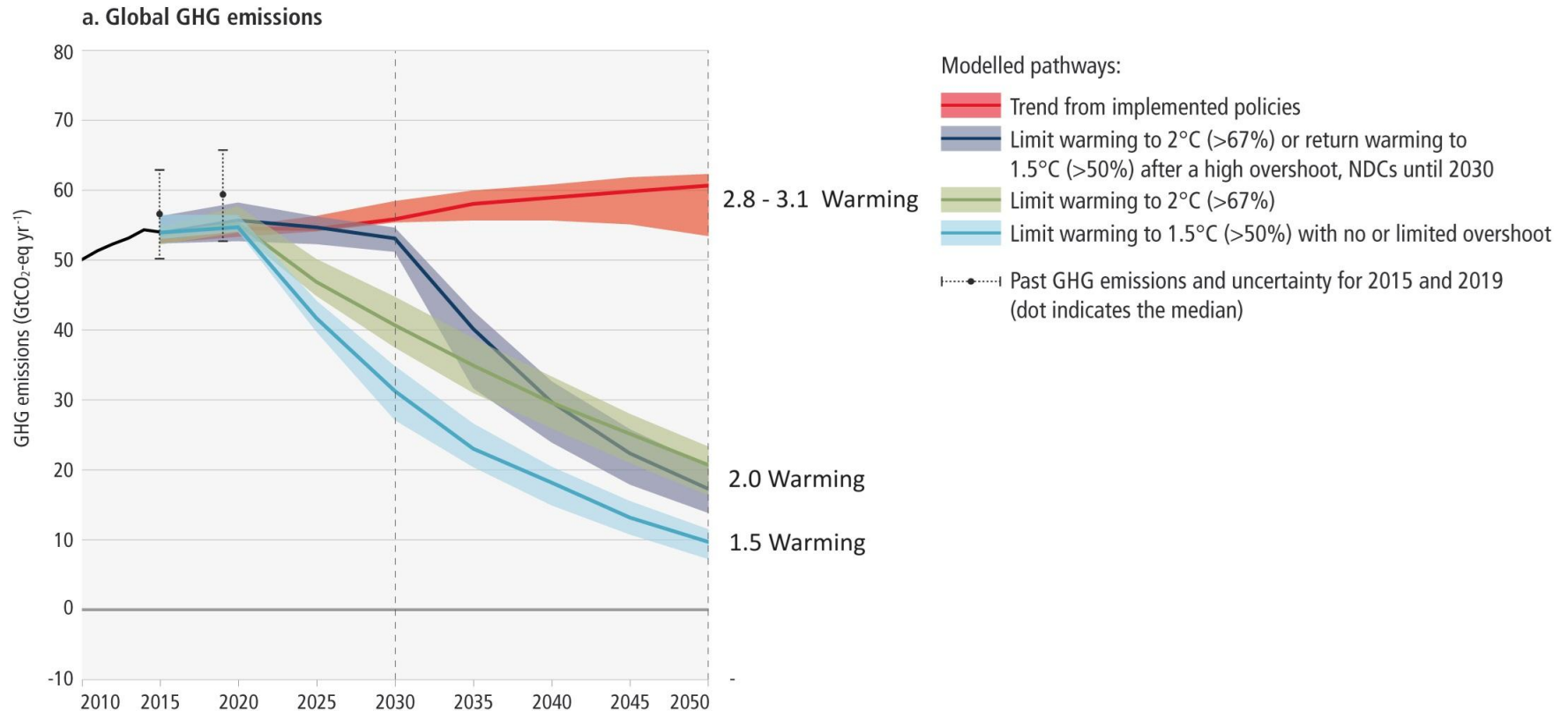


Developing an Earth System framework integrating Climate Interventions (CDR and SRM) in CESM

*Peter Lawrence, Dave Lawrence, Simone Tilmes,
Andrea Smith, Monica Morrison, Michael Barton,
Cheryl Harrison, and Tyler Felgenhauer*

