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Uncertainties in climate sensitivity and residual carbon emissions permit for a hothouse climate ahead

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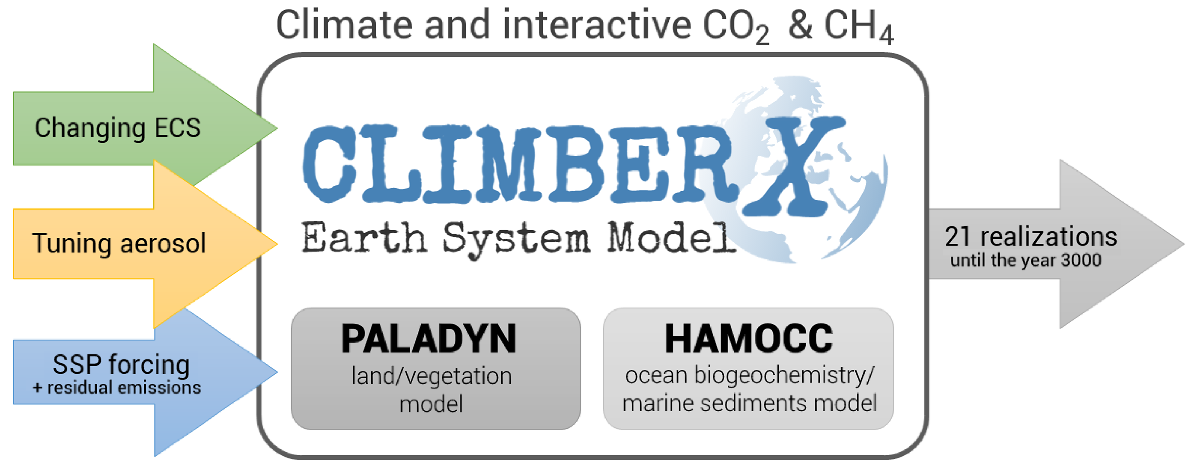
1. Motivation

Climate change predictions are largely dependent on equilibrium climate sensitivity (ECS), the steady-state global-mean surface air temperature change due to a doubling atmospheric CO_2. State-of-the-art Earth system models currently exhibit low agreement in this sensitivity; the IPCC reports that the **very likely range of ECS is 2-5 K** [1]. This is largely because models with very different ECS can still represent the historical global-mean temperature increase by e.g., tuning the strength of aerosol forcing [2].

If ECS is indeed larger than the **best estimate of 3K**, temperatures will not only be higher than usually expected, but the forcing from CO_2 emissions could additionally trigger a chain of positive feedbacks in the carbon cycle [3]. This could lead to the destabilization of the Earth's climate system and push it onto a path of continued warming — even after emissions are considerably reduced.

We investigate the plausibility of such a hothouse Earth by performing millennium-long simulations of the future climate under (1) three low-to-intermediate GHG emission scenarios as defined by the shared socioeconomic pathways (SSP), and (2) using different model versions that emulate different ECS in the range of 2-5 K.

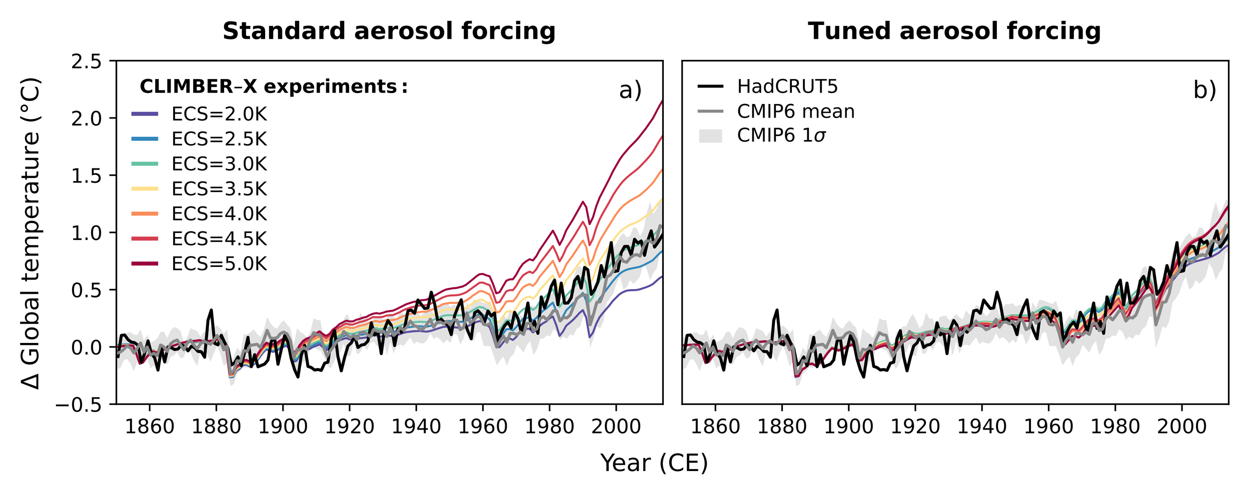
2. Methods



We use the fast Earth system model CLIMBER-X, whose climate [4] and carbon cycle [5] has been validated for the present-day.

