Simulating Past Climates with CESM3-MOM6: The Last Glacial Maximum and Beyond

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The Last Glacial Maximum (LGM)

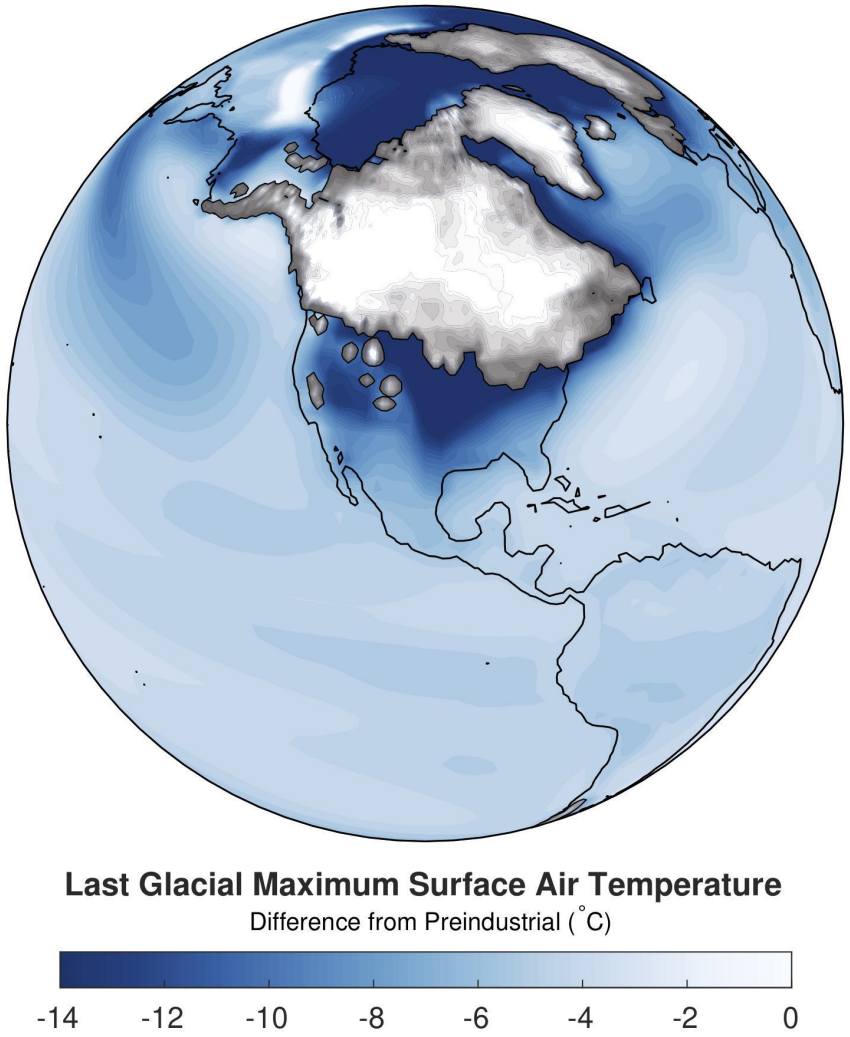


Figure credit: J. Tierney

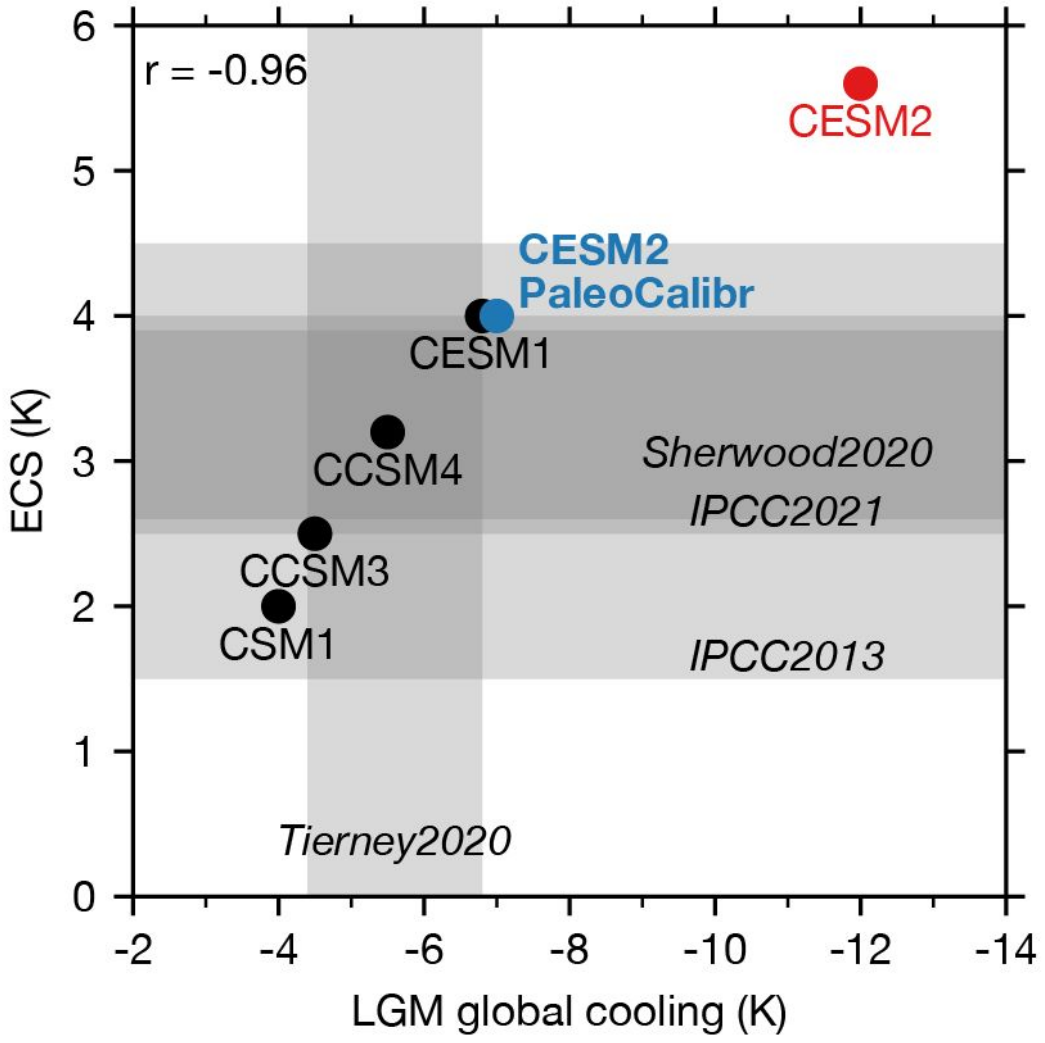
- ~6 ℃ colder than the preindustrial

  (Tierney et al., 2020, Nature)

