Potsdam Institute for Climate Impact Research

Climate change mitigation scenarios with temperature overshoot and broad CDR portfolio for use in ESMs

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PIK RD3 Transformation Pathways

Summary

The door to 1.5°C closes rapidly and exceeding this target set by the Paris agreement, at least temporarily, may become inevitable in only a few years. Large-scale **Carbon Dioxide Removal** (CDR) may facilitate a drawdown of temperatures after reaching the peak, however, neither a) economic implications of such an overshoot pathway nor b) the consequences for the earth system are well understood.
Using the REMIND-MAgPIE **Integrated Assessment Model** (IAM), we derive a set of climate change mitigation scenarios **with** and **without overshoot** for further use in Earth System Models (ESM) to assess earth system feedbacks

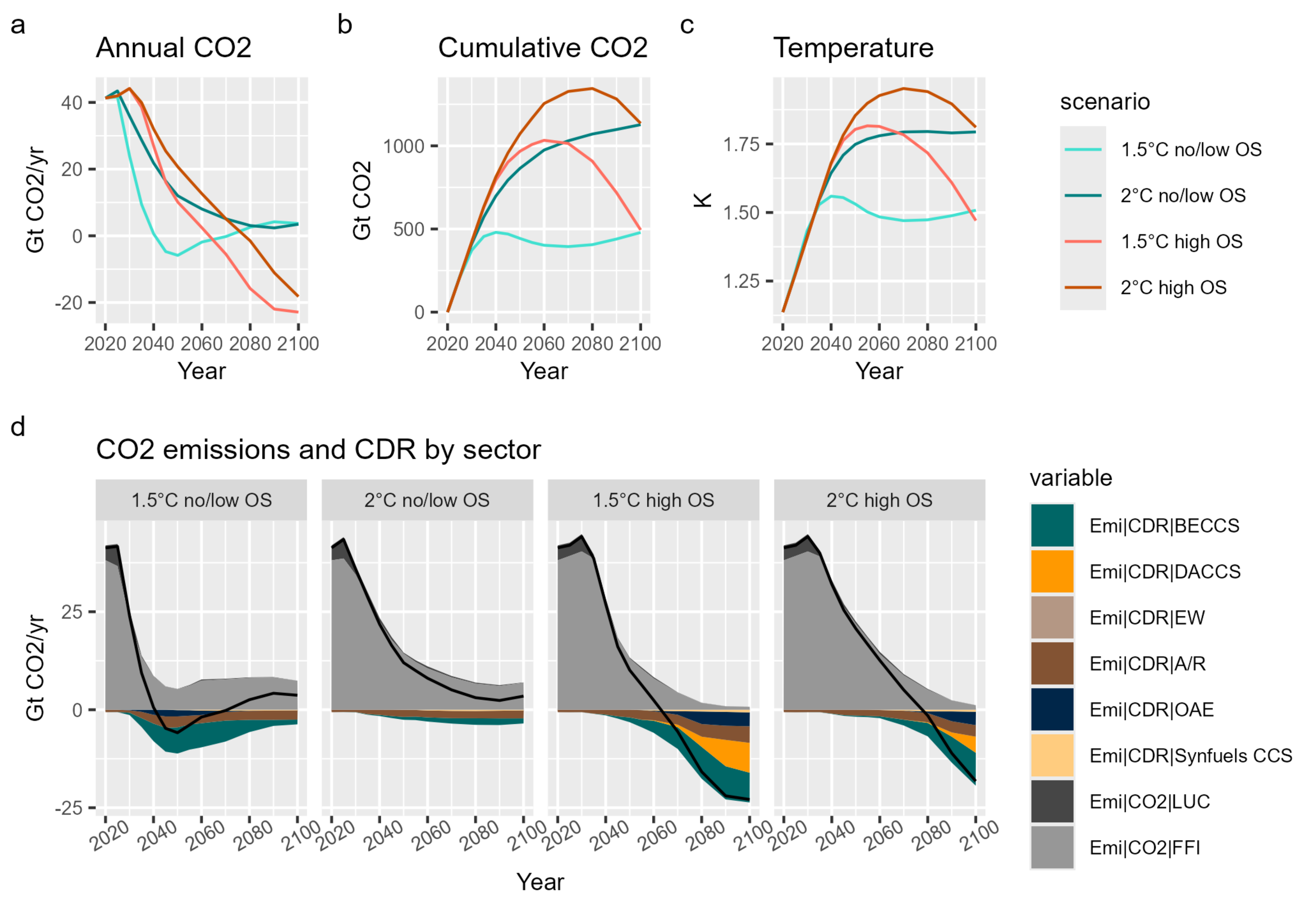

Fig. 1| Scenario overview showing **(a)** annual CO2 emissions, **(b)** cumulative CO2 emissions from 2020, **(c)** global mean surface air temperature increase and **(d)** annual CO2 emissions and CDR by sector.

Energy sector

All scenarios show a **continuous growth** in **renewable energy** sources reaching similar levels by the end of the century. The transition happens at different velocities: While in the 1.5°C no/low OS scenario 40% of primary (190 EJ/yr) originates from solar PV or wind turbines already by 2040, it is only 21% (118 EJ/yr) in the 1.5°C high OS scenario. Accordingly, in the **1.5°C no/low OS** scenario **fossil energy is phased out** substantially faster, reaching almost zero coal use in 2040. In contrast, there are no fossils left in the 1.5°C high OS scenario in 2100, and **17%** of the total **final energy demand** is related to **CDR**. Particularly, three quarters of total hydrogen production (71 EJ/yr) is required to fuel CDR processes - more than global natural demand today.

