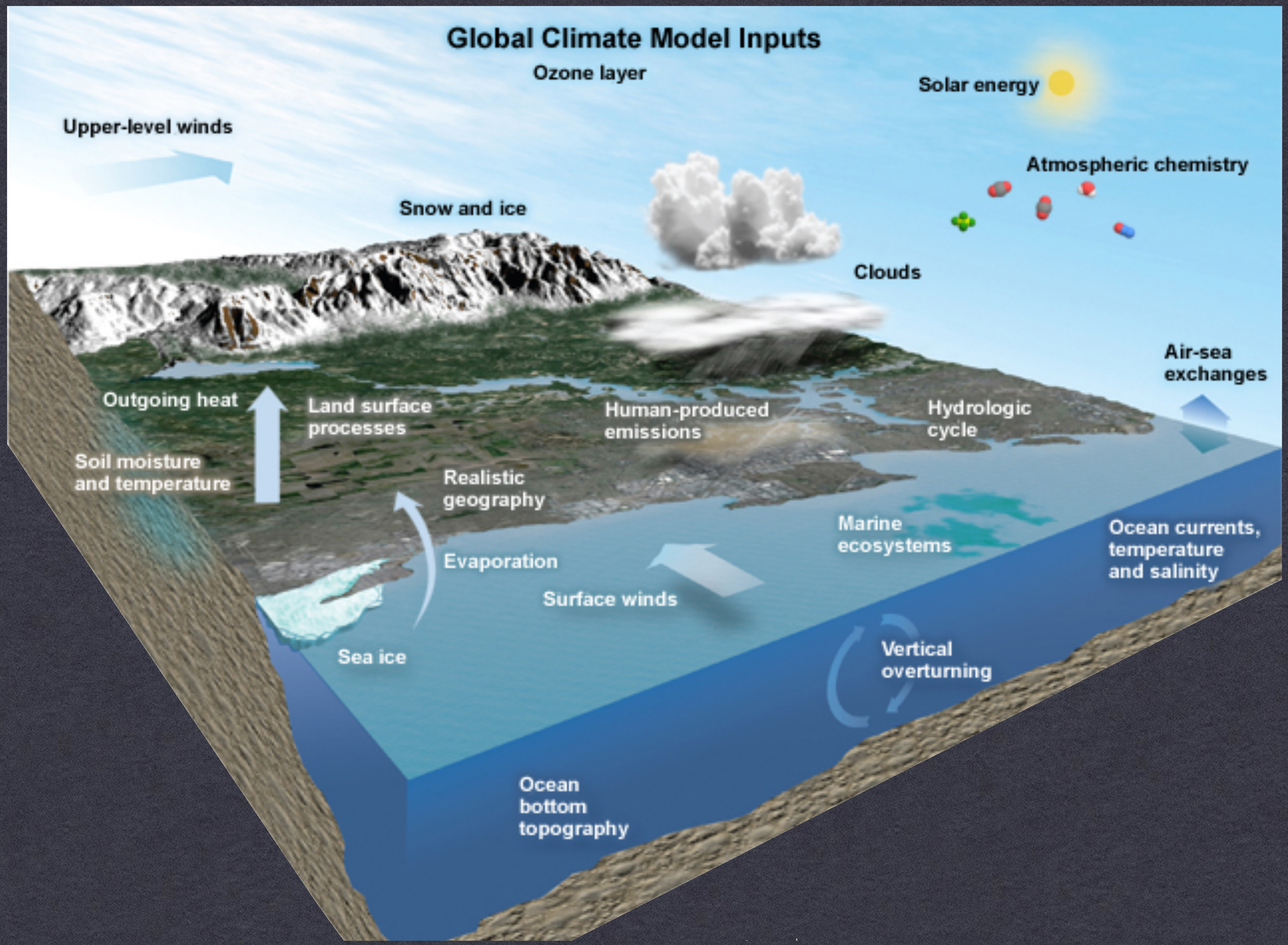


MIND THE GAP

HUMAN SYSTEMS ARE A MISSING, CRITICAL COMPONENT FOR EARTH SYSTEMS MODELING

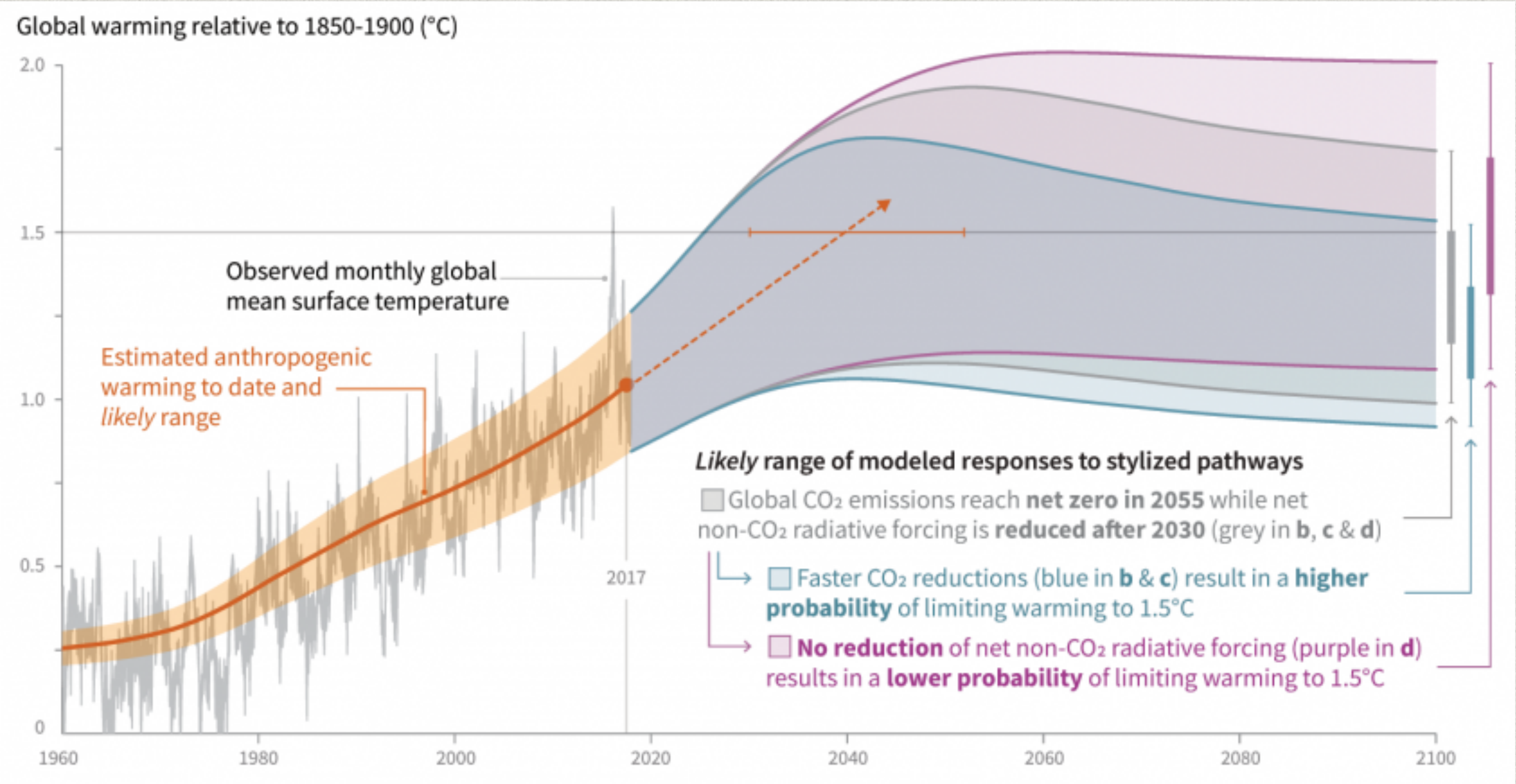
Michael Barton, Manuela Vanegas Ferro, & Scott Foster, Arizona State University

30 Years of Earth Systems Modeling

- A science success story
- No longer just a computer tool for a few nerdy scientists

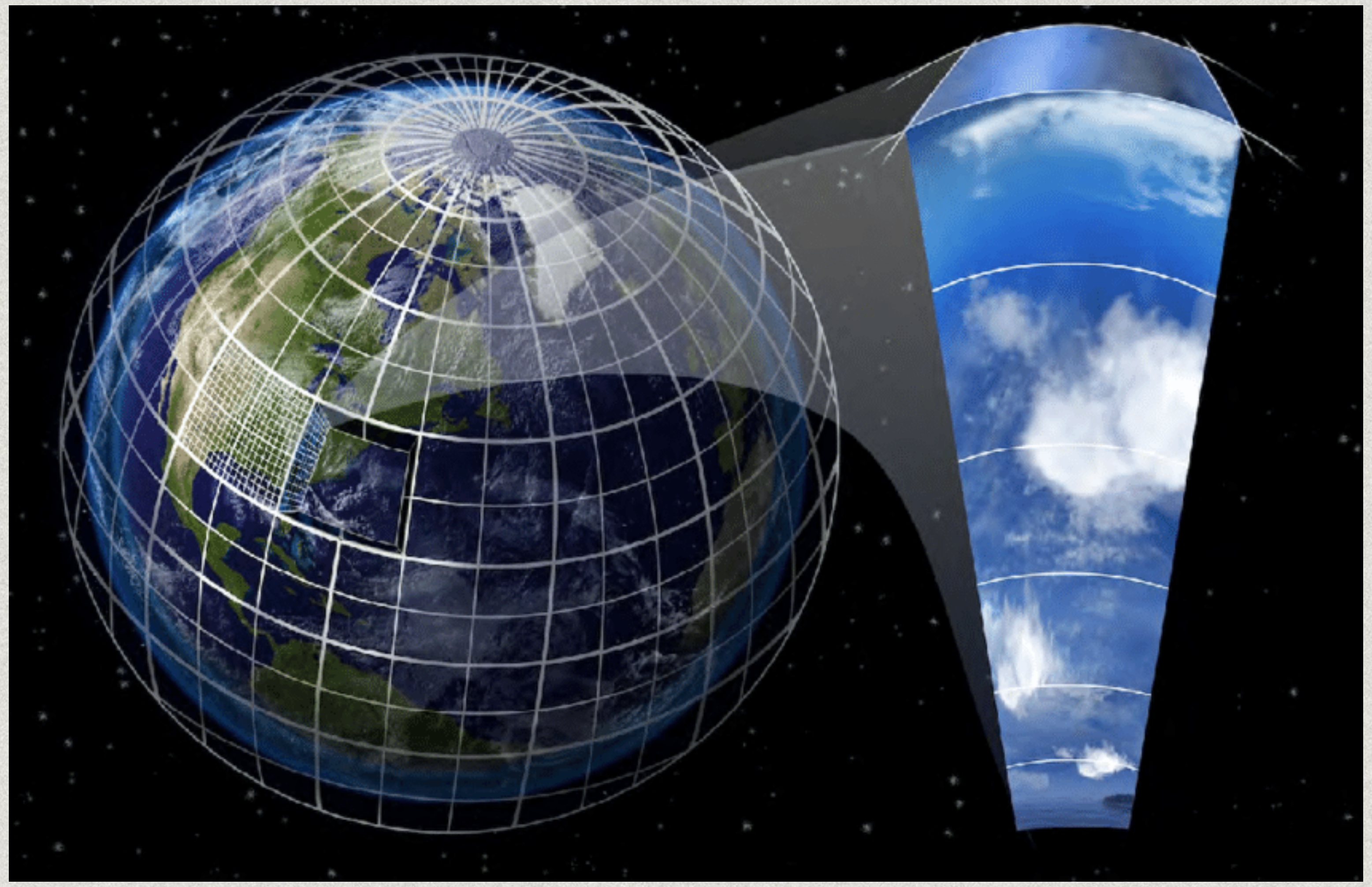
30 Years of Earth Systems Modeling

- A science success story
- No longer just a computer tool for a few nerdy scientists
- Growth from modeling the atmosphere to modeling Earth systems
- Now informing a wide range of global science and policy



