Ocean Initialization for Climate Simulations

JOINT WGNE & WGSIP MEETING

Gokhan Danabasoglu
US National Science Foundation (NSF) National Center for Atmospheric Research (NCAR)
Boulder, CO USA

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Ocean Equilibration Timescales

Mixing across density surfaces is extremely small once water masses are buried below the mixed layer base.

Scaling argument for deep adjustment time (**diffusive timescale**):

$$H^2/\kappa = (3500\ \text{m})^2 \ / \ (1 \times 10^{-4}\ \text{m}^2/\text{s}) = \text{O (4,000) years}$$

Tidal mixing can reduce this time scale in certain regions.

Bottom line for climate ……

- Performing long “equilibrium” simulations are not practical, particularly at eddy-resolving / permitting resolutions
- Must live with deep / abyssal ocean not being at equilibrium in most simulations

(Common) Ocean Initialization Approaches for Climate Simulations

No accepted / coordinated / standard approach!

Start from some observational potential temperature (T) and salinity (S) dataset, usually January-mean, and state of rest

- Observations are usually from the World Ocean Atlas (WOA) or Polar Hydrographic Climatology (PHC)

Start from another simulation or a sequence of simulations. This could include starting from OMIP simulations.

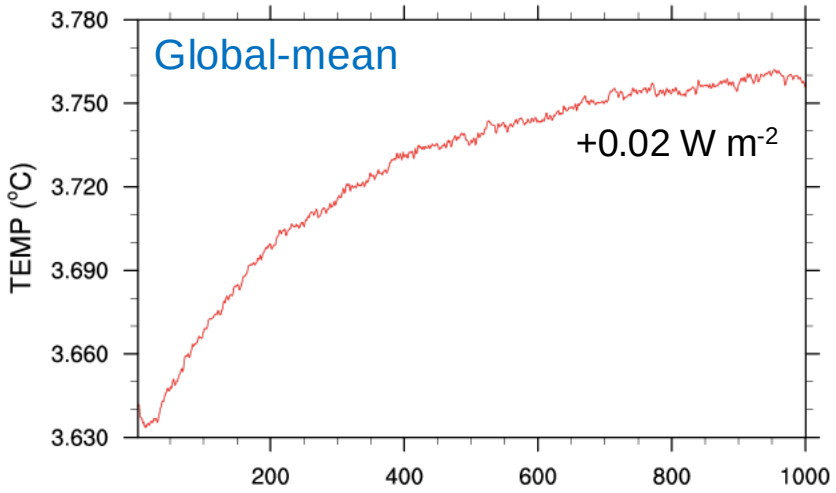
Run ocean model with surface forcing from a coupled simulation.

Another option for high-resolution simulations could be starting from interpolated T & S fields from a low-resolution simulation and state of rest.

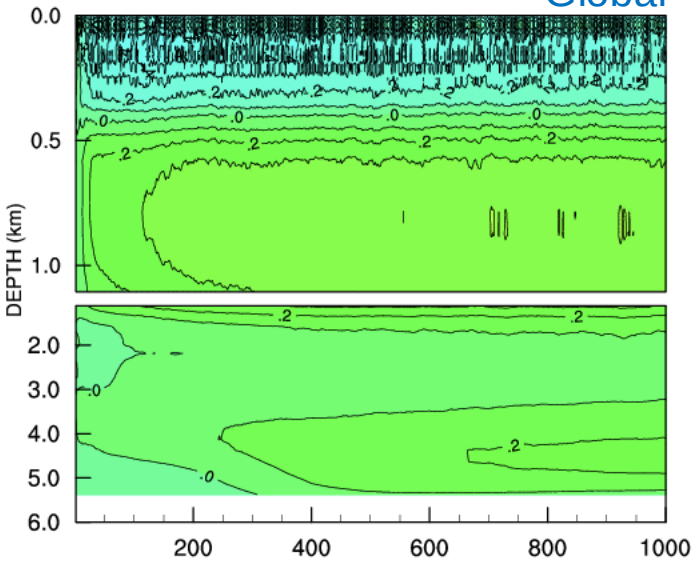
Acceleration approaches such as increasing tracer time steps (with depth); using coarser grids for tracers; etc.

CESM1 Pre-Industrial Control

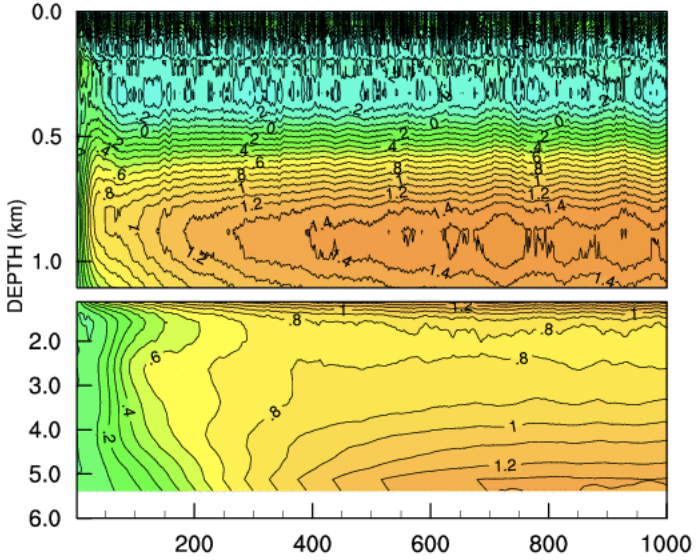
Ocean initial T & S are from PHC2 datasets



