World Climate Research Programme

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The Future of Ocean Modelling

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World Climate Research Programme

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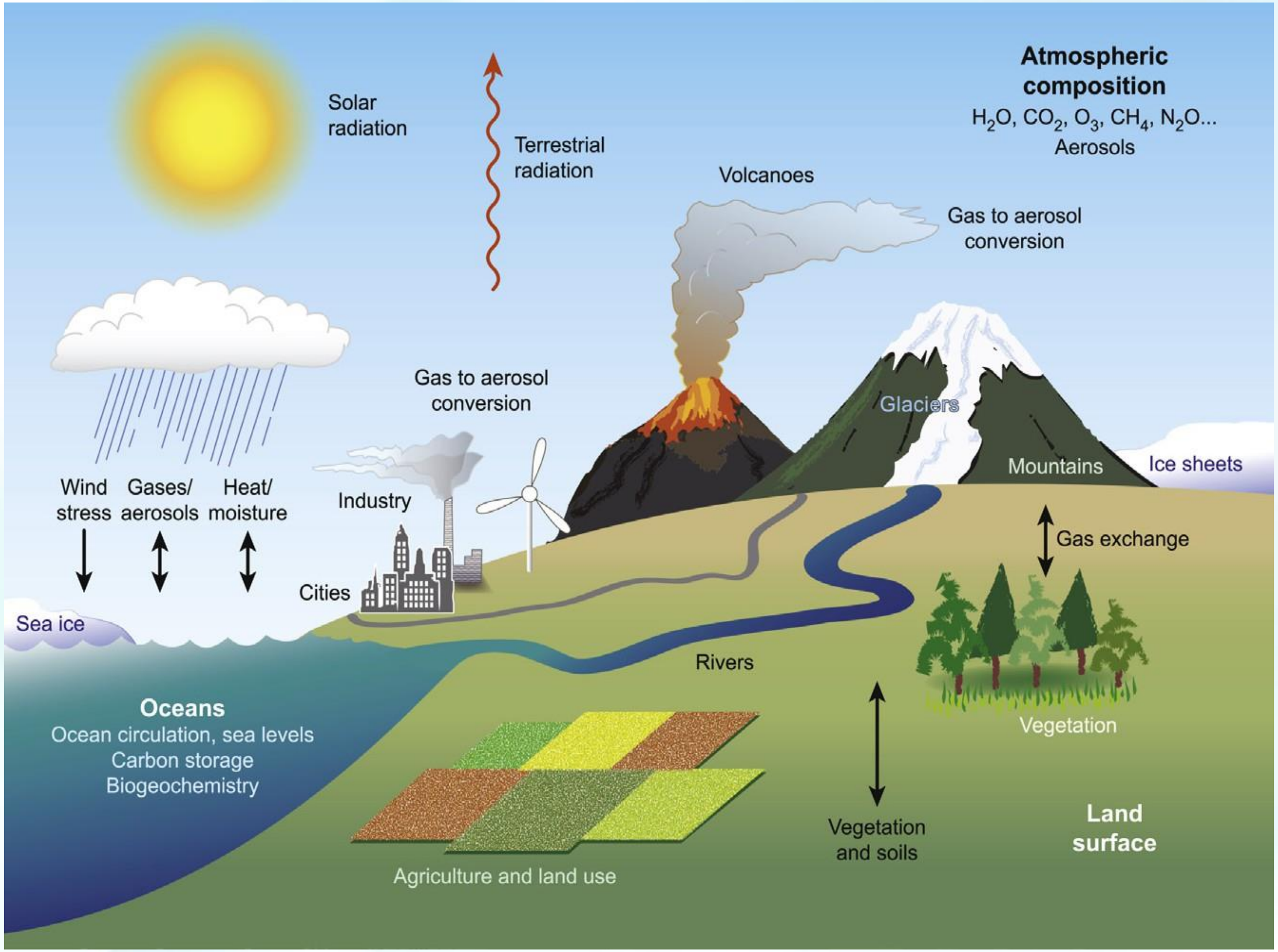
The whole Earth System



The physical climate
(the interacting atmosphere, ocean, land surface, and sea ice)
+

Biogeochemical processes that interact with this physical system (e.g. the carbon cycle and its connections to the terrestrial and oceanic ecosystems)
=
The whole Earth System (as we know it today)

D. Hartmann, (2016)

History of climate modelling

- The earliest and most basic numerical climate models are Energy Balance Models (EBMs). EBMs do not simulate the climate, but instead consider the balance between the energy entering the Earth's atmosphere from the sun and the heat released back out to space. The only climate variable they calculate is surface temperature.