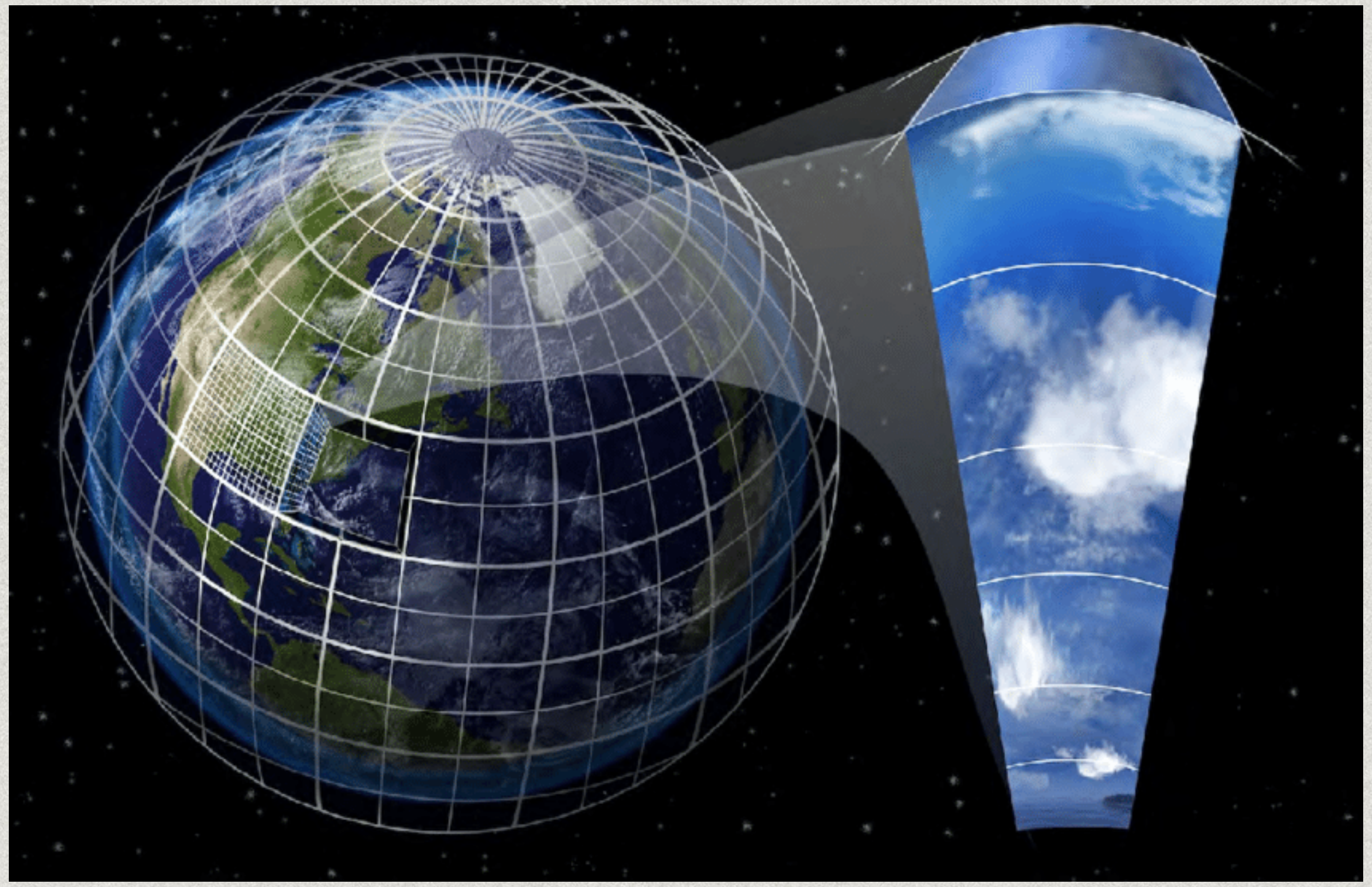
Atmosphere to Earth System

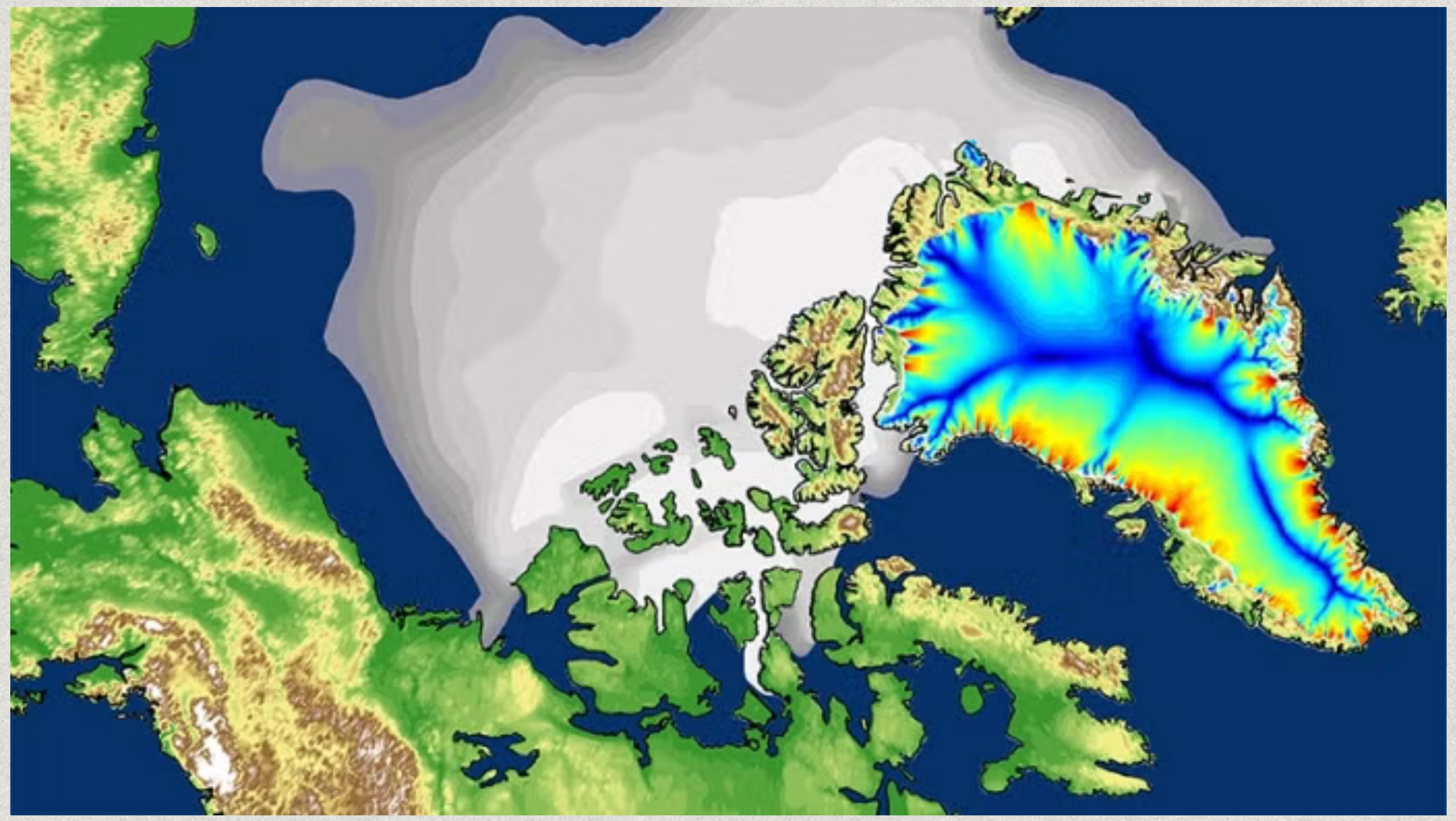
- CESM began as a simulation of atmospheric physics and chemistry: CCSM/CAM
- Why did an atmosphere/climate model evolve into an Earth system model?



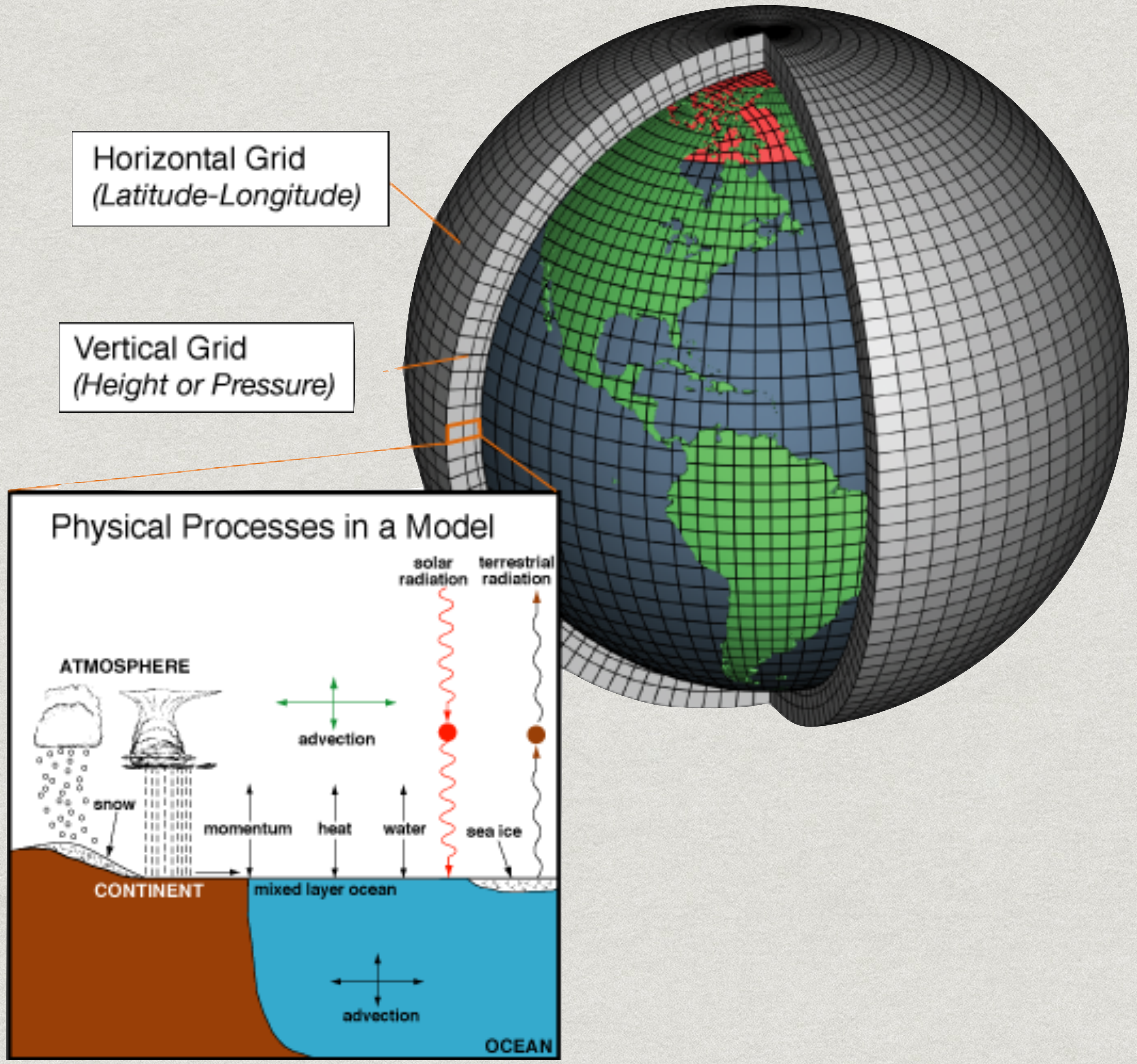
Atmosphere to Earth System

- CESM began as a simulation of atmospheric physics and chemistry: CCSM/CAM
- Why did an atmosphere/climate model evolve into an Earth system model?
- Recognition that dynamics of the atmosphere are influenced in important ways by interactions and feedbacks with other components of Earth's critical zone
    - Ocean surface and subsurface
    - Land, including vegetation and biogeochemistry more broadly
    - Land and sea ice





