Emissions-Driven CESM for Investigating Carbon and Climate Responses to Historical and Future Scenarios

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CESM LMWG – February 26 2025

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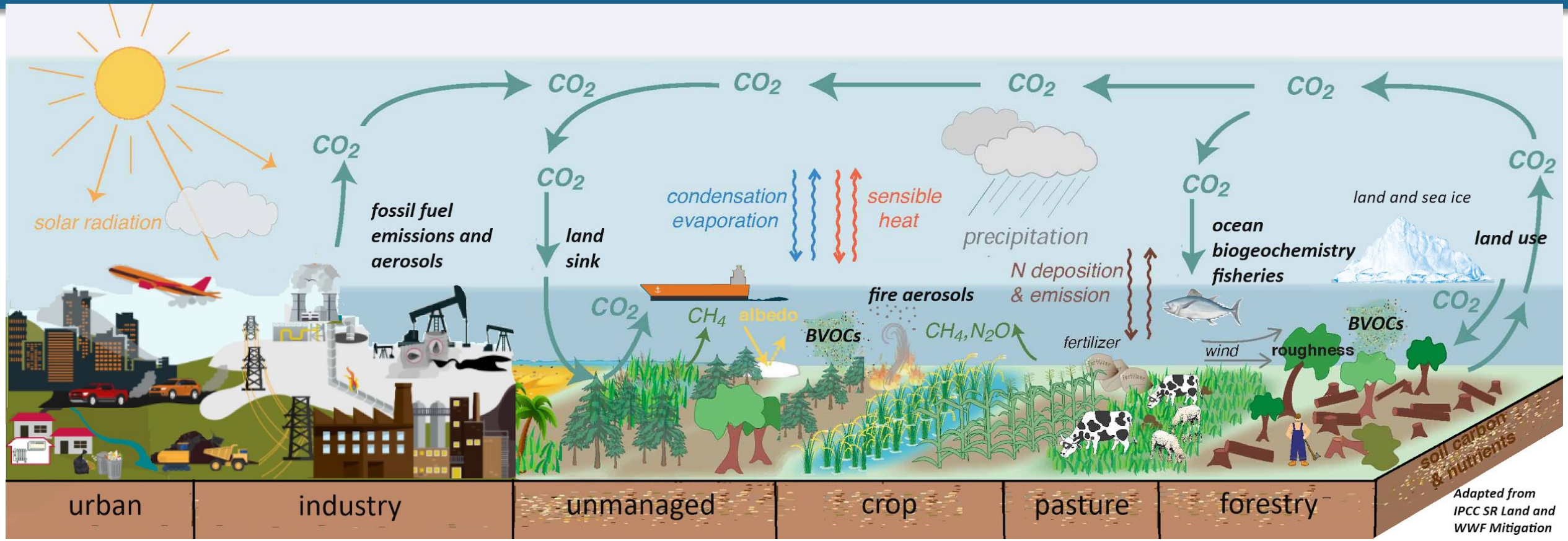
Configuring CESM with Emissions and Active Aerosols

1. CESM 2.1.5 has been expanded to include new capabilities that allow for active fire and biogenic aerosols, the new 4p2z ocean biogeochemistry, updates to CLM5 surface data to be consistent with CTSM 5.3.
2. Emissions factors for Fire and Volatile Organic Compounds are reduced from default values to match CMIP6 Forcing values. The known FUN Bug Fix was applied.
3. Five Historical Ensemble Members have been run from years 130, 135, 140, 145, 150 of the 1850 Preindustrial Control.
4. Five Ensembles run for the Highly Optimistic Projections Ensembles (HOPE) Project for SSP1-1.9, 2-4.5 and 3-7.0. Each Ensemble member starts from the end of the Historical members.
5. Basis for the Community Climate Intervention Strategies (CCIS) Ensemble being run with Carbon Dioxide Removal and Solar Radiation Modification

The NCAR Community Earth System Model (CESM) 2.1.5

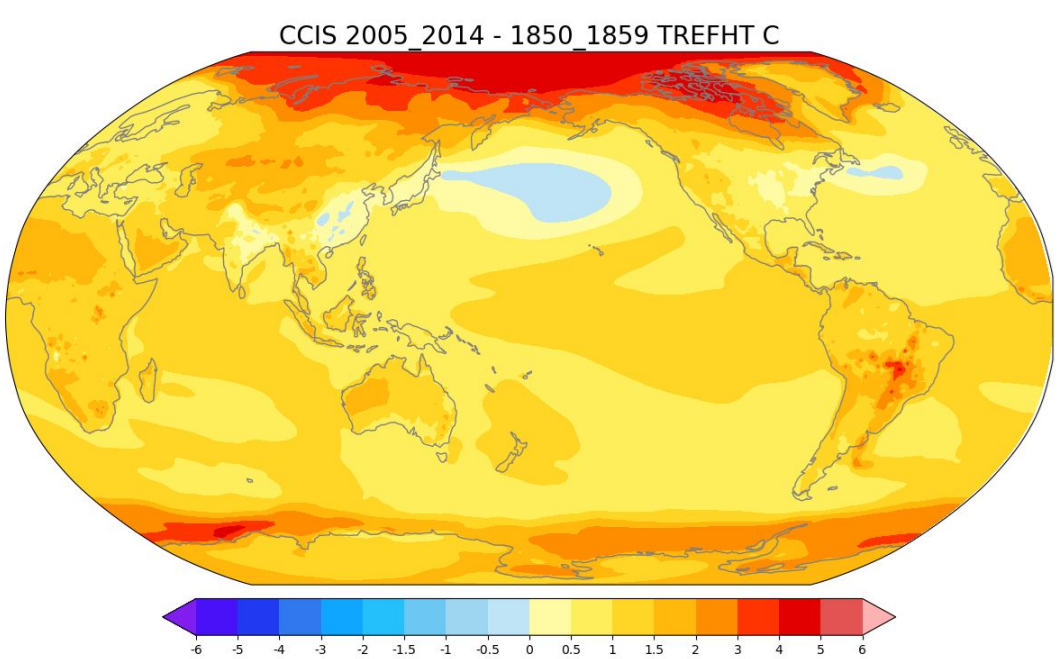


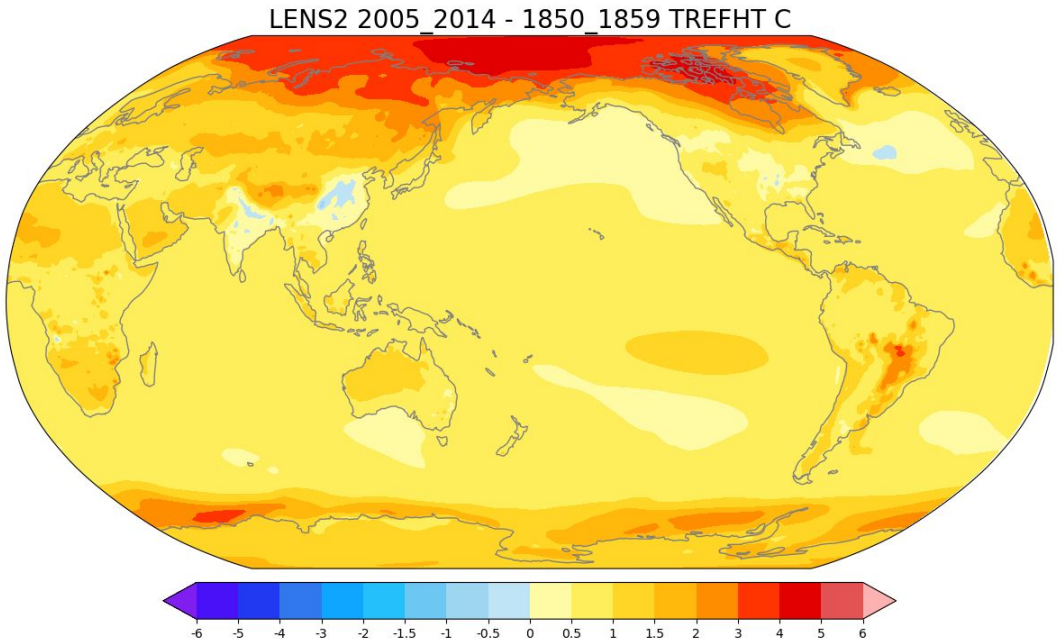
Community Climate Intervention Strategies Ensemble (CCIS Ens):

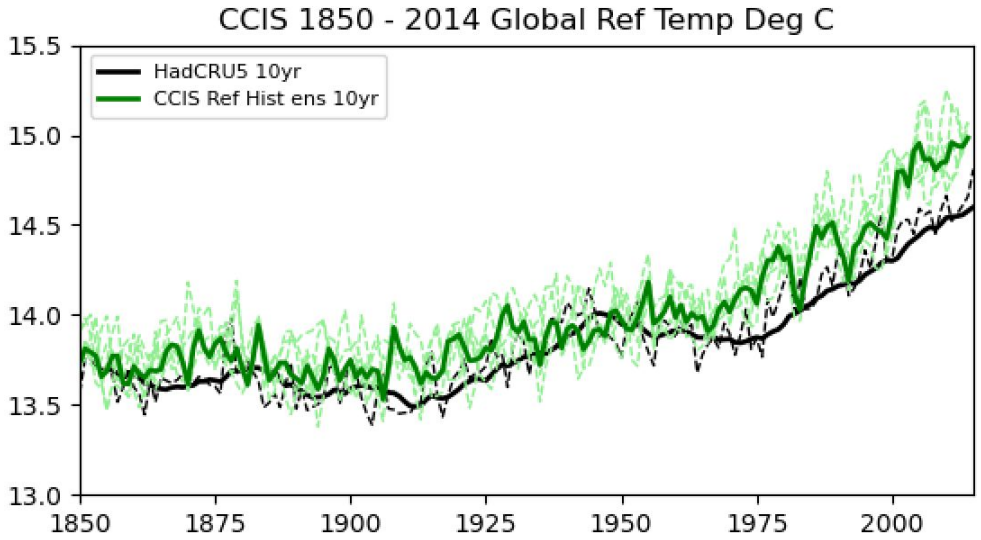
- CESM 2.1.5 (LENS2 Science) CO2 and Aerosols dynamically modeled.
- CMIP6 Fossil Fuel CO2, Methane, and Aerosol Emissions
- Historical, SSP 1-1.9, SSP 2-4.5 and SSP 3-7.0.
- Active Fire Aerosol Emissions
- Active Biogenic Volatile Organic Compound (BVOC) Emissions
- Marine Coccolithophores in New Ocean BGC – FEISTY Fish Model

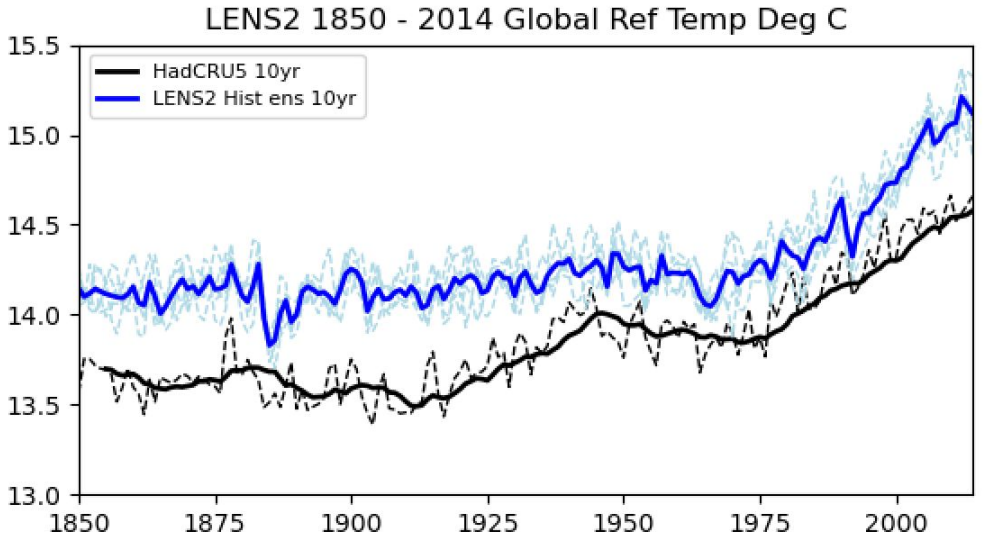
- **Atmosphere SRM:** Stratospheric Aerosol Injection (SAI) -- Marine Cloud Brightening (MCB)
- **Land CDR:** Re/Afforestation -- Bio Energy and Carbon Capture and Storage (BECCS) -- Direct Air Capture (DAC with CCS)
- **Ocean CDR:** Enhanced Alkalinity -- Macroalgae (Kelp) with Biomass Sinking -- Electrochemical CO2 removal from sea water

Evaluation of CESM CCIS Historical Reference Height Temperature versus LENS 2.

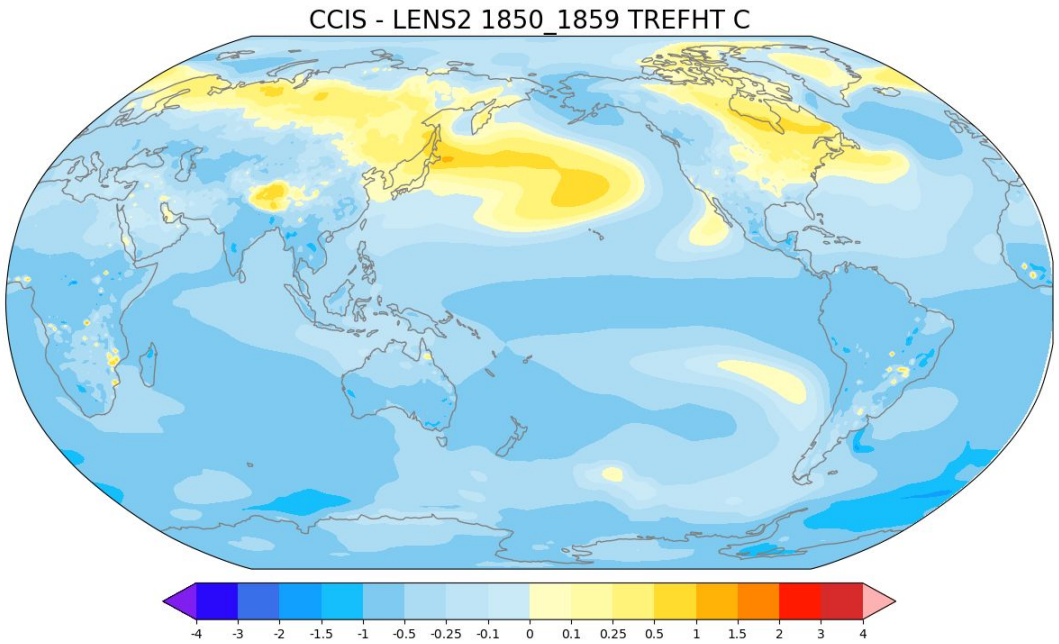


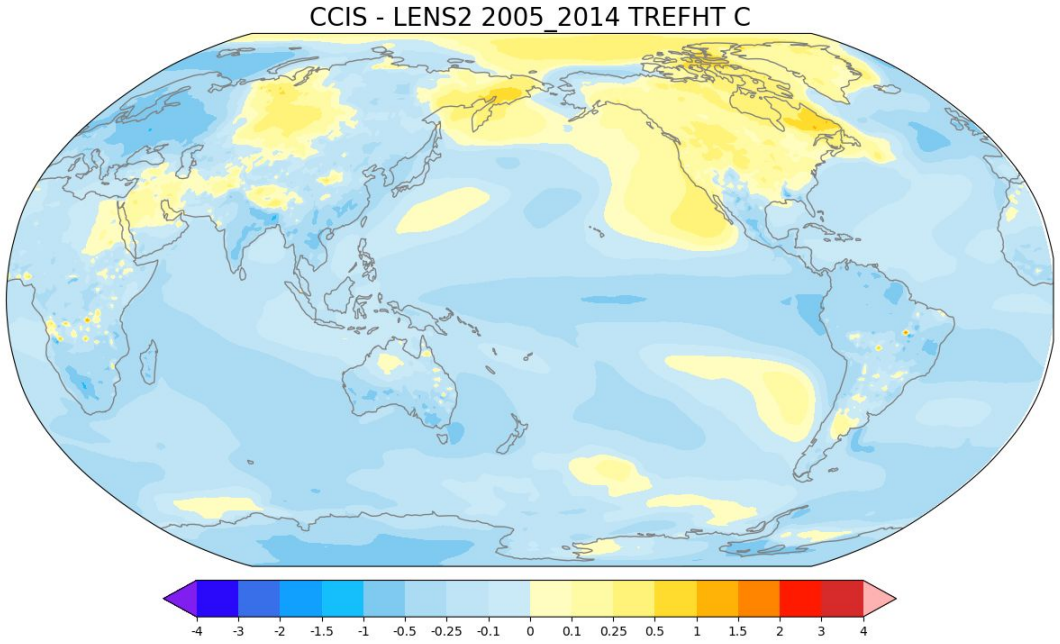


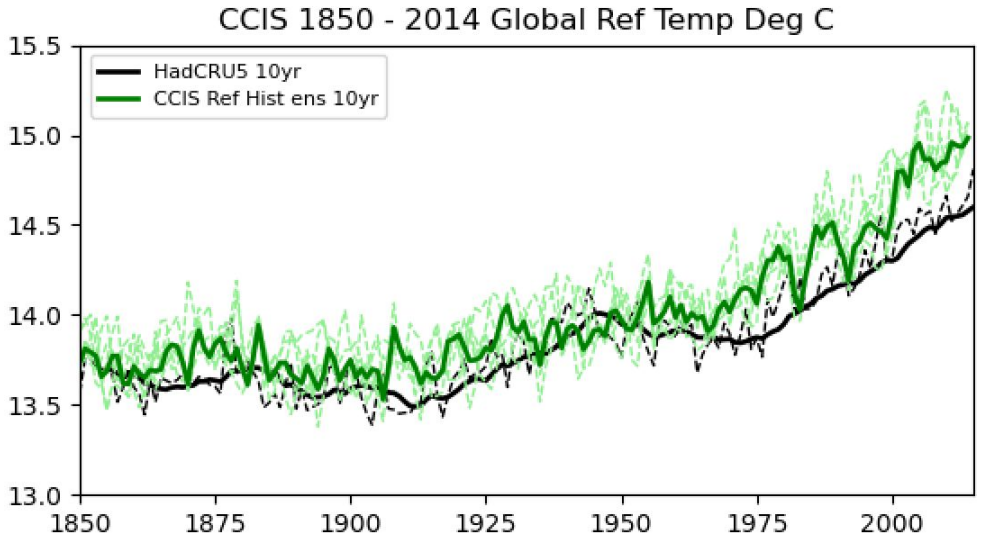


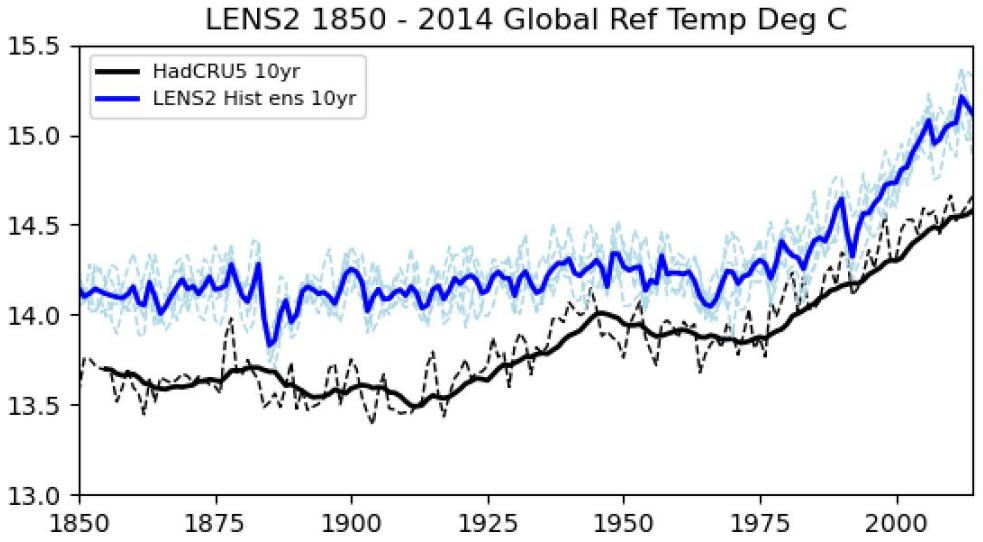


Evaluation of CESM CCIS Historical Reference Height Temperature versus LENS 2.

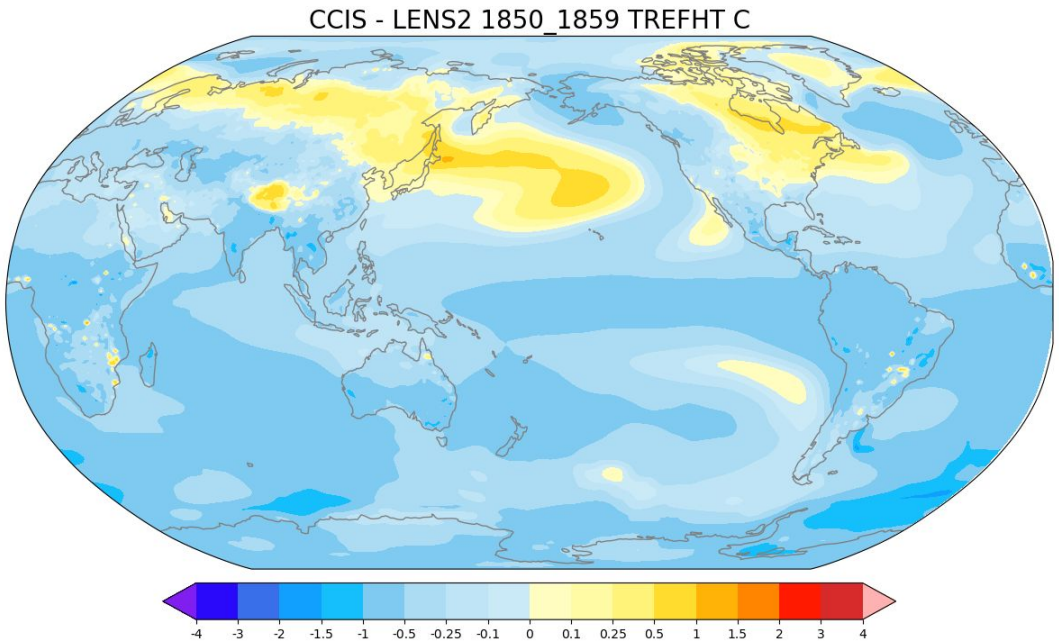


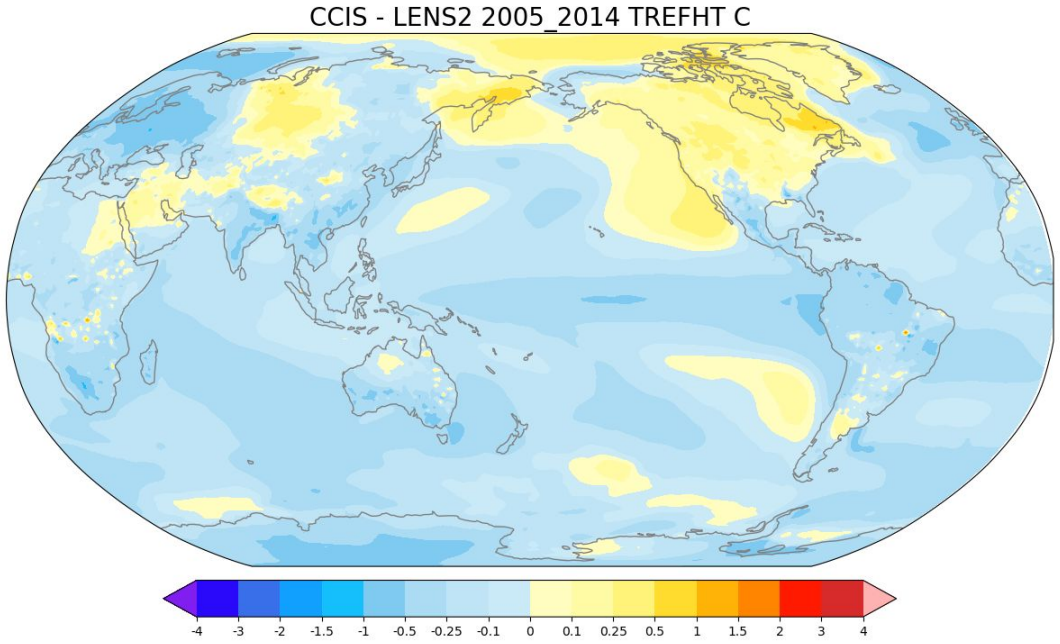


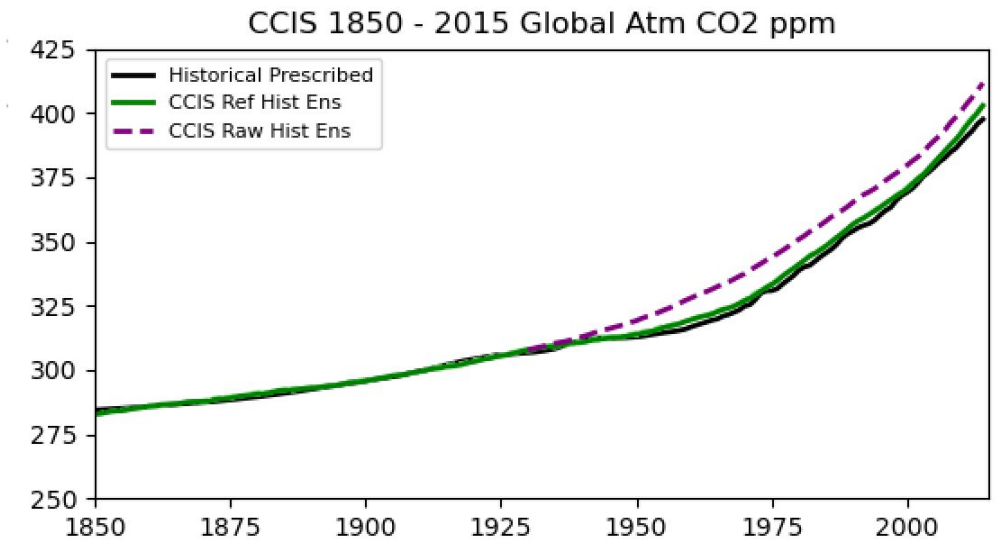


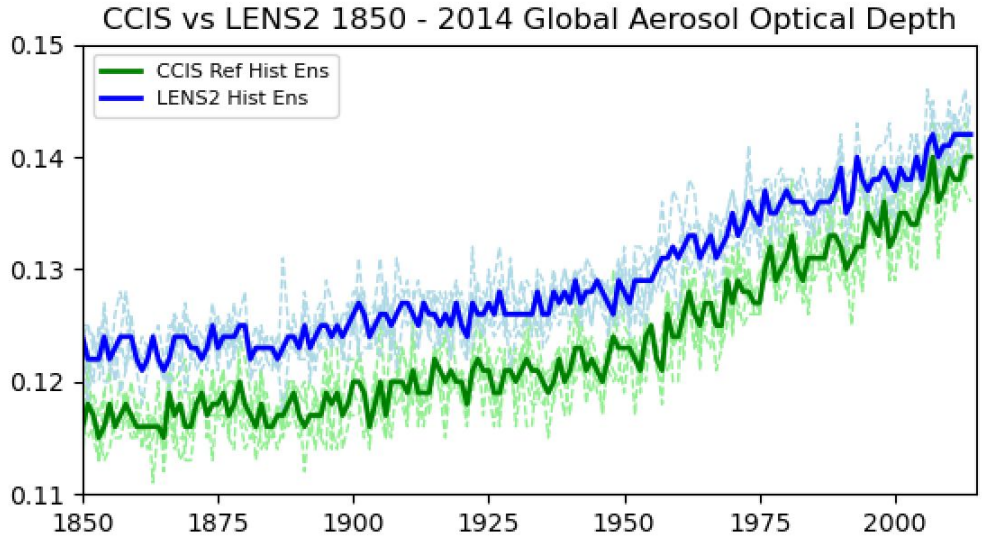


Evaluation of CESM CCIS Historical Reference Height Temperature versus LENS 2.