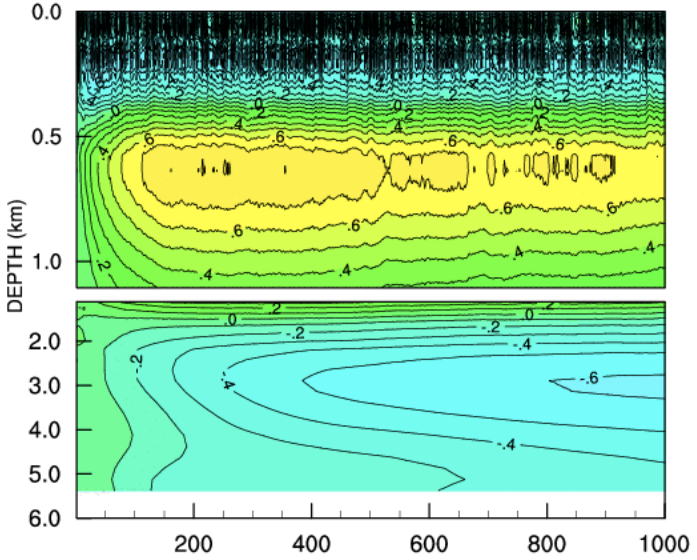
Global



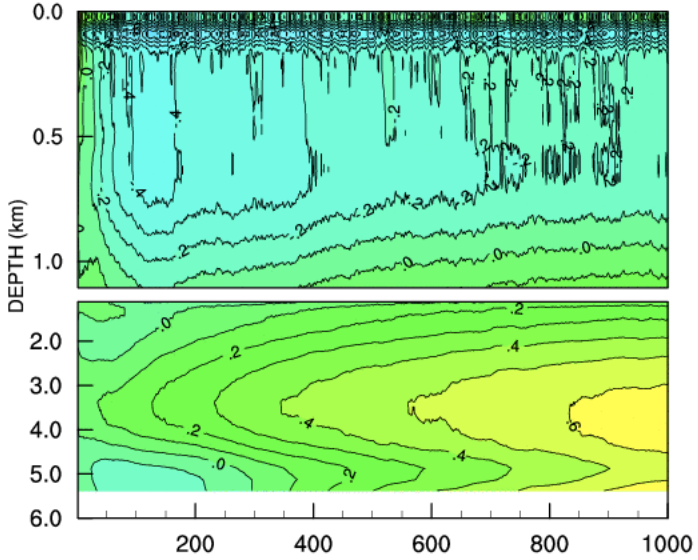
Atlantic



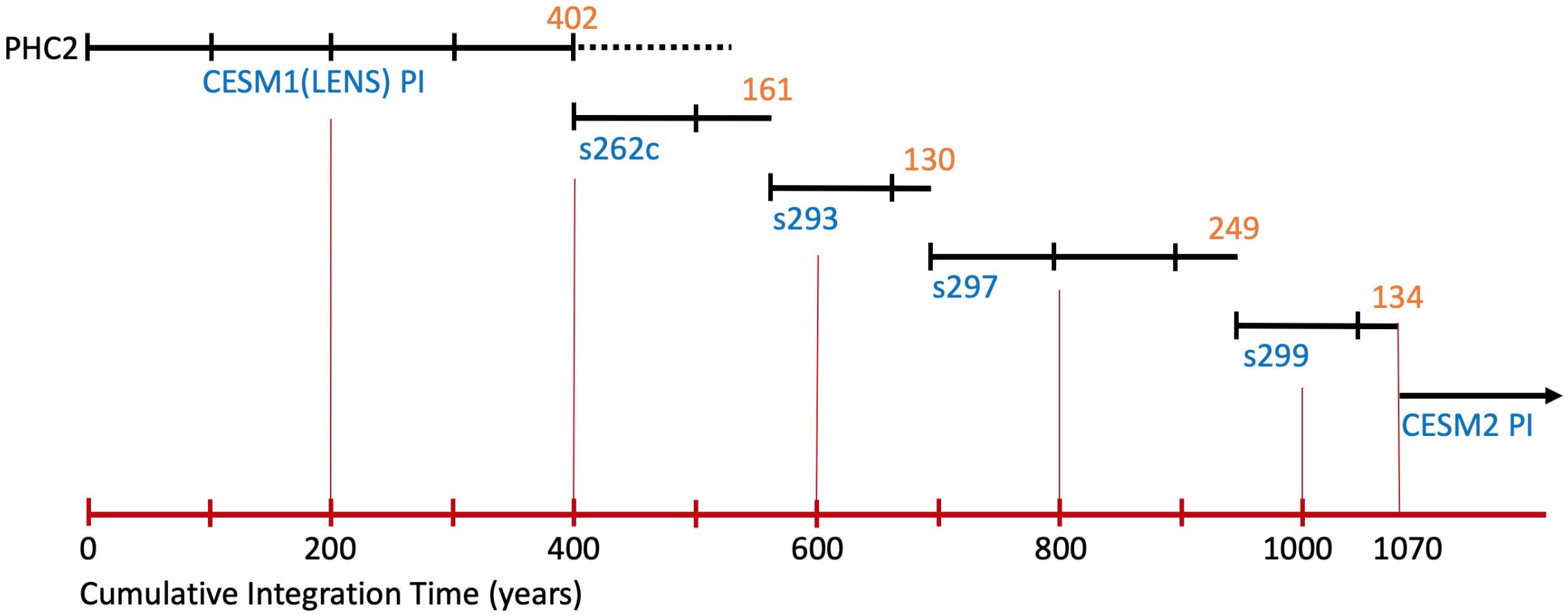
Pacific



South ern

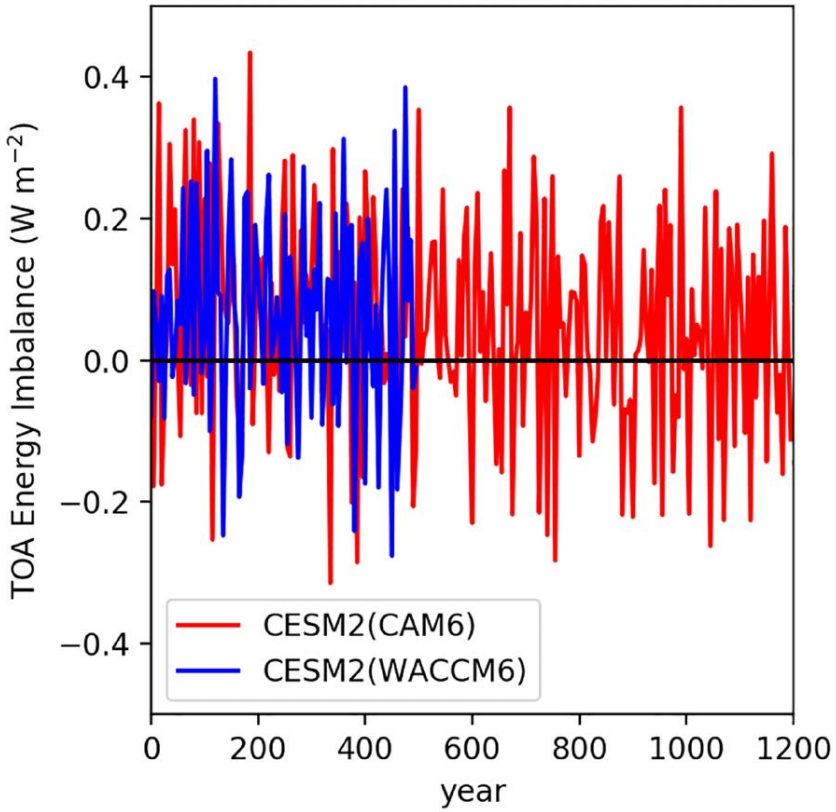


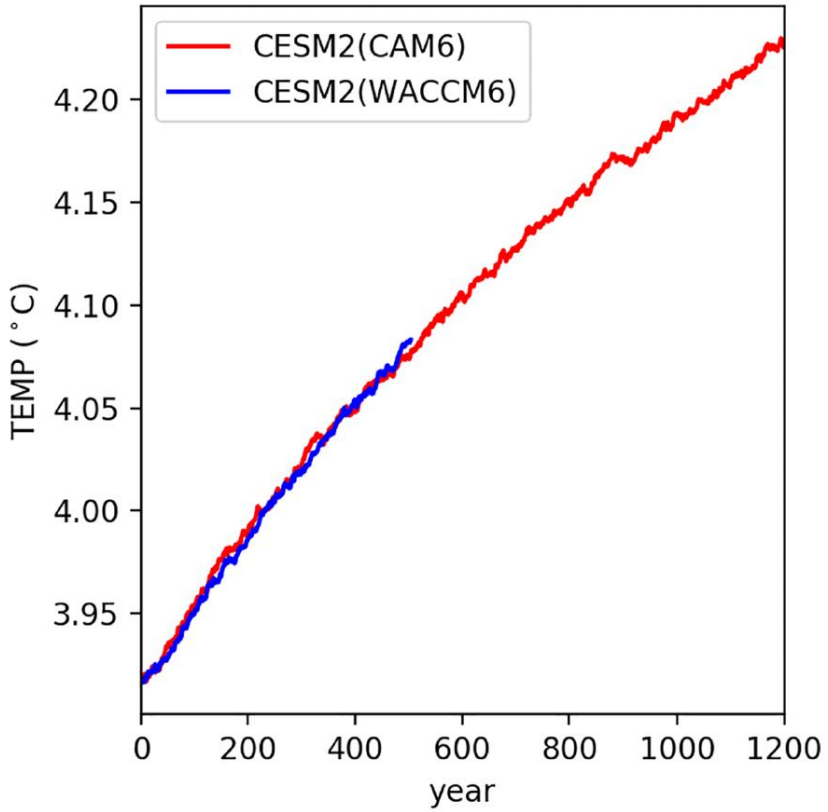
Sequence of Simulations Used to Obtain Ocean and Sea-Ice Initial Conditions for the CESM2 PI Control Simulation



Danabasoglu et al. (2020, JAMES)

