On the need to constrain Earth System Models using observations

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Accelerated Climate Change …

10 years after COP21 and shortly before COP30:

- **Human-induced changes have led to profound and widespread changes**. The last three decades has been successively hotter than those before; global surface temperatures soon surpassing 1.5°C.
- The increasingly rapid human-induced changes in the Earth's climate have led to **profound and widespread changes in the atmosphere, ocean, cryosphere, and biosphere.**
- **The world is in a state of 'polycrises' leading to cascading systemic risk and increasing inequality**, with unabated climate change being one of the greatest threats to humanity.
- **Emissions close to today's levels in the coming decades imply exceeding 2°C by the 2050s and close to 3°C by the end of this century.**

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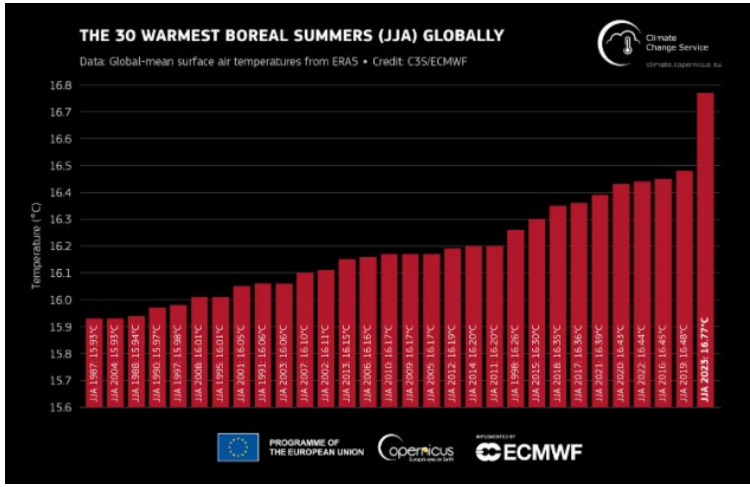
… rapidly changes the Context of Climate Research

- Climate change impacts are intensifying.
- Losses and damages, climate anxiety are intensifying.
- We see significant environmental degradation that needs to be considered by climate and environmental science.
- Growing tension about resources of water, energy, and food.
- Multiplication through regional conflicts and international tension.
- Growing inequalities, nationalism and populism.
- Declining social cohesion, increased polarization.
- Disinformation and erosion of trust in science.

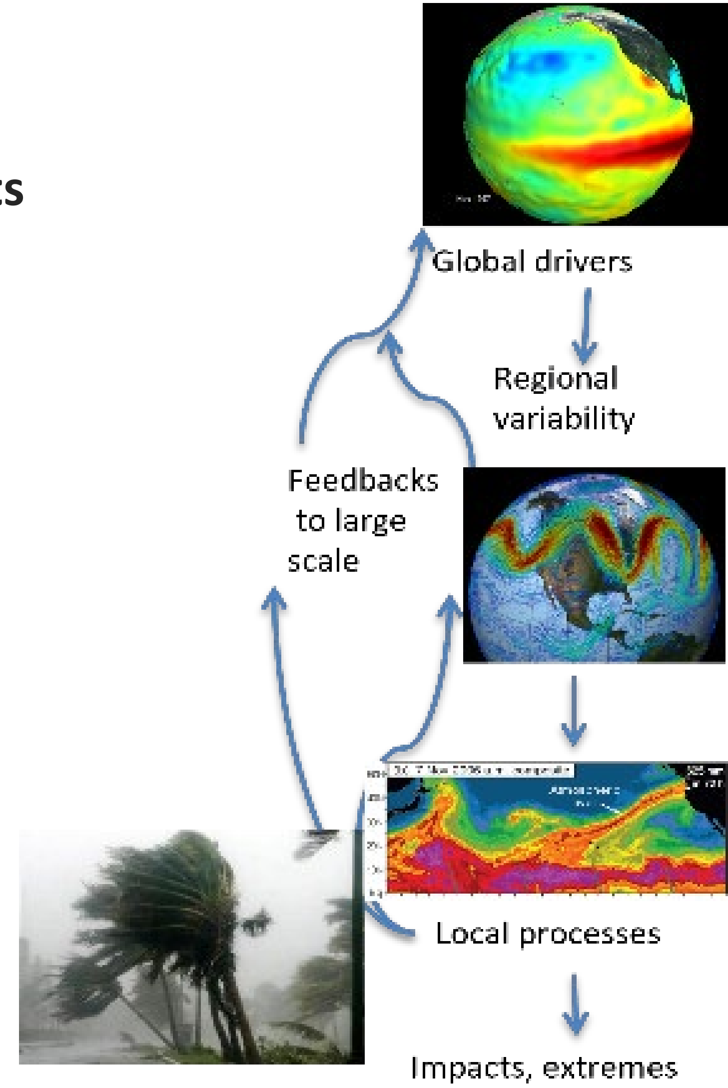
Challenge: System Understanding and Prediction

- **There are many aspects of climate system behaviour for which we still lack understanding.**
- **Specifically, an understanding of future circulation changes in the atmosphere and ocean, and the role of internal variability and forced responses is reqired – all crucial aspect of regional climate changes.**
- **Required is a better understanding of internal variability, tropical-extratropical interactions, ocean-land-atmosphere interactions**, eddies, jets, a more accurate localization of extremes, storms, and monsoon systems at the intraseasonal time scales.
- **Non-linearities and feedbacks need to be included.**
- **We should be capable of predicting anomalous years like 2023 as we should be able to predict other extremes around the world.**
- **Beyond increased basic knowledge, we need to develop solutions.**



