CliMA: A New Open Source Code for Climate Science

Julia Sloan
SCALE 2025

CliMA is building an open source Earth System Model from scratch in Julia

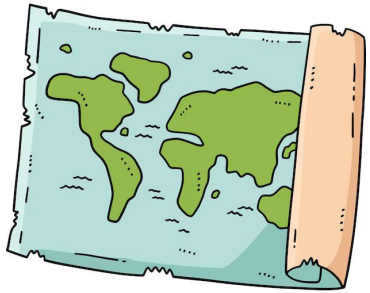
CliMA
CLIMATE MODELING ALLIANCE

Caltech

MIT

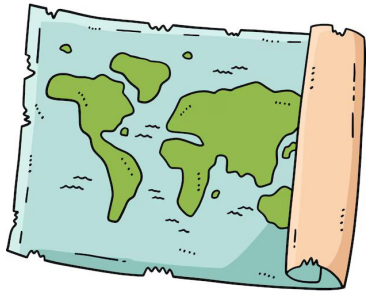
julia

Roadmap



- What is an Earth System Model (ESM)?
- How do ESMs work?
- Challenges faced by ESMs
- Current capabilities of the CliMA model
- How does CliMA address the challenges faced by ESMs?

Roadmap



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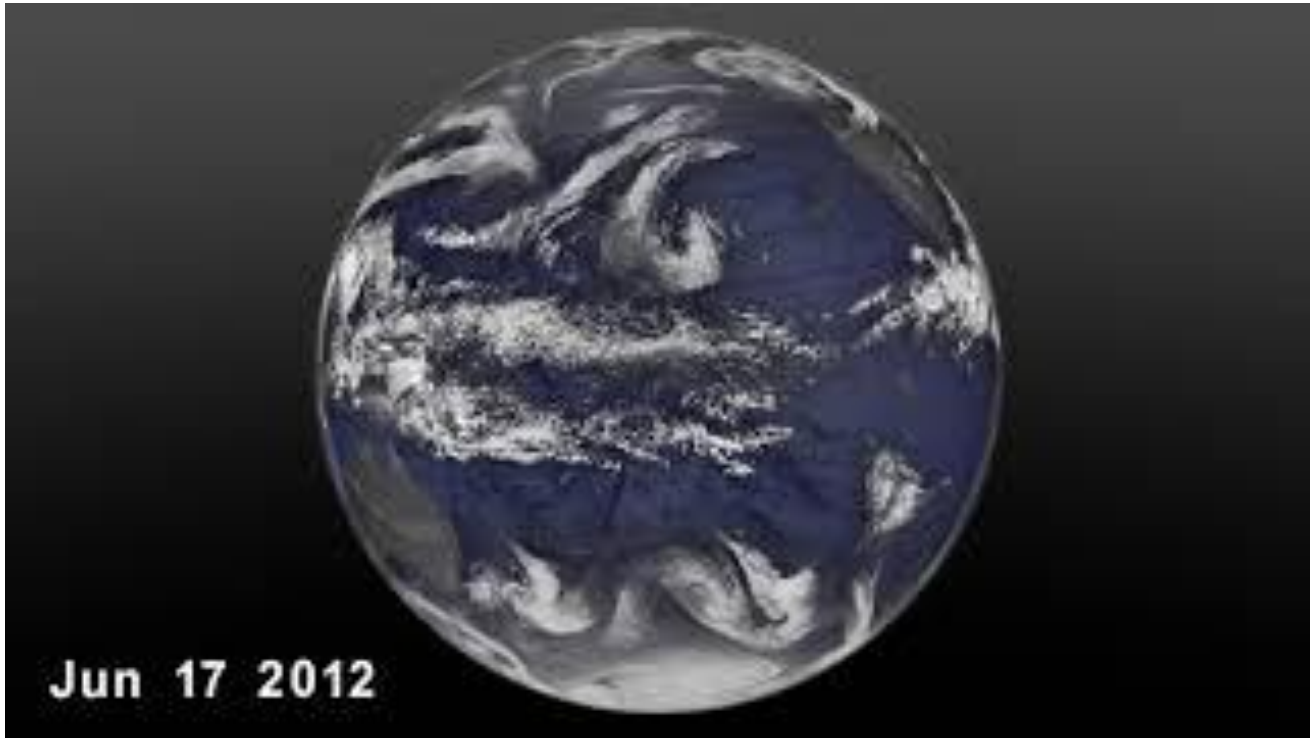
Earth System Models (ESMs) simulate physical processes of the Earth

Simulated cloud cover and dynamics

NASA GEOS-5 model

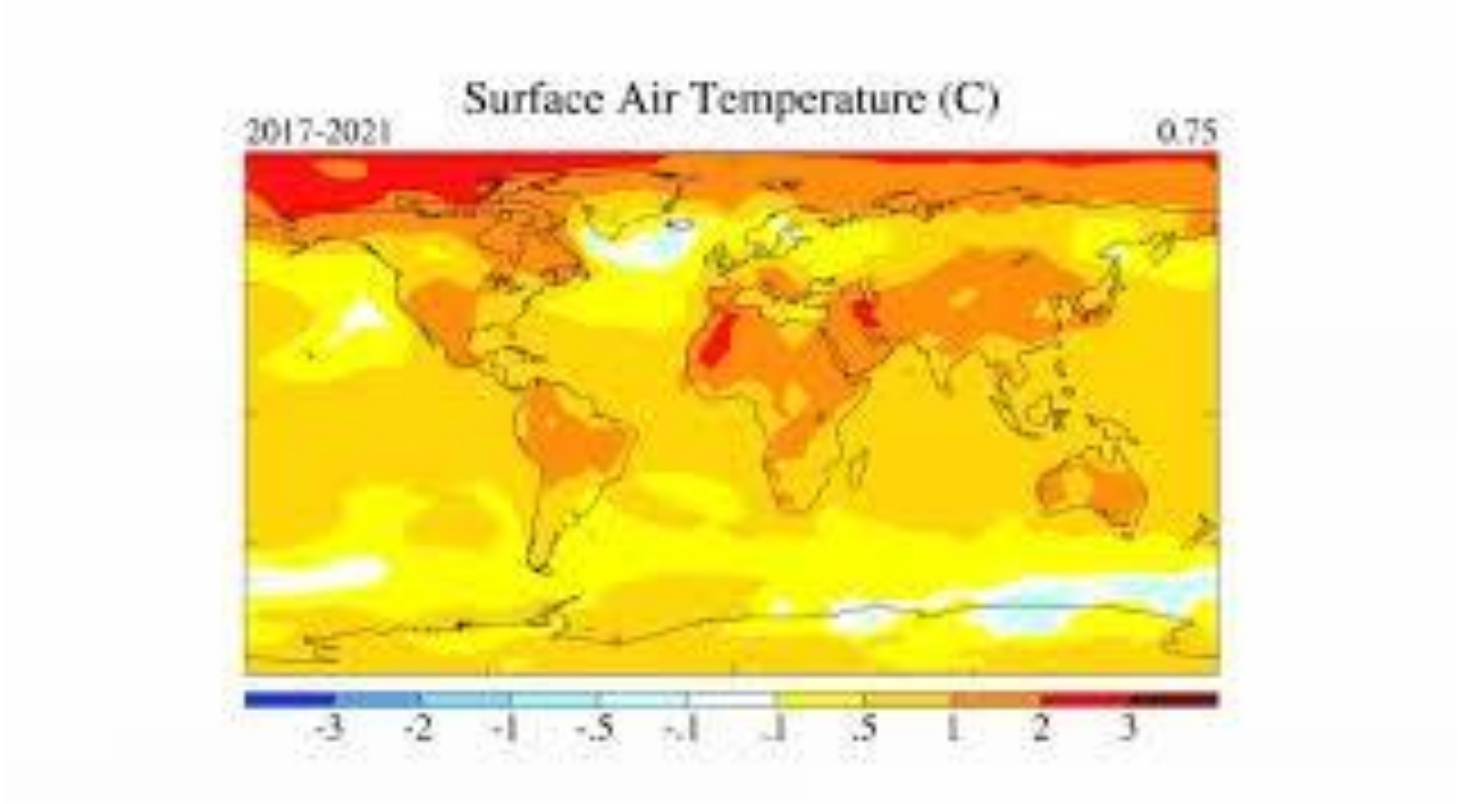


Source: “Earth Day 2020: GEOS-5 Modeled Cloud Cover”. Youtube, uploaded by NASA Scientific Visualization Studio, April 24, 2020.