Approach to Equilibrium in CESM2 Fully-Coupled Simulations

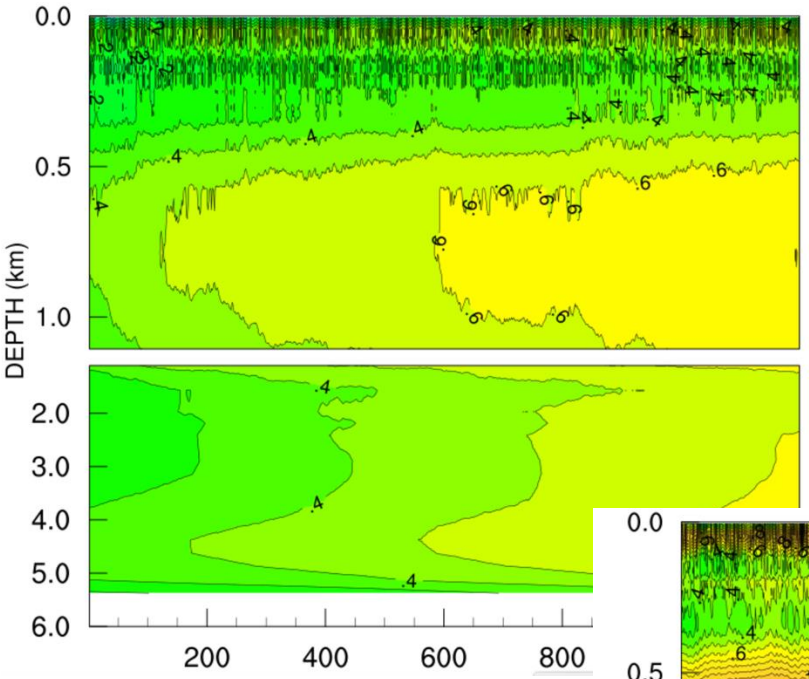




Top-of-atmosphere imbalances: +0.03 W m^{-2} during 701-1200 for CESM2(CAM6)

+0.06 W m^{-2} during 301-500 for CESM2(WACCM6)

Approach to Equilibrium in CESM2 Fully-Coupled Simulations



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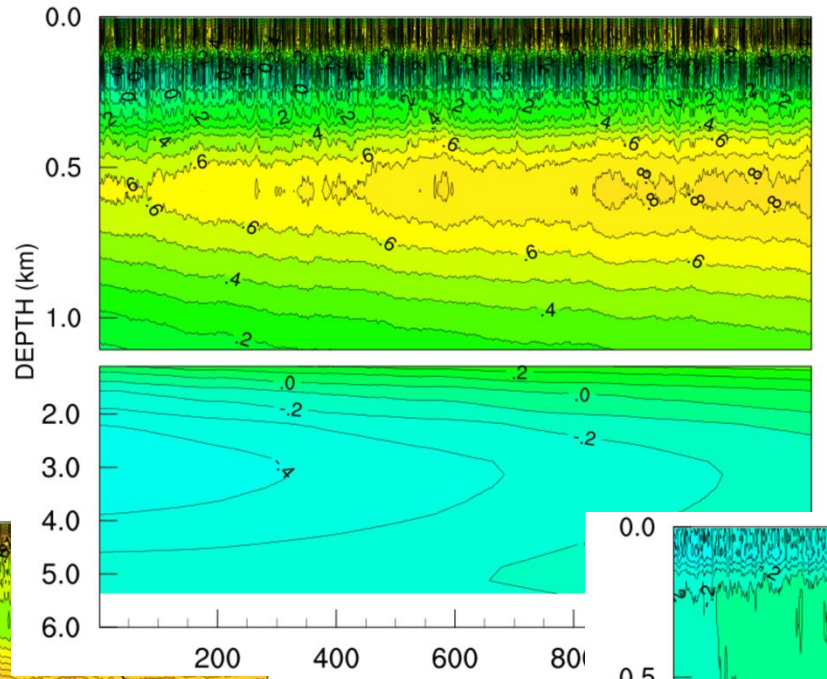

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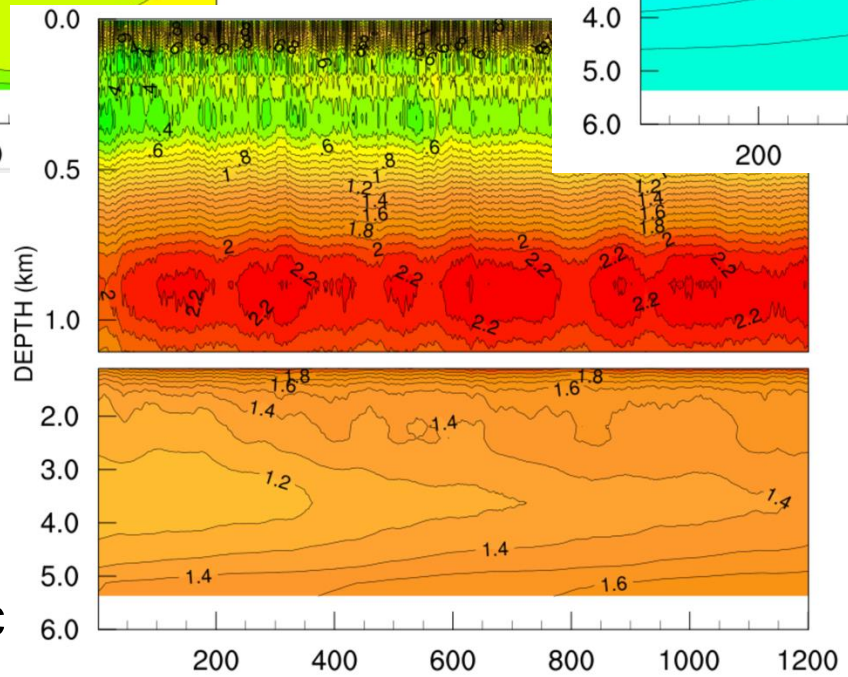

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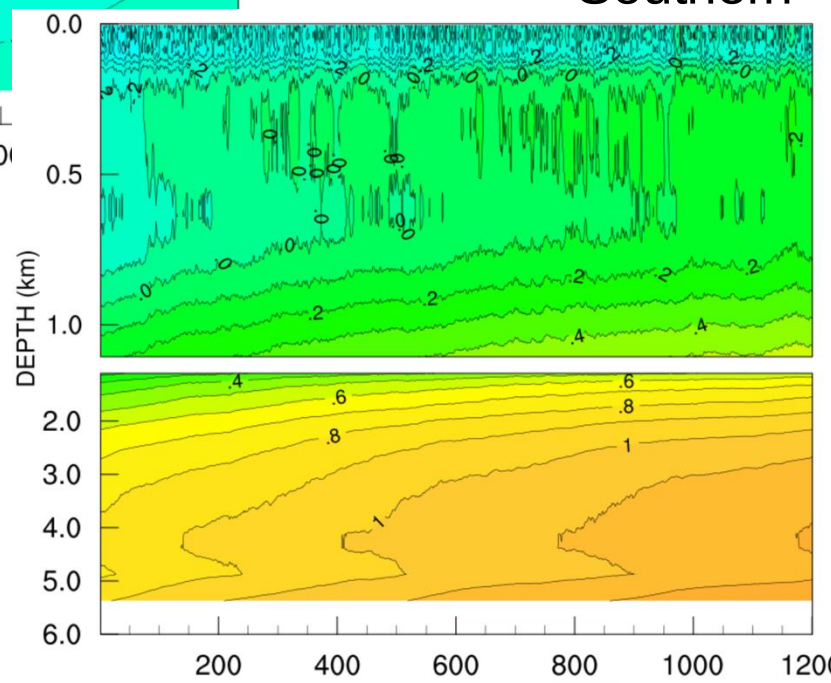
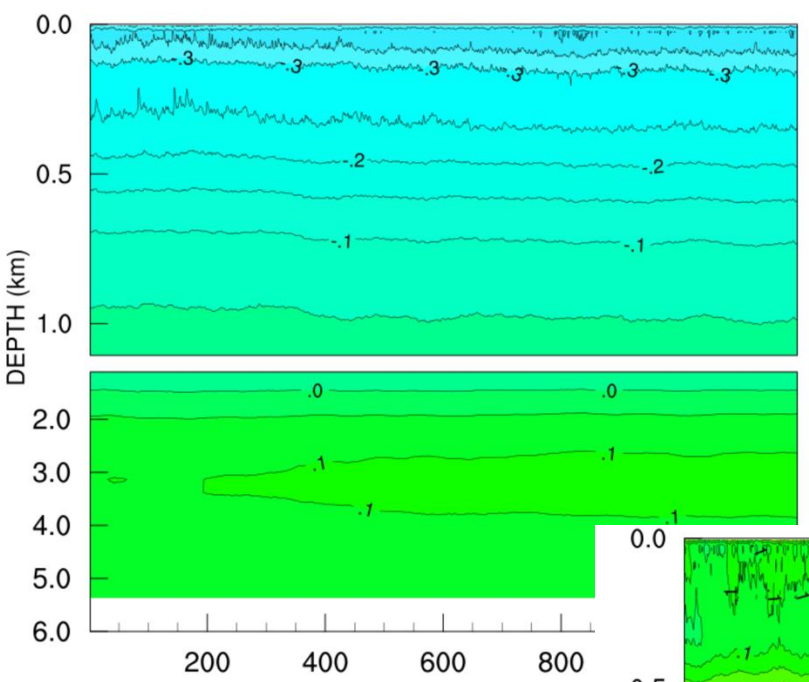