COP Paris Targets – AR6 WG3 – Emissions and CDR



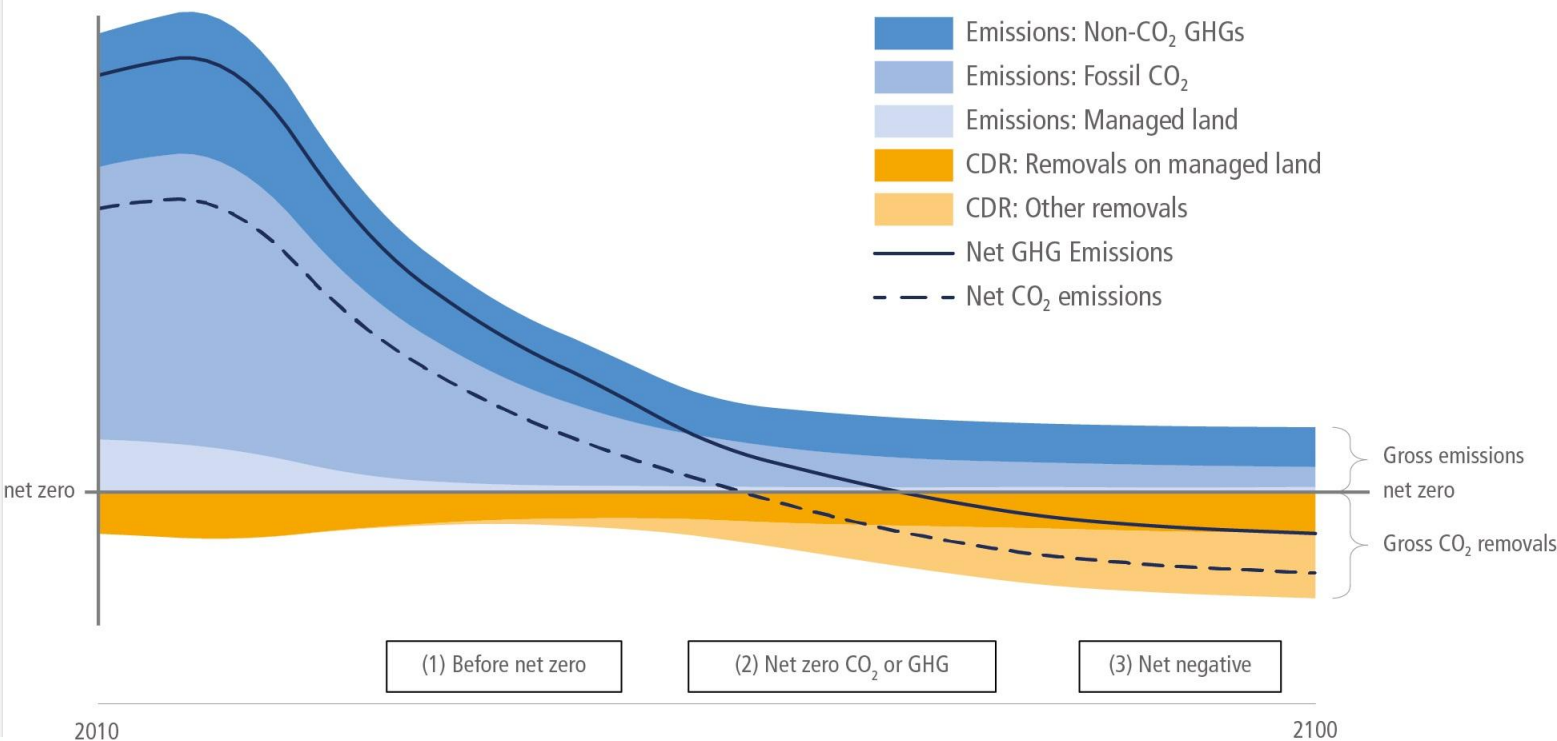
We are not on the right track to keep global surface temperatures below 1.5C

- Continued warming will most likely lead to overshoot of temperature targets
- Increases potential risk of reaching climatic tipping points
- Increases impacts on vulnerable societies and ecosystems

What Climate Responses are available or can be developed to help reduce some of the projected

COP Paris Targets – IPCC SR 1.5C – Emissions and CDR

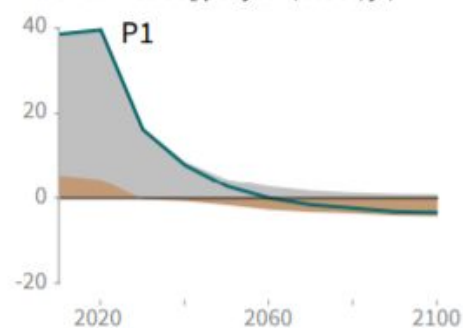
Greenhouse gas emissions (stylised pathway)



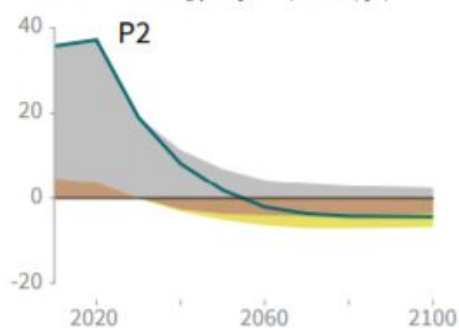
Breakdown of contributions to global net CO₂ emissions in four illustrative model pathways