Future directions for Climate and Earth System Research

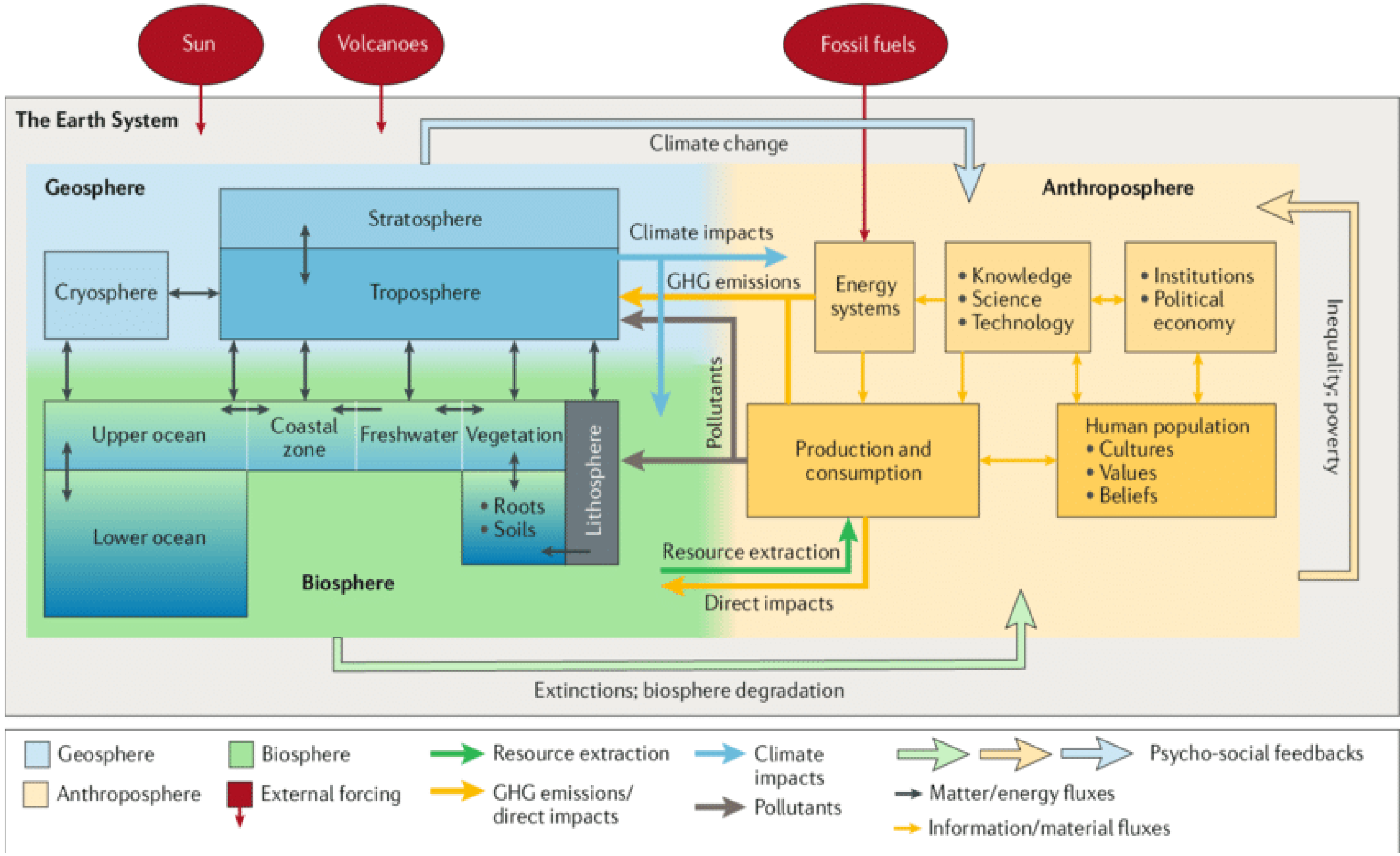
- Improve knowledge reg. water availability, biomass, land, ecosystem services.
  - **Support sustainable use of water, land, ocean (environment)**
  - **Establish plausibility and equity of scenarios - biogeophysical constraints**
- Assess mitigation and adaptation measures vs. new equilibrium climates.
  - **Feedbacks, regional variability, local processes**
  - **Patterns of sea surface change: How will tropical ocean temperature patterns co-evolve with those at higher latitudes?**
  - **Changing extremes: How will dangerous weather patterns evolve?**
  - **Water-carbon-climate nexus: How will the Earth respond to human efforts to manage the carbon cycle?**
- Assess possible new climates, their likelihood, their interaction with society.
  - **How will living be in a 4℃ or 5℃ world**
  - **What are the risks of triggering irreversible changes across possible climate trajectories?**
- **Provide climate information for all regarding climate change hotpots, ecosystem stewardship.**



New challenges require improved Earth System Models

To cope with this, the role of climate modeling must evolve to: supporting science, providing answers, informing decision makers

- Go **beyond the physical climate system** to include a predictive capability for marine and terrestrial ecosystems
- Provide an **accurate description/ simulation** of the Earth System (Earth System Reanalysis, digital twin).
- Provide a **predictive capability** for the Earth System on time scales (days, seasons, decades).
- Provide policy and decision relevant information on the implications and ramifications of environmental prediction (Earth System Services).



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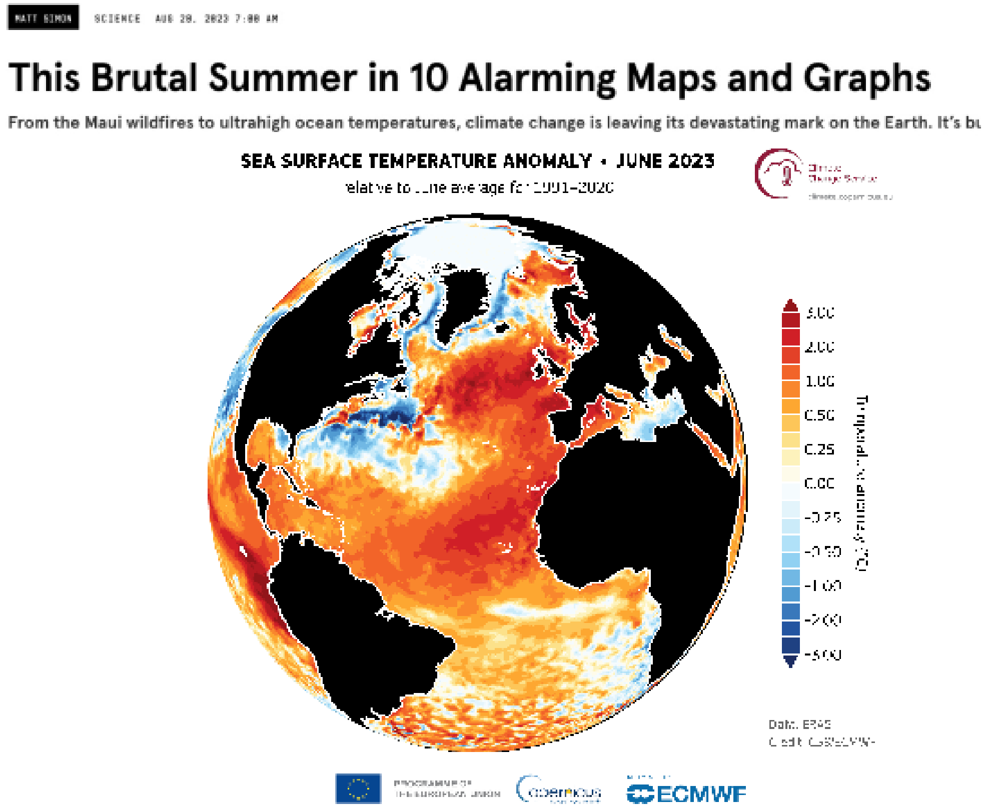
Challenges: Regional Climate Modeling

