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# Long-Term Negative Emissions and Irreversibilities following Temporary Overshoots: An Earth System Model Perspective

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Our understanding of impacts and feedbacks associated with temporarily overshooting the Paris Agreement temperature goal - where the 1.5 °C global warming target is exceeded and retraced at a later time period - is currently limited. Such overshoot scenarios are of increasing likelihood and have the potential to be devasting in terms of both their peak impacts and irreversibility, affecting natural and human systems.

Here, we apply the Earth System Model GFDL-ESM2M coupled to the Adaptive Emission Reduction Approach (AERA) in order to perform novel policy-relevant simulations over the 1861 to 2500 period that temporarily overshoot the global warming target of 1.5 °C at various levels of peak global warming (2.0, 2.5 and 3.0 °C), and compare these to a reference scenario that stabilizes at 1.5 °C. We use this framework to isolate features arising from the overshoots, and investigate **(1)** negative emissions needed to reverse an overshoot and their impacts for cumulative emissions, **(2)** spatial differences in surface warming and oceanic heat content between overshoot and 1.5°C stabilization case, and **(3)** impacts that these spatial differences have for precipitation, sea level rise and ocean ecosystem stressors.

Our framework suggests levels of negative carbon emissions of up to 9 Pg C yr$^{-1}$ to revert the global temperature the most extreme overshoot of 3.0 °C back to 1.5 °C, with less cumulative emissions allowed in the long-term than in the 1.5 °C simulation to maintain global temperature at 1.5°C. We detect long-term high latitude warming of up to 2.1 °C averaged over the North Atlantic and 0.5 °C over the Southern Ocean that persists after the overshoot. We attribute the persistent warming in the high latitudes to the recovery of both Atlantic Meridional Overturning Circulation and Antarctic abyssal overturning, which retrace to even higher levels in the overshoots than in the 1.5 °C stabilization case. These impact the distribution of precipitation, for instance stronger precipitation found in the high latitudes in the overshoots, as wells as the Pacific Walker Cell. The model also shows that due to excess heat storage in the subsurface of low latitudinal oceans, sea level rise does not recover back to 1.5 °C stabilization levels in overshoot scenarios, remaining up to 20 % higher in the strongest overshoot. The persistent long-term changes that the overshoots that we detect imply consequences for regional climates, cryosphere and marine ecosystems lasting for decades or even centuries after the overshoot reversal.