● Fossil fuel and industry ● AFOLU ● BECCS

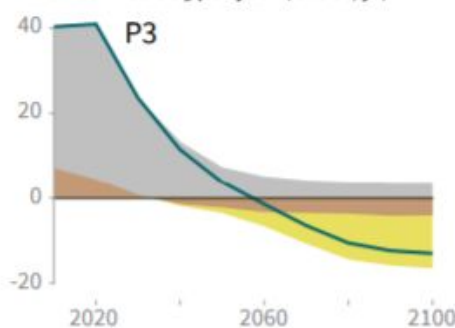
Billion tonnes CO₂ per year (GtCO₂/yr)



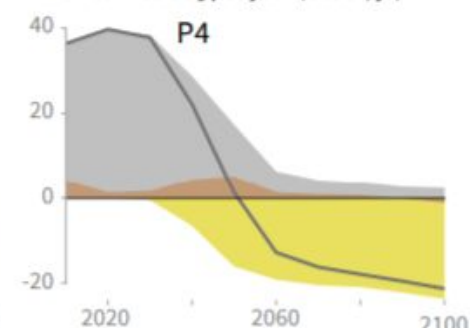
Billion tonnes CO₂ per year (GtCO₂/yr)



Billion tonnes CO₂ per year (GtCO₂/yr)



Billion tonnes CO₂ per year (GtCO₂/yr)



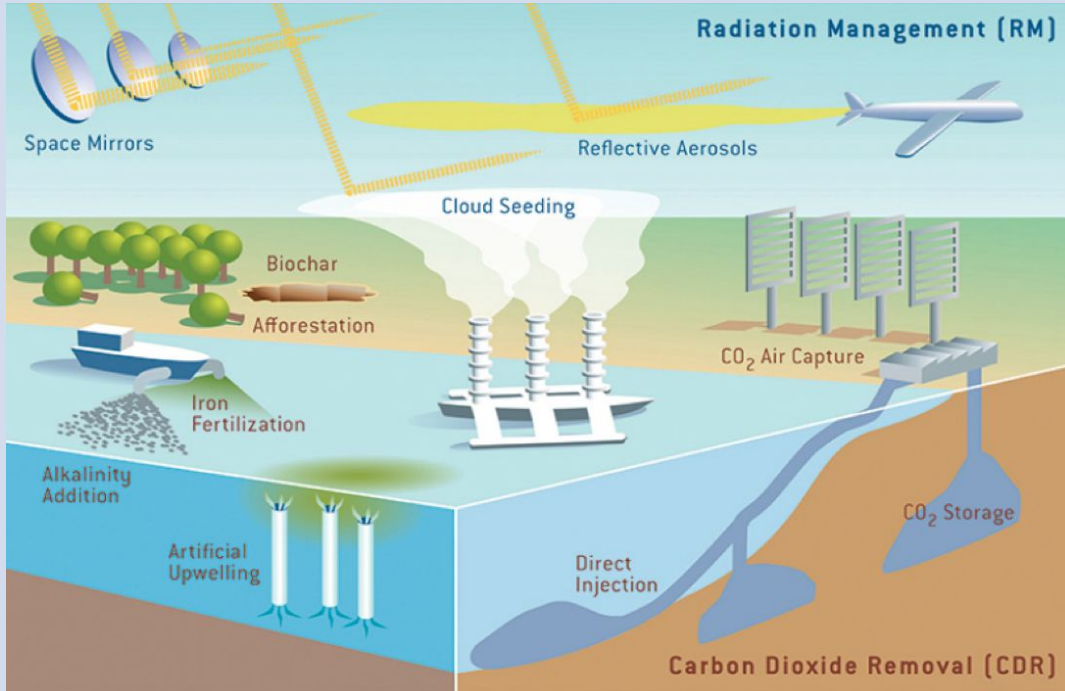
Title: Generating Actionable Research to Investigate Combined Climate Intervention Strategies for Stakeholder Use - 5 years funding (2 phases)

Partners: NCAR/UCAR: Peter Lawrence (Lead), Dave Lawrence, Simone Tilmes, Andrea Smith, Monica Morrison (Convergence Manager); Arizona State University: Michael Barton; Duke University: Tyler Felgenhauer; and Louisiana State University: Cheryl Harrison

Collaborators: Earth system modelers, scenario designers, community partners (WWF, TNC, IPCC, UCAR Office of Government Relations), regional impacts researchers, philosophers of science and ethics, human systems researchers, public communication and engagement specialists, SAI, MCB, CDR and other Climate Intervention specialists, societal decision modelers

NSF GCR Program: “Supports transitioning teams from research that is multidisciplinary to research that transcends disciplinary boundaries with novel conceptual frameworks, theories and methods.”

