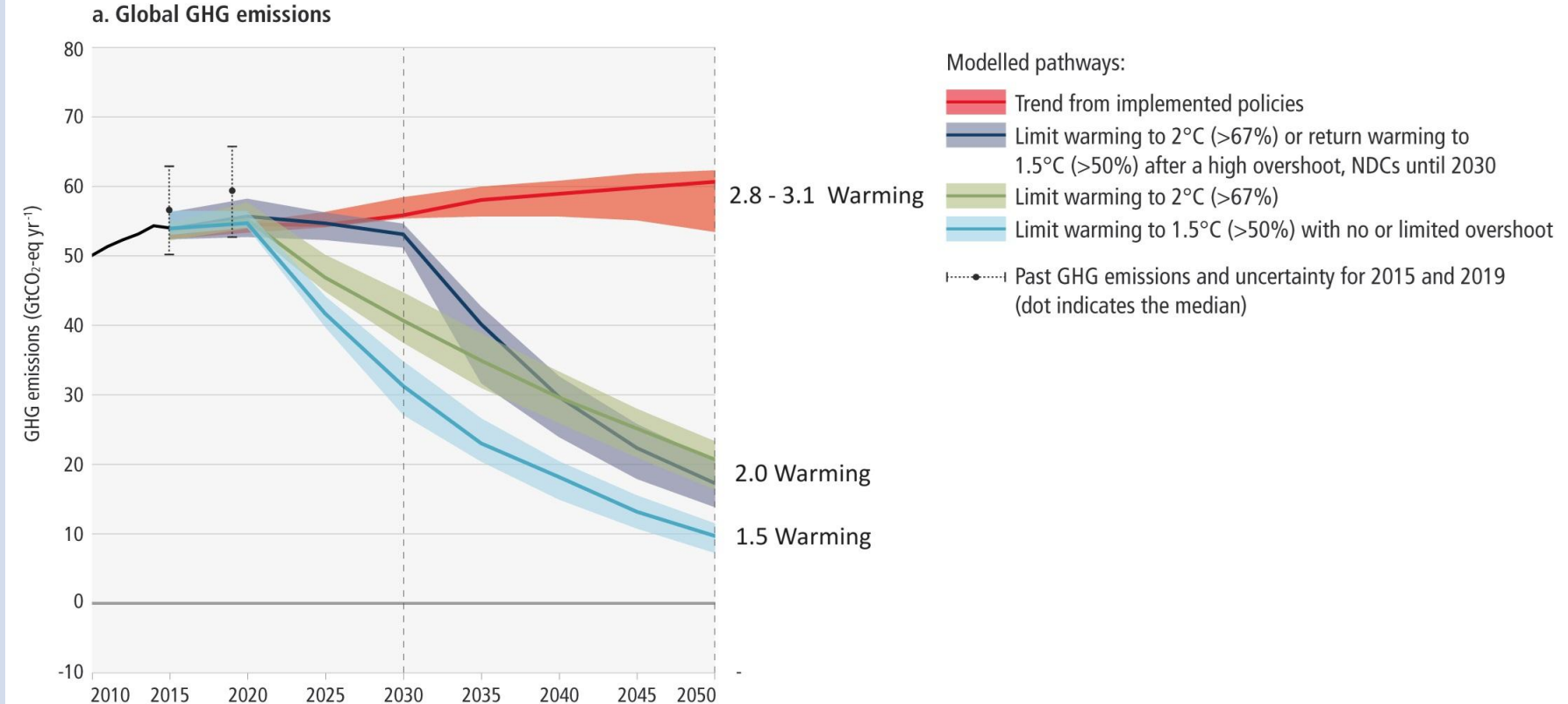


Using CESM to Assess Climate Interventions of Carbon Dioxide Removal and Solar Radiation Modification