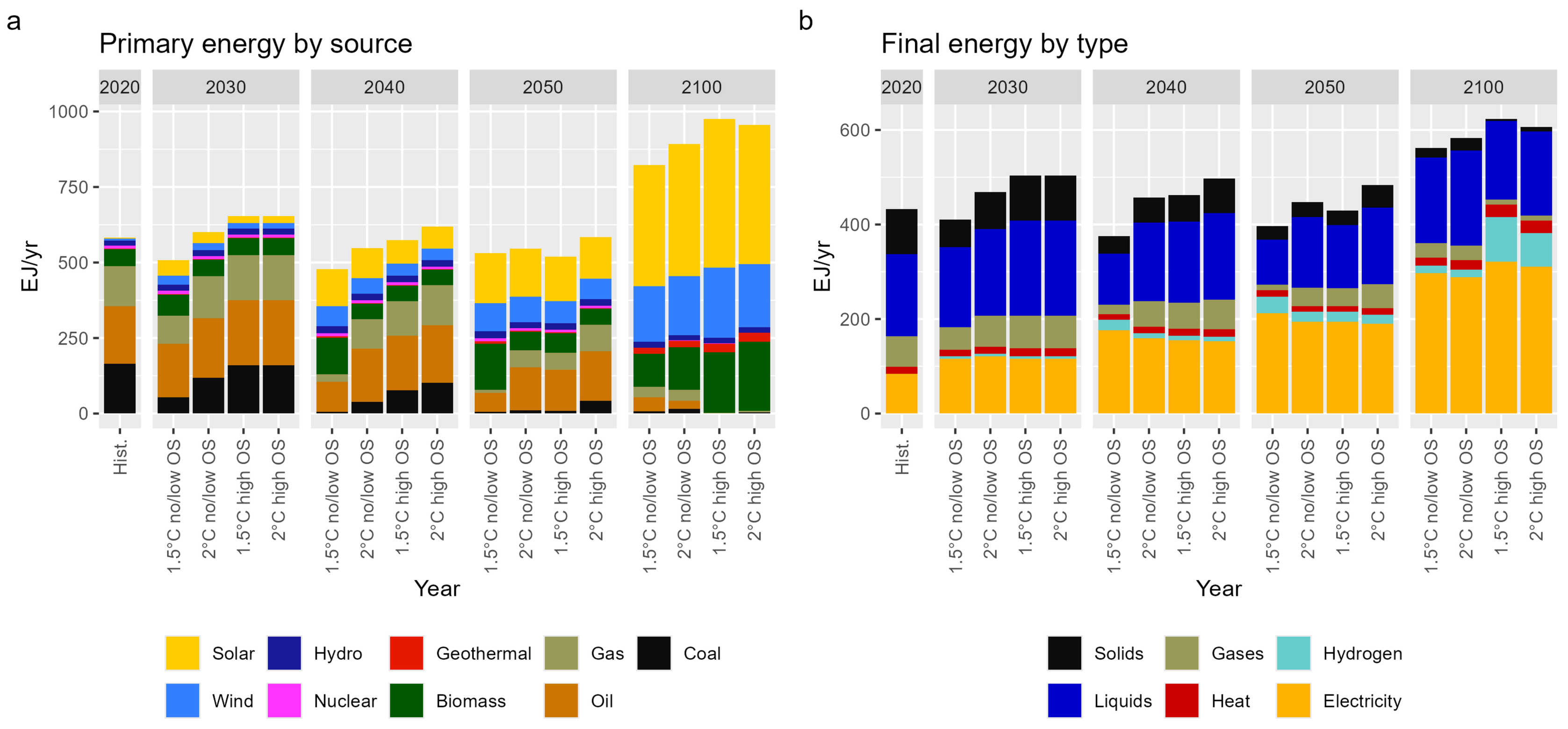

Fig. 2| (a) Primary energy production by source **(b)** final energy demand by energy type.

Land sector

The high early mitigation pressure in the 1.5°C no/low OS scenario is also translated to the Agriculture, Forestry and Other Land-Use (AFOLU) sector. We find that **biomass** use increases to more than 120 EJ/yr globally already by 2040, requiring substantial and fast **crop yield increases**. In contrast, the delay in mitigation leads to more bioenergy and even higher yield improvements by the end of the century in the 1.5°C high OS scenario and involves a lot of land-cover change from pasture and non-bioenergy cropland to forest area and cropland dedicated to bioenergy.

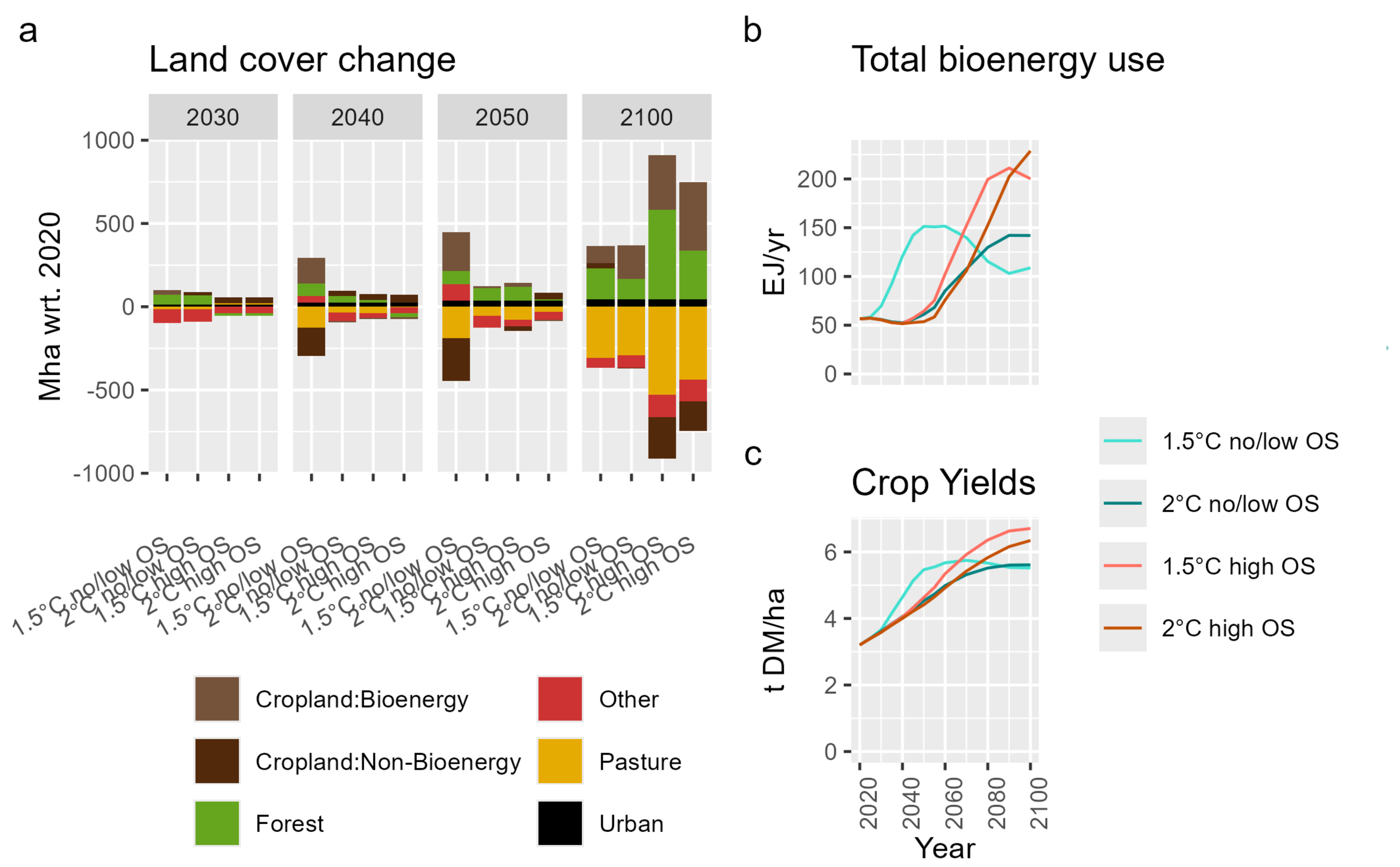

Fig. 3| (a) Land-cover change from 2020 onwards. **(b)** Primary energy from biomass. **(c)** Globally averaged crop yields of food crops.

Carbon economy

The tight carbon budget in the no OS 1.5° C scenario requires a very early and **fast Carbon Capture and Storage (CCS) ramp-up**. Already in 2040 7 Gt CO2/yr are being stored geologically, which is substantially more than in all the other scenarios at that point in time. The maximum CCS growth rate is, with an annual increment of 600 Mt CO2 in the period between 2030 and 2035, only slightly larger than the highest observed scale-up rates in the OS scenarios in the second half od the century.