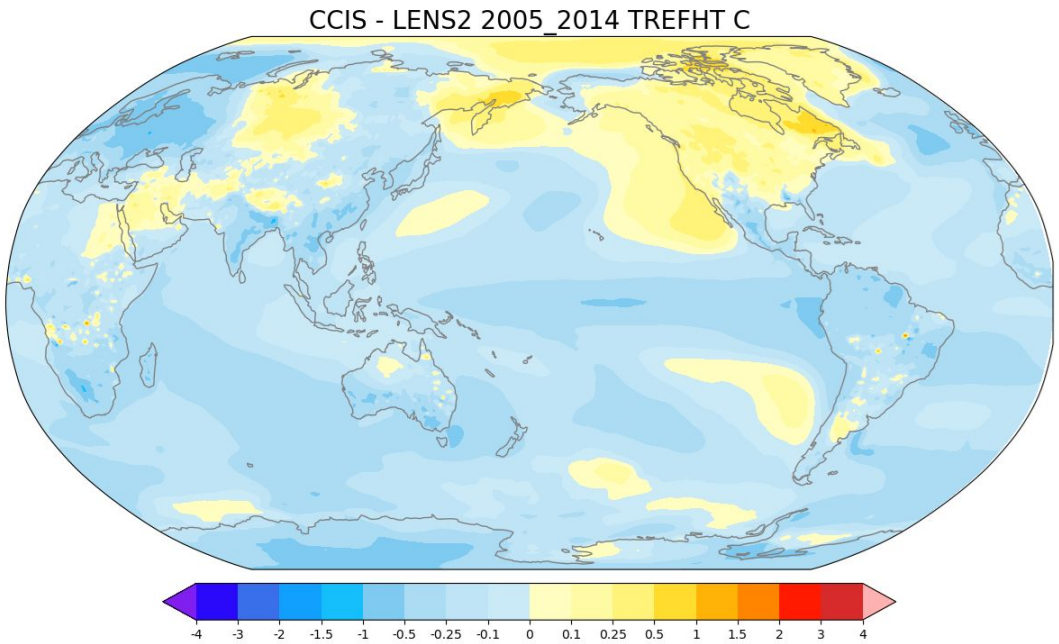


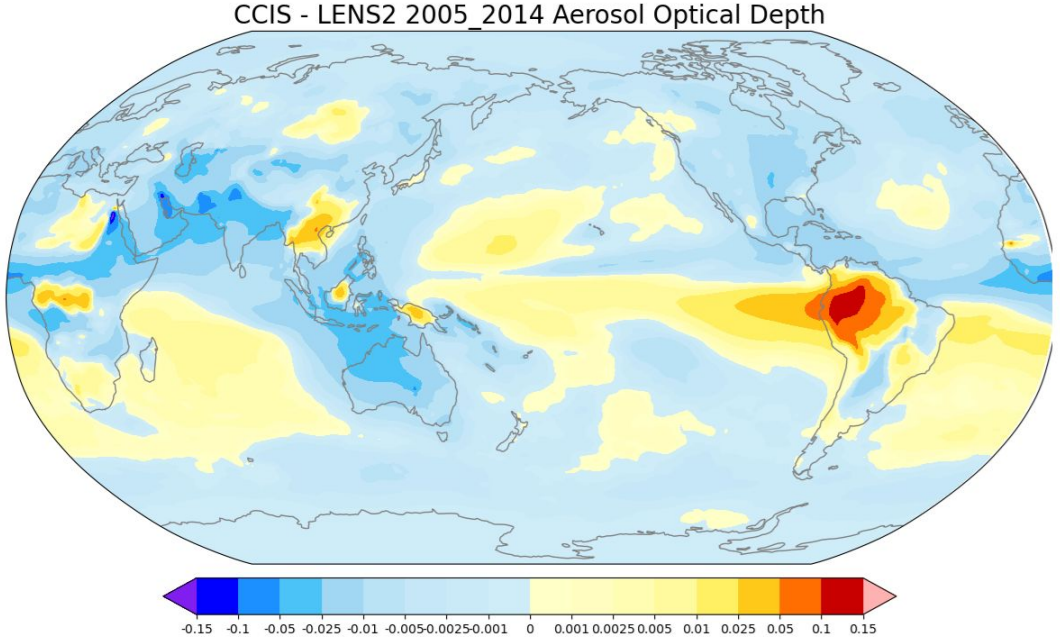


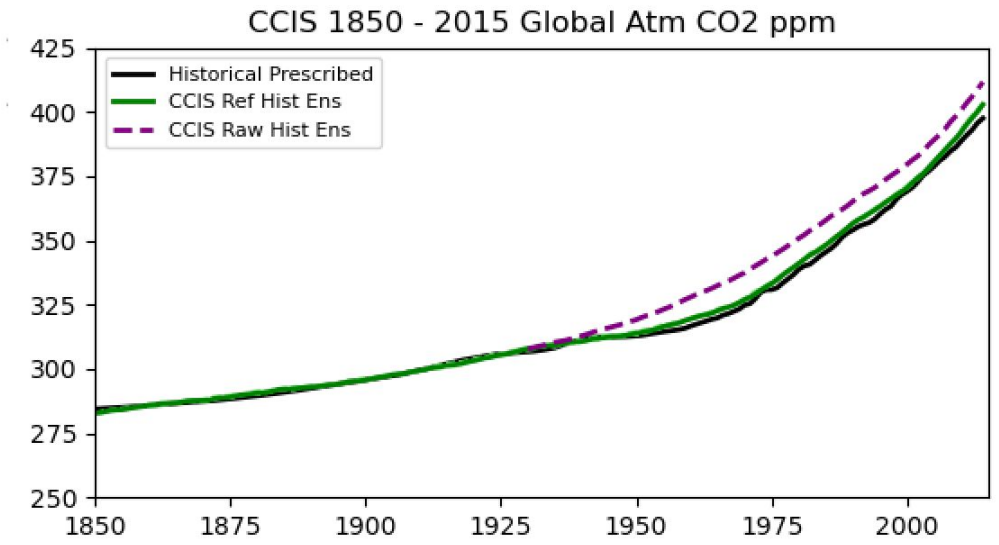


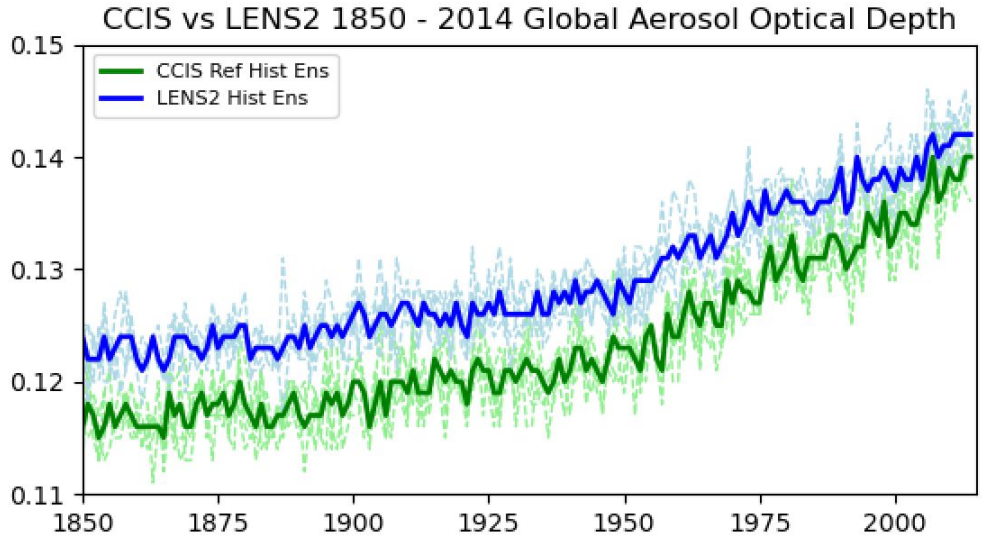


Evaluation of CESM CCIS Historical Reference Height Temperature versus LENS 2.

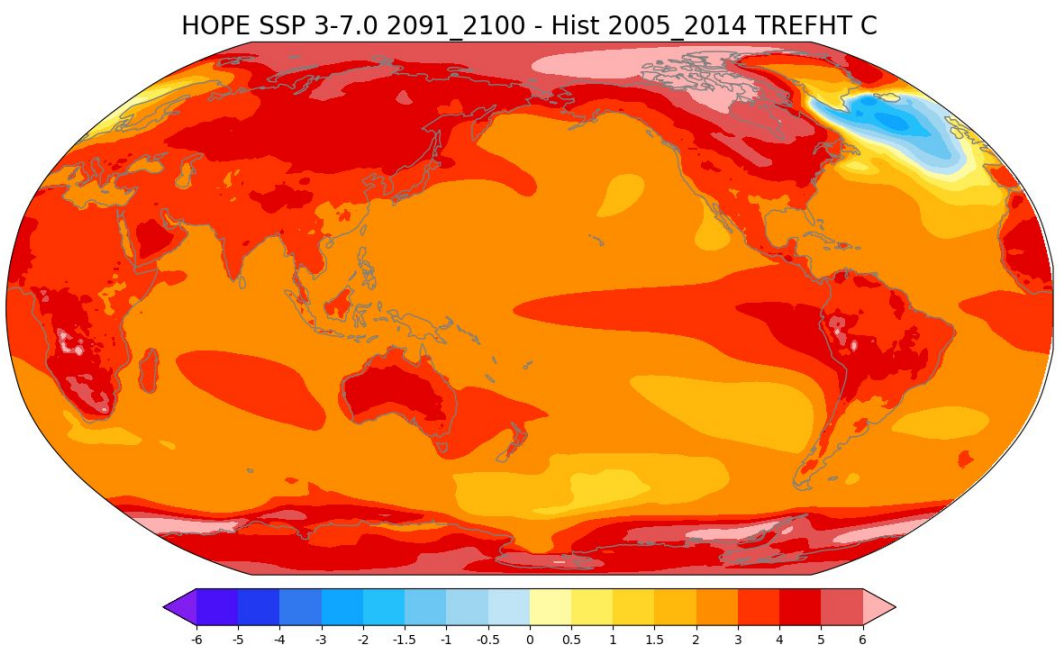


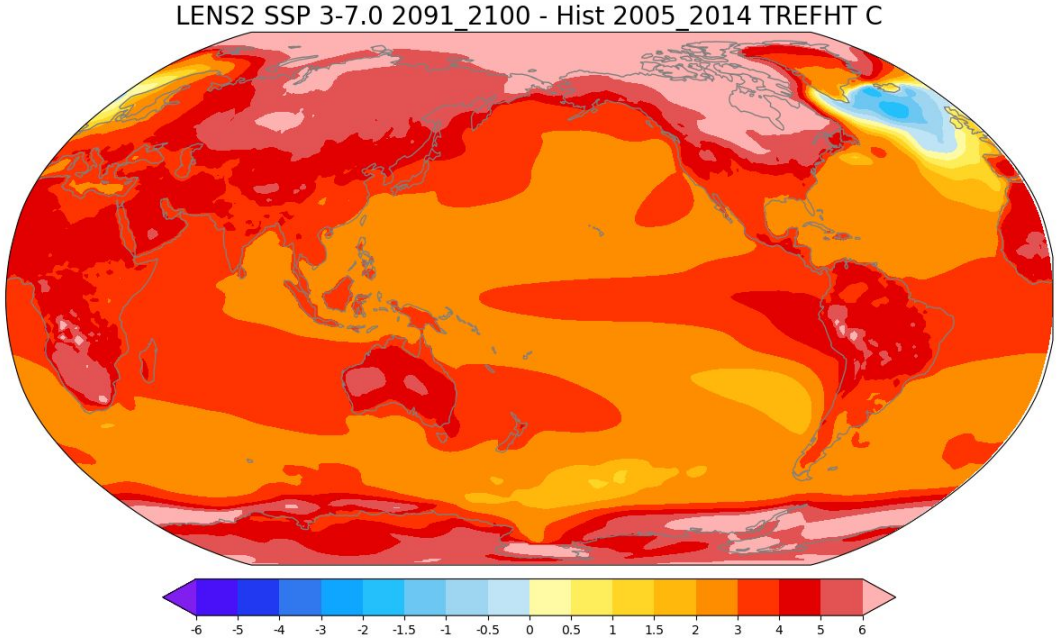


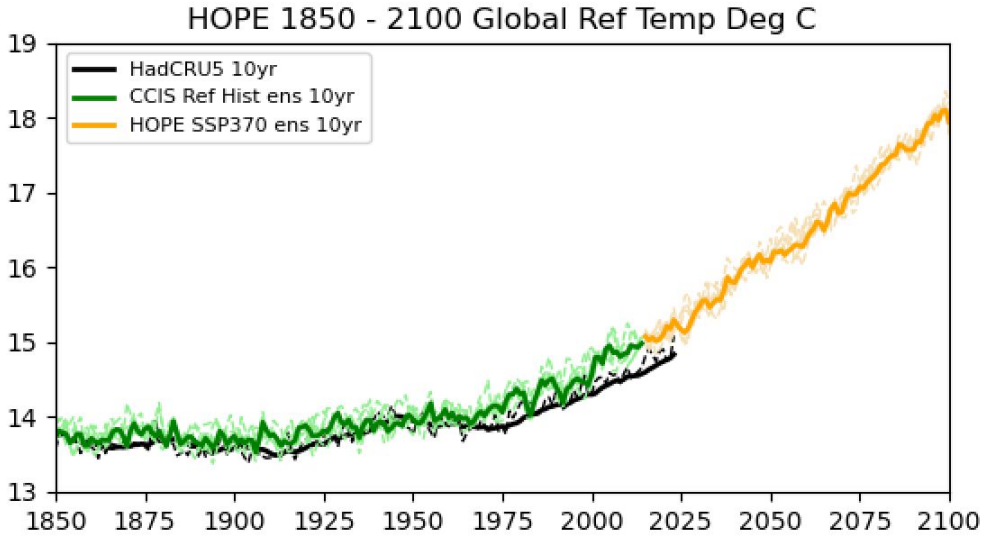


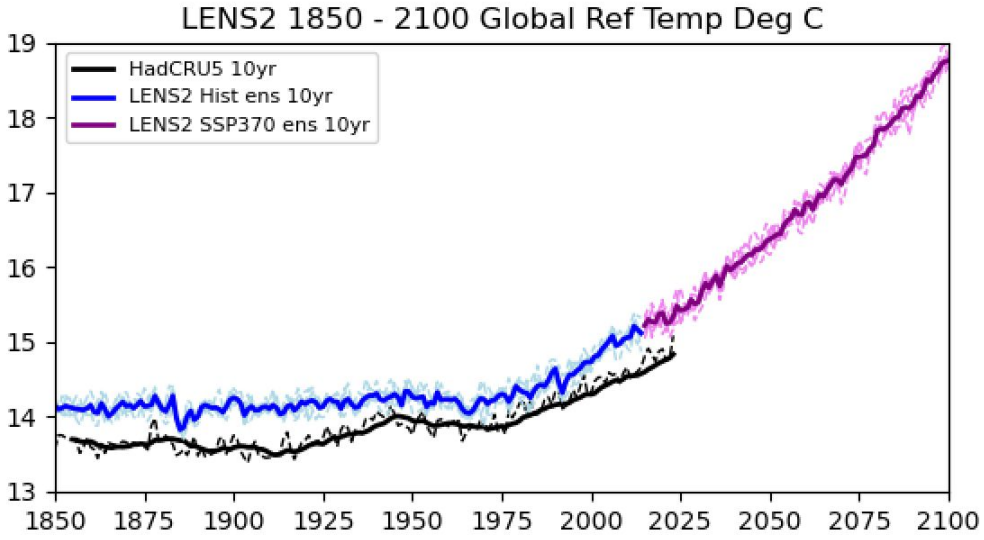


Evaluation of CESM HOPE SSP 3-7.0 Reference Height Temperature versus LENS 2.

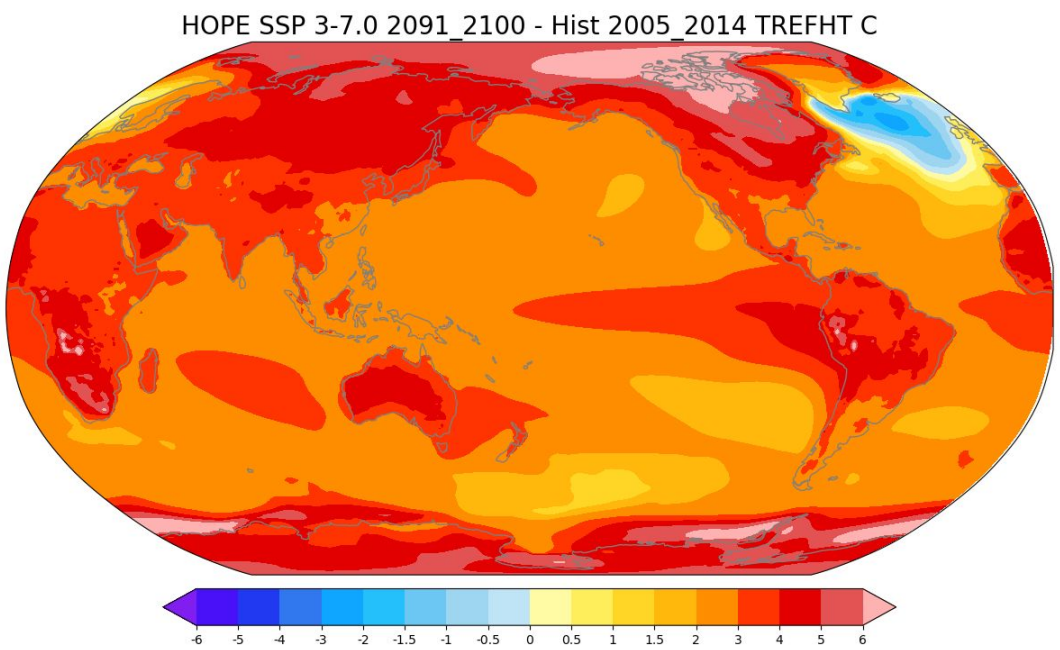


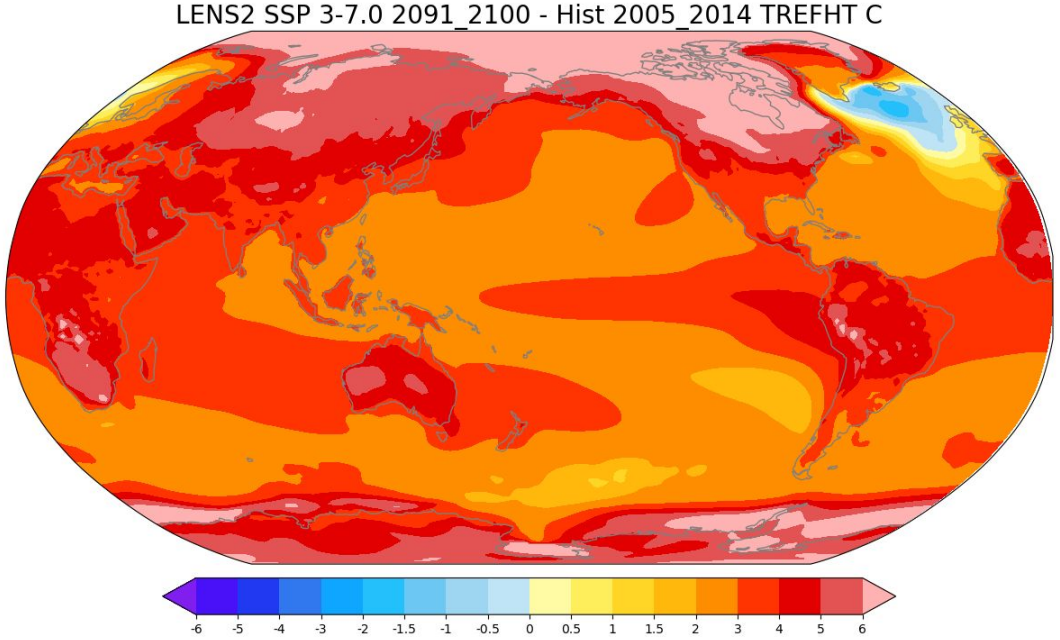


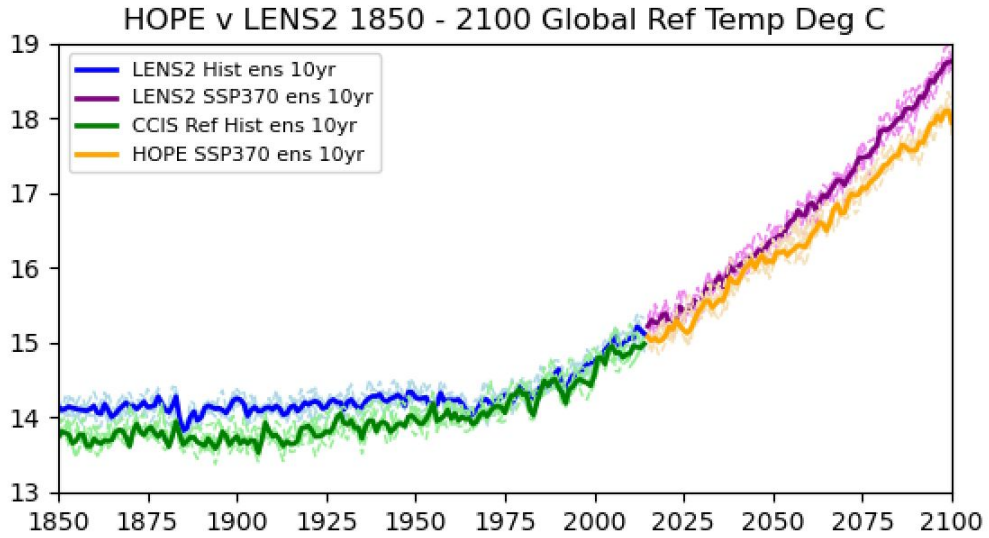


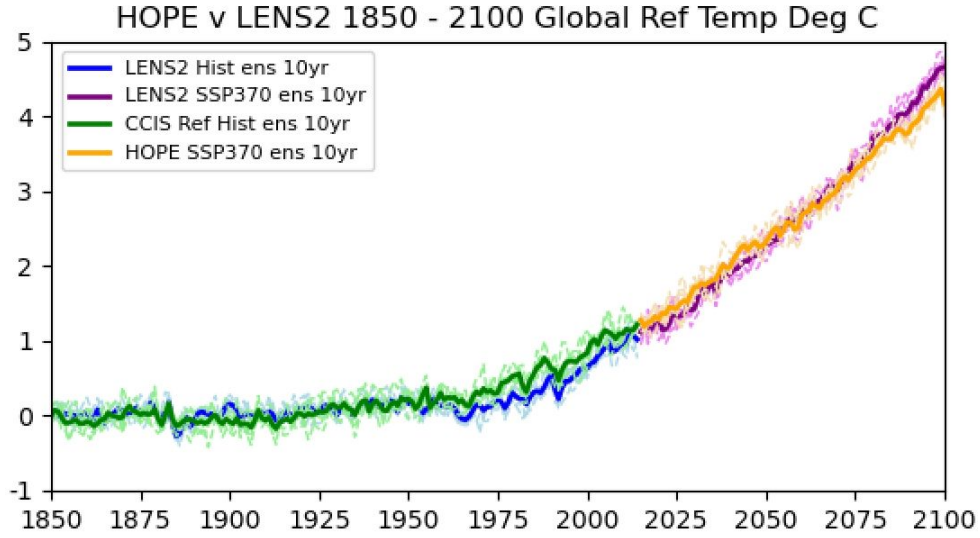


Evaluation of CESM HOPE SSP 3-7.0 Reference Height Temperature versus LENS 2.