Southern

Potential Temperature (°C)

Differences from obs

Approach to Equilibrium in CESM2 Fully-Coupled Simulations



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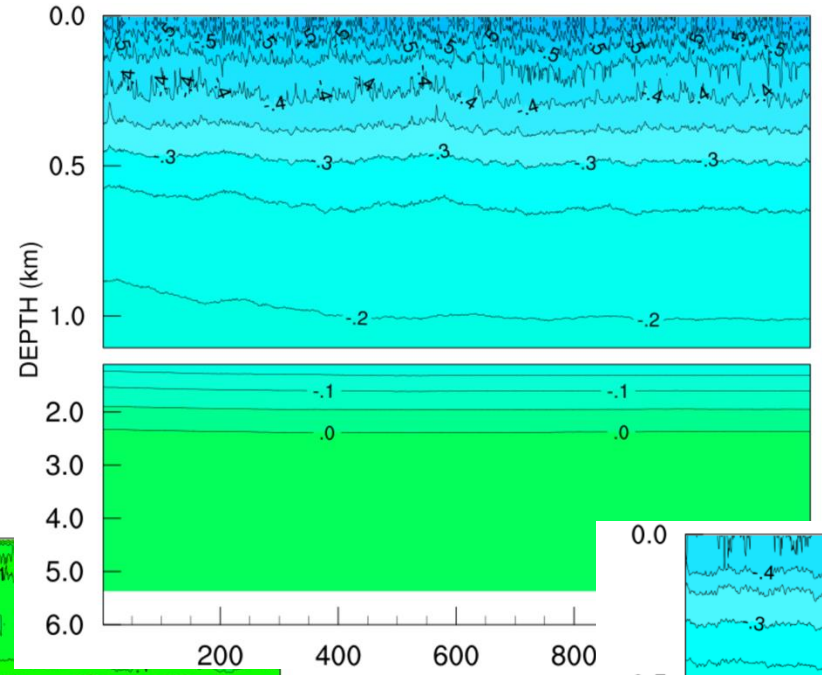

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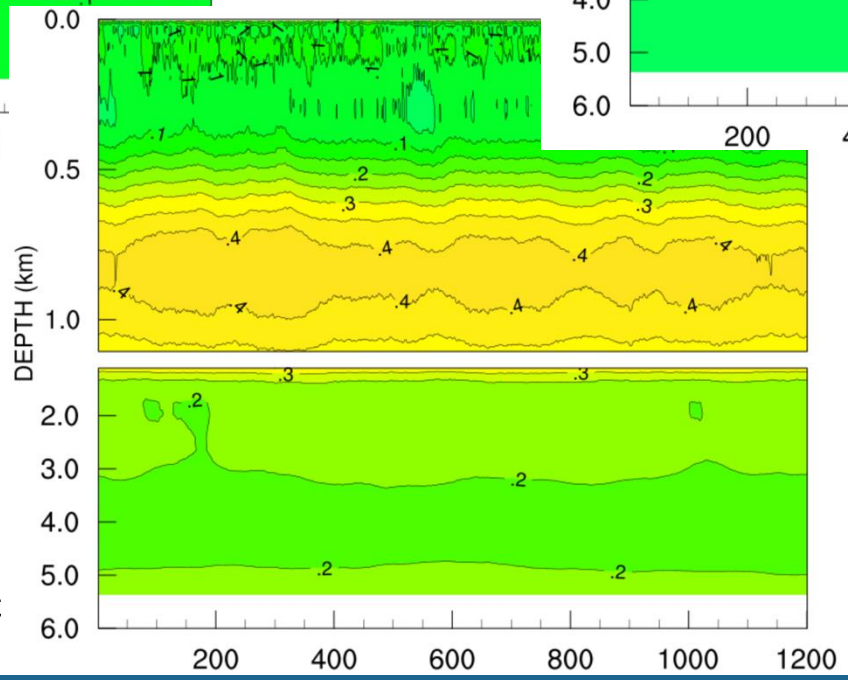

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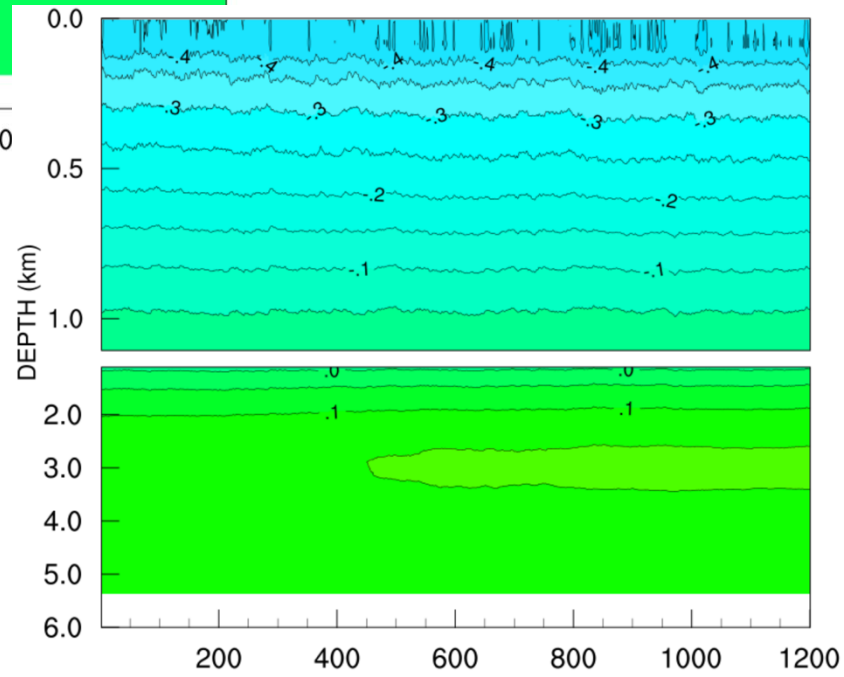


Southern

Salinity (psu)