- Climate models emerged from models that were developed for weather prediction since around 1940. Modelling atmospheric processes and circulation is the cradle of climate model development.

- In the mid 1960s, almost 20 years after the development of the first models for the circulation in the atmosphere, three-dimensional ocean models were formulated (Bryan and Cox, 1967; Bryan, 1969).

A numerical investigation of the oceanic general circulation

By KIRK BRYAN and MICHAEL D. COX, *Geophysical Fluid Dynamics Laboratory, Environmental Science Services Administration, Washington, D.C.*

(Manuscript received October 5, 1965)

History of climate modelling - ocean

- **Syukuro Manabe** was a pioneer in developing the first coupled climate models. In a collaboration with **Kirk Bryan**, they presented the first coupled climate model that **simulated the general circulations of both atmosphere and ocean (Manabe and Bryan, 1969).**

- This configuration captured the essential elements of the global climate system while still computationally feasible in the mid 1960ies.

- The salient features of the atmosphere, and the key elements in the ocean, such as the vertical temperature distribution, the gyre circulations with their western boundary currents, and the thermohaline circulation, were simulated.

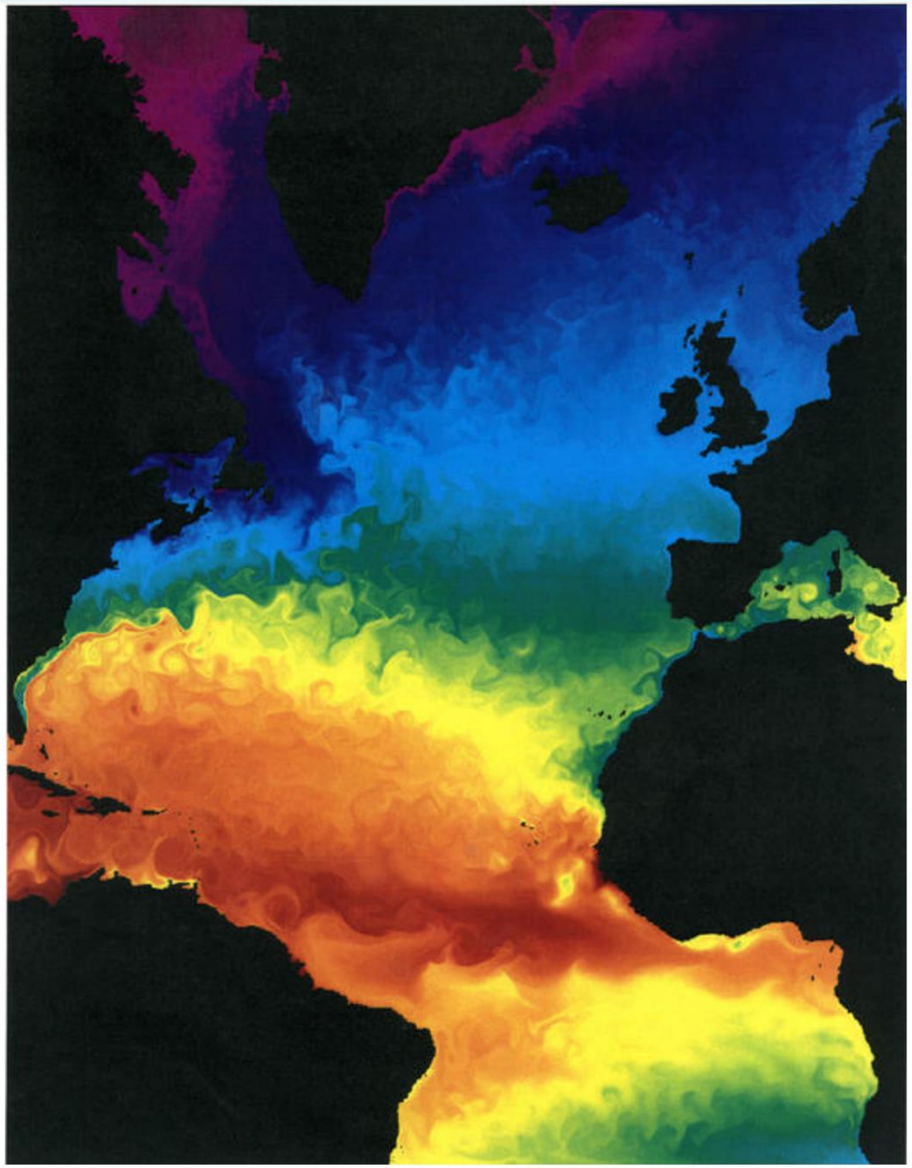
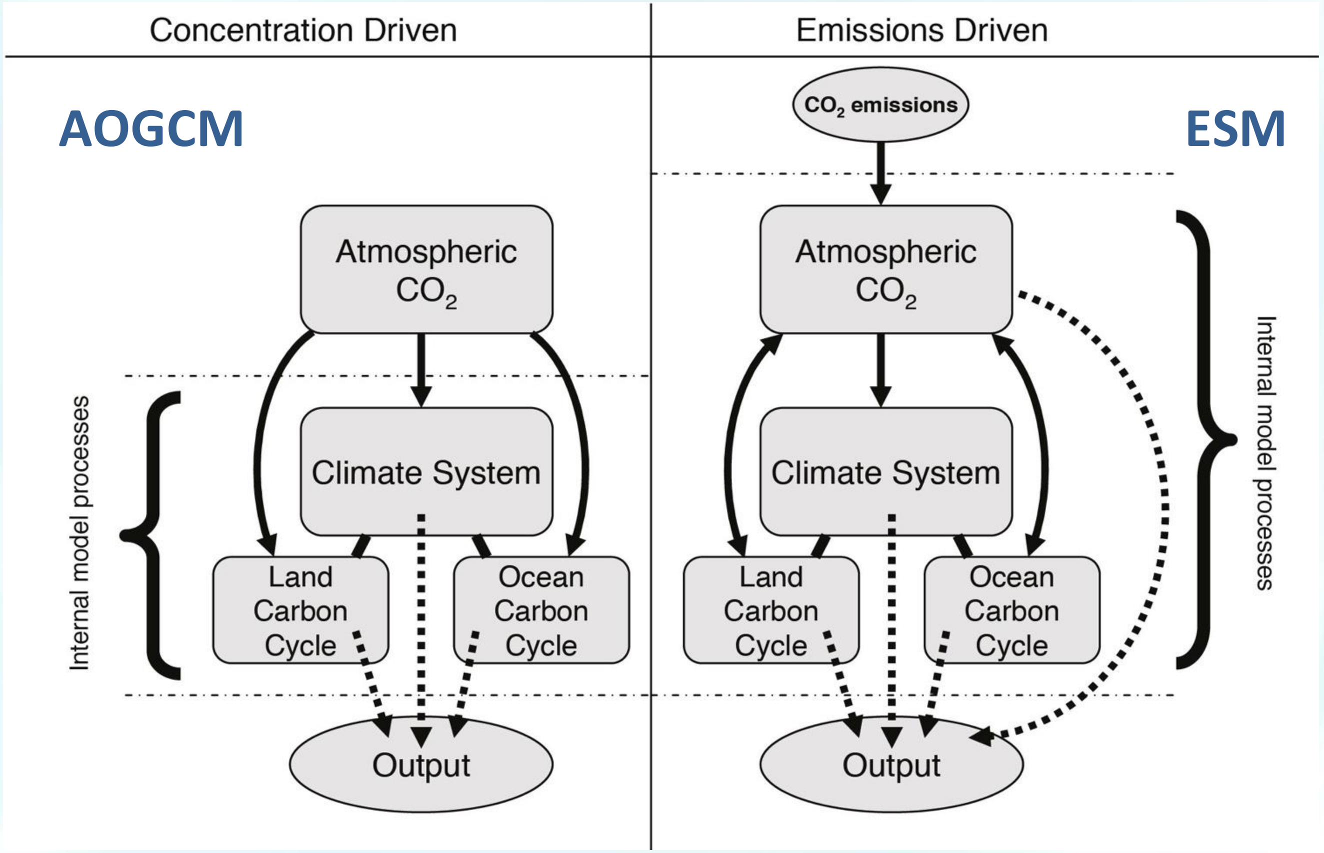


Figure 13: Instantaneous sea surface temperature from a fine-resolution OGCM for the Atlantic basin (Smith et al., 2000).

Coupled Earth System Modelling (ESMs)

ESMs include many spheres – atmosphere, ocean, cryosphere – as well as the chemistry and biology of the carbon cycle and the hydrology of the water cycle and can project broad outlines of the future climate.