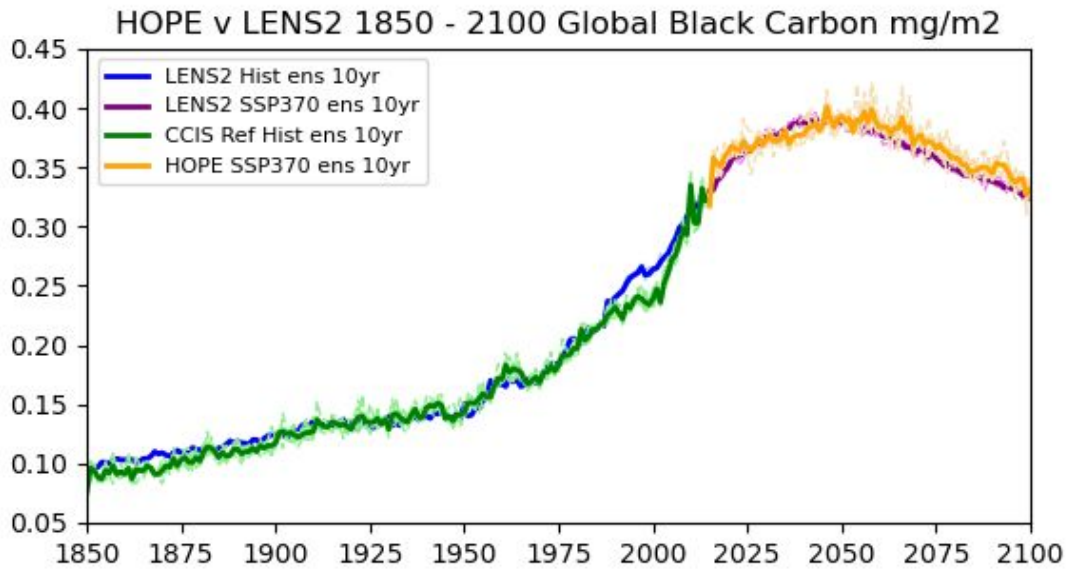


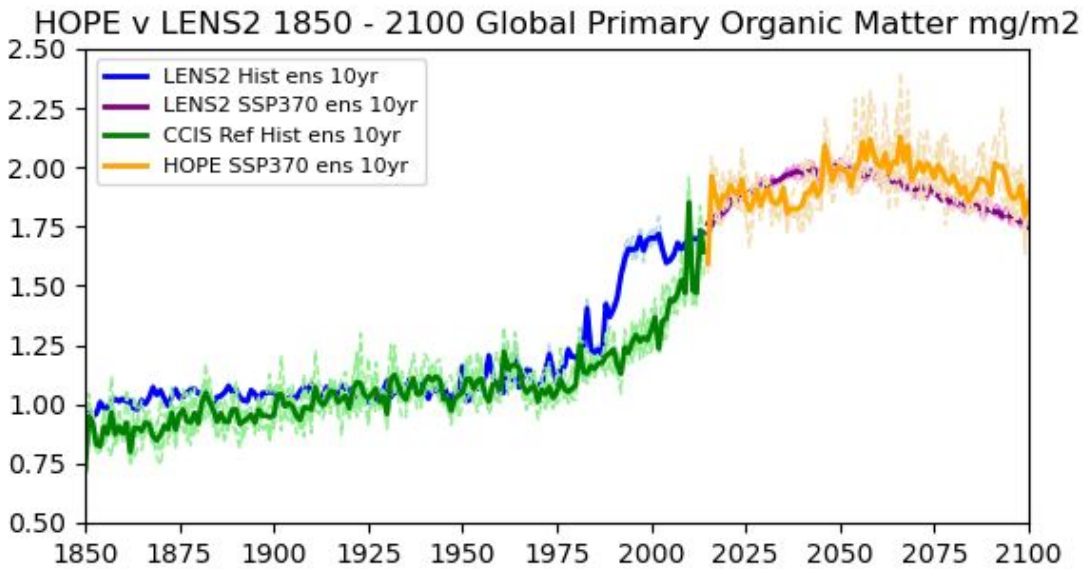


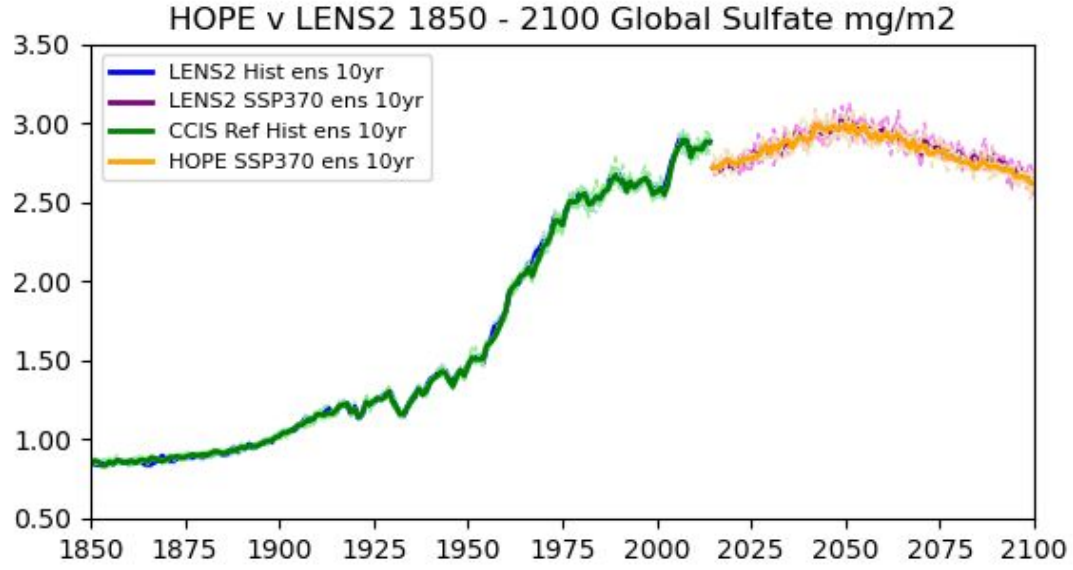


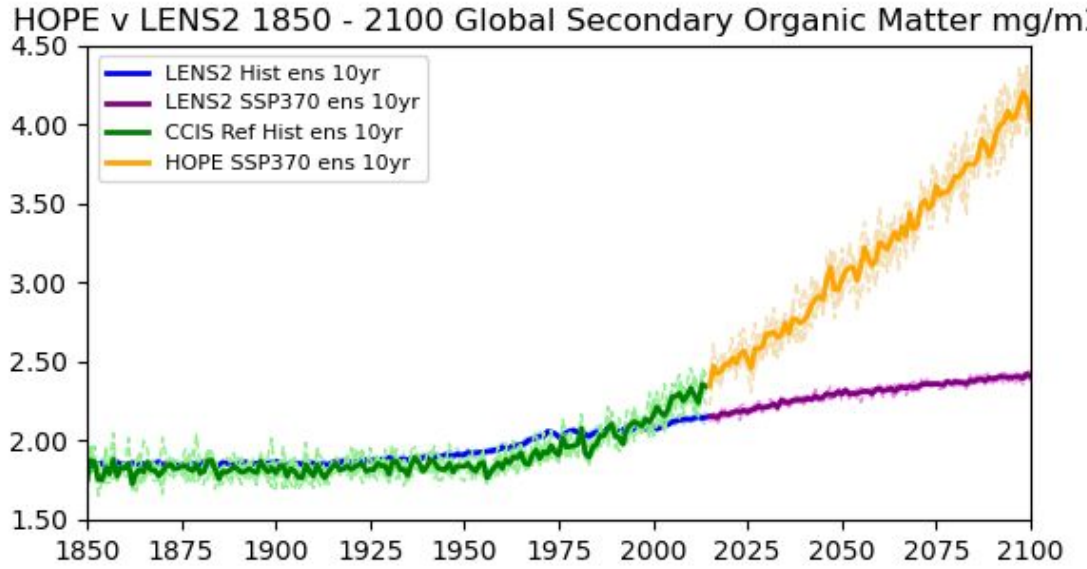


Evaluation of CESM CCIS and HOPE SSP 3-7.0 Aerosol Burdens versus LENS 2.









Evaluation of CESM CCIS SSP 3-7.0 Reference Height Temperature versus LENS 2.

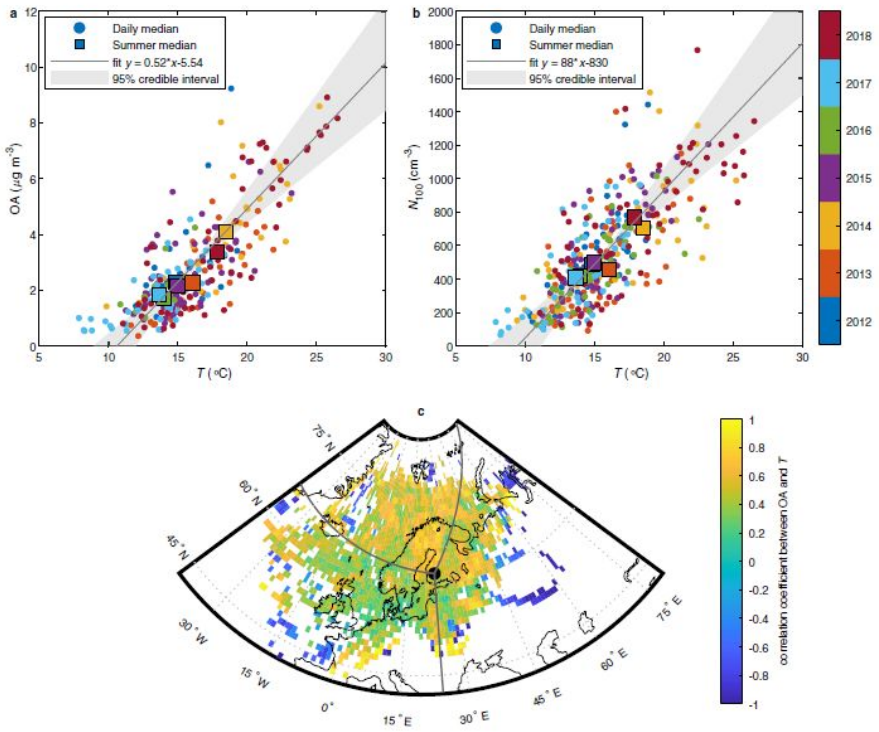


Fig. 1 Field observations on changes in organic aerosol (OA) mass loading and number concentration of cloud condensation nuclei-sized particles with temperature (*T*). **a** OA mass concentration as a function of temperature. **b** Number concentration of particles larger than 100 nm (N_{100}) as a function of

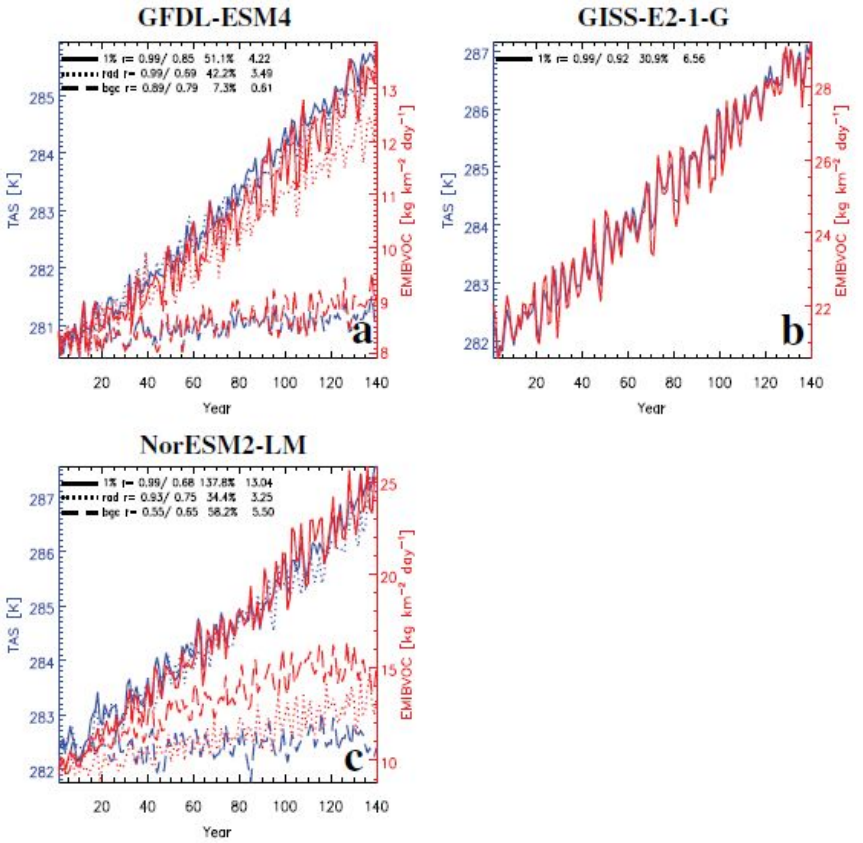
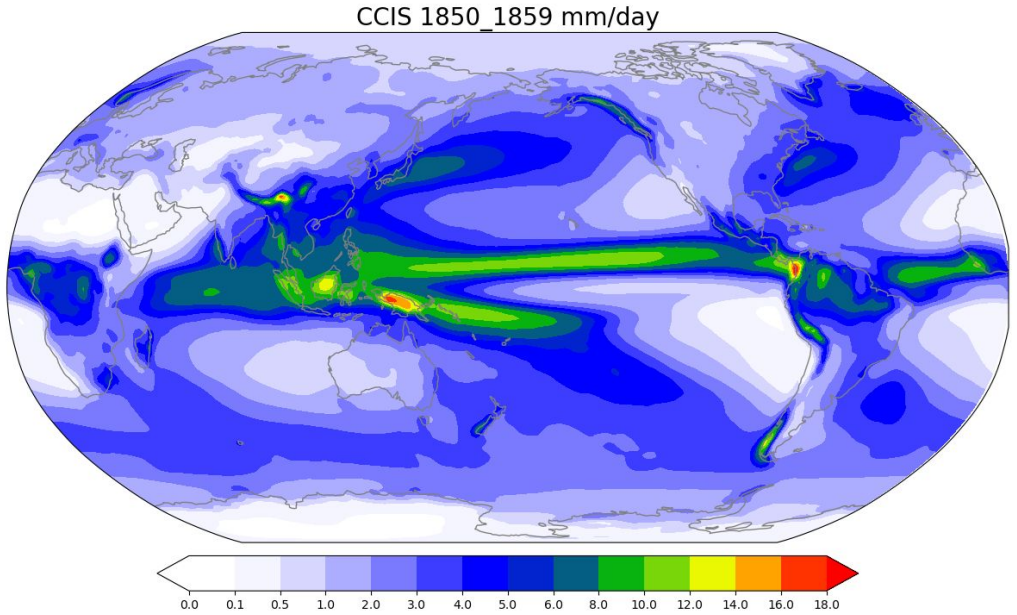


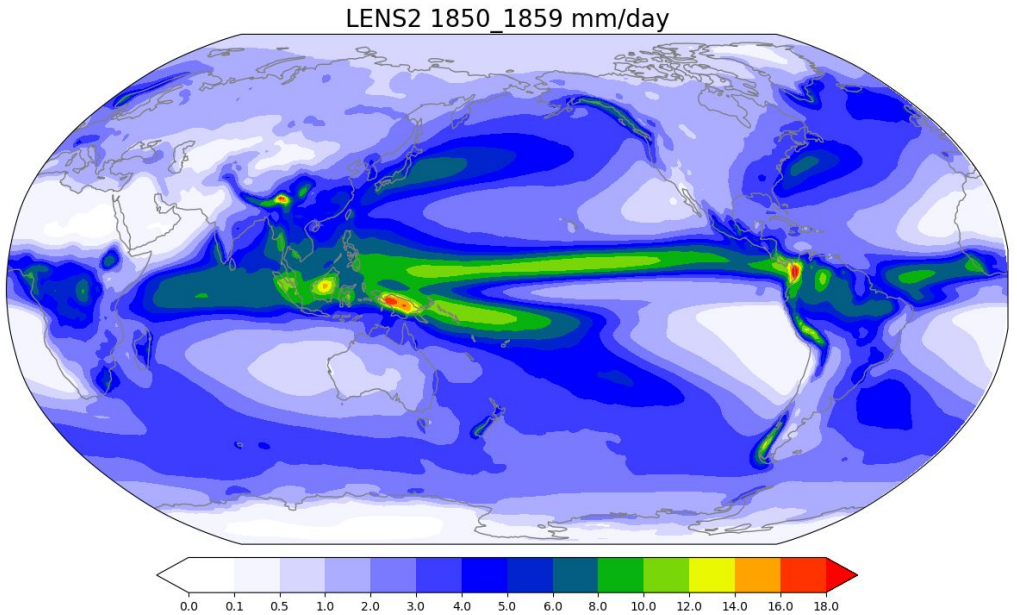
Fig. 5 Global land mean time series of surface temperature and BVOC emissions. Surface temperature (TAS; blue) [K] and BVOC emissions (EMIBVOC; red) [kg km^{-2} day^{-1}] for four models that include climate-dependent BVOC emissions, including **a** GFDL-ESM4; **b** GISS-E2-1-G; **c** NorESM2-LM; and

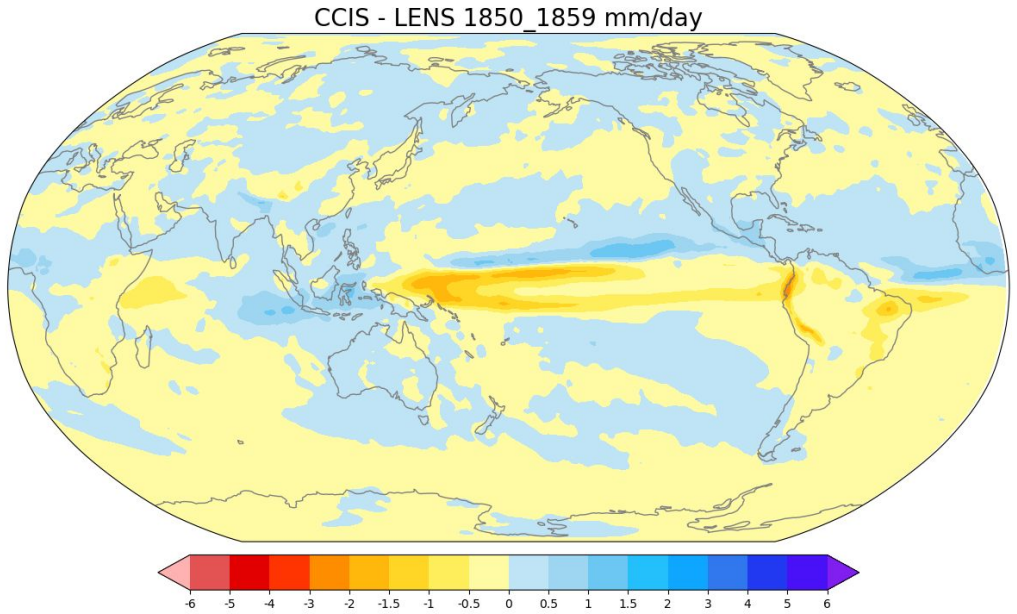
Observations of Organic Aerosols and Temperature for Boreal Areas from Yli-Juuti et al. (2021).

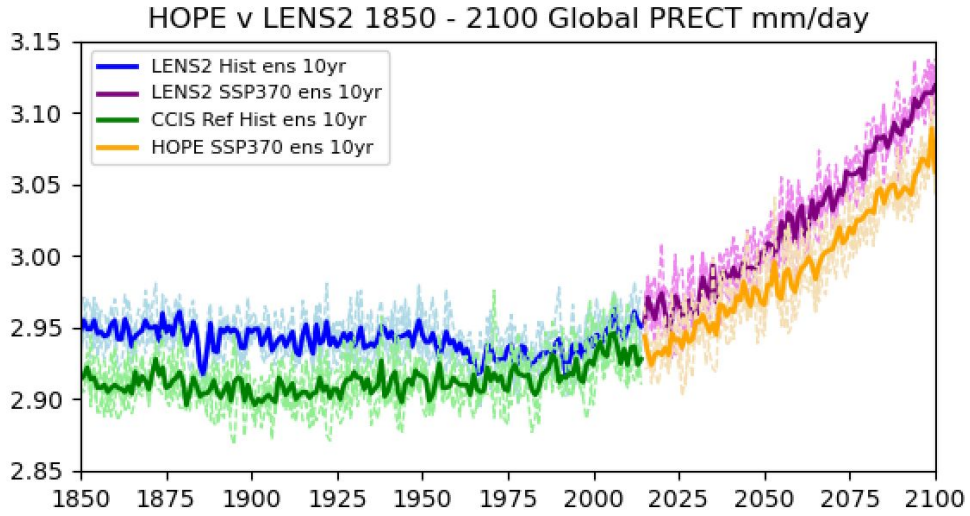
Global BVOC emissions against temperature for CMIP6 idealized 1% CO2 ramping exercises from Gomez et al. (2023)

Evaluation of CESM HOPE SSP 3-7.0 Precipitation versus LENS 2.

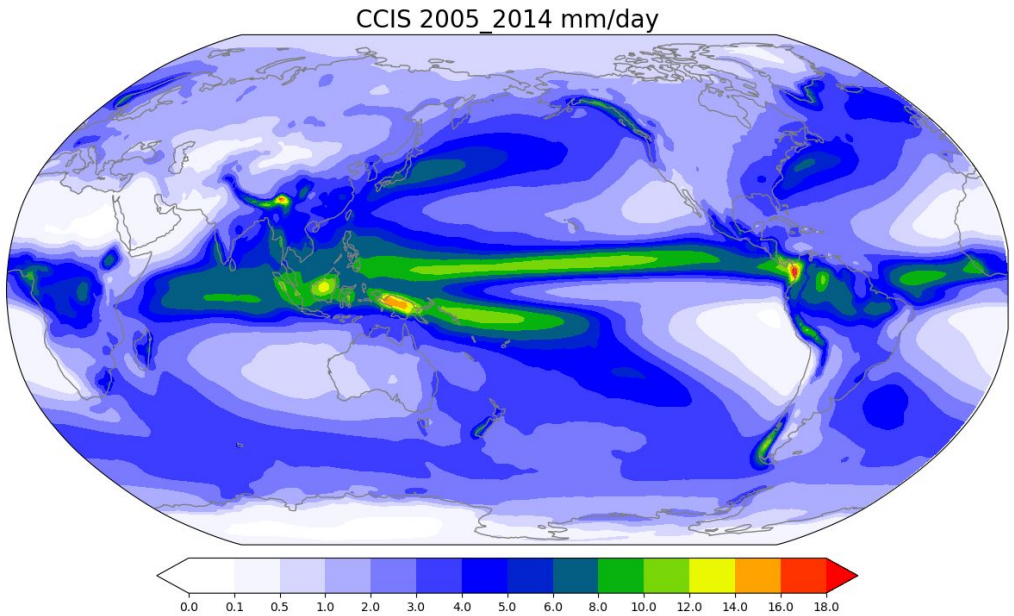


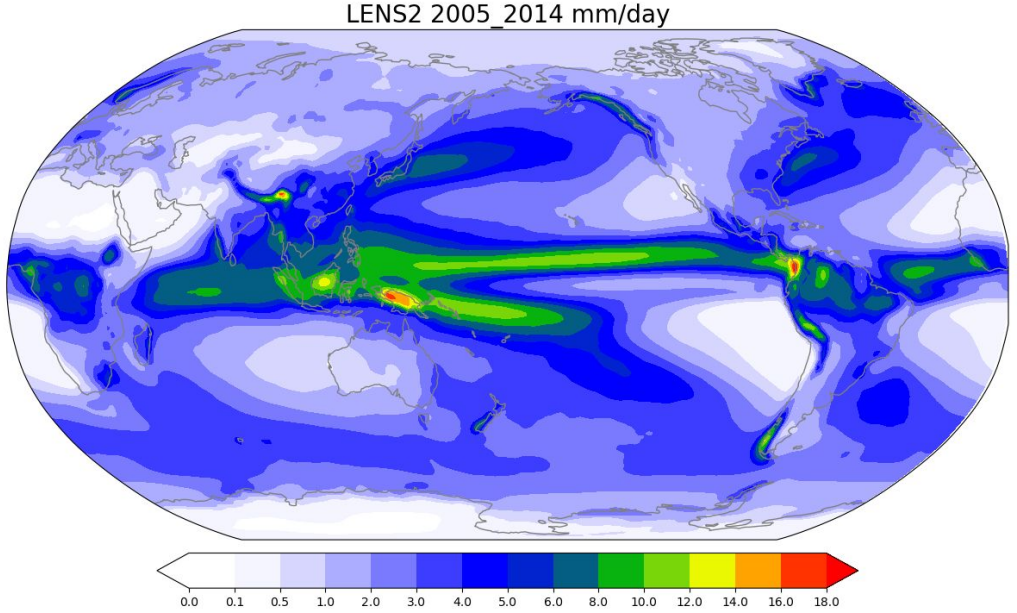


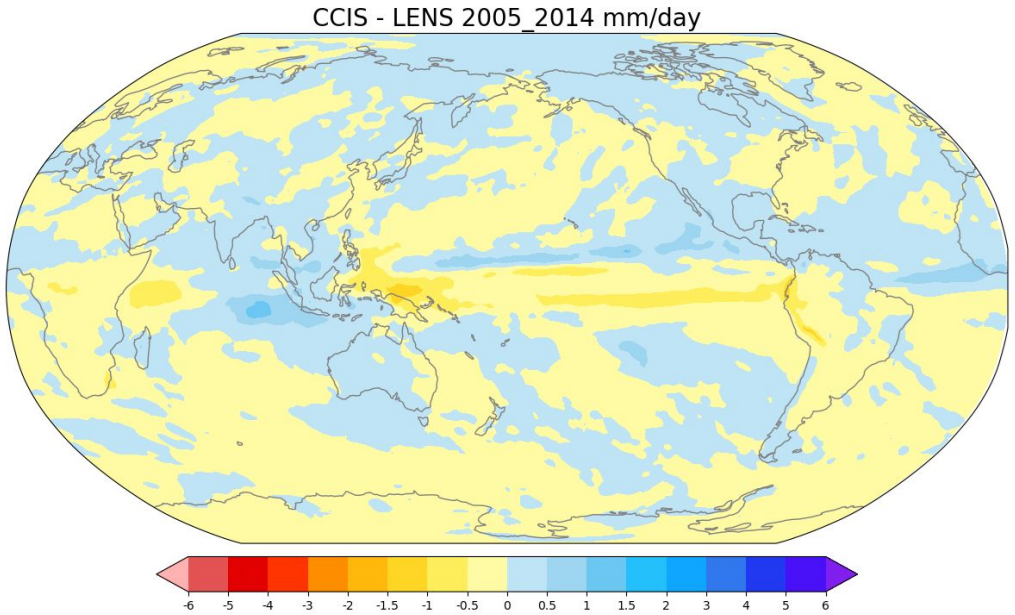


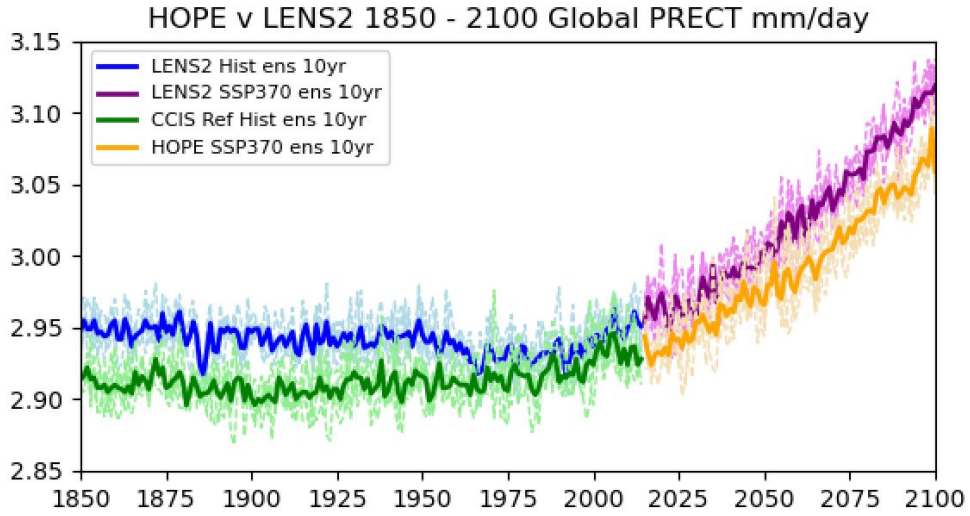


Evaluation of CESM HOPE SSP 3-7.0 Precipitation versus LENS 2.