- Climate forcings
  - Lower GHGs *(e.g., CO_2 = 190 ppmv)*
  - Expanded ice sheets

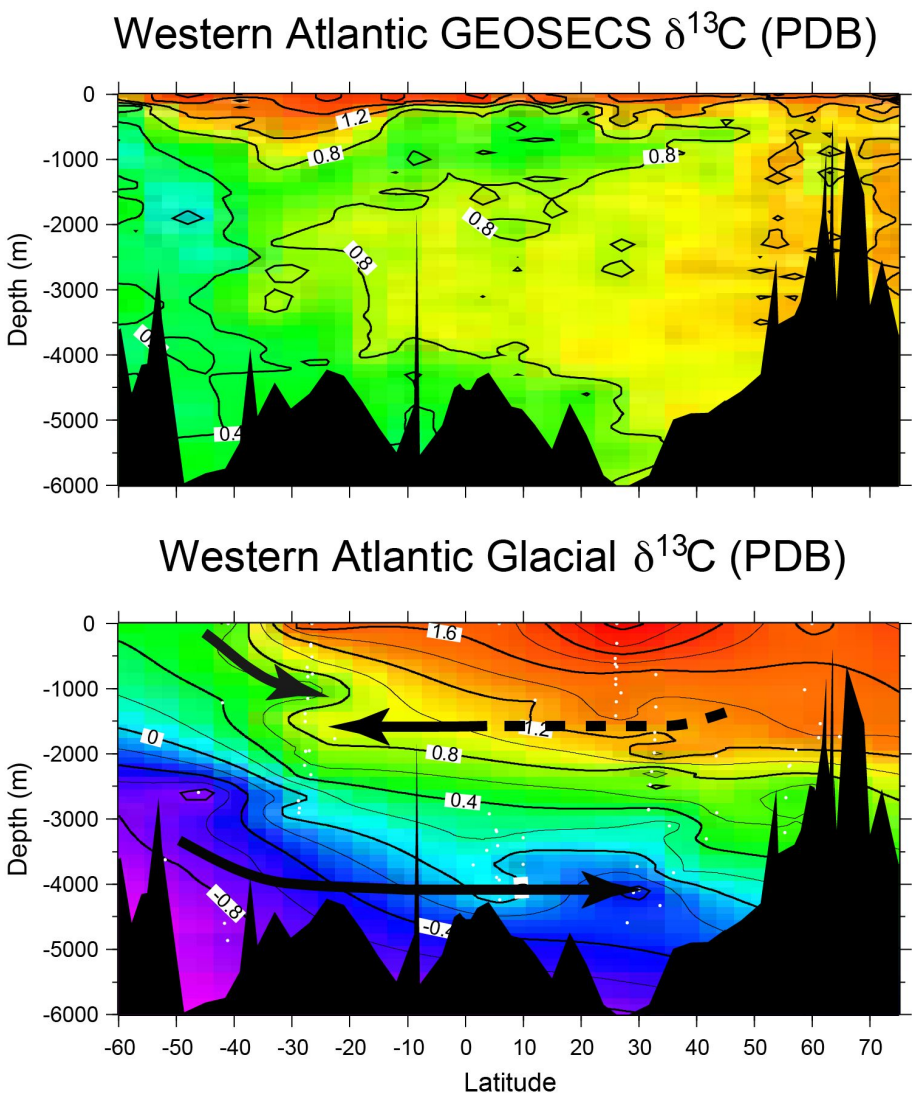
Use LGM to assess model climate sensitivity

The idea dated back to
Manabe & Broccoli (1985, JC)



Shin et al., 2003, CD
Otto-Bliesner et al., 2006, JC
Brady et al., 2013, JC
Zhu et al., 2017, 2020, GRL
Tierney et al., 2020, Nature
Zhu et al., 2022, JAMES