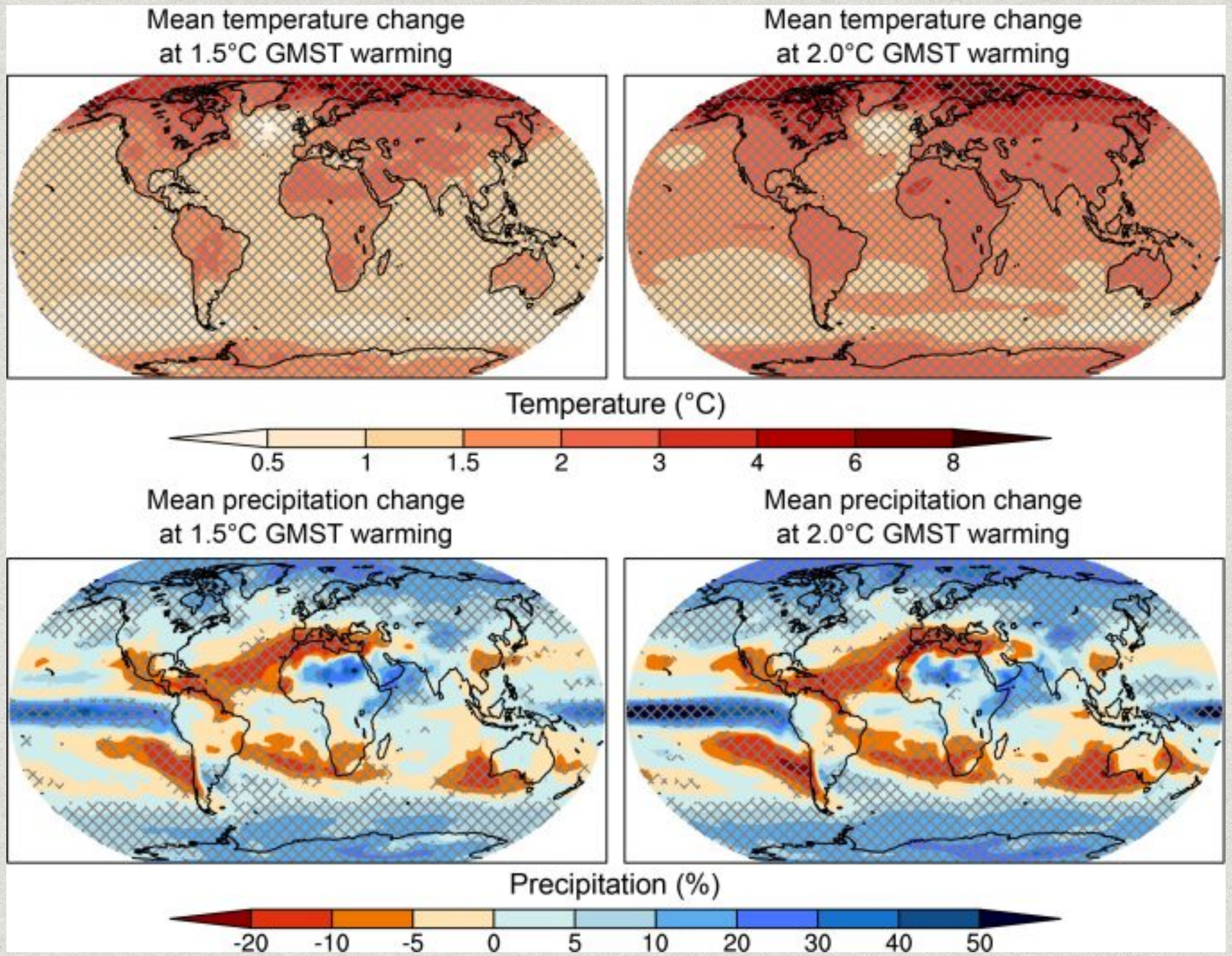
Incomplete and Useful Models

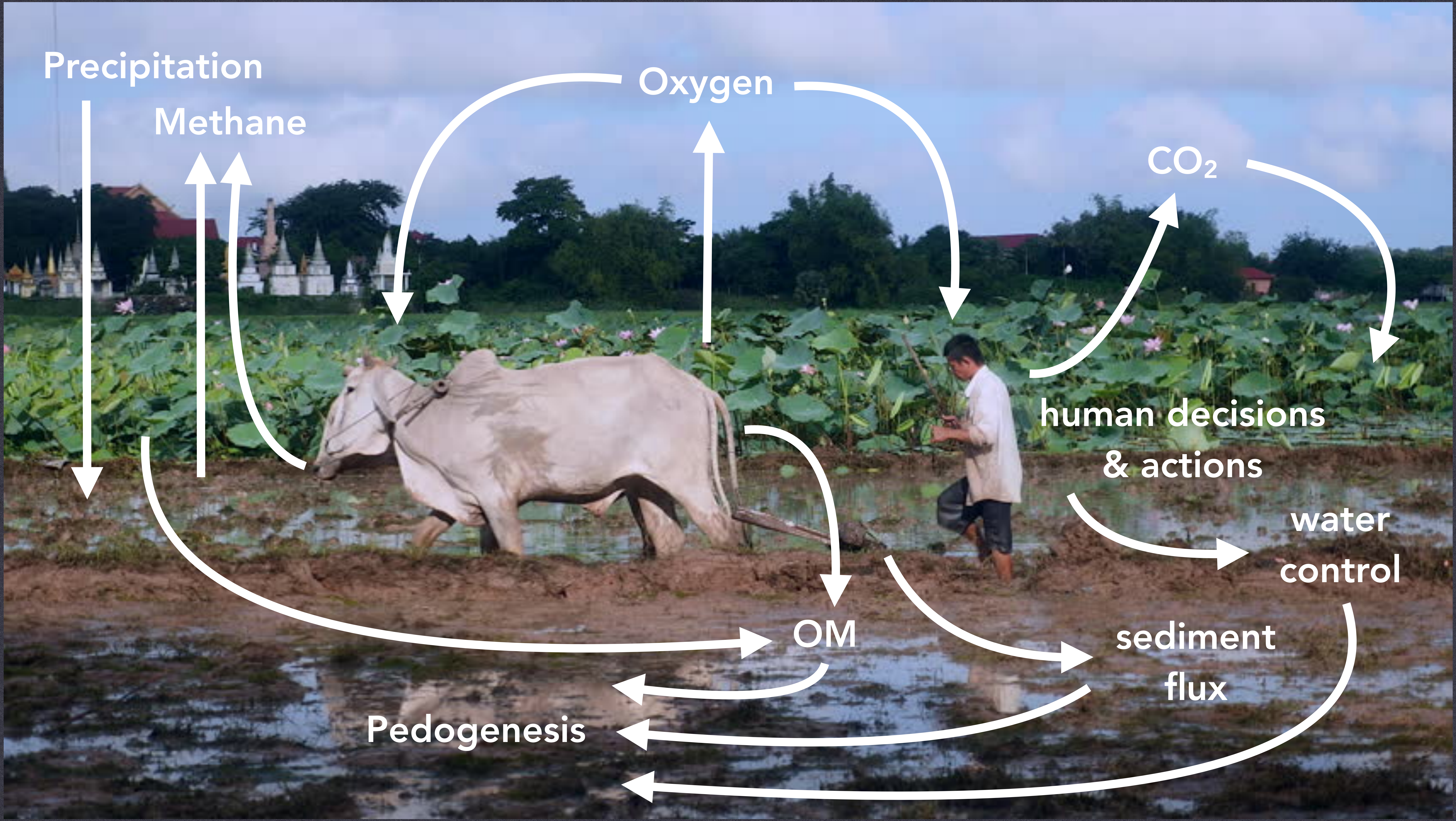


- But how many here are confident that we fully understand and model <u>all</u> the important processes of Earth systems?
  - After more than 2 centuries of scientific study we still do not fully understand all the processes of atmospheric circulation.
  - And we cannot (or choose not to) model all the processes we do understand
  - Equally the case for ocean physical circulation and thermal properties, or its biogeochemistry. And the same for terrestrial biogeochemistry
- In spite of these shortcomings, the CESM modeling environment has still proven very useful for understanding the past, present, and potential futures of Earth's critical zone

CESM for Science and Policy

- Developing and running simulations has made important contributions to scientific understanding of atmosphere dynamics
- Even more significantly, it has demonstrated and modeled impacts of anthropogenic GHG on current and future climate
- CESM also used to assess impacts of anthropogenic climate change on food production, human health, urban heat, built environment and infrastructure, human migration, to name but a few.
- Like atmosphere, oceans, land, and ice, there are significant feedbacks between human society and all other components of Earth systems–but not modeled dynamically in CESM

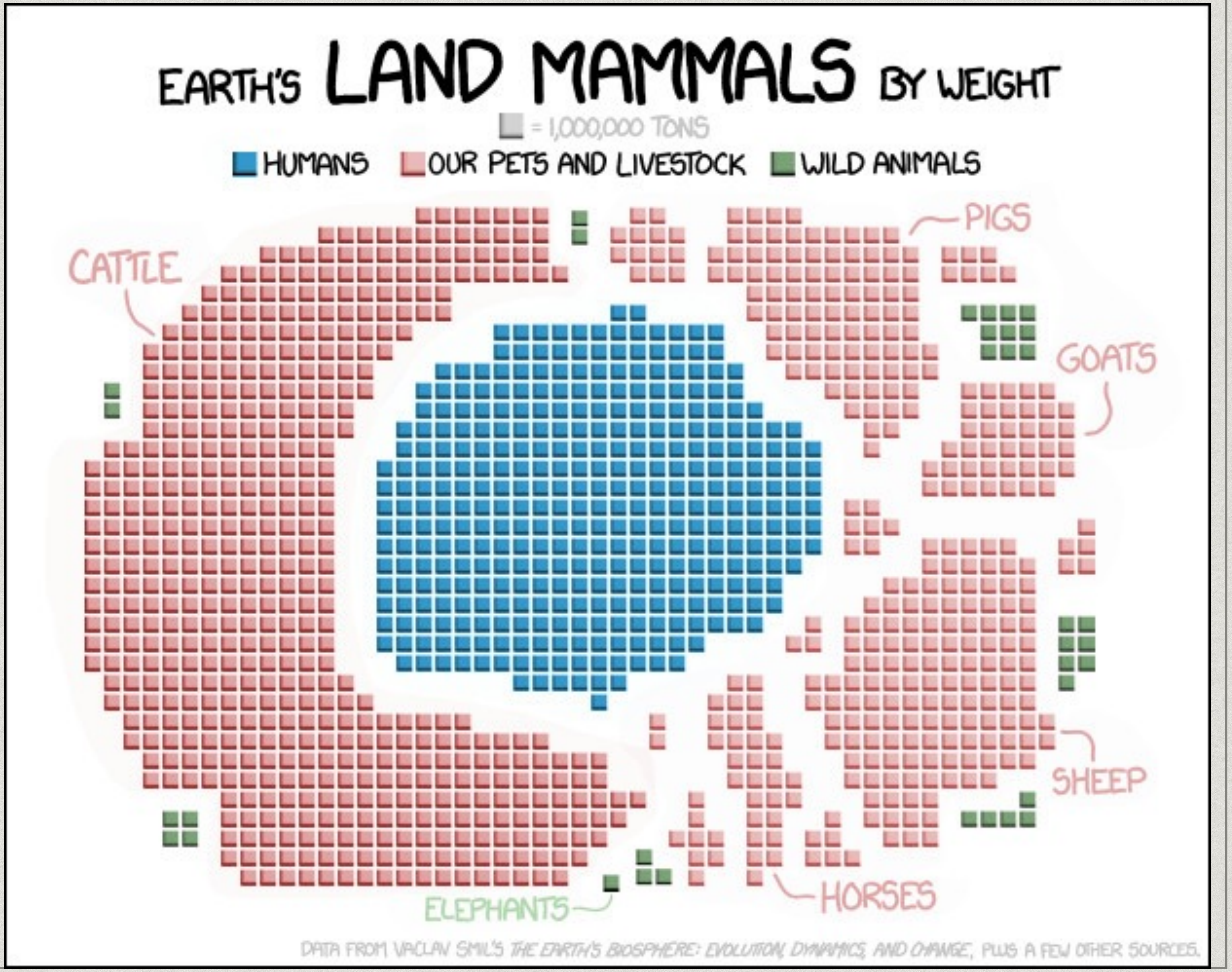




THE EARTH SYSTEM IS A DYNAMICALLY COUPLED HUMAN/NATURAL SYSTEM

A Coupled Human/Natural System

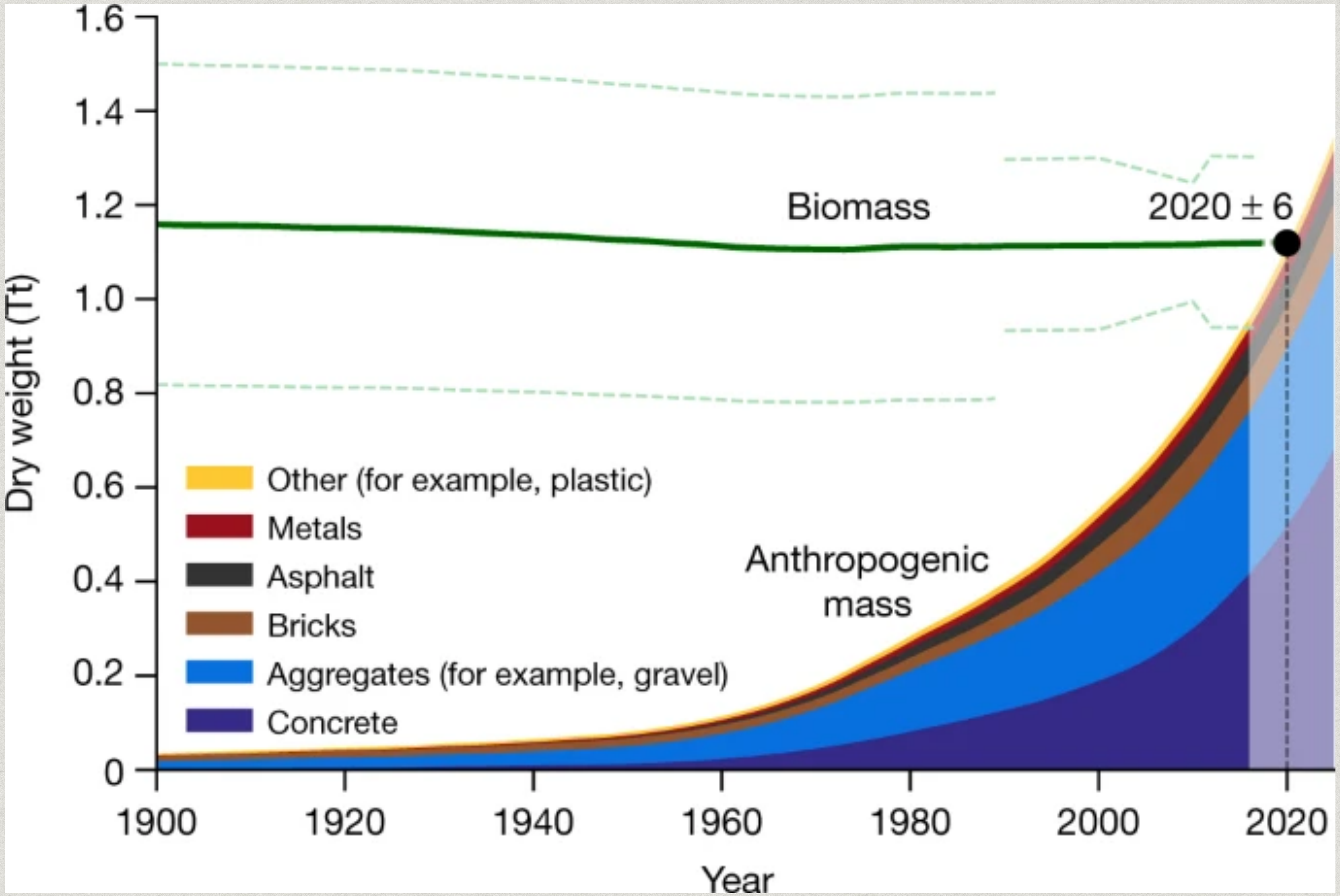
- Mass of humans plus domestic animals greater than all terrestrial vertebrates combined.
- Humans plus agro-biomass >3 billion tons. More than all other vertebrates combined (land and sea)



(Bar-On, et al 2018; Munroe 2014)

A Coupled Human/Natural System

- Human created mass (including all constructions) exceeds all of the planet's biomass
- Human produced energy nearing total planetary NPP
  - Humans energy production ~1.8 x 10^{10} Tj/yr
  - Total planetary NPP ~2 x 10^{12} Tj/yr of energy



(Elhacham, et al 2020; Ritchie et al 2024; Schramski et al 2015)

A Coupled Human/Natural System

- > 45% of all habitable land in crops or pasture

(Ritchie and Roser 2019; 2021)

A Coupled Human/Natural System

- > 45% of all habitable land in crops or pasture
- > 30% of all forests cleared in the Holocene; more cleared and reforested

(Ritchie and Roser 2019; 2021)

A Coupled Human/Natural System

- Coastlines engineered

(Khokhar 2017; Vitousek et al 1997; Wilkinson 2005)

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- > 70% of available fresh water used for human food production