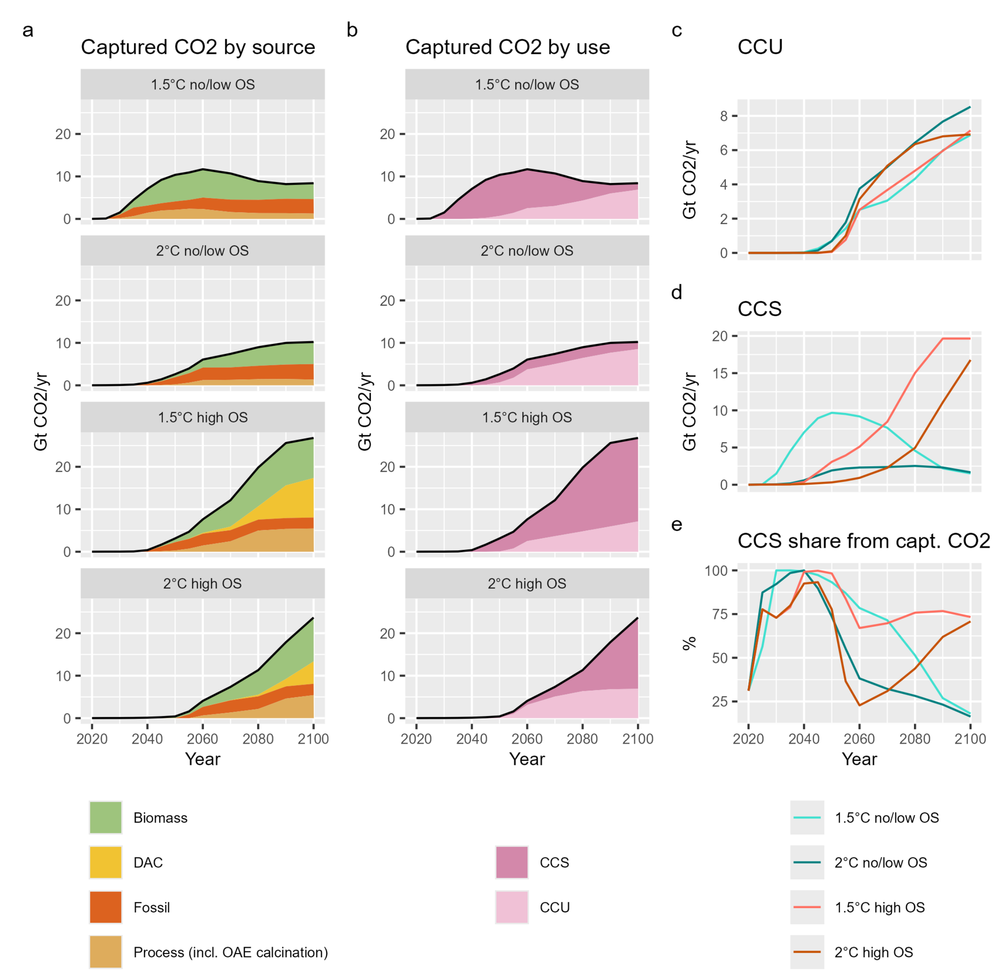

Fig. 4| Captured CO2 by source **(a)** and by use **(b)**. The CCU and CCS quantities are also shown in **(c)** and **(d)**, respectively. **(e)** shows the share of geologically stored CO2 per unit of captured CO2.

Key findings

- **Delaying mitigation** eases pressure today but burdens future generations by demanding even large quantities of bioenergy and CDR, revealing strong intergenerational trade-offs.
- Bringing down temperatures after an overshoot involves a **larger portfolio of CDR** options than directly limiting warming below 1.5°C

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RESCUE

OptimESM
Optimal high resolution **Earth System Models** for exploring future climate change

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Mitglied der Leibniz Gemeinschaft

Differences in Carbon Dioxide Removal -CDR- Representation between Integrated Assessment Models -IAMs- and Earth System Models -ESMs-

by Chiara Ciscato[1], Momme Butenschön[1], Tomas Lovato[1], Daniele Peano[1]

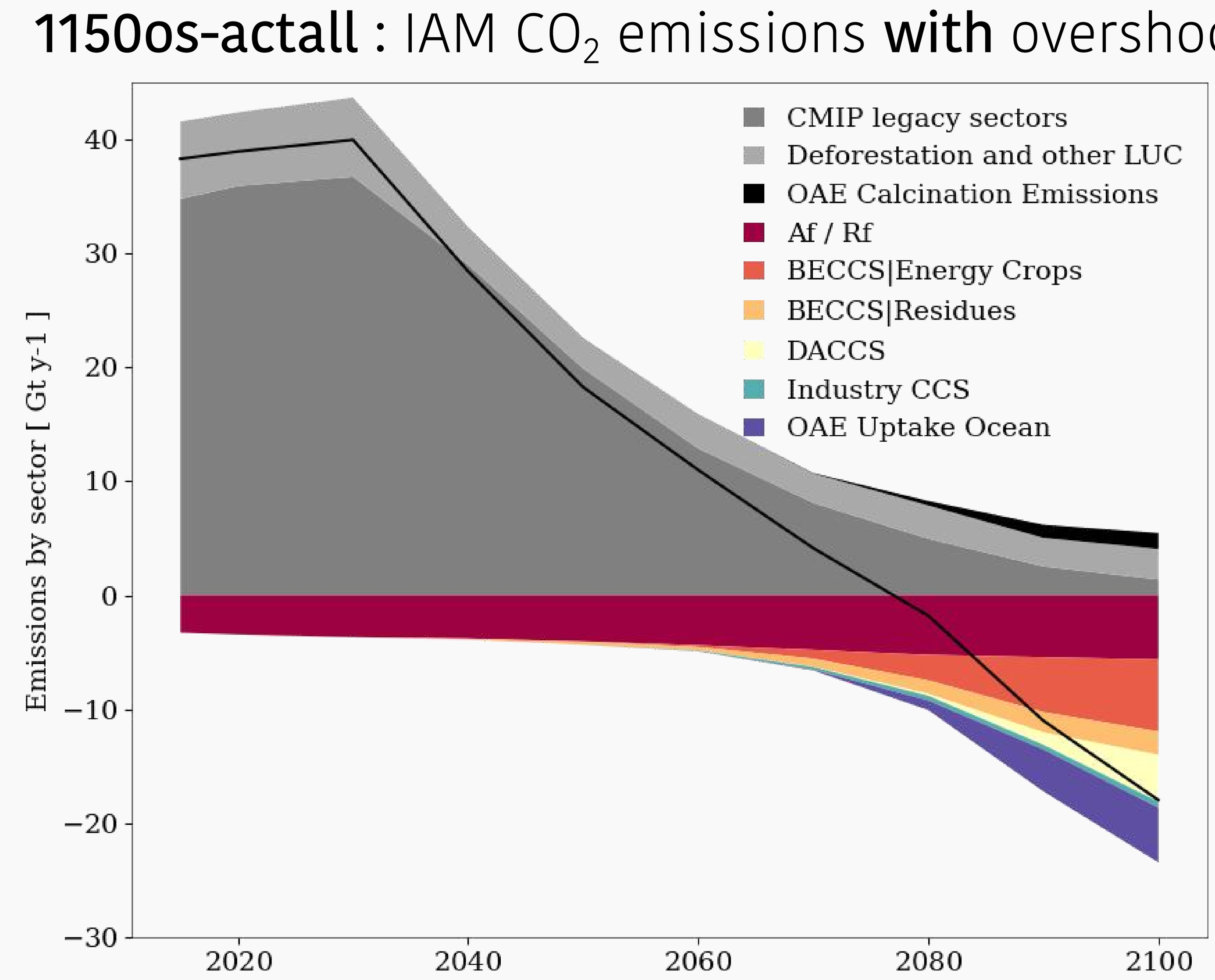
[1]CMCC Foundation - Euro-Mediterranean Center on Climate Change

SCIENTIFIC FRAMEWORK The world is currently **on track to overshoot** both the 1.5°C and the 2°C Paris targets, so the deployment of **large-scale CDR** is required to balance the carbon budget.