ESMs show how global trends vary over time

Simulated surface air temperature 1880-2100,

NASA GEOS-5 model

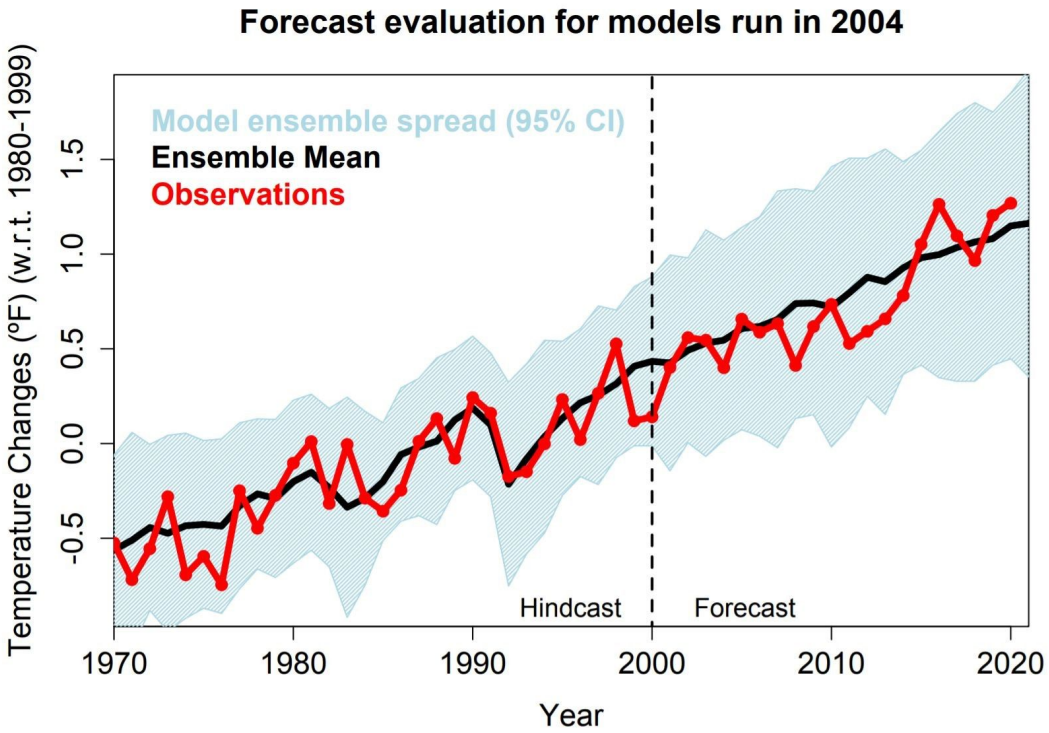


Source: "Climate Simulation of Surface Air Temperature". Youtube, uploaded by NASA Climate Change, January 9, 2020.

Using results from an ensemble of ESMs reduces mean errors

Models sometimes use different physical representations

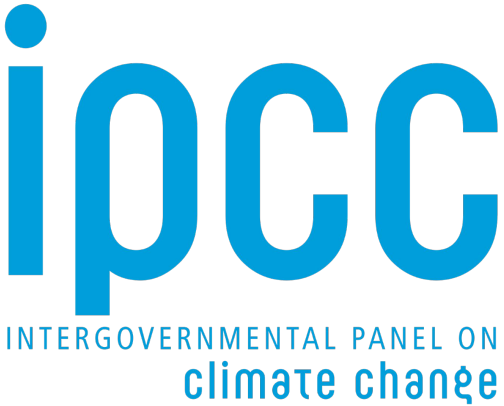
Using ensemble reduces errors from individual models



Source: "Basics of Global Climate Models". Climate Hubs, U.S. Department of Agriculture.

Climate Model Intercomparison Project (CMIP) informs governments via IPCC reports

- CMIP looks at **100 models** from 49 centers
- Released every 6-7 years
  - most recently in 2023
- Literature review to understand and quantify current status of climate change
- Report targets education and action
  - Causes, impacts, response options



ESMs are also used by scientists to test hypotheses

- Climate scientists can’t run experiments in a lab
- ESMs allow scientists to test physical hypotheses

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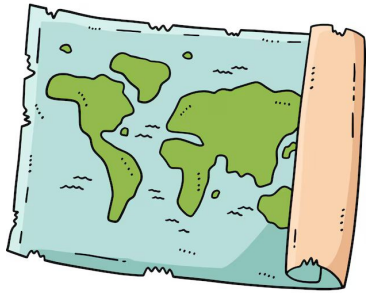

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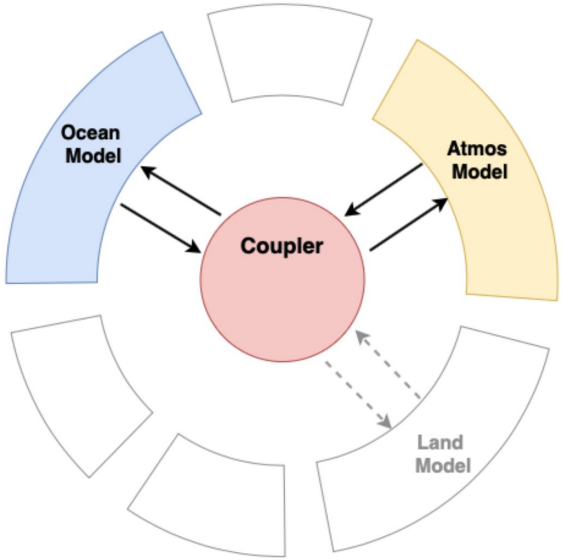
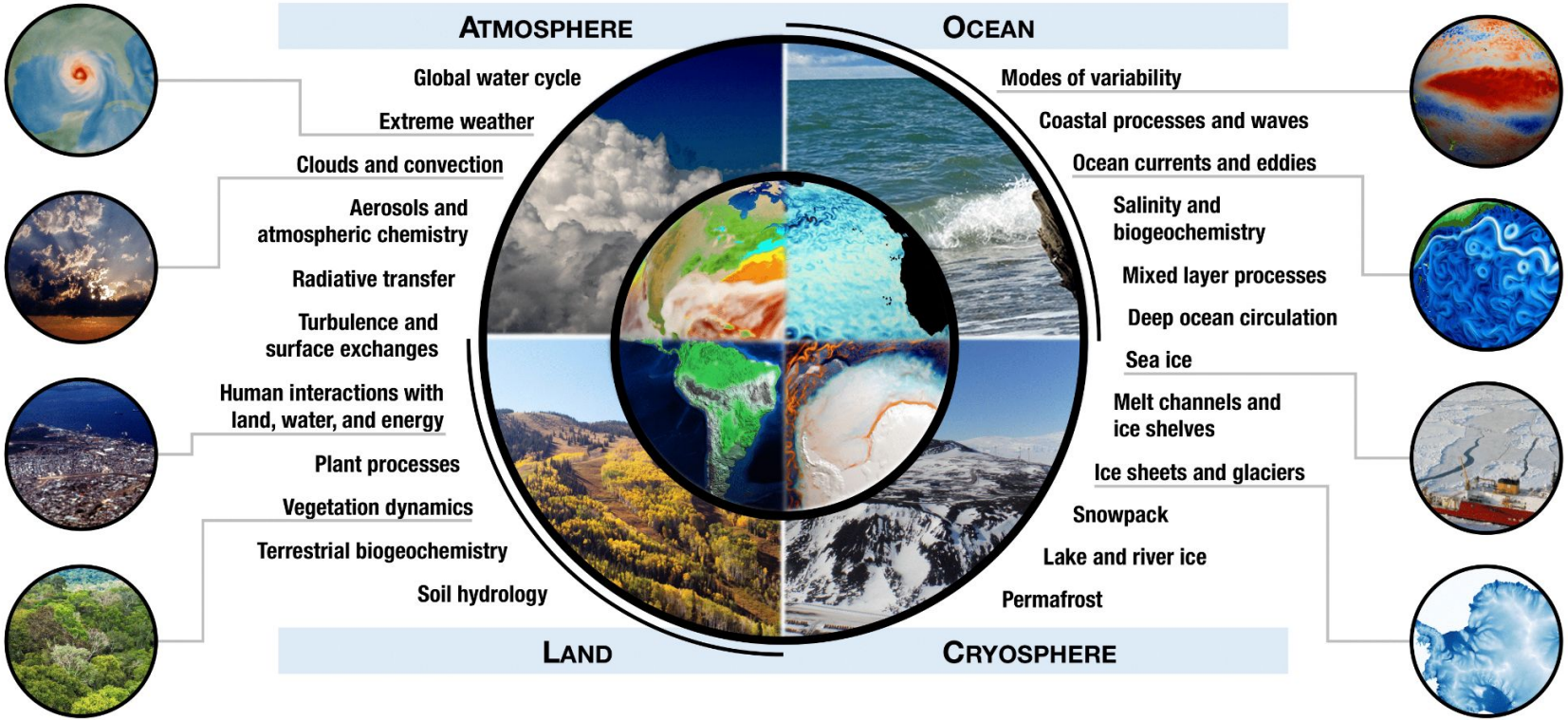
ESMs contain component models and additional infrastructure