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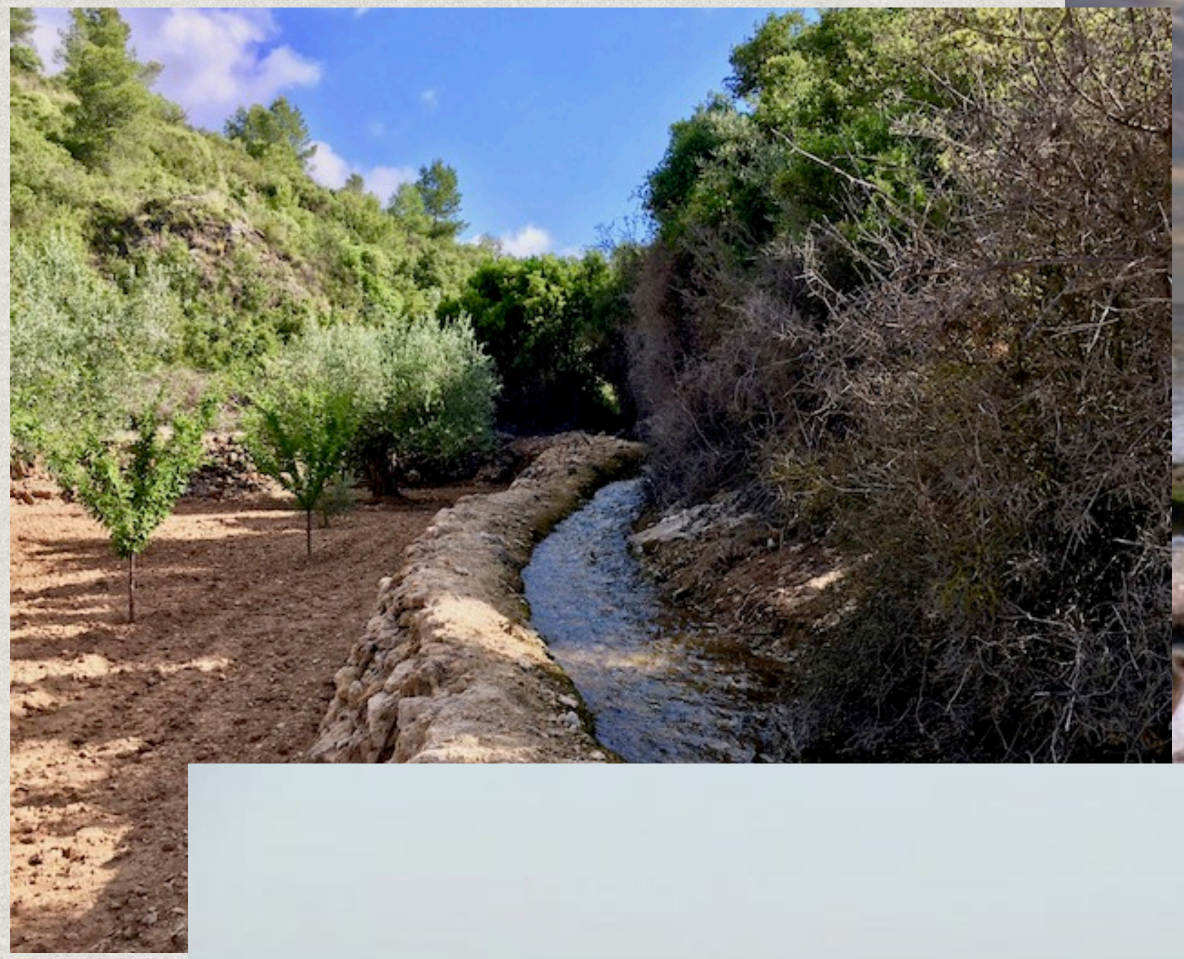
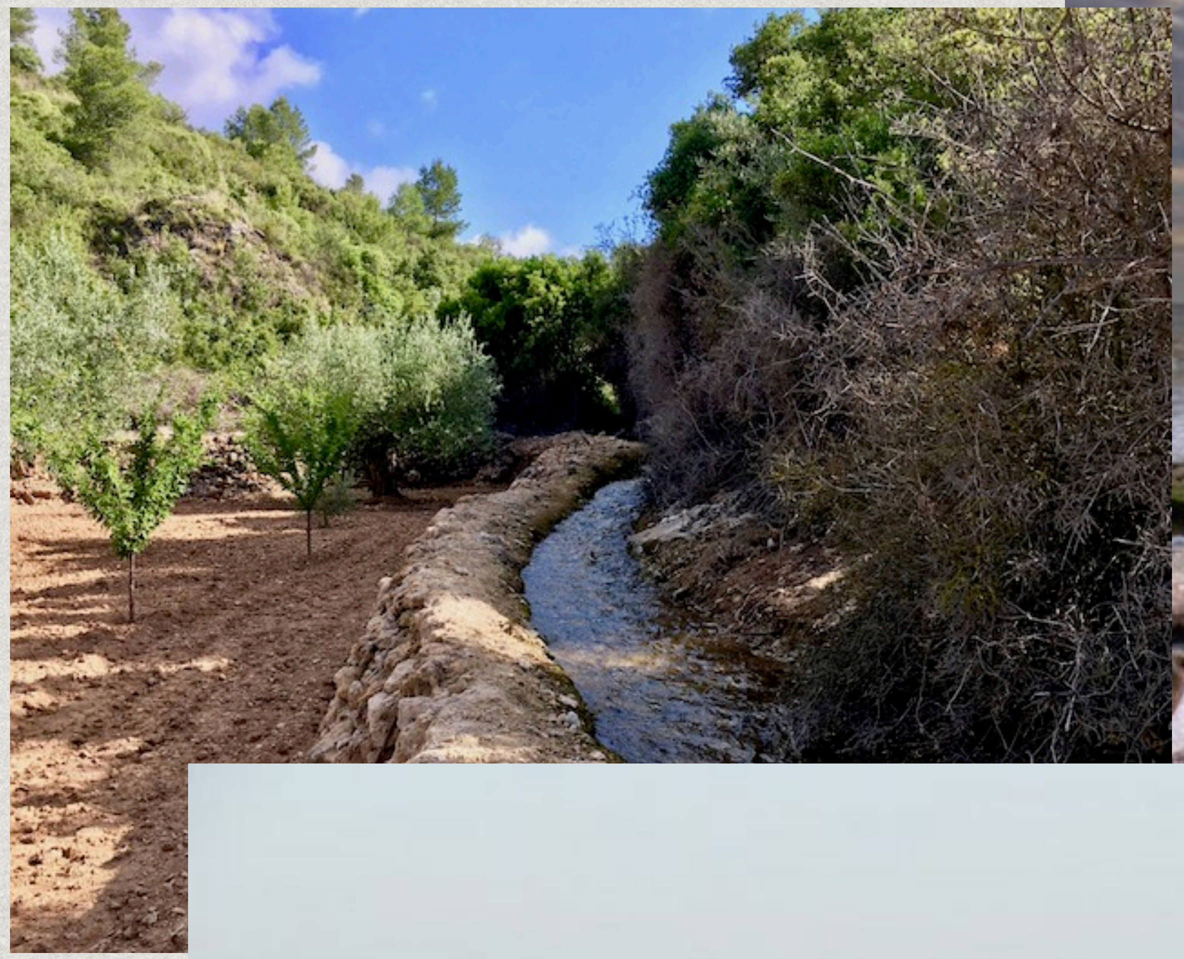
- > 70% of available fresh water used for human food production
- N cycled by human processes ≥ non-human processes



(Khokhar 2017; Vitousek et al 1997; Wilkinson 2005)

A Coupled Human/Natural System

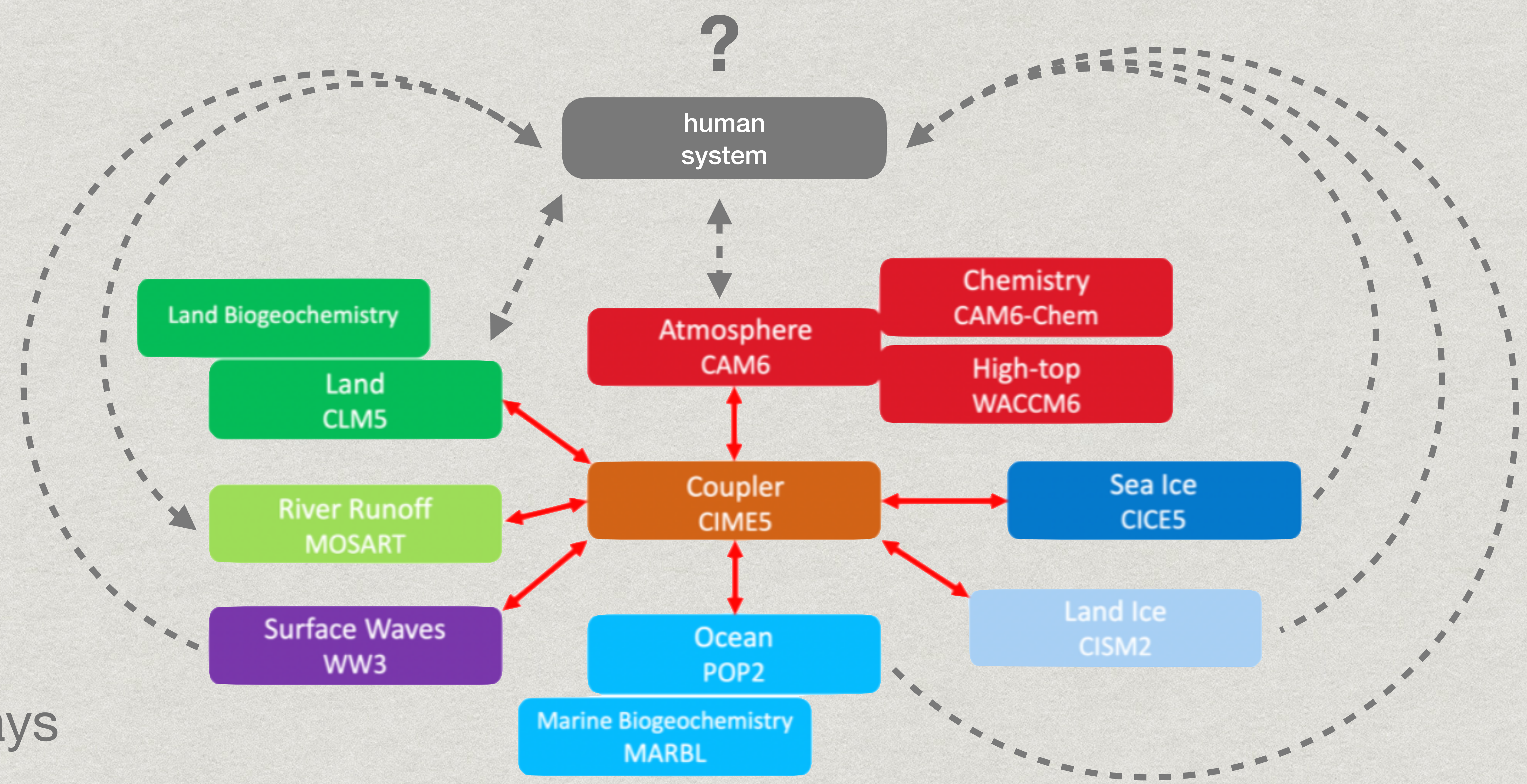
- Coastlines engineered
- > 70% of available fresh water used for human food production
- N cycled by human processes ≥ non-human processes
- Sediment transported by human processes > non-human processes




(Khokhar 2017; Vitousek et al 1997; Wilkinson 2005)

The Human System - ESM Gap

- If we accept CESM simulation results
- If we accept global scientific data of the impact of 8+ billion people on the atmosphere, land, and oceans
- If we accept the data that people are significantly impacted by climate
- If we accept that human decisions and actions respond in diverse and complex ways to changes in their environment



- We must acknowledge that ESMs are missing a critical Earth system component and their simulations of potential futures are significantly less reliable and useful than they could or should be

Closing the Gap: an Example

- How can we begin to bridge the gap of missing human systems in ESMs?
- An example is the *Societal Dynamics Model for Climate Interventions* (SDM4CI)
- Part of a collaborative NSF project: *Generating Actionable Research to Investigate Combined Climate Intervention Strategies for Stakeholder Use**
- Collaboration between NCAR, LSU, Duke University, and ASU
- CESM modeling of environmental and societal impacts of alternative CI strategies, and active stakeholder engagement
- Testing eight currently proposed strategies for decarbonization and solar radiation management

NCAR Operated by UCAR
LSU
Duke UNIVERSITY
ASU

*NSF Grant OIA2218758

SDM4CI Overview

- ASU's role is developing a prototype modeling environment for simulating interactions between biophysical systems and human society
- Proof-of-concept of new modeling components for simulating human systems, that can be coupled with CESM biophysical components
- This project focuses on climate intervention (CI) resulting from societal decisions and actions
- But broader vision is to develop components with flexibility to model other aspects of human systems of relevance to Earth systems

SDM4CI Goals

- To develop a platform where experiments on the potential environmental and social consequences of feedbacks between climate impacts (including impacts of CI) and societal decision/actions (including CI policies) can be systematically simulated and modeled in ways not possible for ESMs today