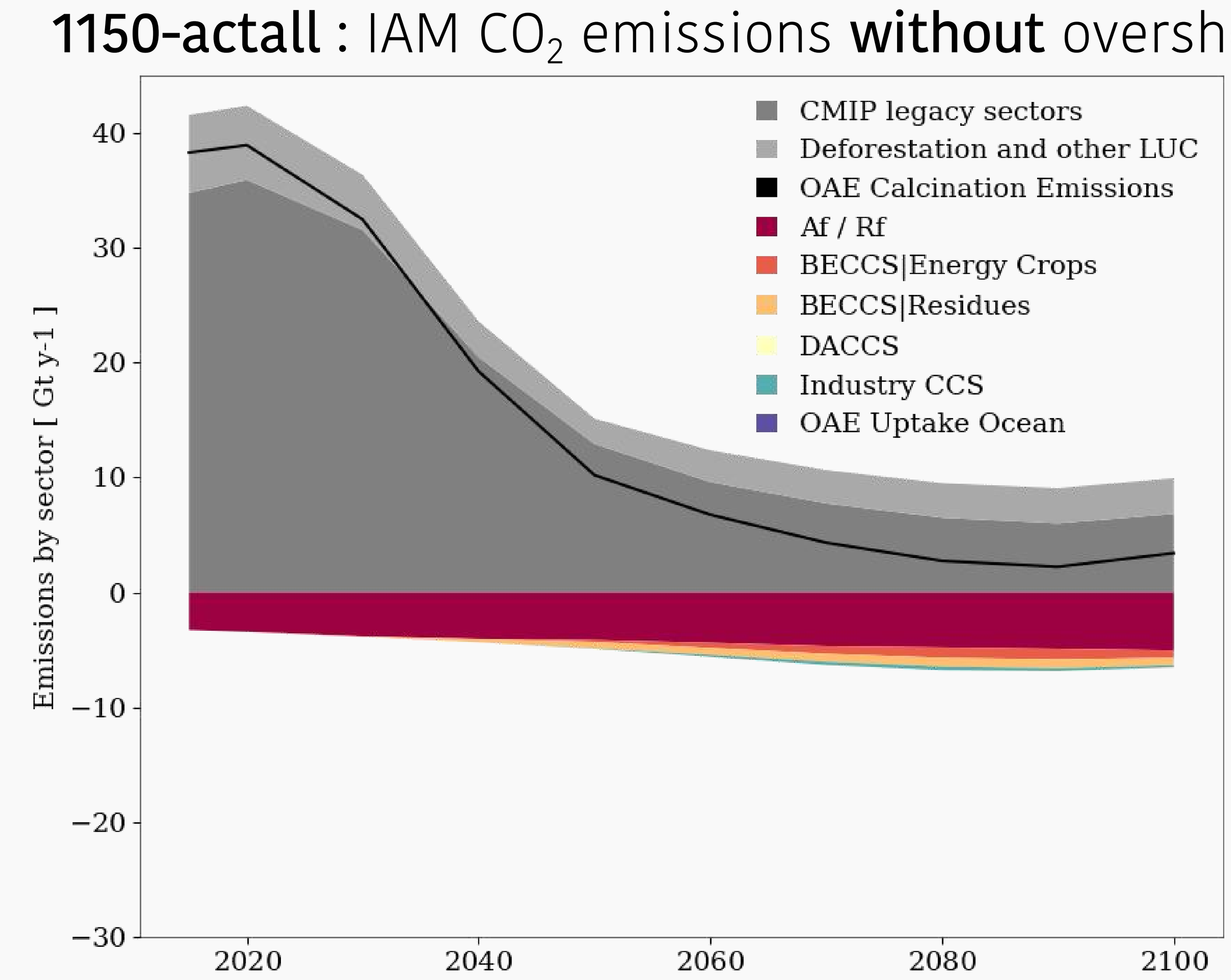
SIMULATION DESIGN CMCC-ESM2[1] is run in emission-driven mode with forcings provided by REMIND-MAgPIE[2,3]. The CO_2 budget is set to **1150 Gt by 2100** to stay **well below 2°C** of warming compared to pre-industrial levels. A portfolio of **four land-** and **ocean-based CDR** is explicitly parametrised in the ESM:

- Dynamical **B**io**E**nergy with **C**arbon **C**apture and **S**torage
- Dynamical **O**cean **A**lkalinity **E**nhancement
- Prescribed **A**fforestation- **R**e**f**orestation
- Prescribed **D**irect **A**ir **C**apture and **S**torage

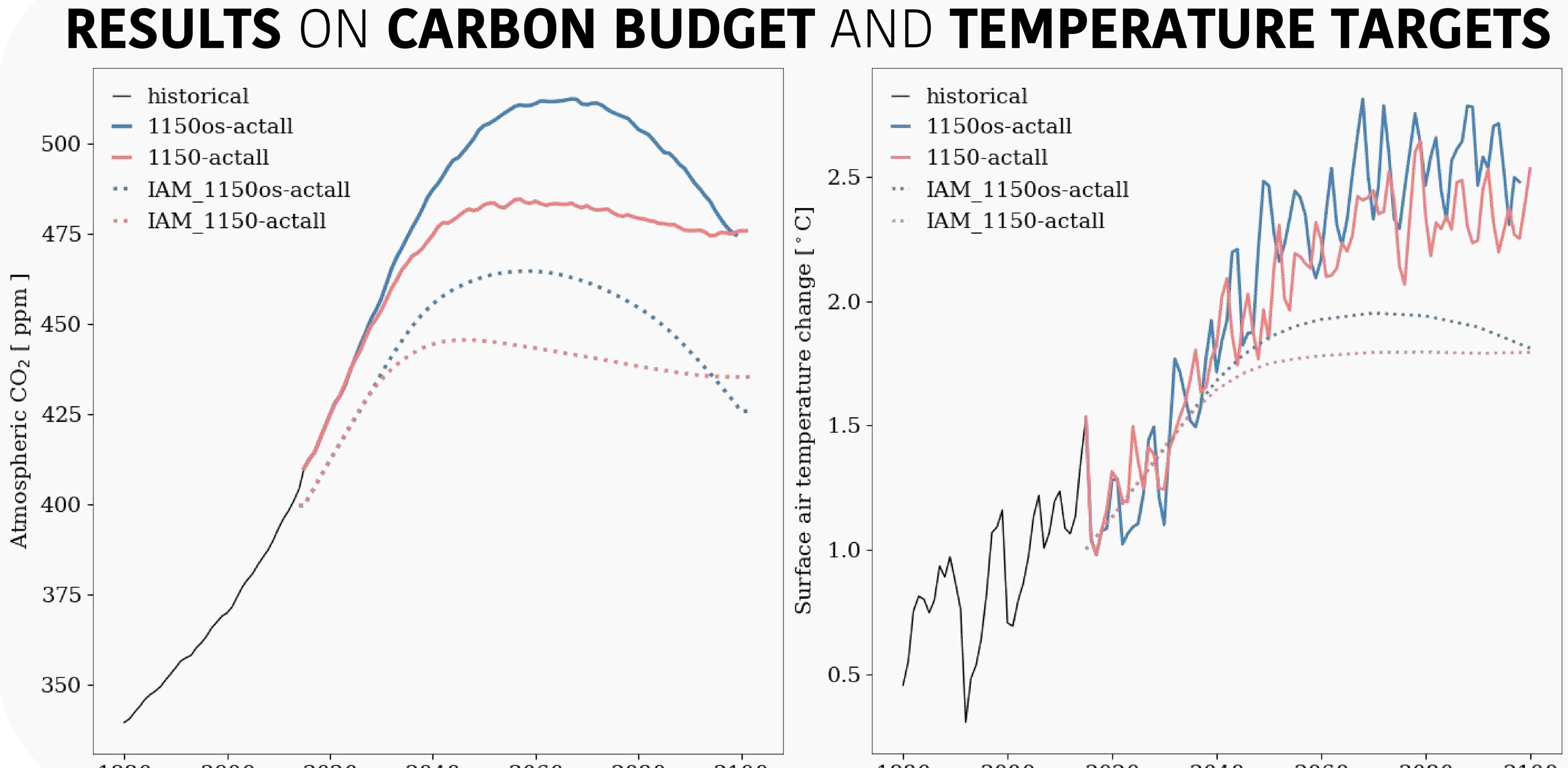
1150os-actall : IAM CO_2 emissions **with** overshoot