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

COP Paris Targets – AR6 WG3 – Emissions and CDR

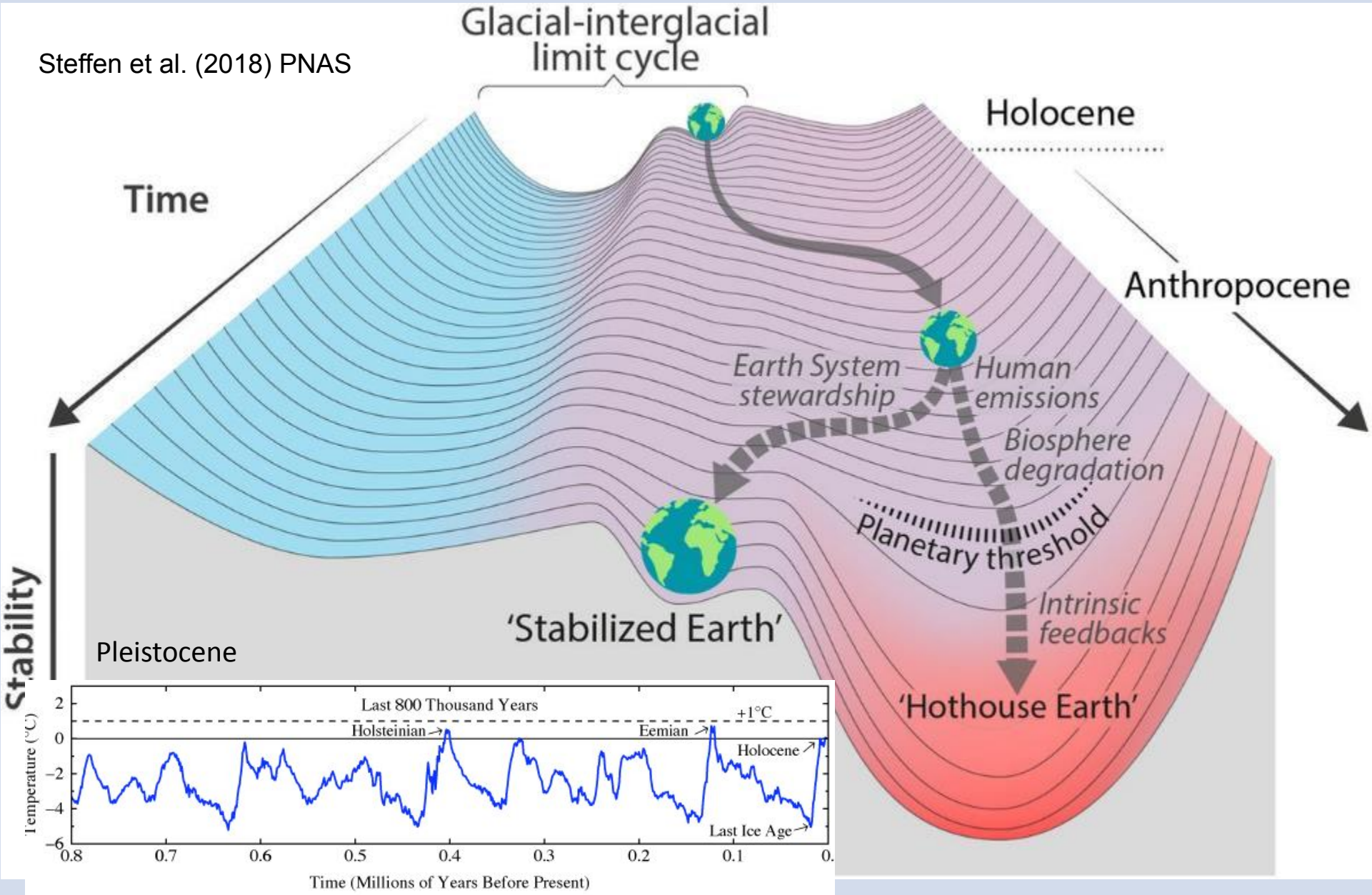


We are not on the right track to keep global surface temperatures below 1.5C

- 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 future

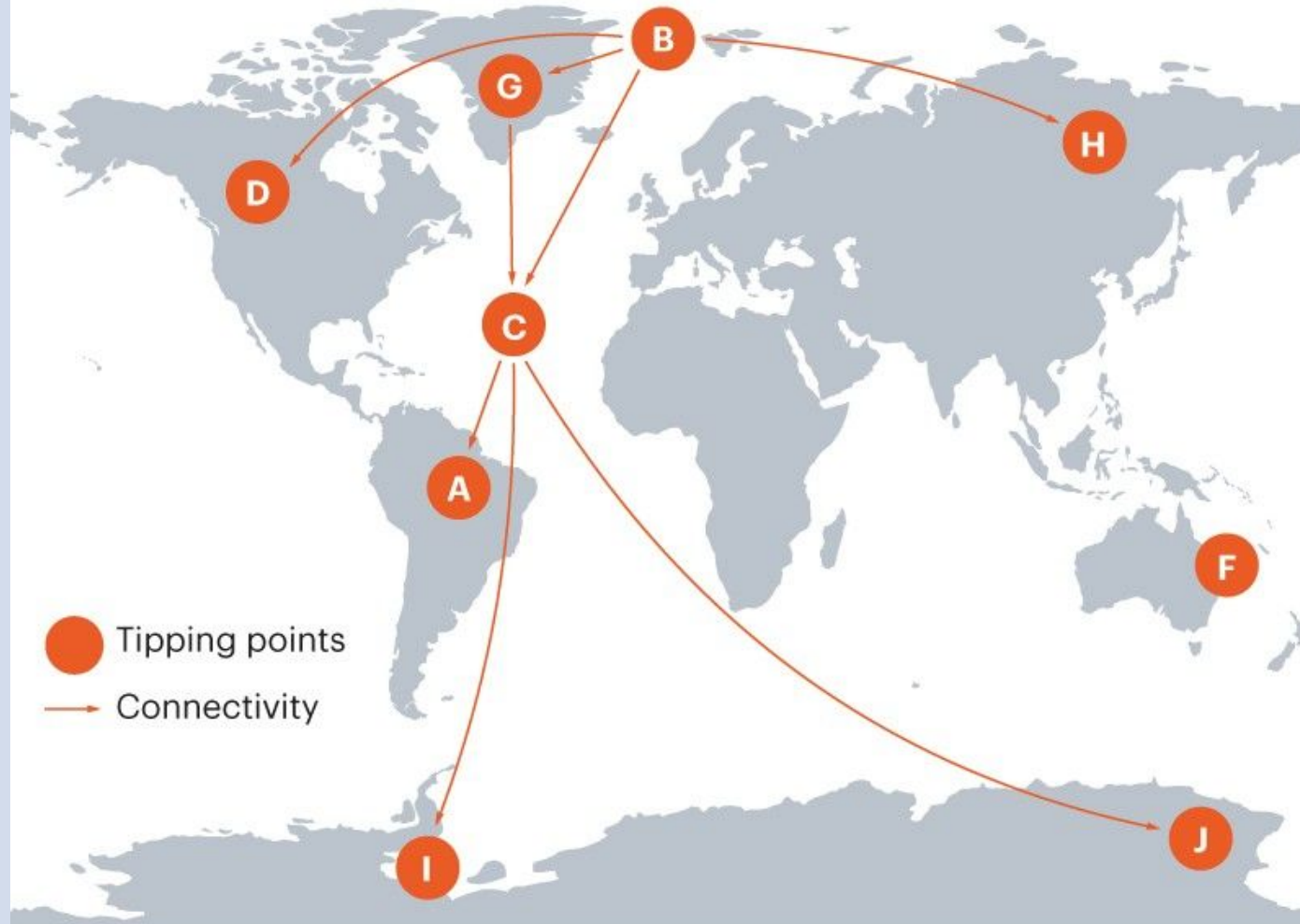
Climate Stability and Thresholds



Climate Tipping Points and Carbon Vulnerability

RAISING THE ALARM

Evidence that tipping points are under way has mounted in the past decade. Domino effects have also been proposed.



A. Amazon rainforest
Frequent droughts

B. Arctic sea ice
Reduction in area

C. Atlantic circulation
In slowdown since 1950s

D. Boreal forest
Fires and pests changing

F. Coral reefs
Large-scale die-offs

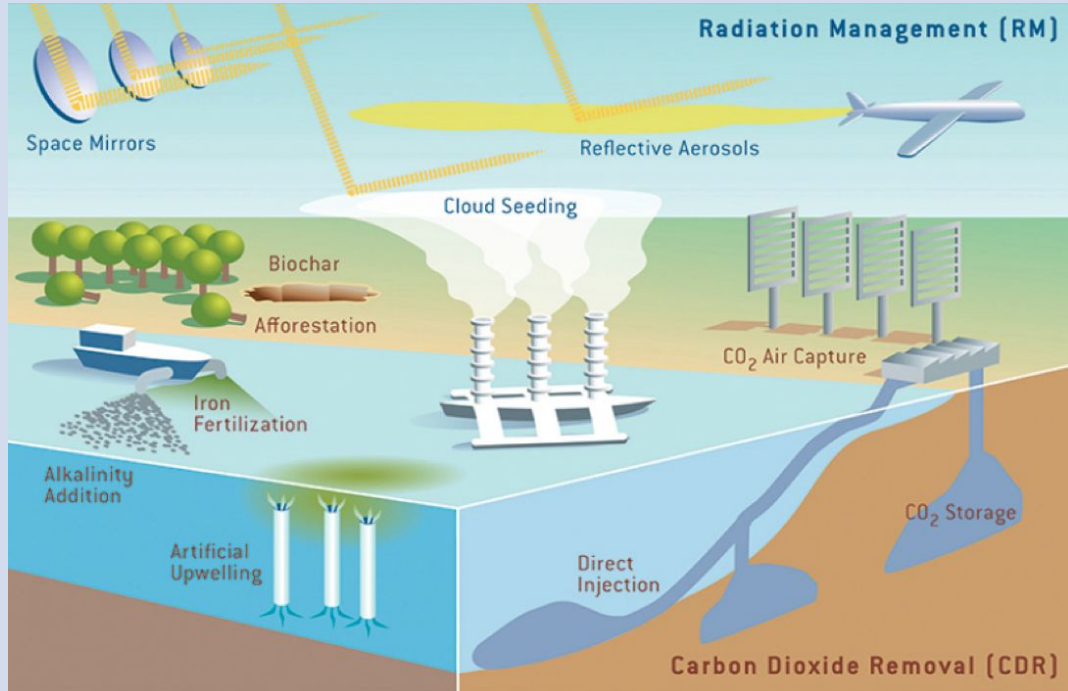
G. Greenland ice sheet
Ice loss accelerating