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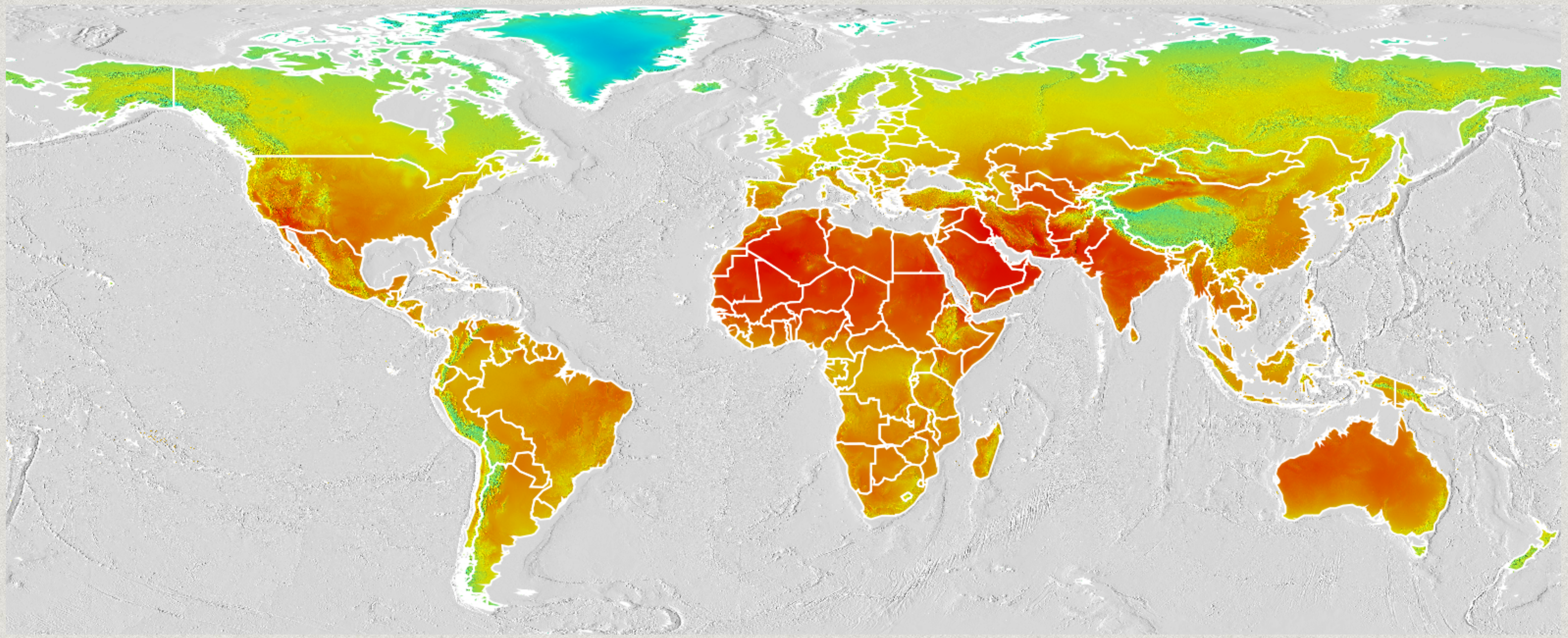
- How many here believe that in the near future CI strategies will be implemented by a unified world, in a scientifically guided, optimum way to maximize global human well-being?

SDM4CI Goals

- To develop a platform where experiments on the potential environmental and social consequences of feedbacks between climate impacts (including impacts of CI) and societal decision/actions (including CI policies) can be systematically simulated and modeled in ways not possible for ESMs today
- How many here believe that in the near future CI strategies will be implemented by a unified world, in a scientifically guided, optimum way to maximize global human well-being?
- This is the way ESM modeling is normally carried out.
- Can be useful as an ideal outcome, but imperative to also understand the consequences of CI policy in a non-unified world

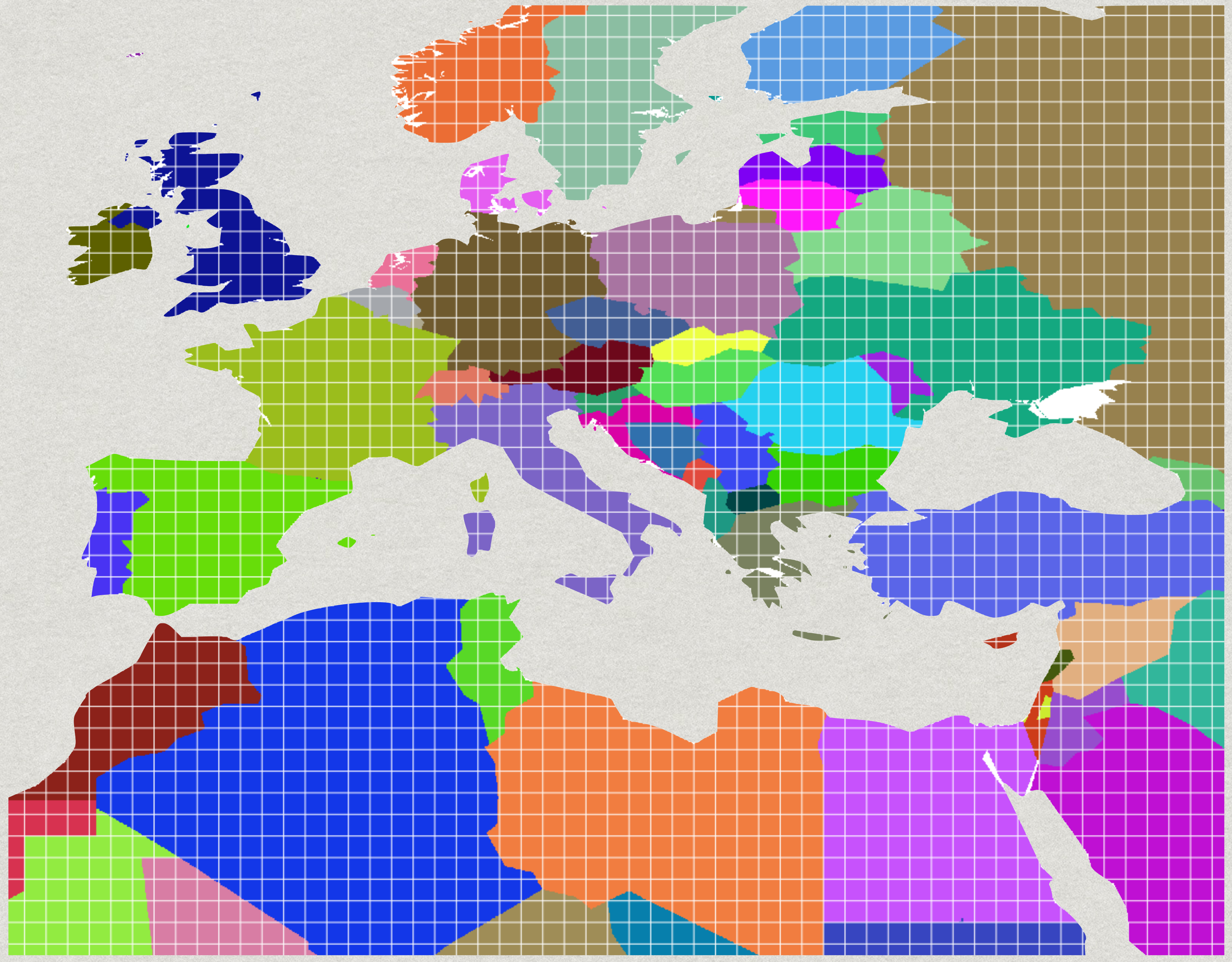
SDM4CI Goals

- The implementation of CI strategies will be driven by policies at national or supranational scales, responding to significant climate-driven impacts on regional populations and sociopolitical conditions
- SDM4CI approach developed to represent
  - diverse geopolitical actors
  - at different societal scales,
  - in different geographic locations,
  - experiencing societally-relevant impacts of climate change differently,
  - with varying goals and capacities for action

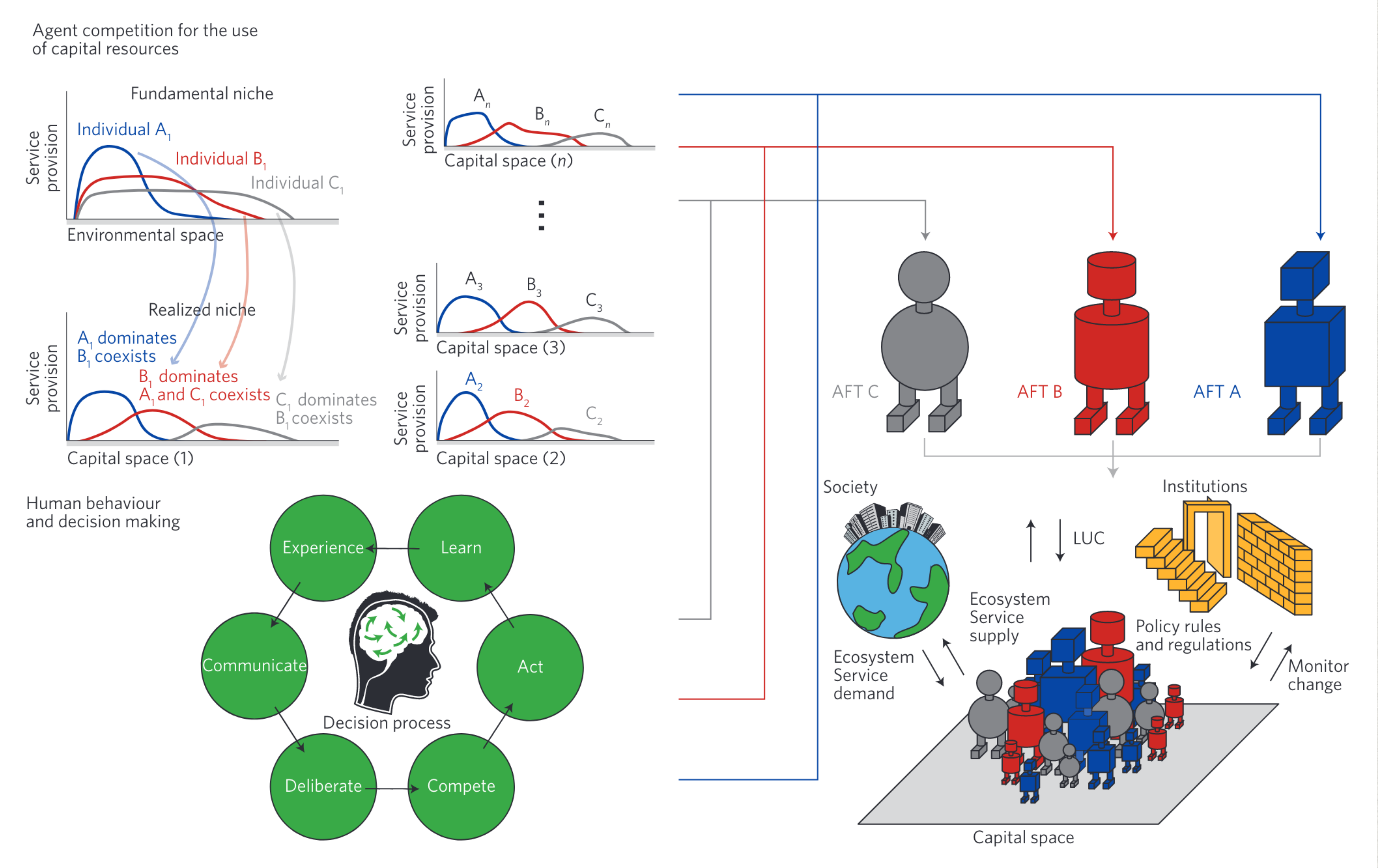


SDM4CI Modeling Approach

- A gridded multi-agent formalism like CESM
- Interfaces with CESM inputs and outputs more easily and flexibly
- Grid cells and groups of cells can represent human systems at multiple scales (e.g., cities, rangeland, nations, economic blocks)
- A cell can likewise contain subdivisions, representing agents at finer spatial scales



SDM4CI Modeling Approach



agent functional types (Arneth et al 2014)

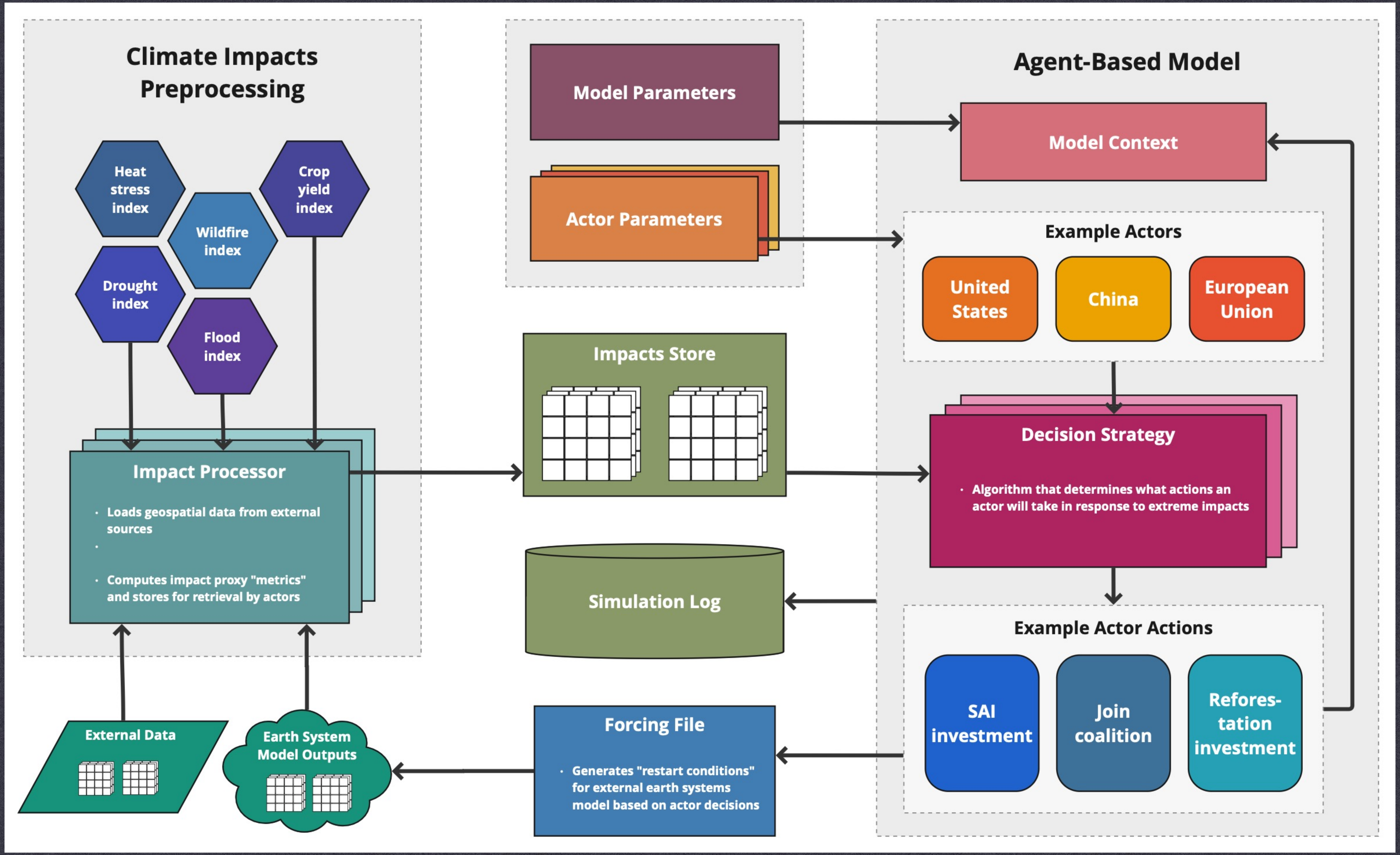
- Multi-agent modeling enables representation of social actors (individuals or groups) as heterogeneous agents with different histories, biases, contexts, and relationships with other agents
- Agents independently implement algorithms for responding to conditions in the simulated biophysical and societal worlds—much like CESM grid cells.
- Because grid cell agents are located in geographic space (e.g., countries or cities) they can experience geographically different simulated conditions, including climate impacts
- Agents also can act and interact across spatial scale (e.g., international trade or finance) and not just with adjacent grid cells