- Component models
  - Atmosphere
  - Ocean
  - Land
  - Ice
- Coupler
  - Exchange between components



“Hub and spoke” model

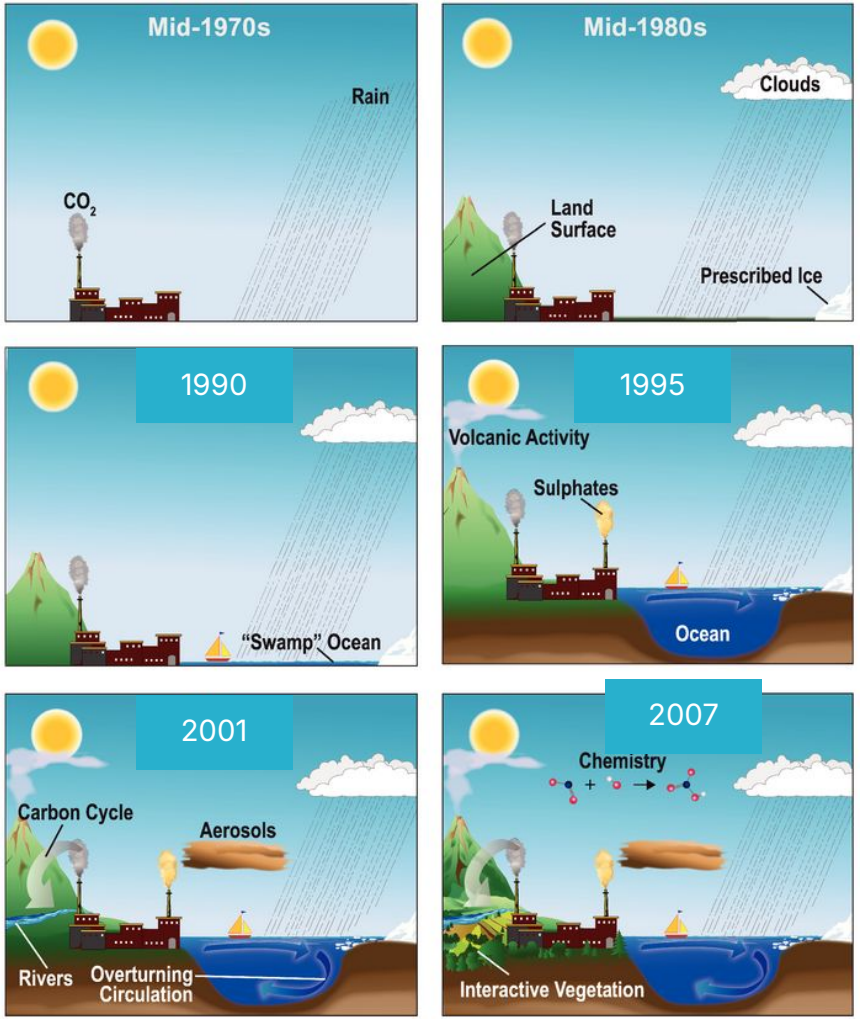
Each domain of the ESM contains many physical processes



Source: Paul Ullrich, Dept. of Energy Office of Science. energy.gov/science/doe-explainsearth-system-and-climate-models

ESM complexity is always increasing

- Better scientific understanding
- Improved computational resources and efficiency



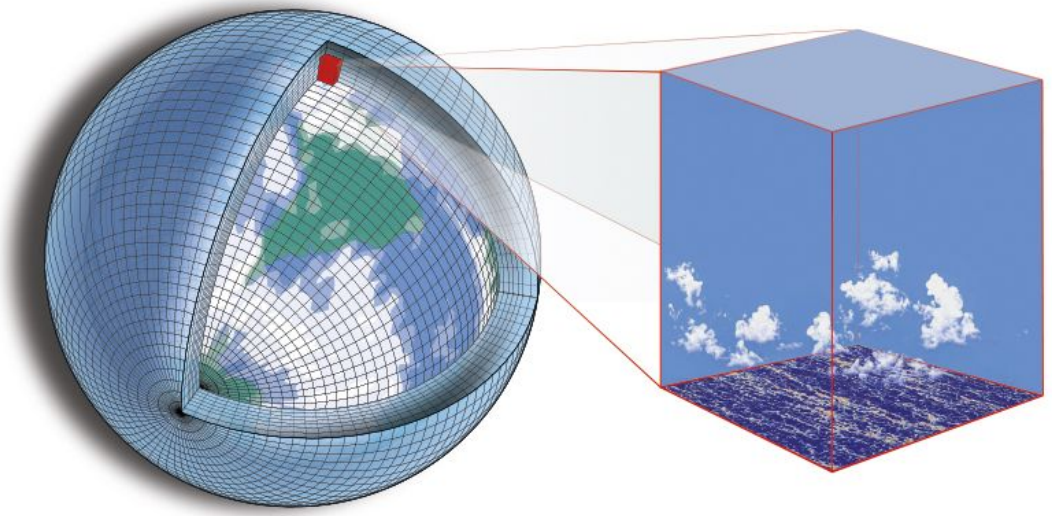
Source: McSweeney, R., Hausfather, Z. "Q&A: How do climate models work?" Carbon Brief.

ESMs discretize the globe spatially and solve system of differential equations

Start with initial conditions

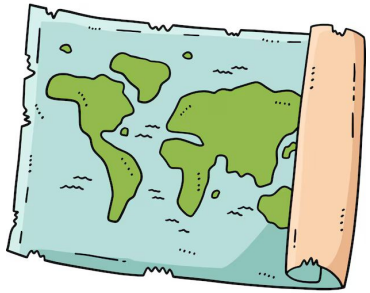
Step variables forward in time

$$\frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}$$



Source: Springer Nature, Nature Climate Change, “Climate Goals and Computing the Future of Clouds,” Tapio Schneider, João Teixeira, Christopher S. Bretherton, Florent Brient, Kyle G. Pressel et al., 2017.