1150-actall : IAM CO_2 emissions **without** overshoot

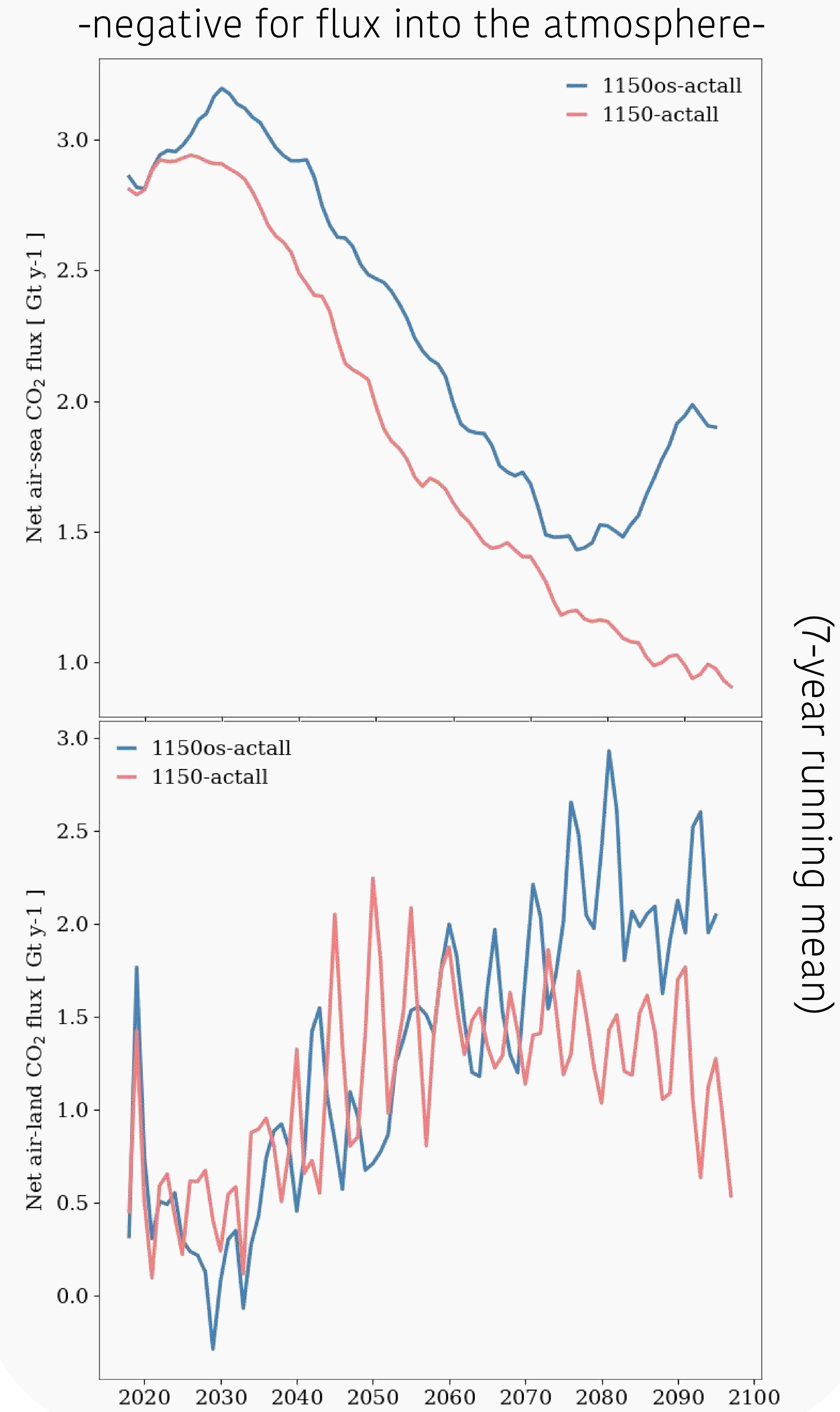


RESULTS ON CARBON BUDGET AND TEMPERATURE TARGETS



RESULTS ON CARBON FLUXES

-negative for flux into the atmosphere-



KEY CONCLUSIONS

Differences between the ESM and the IAM are **systematic** and, although the **temperature target** is **not met** by the ESM, the change is coherent with simulated atmospheric CO_2.

CDR efficiencies are **significantly reduced** due to Earth System feedbacks, **pending a deeper analysis** of inconsistencies between IAMs and ESMs, and comparison with other ESMs.

WAY FORWARD

Investigate dynamical versus IAM-prescribed CDR differences

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[3] Dietrich, J. P., Bodirsky, B. L., Humpenöder, F., Weindl, I., Stevanović, M., Karstens, K., ... & Popp, A. (2019). MAgPIE 4–a modular open-source framework for modeling global land systems. Geoscientific Model Development, 12(4), 1299-1317.

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Response of the Earth system to the RESCUE overshoot scenarios: insights from OSCAR model