SDM4CI Modeling Approach

- Multi-agent model formalism enables simulation of potential impacts of CI strategies in a more realistic social world with…
    - CI policies carried out by distinct geopolitical agents, each with their own agendas, some of whom may be working together, and others who may act independently.
    - CI decisions of each agent influenced by unique combinations of current and past biophysical and societal conditions—including the actions of other agents
    - Agent CI choices may or may not be influenced by information from CESM simulations of potential future impacts for different strategies
- SDM4CI will interface with CESM by stopping and restarting simulation at regular intervals (e.g., annually)
- During a simulation pause, each agent will read and parse simulated conditions in the biophysical world from intermediate CESM output files and decide on a CI action (or non-action).
- Then SDM4CI will aggregate actions of all agents to generate forcing files that change CESM parameters at restart

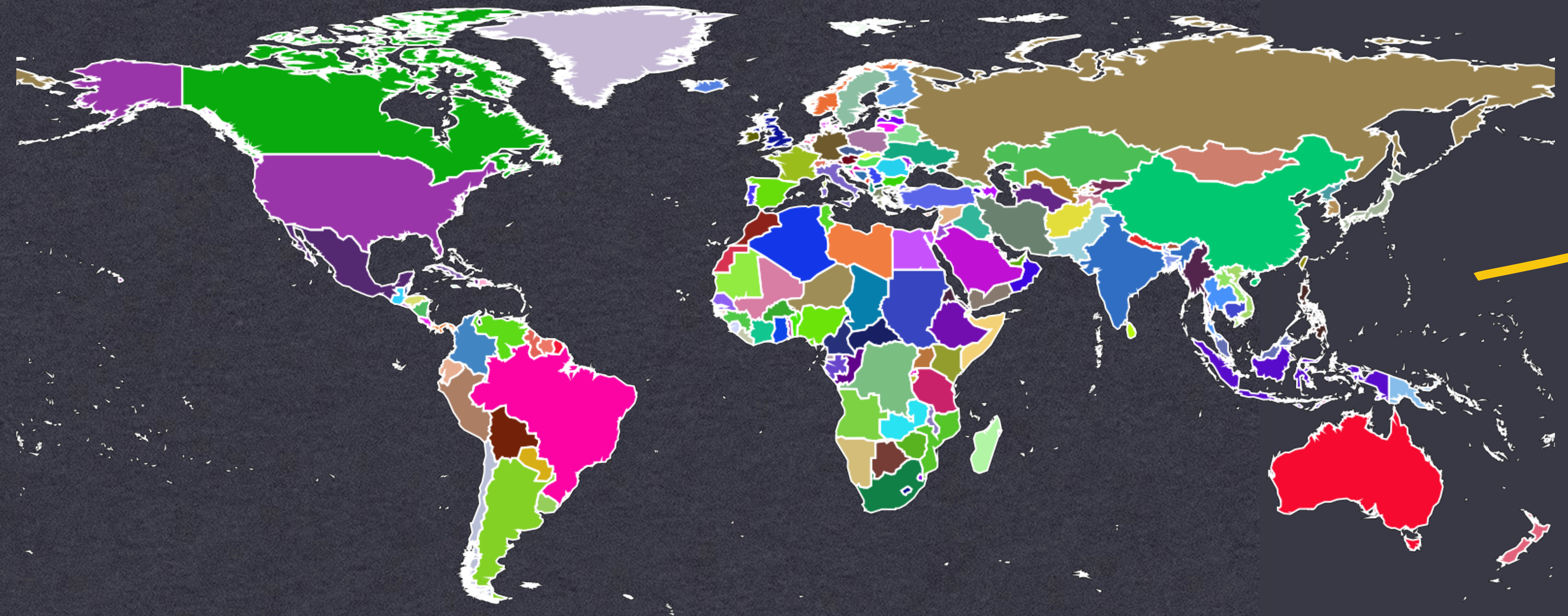
SDM4CI ARCHITECTURE: INITIAL 2 YRS DEVELOPMENT

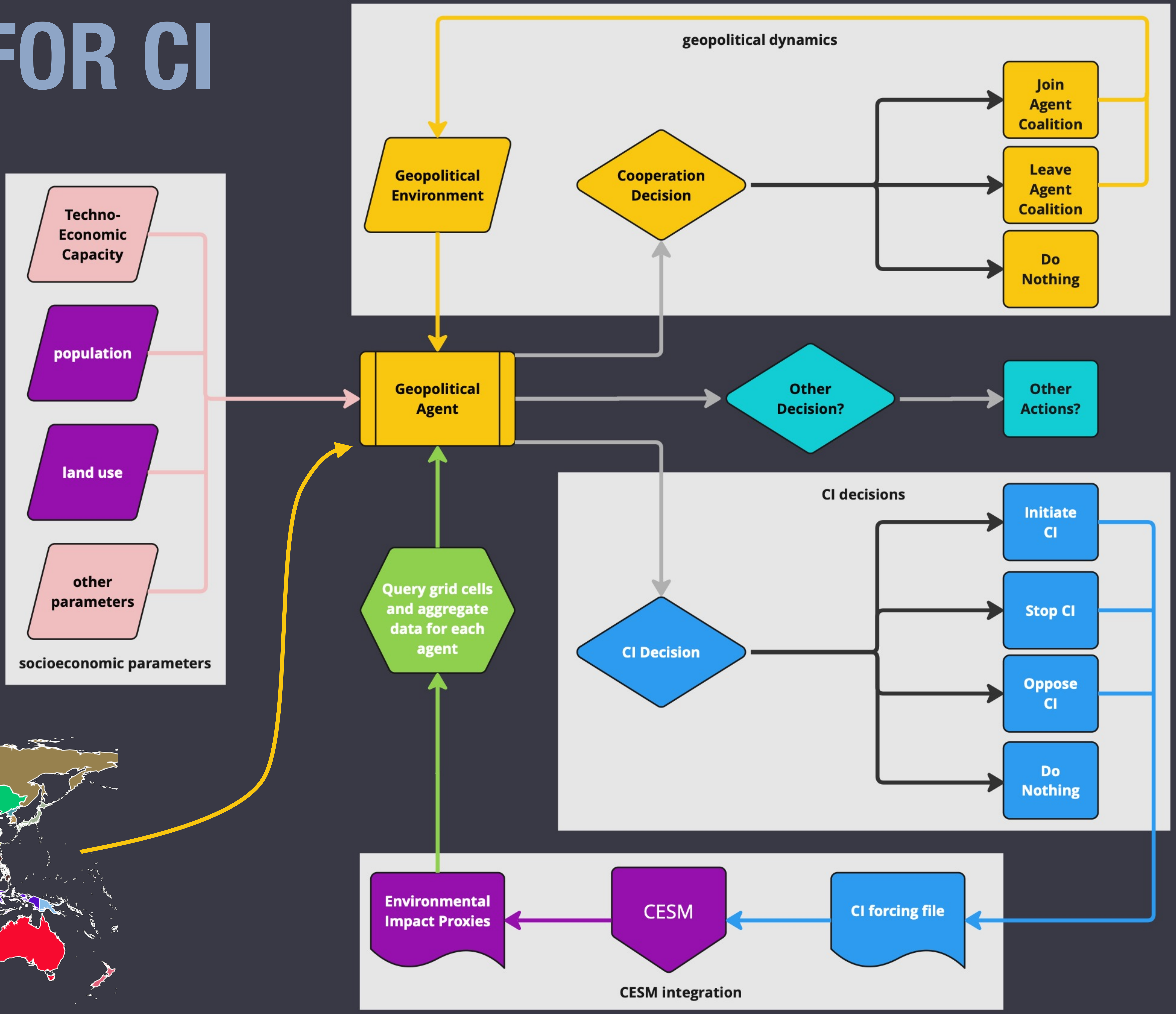
- Coded in Python
  - Modular architecture
  - Loose coupling using NetCDF files as I/O
- Designed with CESM in mind, but potential to be used with any ESM that …
  - can be stopped and restarted
  - uses NetCDF (or other) files for I/O and forcings
- Also exploring the potential to SDM4CI with ESM emulators



SDM4CI AGENTS FOR CI

- Each geopolitical agent each time step
- Agent = group of cells at CAM or CLM resolution that correspond to a geopolitical entity (e.g., nation state)
    - Parses CESM output for impacts to corresponding cells
    - Parses information about other geopolitical agents
    - Generates CI decisions/actions
- CI actions of all agents combined into forcing file for CESM





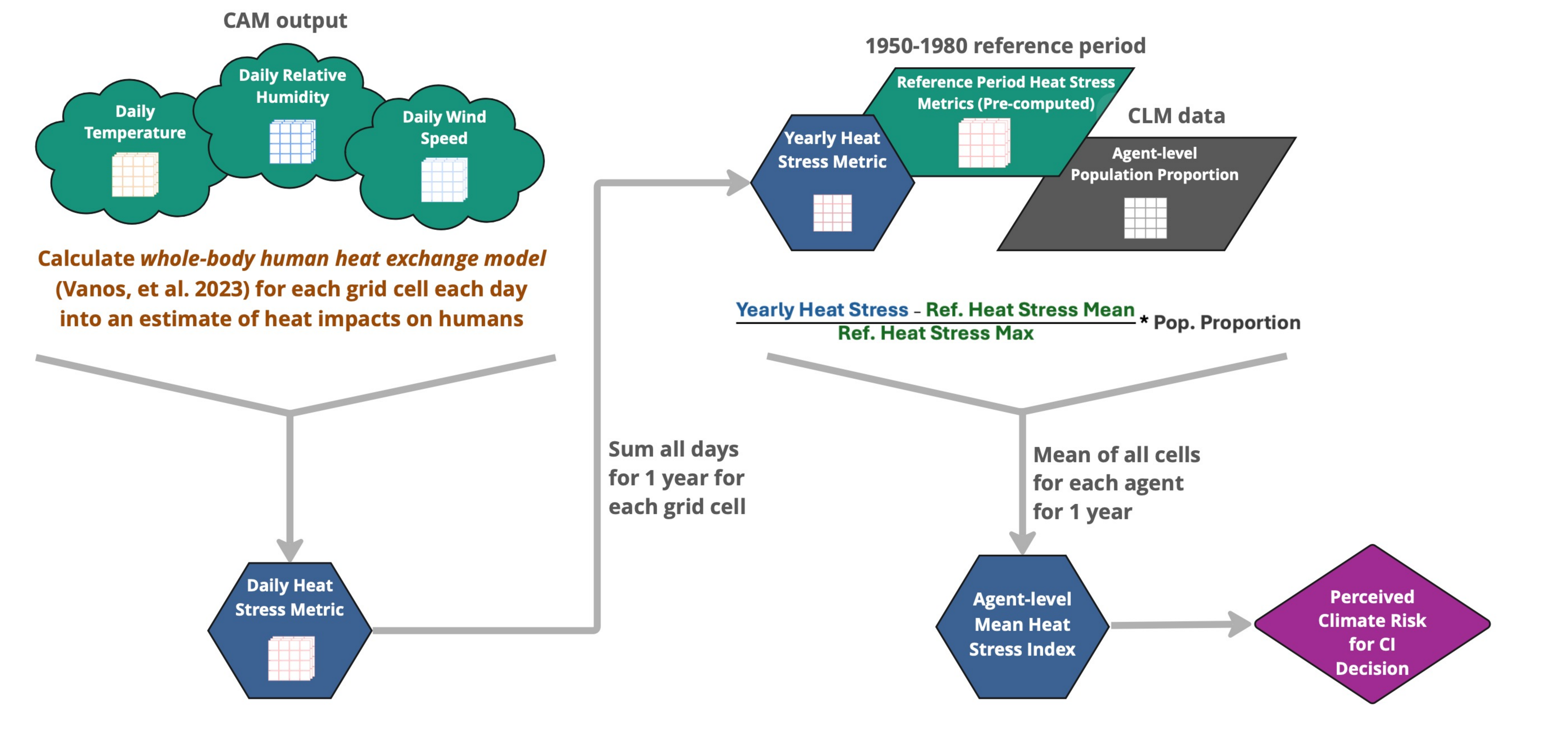
SDM4CI Prototype Development: 1 CI and 1 Impact

- Initial development using SAI for CI investment and extreme heat for societally significant impacts
  - SAI forcing approach already well developed and Python controller scripts for dynamically interacting with CESM for SAI already exist (e.g., ARISE)
  - SAI can have near term impacts, with potential for considerable benefits & considerable risks that vary geographically
  - Makes simulation of SAI implementation in more realistic societal simulation especially useful