Shallower AMOC (Atlantic Meridional Overturning Circulation) at LGM

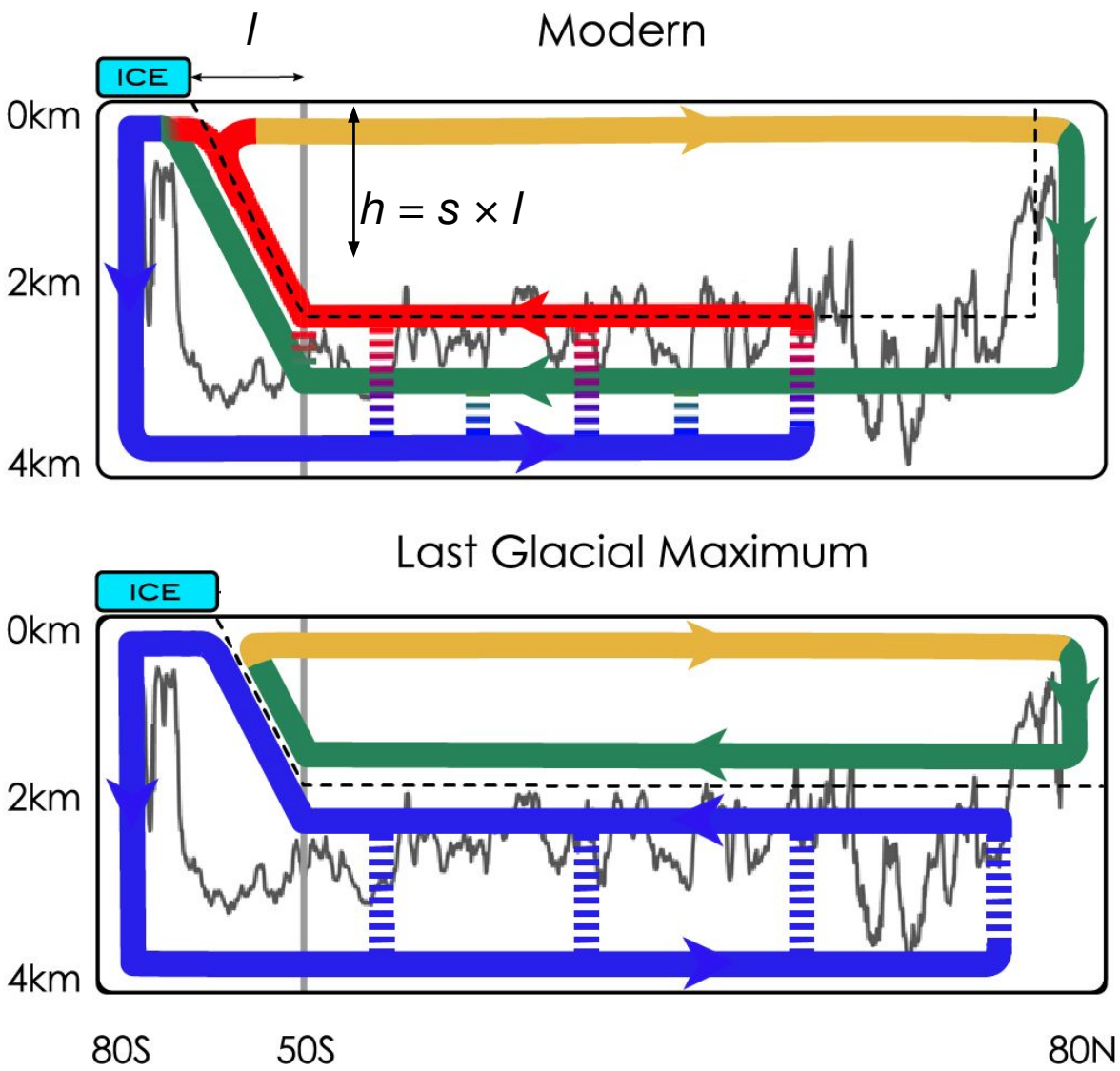


Curry & Oppo, 2005, Paleoceanography

Robust interpretation supported by later studies

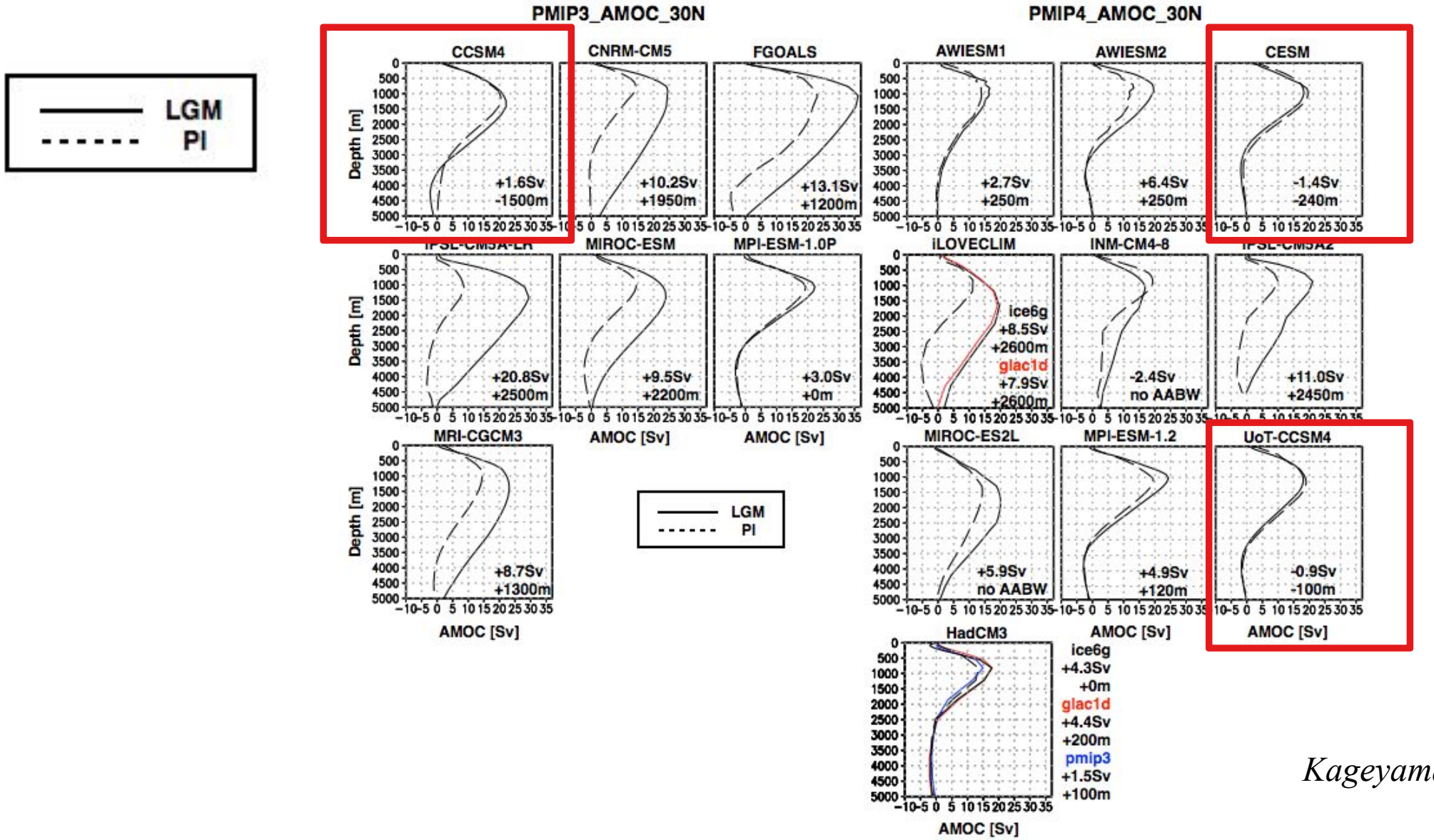
- Shallower by ~500 m *(Oppo et al., 2018, Paleoceanogr Paleoclimatol.)*
- Shallower & strength unknown *(Muglia & Schmittner, 2021, Paleoceanogr Paleoclimatol.)*
- Shallower by 1 km & weaker by 40% *(Poppelmeier et al., 2023, Nat. Geosci.)*

