Variability of atmospheric CO_2 in Earth System model large-ensemble simulations

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Why It Matters:

- As CO_2 is the major contributor to global climate change, atmospheric CO_2 concentration has increased from around 280 parts per million (ppm) in 1800 to over 412 ppm in 2020 (Global Carbon Budget, 2022). Changing seasonal and spatial variation in CO_2 is important to understand as it impacts policy planning.
- Observational measurements alone cannot capture the interactions between CO_2 emissions and carbon sinks in the global carbon cycle, both of which are necessary for understanding the evolution of the future climate.
- Modelling the Earth System in large-ensemble simulations with an interactive carbon cycle helps fill this gap in understanding atmospheric CO_2 variability in a changing climate. Using a large ensemble allows for a more robust analysis of variability (Li et al., 2018).

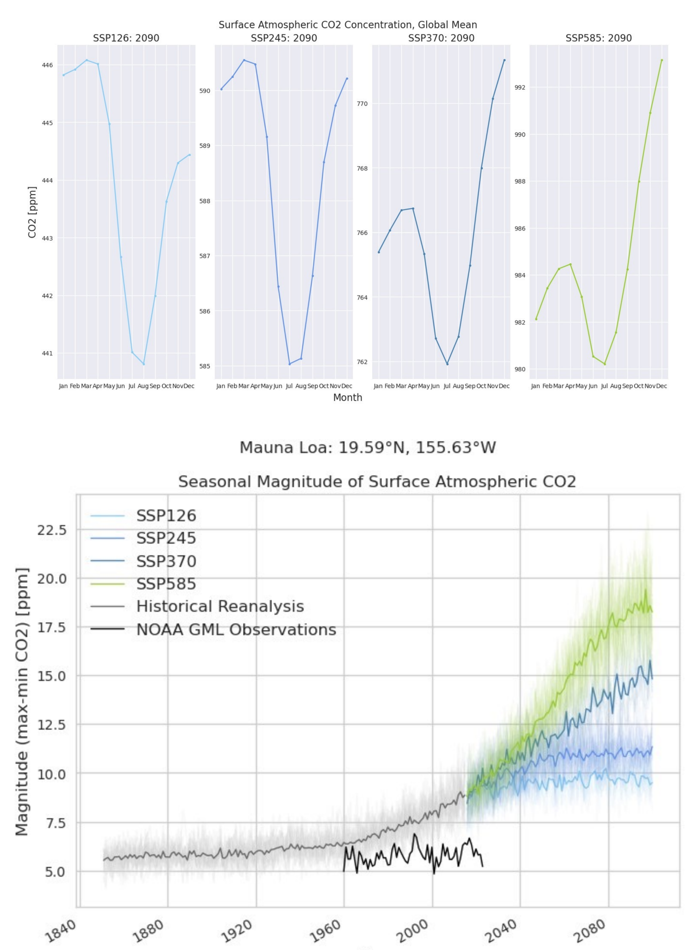
Research Question

How do MPI-ESM-1.2-LR large-ensemble Earth System model simulations improve our understanding of the variability of atmospheric CO_2 until 2100?

Key Messages:

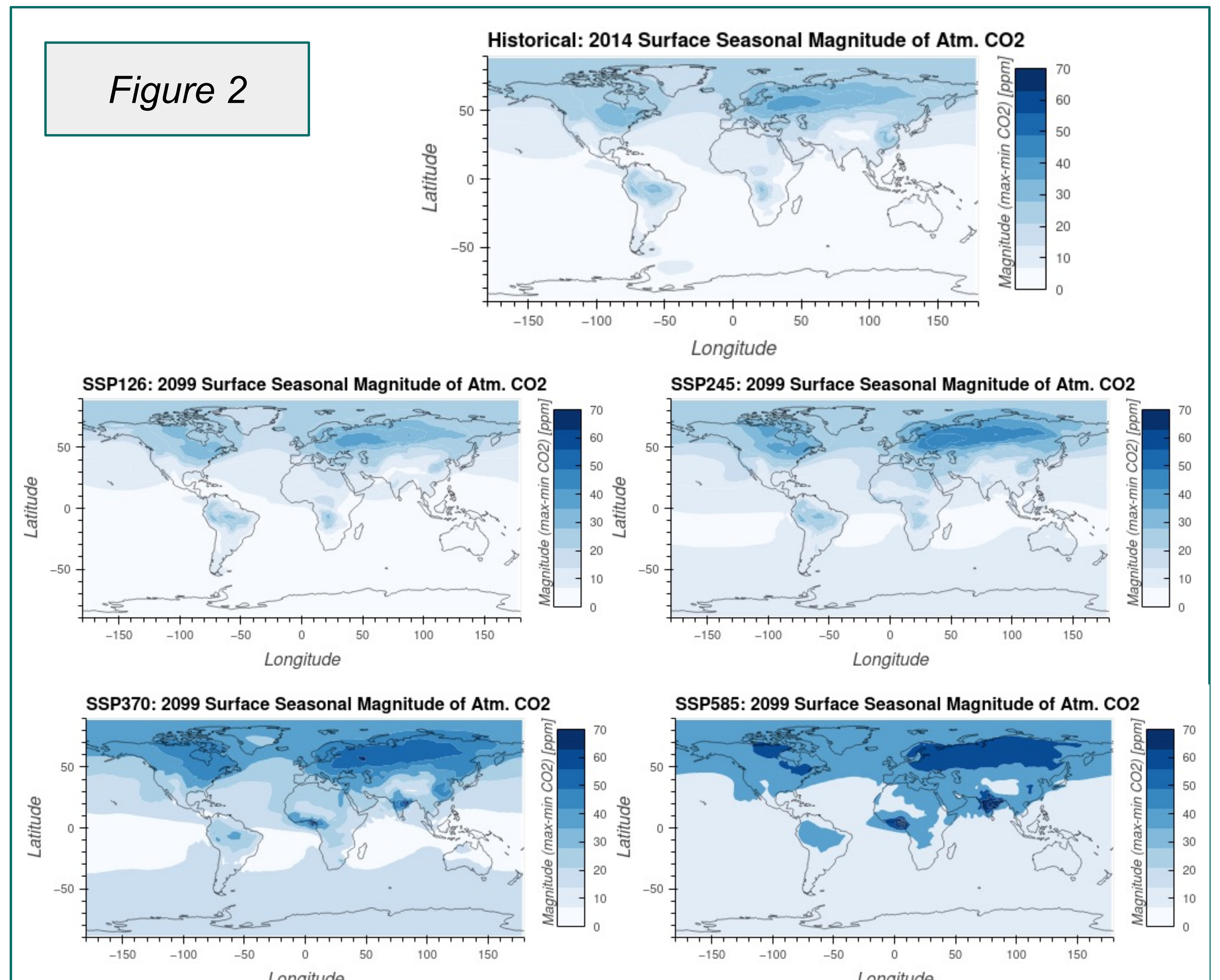
1. The annual seasonal magnitude (the maximum minus the minimum CO_2 concentration for each year) of surface level atmospheric CO_2 increases significantly in the model by 2100 for scenarios SSP370 and SSP585, indicating a stronger seasonal variability. Annual seasonal magnitude for scenarios SSP126 and SSP370 do not show a marked increase by 2100, though still rise over the historical period (*Fig. 1*).
2. As expected, the modeled northern hemisphere, which is the source of most CO_2 emissions and the majority of the land carbon sink, experiences greater variability in surface level atmospheric CO_2 by 2100 than the southern hemisphere, although hot spots emerge in certain areas near the equator, particularly in South Asia and off the coast of West Africa (*Fig. 2*).
3. CO_2 concentrations in the model's upper atmospheric levels in the historical reanalysis are less pronounced when compared to the surface, but the distribution of atmospheric CO_2 varies by 2099 in the four SSP simulations, with the modeled stratosphere in the SSP126 simulation in particular accumulating CO_2 compared to other simulations (*Fig. 3*).