Roadmap



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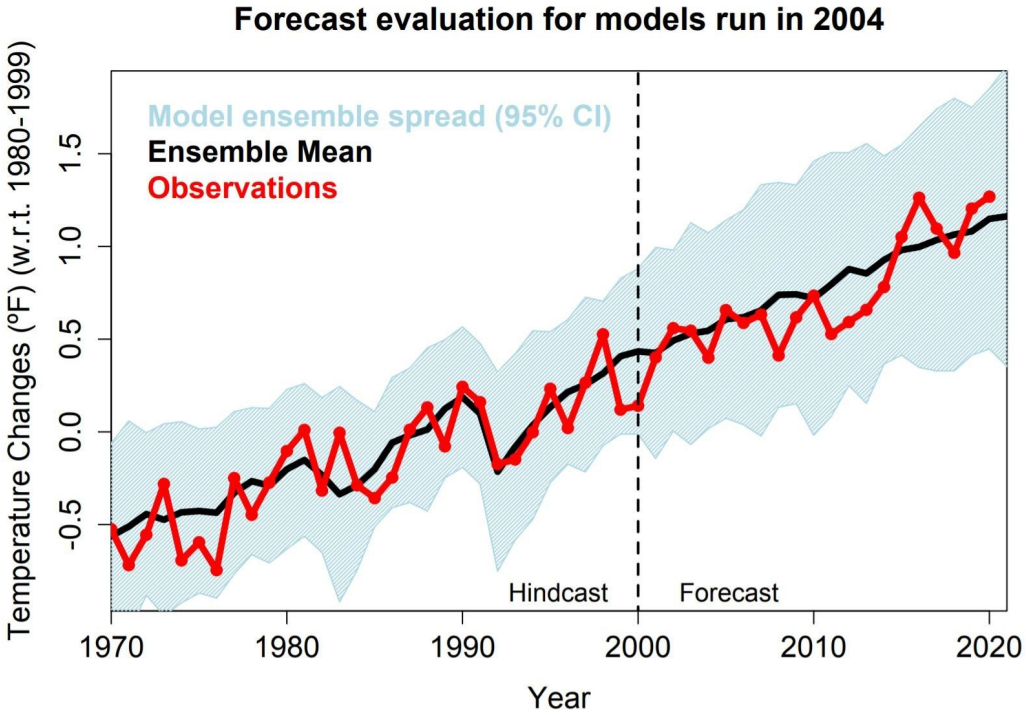
Existing ESMs perform well in the historical period

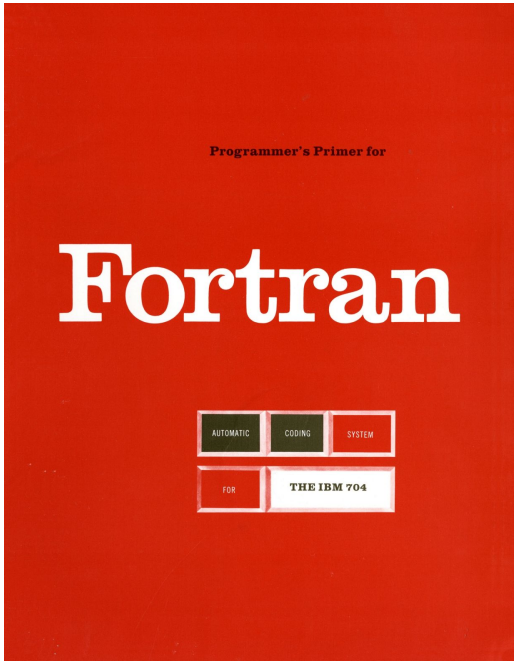


Source: "Basics of Global Climate Models". Climate Hubs, U.S. Department of Agriculture. https://www.climatehubs.usda.gov/hubs/northwest/topic/basics-global-climate-models

ESMs are complicated pieces of software

- Processes act on different scales in time and space
  - Atmosphere: fast, low resolution
  - Ocean: slow, high resolution
- Communication between models
  - Regridding, parallel computing
- Often 1,000,000s lines of code
  - Linux kernel: ~30,000,000 lines of code

Most ESMs don’t leverage modern computing



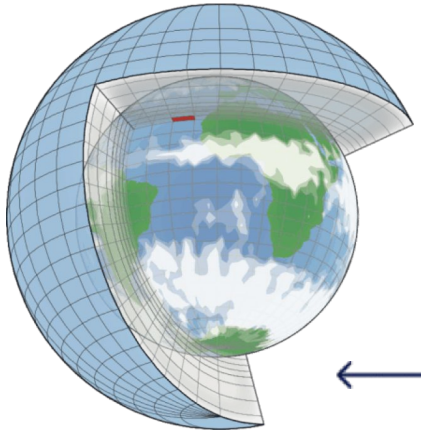
Source: “Computation, circa late 1970s”. Melissa Kean, Rice History Corner. April 14, 2022.

ESM simulations are very computationally expensive

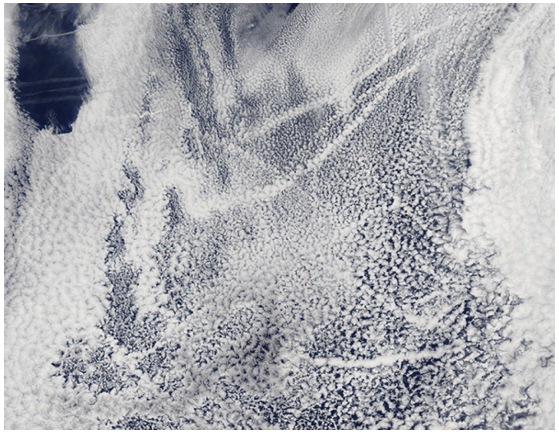
- ESMs typically run on 1,000-10,000s of CPU cores for weeks-months
  - Simulated years per day (SYPD) performance metric

- Requirements depend on temporal and spatial resolution

Many processes in the Earth system cannot be resolved at the global scale



Cloud scales:
~10-100 m



Global model:
~10-50 km resolution

Source: NASA MODIS

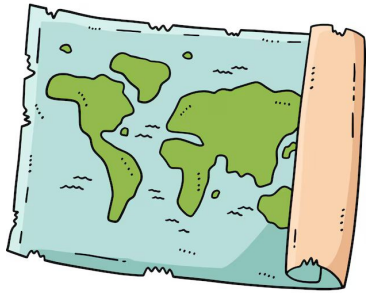
Parameters are often not well-constrained

- Some parameters can be precisely estimated
  - Gravitational constant (G)

- Many are not
  - Evaporation rate parameters

Performing scientific experiments with existing ESMs can be challenging

Roadmap



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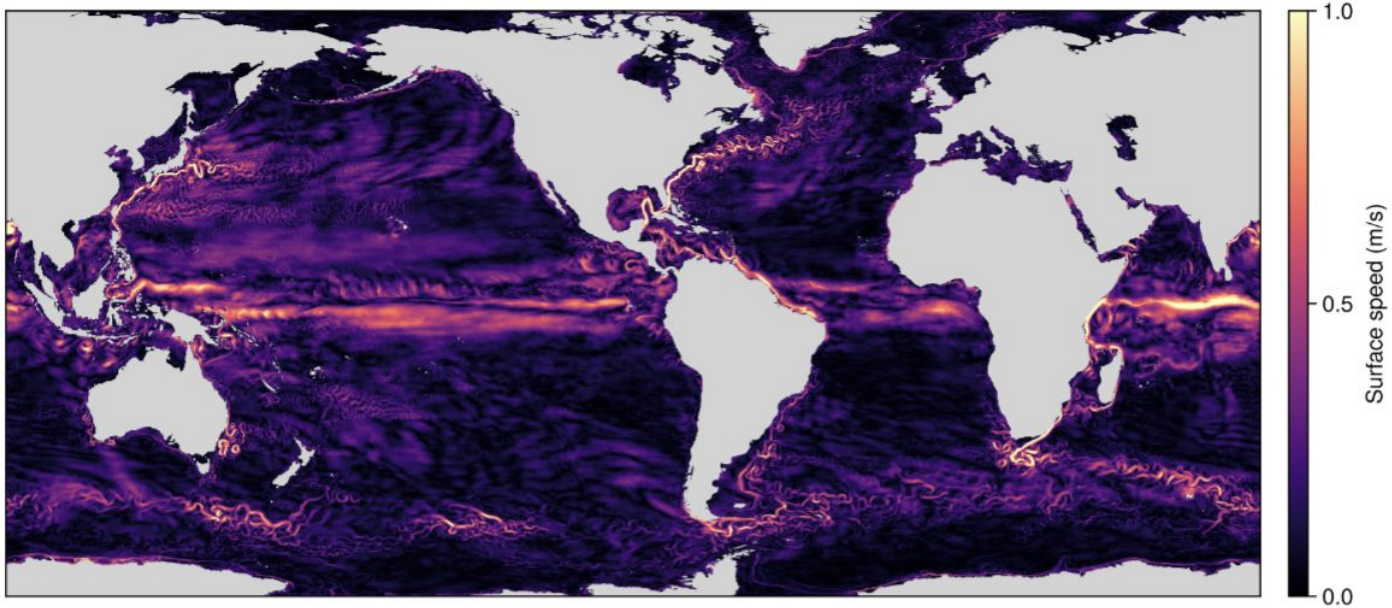
Oceananigans.jl is the first global ocean model to run on GPU