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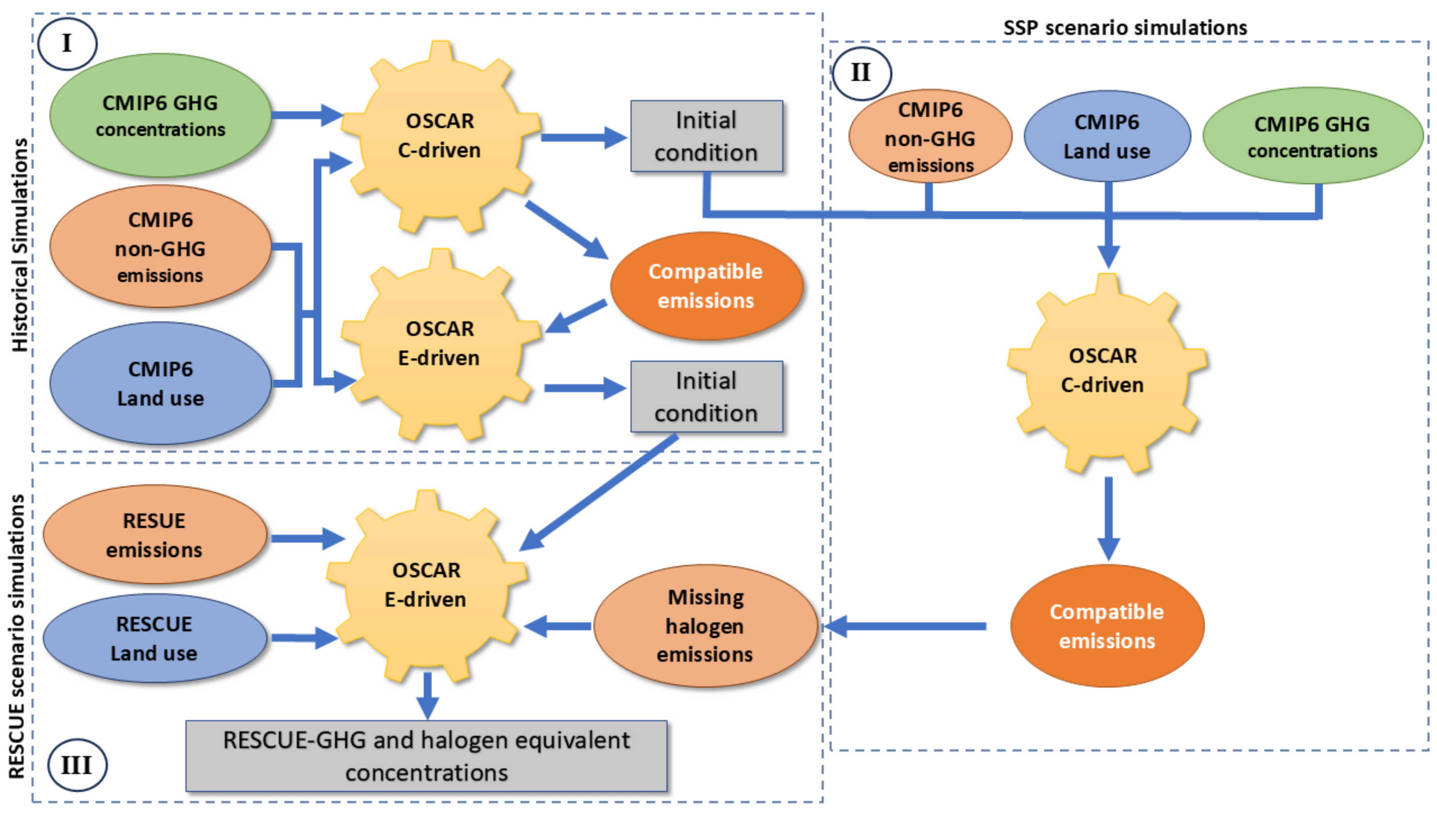
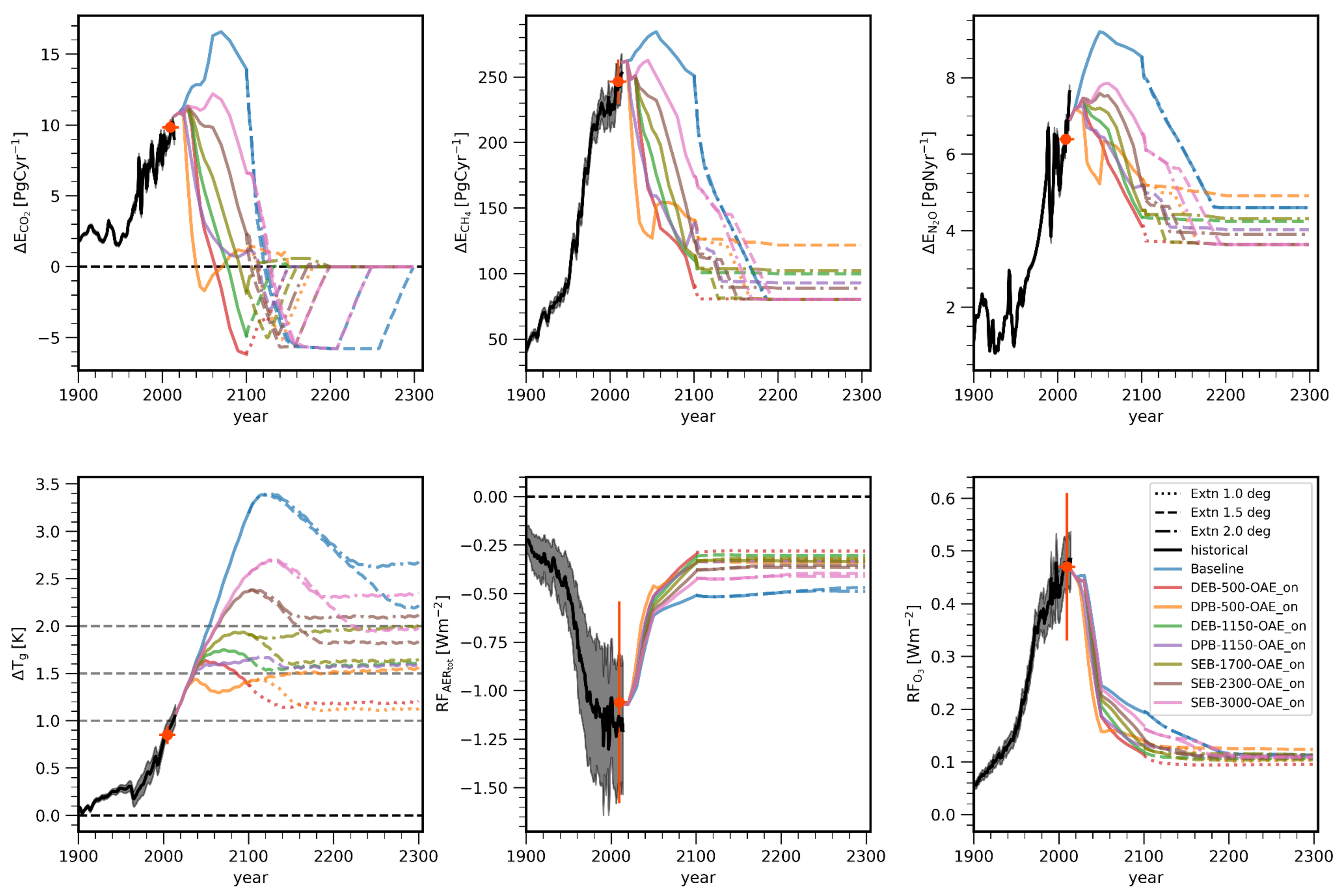
- Overshoot scenarios, where global temperatures and greenhouse gas (GHG) concentrations temporarily exceed climate targets, illustrate possible pathways for mitigating climate change through large-scale carbon dioxide removal (CDR). They allow assessment of the reversibility of climate impacts, system resilience, and long-term Earth system dynamics.
- In this context, the RESCUE project provides a comprehensive set of future emission scenarios extending beyond 2100, with varying levels of temperature overshoot. These include pathways that aim to return warming below 1.0 °C, 1.5 °C, or 2.0 °C, using different CDR strategies such as ocean alkalinity enhancement (OAE), BECCS, afforestation, and direct air capture.