- Although the global picture of climate change is consistent, and well explained, thanks in part to the modelling, the emerging **observational record is increasingly showing patterns of change that we can't explain and model**.
- **Problems of longstanding climate model biases remains**, notably in regional precipitation and teleconnection patterns.
- **Reducing model deficiencies** in simulating internal variability modes, tropical-extratropical interactions, and ocean-atmosphere-land interactions are all important.
- **Increazing model resolution** will remedy many problems.



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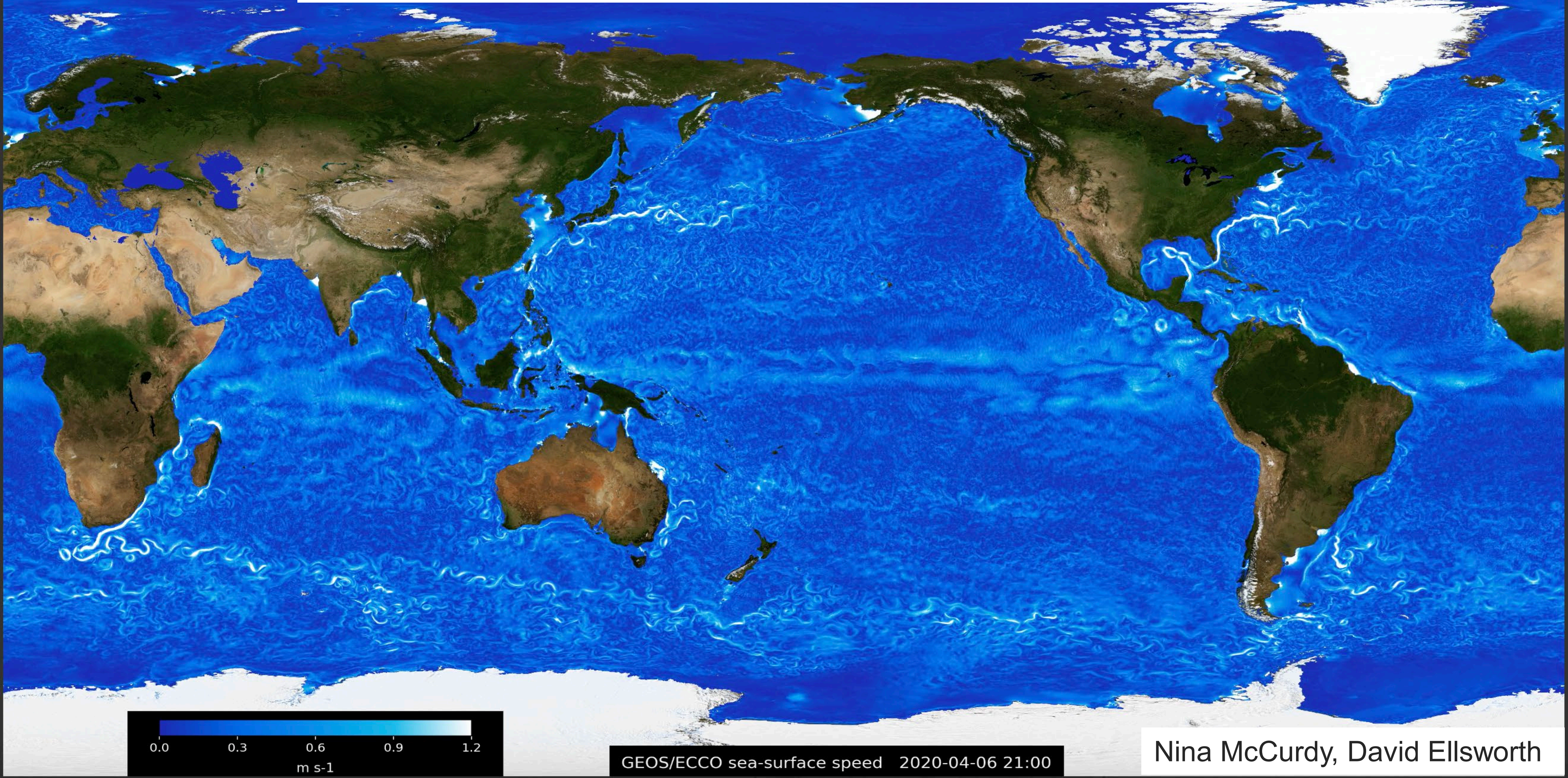
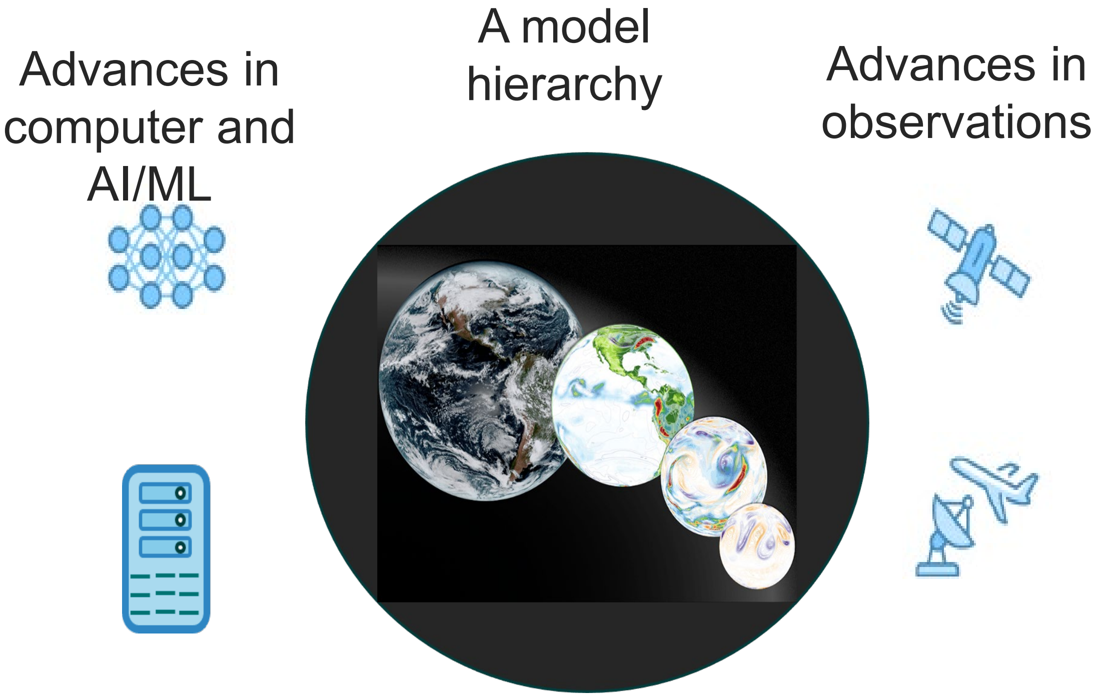
Coupled ocean-atmosphere model, 1km resolution