National Academies Climate Intervention



Reduce global warming through stabilizations and reduction of atmospheric GHGs

- Mitigation
- Carbon Dioxide Removal (CDR)

Reduce global warming through artificially changing the reflectivity of the planet

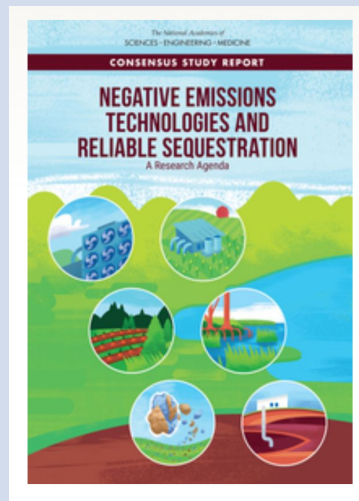
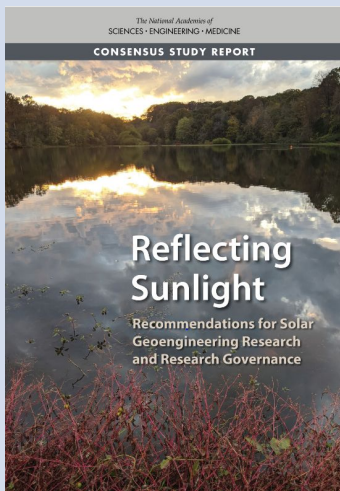
- Global Solar Radiation Modification (SRM)
- Including Stratospheric Aerosol Interventions (SAI) and Cloud Modification

Reduction of impacts and suffering

- Adaptation
- Regional SRM

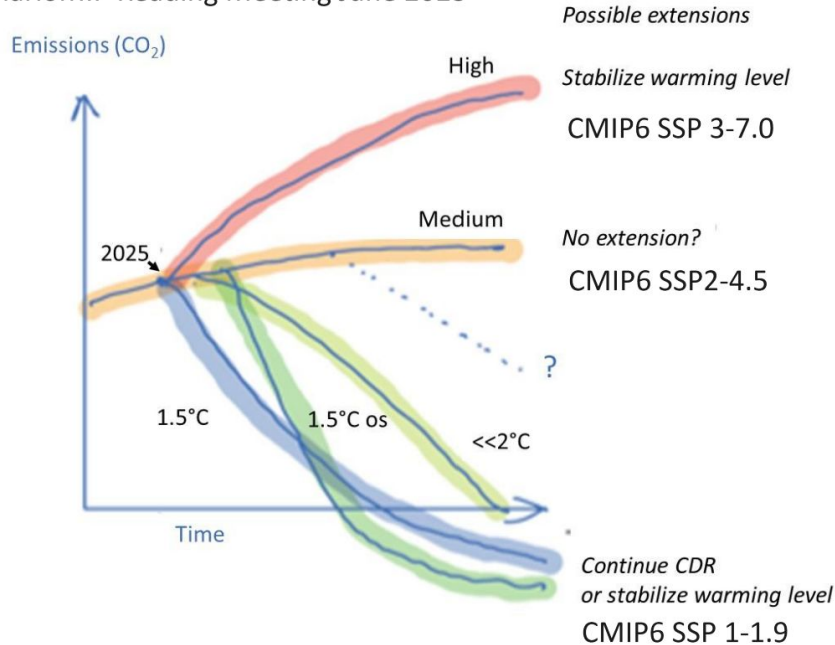
National Academies of Science, Engineering and Medicine

- Reflecting Sunlight
- Negative Emissions Technologies and Reliable Sequestration



Community Ensemble of CESM Simulations – CCIS Ensemble

CMIP7 Proposed Emission Pathways
ScenarioMIP Reading Meeting June 2023



Climate Interventions from existing research:

All activities are applied to the SSP 2-4.5 (Medium) and SSP 3-7.0 (High) Baseline Pathways to allow efficacy and impacts to be studied by CCIS community and stakeholders

Minimal Model Development:

To ensure we can start simulations as quickly as possible climate interventions are being represented through forcing files and existing code

Mitigation Baseline Pathways:

Using CESM 2.1.5 (LENS2) with existing CMIP6 fossil fuel CO₂, Methane, and aerosol emissions for:

- SSP 1-1.9, 2-4.5 and 3-7.0.
- These represent 1.5C mitigation, medium and high warming scenarios.
- All Baseline SSPs have Current Day Land Use to allow for widespread land-based CDR.