H. Permafrost
Thawing

I. West Antarctic ice sheet
Ice loss accelerating

J. Wilkes Basin, East Antarctica
Ice loss accelerating

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

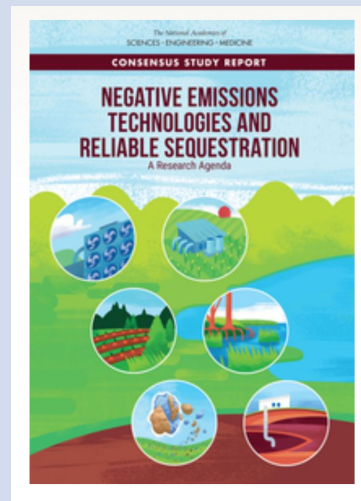
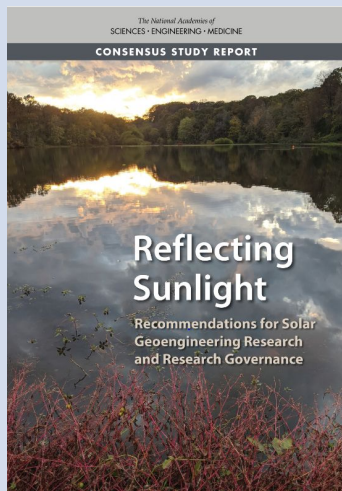
- Global Solar Radiation Modification (SRM)
- Including Stratospheric Aerosol Interventions (SAI) and Cloud Modification

Reduction of impacts and suffering

- Adaptation
- Regional SRM

National Academies of Science, Engineering and Medicine

- Reflecting Sunlight
- Negative Emissions Technologies and Reliable Sequestration





Growing Convergence Research: Award 2022 - 2027

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

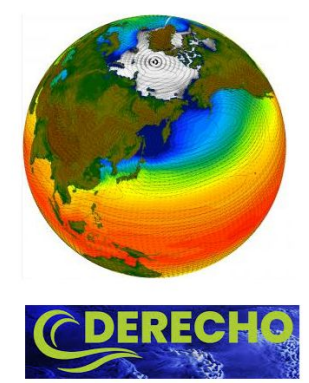
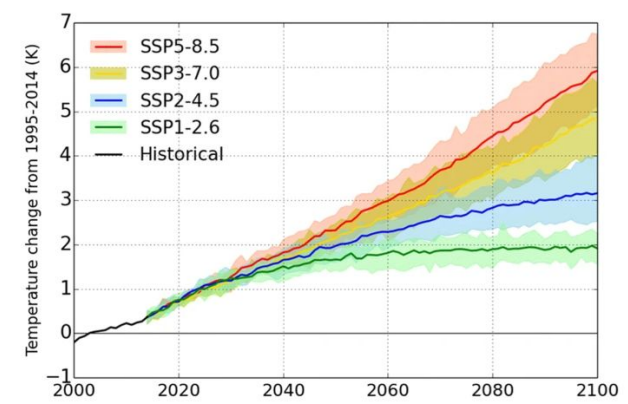
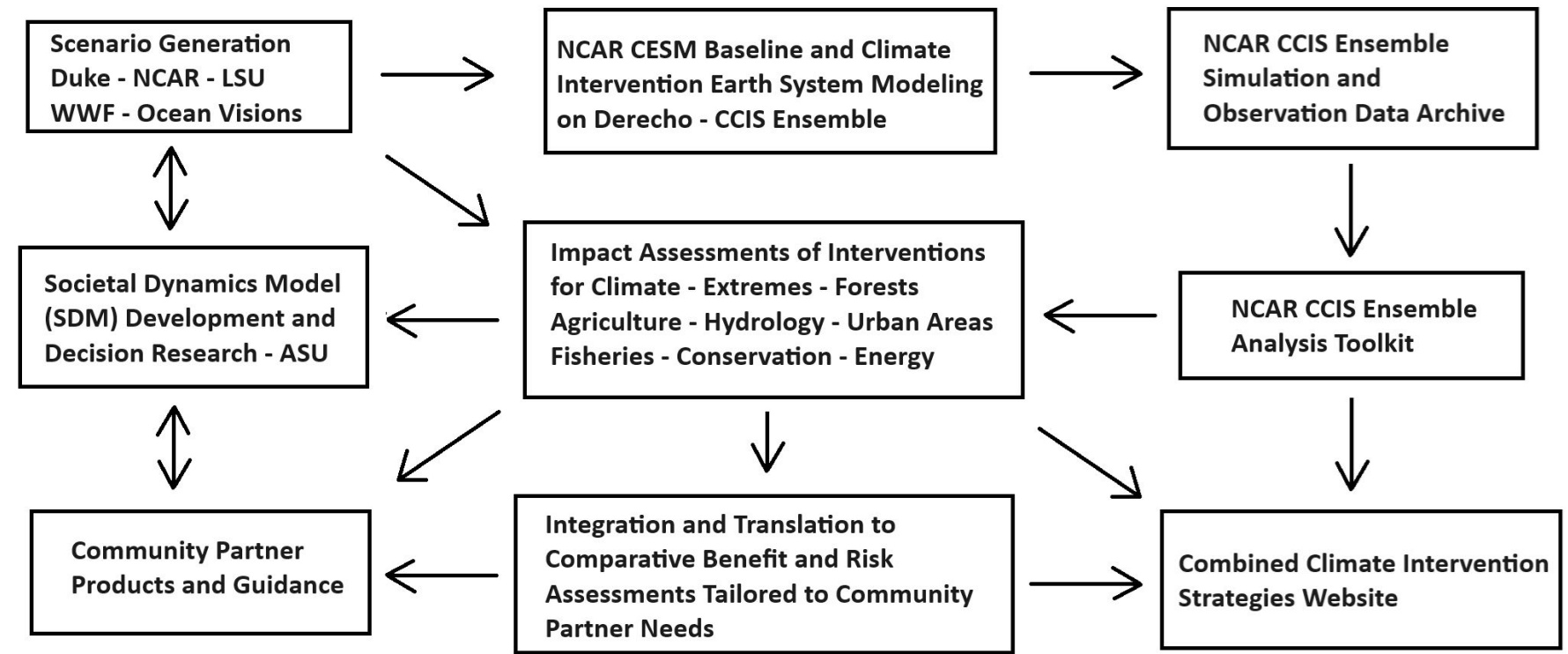
Partners: NCAR/UCAR: Peter Lawrence (Lead), Dave Lawrence, Simone Tilmes, Andrea Smith, Monica Morrison (Convergence Manager); Arizona State University: Michael Barton; Duke University: Tyler Felgenhauer; and Louisiana State University: Cheryl Harrison