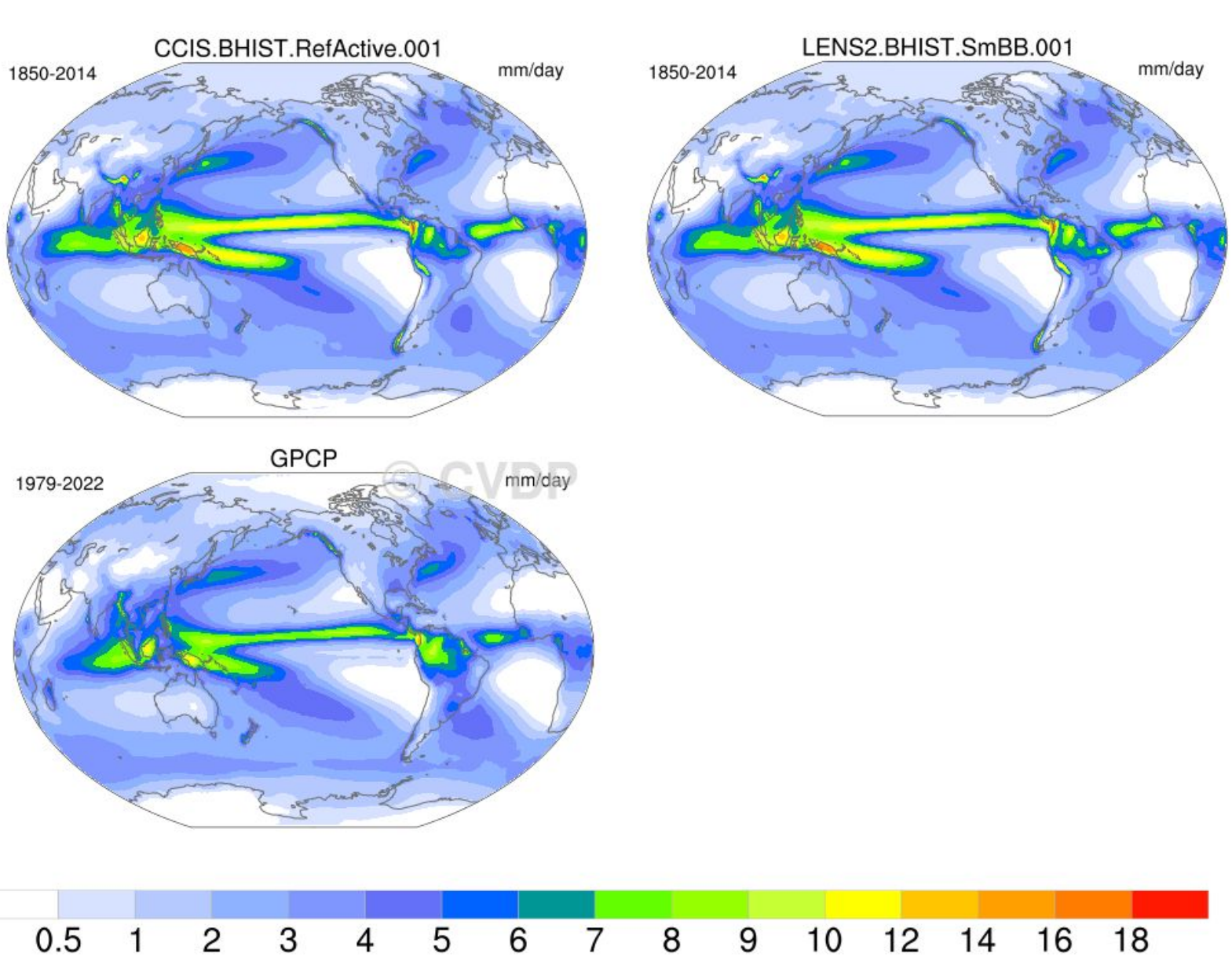




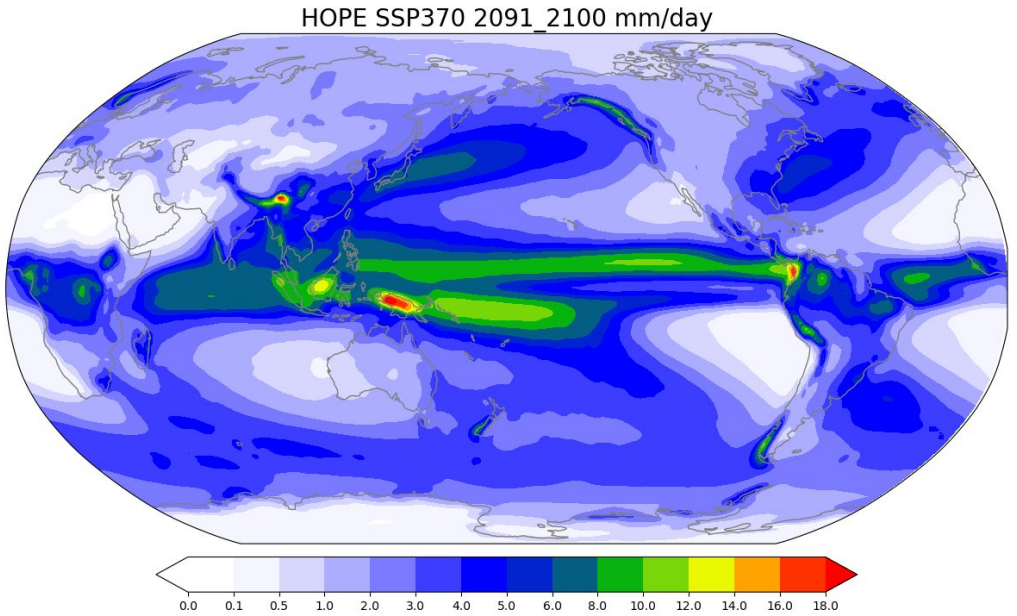


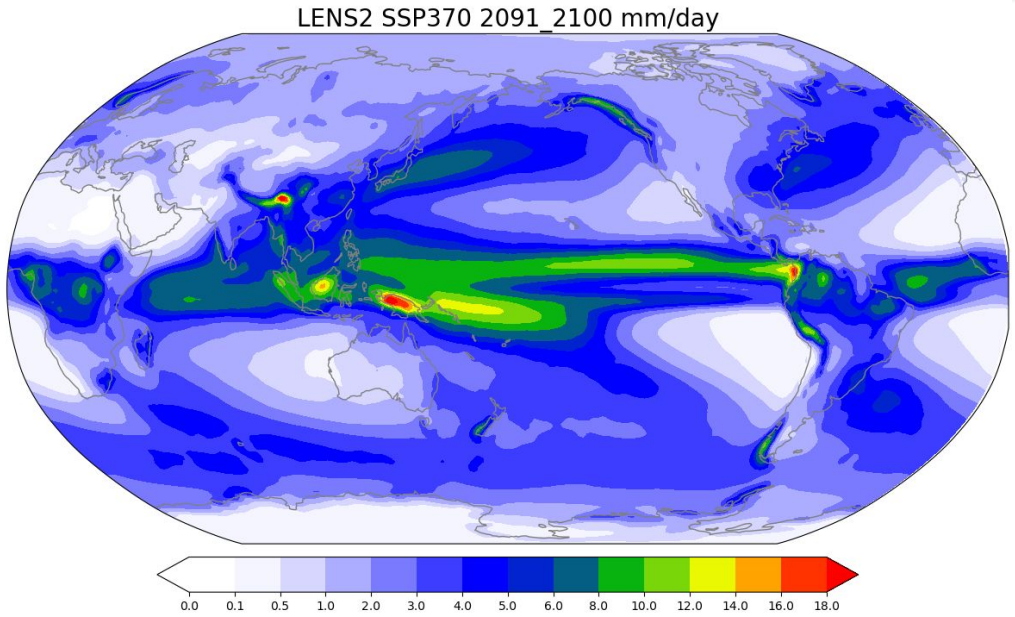


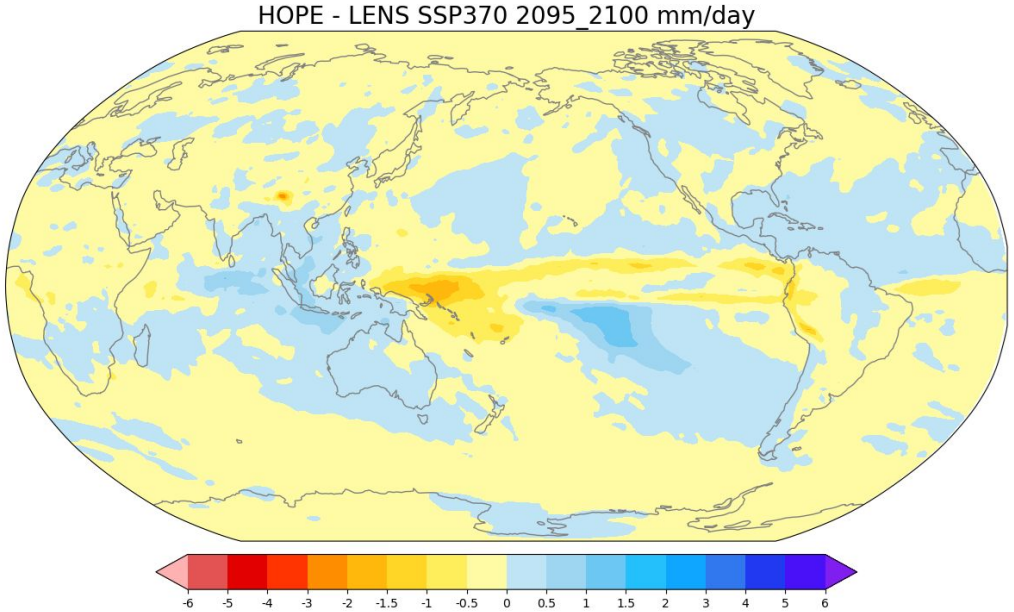
Evaluation of CESM HOPE SSP 3-7.0 Precipitation versus LENS 2 vs GPCP

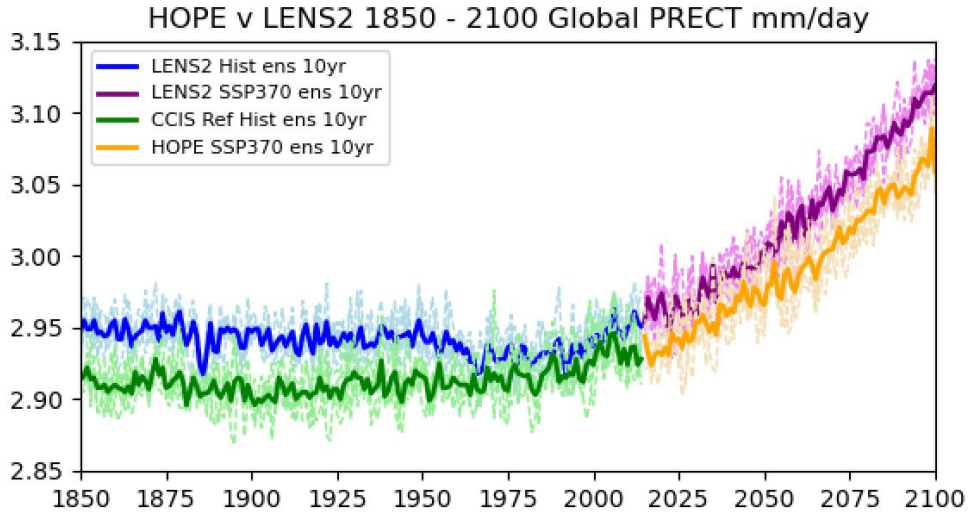


Evaluation of CESM HOPE SSP 3-7.0 Precipitation versus LENS 2.

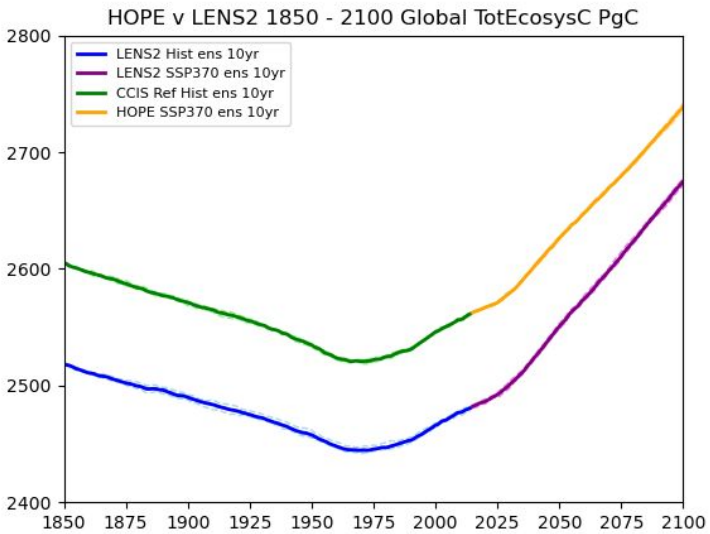


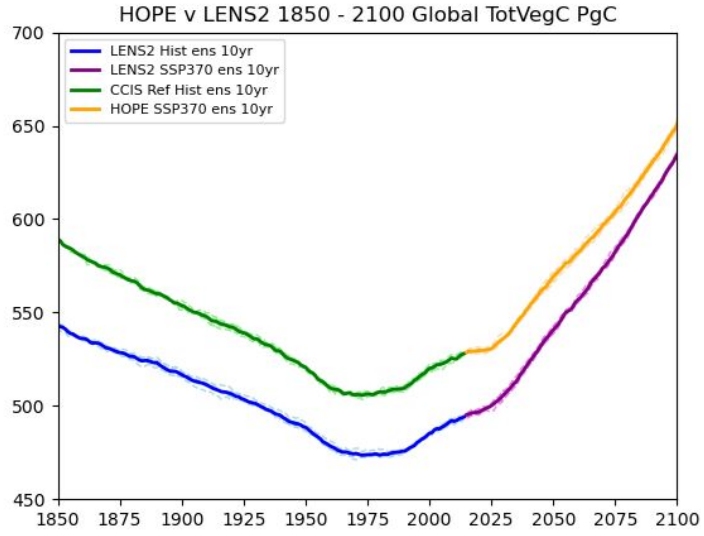


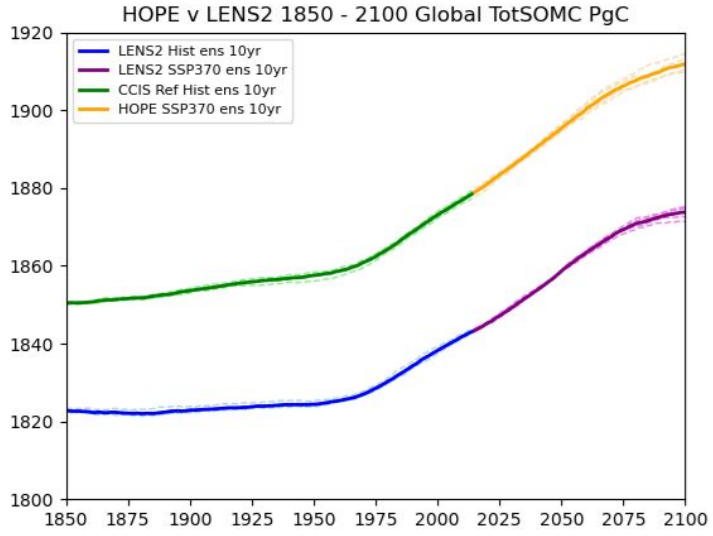


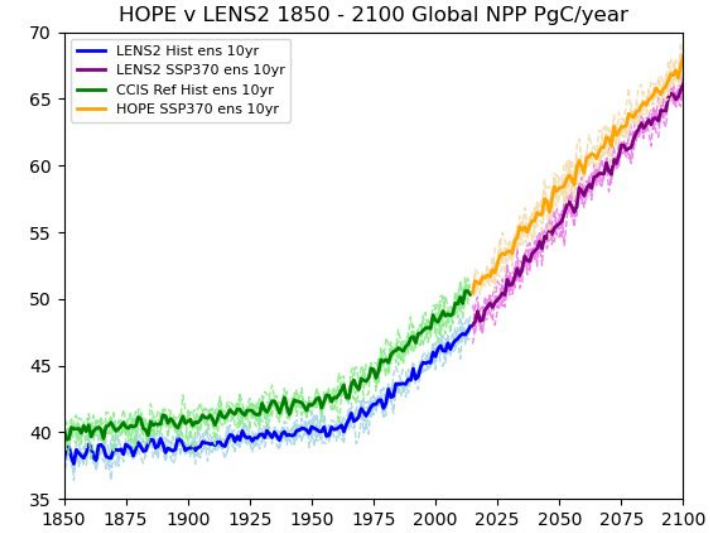


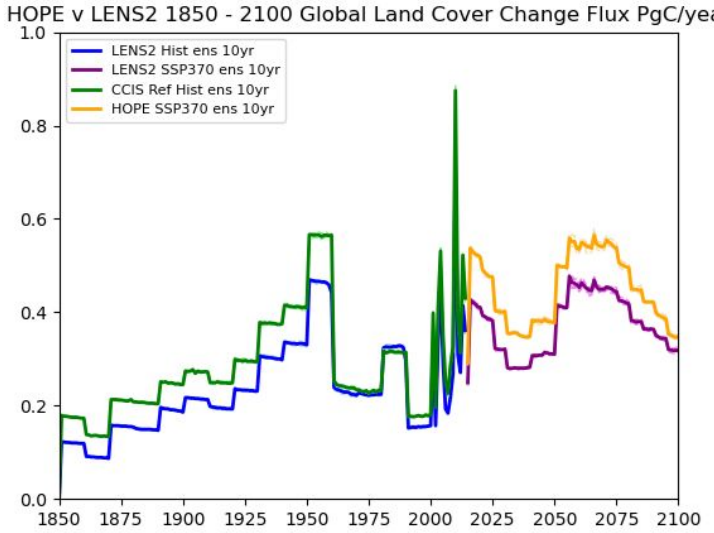
Evaluation of CESM HOPE SSP 3-7.0 Land Carbon Cycle versus LENS 2.

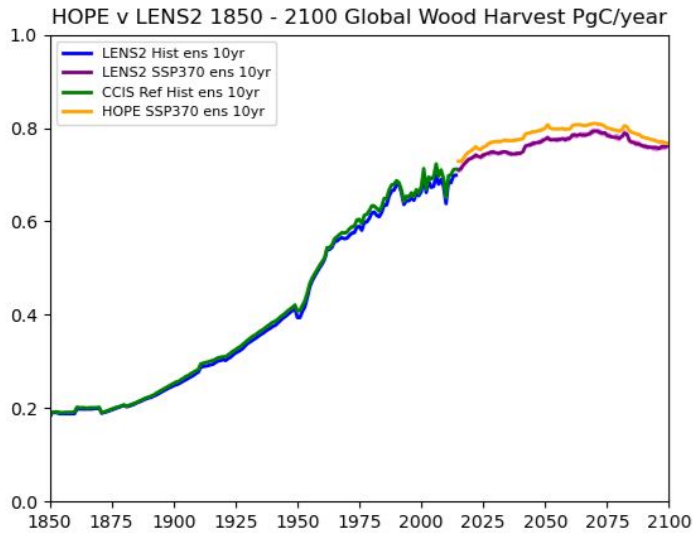




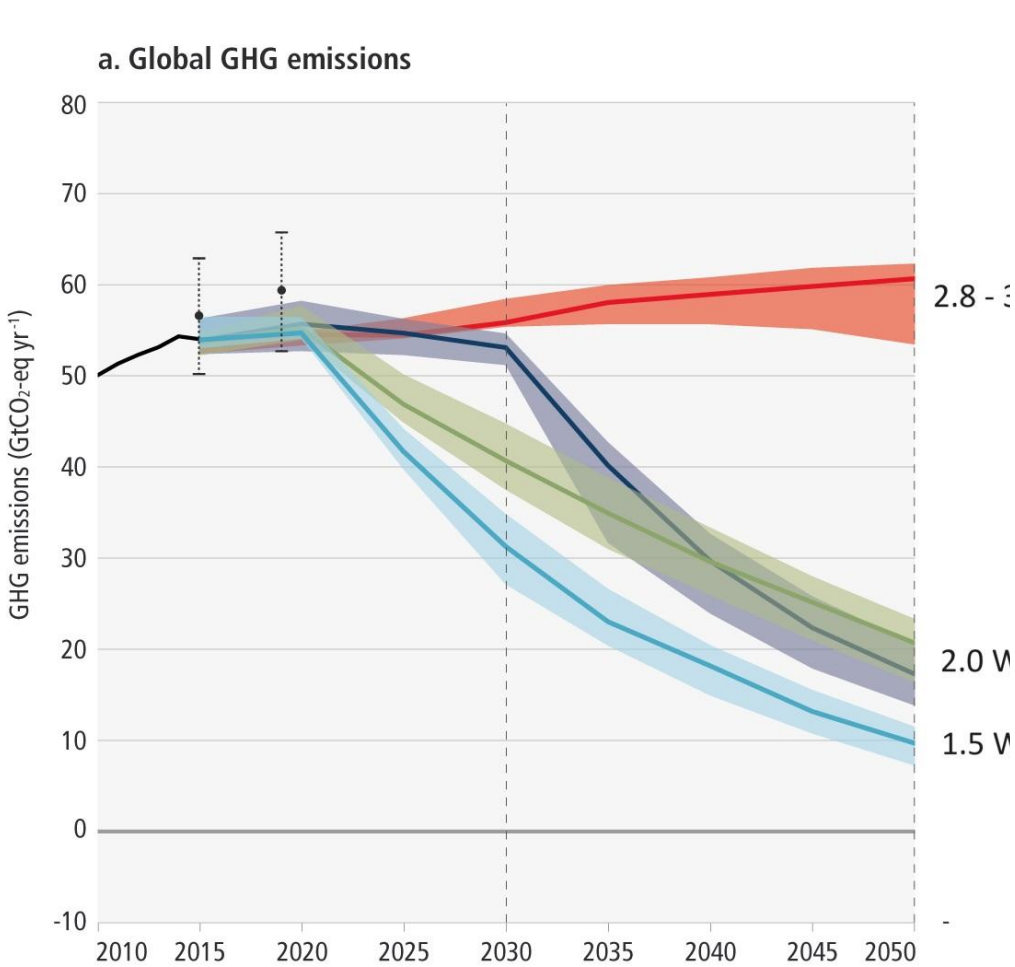


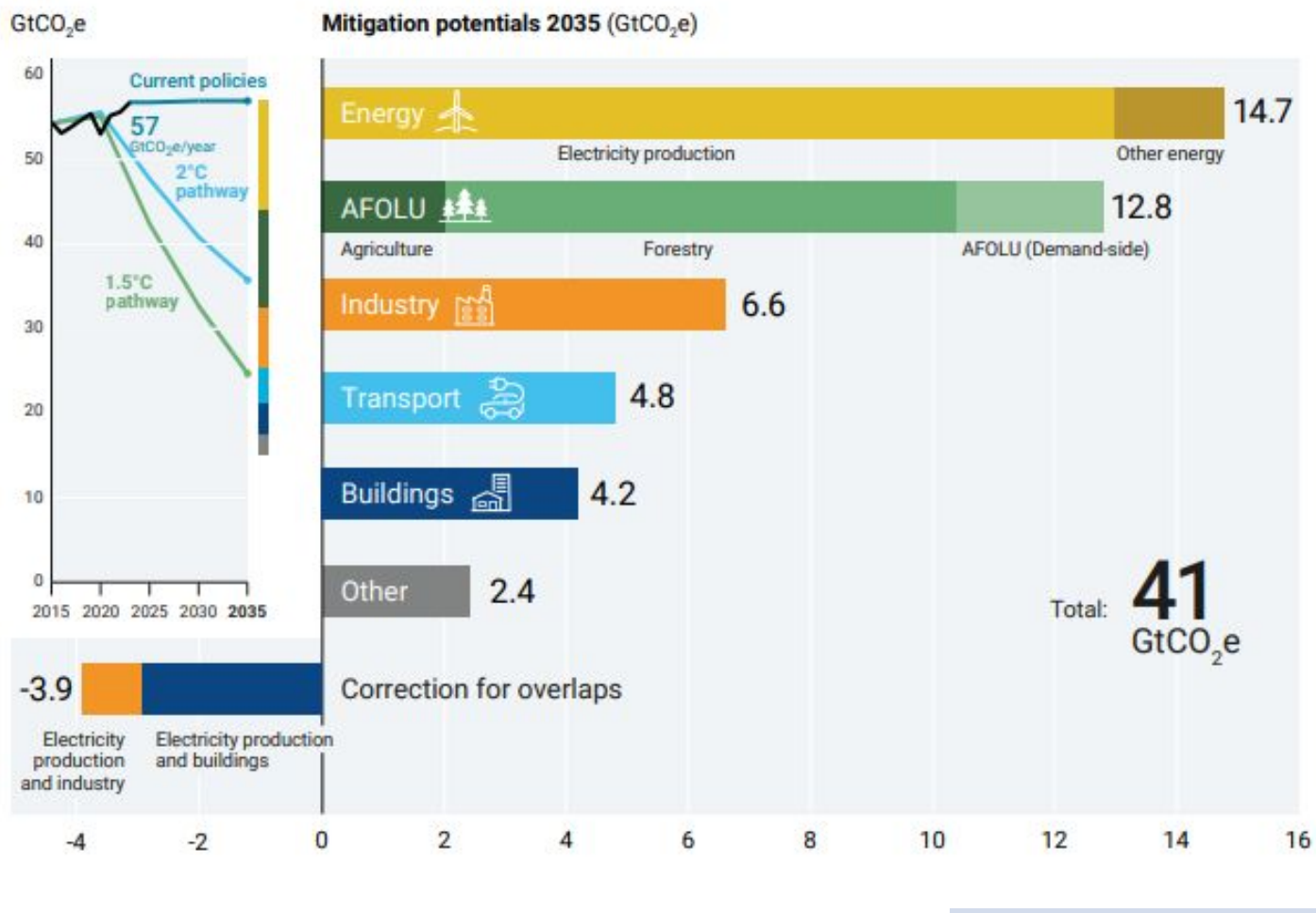






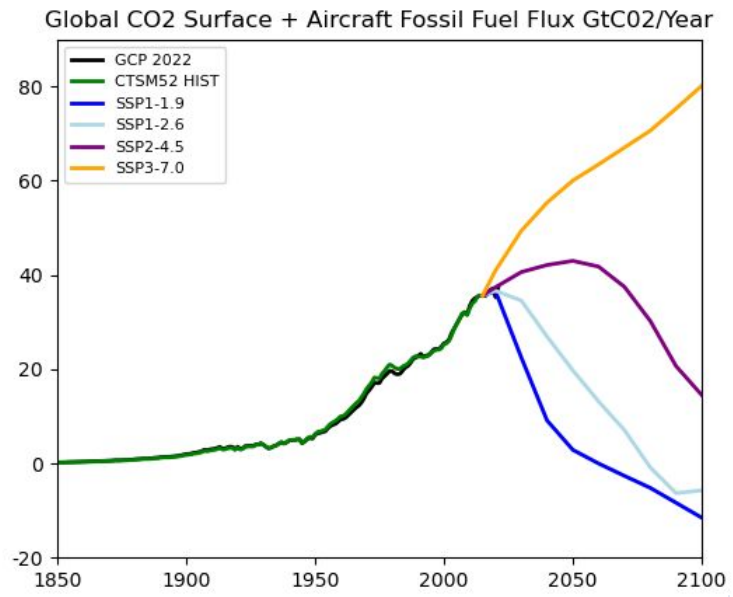
CESM Highly Optimistic Project Ensembles (HOPE)

