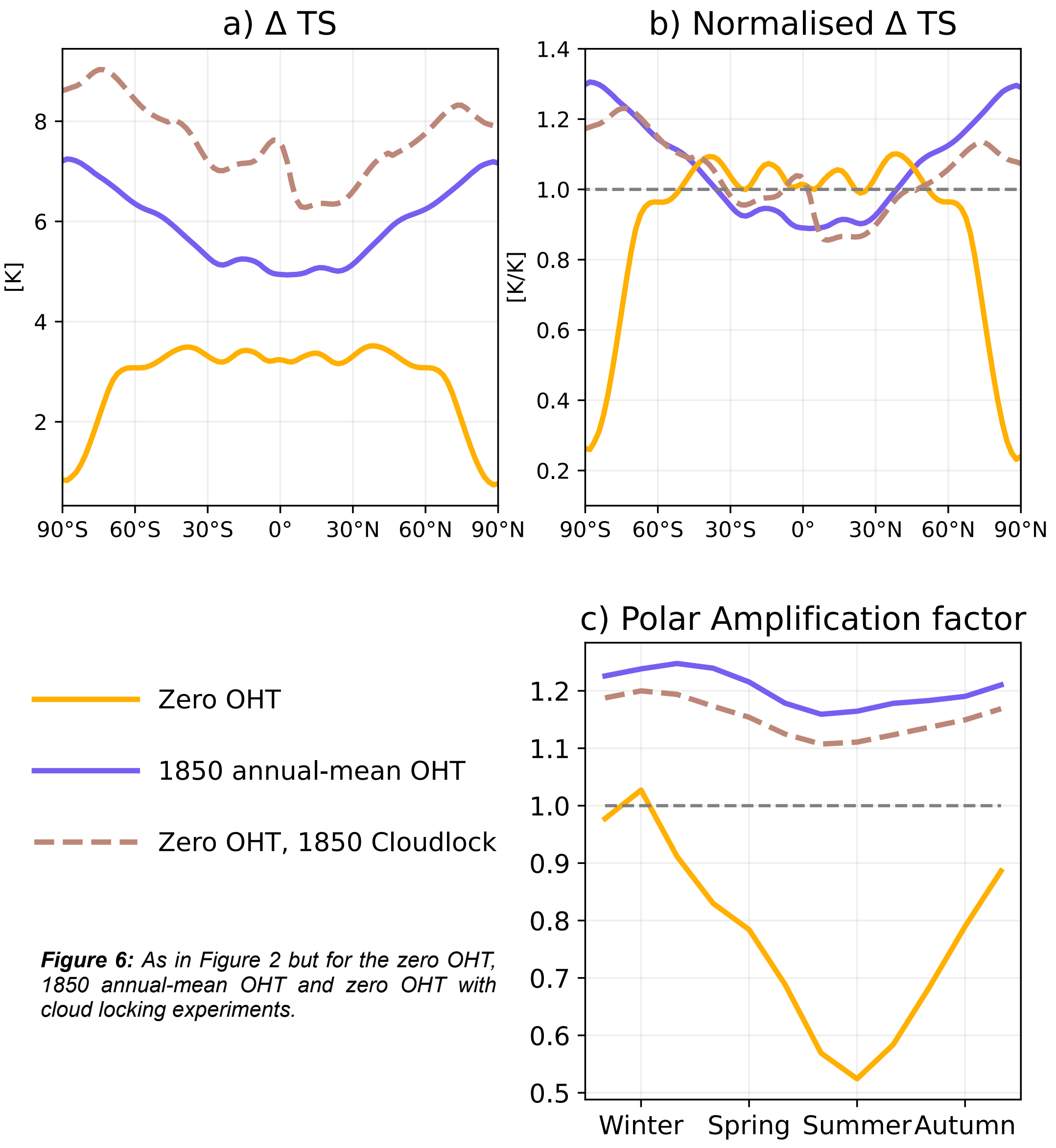


Figure 6: As in Figure 2 but for the zero OHT, 1850 annual-mean OHT and zero OHT with cloud locking experiments.

Implications and discussion

- **(i) Polar amplification does not require sea ice to occur, and (ii) robust polar amplification is a ubiquitous response of a coupled atmosphere-ocean system.**
- Under high emissions scenarios, comprehensive models project that Arctic sea ice cover will disappear by the end of the 22nd century[8]. Our results indicate that Arctic Amplification will be a persistent (but reduced) phenomenon if the planet enters an ice-free climate.
- Configuration of idealised model (e.g., use of zero q-flux) can shape climate response.
- Open questions: How robust is cloud-based mechanism across different models?