Figure 1



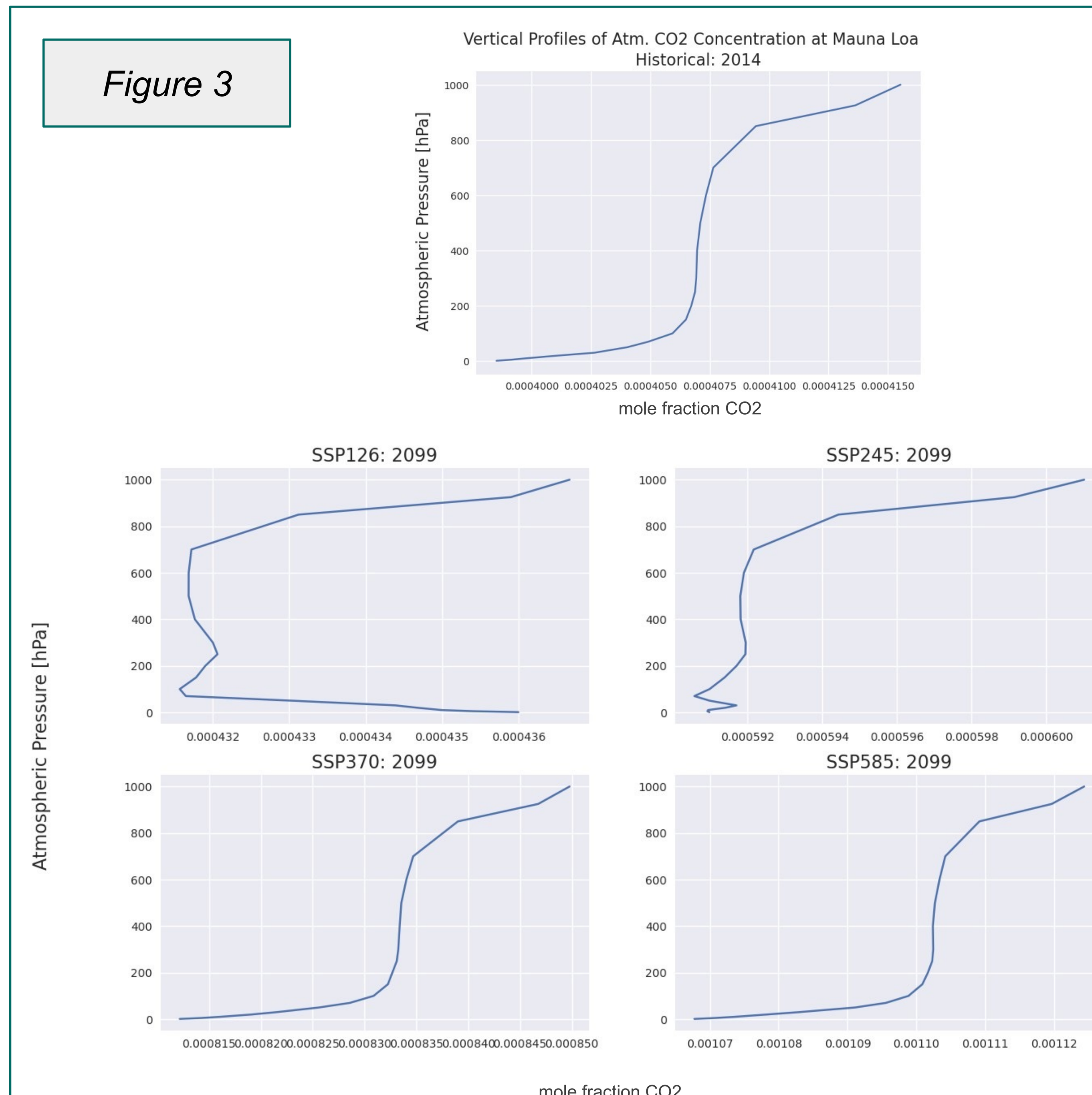
- General variations in seasonal cycle of surface-level, ensemble mean atmospheric CO_2 can be seen in comparing the global mean values for the final year of the four SSP simulations.
- Seasonal magnitude of atmospheric CO_2 at the surface level at Mauna Loa, calculated by subtracting the minimum from the maximum CO_2 values per year for each SSP scenario. Higher magnitude values correspond to more extreme seasonal CO_2 variability. Ensemble mean taken after magnitude calculation.
- Observational measurements of atmospheric CO_2 (NOAA, 2023) are lower than the large-ensemble model's prognostic CO_2 concentrations, as reflected in lower magnitude values.

Figure 2



- Seasonal magnitude variation in global surface level atmospheric CO_2 in 2014, the last year of the historical reanalysis dataset. Shown compared to the seasonal variation in surface level atmospheric CO_2 in 2099, the last year of the modeled large ensemble simulations, for all four selected SSP scenarios. The ensemble mean is taken after the seasonal magnitude calculation.
- SSP370 and SSP585 are the only two model simulations to show seasonal magnitude values of over 70 ppm by 2099, in large parts of the northern hemisphere, as well as parts of South Asia and West Africa near the equator.

Figure 3



- Vertical profiles of atmospheric CO_2 concentrations for the final year of the historical reanalysis and each of the four SSP simulations, taking the ensemble mean at Mauna Loa.
- The seventeen levels of the model's atmosphere, from the surface level at 1000 hPa to the upper stratosphere at 0 hPa, show differences in the distribution of CO_2 concentration during the final year of the four SSP simulations.

Methodology:

- We use a low-resolution configuration of the Max-Planck-Institut für Meteorologie's coupled Earth System Model v1.2 (MPI-ESM-1.2-LR).
- Based on this model, we have done a novel set of 10- and 30-member ensemble simulations driven by anthropogenic CO_2 emissions. In such simulations, atmospheric CO_2 concentrations are computed prognostically, modulated by the strength of CO_2 fluxes to the land and the ocean.
- We consider four different Shared Socioeconomic Pathway (SSP) scenarios to represent future anthropogenic CO_2 emissions (IPCC AR6, 2022).

What's Next?

We aim to incorporate emission seasonality and transportation patterns into the model and further explore the representation of the model's upper atmosphere.

References: IPCC AR6 Climate Change (2022), Global Carbon Budget (2021), NOAA Global Monitoring Laboratory (2023), Li, H. & Ilyina, T. (2018)

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