Sea-surface speed from a coupled ocean-atmosphere simulation with kilometer-scale resolution. Speed increases from black (0 meters per second, or sm/s) to blue (~0.5 m/s) to white (>2.5 m/s). The animation shows many concurrent processes including large scale and mesoscale eddies, tides, and the surface signature of internal waves. *Nina McCurdy, David Ellsworth, NASA/Ames*

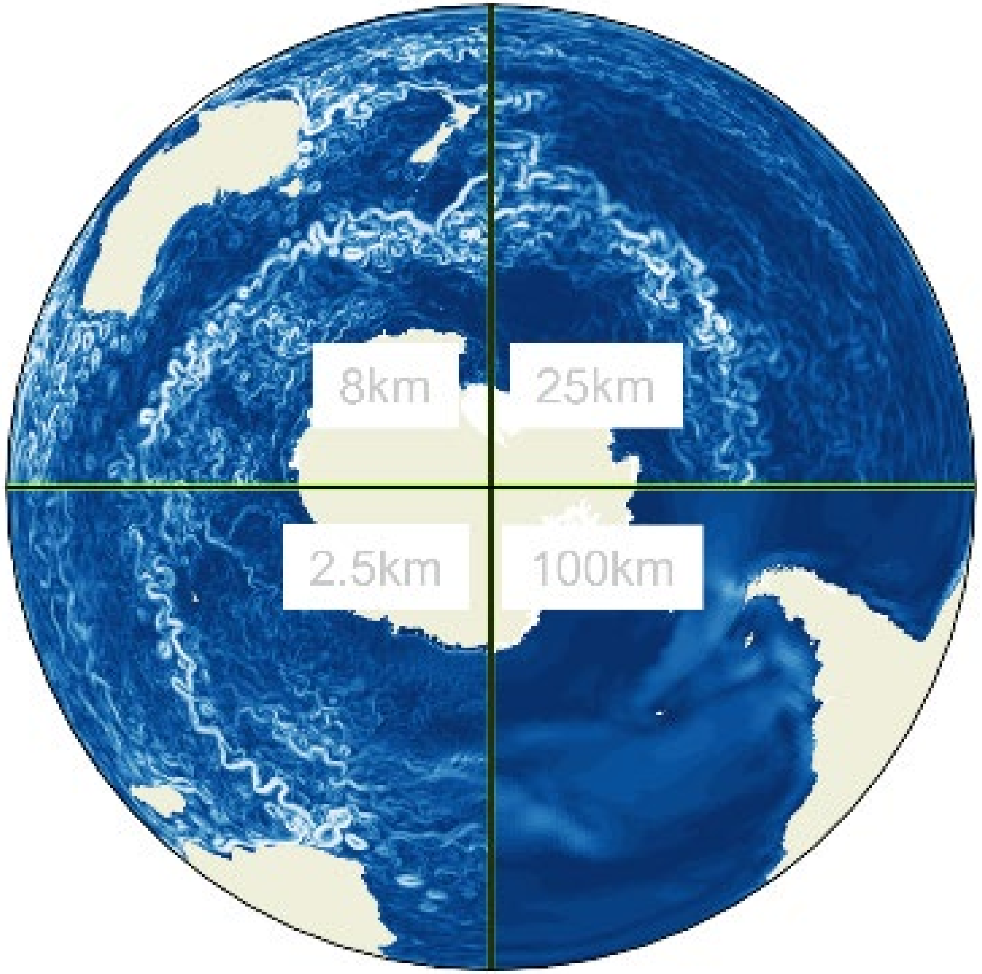
Opportunities Climate Modeling

- **However, climate models will always be prone to some biases and will produce climate features and variability which will differ from the real world.**
- Without understanding **the causes of regional model-data differences** and their cure it will be difficult to **effectively communicate impacts of regional climate change to the public** or to produce actionable climate information.
- A model hierarchy is required to better connect models with theories and observations and to improve models in support of climate research.
- **Data Assimilation needs to be part of this hierarchy as an integral means to reduce biasses, to provide syntheses/reanalyses and to support predictions.**



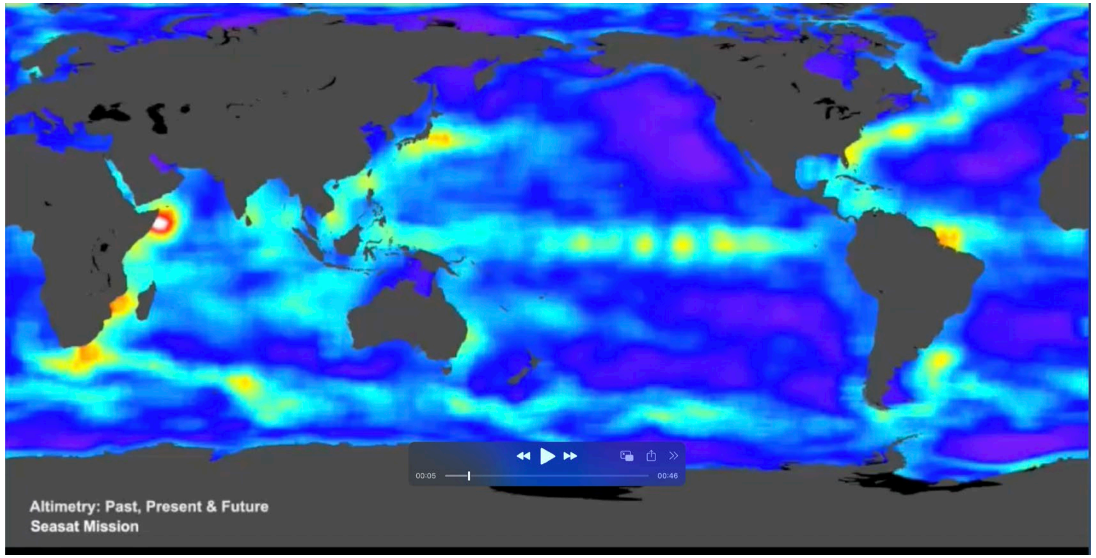
Need for an Earth System Modeling Framework