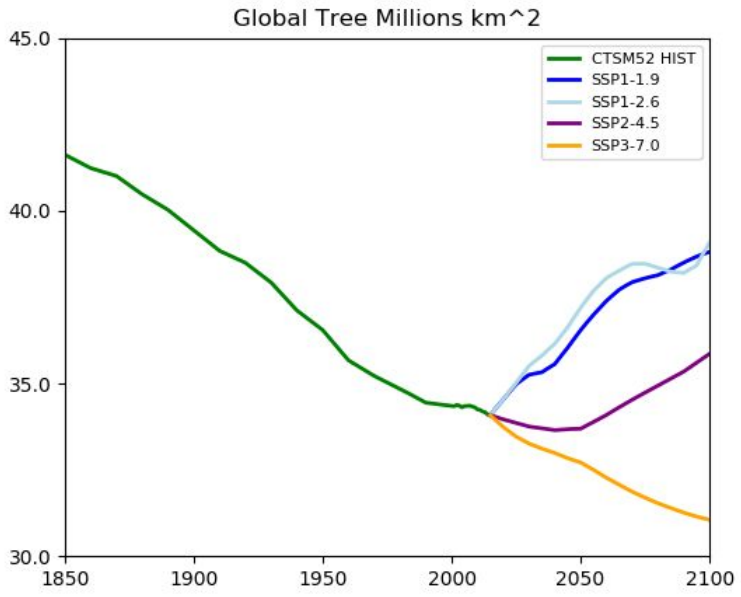


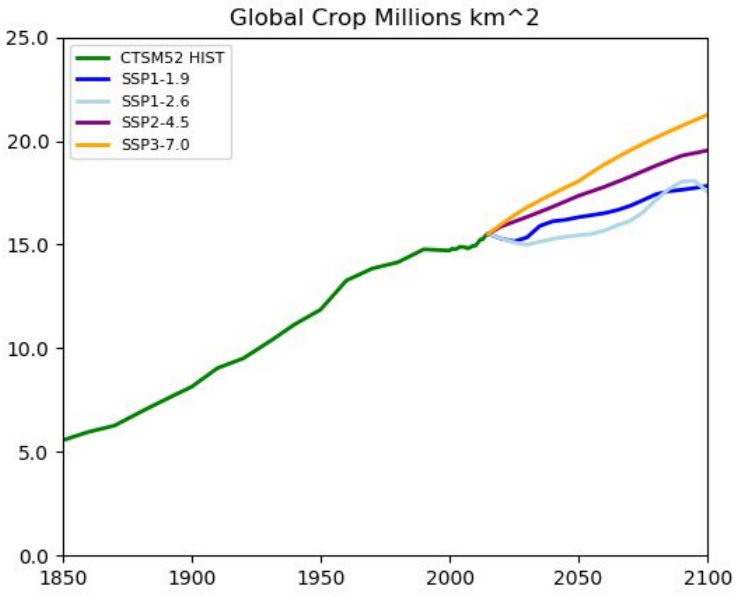


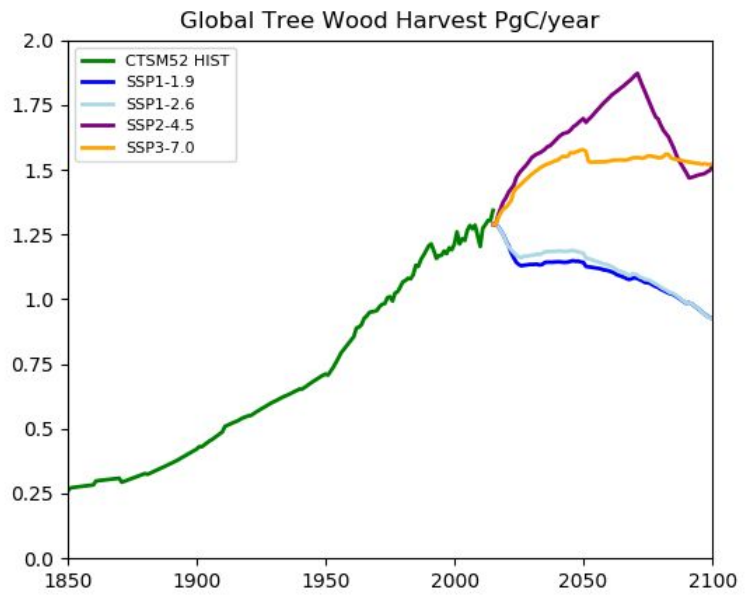
The HOPE project is a collaborative activity being conducted by the Community Earth System Model (CESM) Land Model and Biogeochemistry Working Groups (LMWG and BGCWG). The project explores the climate trajectory of SSP1-1.9 (1.5C) which is the most highly optimistic climate future found in the CMIP6 ScenarioMIP project. This is compared with the increasingly higher warming in SSP2-4.5 (2.5C) and SSP3-7.0 (4C)

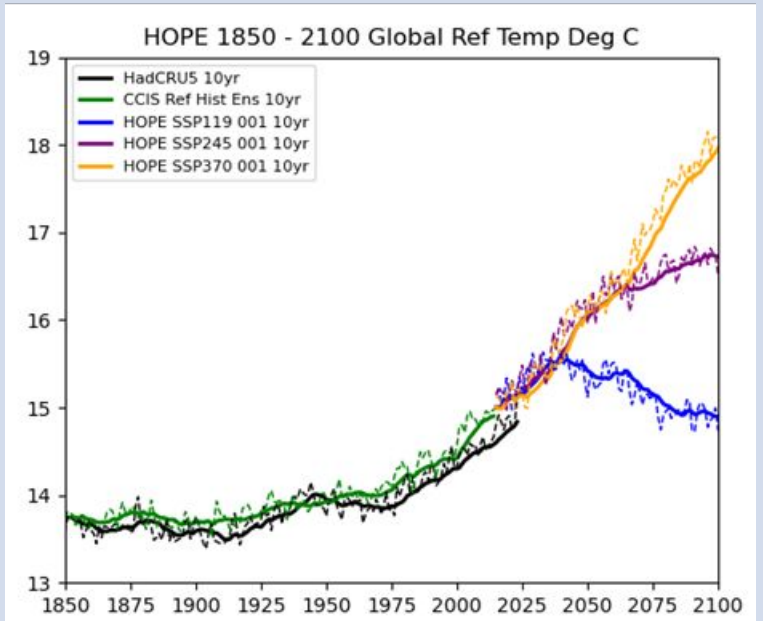
CESM Highly Optimistic Project Ensembles (HOPE)

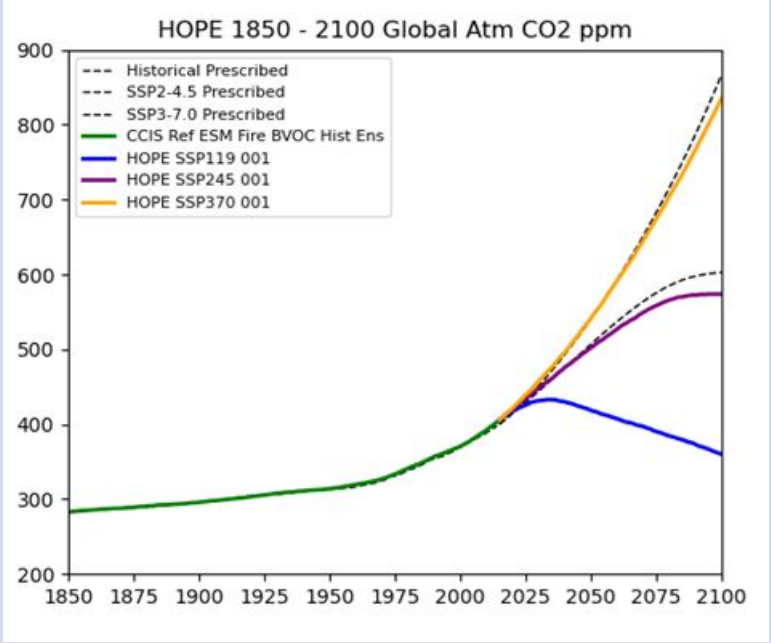












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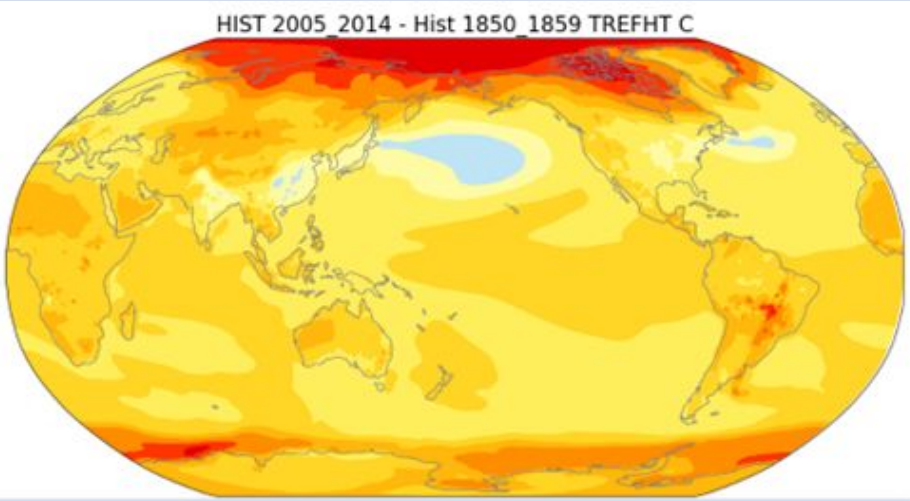

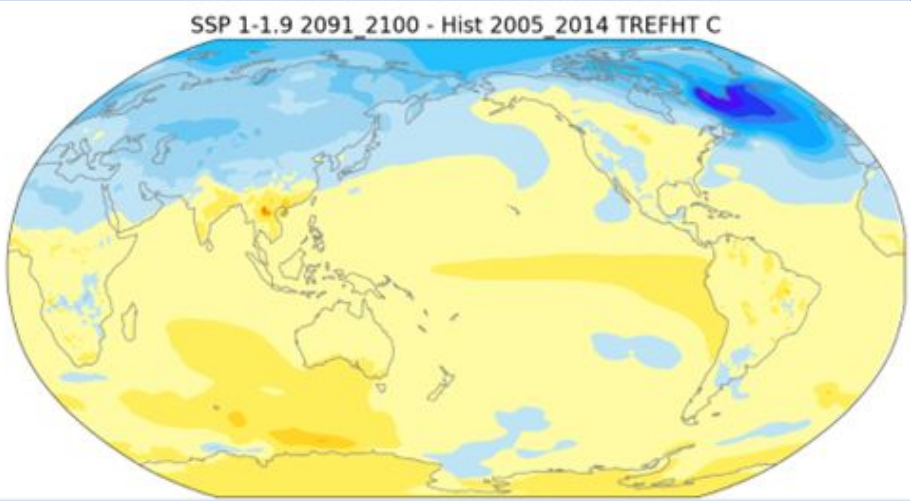

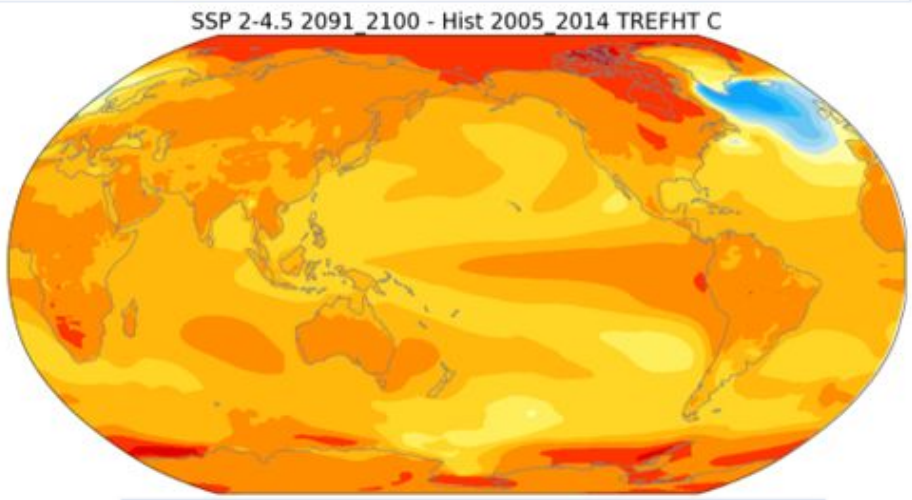

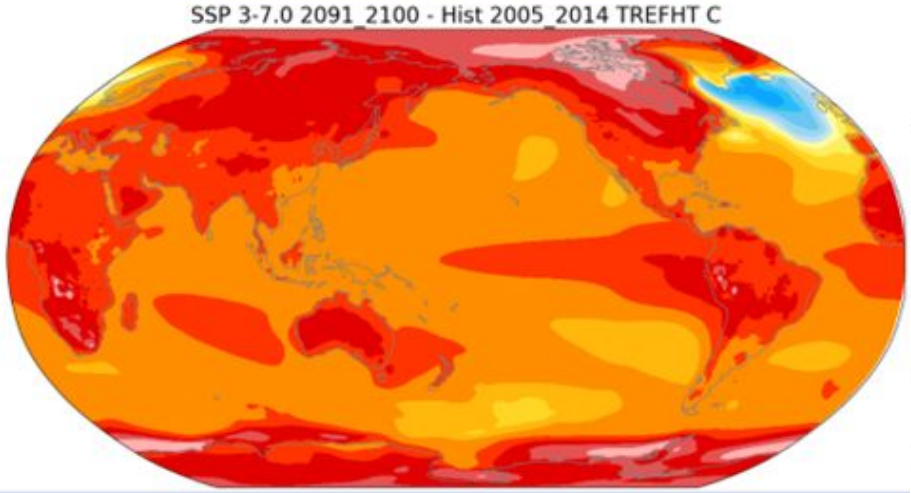

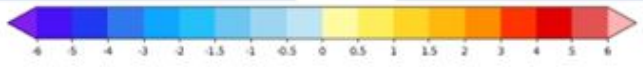

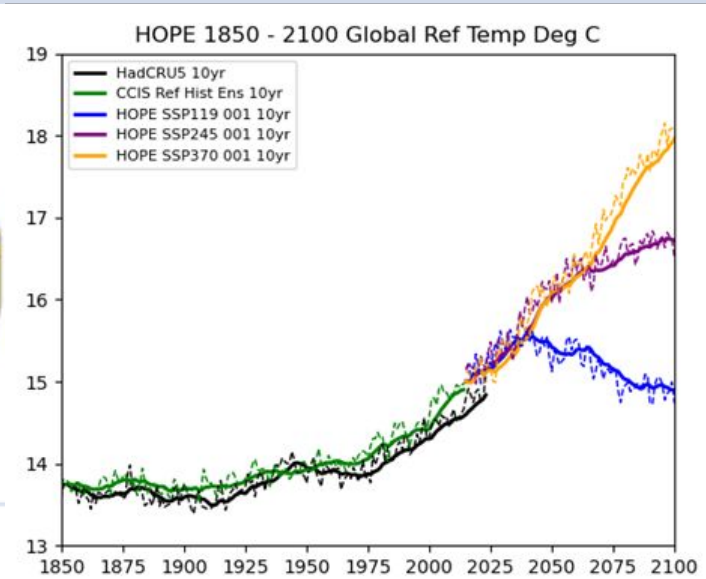

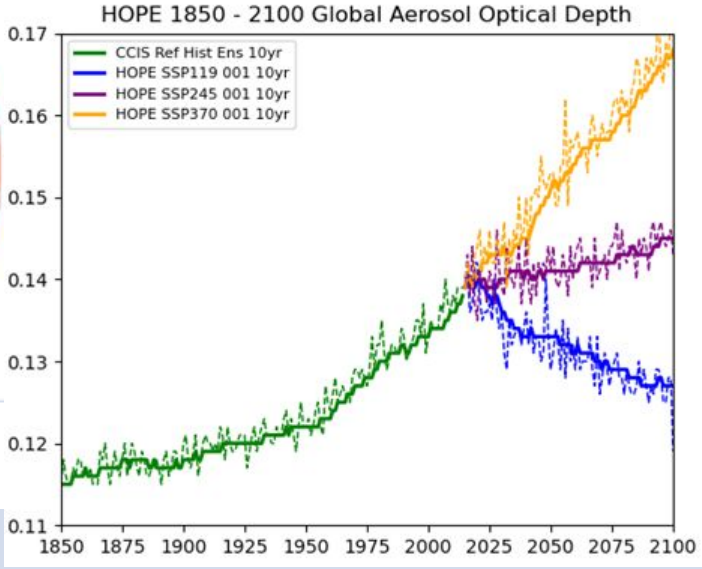

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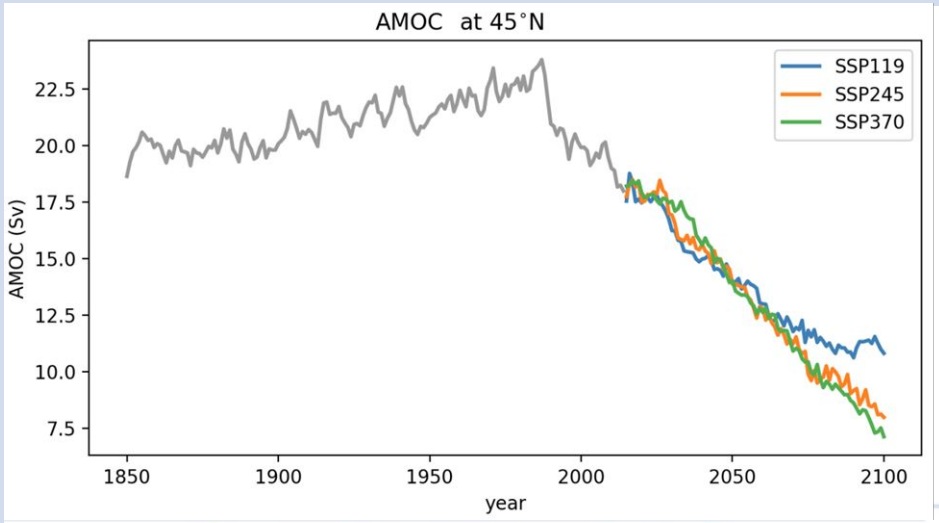