SIMULATION DETAILS



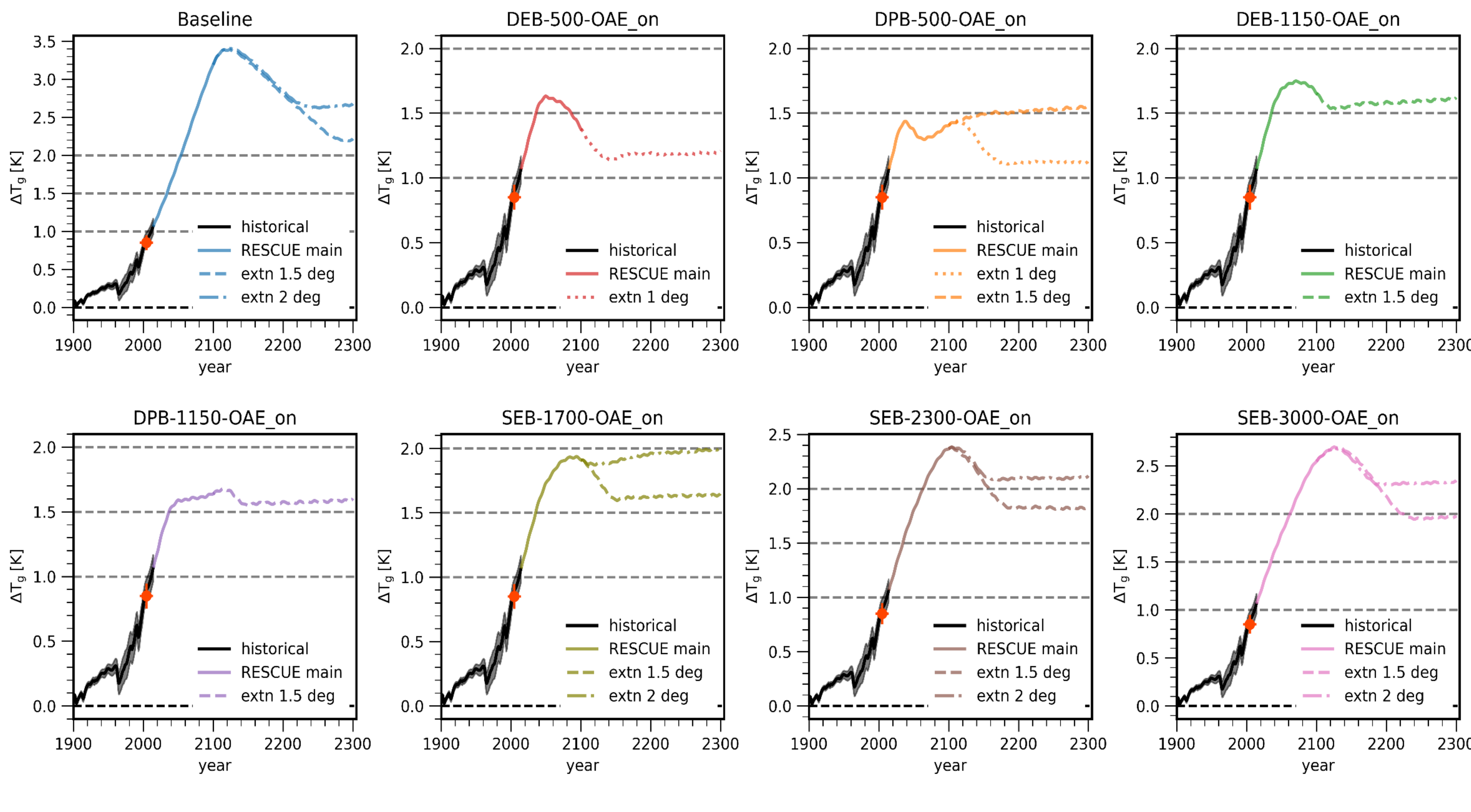
- Simulations are performed using 5000 ensemble of initial parameters generated in a MC setup
- Historical simulations are conducted using CMIP6 emissions
- Additional simulations are carried out for SSP scenarios to complement the emissions of missing halocarbon species

INPUT EMISSIONS AND CONSTRAINTS



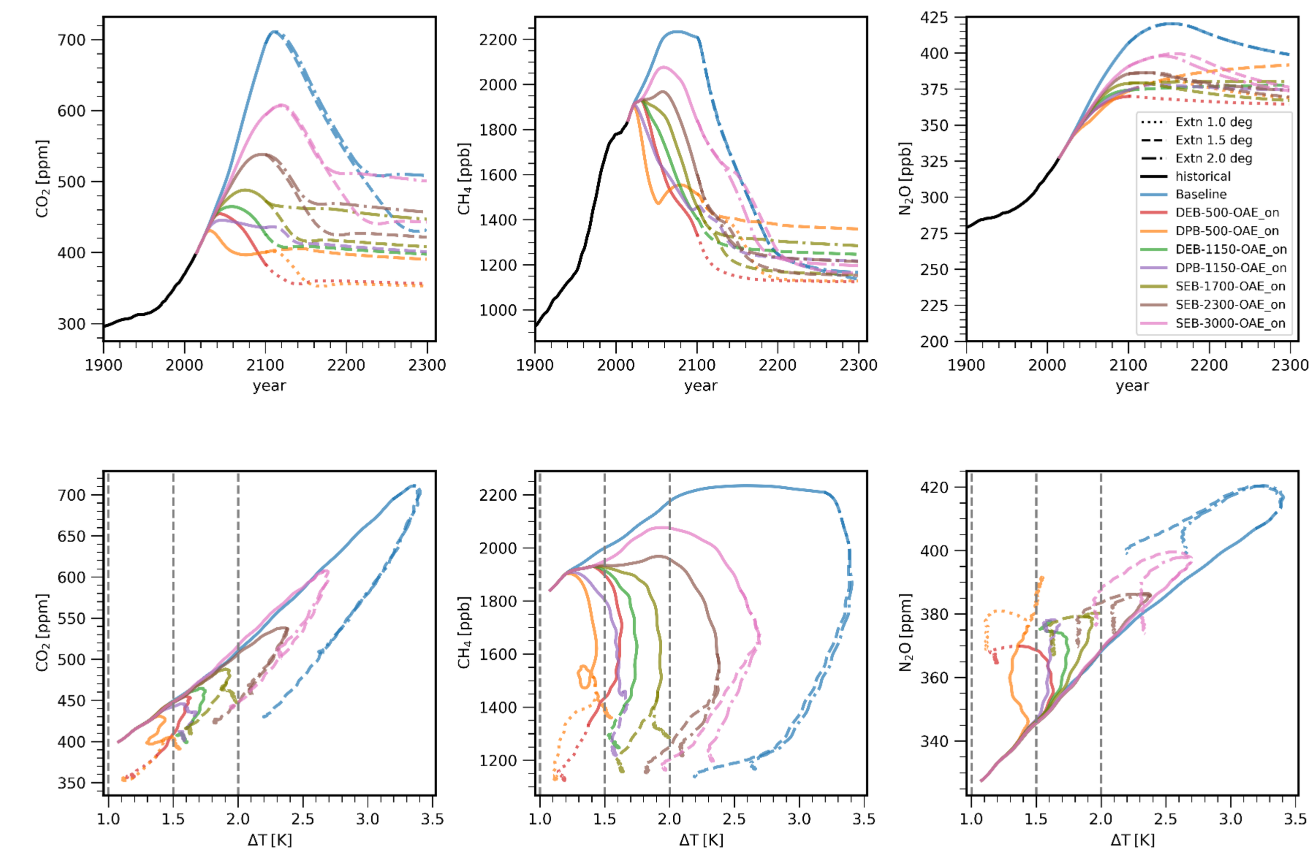
- We constrain input historical emissions of three major GHGs, historical GMST anomaly, total aerosol and Ozone radiative forcings
- Additionally, we also constrain total land and ocean carbon storage to their values in the SSP2-4.5 scenario