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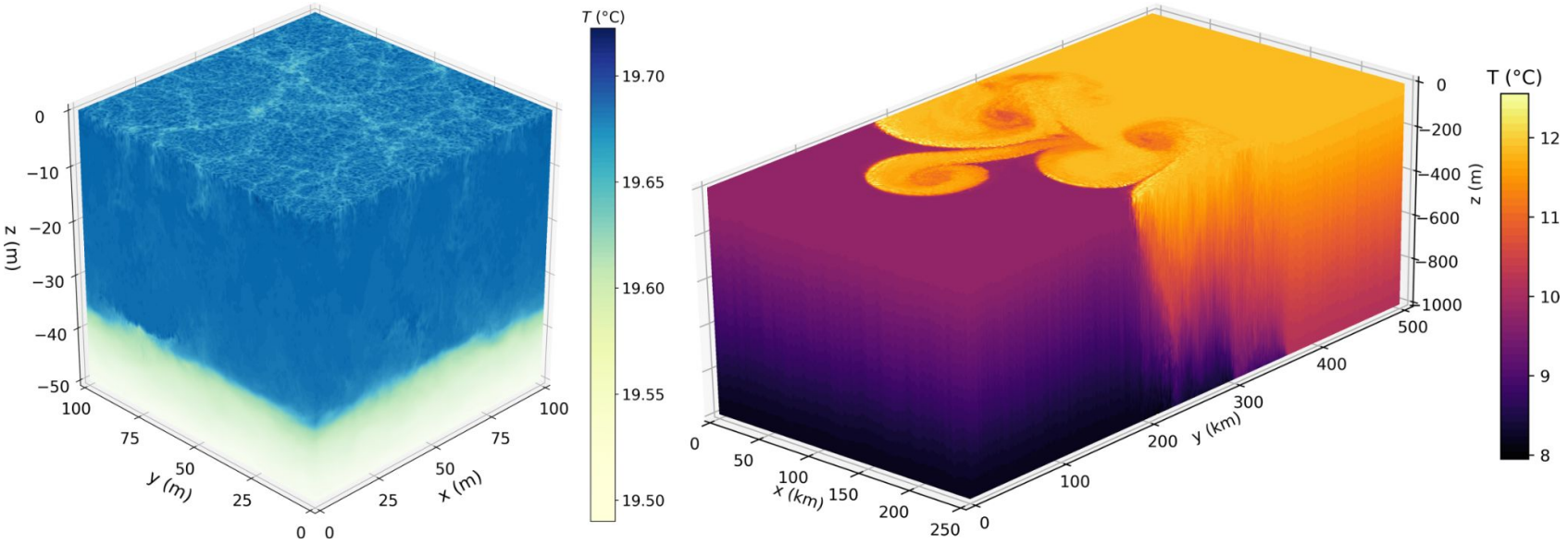
The ocean can be simulated on a regional domain



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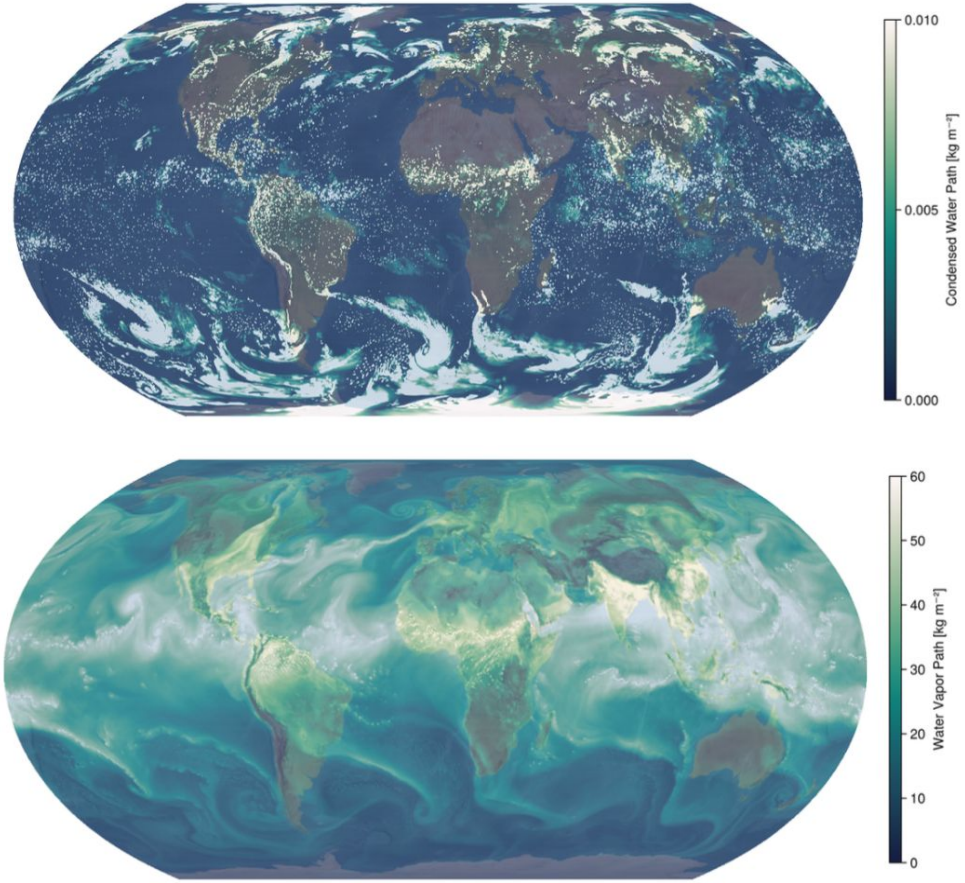
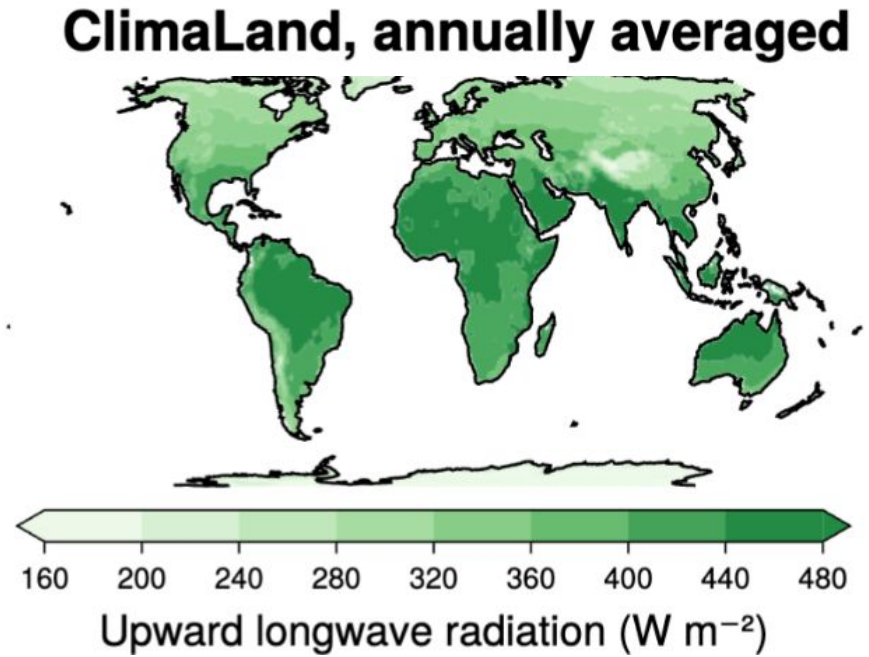
ClimaAtmos.jl output: clouds and humidity