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

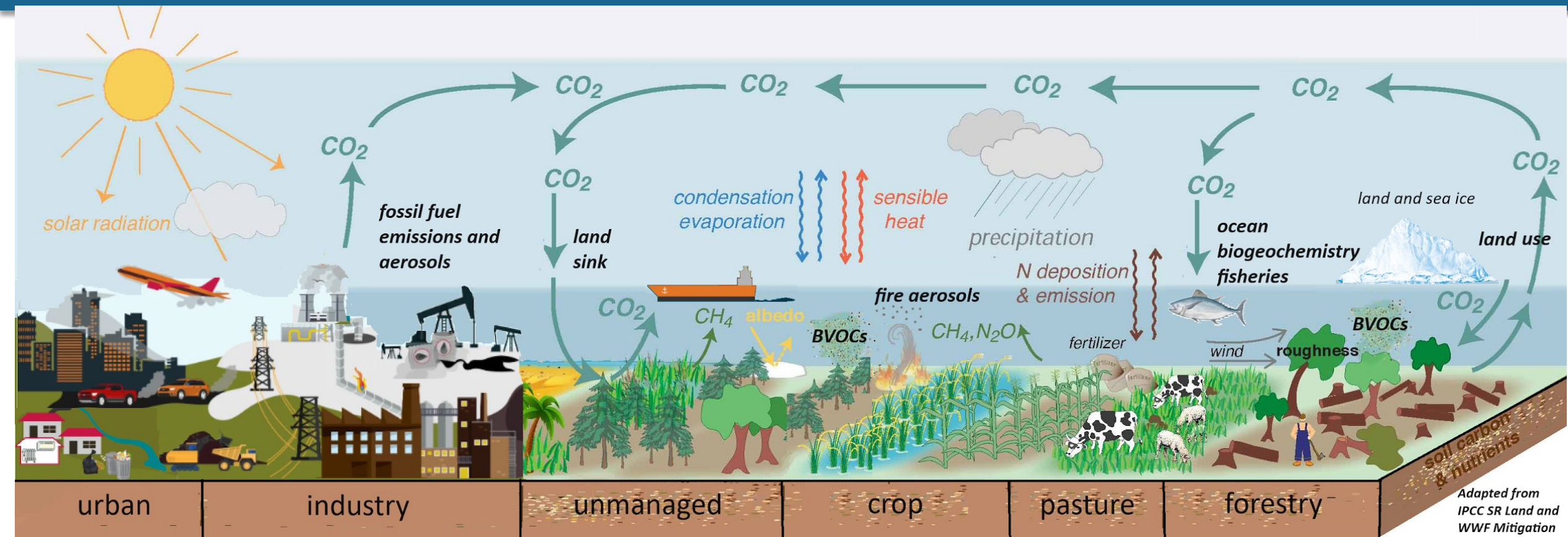
NSF GCR Program: “Supports transitioning teams from research that is multidisciplinary to research that transcends disciplinary boundaries with novel conceptual frameworks, theories and methods.”

Project Management:

- Project Activities
- Areas of Integration
- Workflow



CESM Framework Climate Interventions Impact and Management

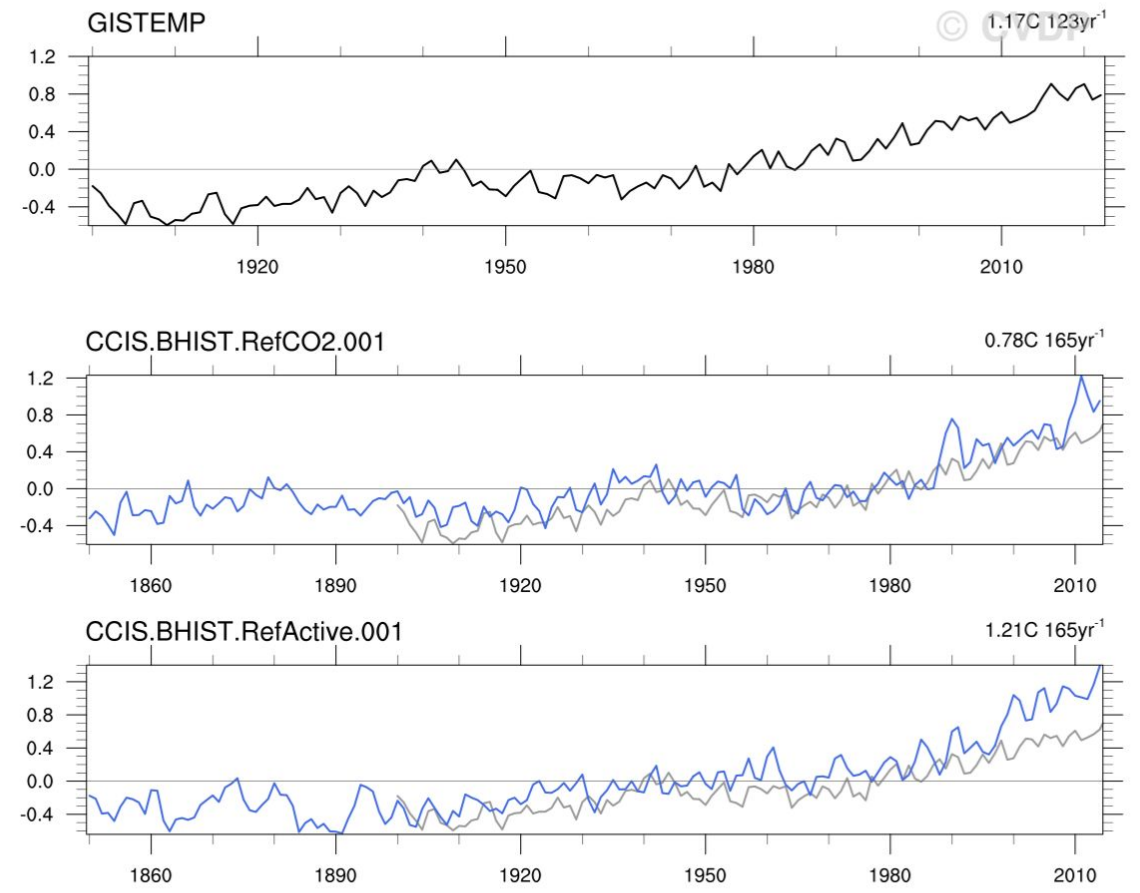
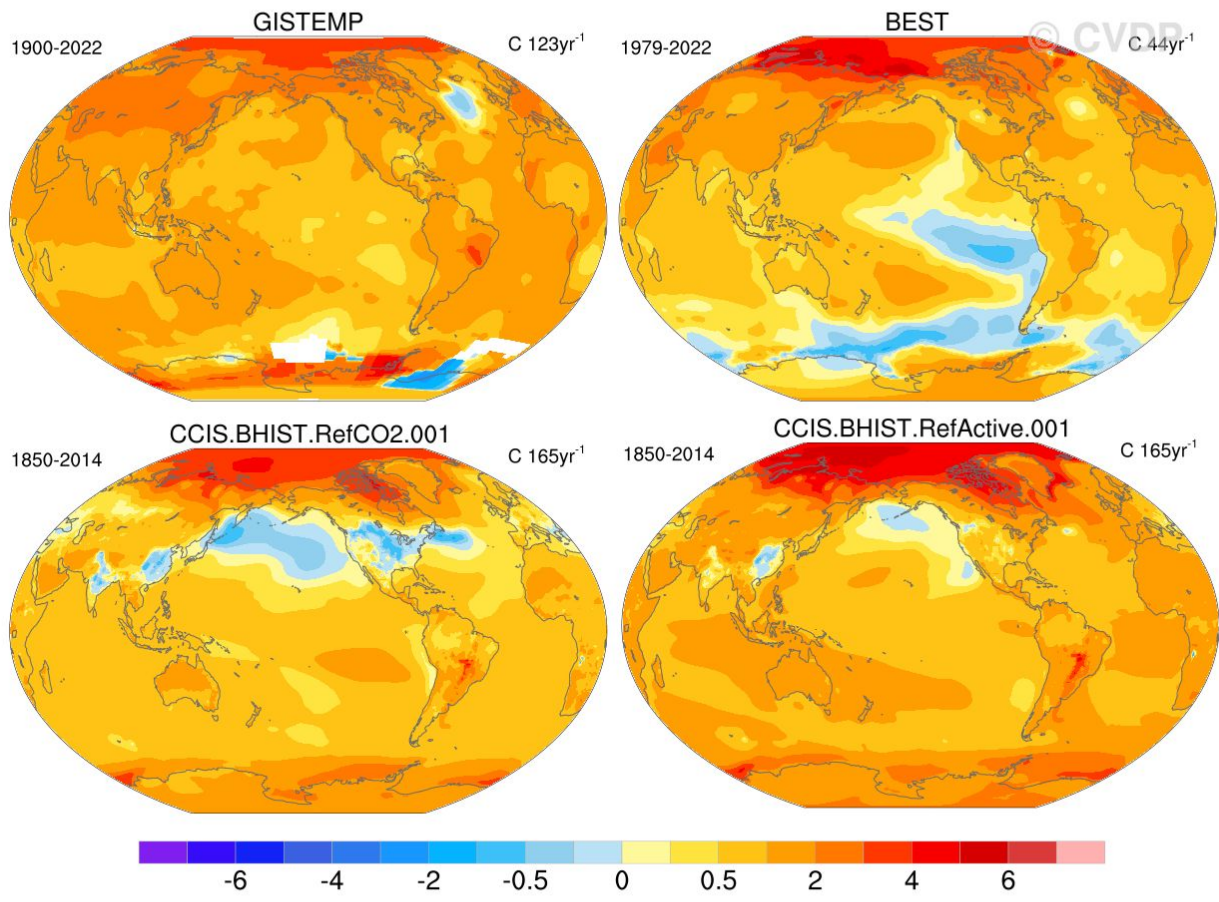