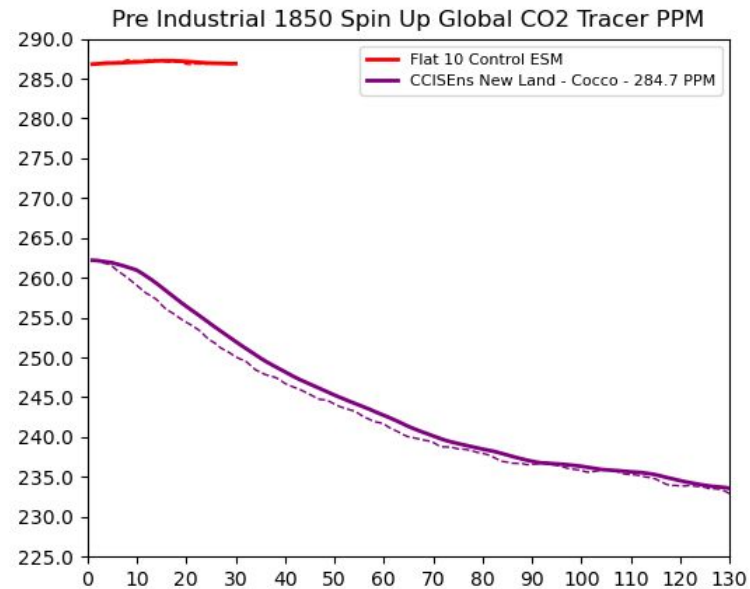
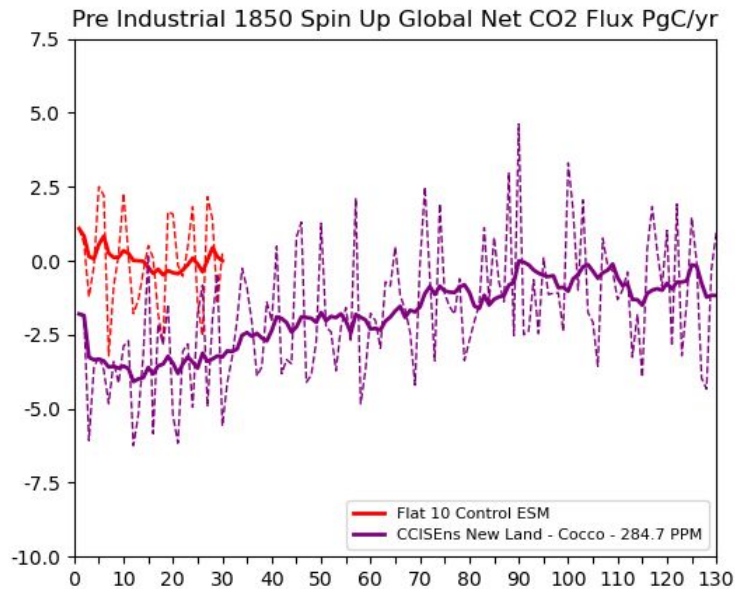
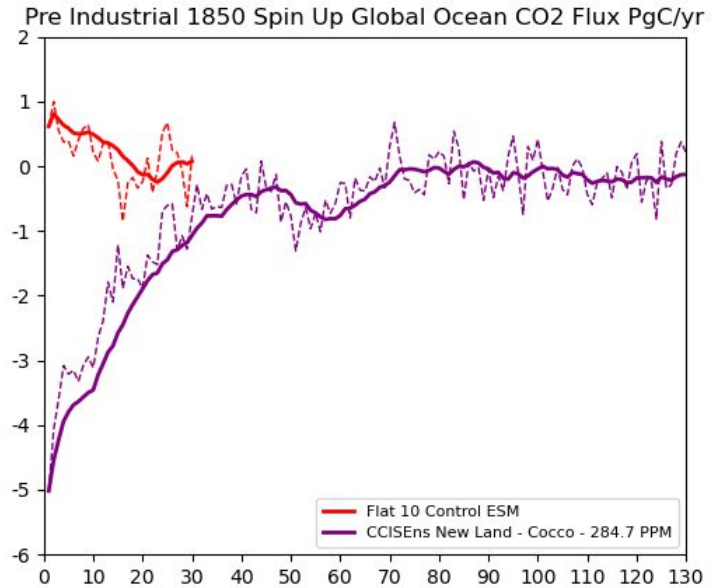
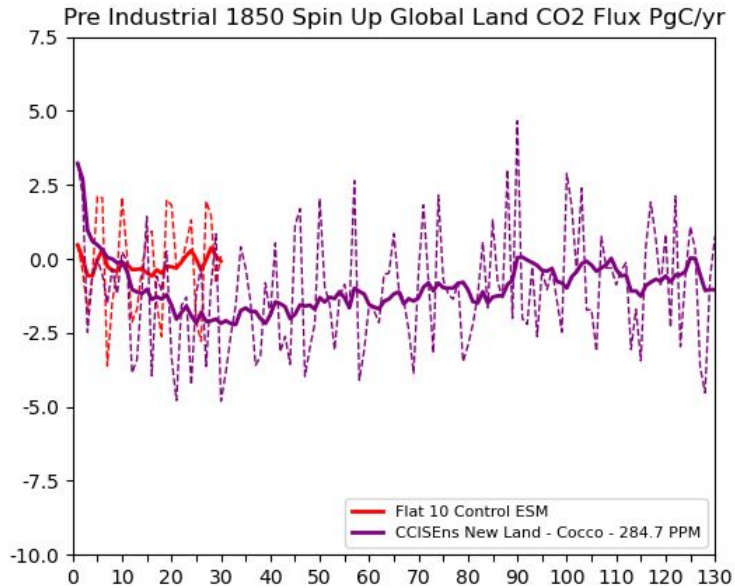
Additional Configuration Specification:

- Active Fire Aerosol Emissions
- Active Biogenic Volatile Organic Compound (BVOC) Emissions
- Marine Coccolithophores in Ocean BGC
- Individual Scenarios Ensembles of 5x Initial Conditions from new 1850 Control with associated Historical Emission Driven Simulations.

Key Project Tasks for Baseline CCIS Ensemble

- 1. Getting CESM2.1.5 on Derecho Supercomputer.** Initial Baseline Emission Driven Simulations have started with a Large NCAR Strategic Computing Request for 18.0 million core hours awarded end of 2023. CCIS Ensemble GitHub repositories for each CESM component.
- 2. Bringing in MARBL with Coccolithophores.** New Ocean Ecosystem with four phytoplankton, two zooplankton and coccolithophores (4p2z). Kristen Krumhardt and Keith Lindsey provided guidance and example cases and 1850 initial conditions. This required some minor source changes to POP tracers and drivers, updating some scripts, and updating Externals_POP to reference the new MARBL model. Even with the new initial conditions files the model needs time to spin up to the CESM2.1.5 climate. The new Ocean Ecosystem model provides data for running the Fisheries model FEISTY.
- 3. Updating CLM5 with New Land Cover Dataset and Fixing known bugs –** New Land Use and Land Cover datasets have been incorporated for the CCIS Ensemble using the latest CTSM 5.2 PFT and CFT datasets to provide the capability of representing Reforestation, BioEnergy with Carbon Capture and Storage (BECCS), and other alternative and management practices. Additionally fixes were implemented for the known FUN Fixation Bugs, Low Irrigation targets identified by Yi Yao.
- 4. Active Fire Emission and MEGAN BVOC implemented for MAM4.** Recent work done to allow for CAM6 to use Fire and MEGAN BVOC emissions directly without CAM Chemistry was included in the CCIS Ensemble. This replaces the CMIP6 emission files that directly specify these values with those calculated in CESM.

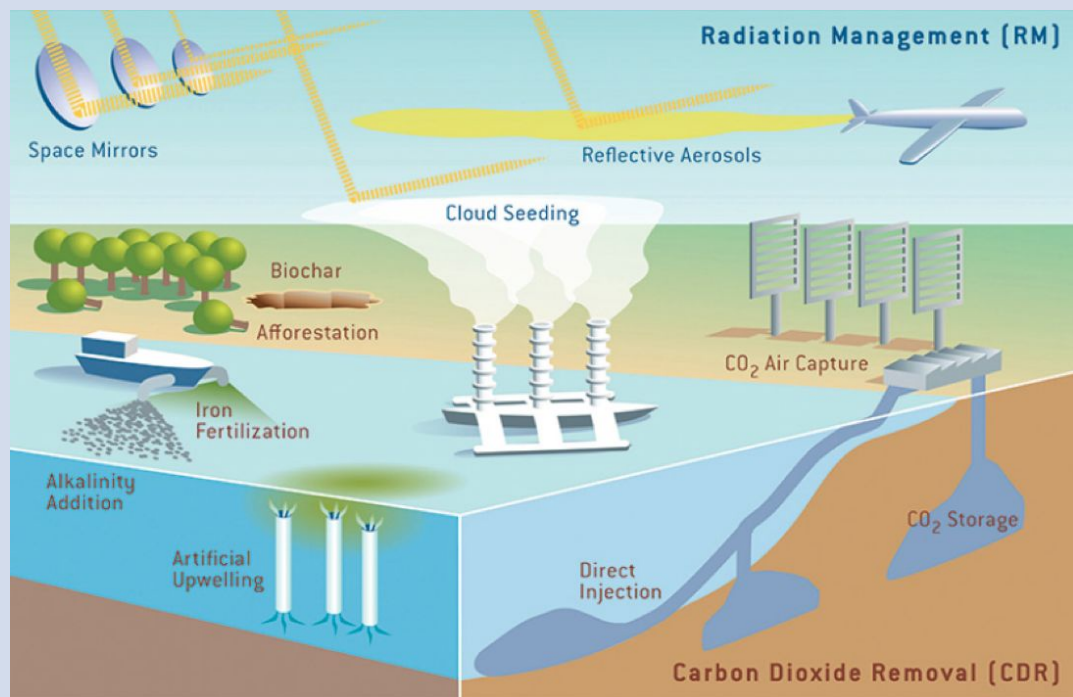
Spinning Up CCIS Ensemble PI 1850 with Prescribed CO₂