Theory of the Glacial AMOC



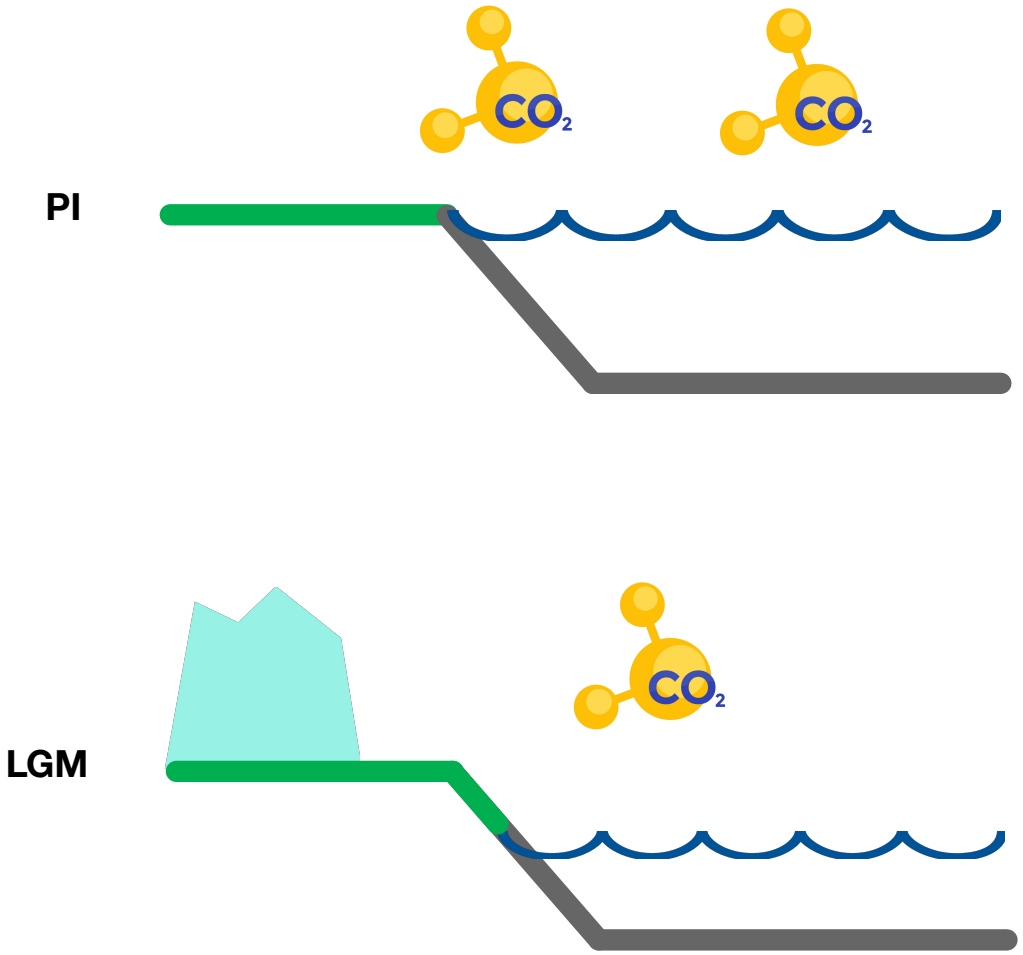
- *Southern Ocean sea ice ⇒ shallower*
  - *Shin, Liu, Otto-Bliesner, et al., 2003, CD*
  - *Ferrari et al., 2014, PNAS*
  - *Klockmann et al., 2016, CP*
  - *Jansen, 2017, PNAS*
  - *Sun et al., 2018, GRL*
  - *…*
- *North Atlantic forcing ⇒ strength?*
  - *Oka et al., 2012, GRL*
  - *Zhu et al., 2014, GRL*
  - *Zhang et al., 2014, Nature*
  - *Muglia and Schmittner, 2015, GRL*
  - *…*

CESMs are the only PMIP3/4 models that simulate a shallower glacial AMOC



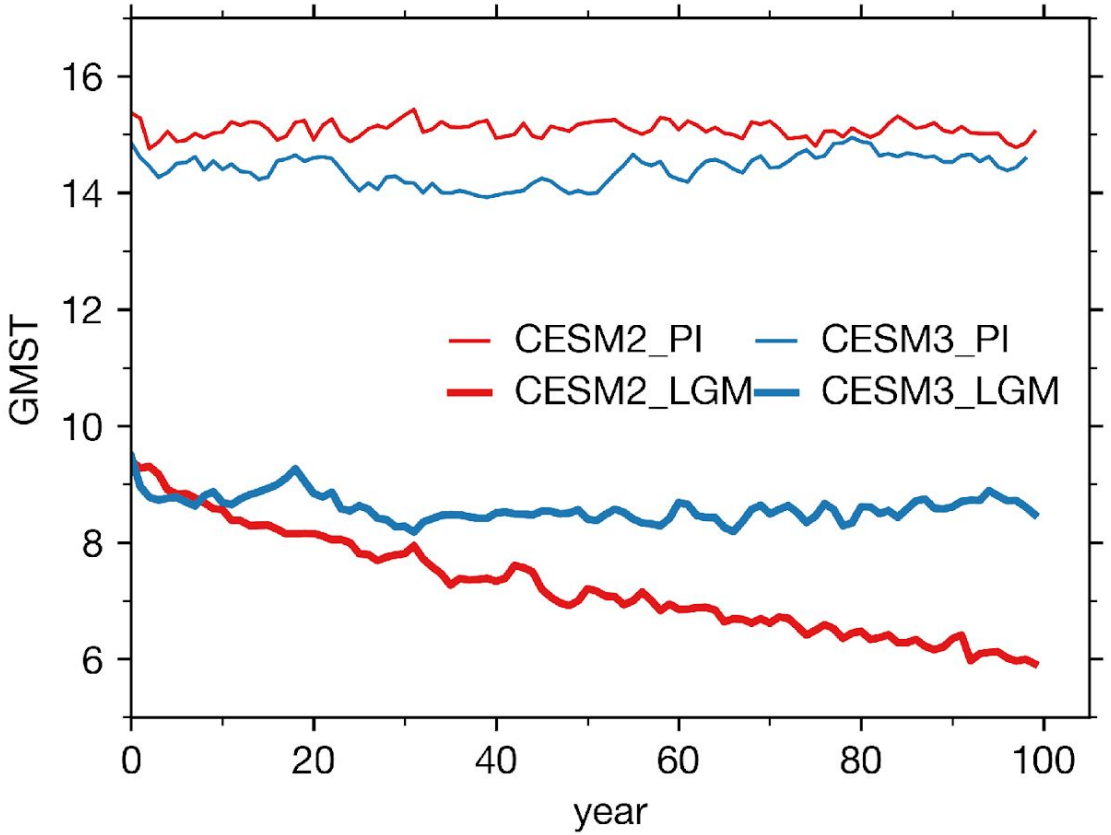
Kageyama et al., 2021, CP

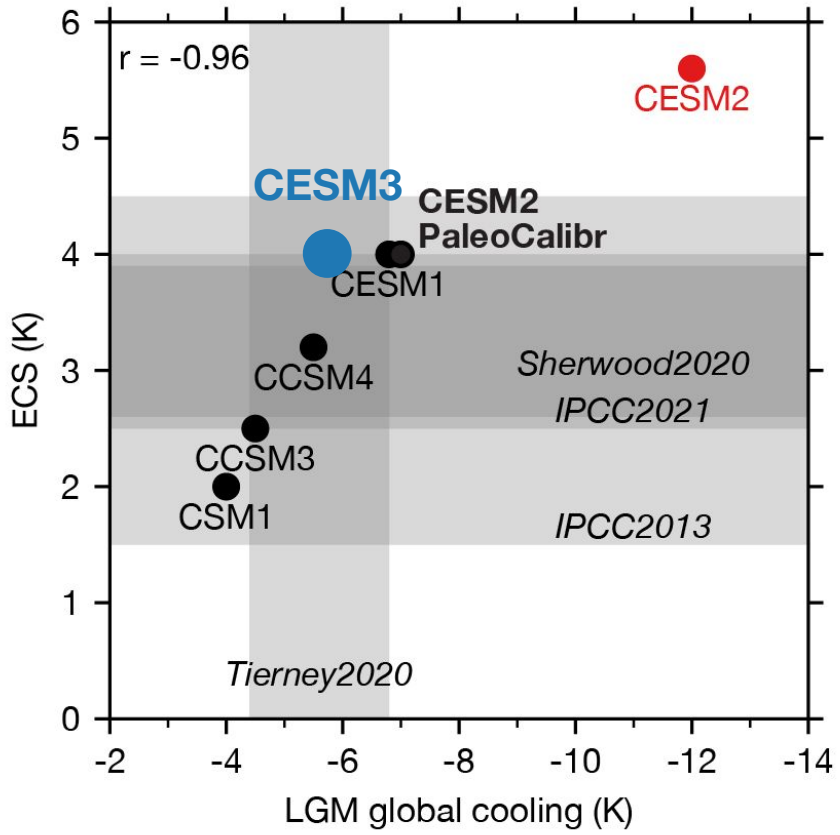
Goal: Perform LGM simulation to assess CESM3's climate sensitivity & AMOC