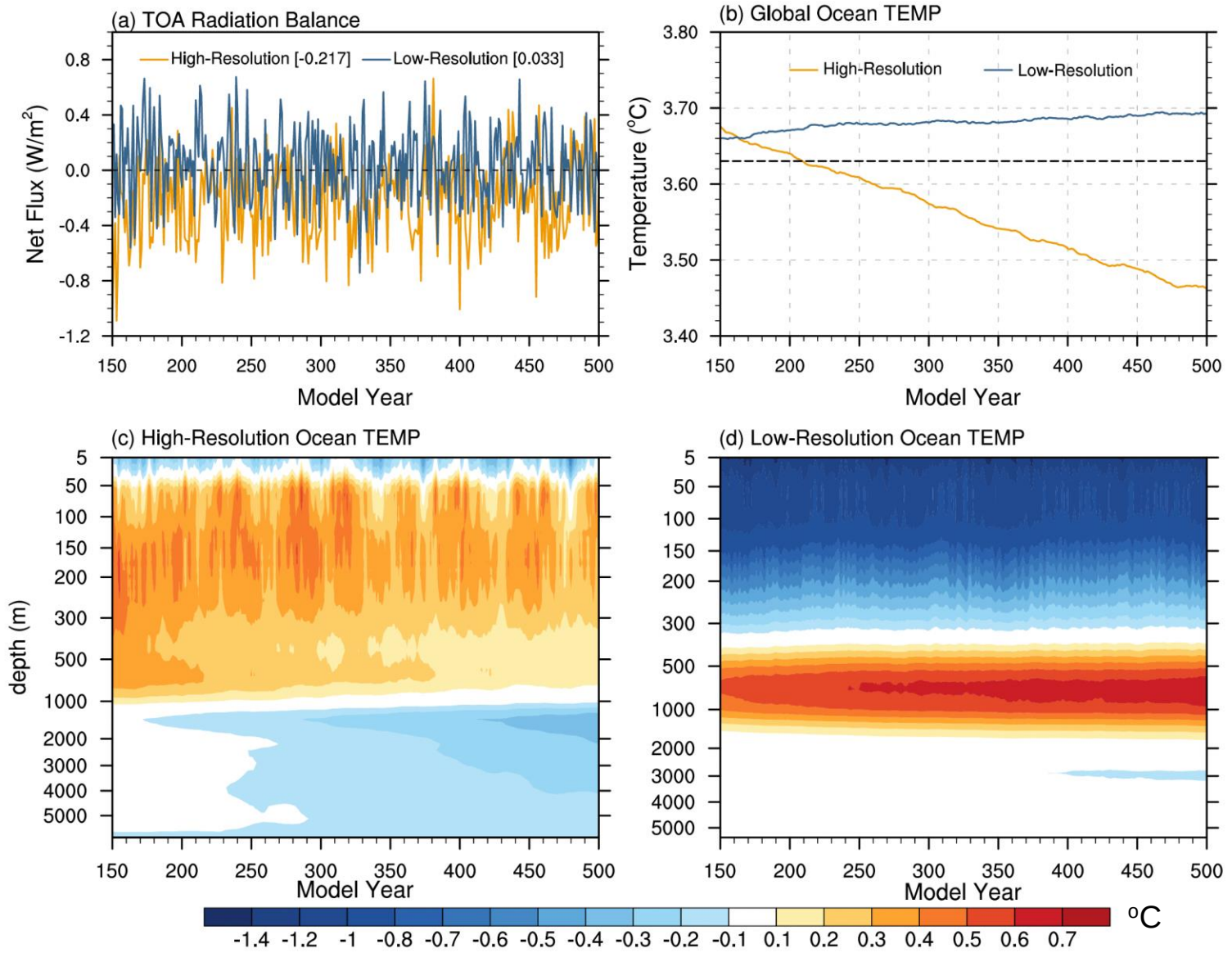
Global-mean trend:

-5×10^{-5} psu century^{-1}

Low- vs High-Resolution Approach to Equilibrium

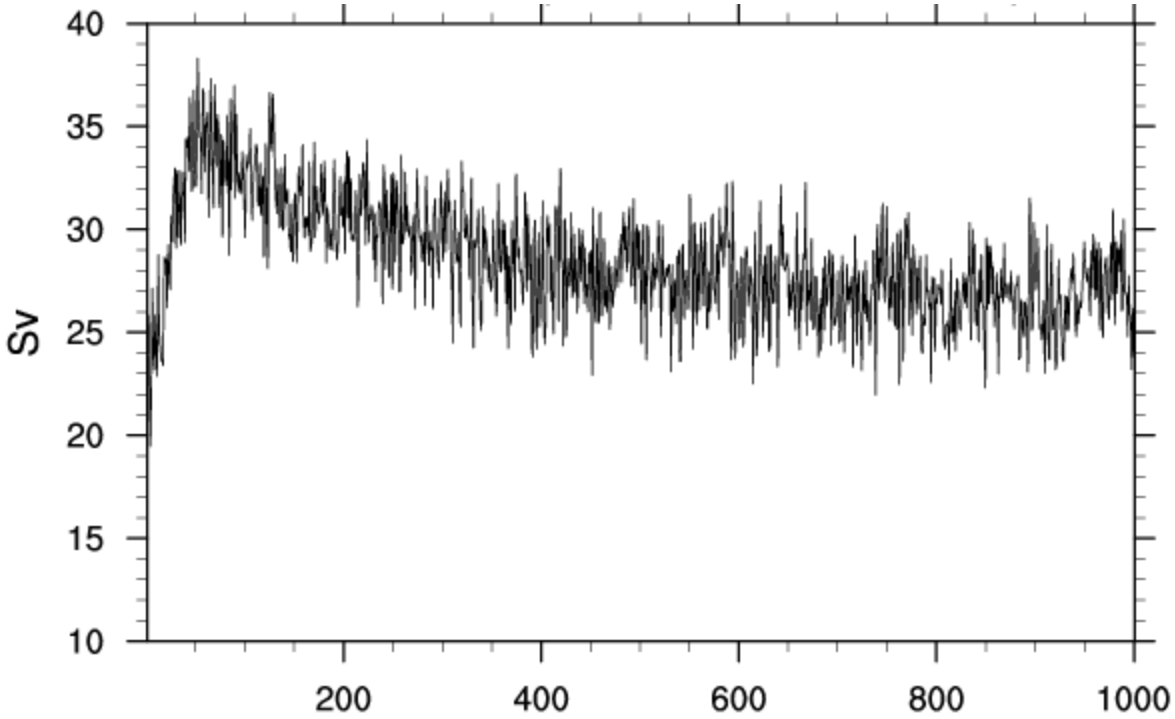
Low resolution: ~1º

High resolution: 0.1º



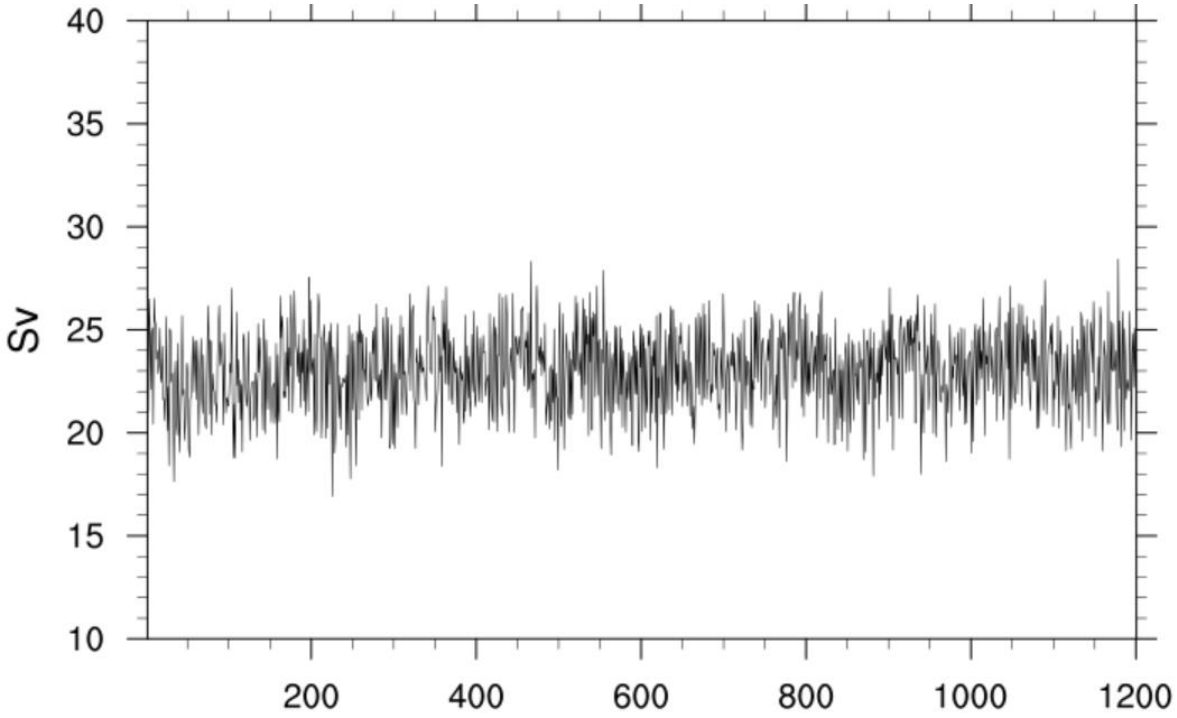
Chang et al. (2020, JAMES)