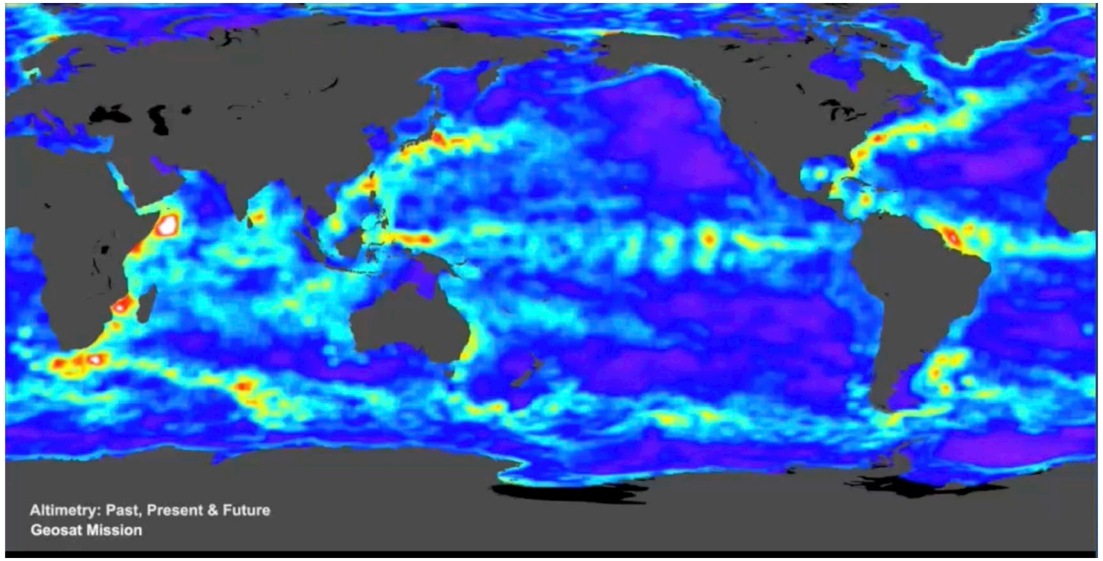
- Establish work across the modelling multiverse:
  - **km-scale coupled atmosphere, ocean, land surface and ice modeling**
  - **Link up resolution, ensembles and complexity with regional and local information (city scale).**
- Assess and **improve Earth System observational capabilities** within an **Earth System Reanalysis** and predictive context.
- Develop **advanced forecasting capabilities** for all aspects of the Earth system on lead times of weeks to seasons to decades (early warning)
- Develop **improved assimilative approaches as integral part of ESMs** to **facilitate coupled Earth System Reanalysis for model improvement, bias reduction, initialization, accounting for new observing capabilities.**