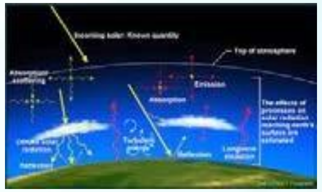
Prescribed global mean atmospheric CO_2 not affected by the simulated changes in the climate system

Prescribed CO_2 emission and atmospheric CO_2 interactively calculated

(IPCC AR5, 2013, Box 6.4, Fig. 1)

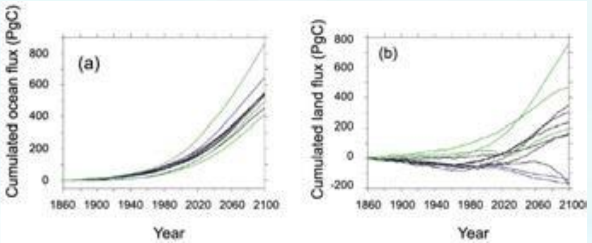
Coupled Earth System Modelling (ESMs)- challenges

Modeling **subgrid processes of convection, clouds, and aerosols** represents a major source of uncertainty in projections of climate and water cycle changes



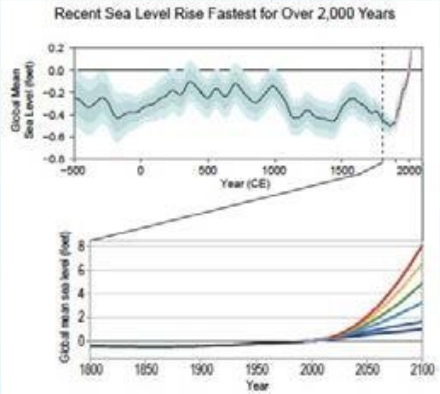
Modeling **carbon and nutrient cycles and human influence** is a major source of uncertainty in projecting 21st century warming

(Burrows et al. 2020 JAMES)



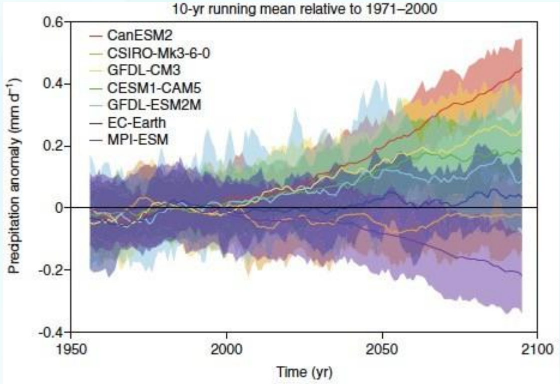
(Friedlingstein et al. 2014 JCLIM)

Modeling **ice shelf and ice sheet instability** is a major source of uncertainty in projecting sea level rise

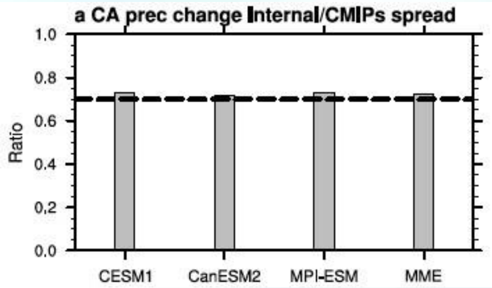


(Climate Science Special Report 2016)

Internal variability represents a major source of uncertainty in regional projections



(Deser et al. 2020 NCC)



(Dong et al. 2021 NCOMM)

Kilometre-Scale Modelling : A New Paradigm for Climate Prediction

- Costliest impacts of climate change will be felt via local and regional extremes, such as extreme weather, multi-year drought and inundation from sea-level rise combined with storm surge, which these models cannot project.