SDM4CI Prototype Development: 1 CI and 1 Impact

- Initial development with extreme heat for perceived climate impacts
  - Likely to have growing impact in near future
  - Can be directly affected by SAI
- Using heat index based on work of J.Vanos (Vanos, et al 2023), calculated from CESM output
  - Livability (ability to carry out activities outside)
  - Survivability (risk of heat stroke)
  - Combined into single heat impact metric

SDM4CI: Extreme Heat



SDM4CI: Agent Decision Algorithm Alternatives

Deterministic probability with decay: **P(Invest)** is the probability of investing in CI strategy

$$P(Invest_t) = d * (1 - w) * P(Invest_{t-1}) + (w * \frac{1}{1 + e^{-(a_0 + a_1 * PCI_t)}})$$

investment probability for each CI strategy

- **d:** decay factor for last year's investment probability
- **w:** weight given to current year's impacts vs last year's investment probability
- **PCI:** perceived climate risk = f(heat stress, other, …)
- **a_0, a_1:** parameters for logistic function (modulating

Bayesian updating of climate risk beliefs

$$P(L \rightarrow H \mid PCI_t) = \frac{1}{1 + e^{-(b_0 + b_1 * PCI_t)}} \qquad P(H \rightarrow L \mid PCI_t) = d + (1 - d) * \frac{1}{1 + e^{-(c_0 + c_1 * PCI_t)}}$$

prior probabilities

$$Belief_t = \left(1 - P(H \rightarrow L \mid PCI_t)\right) * Belief_{t-1} + P(L \rightarrow H \mid PCI_t) * (1 - Belief_{t-1})$$

posterior probabilities

$$P(Invest_t) = Belief_t * P_{invest-high} + \left(1 - Belief_t\right) * P_{Invest-low}$$

investment probability for each CI strategy

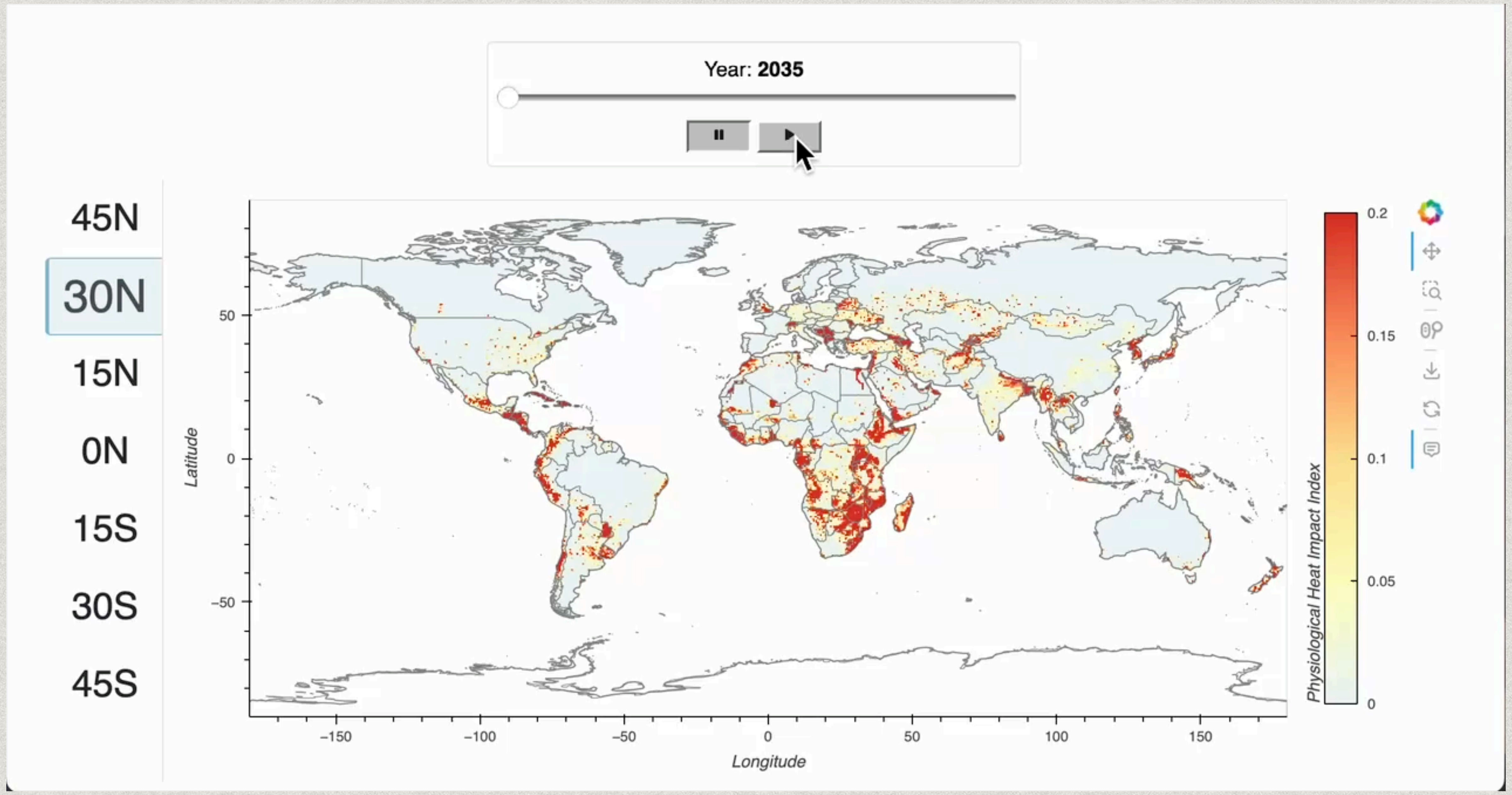
- **L → H:** climate risk lower in prior time step than current time step
- **H → L:** climate risk higher in prior time step than current time step
- **b_0, b_1, c_0, c_1 :** parameters for logistic functions (modulating mid-point and sensitivity)
- **Belief:** posterior probability of belief that the current state is high
- **$P_{invest-high}$:** probability of investment in SAI if actor perceives climate risk to be high
- **$P_{invest-low}$:** probability of investment in SAI if actor perceives climate risk to be low

LLM Impersonation (="AI")

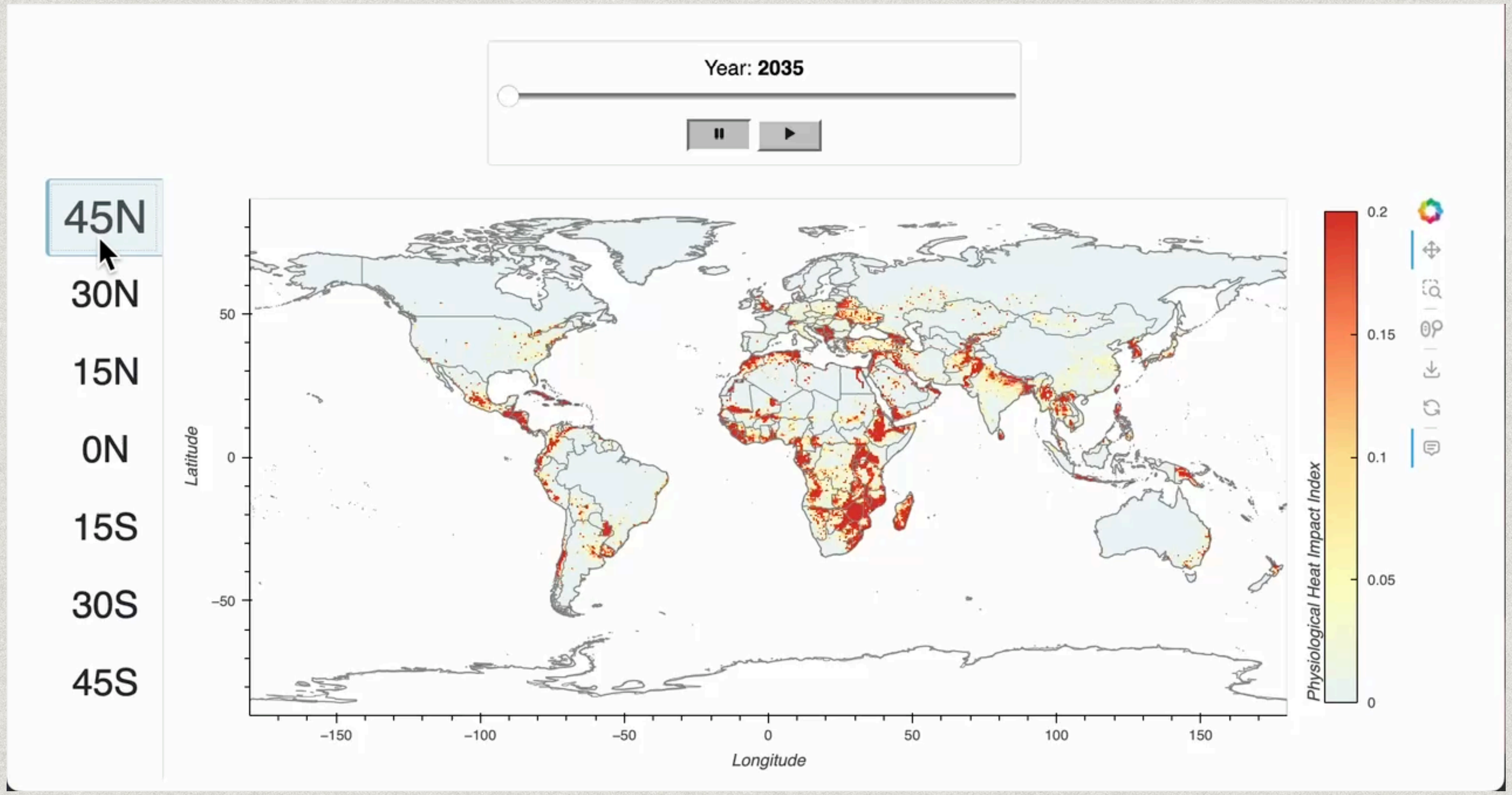
Example Prompt:

"You represent the government of [geopolitical actor] and the year is [Y]. Your goal is to minimize the impacts of climate change on your territory, as measured by the following impact indices: [describe each index and how it is calculated]. Your options are to invest or not in SAI, considering its costs and the eventual political costs that such a decision can bring among the [actor's] population. Given this year's impact indices, do you decide to invest in SAI? Provide a complete explanation of your decision."

SDM4CI: SAI & Extreme Heat Index



Effects of **SAI injection choice by one agent** on extreme heat index for rest of world for 10 years*

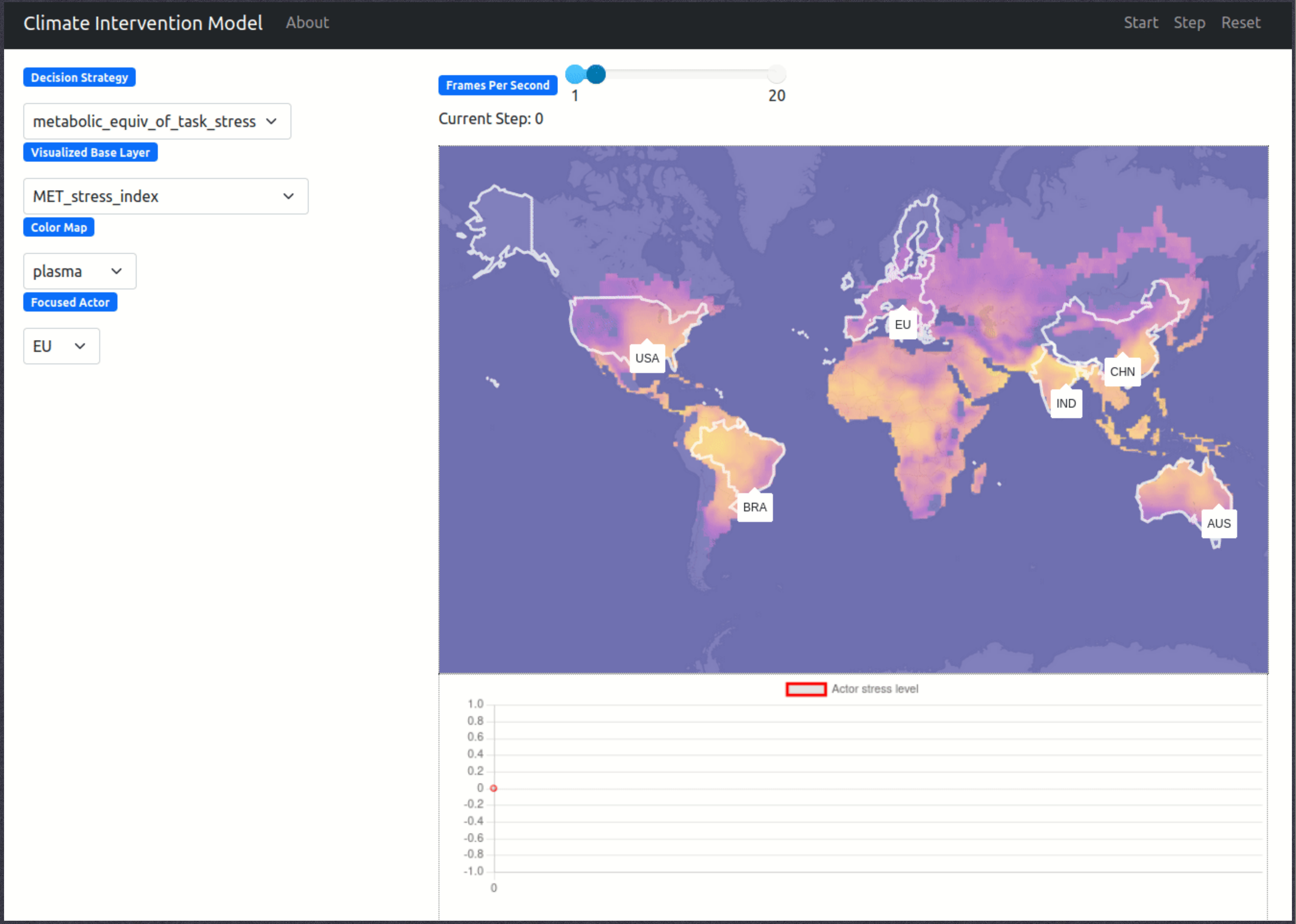


Effects of **SAI injection choices by different agents** on extreme heat index for rest of world for 10 years

(*Data provided by D. Visioni, Cornell University [see Richter et al 2022])

SDM4CI: PROTOTYPE

- 6 geopolitical agents each time step over 2 decades
  - Assess extreme heat impacts
  - Decide whether or not to invest in SAI
  - Outline color indicates aggregate heat stress and probability of investing in SAI



Expanding SDM4CI Prototype

- Planned to include other extreme impacts in agent decisions beyond heat, e.g.:
  - Extreme drought with crop/livestock failures and food insecurity
  - Extreme storms and floods
  - Wildfires
  - Sea level rise
- Other CI strategies like direct air capture or ocean de-acidification
- In the future, an SDM-like platform could alter other CESM parameters like GHG emissions in response to societal decisions

Bridging the Gap: Human Systems in Earth System Modeling

- More imperative than ever to represent human systems in ESMs
  - Anthropogenic changes to Earth systems now generating a growing range of extreme events with significant impacts to survival and well-being of large numbers of people: extreme weather, sea level rise, wildfires, agricultural failure, and more
  - At same time, global society is becoming less unified as it is becoming more connected globally. Potential for rapid and unexpected cascades of societal transformation.
  - Growing potential for CI actions by independent global actors seeking relief from climate change impacts
- ESM community needs to recognize that this is a serious issue for useful Earth system modeling (e.g., Beckage et al 2020).