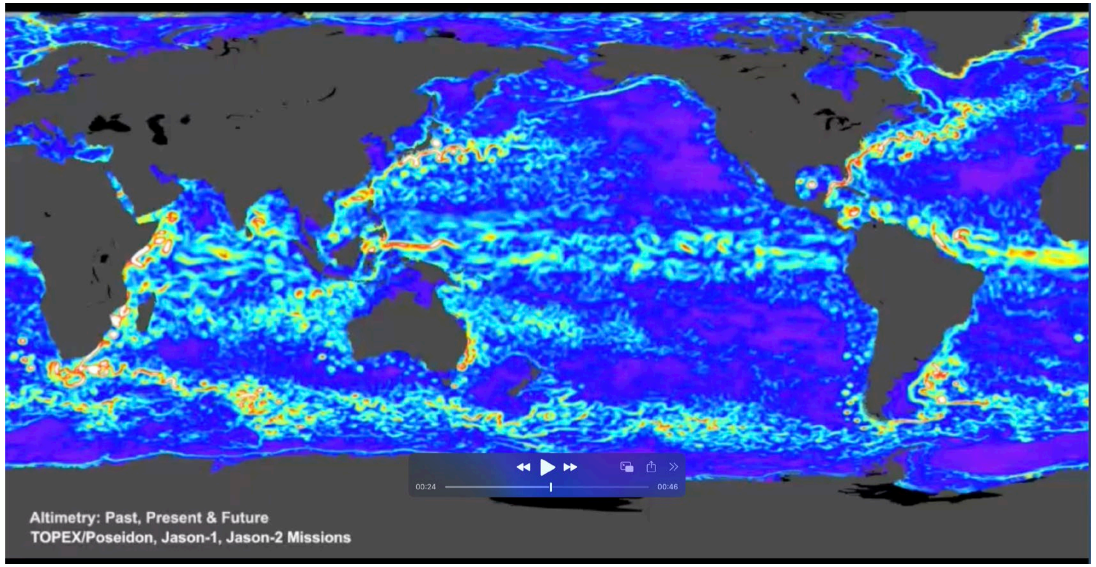


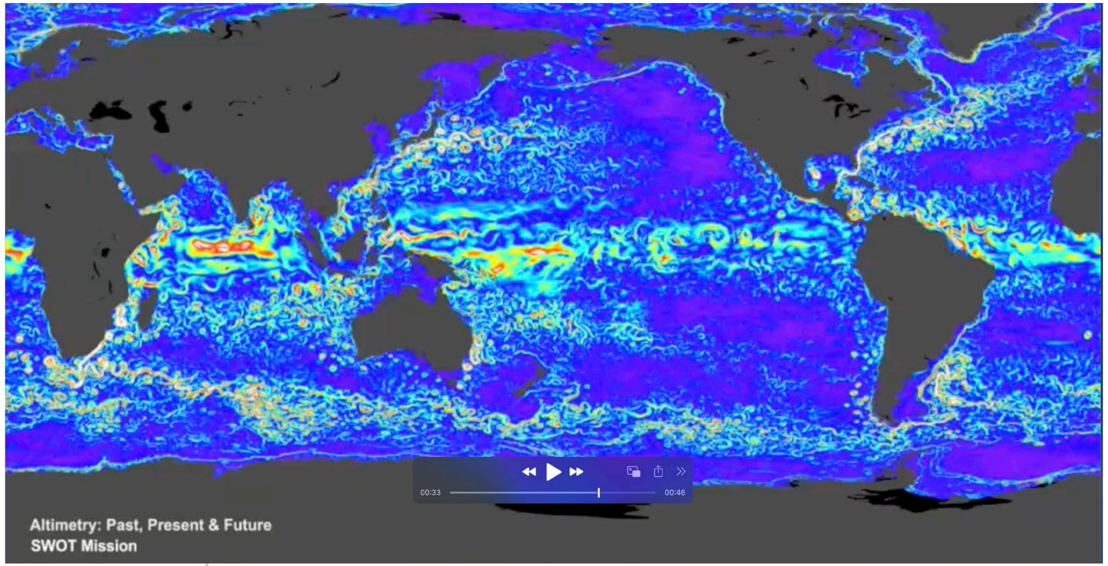
Hewitt et al., 2022

Example: Advancement Altimetry from Seasat to SWOT









Opportunities Coupled Climate Data Assimilation

- DA will be the central tool to bring **coupled climate models and climate observations** into consistency, by improving initial conditions, inferring uncertain model parameters and structure, and **quantifying uncertainty**.

- To realize the full capabilities of **climate DA**, we as a community, need to **advance science and technologies** for analyzing and merging global observations and Earth system model data.

- This step needs to be rapidly taken before **full Earth system models, including representation of biogeochemical cycles and ecosystems**, can successfully be constrained and improved by the existing stream of Earth observations in the context of **Earth System Reanalysis**.

Complementarity of Traditional Data Assimilation and ML

- There will be **advantages and complementarities of assimilation approaches**, including adjoint-based smoother approaches, ensemble-based filter approaches, or new ML/AI-inspired approaches.

- Using the complementarity in a hybrid approach, **blending tools and concepts** from variational, ensemble, and ML methods will be required in the future. In this context, ML could be important to handle nonlinear responses and to better approximate non-Gaussian distributions.

- But more and more processes need to be included such as ground water and biogeochemical cycles in the full Earth system.

- Ever-increasing model resolution will present **growing challenges** arising from computational cost, calling for new ways of performing data assimilation and model optimization, also dealing with non-linearities or data sparseness.

Steps required for Progress in Earth System Data Assimilation

- Improve Exploitation of Earth Observations and model-data differences
- Development of AD and ML Infrastructure
- Advances in Ensemble and Variational DA and ML Theory and Methods
- Model Improvements through Parameter Estimation
- Performing full Earth System Reanalyzes
- Enhanced knowledge of the Earth system and its future evolution and improving climate forecasts and early warning systems

Outcome of Workshop: Improving Climate Models and Projections Using Observations Workshop 2023

Workshop Report BAMS, 105, pages E1399-E1406, DOI10.1175/BAMS-D-24-0110.

Development of AD and ML Infrastructure

DA requires the availability of modern infrastructure and effective training.

Calls for open-source AD tools for the generation of adjoint codes and the availability of ML environments tailored to Earth system modeling applications that seamlessly integrate with climate model codes.

The existing Earth system model environment needs to be able to deal with both.

Actions/Opportunities:

- Develop, maintain **open-source DA and AD toolboxes for modern code differentiation and optimization.**
- Develop **ML toolboxes** applicable for **unstructured observations**.
- Cyber infrastructure and hardware considerations
- Improve computer software
- Development of **cookbook**, sharing information

Exploitation of Earth Observations

DA depends on the availability of calibrated and quality-controlled observations.

However, much more information is required from observations prior to performing DA.

DA can feed back information about the observing system and its required modifications.

Actions/Opportunities:

- Maintain assimilation data streams (move from **obs4mips to obs4assi**): provide obs. as original as possible plus uncertainties; holds for all Earth system components
- **Generate reference data sets**, removing inconsistencies. Produce error information (error covariances). Infer correlation matrices.
- **Study information content and flow from model-data differences**: spacetime dependent errors vs processes (e.g., ensemble spread).
- Promote **data archeology**.
- **Identify gaps in observing system** (e.g., more Argo in Arctic). Exploit untapped parameters existing in the suit of available obs.

Advances in Ensemble and Variational DA and ML Methods

Significant innovation in DA approaches and theoretical advances are required.

This also applies to uncertainty assessment and to ways modeling can be driven or at least guided by observations:

Actions/Opportunities:

- **Theory** for uncertainty quantification
- Data assimilation **approaches for coupled data assimilation**
- Improve understanding of **information flow**
- Improve theories and methods to deal with **sparse, nonlinear systems**
- Further advance **data-driven climate modeling and model improvements**
- Improve exploitation of existing data sets; expand suit of parameters that get assimilated (e.g., cloud or aerosol information).
- Dealing with **chaos and non-linearities in the data assimilation** (e.g., synchronization)
- Exploring potential of **hybrid assimilation methods** (mix of smoothers, filters, ML …)

Model Improvements through Parameter Estimation

To reduce model biases, model physics needs to be improved by improving model structure and optimizing model parameters based on observations.

It is especially the latter aspect that can lead to progress, although the former aspect can be addressed as well. Several steps are needed:

Actions/Opportunities:

- **Model improvements** through (non-local) **parameter estimation** (bias reduction); has to be model resolution dependent … Should maximize usage of flow of information.
- Include **missing component**s, e.g., wave models, bottom topography, …
- Estimation of unknown mathematical formulations (ML). E.g., Improving formulations and parameters in (no-linear) boundary layers.
- **Inclusion of more control parameters and observations** (e.g., clouds, aerosols, soil moisture, land surface coverage, bottom topography, ice shelfs, loading and (self) attraction, BC, …)

Pilot Earth System Reanalysis

Strongly coupled variational data assimilation featuring long assimilation windows

CESAM (Centre for Earth System Science Earth System Assimilation Model)

- **Components**
  - + **Ocean** general circulation model MITgcm
  - + **Atmosphere** spectral general circulation model PlaSim
  - + **Land surface and soil** parameterizations
  - + **Sea ice** fraction climatology
- **4D-VAR/adjoint** for coupled system (strongly coupled) from AD compiler