ClimaLand.jl output: temperature

longwave radiation:
infrared radiation from
Earth's surface
(heat energy)



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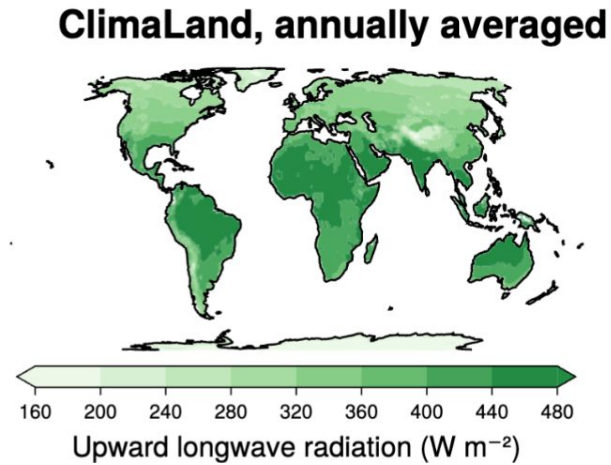
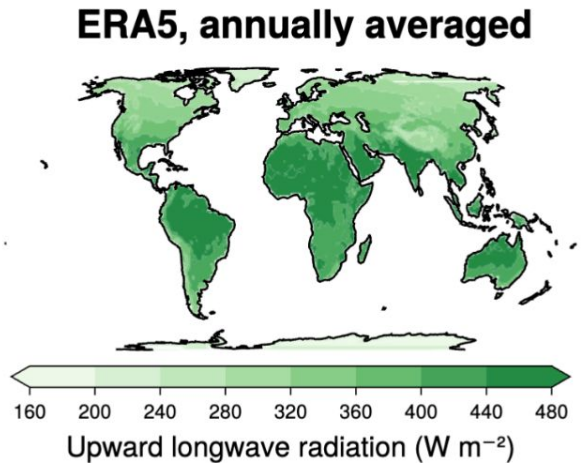
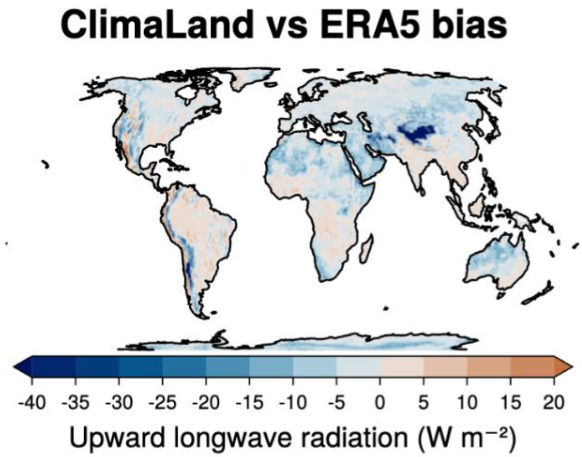
ClimaLand.jl performs well compared to data







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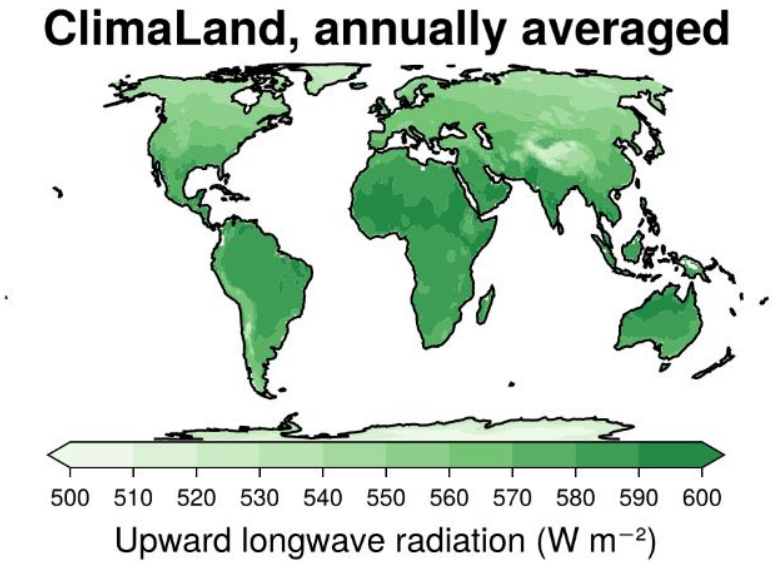
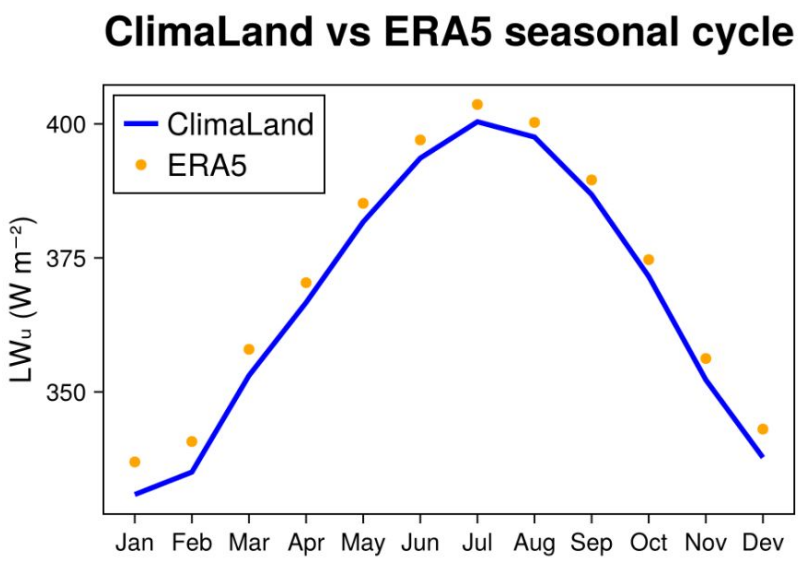
ClimaLand.jl captures the seasonal cycle





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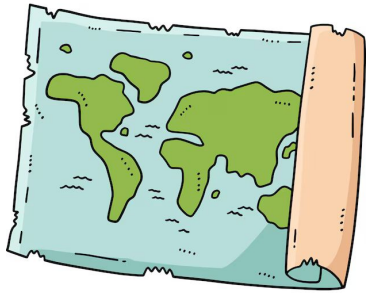

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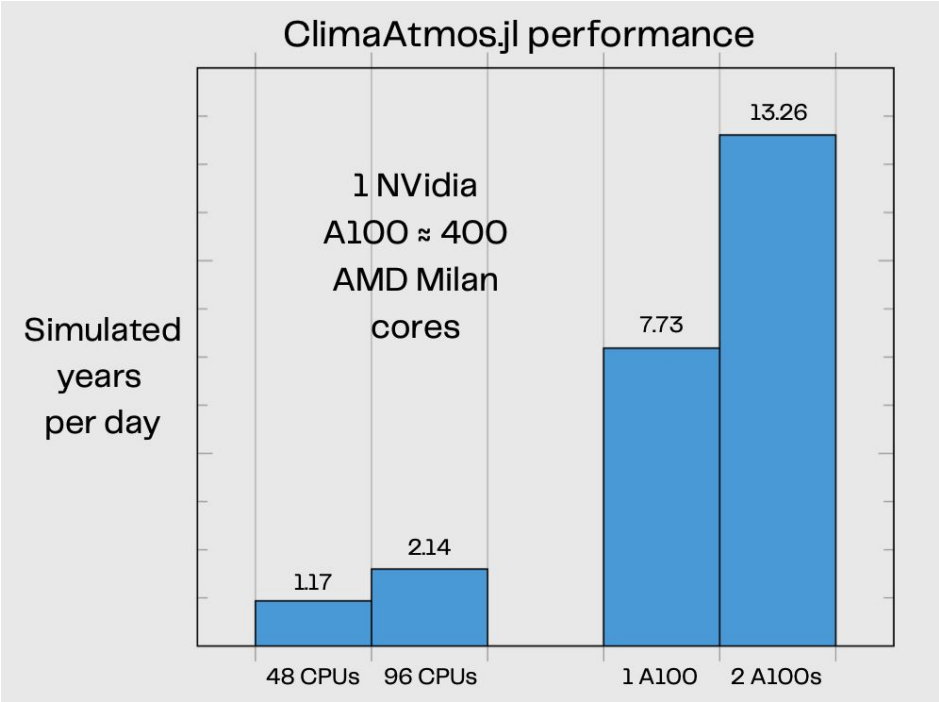
CliMA aims to tackle some main challenges of ESMs