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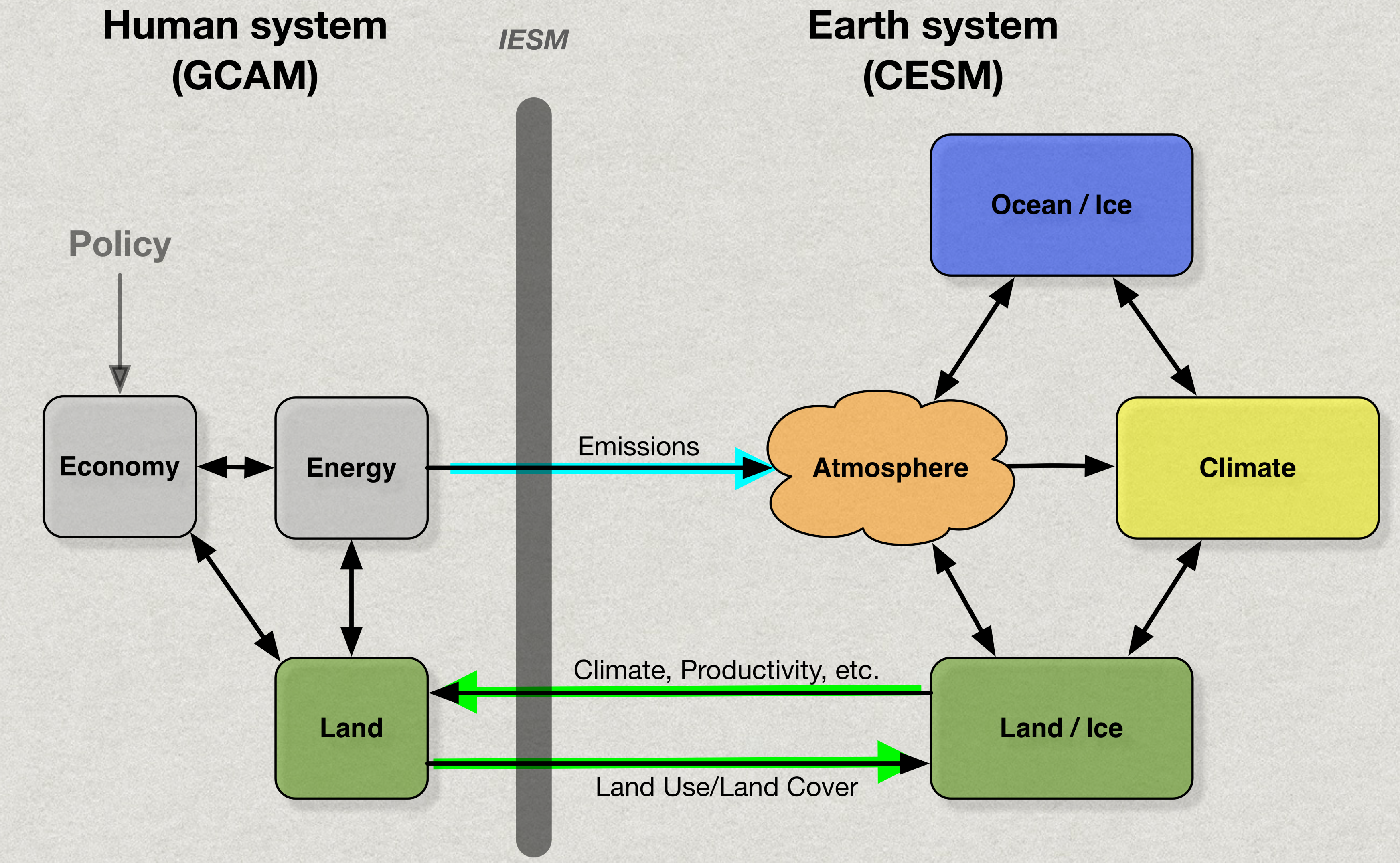
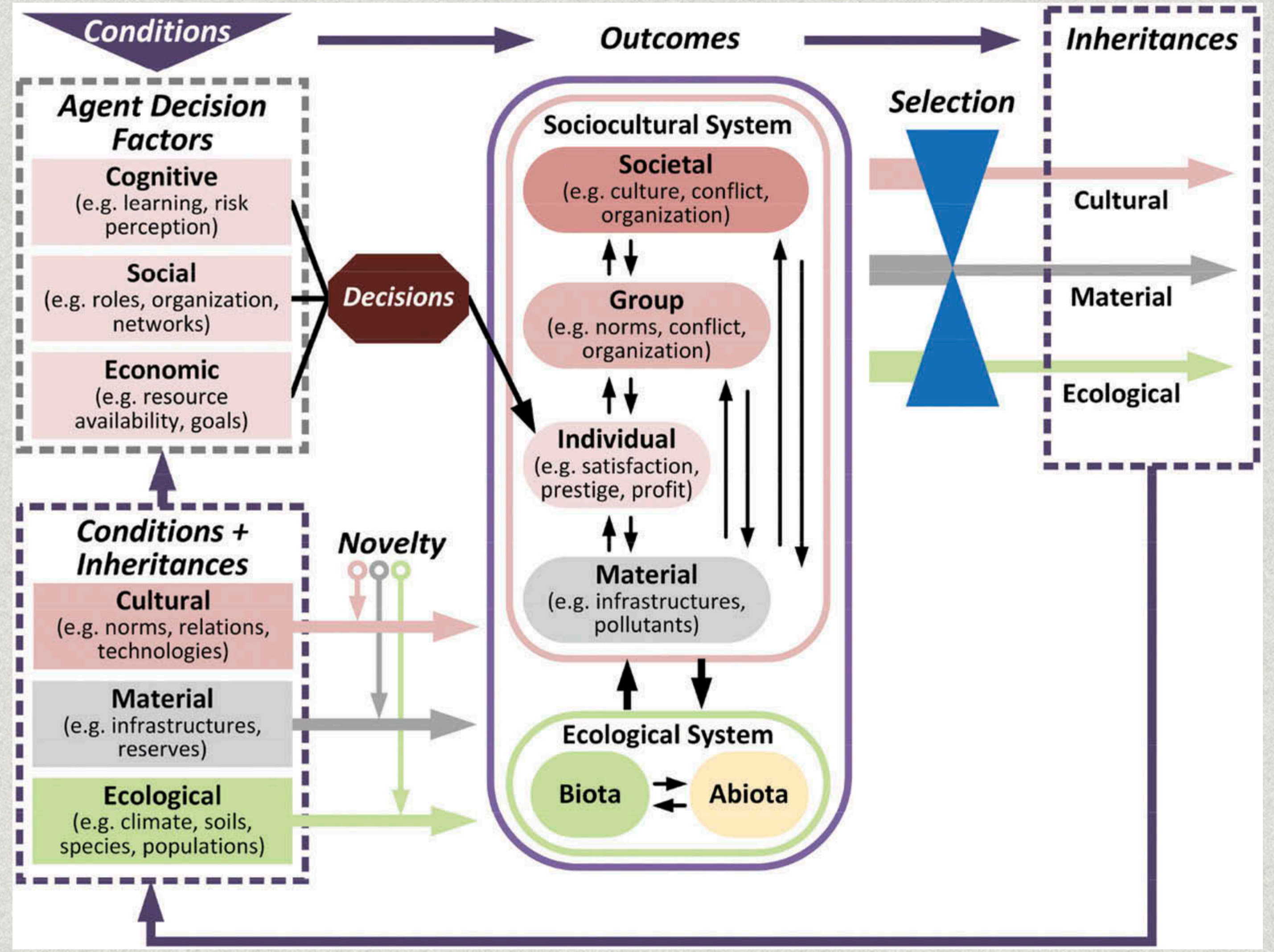
Bridging the Gap: Human Systems in Earth System Modeling

- We need a concerted, collaborative effort for developing representations of human system dynamics within ESMs, building on initial work like SDM4CI
- ASU cannot do this alone. At the end of funds in current NSF grant for this work
- In spite of critical need for developing human systems modeling in ESMs, resources for doing so are rapidly disappearing
- But even with significant funds, expanding an SDM4CI prototype to simulate more CI strategies and additional human system dynamics will take a large scale effort.
- CESM 3 builds on 6 decades developing and improving GCMs

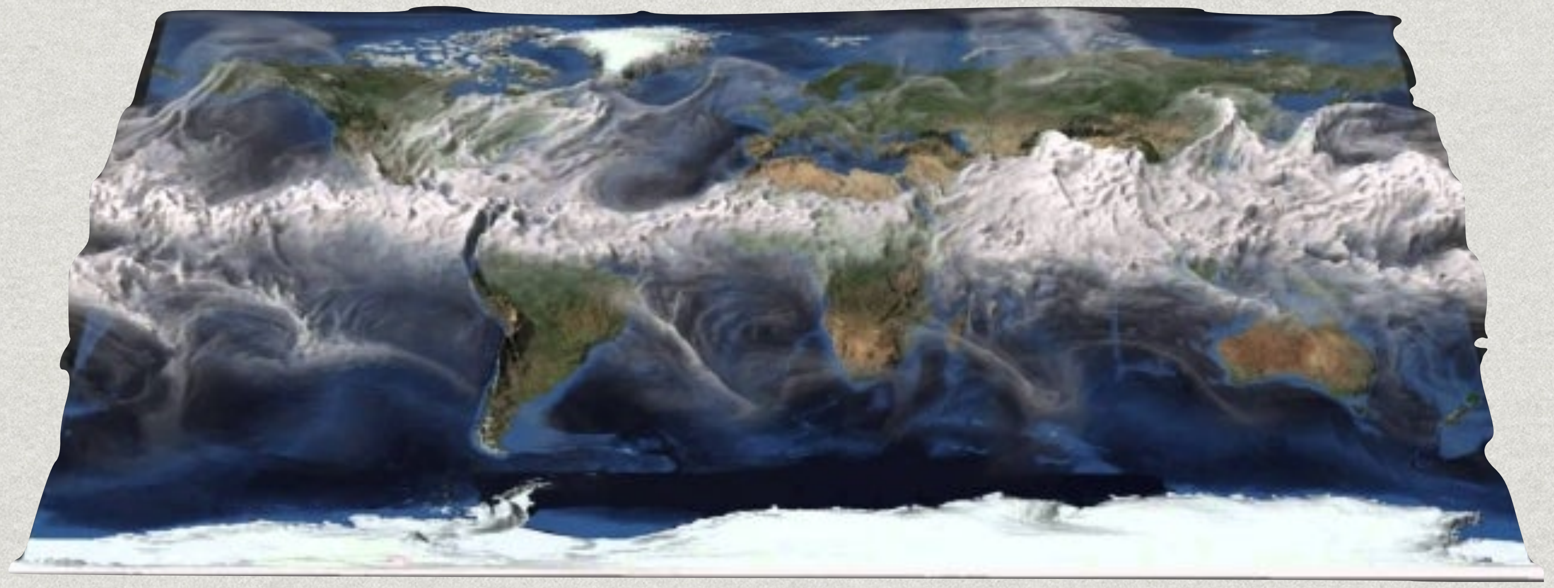
Bridging the Gap: Human Systems in Earth System Modeling

- Many other research groups are working independently on similar concepts and code (e.g, Calvin & Bond-Lamberty 2018; Collins, et al 2018; Magliocca & Ellis 2016; Robinson, et al 2018; Thornton, et al 2017; Verberg, et al 2016)
- With a framework for greater collaboration and coordination, these research groups could accomplish much more
- CESM working groups provide recognized research umbrellas to promote this kind of coordination and knowledge sharing needed for developing and using critical components of ESMs
- The *Societal Dimensions Working Group* was formed in 2011 to provide this kind of coordination
- Unfortunately, it dissolved after precipitous actions taken in response to political contexts similar to but less extreme than the ones we face today





Bridging the Gap: Human Systems in Earth System Modeling



- The *SDWG* cannot be revived, based in NCAR as it was in 2011.
- A new working group framework within the ESM community is needed more than ever to support the collaborative science needed for developing human systems components for Earth systems modeling
- CESM is the world's foremost ESM platform and modeling community
- I want to close by challenging the CESM community to lead the way in organizing a framework for global collaboration to bridge the human systems gap in Earth systems modeling

Acknowledgements

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* Colleagues at NCAR, Duke, and LSU

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