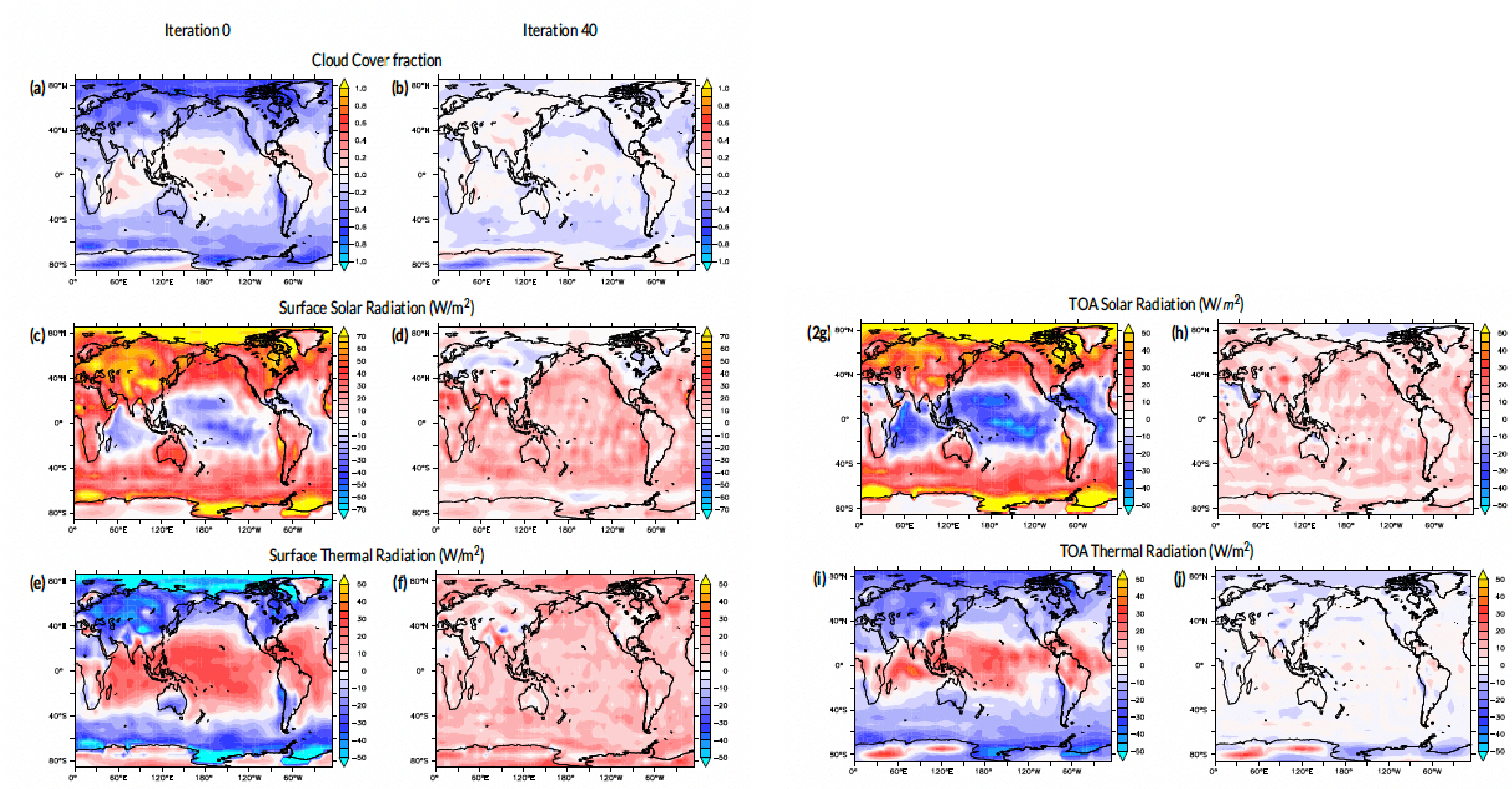
Optimization over 39 years, using the intermediate complexity adjoint **Earth System Model CESAM**.

Demonstration that **efficient assimilation** of in situ and satellite ocean data and reanalysis atmospheric data is possible by adjusting the surface fluxes and internal model parameters.

This **pilot application** requires nearly complete information on the atmospheric state for synchronization (ERA5 data) and a simple nudging technique to achieve synchronization.

Köhl, A., I. Polkova, G. Lyu, F. Lunkeit, A. Banerjee, S. Schubert, D. Stammer 2025:
A pilot variational coupled reanalysis based on the CESAM climate model. QJRMS, under revision.