GLOBAL MEAN SURFACE TEMPERATURE ANOMALY



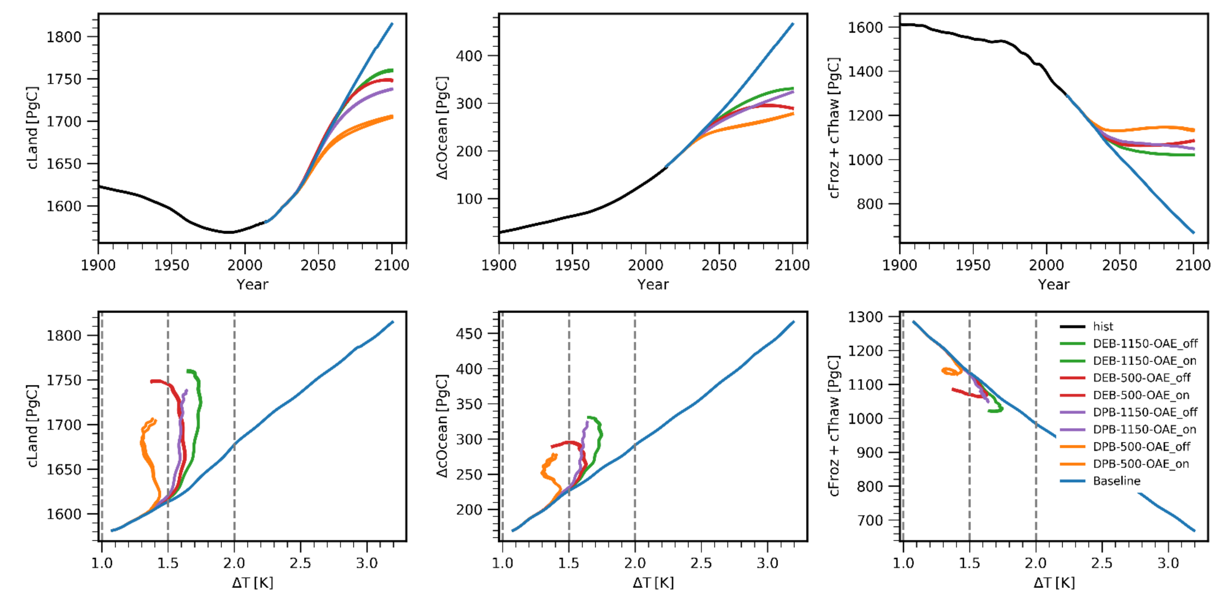
- GMST reaches a maximum, declines and stabilizes to target temperatures in all scenarios
- Height of the overshoot increases in high warming scenarios, highlighting the path dependence

GHG CONCENTRATIONS



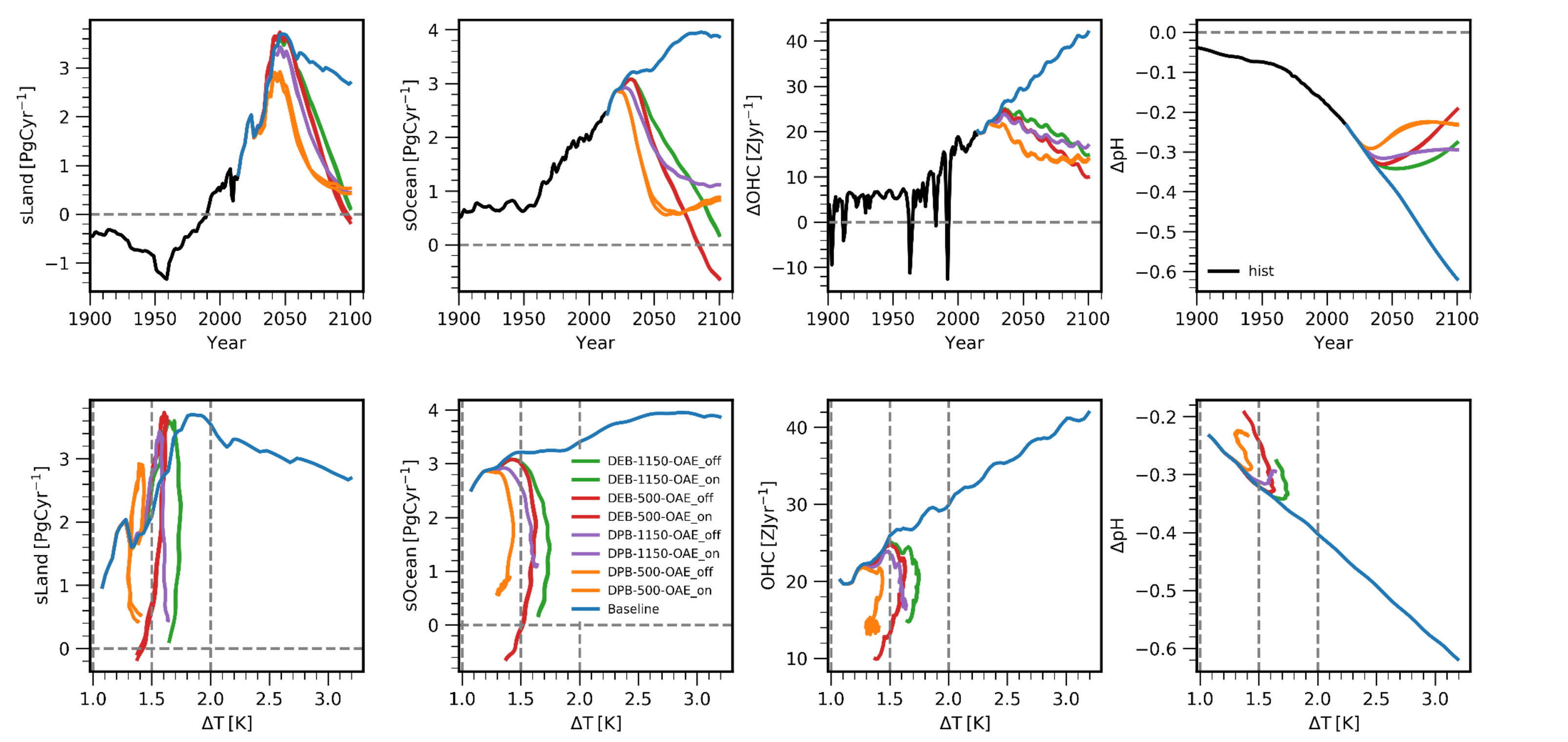
- GHG concentrations decline after reaching their peak
- CH_4 declines rapidly, while N_2O remains slow to respond across all CDR scenarios
- GHG concentration exhibit nonlinear and hysteretic behavior, reflecting climate system inertia

CARBON STOCKS



- Land/Ocean carbon stocks steadily increase but slows down post 2050 due to CDR and show hysteresis
- Total permafrost carbon (frozen + thawed) declines in all scenarios and does not increase after overshoot, indicating a likely irreversible carbon loss

FLUXES AND OCEAN ACIDIFICATION RESPONSE



- Land/Ocean carbon sink declines and Ocean heat uptake slows down
- DEB-500 shows most drastic trend for Ocean carbon sink where it turns slightly negative
- Ocean pH drops but stabilizes (partially recovers) in CDR scenarios but not completely reversed
- Both sinks display degradation under temperature overshoot. The OHC shows persistent heat storage

SUMMARY

- Temperature overshoot and recovery depend strongly on the timing and scale of CDR deployment; early and intensive strategies (e.g. DEB-500) achieve faster return below 1.5 °C
- Carbon sinks (land, ocean, permafrost) exhibit hysteresis and lag. Their responses during cooling differ from warming, indicating partial irreversibility and sink saturation
- Ocean acidification slows down or stabilizes under CDR, but does not fully recover, showing the lasting effects of excess CO_2
- Short-lived gases like CH_4 respond quickly to mitigation, while long-lived gases like CO_2 and N_2O require sustained removal efforts to decline significantly

REFERENCES AND ACKNOWLEDGEMENTS

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