Atlantic Meridional Overturning Circulation (AMOC) Maximum Transport Time Series



Ocean initialized from PHC2 climatology (CESM1-LE)

Ocean Initialized from other simulations (CESM2)



Initialization of Ocean Biogeochemical Fields (Passive Tracers)

Online Spinup

Usually a data-atmosphere component is used to read in and repeatedly cycle through multiple years of surface forcing datasets from a coupled simulation.

To avoid drift of the ocean physical state, it is reset to its initial condition at the beginning of each cycle, keeping it synchronized with the surface forcing.

Acceleration techniques Examples include a Newton-Krylov (NK) based solver (Lindsay 2017), sequence acceleration (Khatiwala 2024), ….

These acceleration methods are not usually successful with active tracers.

CESM2 used a combination of online spin-up and NK solver

A Survey of Modeling Groups

The Wondering about Ocean Spin-Up Team: Baylor Fox-Kemper, Gokhan Danabasoglu, Julie Deshayes, Helene Hewitt, Andrew Gettelmann, Tim Graham, and Andy Moore

Q1. Are you aware of the specific steps taken to initialize (a.k.a.) spin up the ocean state in your coupled weather prediction, subseasonal, seasonal, decadal and/or climate modeling system? What is the name of this system? If you are not, can you please connect us with the email address of someone who is?

Q2. What are the basic principles behind your spin-up approach?

Q3. Are there references documenting this approach and how it was selected?

~20 unique responses received

A Survey of Modeling Groups

No surprises in answers received!

Groups use one of the ocean initialization approaches introduced earlier for climate simulations.

However, there is a lot of diversity in creation of ocean initial states used for prediction purposes. These seem rather ad-hoc and some are rather complicated.

They include:

- Data assimilation methods …. Ocean-only, weakly-coupled, strongly-coupled
- Restoring / nudging techniques at various time scales and spatial locations
- Surface flux adjustments
- Ocean hindcast (OMIP) simulations

Some thoughts ….

Initialization approaches remain ad-hoc partly because there are practical reasons during model development cycles, including resource limitations.

Different initializations and in particular different lengths of pre-industrial control simulations make the comparison of simulations rather difficult for oceanic heat uptake and sea level changes (and possibly others).

Clearly the minimum integration length of 500 years for CMIP pre-industrial control simulations is not enough, possible even for AMOC studies.

Rather ad-hoc nature of creation of initial states for prediction simulations is concerning. It would be good to assess impacts on prediction skill in a coordinated way.

These challenges are even more so for high-resolution simulations, including for HighResMIP.