1. Outdated computing practices (Fortran)
2. Prohibitively large compute requirements
3. Estimating small-scale processes
4. Poorly-constrained parameters
5. Enabling scientific experiments is difficult

GPU compatibility enables improved performance in ClimaAtmos

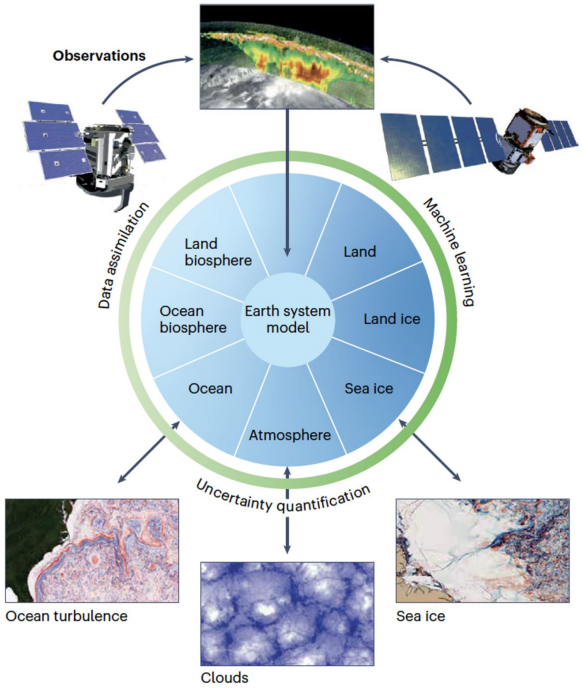
ESM challenge 1: outdated computing practices

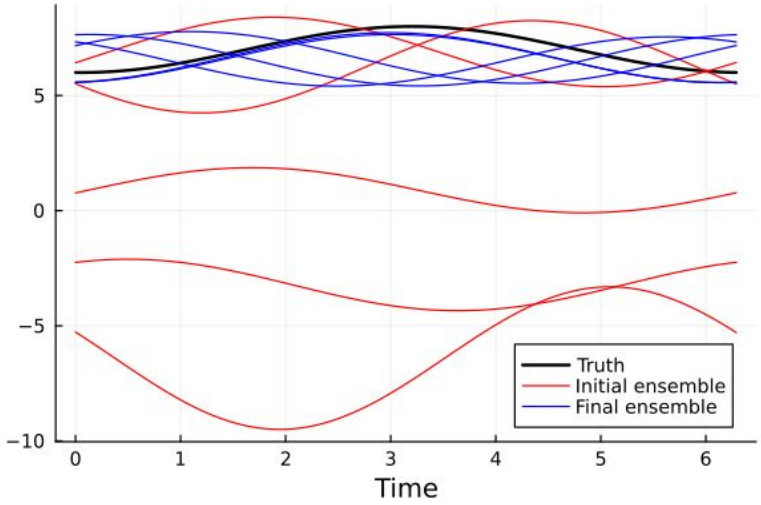
ESM challenge 2: prohibitively large compute requirements



Credit: Gabriele Bozzola, CliMA.

CliMA uses machine learning to calibrate parameters with observational data

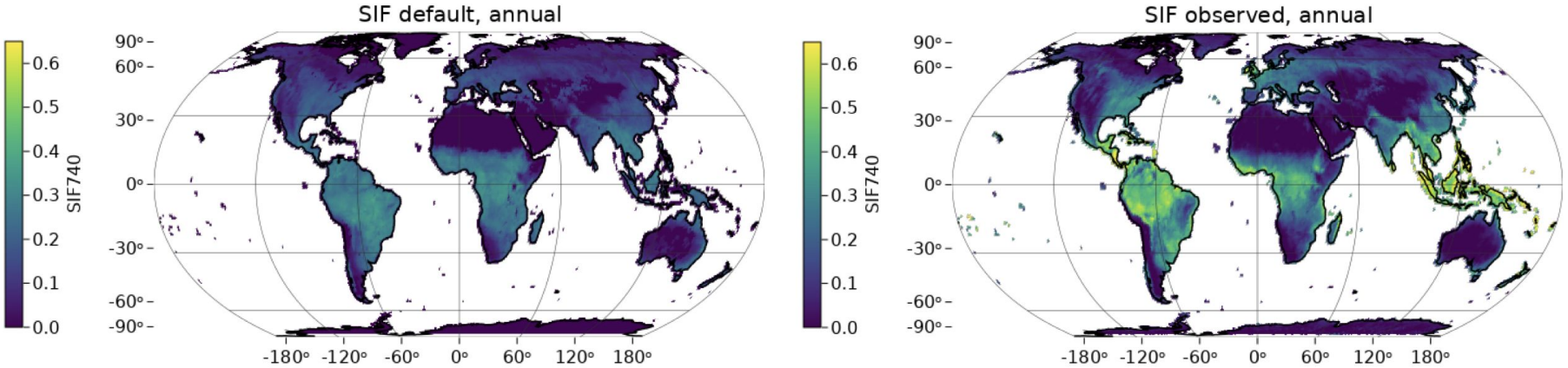




ESM challenge 3: estimating small-scale processes

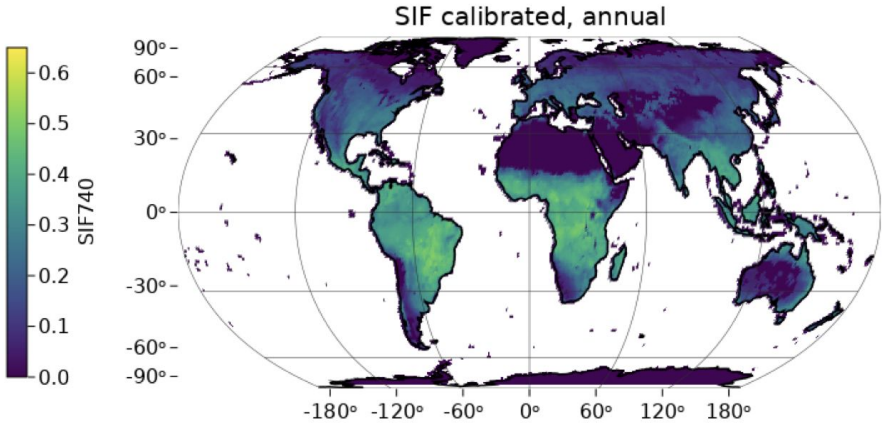
ESM challenge 4: poorly-constra parameters