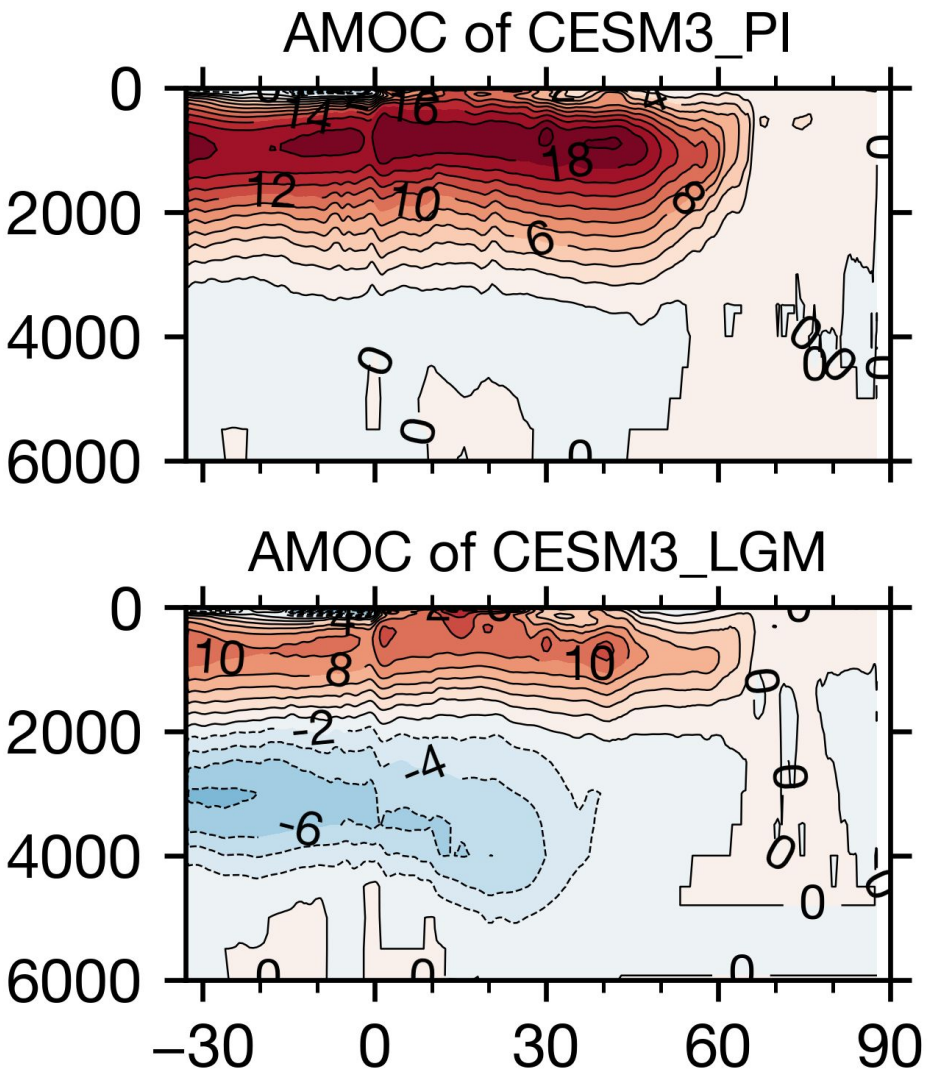
- CESM3_beta04 (Run # 121)
- Boundary conditions
  - lower CO_2
  - Ice sheets: higher albedo & topography, altered land surface, and lower sea level (~120 m)
- Initial condition: CCSM4 LGM *(Brady et al., 2013, JC)*
- Setup tools
  - Notebooks: https://github.com/jiang-zhu/paleowg-recipes
  - mom6_bathy by Alper Altuntas: https://github.com/NCAR/mom6_bathy
  - Multiple HYCOM1 coordinate targets from Prof. Ian Grooms

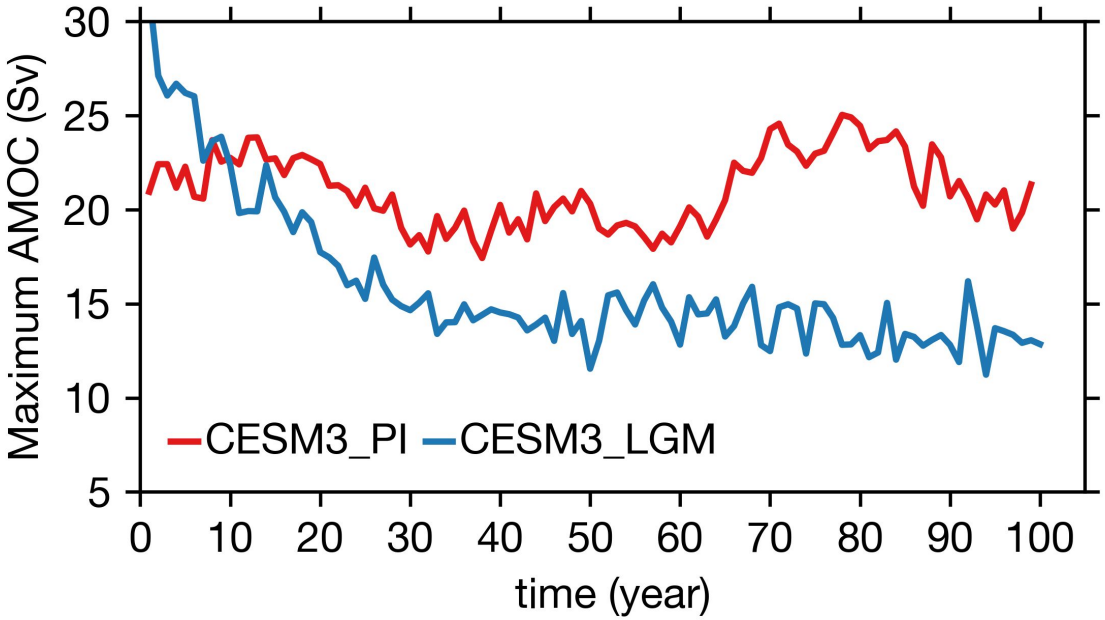
Realistic LGM global temperature, supporting CESM3's climate sensitivity