Community Climate Intervention Strategies Ensemble (CCIS Ens):

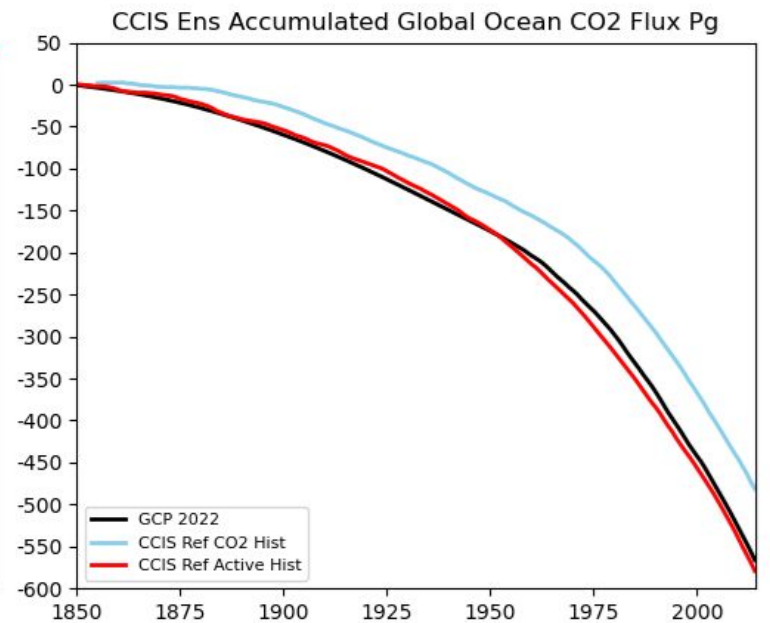
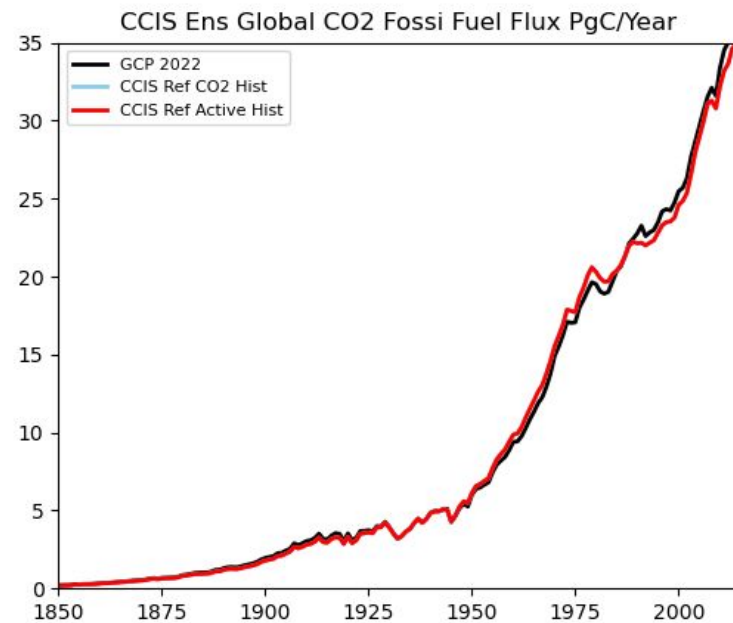
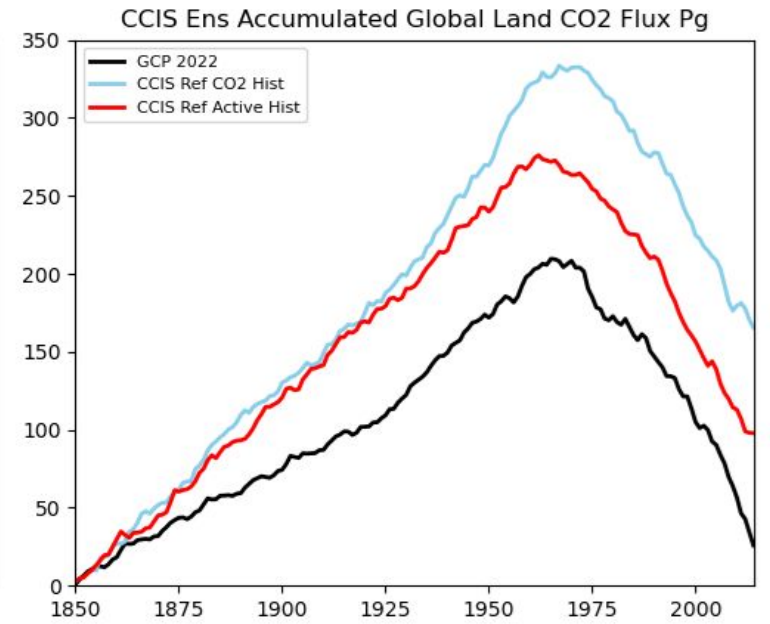
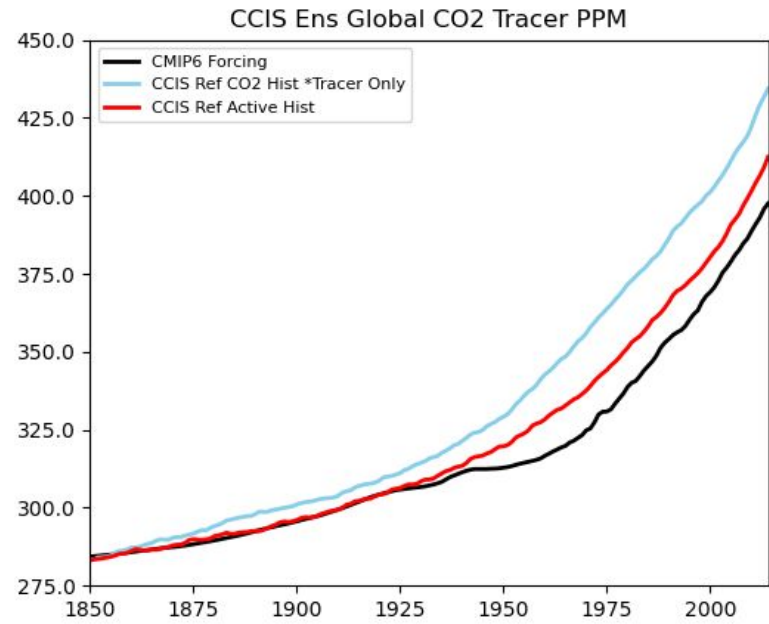
- CESM 2.1.5 (LENS2 Science) CO₂ and Aerosols dynamically modeled.
- CMIP6 Fossil Fuel CO₂, Methane, and Aerosol Emissions
- Historical, SSP 1-1.9, SSP 2-4.5 and SSP 3-7.0.
- Active Fire Aerosol Emissions
- Active Biogenic Volatile Organic Compound (BVOC) Emissions
- Marine Coccolithophores in New Ocean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