Model tuning for different climate sensitivities:

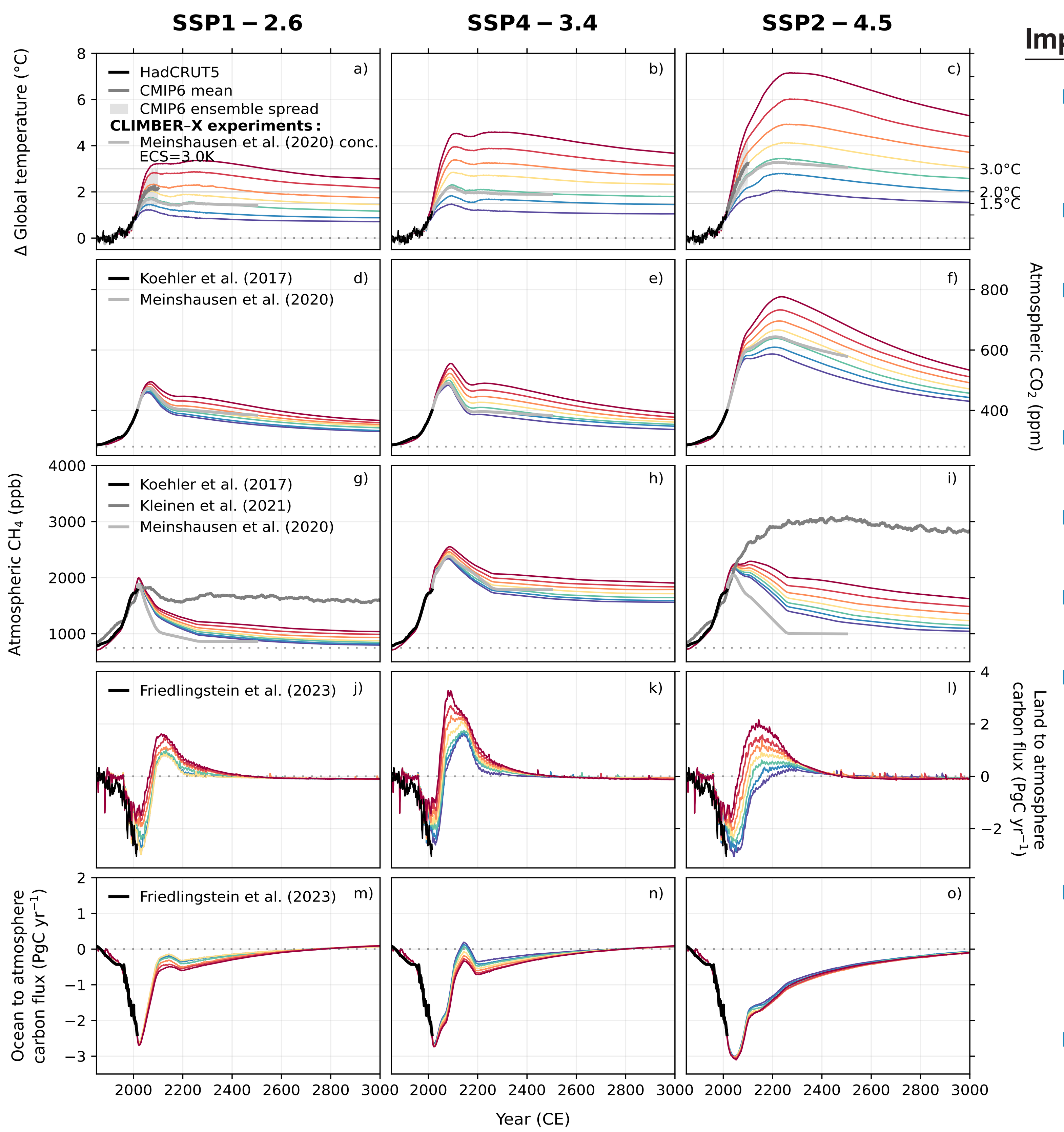
- Scaled the equivalent CO_2 in the long-wave radiation scheme in order to mimic different ECSs from 2-5K
- Tuned sulfate aerosol forcing so each member shows good agreement (i.e., minimized RMSE) with HadCRUT5 observations



Experimental set-up:

- Run from 1850-3000 CE under different ECSs and extended SSP1-2.6, SSP4-3.4 and SSP2-4.5 scenarios (prescribed emissions and land use change)
- Added 0.5 and 1 PgC yr^{-1} residual emissions to SSP2-4.5