HighResMIP 2

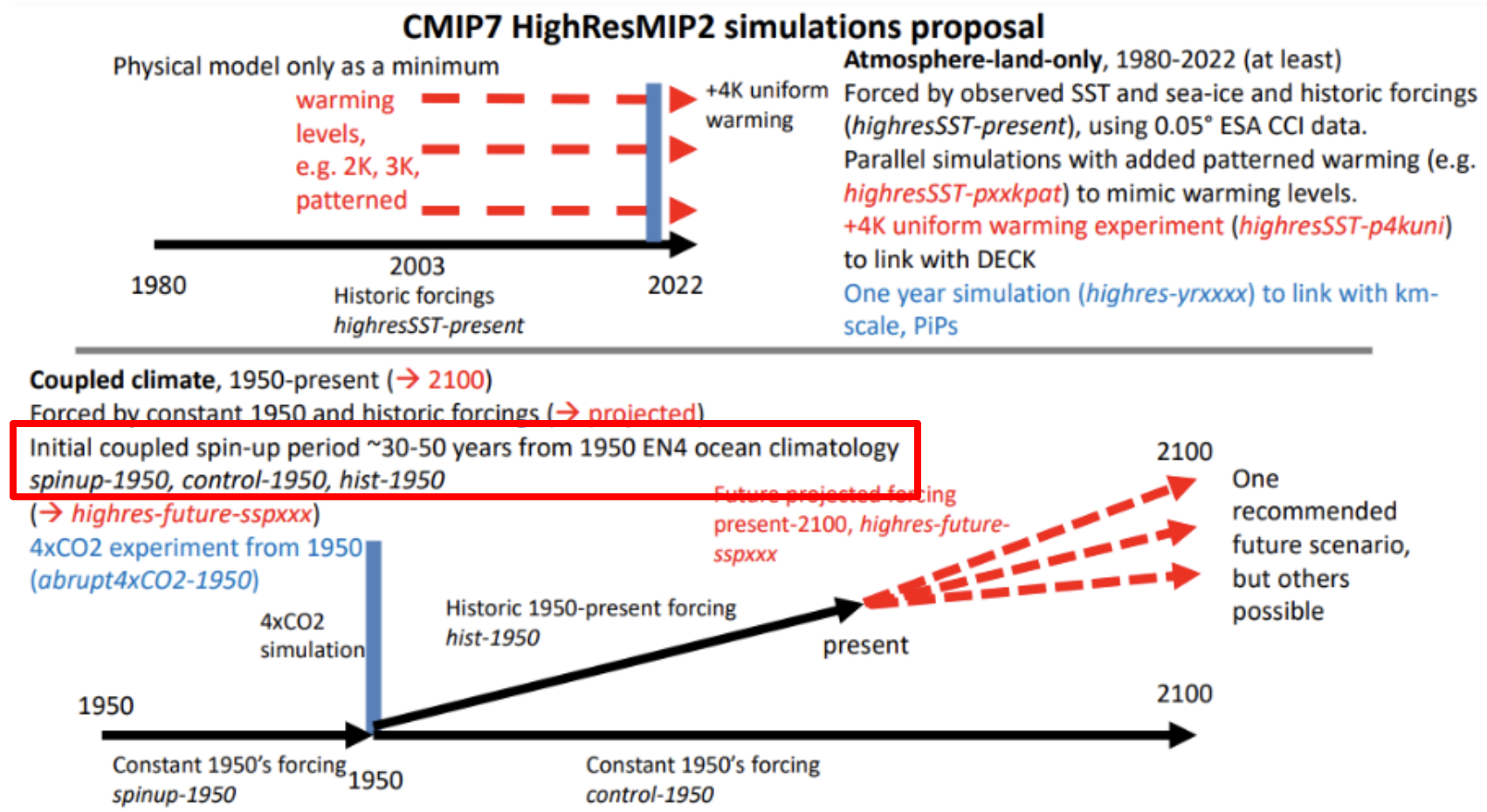


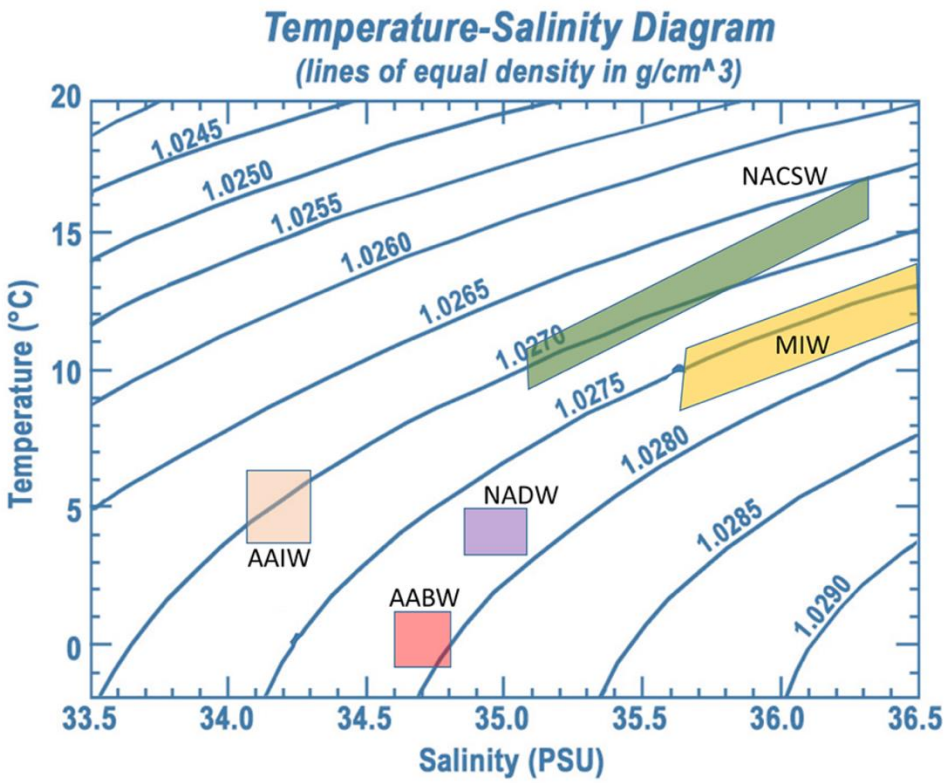
Figure 2: Illustration of the HighResMIP2 simulations in Tiers 1-5 for (upper) atmosphere-only and (lower) coupled model experiments.

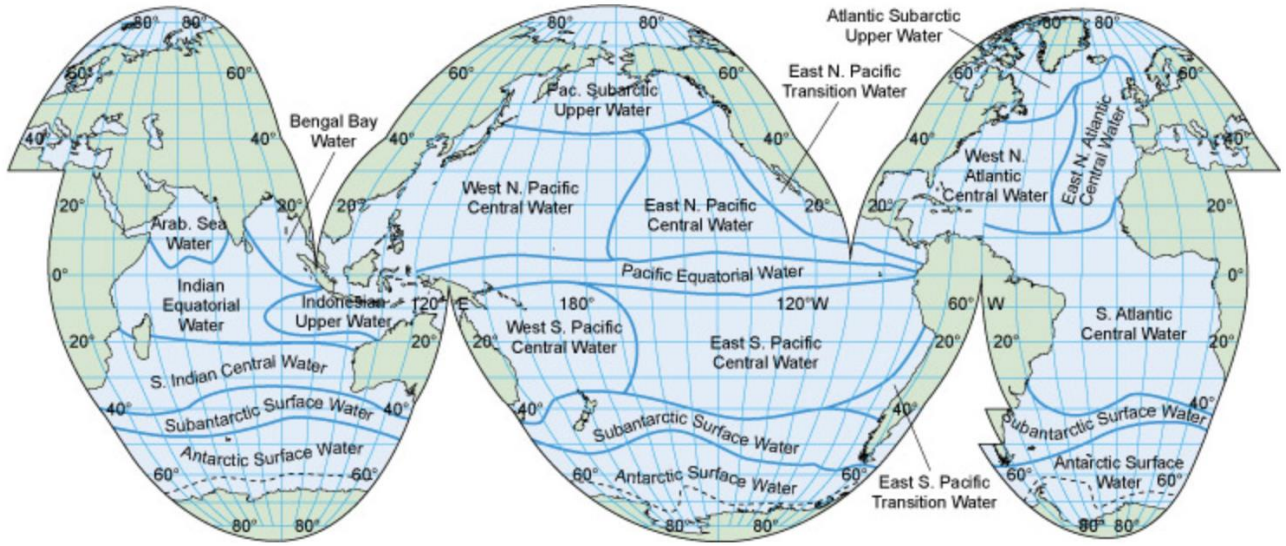
Roberts et al. (2025, GMD, in review)

Outline

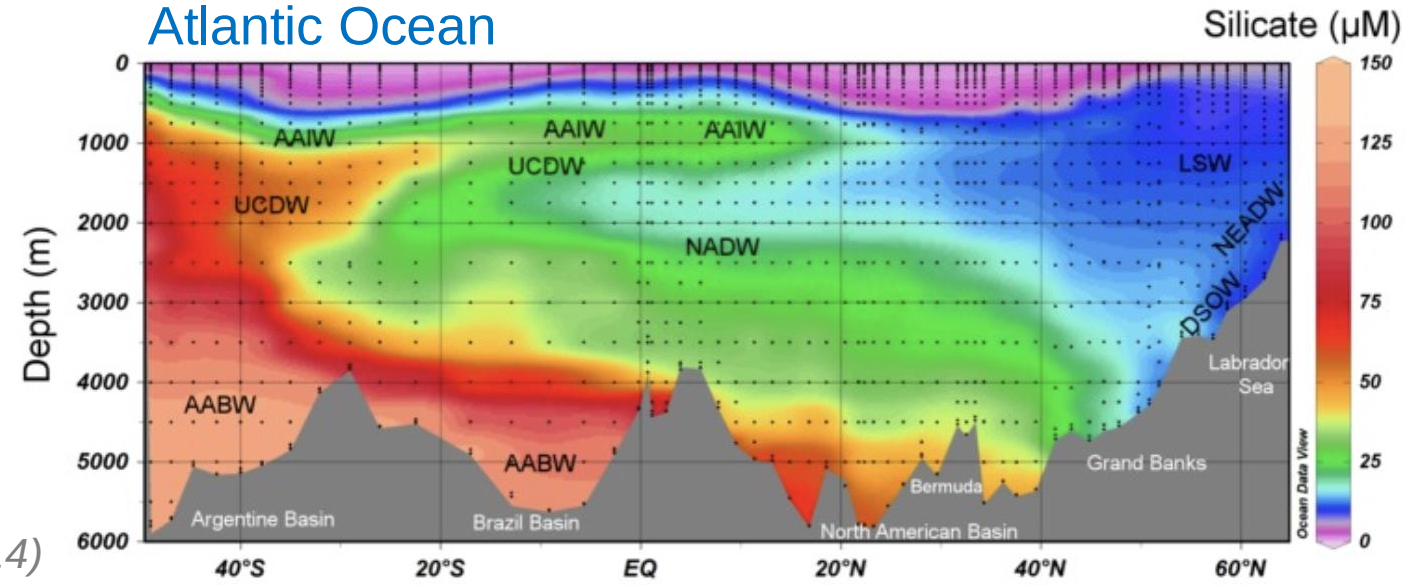
- Oceanic equilibrium time scales
- Ocean initialization approaches
- Approach to equilibrium examples
- Initialization of ocean biogeochemistry
- HighResMIP protocol
- Survey of modeling groups
- Some thoughts

Because of weak interior mixing, water masses can be named and followed around in the oceans ….