Key Project Tasks for Baseline CCIS Ensemble

- 1. Completing PI 1850 Spin Up.** The PI 1850 with Prescribed 284.7 PPM CO₂ is nearly complete. This needs to transition to ESM 1850 with active CO₂ as performed with the CMIP7 Flat 10 simulations. A final version of the active aerosols simulations also need to be finished.
- 2. Running Historical 1850 – 2015 Simulations with both CMIP6 Emissions and Concentrations.** Once the 1850 Spin Up is complete five ensemble members will branch at different points. Four of these will be Emission driven with a fifth concentration driven as a carbon and climate reference.
- 3. Running Baseline 2016 – 2100 SSPs for 1-1.9, 2-4.5 and 3-7.0 –** The final component is to run the Baseline SSPs. These will have current day land use to allow for a clean comparison to Reforestation, Bio Energy crops and alternative land use methods. These will branch off the five Historical simulations.
- 4. Developing and Running the 8 Climate Intervention Pathways.** The next component once the CCIS Ensemble framework is completed is to generate and run ensembles of Climate Interventions on top of the SSP Baselines.

National Academies Climate Interventions in CESM



Scenario Narratives for eight Individual Interventions Plausible and Max Feasible.

Atmosphere SRM

- (a) Stratospheric Aerosol Injection (SAI)
- (b) Marine Cloud Brightening (MCB)

Land CDR

- (a) Re/Afforestation
- (b) Bio Energy and Carbon Capture and Storage (BECCS)
- (c) Direct Air Capture (DAC with CCS)

Ocean CDR

- (a) Enhanced Alkalinity
- (b) Macroalgae (Kelp) with Biomass Sinking
- (c) Electrochemical CO₂ removal from sea water

Climate Interventions from existing research:

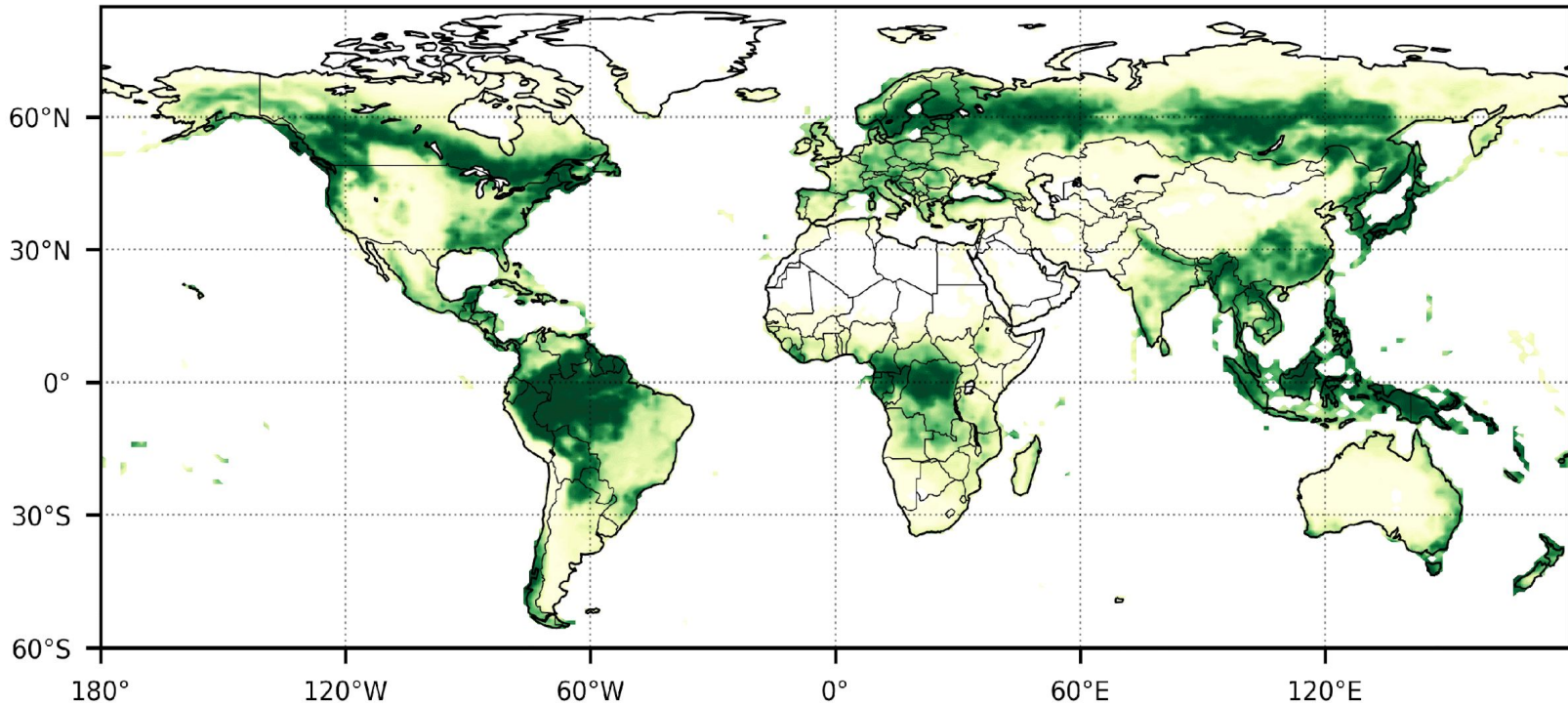
All activities are applied to the SSP 2-4.5 (Medium) and SSP 3-7.0 (High) Baseline Pathways to allow efficacy and impacts to be studied by CCIS community and stakeholders