3. Results

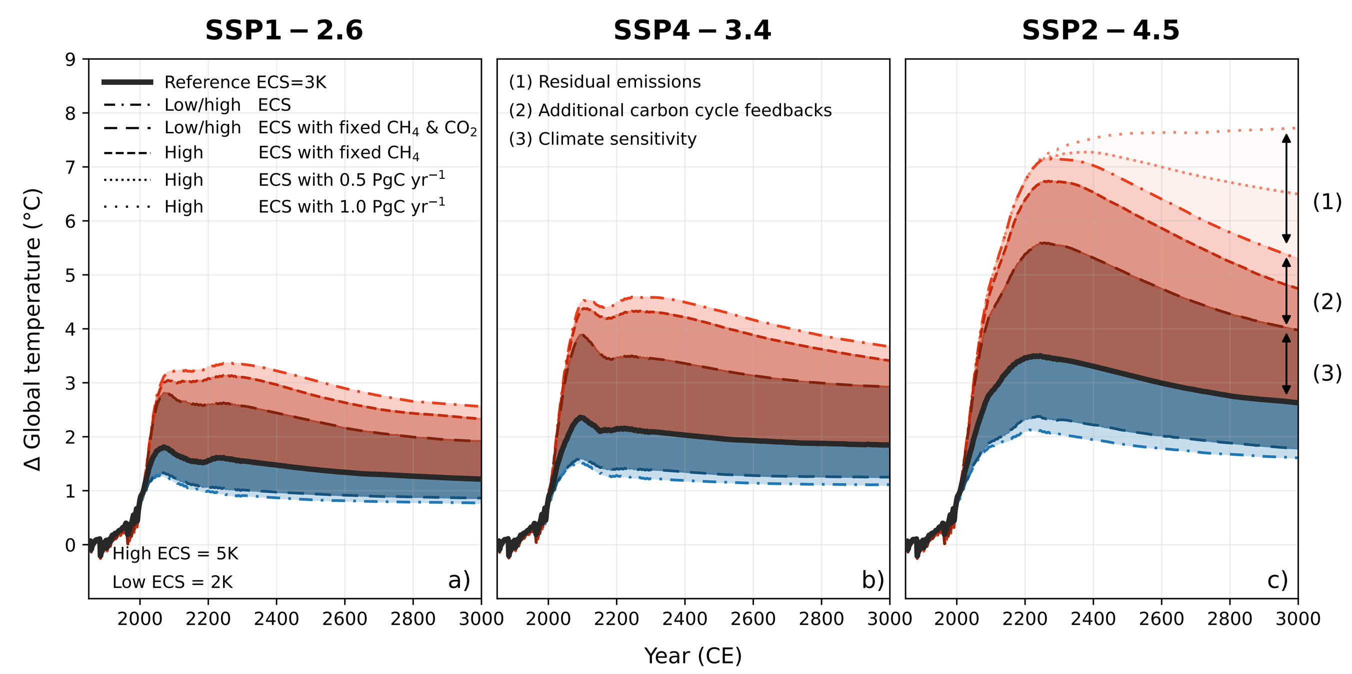


Impact of ECS on climate & carbon cycle response:

- All model versions with different ECS reproduce historical temperature changes (tuning criteria), but also atmospheric CO_2 and CH_4 concentration
- Rapid increase of atmospheric CO_2 concentration, largely controlled by the SSP scenario
- Higher CH_4 levels than Meinshausen because we account for increases in natural emissions; lower CH_4 levels than Kleinen because we assume lifetime of CH_4 is constant
- Peak temperatures of 1.8, 2.3, 3.5 °C across the different scenarios in our reference run (ECS=3K)
- Vegetation changes driven by NPP; ECS strongly impacts the amount of carbon stored in soils
- Ocean is a carbon sink in all experiments and response similar for different ECS
- **Simulated additional warming under high ECS is disproportionately larger than expected from a simple linear relation between ECS and global warming**

Contribution from carbon cycle feedbacks:

- We ran a secondary set of experiments where we prescribe CH_4 (and CO_2) from the original reference simulation to isolate the effect of carbon cycle feedbacks
- Carbon cycle feedbacks are responsible for about half of the warming for high ECS runs; temperature contribution from CO_2 larger than CH_4