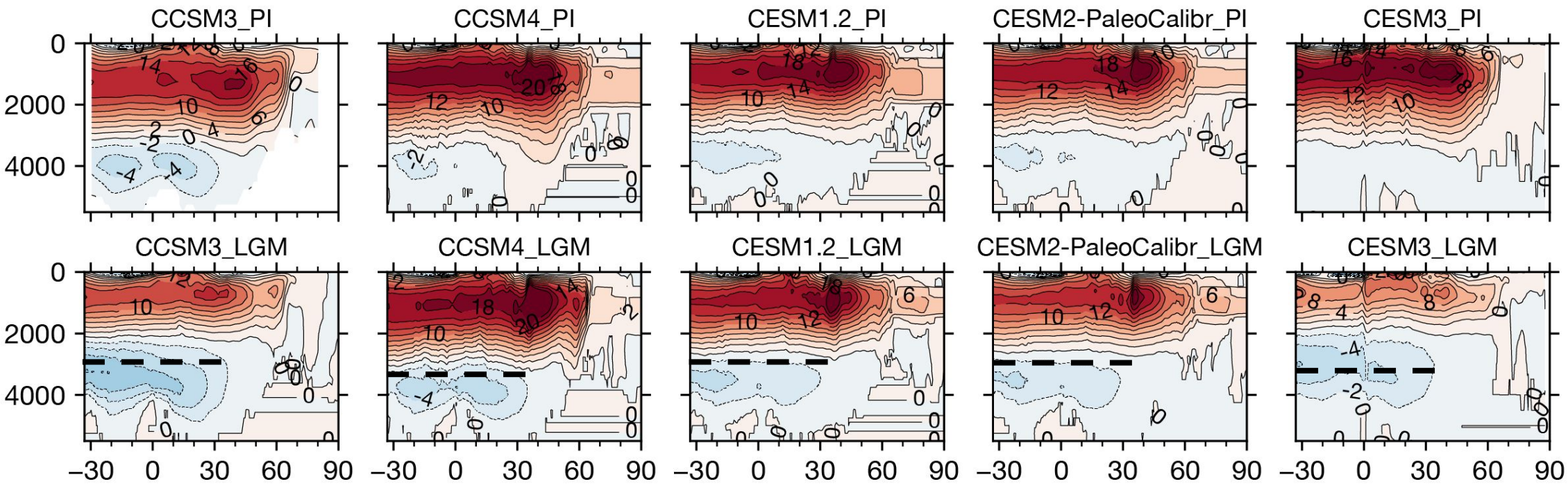
Shallower and much weaker glacial AMOC





- Excellent agreement with *Poppelmeier et al., (2023, Nat. Geosci.):* 1-km shallower & 40% weaker
- Longer simulations are needed to see whether AMOC is stable