Evaluating CCIS Ensemble Historical Temperature Prescribed vs Active CO2 and Aerosols

TAS Trends (Annual)



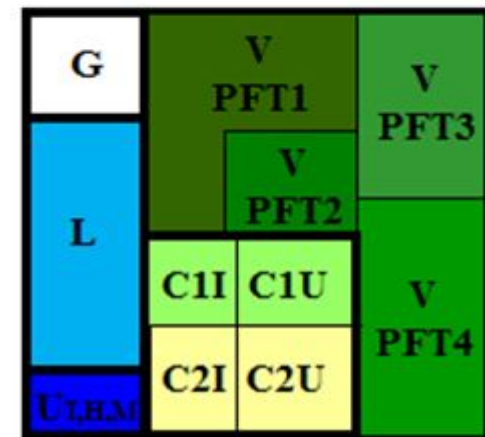
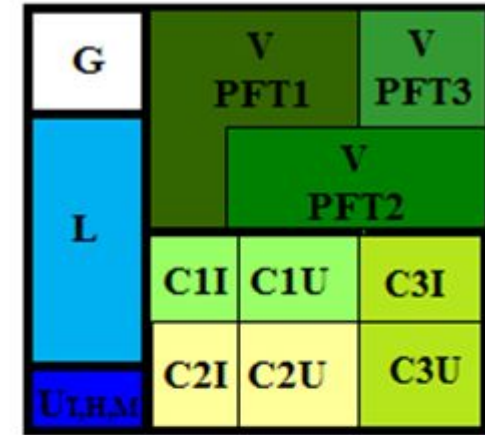
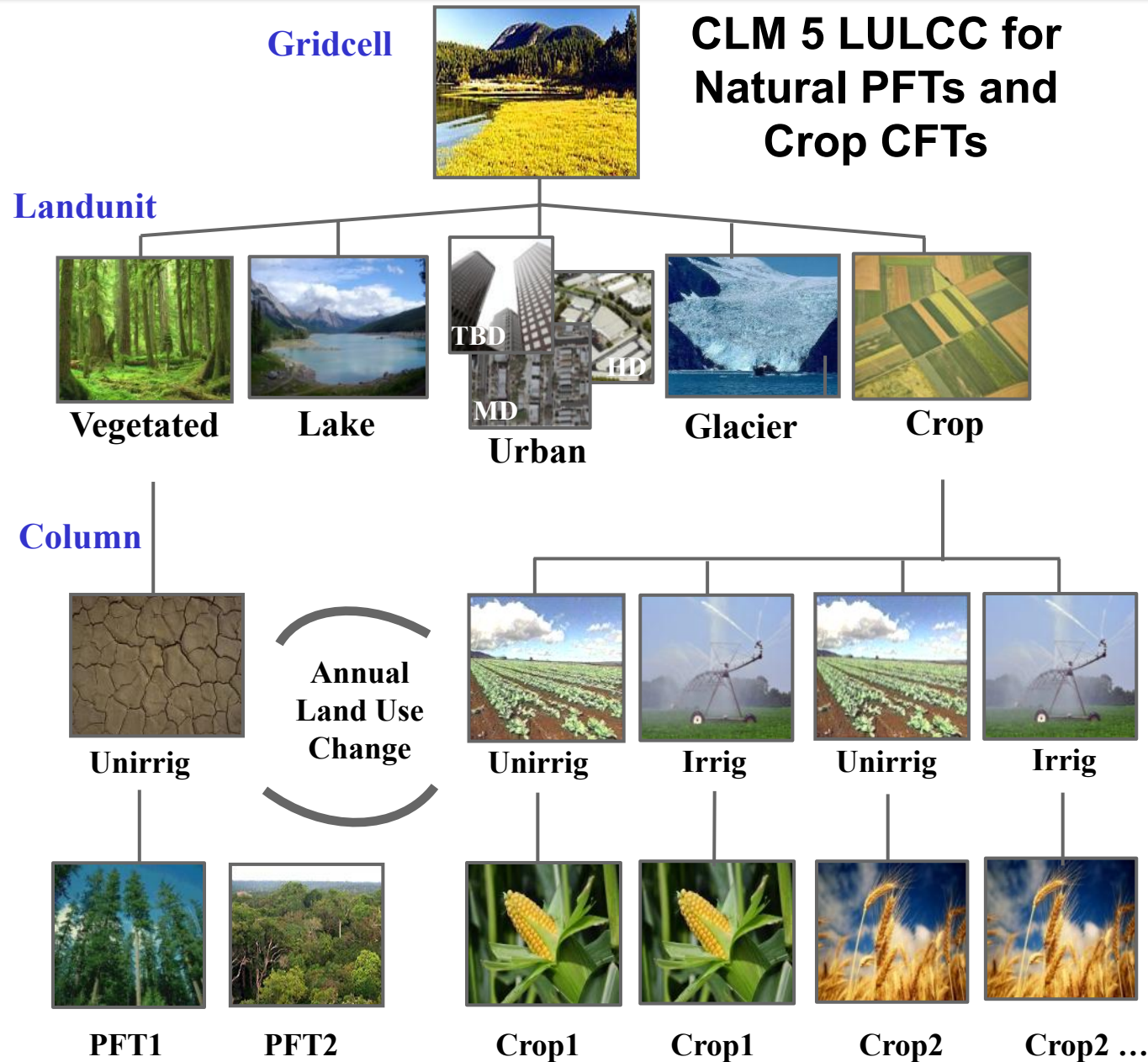
Evaluating CCIS Ensemble Historical Carbon Cycle – Prescribed vs Active CO2 and Aerosols compared to the Global Carbon Project (2022)