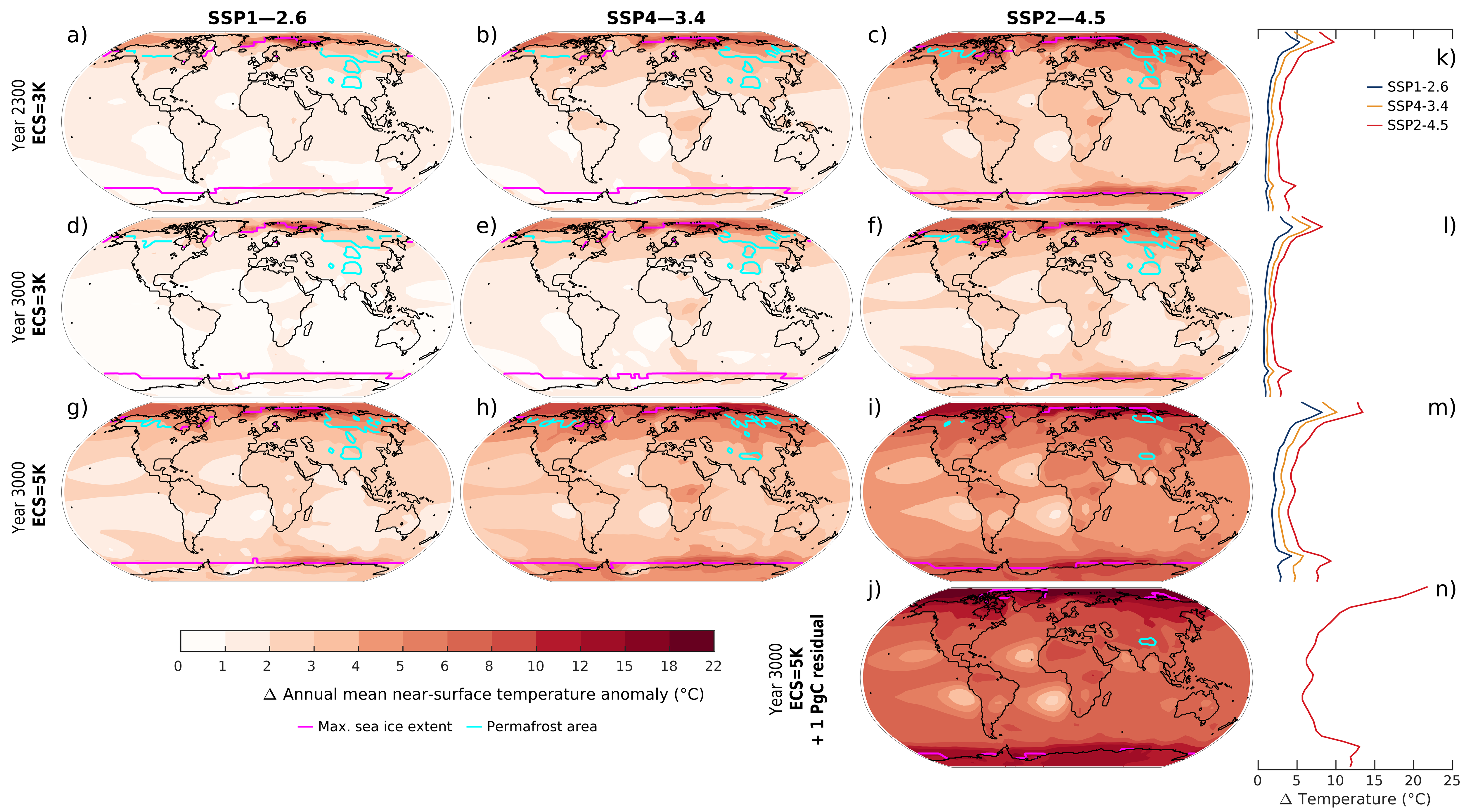


Sustained warming from low residual emissions:

- Residual emissions of even 0.5 PgC yr^{-1} (~95% reduction from present-day) prolongs warming
- Temperatures continue to increase and are prevented from declining over the next millennium with 1.0 PgC yr^{-1}
- The combined effect of residual emissions and ECS>3K can have temperatures differences larger than 5°C compared to the reference, which can persist until the end of the millennium

Spatial distribution of global warming:

- High-latitudes consistently show largest changes in temperature as a result of polar amplification, caused by the reduction of sea ice and snow (surface-albedo feedback) and surface confinement of warming (lapse-rate feedback)
- Under the reference run, Arctic temperatures at the year 3000 CE are still significantly increased under any scenario
- Most extreme scenario (high ECS, 1 PgC yr^{-1} residual emissions) has Arctic temperatures up to 20 °C larger than pre-industrial at 3000 CE



4. Conclusions

- Simulated temperature changes for high ECS values are within the range of the paleoclimate reconstructions for the middle Eocene, which often is referred to as a "hothouse climate"
- A hothouse Earth is *not* implausible in the following millennia even in low-to-intermediate emission scenarios given that ECS is high
- The Paris Agreement goal of 1.5 °C is only feasible for SSP1-2.6 if ECS is lower than the current best estimate of 3K, and SSP4-3.4 in the case when ECS-2K
- To stop temperatures from rising, we need at least a 95% reduction from present-day emissions
- Our results are likely conservative, emphasizing the need for more definitive constraints on ECS

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