Consistently shallower glacial AMOC with various strength

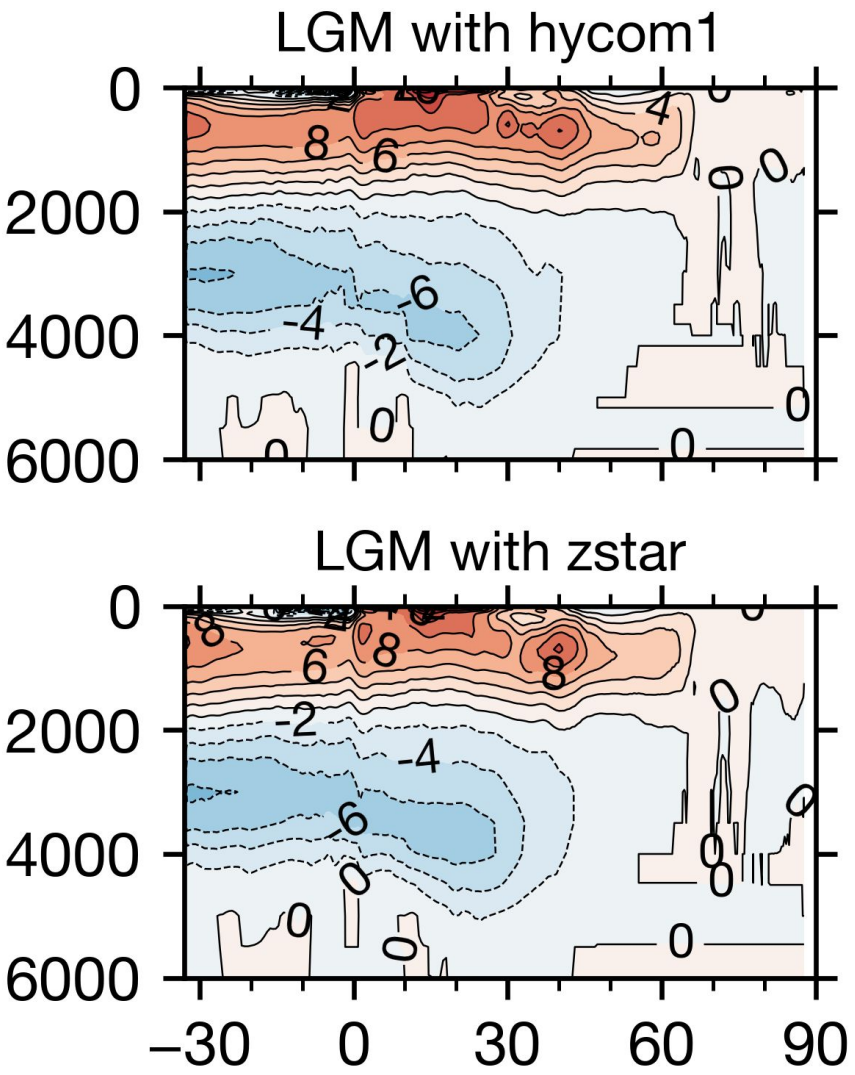


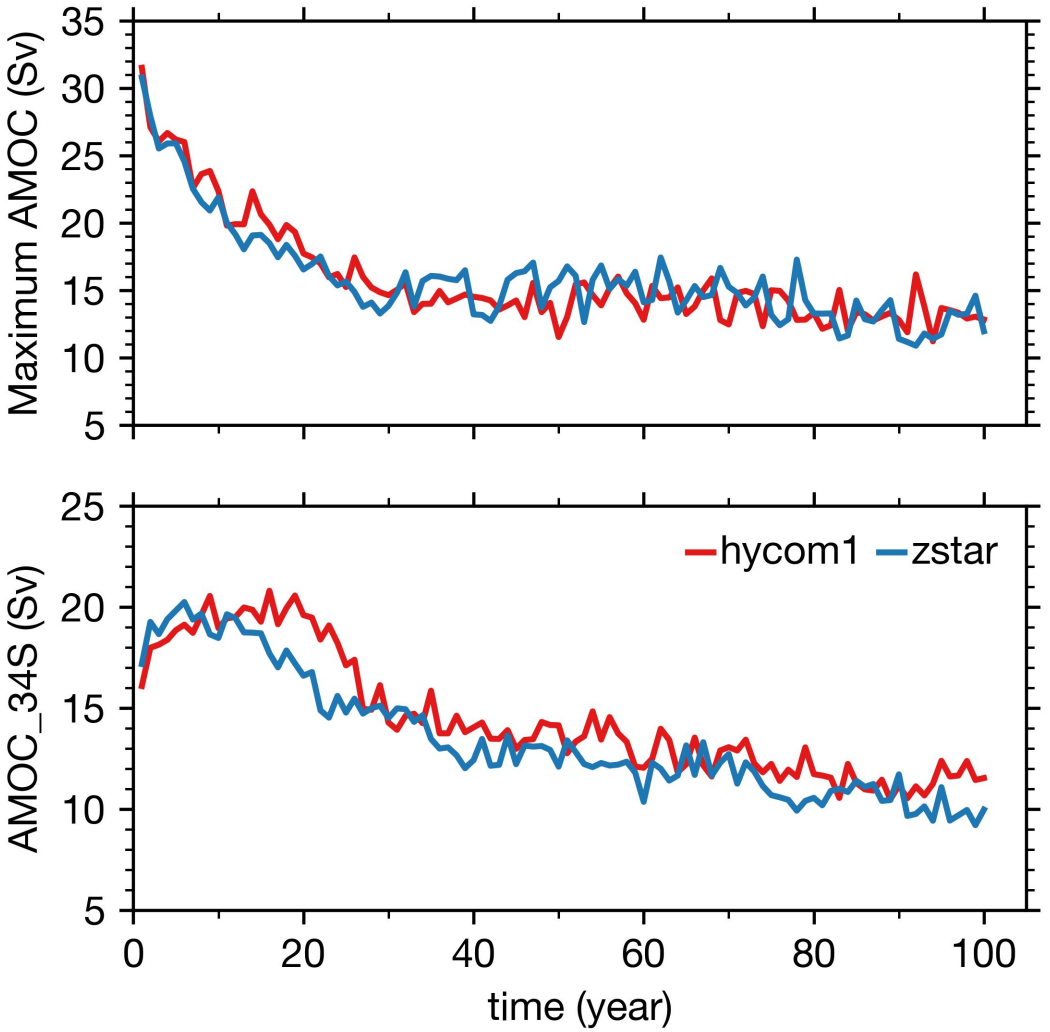
Weak glacial AMOC in CCSM3 and CESM3

- No overflow parameterization? *(i.e., Danabasoglu et al., 2010, JGR-Ocean)*
- Larger sea ice expansion?

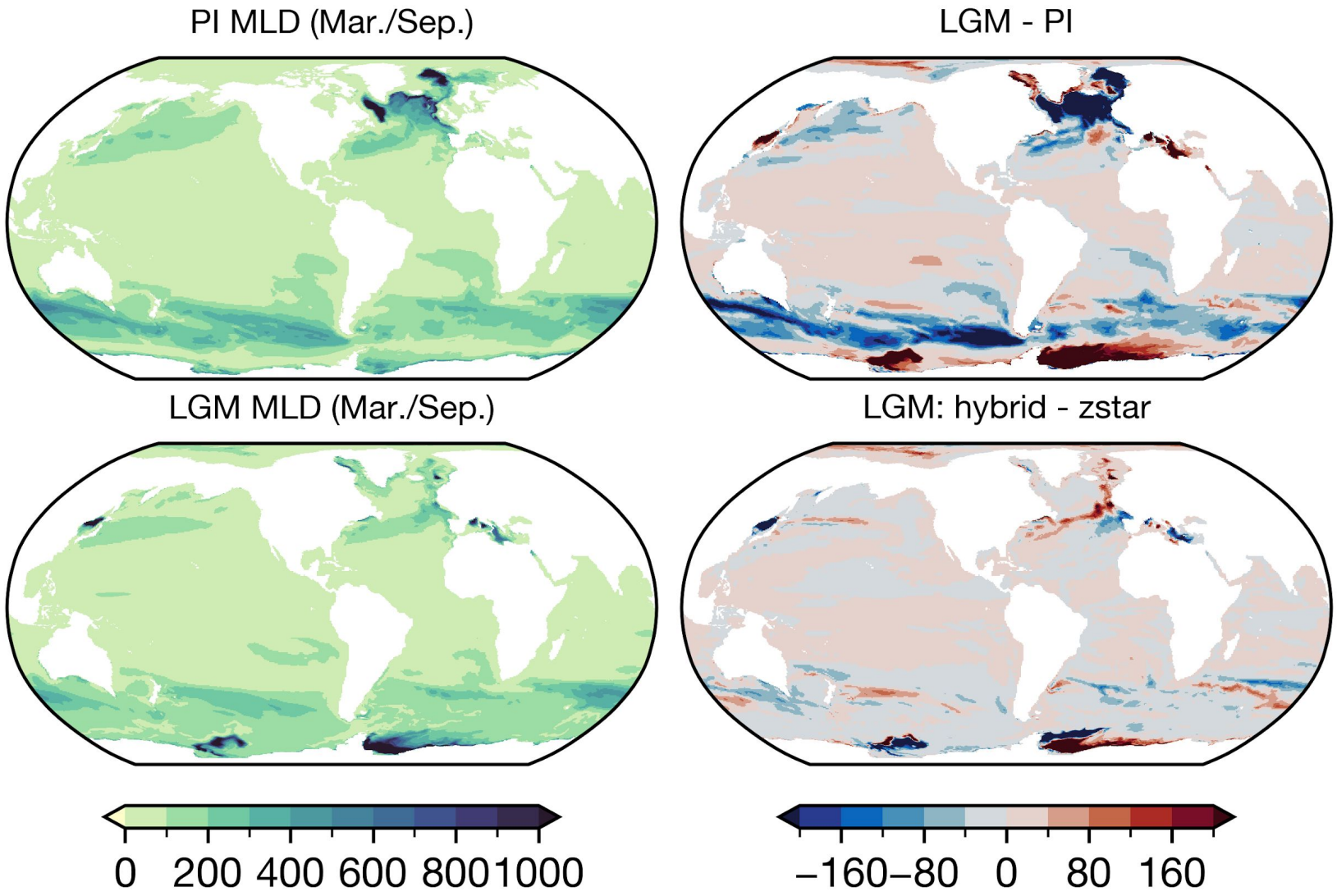
Otto-Bliesner et al., 2006, JC
Brady et al., 2013, JC
Zhu et al., 2020, CP
Zhu et al., 2022, JAMES