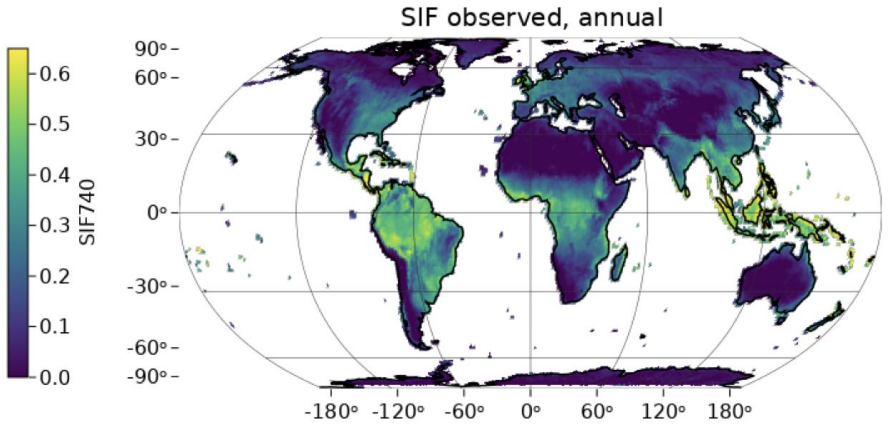
Land model calibration improved photosynthesis predictions



SIF: solar-induced fluorescence (measure of photosynthesis)

Land model calibration improved photosynthesis predictions





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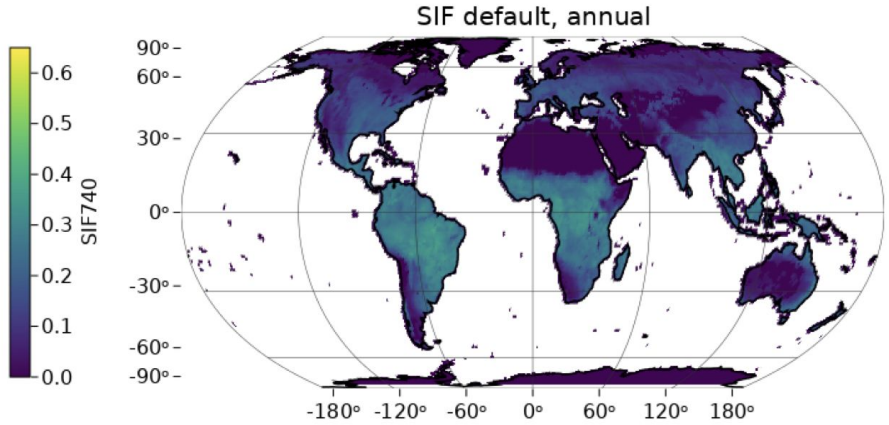
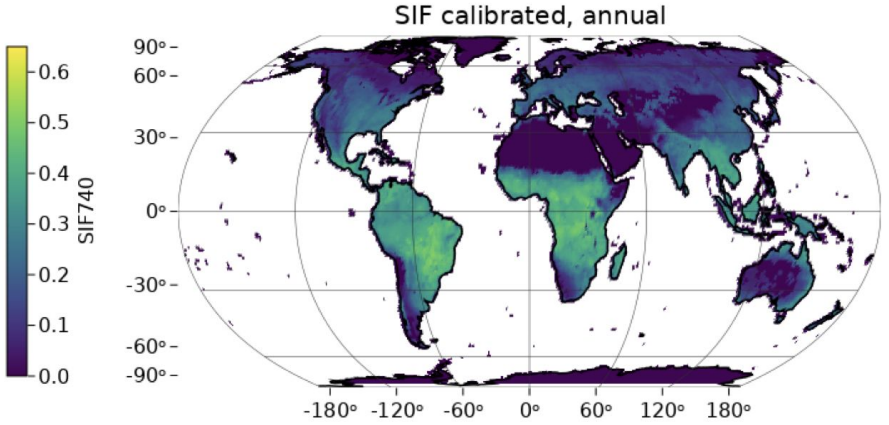
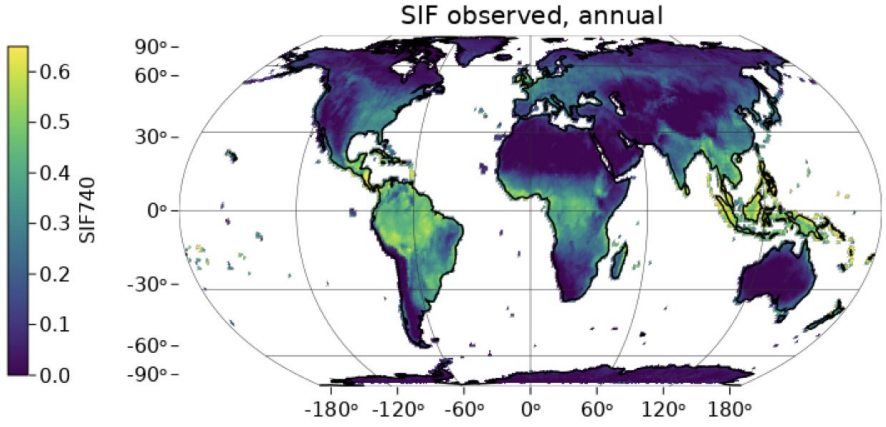

SIF default, annual
SIF740
0.0
0.1
0.2
0.3
0.4
0.5
0.6
90°
60°
30°
0°
-30°
-60°
-90°
-180°
-120°
-60°
0°
60°
120°
180°

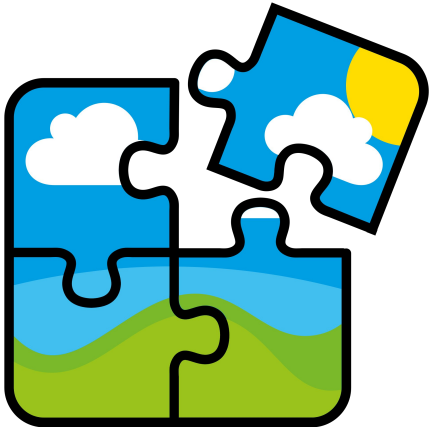

SIF calibrated, annual
SIF740
0.0
0.1
0.2
0.3
0.4
0.5
0.6
90°
60°
30°
0°
-30°
-60°
-90°
-180°
-120°
-60°
0°
60°
120°
180°


SIF observed, annual
SIF740
0.0
0.1
0.2
0.3
0.4
0.5
0.6
90°
60°
30°
0°
-30°
-60°
-90°
-180°
-120°
-60°
0°
60°
120°
180°

CliMA's modular design allows scientists to easily test new theories and compare models

- Modular design throughout the CliMA ecosystem
  - Atmosphere, land, ocean models
  - Model sub-components
  - Representations within model sub-components

- Open source → scientific collaboration!

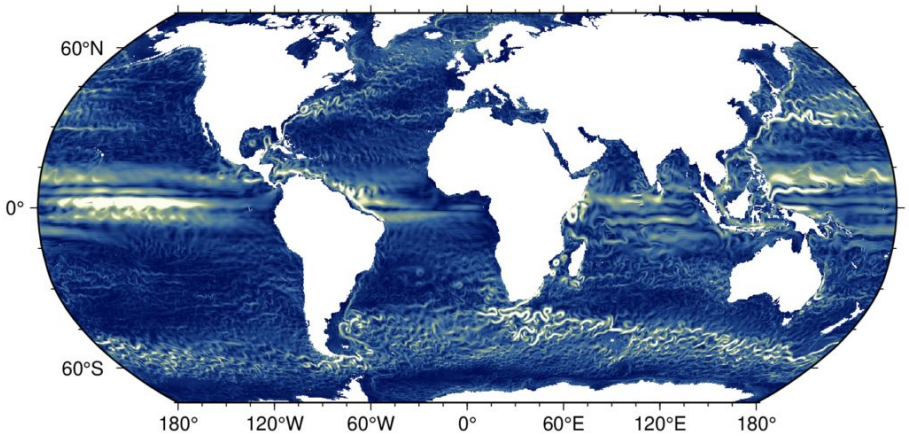


ESM challenge 5: enabling scientific experiments is difficult

Thank you to our sponsors!

Want to run an ocean simulation on your own laptop?

Scan this to see an Oceananigans.jl tutorial →



github.com/CliMA/Oceananigans.jl

Contact:
Julia Sloan
jsloan@caltech.edu

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- “Earth Day 2020: GEOS-5 Modeled Cloud Cover”. Youtube, uploaded by NASA Scientific Visualization Studio, April 24, 2020.
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