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# Using Emission Driven CESM to Investigate Global Tipping Points and Climate Interventions

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CESM Workshop – June 09 2025



## **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. Framework used for the CESM Tipping Point (TIPMIP ESM) and Community Climate Intervention Strategies (CCIS) Ensemble being run at NCAR

#### 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#### **Evaluation of CESM CCIS Historical Reference Height Temperature versus LENS 2.**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 HOPE SSP 3-7.0 Reference Height Temperature versus LENS 2.**





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)







1850 1875 1900 1925 1950 1975 2000 2025 2050 2075 2100

Tipping dynamics are triggered when a change in part of a system (tipping system) becomes self-perpetuating beyond some critical threshold (tipping point), leading to substantial, widespread, often abrupt and / or irreversible impacts.

Abrupt changes in a system are large-scale changes that take place over a few decades or less or are occurring faster than the typical timescale of a system (e.g., decades for an abrupt AMOC collapse), persist for at least a few decades, and cause substantial impacts in human and / or natural systems.

Castruccio, Danabasoglu, Hu, Lawrence, and Otto-Bliesner



Winkelmann et al. (2025, Earth Sys. Dyn., submitted)

#### **CESM2 TIPMIP Nominal 1°, Emissions-Driven Simulations**

TIPMIP ESM Tier 1 experiment protocol: All experiments in CO2-emission mode



#### **TIPMIP-Whatlf Vegetation Experimental Storylines**

meter/yea



TIPMIP ESM Tier 1 emission-driven experimental protocol Simulating climate and carbon changes at ZEC 2K and ZEC 4K Replacement of vegetation - LUMIP deforestation procedure





Amazon rainforest dieback

Regional and total dieback replacing trees with grasses

GGWI: Planting trees in the Sahel

Medium and Extreme GGWI without and with irrigation

Boreal forests & shrubs expanding north, becoming stressed along the southern margin

Regional and total global vegetation shifts



### Amazon Rainforest Collapse – More details

From the CMIP6 1850 Vegetation Map which is being used for all baseline scenarios remove 2% of the Amazon trees per year for 50 years.

The Amazon is defined as a circle centered –2.375, –64.875 with a radius of 18 degrees.

The tree collapse starts at the at beginning (TBD) of GWL (ZEC) 2°C and 4°C stabilizations. A continuation of 50 years after the full collapse is then run compared to the GWL (ZEC) stabilization over that same period.



#### **CESM TIPMIP 2C Warming With and Without Amazon Collapse**





Last 30 years post Amazon collapse at 2C warming compared to with Pre Ind. Amazon at 2C warming:

Ecosystem C: Loss of 203 PgC (745 GtCO<sub>2</sub>)

**CO<sub>2</sub>:** Increase by 65 ppm

**Temp:** Global increase +0.7C – Local increase +5C

**Precip:** Decreases over Amazon (-700 mm/year) and increases over Central Pacific (+700 mm/year)

### Community Climate Intervention Strategies CESM Ensemble - Ongoing

#### **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 <sub>2</sub> Removal (CDR)	land CDR (LCDR)	3. <b>RF/AF</b> – reforestation and afforestation	planting trees at a large scale at optimal locations
		4. DACCS – direct air capture with storage	capturing atmospheric CO <sub>2</sub> at industrial facilities (for follow-on sequestration)
		<ol> <li>BECCS – bioenergy with carbon capture and storage</li> </ol>	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
		<ol> <li>ECCS – electrochemical carbon capture and storage</li> </ol>	electrolysis of seawater to change ocean chemistry, promoting CO <sub>2</sub> 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

#### Prescribed Maximum Afforestation within Climate and Land Use



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

#### Bioenergy crops added to CESM

Traditional crops can be and are used as biofuel feedstocks



But, perennial grasses such as *Switchgrass* and *Miscanthus* have higher productivity and water use efficiency as well as lower demands for irrigation and fertilization



Cheng et al., 2019, JAMES



### **ARISE SAI WACCM Simulations Extended to 2100**



Assessing Responses and Impacts of Solar climate intervention on the Earth system (**ARISE**) SAI and MBC (Richter et al., 2022): 10-member ensemble using CESM2(WACCM6)

- Start: 2035
- Goal: Keep surface temperature at 1.5C above Pre-Industrial Conditions
- Extension of the ARISE dataset from 2070 -2100 conditions
- Used as maximum plausible SAI scenario
- Results are used for combined CDR / SAI studies in the next phase of the project

## Thank you – Questions?





W / m<sup>2</sup>

# Full understanding of impacts of reforestation requires ESM

In CESM2 experiments, the direct radiative forcing (RF) from CO<sub>2</sub> 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<sub>2</sub> removal benefits

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## **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.



### **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**



Peter Lawrence Terrestrial Systems; Land use NSF NCAR



Simone Tilmes Atmospheric Chemistry NSF NCAR



Cheryl Harrison Marine Ecosystem Impacts LSU



**Tyler Felgenhauer** *Policy and Governance* Duke



Michael Barton Anthropology; Complex Systems ASU



David Lawrence Earth System Modeling NSF NCAR



Mari Tye Civil Engineering; Climate Statistics NSF NCAR



Andrea Smith Communication and Outreach COMET UCAR



Monica Morrison Philosophy of Science and Ethics NSF NCAR **Stakeholder Communities and Representatives** 



### <u>Workshops</u>











### **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.