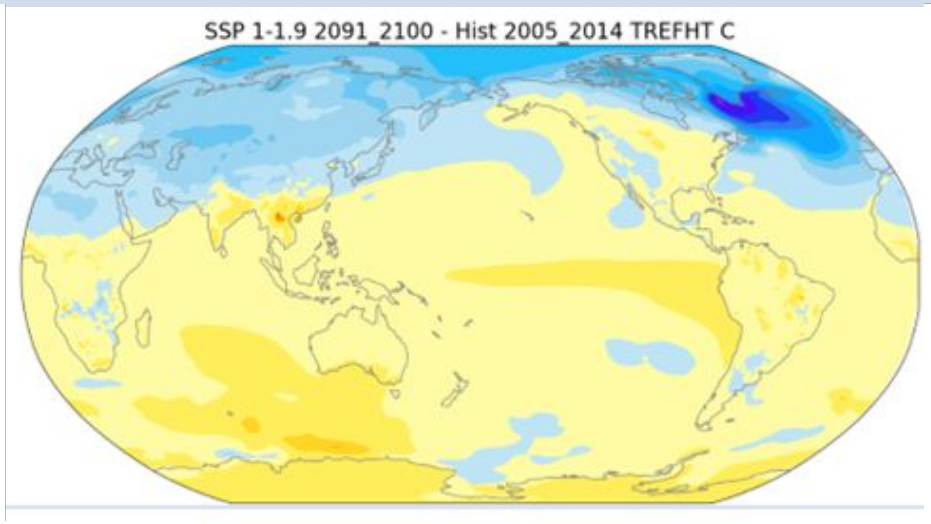

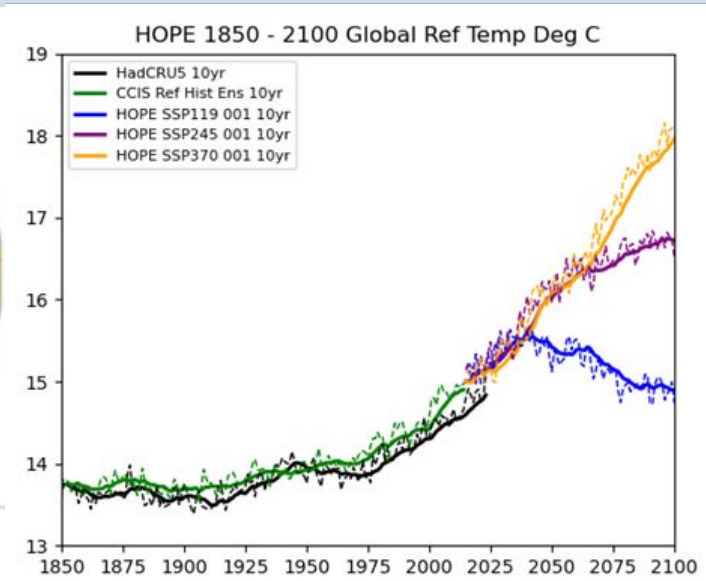

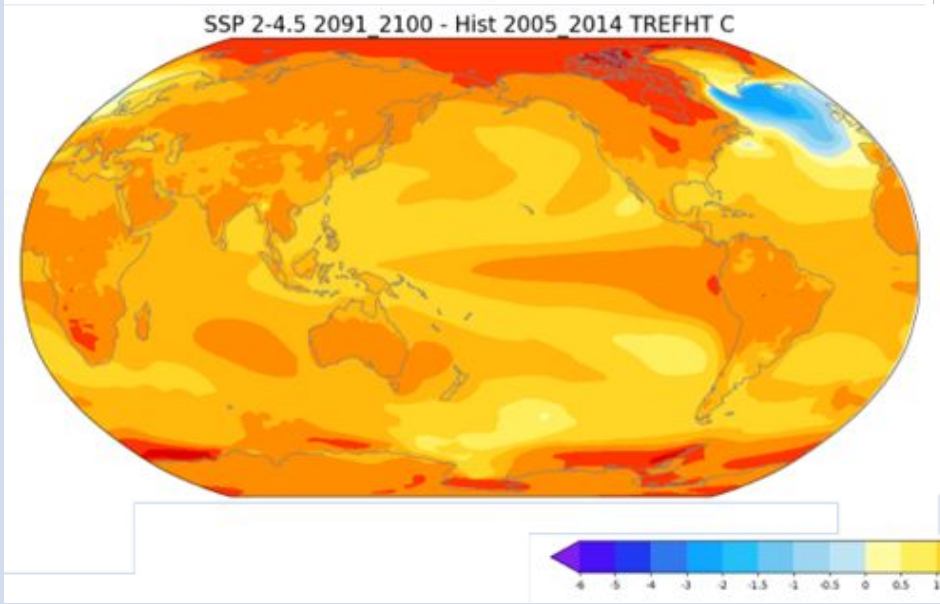

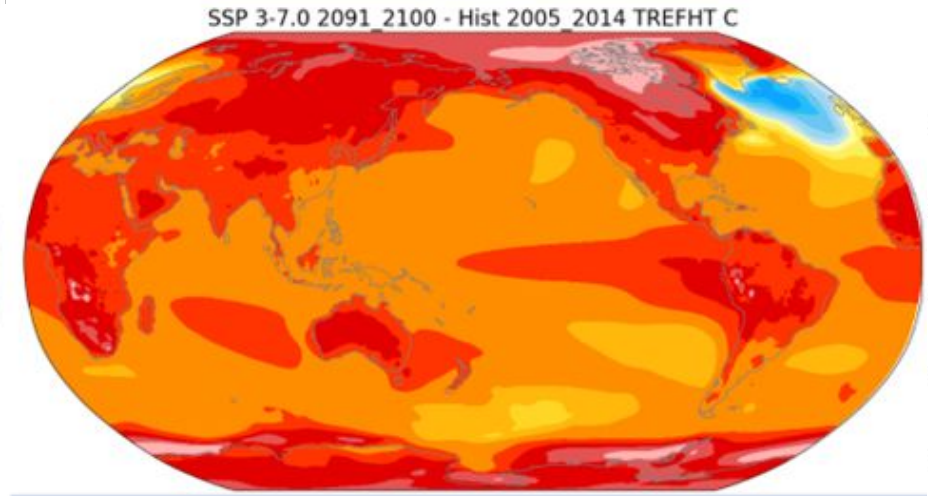

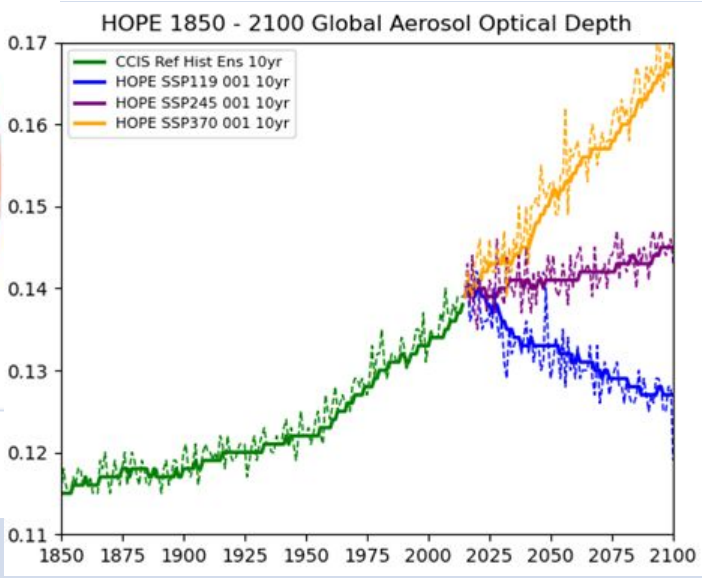

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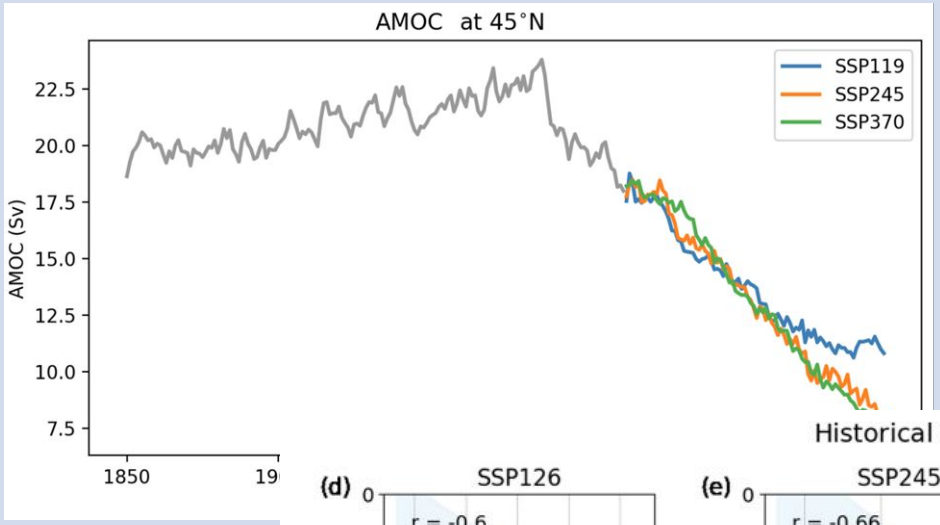
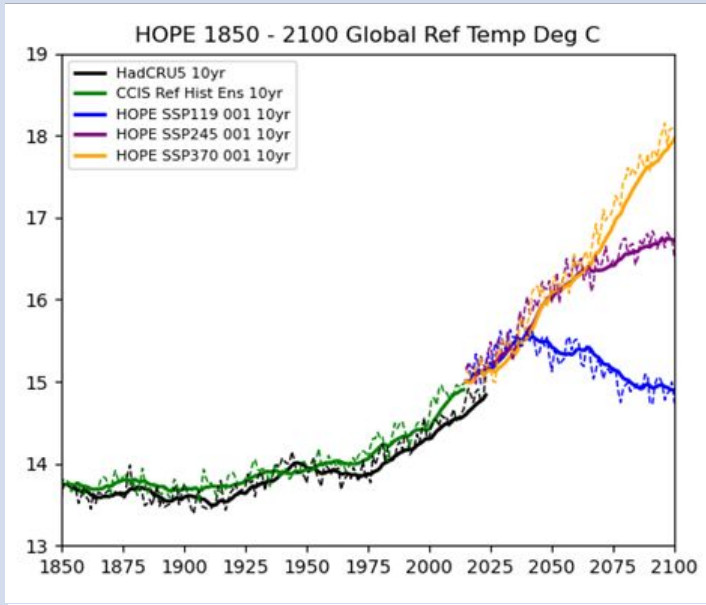
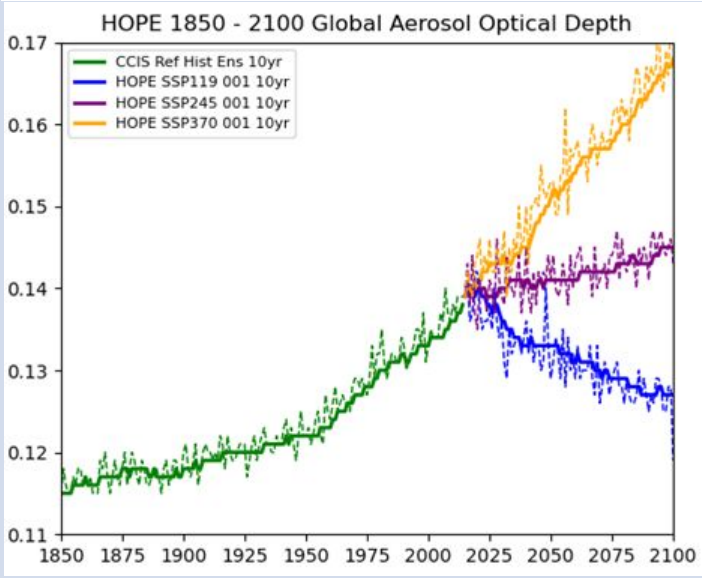
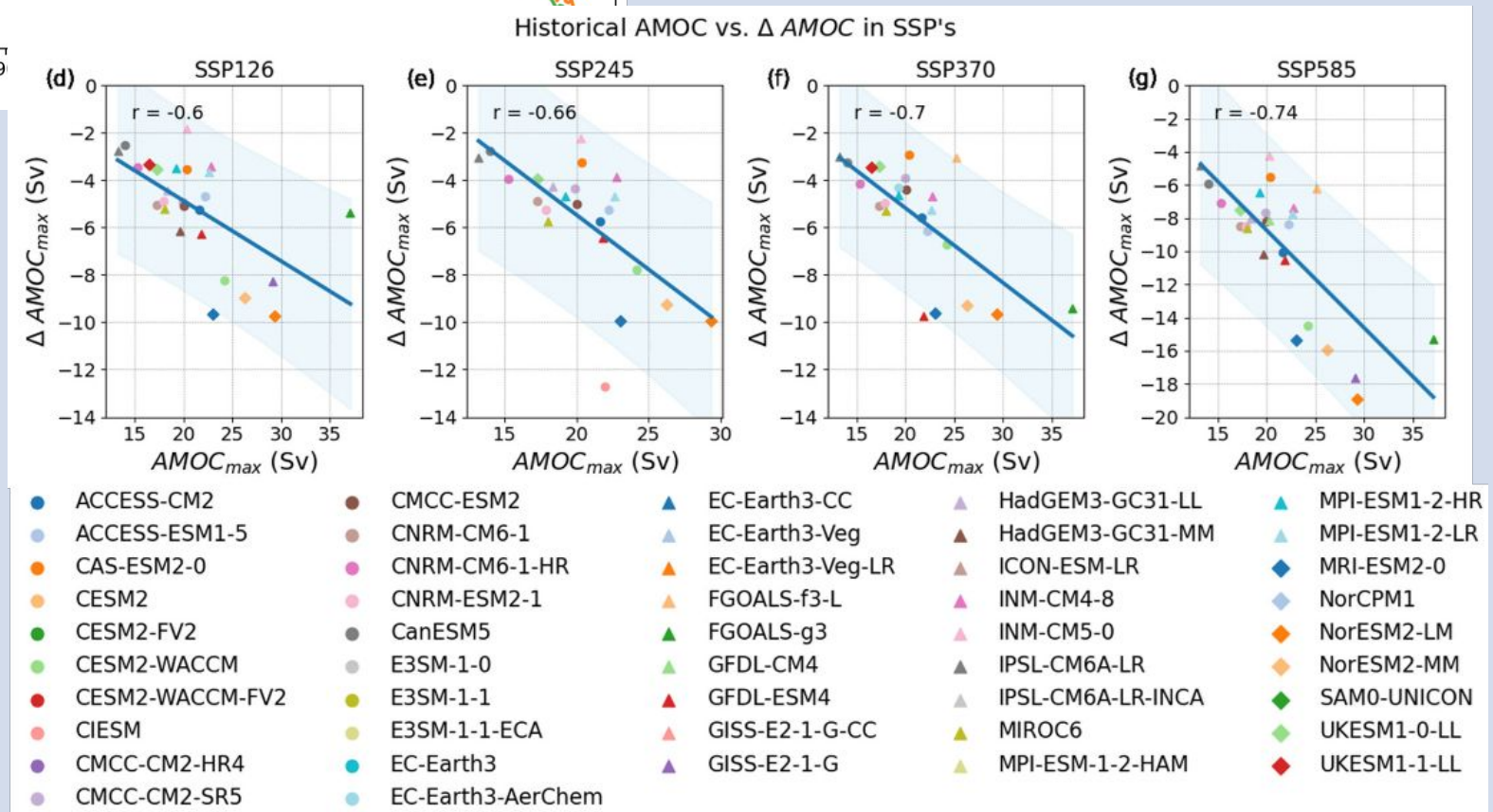


Range of CMIP6 Model AMOC reductions for SSPs from Baker et al. (2023).







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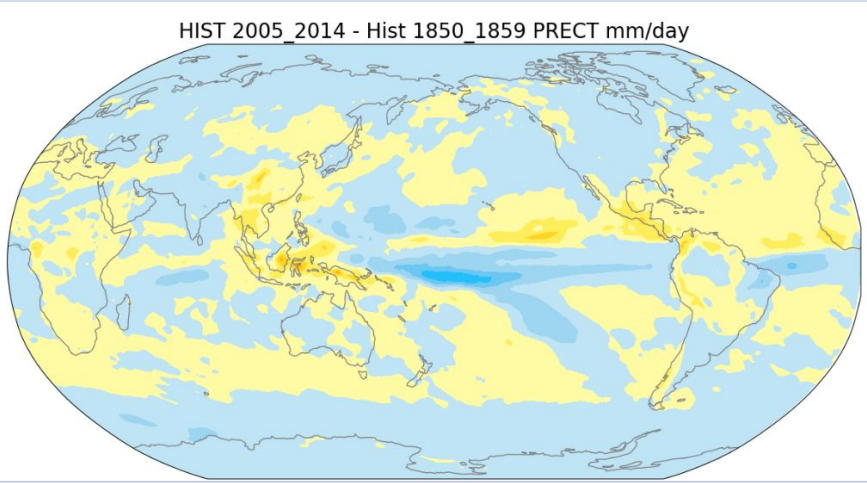

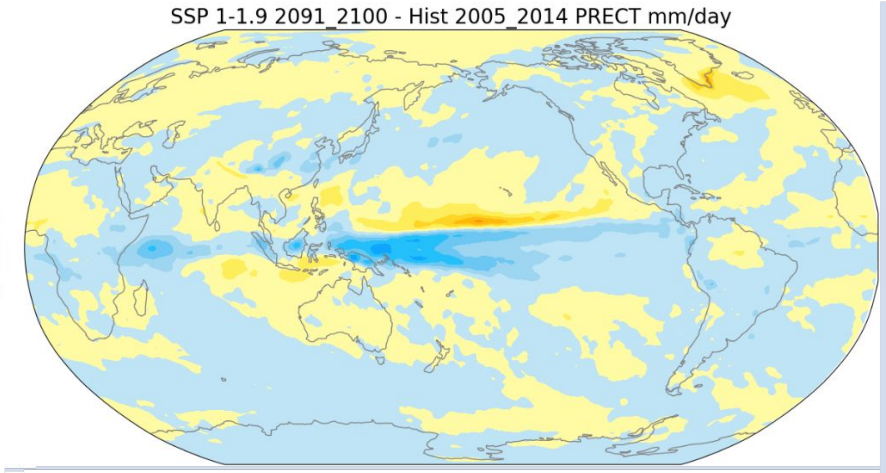

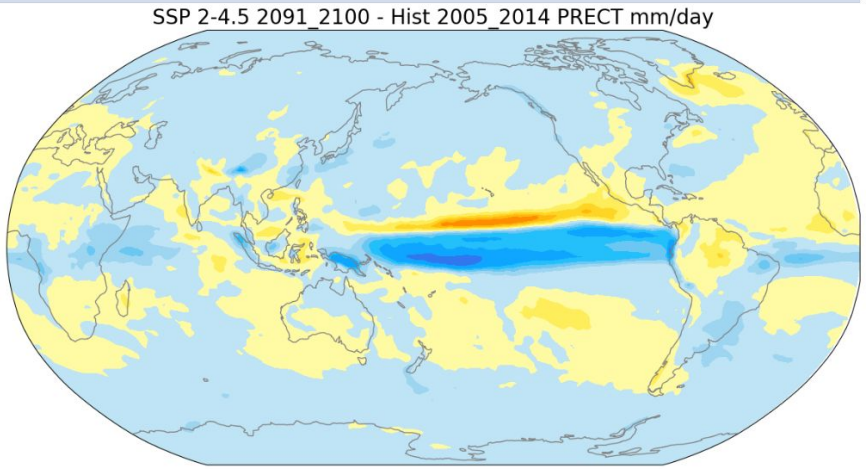

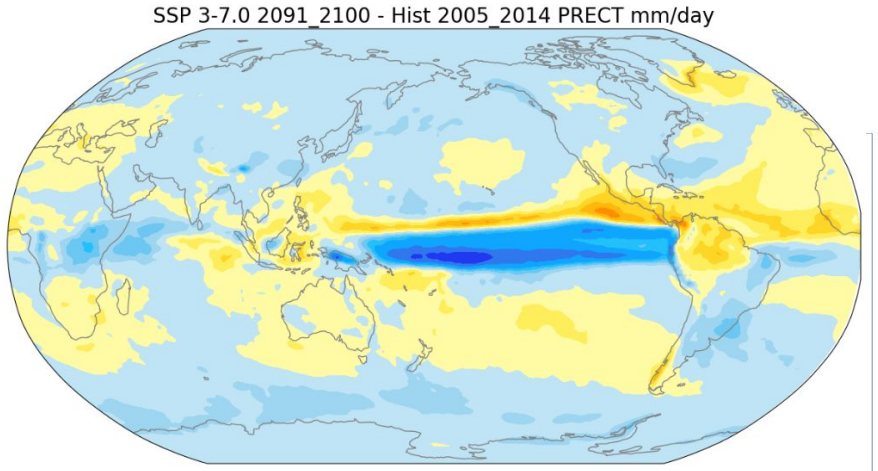

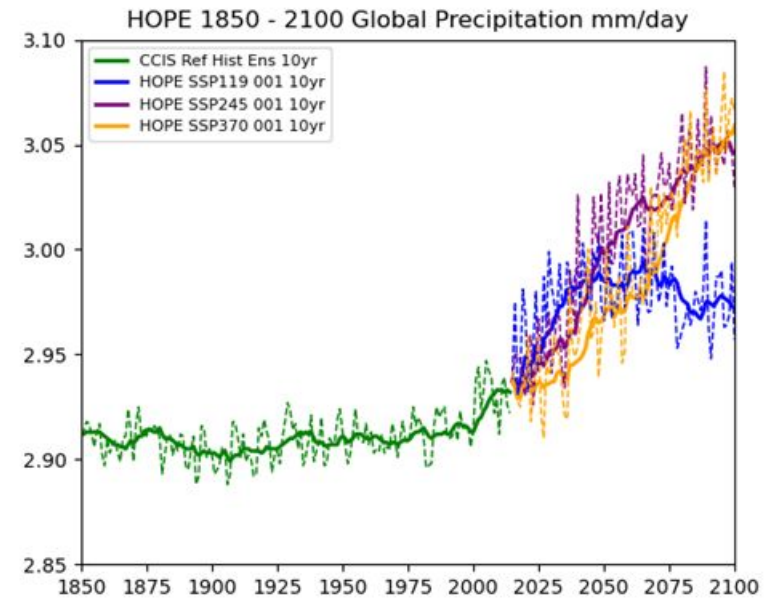

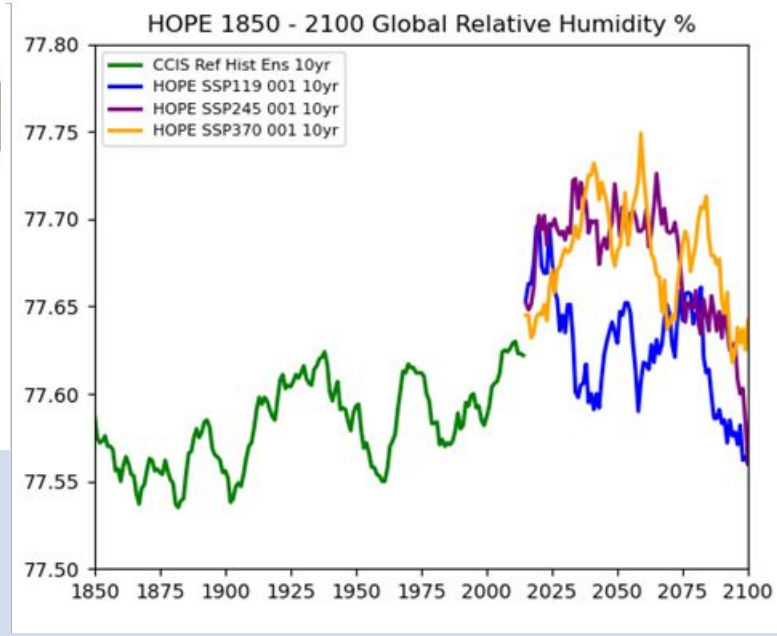

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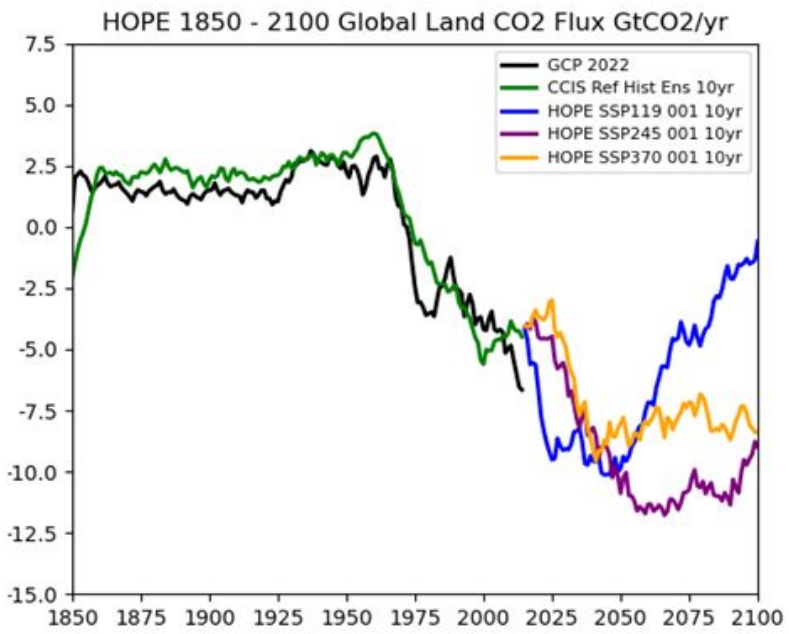