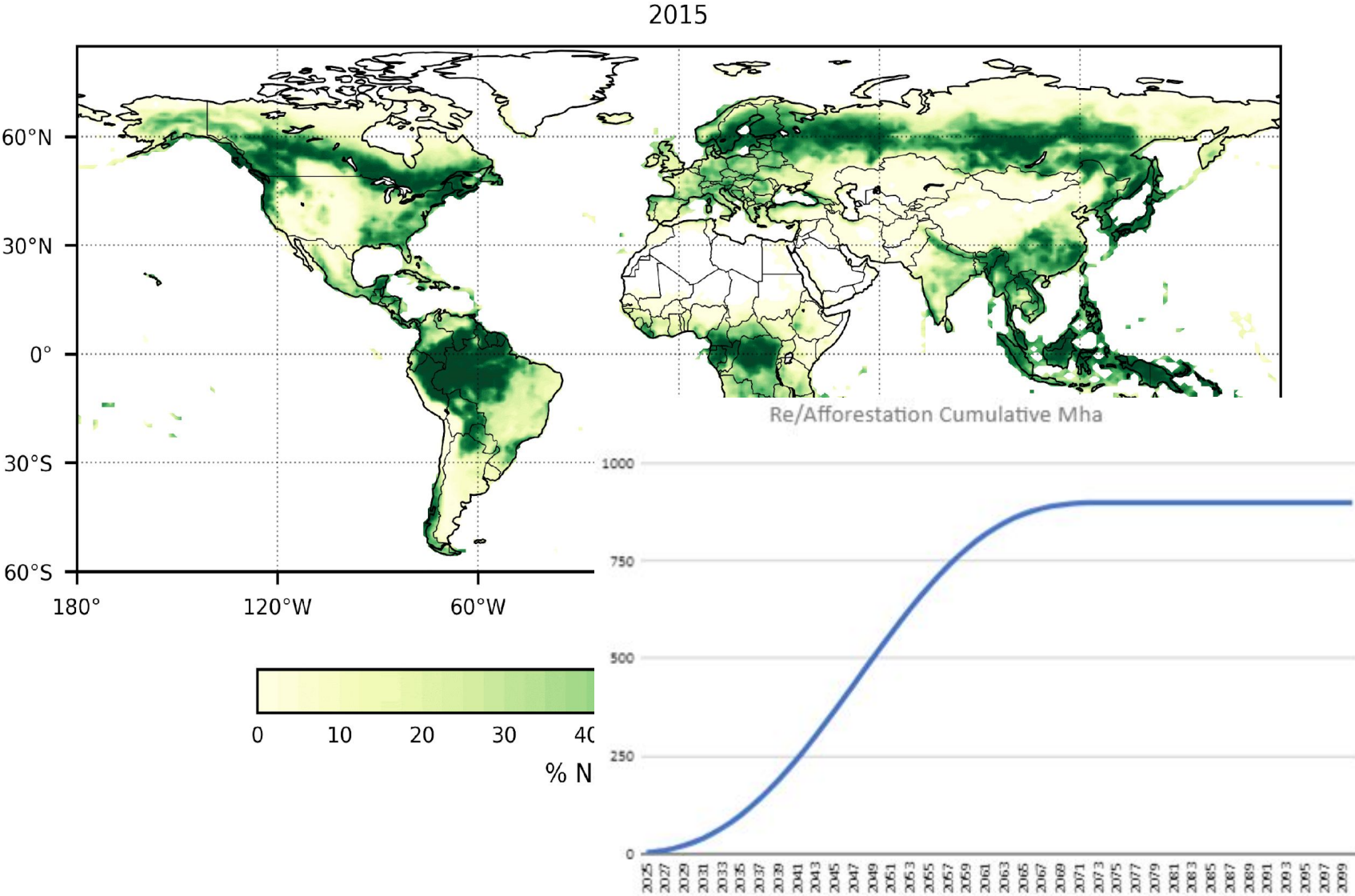
Eight climate intervention strategies

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	

CLM5 Land Cover Change – Prescribed Re/Afforestation



Maximum Afforestation within Climate and Land Use



Thanks to Stephanie Roe WWF and James King for Scenarios and Animation

Bioenergy crops added to CESM

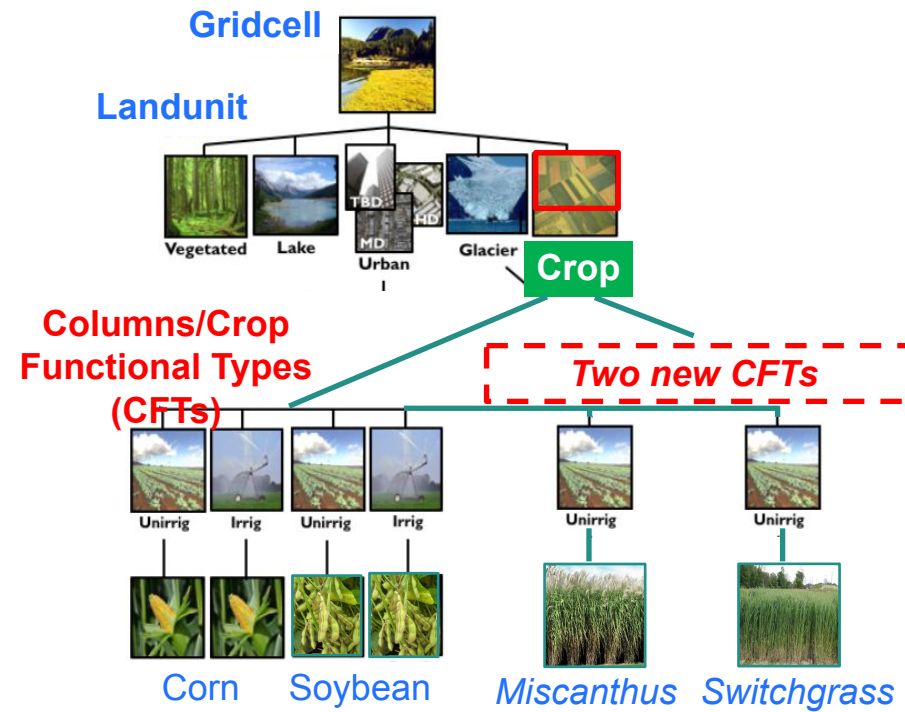
Traditional crops can be and are used as biofuel feedstocks