Atlantic Ocean



Rijkenberg et al. (2014)

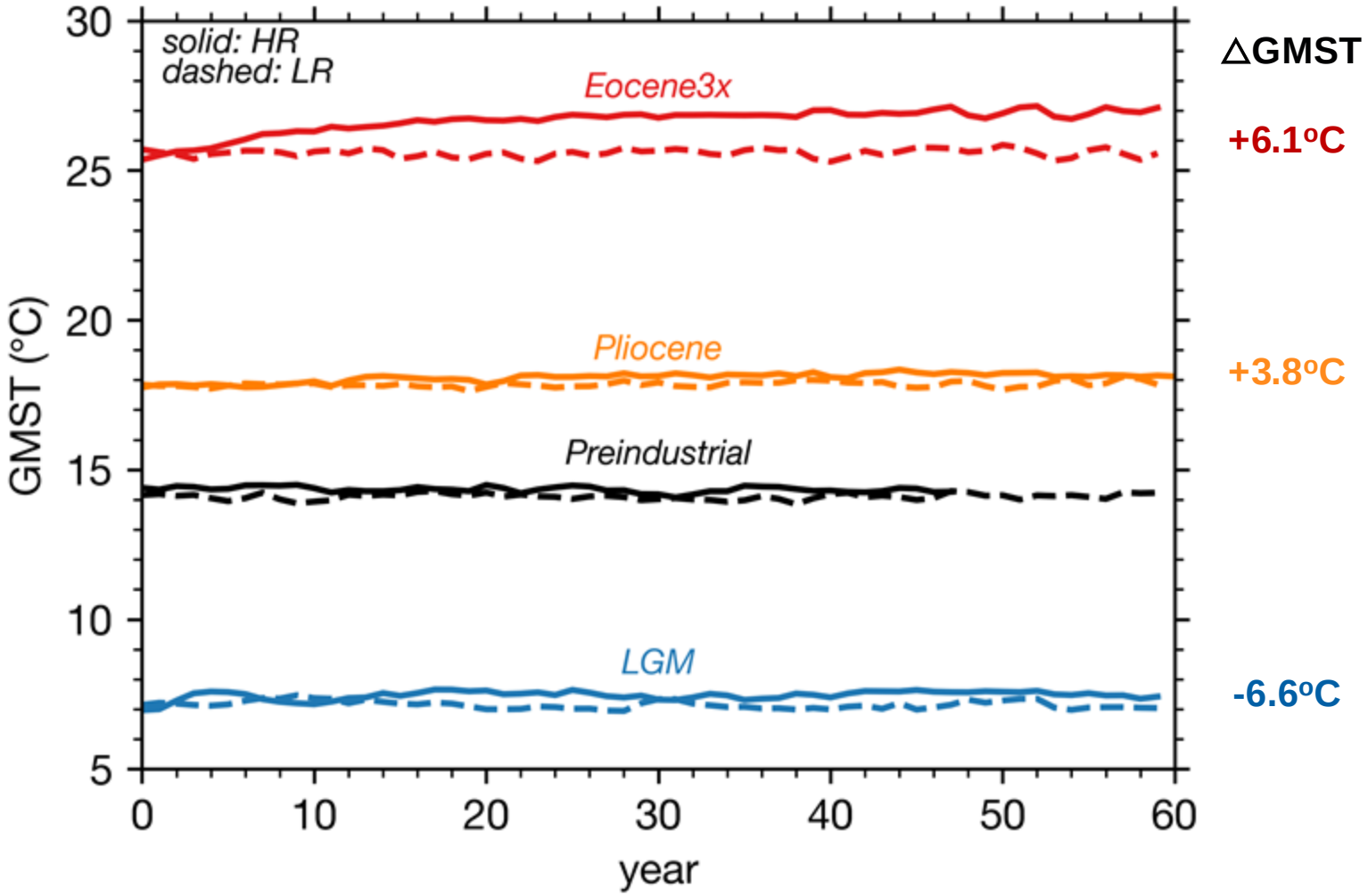
Global Mean Surface Temperature (GMST) – Time Series

- **Water isotope capability**

  iCESM1.3 iHESP

- **HR PI simulation initialized from long (>600 yrs) iHESP HR PI simulation**

- **Paleo HR simulations start from ‘spunup’ paleo LR simulations**



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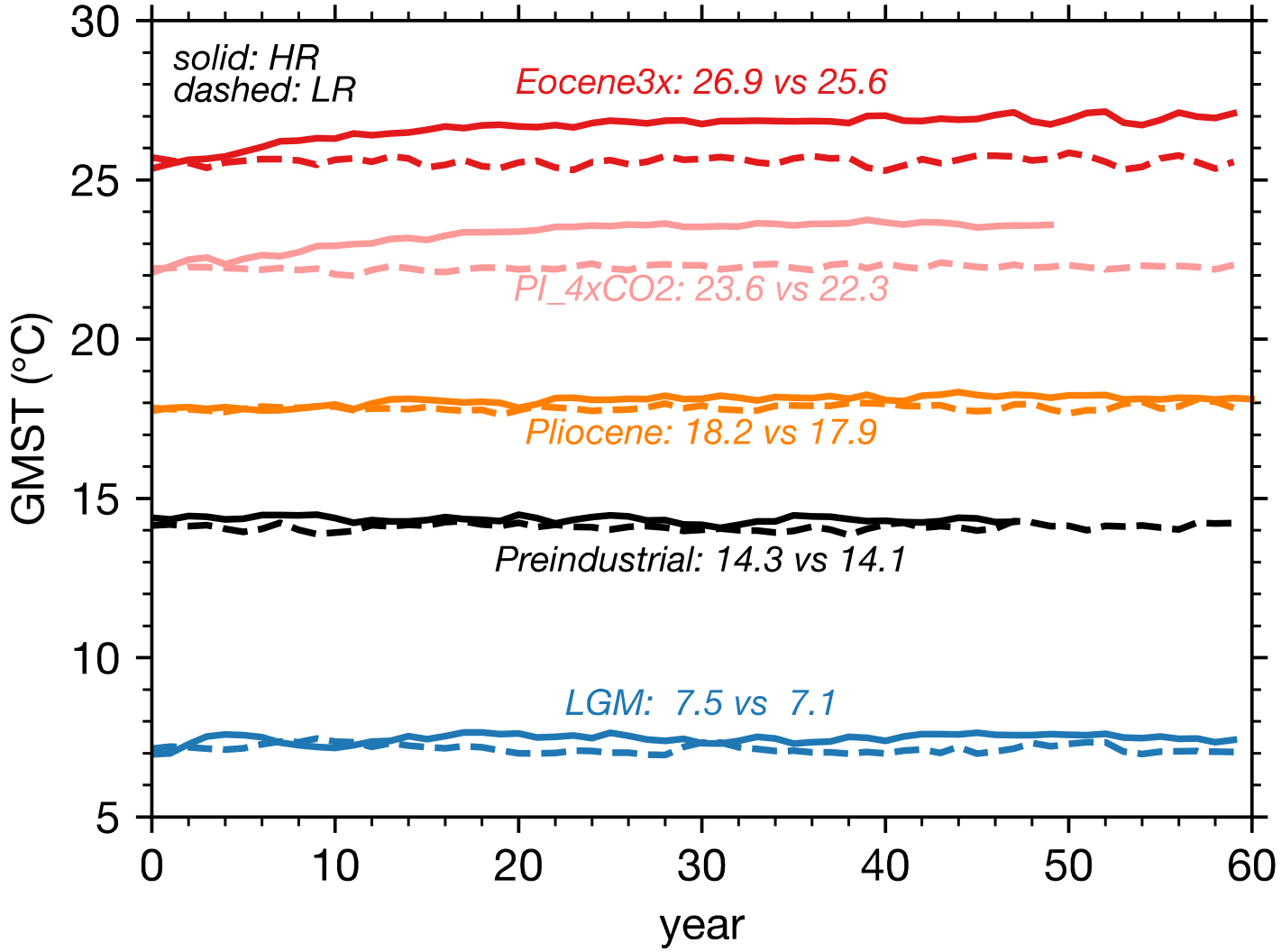

RESTOM