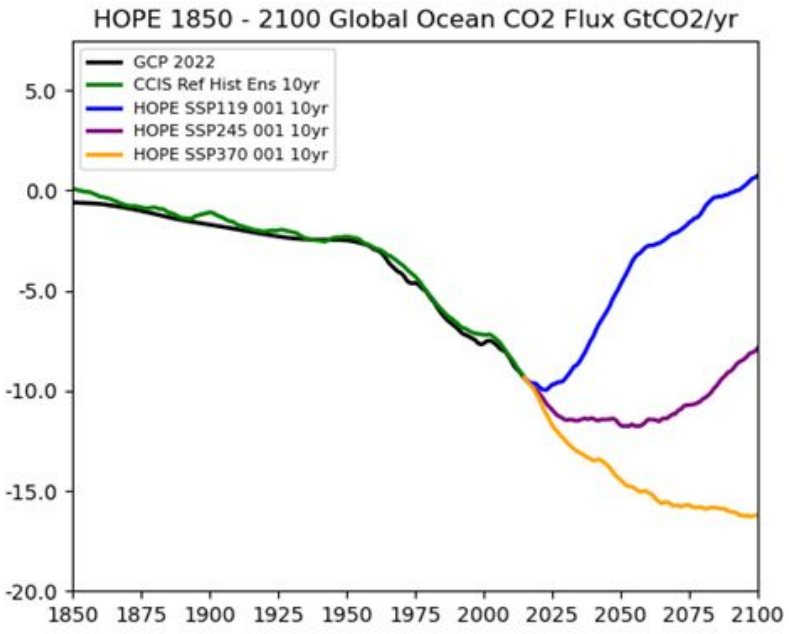

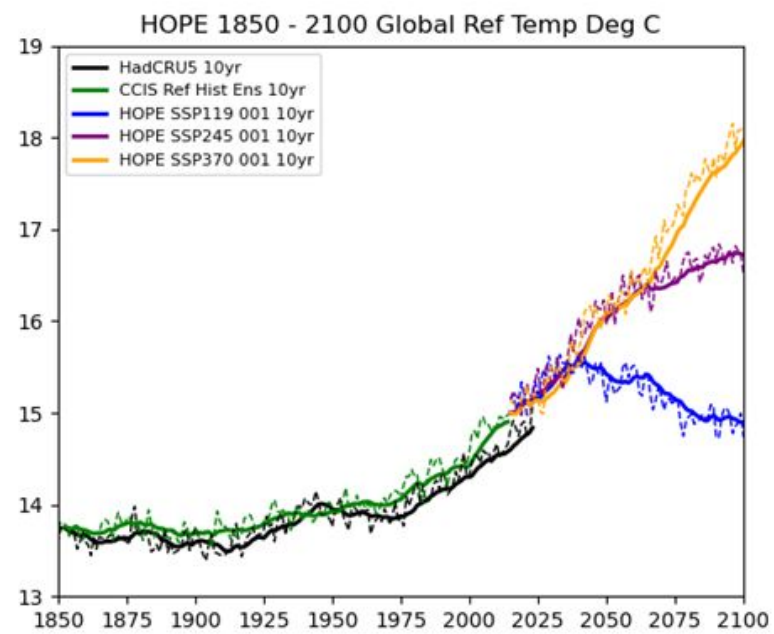

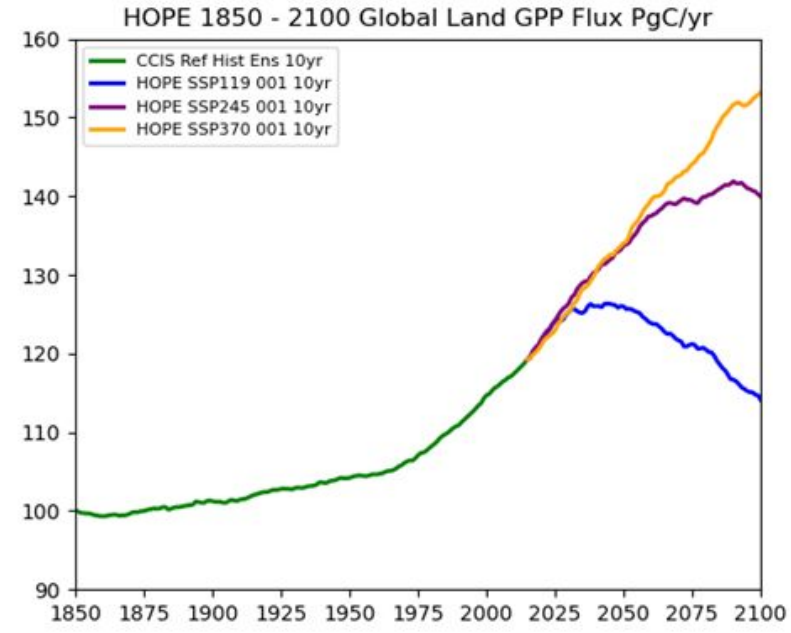

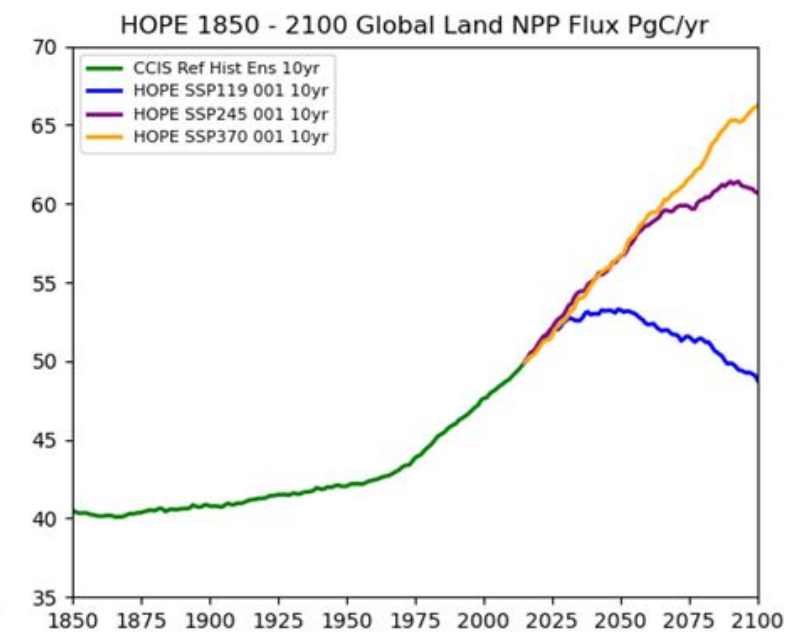

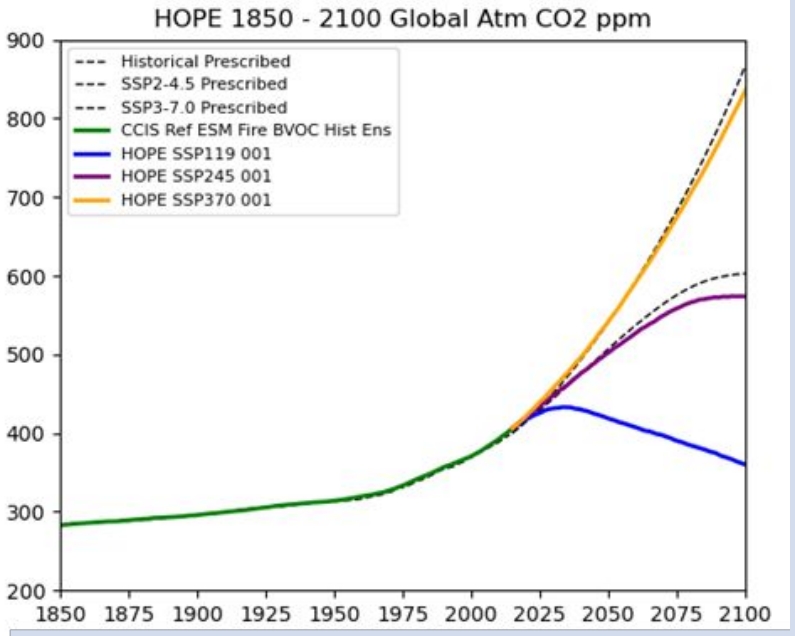

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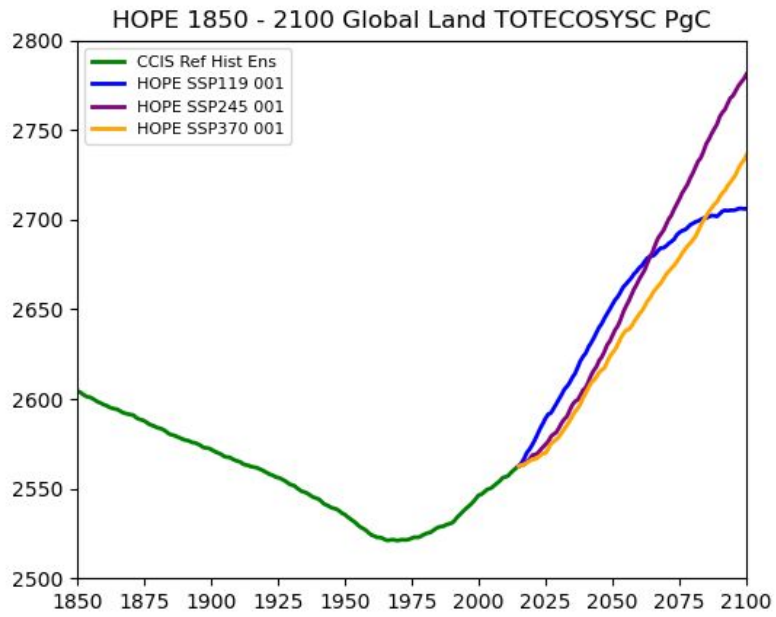
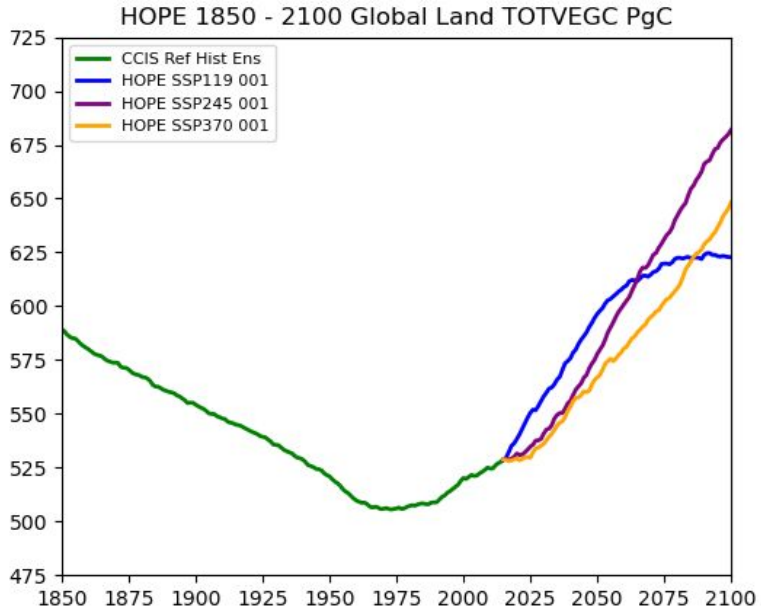
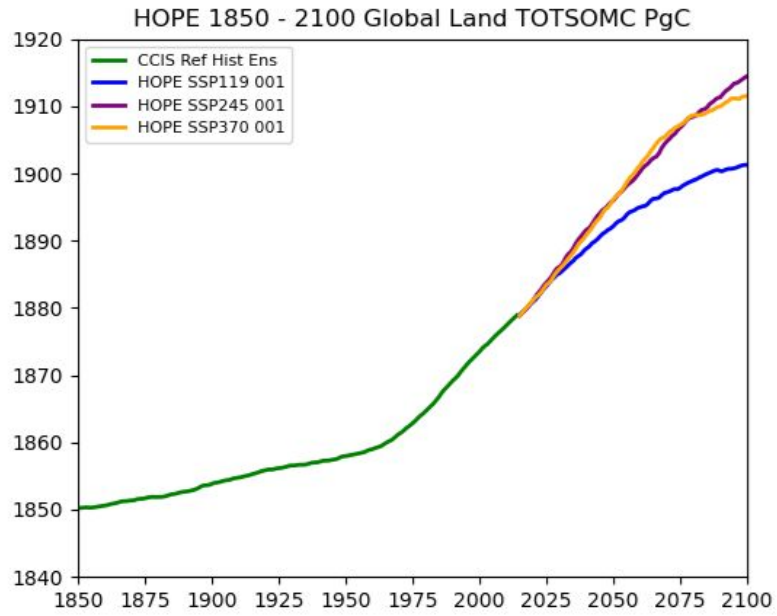
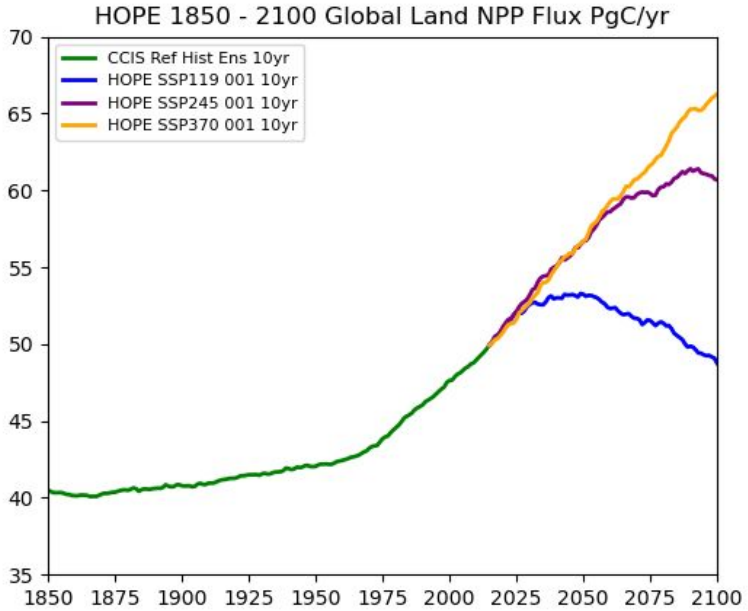
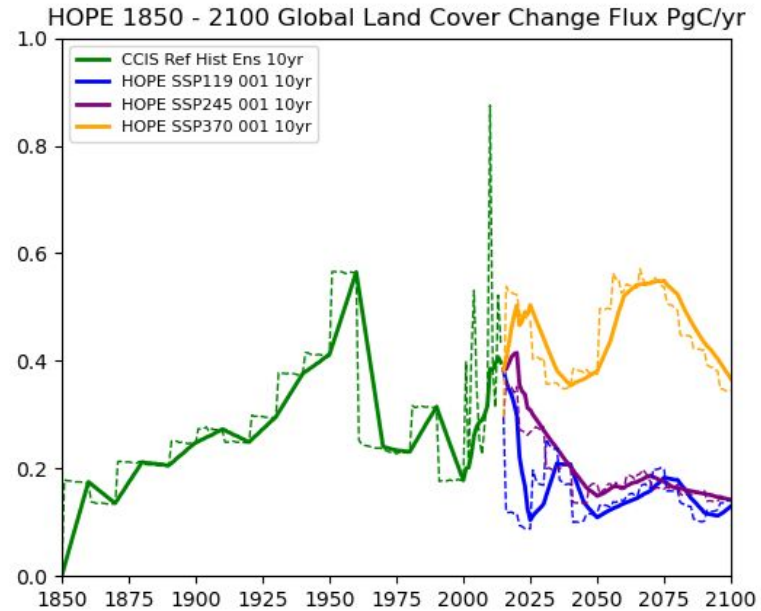
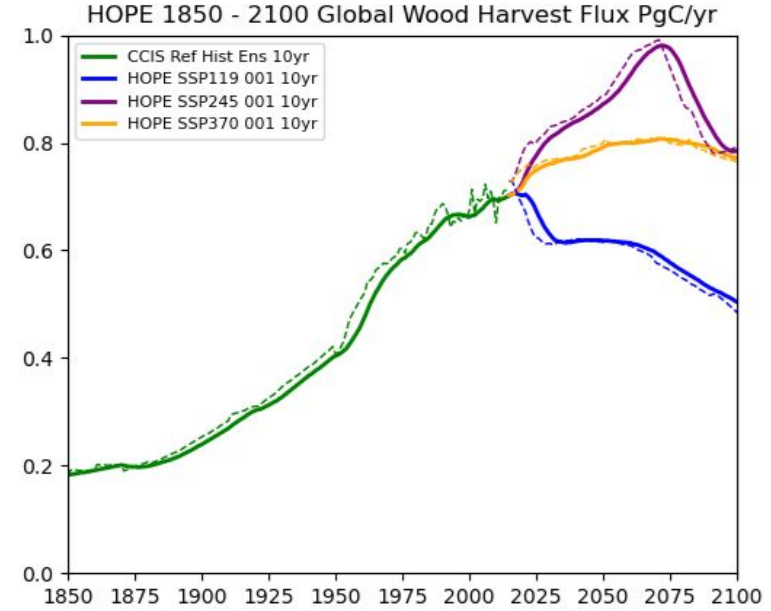












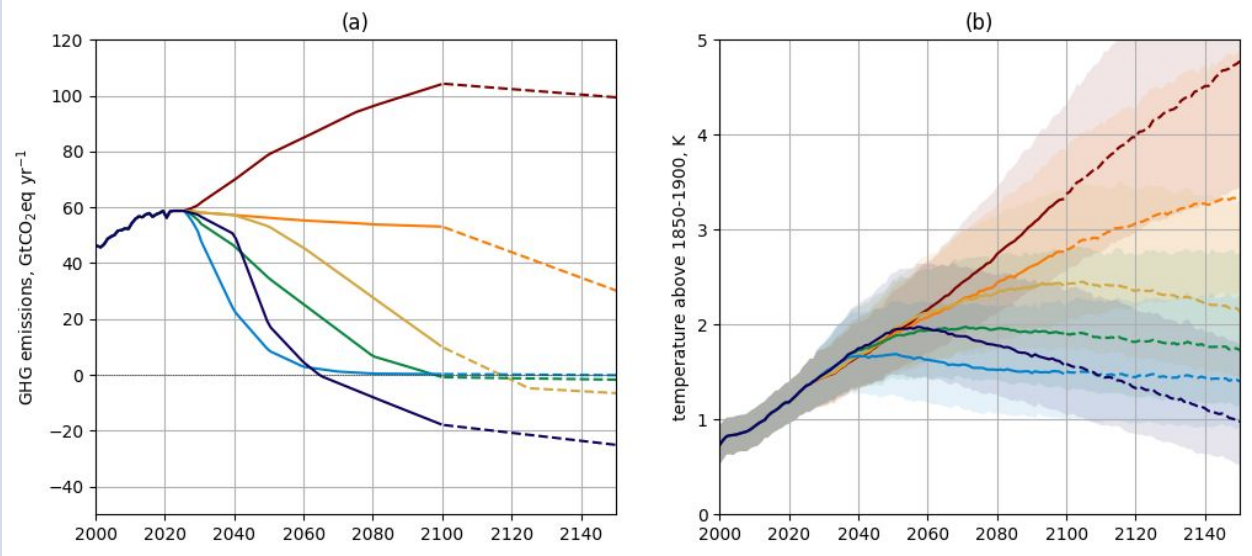
Community Climate Intervention Strategies CESM Ensemble

Eight climate intervention strategies

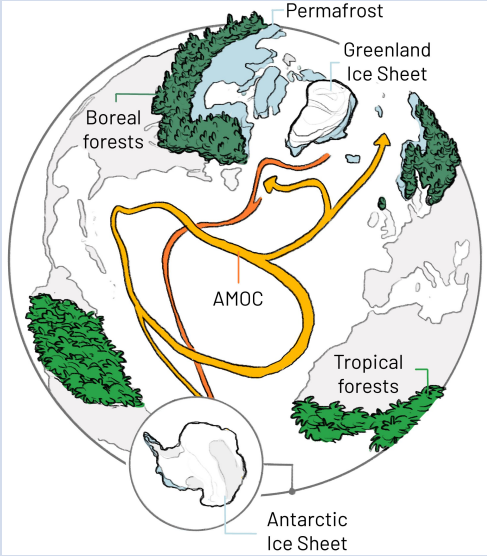
Solar Radiation Modification (SRM)		1. **SAI** – stratospheric aerosol injection	injecting sulphates into the stratosphere from newly-developed airplanes
		2. **MCB** – global marine cloud brightening	spraying sea salt cloud condensation nuclei from ships
CO_2 Removal (CDR)	land CDR (LCDR)	3. **RF/AF** – reforestation and afforestation	planting trees at a large scale at optimal locations
		4. **DACCS** – direct air capture with storage	capturing atmospheric CO_2 at industrial facilities (for follow-on sequestration)
		5. **BECCS** – bioenergy with carbon capture and storage	growing bioenergy crops and co-firing/firing them at electricity generation facilities with CCS capability
	marine CDR (MCDR)	6. **BMS** – biomass sinking	cultivating macroalgae (seaweed) at large scale, which is harvested, baled, and sunk into the deep sea or sediments for long-term carbon sequestration
		7. **ECCS** – electrochemical carbon capture and storage	electrolysis of seawater to change ocean chemistry, promoting CO_2 removal or enhanced storage capacity
		8. **OAE** – ocean alkalinity enhancement	dispersing sodium hydroxide (or crushed limestone) at river mouths or from ships, or via other methods

Ongoing Projects

1. CMIP7 FastTrack – Emissions Driven Earth System Models
2. ScenarioMIP – Emission Driven with Land Use including Reforestation and Bioenergy with Carbon Capture and Storage



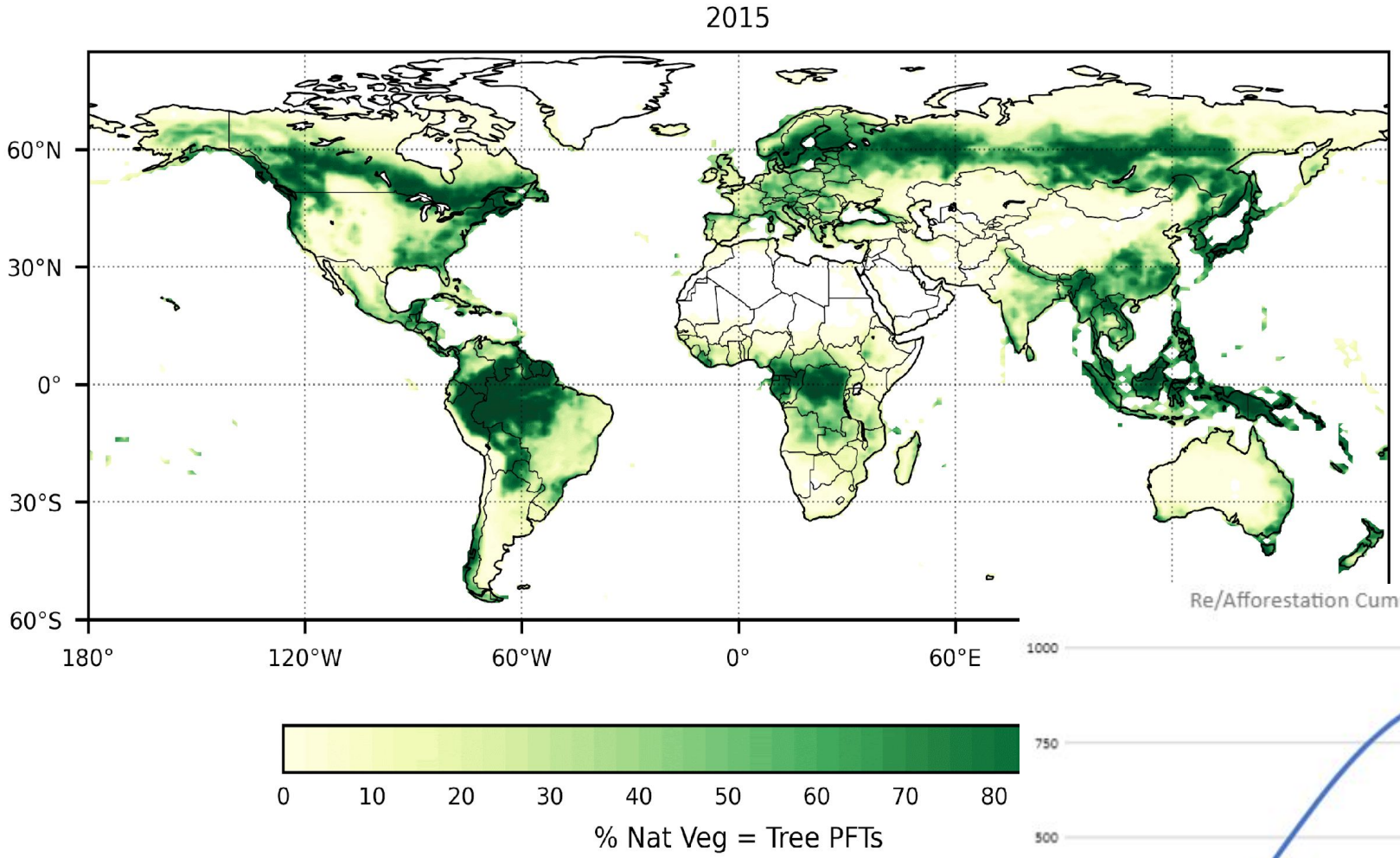
3. Flat 10 Simulations explore CMIP models in idealized emissions space.
4. TIPMIP with Bette Otto-Bliesner, Gokhan Danabasoglu and Aixue Hu. Investigating Tipping Points.
5. WCRP Climate Intervention and Tipping Points Efforts.

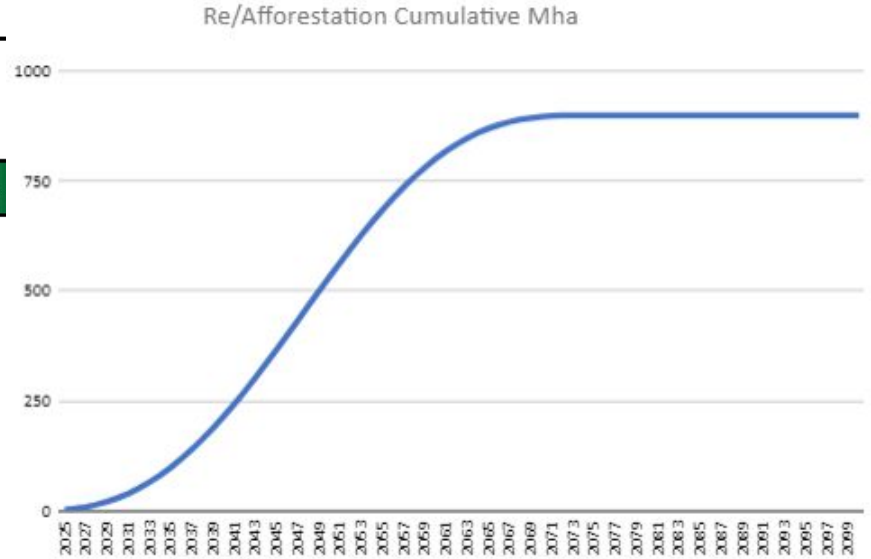


Full talk as an NCAR CGD Seminar at www.cgd.ucar.edu/events/seminar

Thank you – Questions?

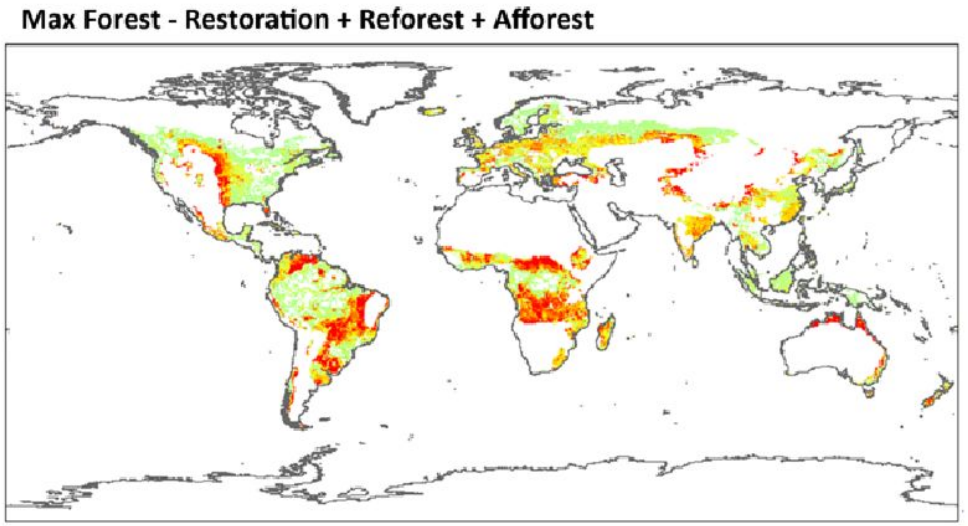
Prescribed Maximum Afforestation within Climate and Land Use

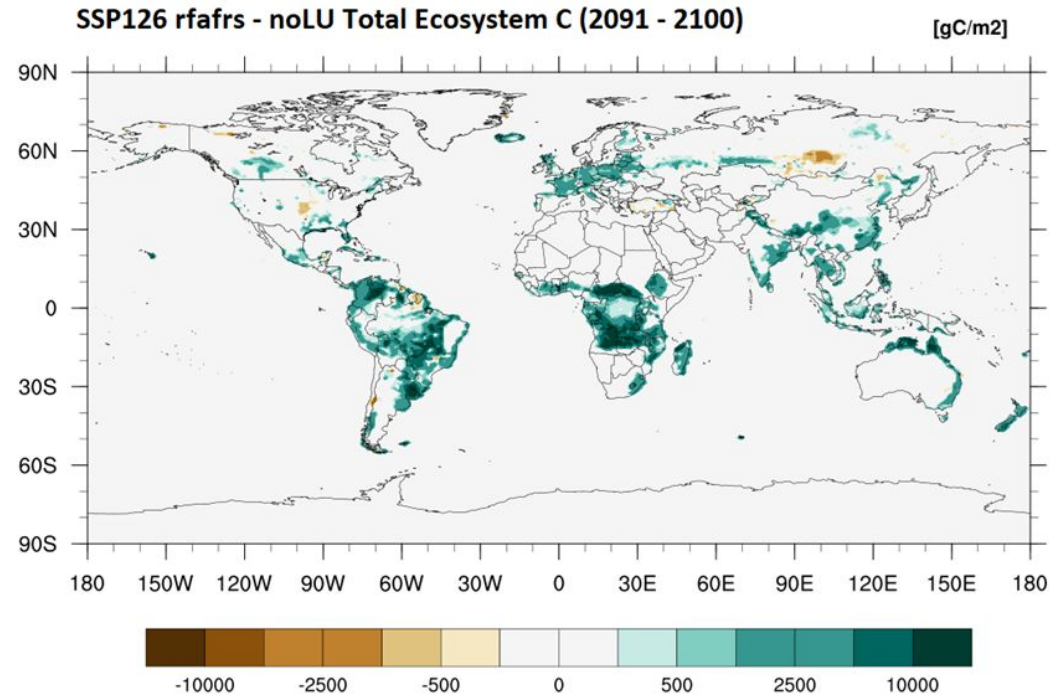


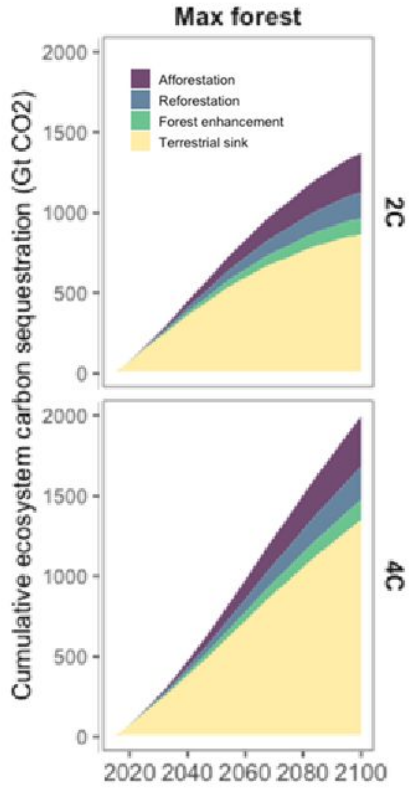


Thanks to Stephanie Roe WWF,
James King and James Weber
for Scenarios, Analysis and Animation