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

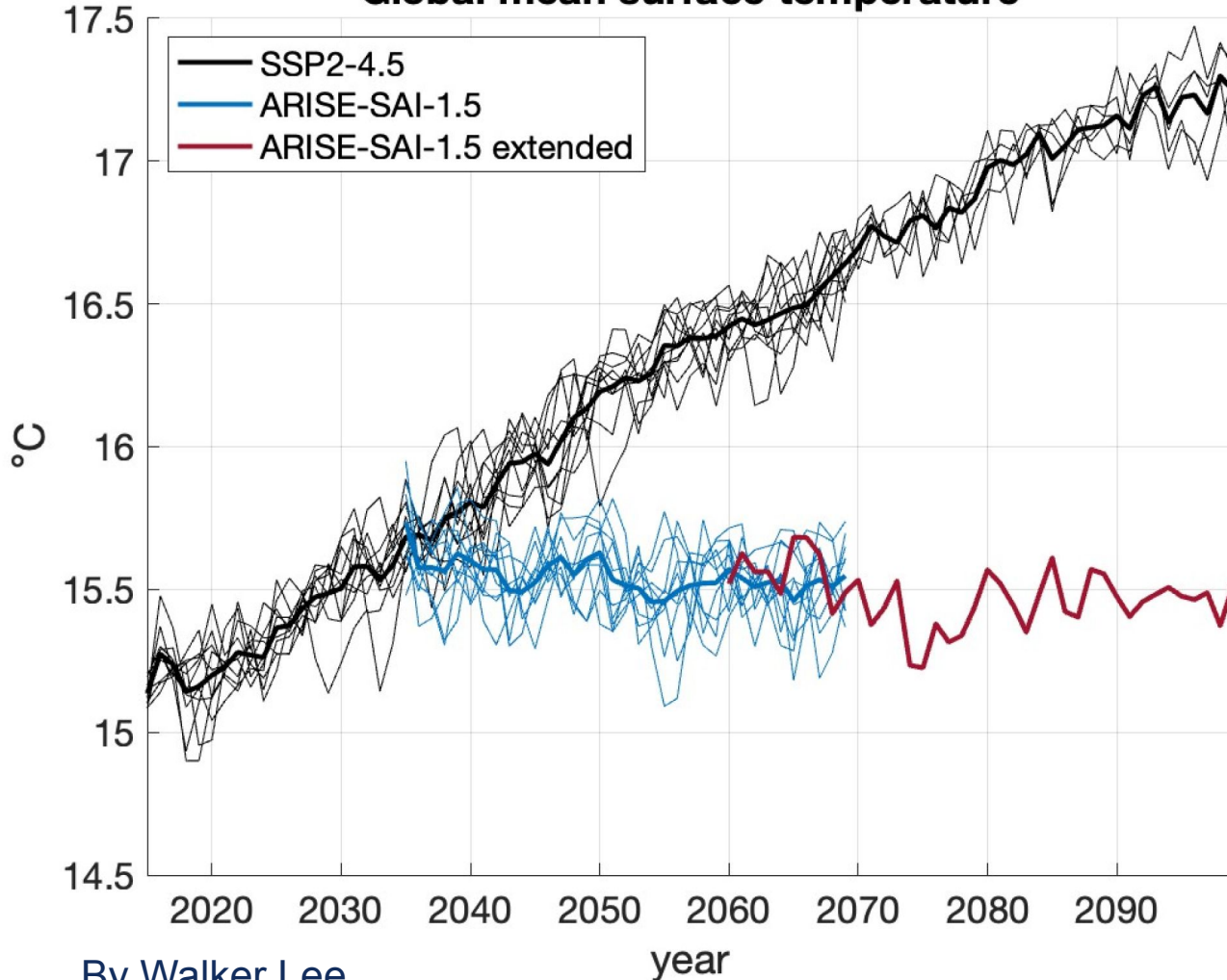
ARISE-SAI-1.5 (Richter et al, 2022)

- 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**

ARISE SAI WACCM Simulations Extended to 2100

Global mean surface temperature



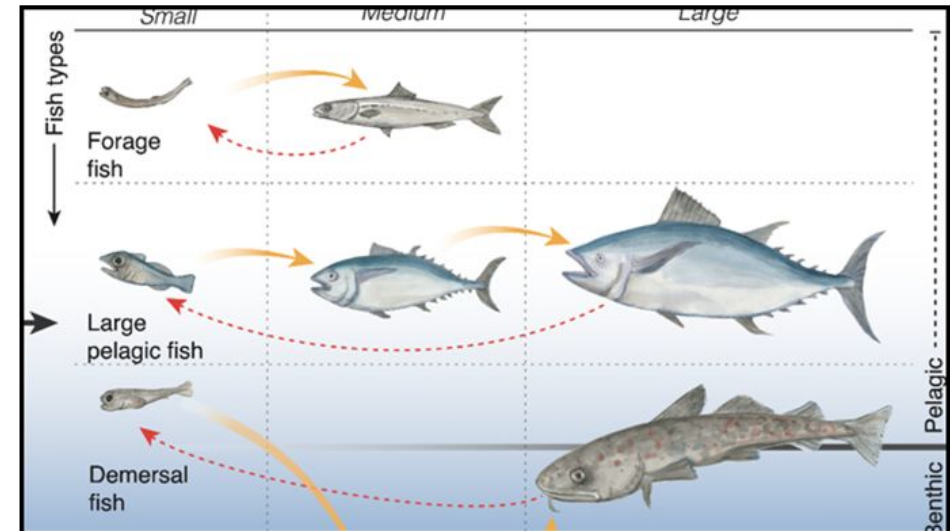
By Walker Lee

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

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



A low-angle photograph of a dense tropical forest. The image shows several large tree trunks in the foreground, some covered in moss and lichen. Sunlight filters through the thick canopy of green leaves, creating a bright, dappled light effect. The overall scene is lush and vibrant.

Thank you – Questions?

Core Research Team



Peter Lawrence
*Terrestrial Systems;
Land use*
NSF NCAR



Cheryl Harrison
*Marine Ecosystem
Impacts*
LSU



Michael Barton
*Anthropology;
Complex Systems*
ASU



Mari Tye
*Civil Engineering;
Climate Statistics*
NSF NCAR



Monica Morrison
*Philosophy of
Science and Ethics*
NSF NCAR



Simone Tilmes
*Atmospheric
Chemistry*
NSF NCAR



Tyler Felgenhauer
*Policy and
Governance*
Duke



David Lawrence
*Earth System
Modeling*
NSF NCAR



Andrea Smith
*Communication and
Outreach*
COMET UCAR

Stakeholder Communities and Representatives



WWA



Workshops



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

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.