Minimal Model Development:

To ensure we can start simulations as quickly as possible climate interventions are being represented through forcing files and existing code wherever possible

Maximum Afforestation within Climate and Land Use

2015



% Nat Veg = Tree PFTs

Thanks to Stephanie Roe and James King for Scenarios and Animation

Bioenergy crops added to CESM

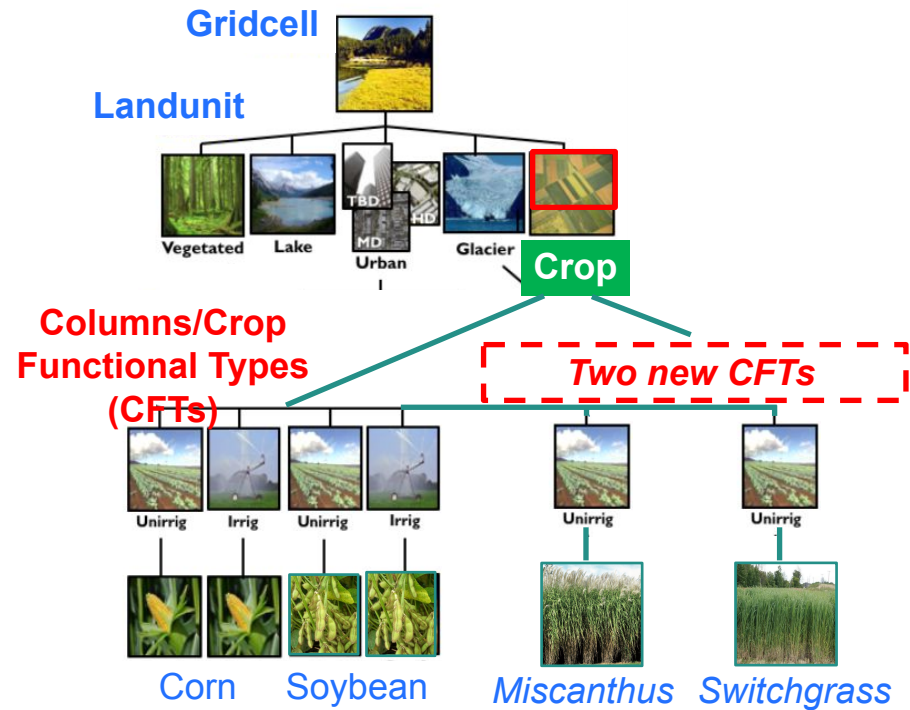
Traditional crops can be and are used as biofuel feedstocks



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



New sets of available SAI WACCM Simulations (NCAR)

Geoengineering Large Ensemble Simulations (GLENS); Peakshaving Simulations, Assessing Responses and Impacts of Solar climate intervention on the Earth system (ARISE) with stratospheric aerosol injection and MBC)

GLENS (Tilmes et al, 2018)

- CESM1(WACCM)
- RCP8.5 scenario
- Start in 2020
- Target: 2010 – 2030 mean
- SO₂ injection at 23 – 25 km altitude
- 20-member ensemble

Peakshaving (Tilmes et al, 2020)

- CESM2(WACCM)
- SSP5-8.5, SSP5-3.4-OS
- Start in 2020 (2034)
- Target: 2020 / 2034 mean
- SO₂ injection at 23-25 km altitude
- 3-member ensemble

ARISE-SAI-1.5 (Richter et al, 2022)

- CESM2(WACCM)
- SSP2-4.5 scenario
- Start in 2035
- Target: 2020 – 2039 mean
- SO₂ injection at ~ 21 km altitude
- 10-member ensemble

Great resource for investigating climate impacts, even two versions of one model show different climate impacts -> **Community Resource to the Community**

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

Thank You – Questions?



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.