CLM5 RCP 2.6 Re/Afforestation – Total Eco Carbon 139 PgC







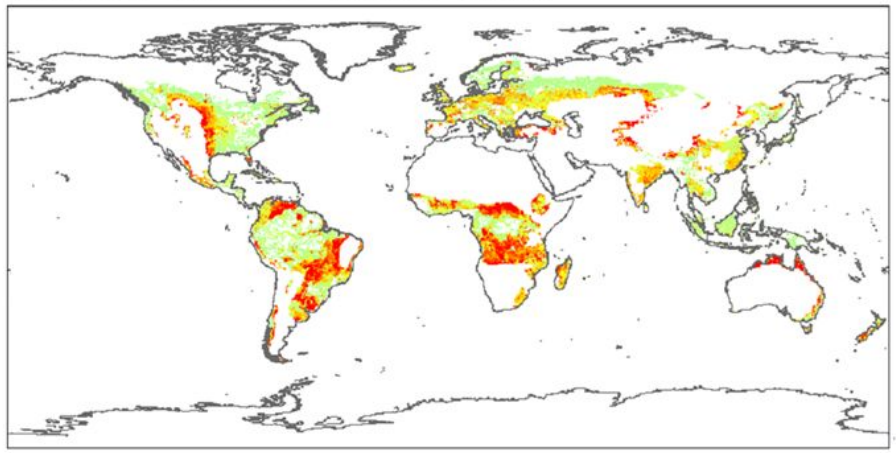
SSP1-2.6

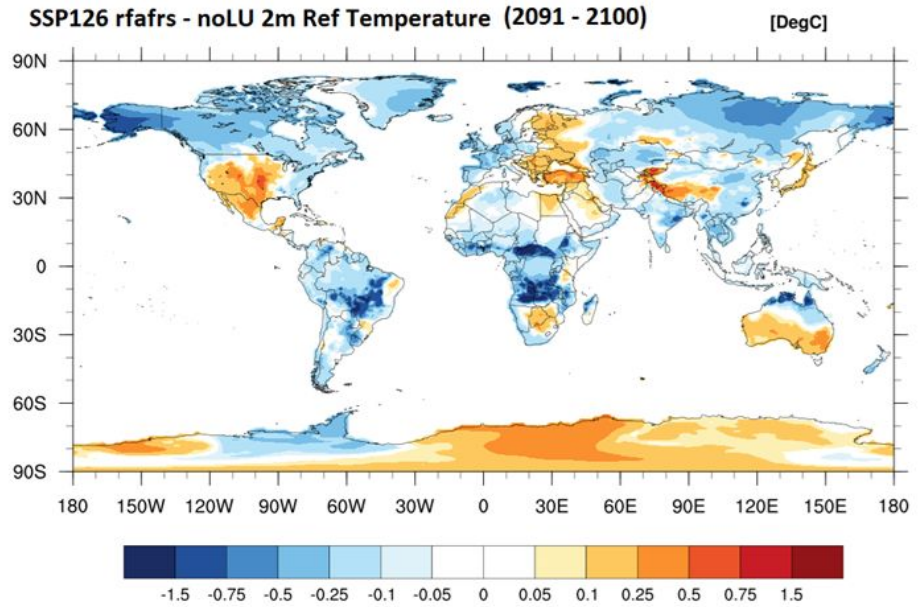
SSP3-7.0

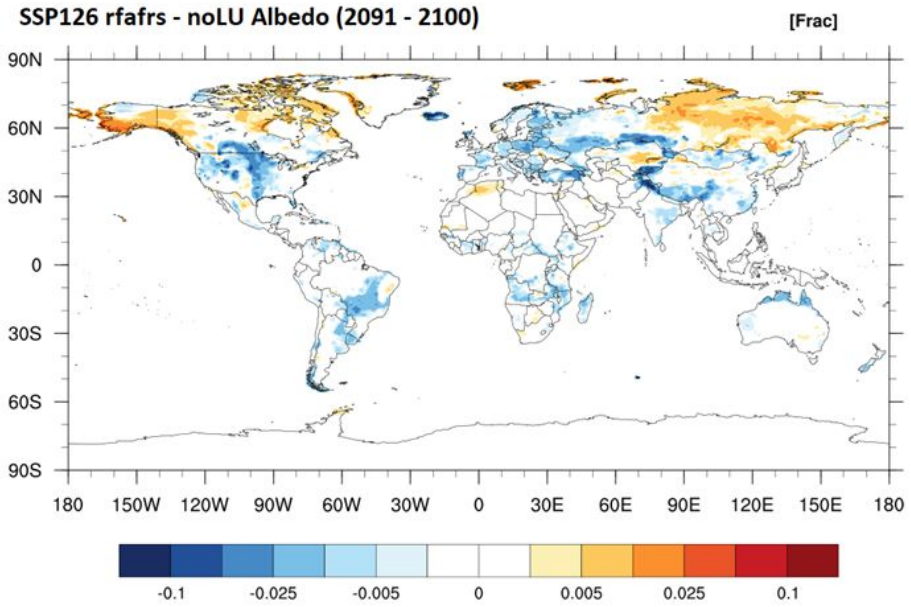
Global Area
Restoration 1.5m km2
Reforestation 2.3m km2
Afforestation 5.5m km2
Total 9.4m km2

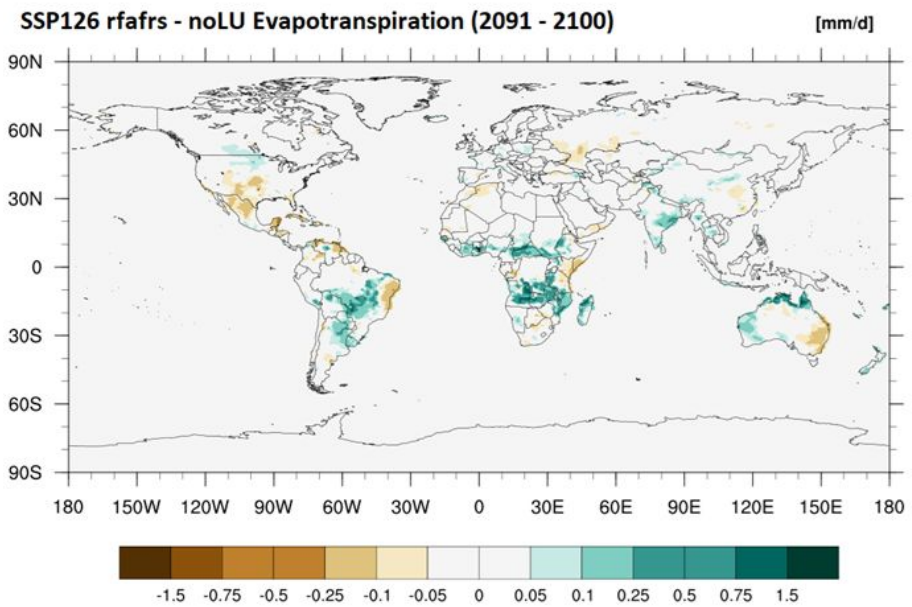
SSP1-2.6 Global Carbon
Restoration 28 PgC
Reforestation 44 PgC
Afforestation 67 PgC
Total 139 PgC

CLM5 RCP 2.6 Re/Afforestation – Air Temp / Evapotrans

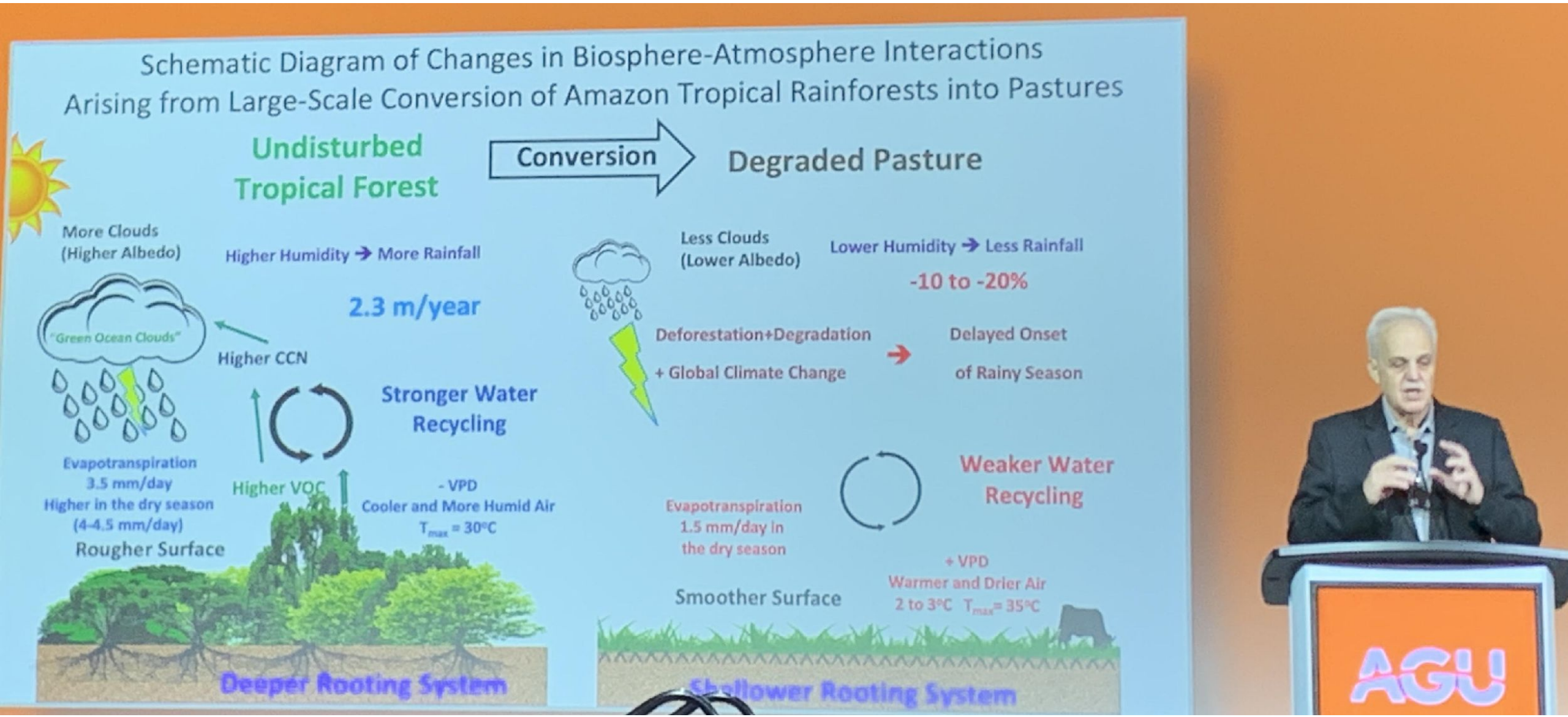




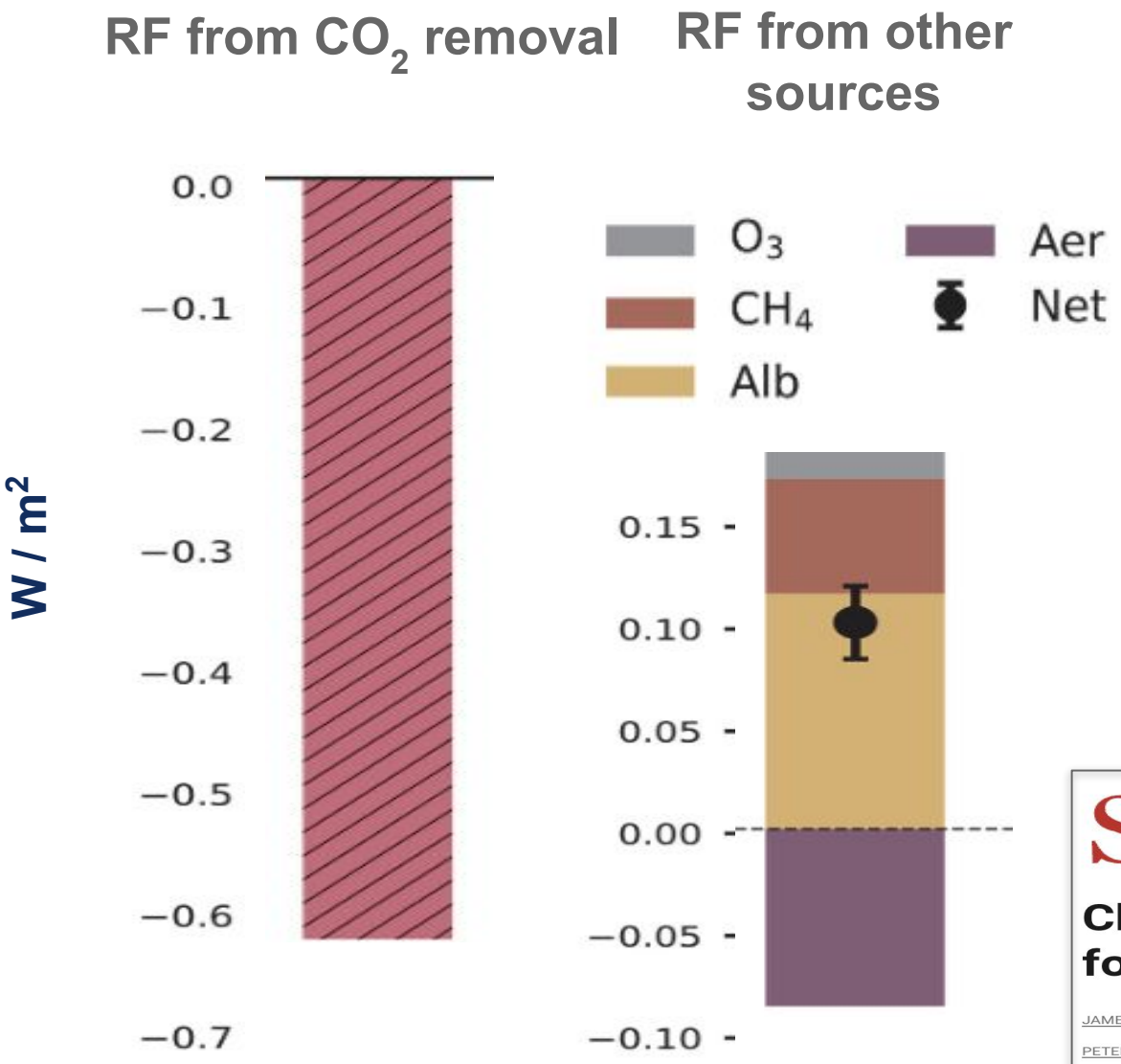




Earth System response to forest changes is complex – Carlos Nobre AGU 2022



Earth System response to forest change is complex



Full understanding of impacts of reforestation requires ESM

In CESM2 experiments, the direct radiative forcing (RF) from CO_2 removal is offset by changes in albedo and BVOC emissions and their impact on ozone, methane, and aerosol burdens

Science

Chemistry-albedo feedbacks offset up to a third of forestation's CO_2 removal benefits

JAMES WEBER, JAMES A. KING, NATHAN LUKE ABRAHAM, DANIEL P. GROSVENOR, CHRISTOPHER J. SMITH, YOUNGSUB MATTHEW SHIN, PETER LAWRENCE, STEPHANIE ROE, DAVID J. BEERLING, AND MARIA VAL MARTIN Authors Info & Affiliations

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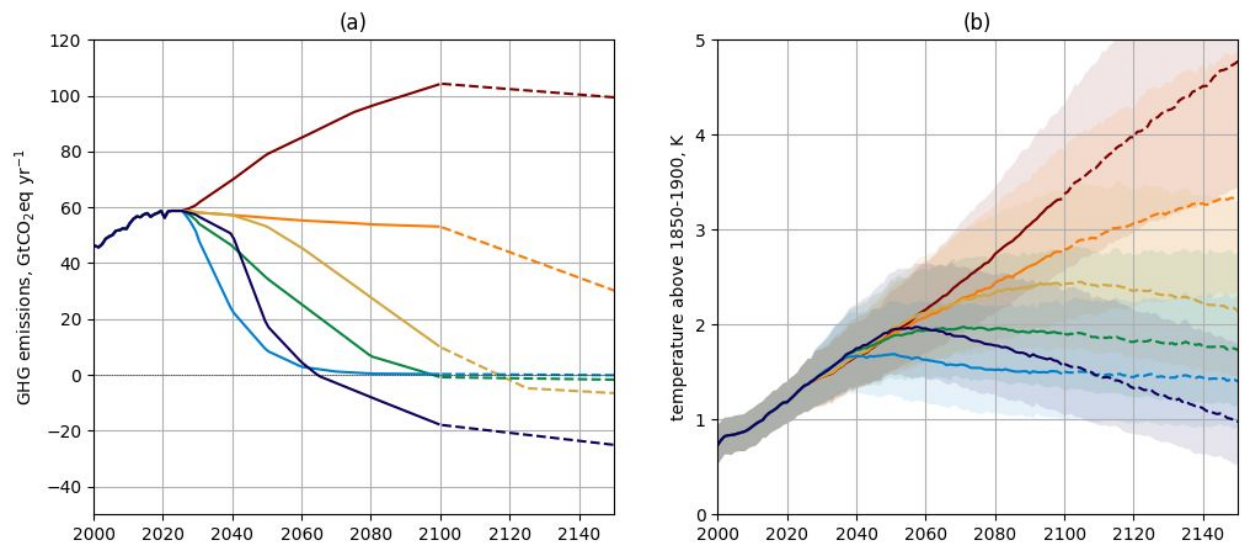
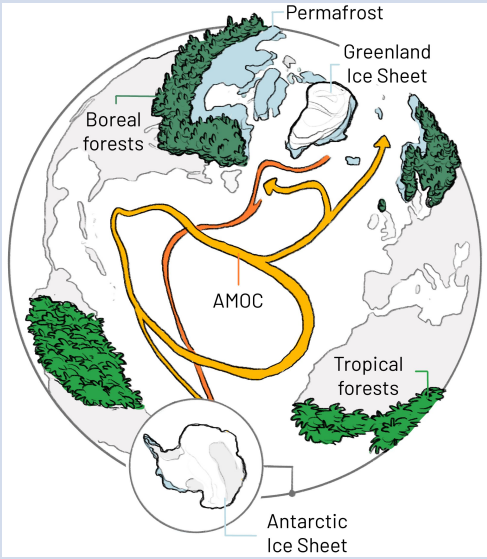
1. CMIP7 FastTrack – Emissions Driven Earth System Models
2. ScenarioMIP – Emission Driven with Land Use including Reforestation and Bioenergy with Carbon Capture and Storage

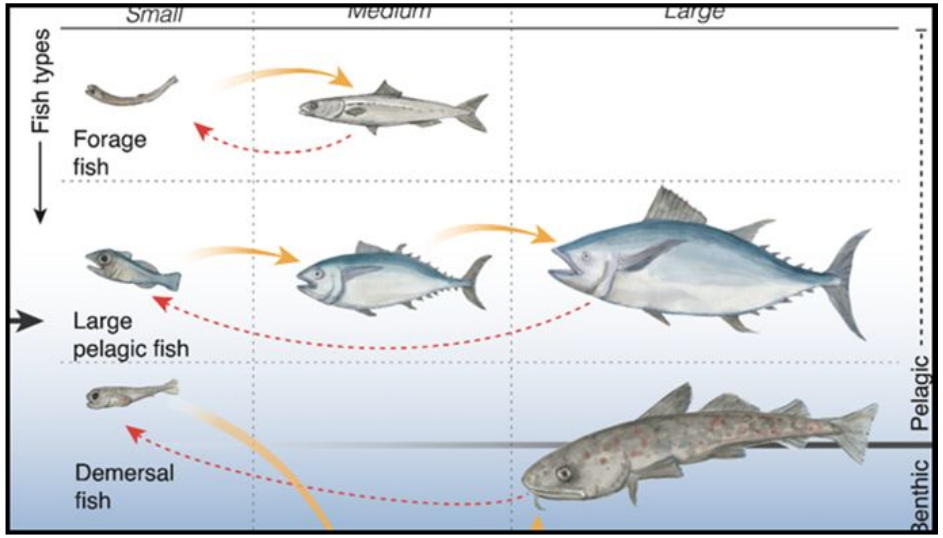


3. Flat 10 Simulations explore CMIP models in idealized emissions space.
4. TIPMIP with Bette Otto-Bliesner, Gokhan Danabasoglu and Aixue Hu. Investigating Tipping Points.
5. WCRP Climate Intervention and Tipping Points Efforts.



CESM Embedded Impacts Model

- Agricultural Yield (CLM Crop)
- Fisheries Modeling (MARBL -> FEISTY)
- Urban Climate (CLM Urban) and Human Health
- Wildland and Crop Fires
- Water Availability and Irrigation Demand
- Wood Production
- Ecosystem Health



Community Climate Interventions Strategies (CCIS)

Mission: Develop actionable research to understand the effectiveness and impacts of a portfolio of climate intervention strategies, that combined with mitigation and adaptation, achieve a climate safe future for human and natural systems.

Main Goals:

- Establish communication between currently disparate research communities to develop a unifying, interdisciplinary and international research program.
- Establish and support integrated working groups
- Support interdisciplinary projects working towards scientific assessments
- Enhance communication, synergize existing efforts, and cultivate new research

History:

- UCAR President's Strategic Award 2019 – NSF, NOAA, AIMES/FutureEarth, CCSP/USGCRP
- NCAR Climate Intervention Strategies Workshop July 30-31 2019
- Webinar Series / Research Framework / Website Development 2020 - 2022
- Community Climate Intervention Strategies Workshop October 2020. Follower up Scenarios Workshop October 2022.
- Award of NSF Growing Convergence Research 2022 - Generating Actionable Research to Investigate Combined Climate Intervention Strategies for Stakeholder Use

Core Research Team

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Terrestrial Systems; Land use
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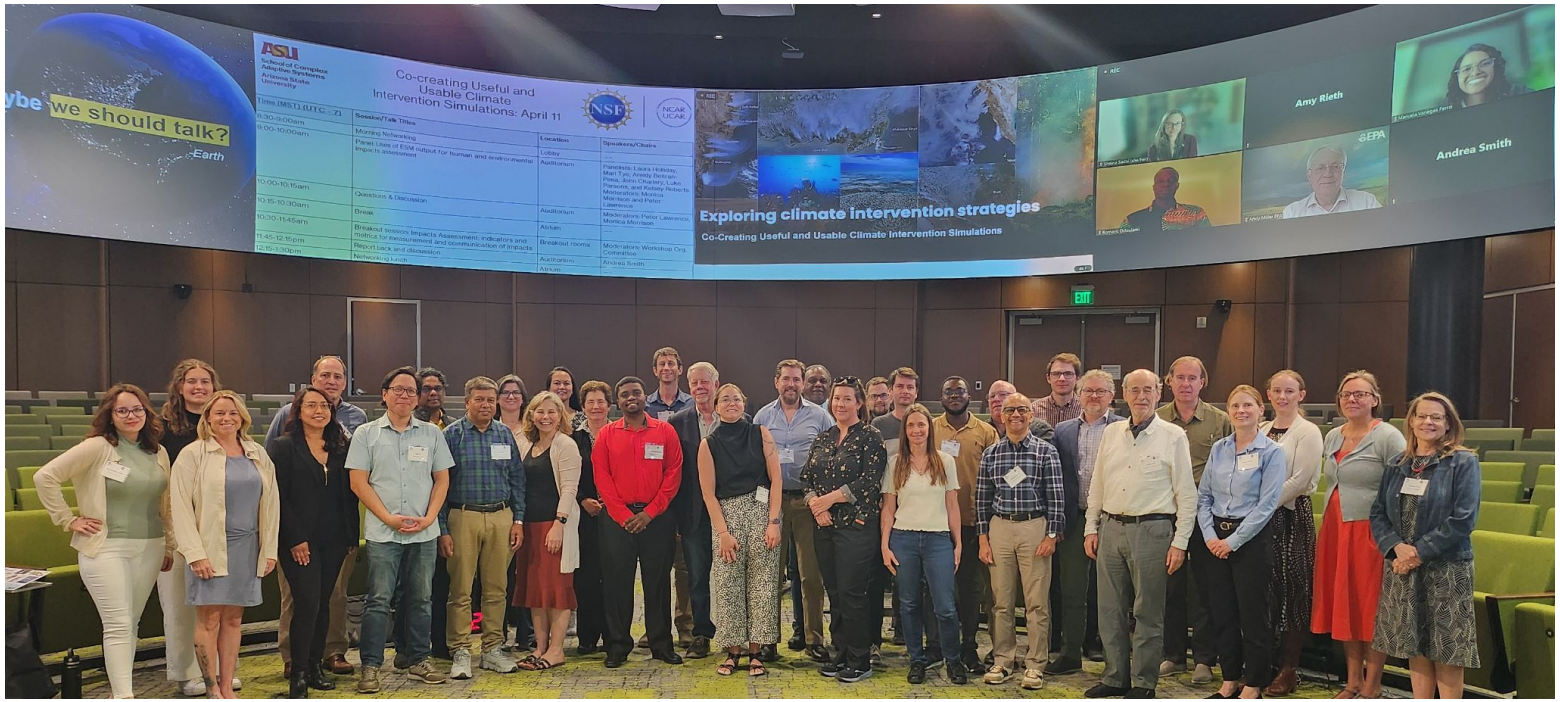
Policy and Governance
Duke

David Lawrence
Earth System Modeling
NSF NCAR

Andrea Smith
Communication and Outreach
COMET UCAR

Stakeholder Communities and Representatives

Workshops


we should talk?
Earth
ASU
School of Complex Adaptive Systems
Arizona State University
Co-creating Useful and Usable Climate Intervention Simulations: April 11
NSF
NCAR UCAR
Exploring climate intervention strategies
Co-Creating Useful and Usable Climate Intervention Simulations
Amy Rieth
EPA
Andrea Smith
EXIT


3. Convergence Process Evaluation

Community Ensemble of CESM Simulations – CCIS Ensemble

- **Climate Intervention Model Configuration**
  - Stratospheric Aerosol Injection (SAI) – Prescribed Stratospheric Aerosols are provided to CAM6 from ARISE WACCM simulations
  - Marine Cloud Brightening (MCB) – Working with Jack Chen and Walker Lee for prescribed MCB using methods being developed in ARISE MCB simulations
  - Land CDR – Re/Afforestation developed through Land Use following Stephanie Roe et al.
  - Land CDR – Bio Energy and Carbon Capture and Storage (BECCS) following Yanyan Cheng et al.
  - Land CDR – Direct Air Capture will use reduced or negative fossil fuel CO2 emissions that have been calculated offline along literature values.
  - Ocean CDR – Enhanced Alkalinity additional fluxes of NaOH to river discharge from Matt Long
  - Ocean CDR – Macroalgae with Biomass Sinking – Offline modeling with fluxes to Ocean BGC provide to remove both CO2 and nutrients from ocean pools and then deposited at depth.
  - Ocean CDR - Electrochemical CO2 removal from sea water represented with forcing file to remove only CO2 from ocean pools.

Idealized CDR simulations already run using negative fossil fuel emissions with the CESM 2.1.4 model configuration.