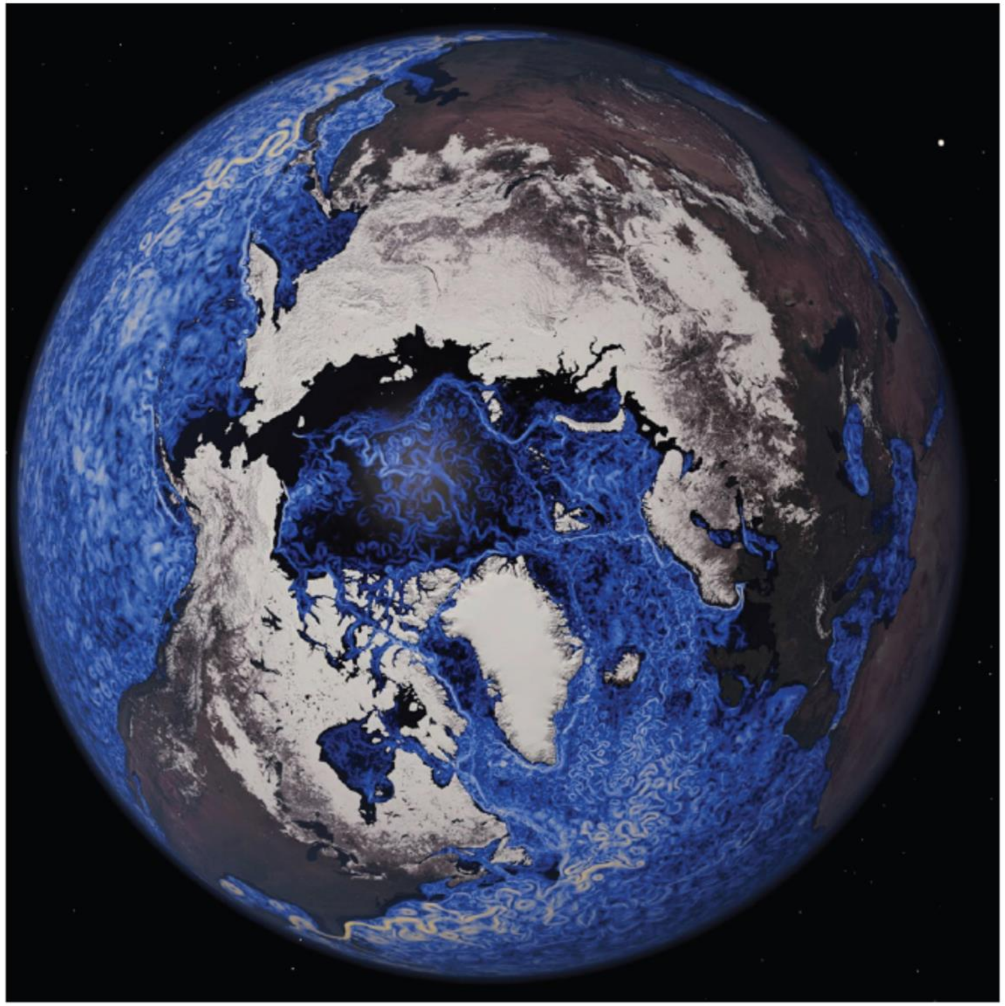
- Adaptation to climate change requires local information. Driven by these imperatives, a new class of regional and global ESMs are now emerging.

“km-scale” models

Horizontal scales of less than 10 kilometres (< 10 km)

Gettelman et al. 2023, WMO

Kilometre-Scale Modelling : are we there yet?



- Large-scale features that affect the storm tracks and air-sea coupling (e.g., Gulf Stream separation) are much more consistent than in coarser models.
- Internal variability is also substantially larger in these eddy-rich models.

However,

- smaller sub-mesoscale features, important for air-sea coupling and biogeochemistry, are still not resolved at km-scales and remain highly sensitive to parameterizations.

Ocean eddies and snow cover from the 1.2km ICON simulation for 5 December 1972 Image. *Simulations produced by the MPI-M with support from the DKRZ and visualized by NVIDIA*

Kilometre-Scale Modelling : are we there yet?

Left: The first full picture of the Earth from space taken by Apollo 17 astronauts on 7 December 1972. Right: Simulated visible satellite image from a 1.25 km resolution simulation of the ICON model initialized with reanalysis fields on 5 December 1972.
Simulations produced by the MPI-M with support from the DKRZ and visualized by NVIDIA

Kilometre-Scale Modelling for ocean : what next?

- Comprehensive models are needed to integrate climate impacts at the regional scale.

Example: representations of ice sheets (IS) for critical interactions of warming ocean and Antarctic IS.

- Better resolution of the complex bathymetry of narrow straits important for ocean circulation would resolve upwelling regions critical for coastal fisheries and for credibly simulating the local consequences of the El Niño/La Niña Southern Oscillation (ENSO).

- Higher resolution resolves small islands, enabling direct assessment of sea-level and coral ecosystem impacts.

The availability of “exascale” – computing resources, offers unprecedented opportunities.

Kilometre-Scale Modelling for ocean : challenges

1. Procuring suitable observational data to serve as initial and boundary conditions (particularly in the ocean, cryosphere, and continental subsurface).

2. Computational challenge for integrating the models but also, challenges in working with and analysing the output from km-scale models.

    - Traditional computational approaches have met their limits, particularly around energy efficiency. The use of hardware accelerators (like graphical processing units) and emulators with Artificial Intelligence/ Machine Learning (AI/ML) methods is starting to significantly speed up (i.e., reduce the cost of) integration and analysis.
    - Projects such as DestineE (Europe) and Pangeo (US) to allow users around the world to interact with what would otherwise be overwhelmingly large amounts of data.

Thank You

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