Parameter Estimation Leads to Strong Bias Reduction



Reduction

of

ocean biasses

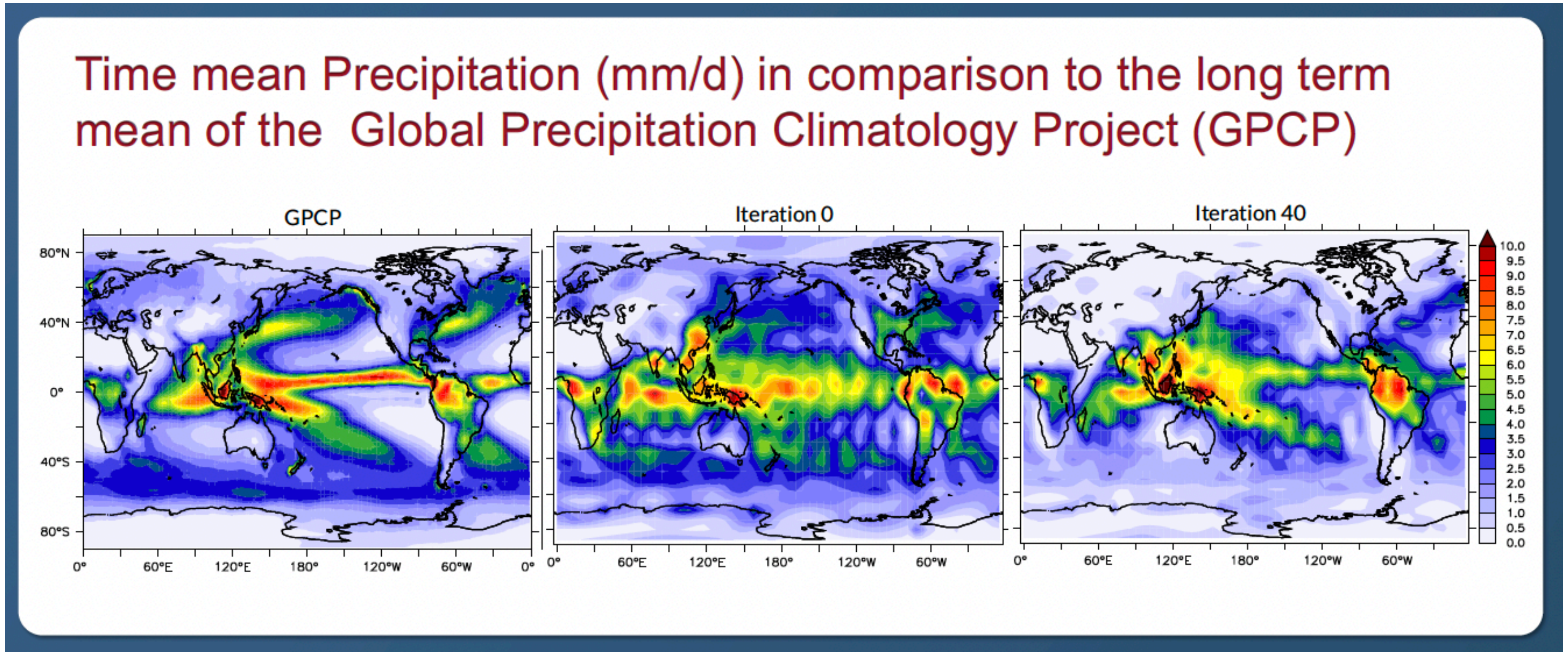
SST

T at 170m

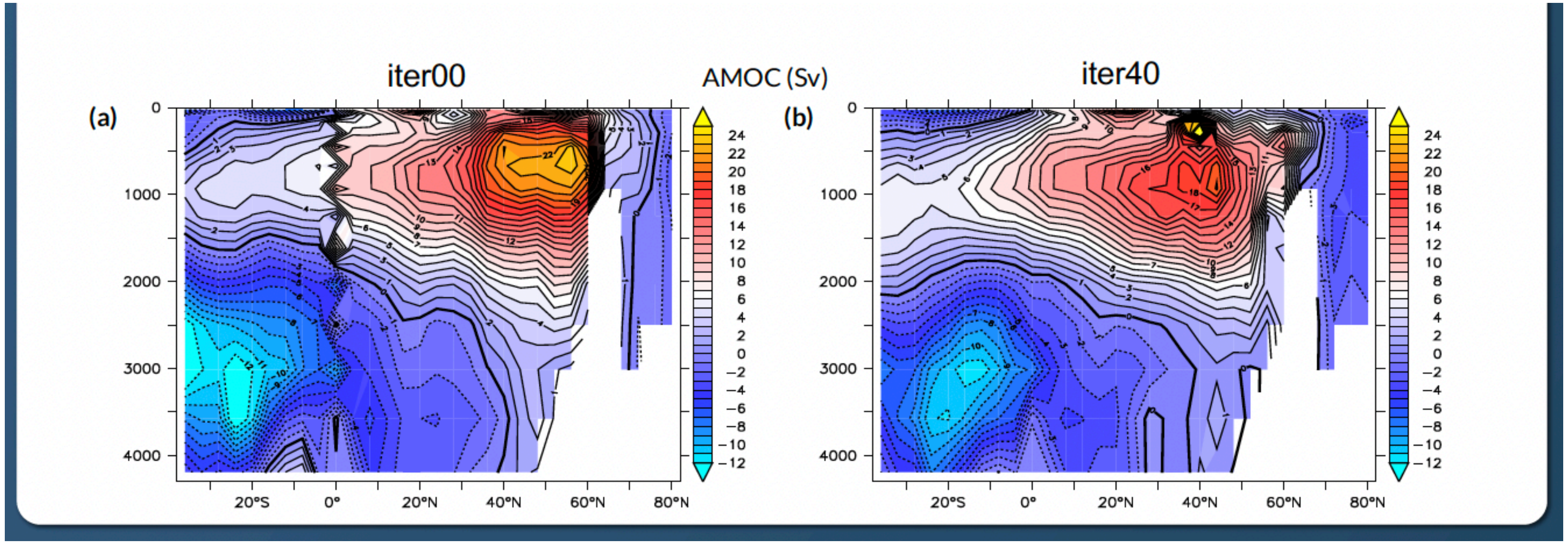
S at 170m

Improvement of (mean) Climate State

Precip.



AMOC



Improvement of (mean) Wind Stress

The Way Forward

- Improving understanding and capabilities to predict Earth system calls for an **Integrated Earth system modeling, calibration, analysis, and assimilation framework**.
- System can be used to continuously improve Earth system models while advancing knowledge about processes involved in the changes in the state and transport of heat, water, carbon, and biogeochemical constituents
- Framework must take advantage of the **vastly expanding, yet diverse observational data streams**. It must go beyond a simple coupling of existing estimation systems by building a **truly integrated system and involving multimodel approaches**.
- Establishing an **Earth system modeling and reanalysis system** represents a **frontier** in climate science involving modeling, observation, DA, and computational science. Requires many steps, involving theoretical aspects of data assimilation, improving assimilation infrastructure, and improving data information extraction.

Call for EU Program on Earth System Data Assimilation

Goal: Realize full Earth System Reanalysis to improve understanding, to improve Earth system models for predictions and projections and to expand climate services.

Needs to include: Regional Earth System Analyses and Predictions

Required DA applications to full Earth system models are far beyond what can be accomplished today. They require fundamental infrastructure developments and bring significant challenges to the forefront, also by including biogeochemical cycles and ecosystems to **improve water, carbon, energy cycle estimates**.

Required **hybrid assimilation concepts** were already called for by Bengtson et al. (2007) involving innovative data assimilation techniques that deal with sparse data and **preserve dynamics and budgets (first principles)**.

Such an EU program will be a win-win situation, **leading to exceptional ground-breaking R&I in the context of transparent and reproducible approaches to** Earth System Modeling and and climate services.

Application: Regional Earth System Analyses and Predictions

- **Develop digital twins for for large-scale AND regional aspects (cities, coastlines, etc.)**
- Develop couple high resolution **assimilation systems** that account for the interactions between humans, climate, CO_2 sinks and sources, air quality, hydrological and biological processes and their perturbations by humans.
- **Deal with regional context-related aspects** coastal systems/sea level, megacities, tropical forest, Arctic …
- Include land surface processes, soil moisture and **agricultural forecasts.**
- Include a predictive capability for **water and water quality, agriculture, disease vectors and other health aspects.**