Using zstar v-coordinate produces slightly weaker AMOC



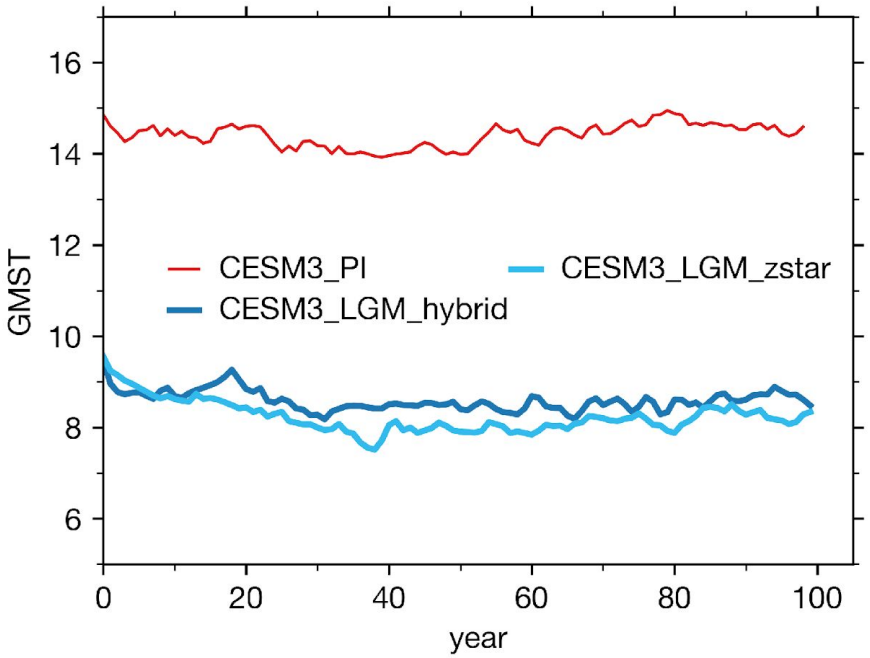


Using zstar v-coordinate produces somewhat different MLD

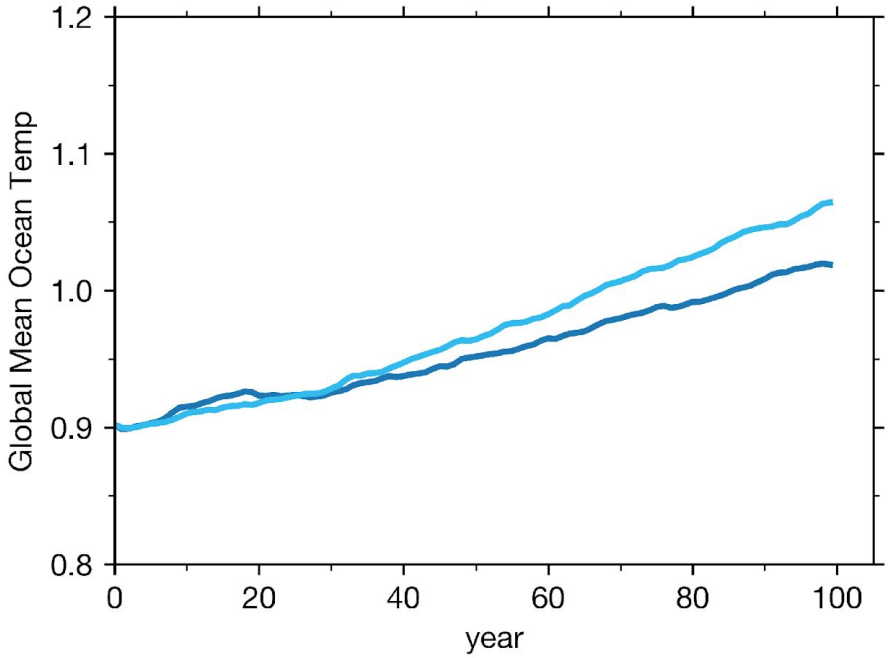


Using zstar v-coordinate leads to greater trend in deep ocean

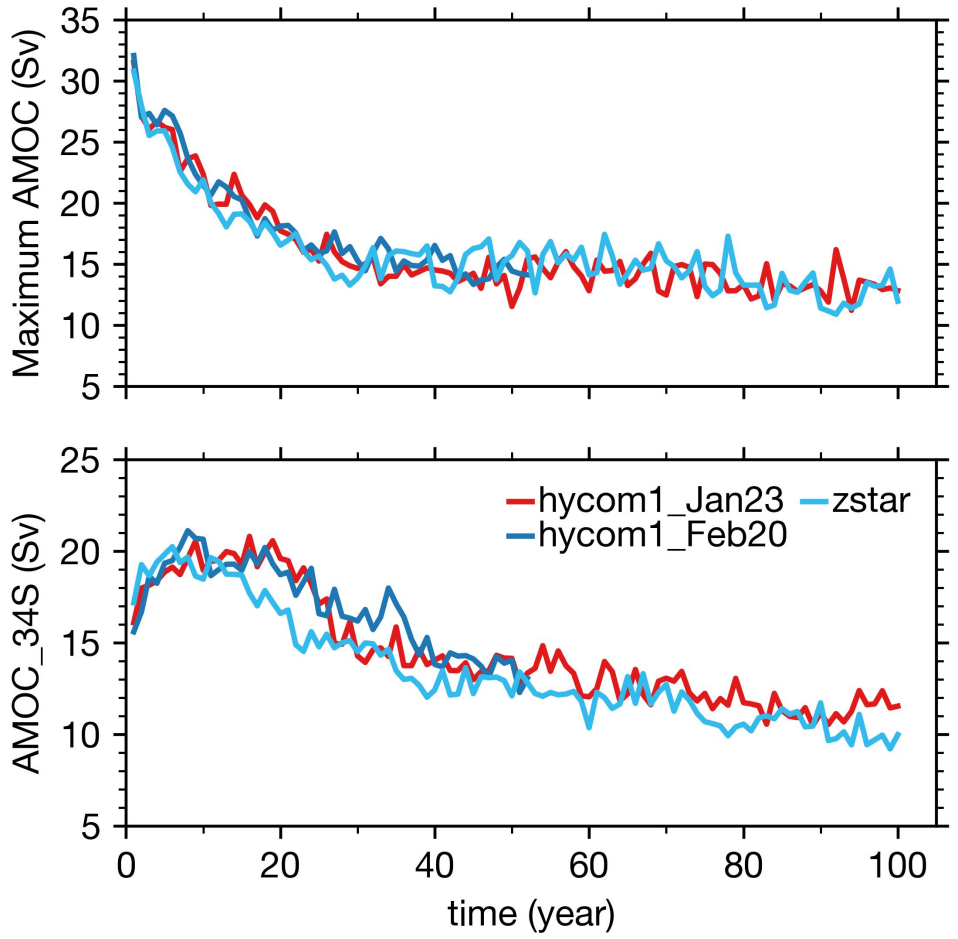
Global Mean Surface Temperature



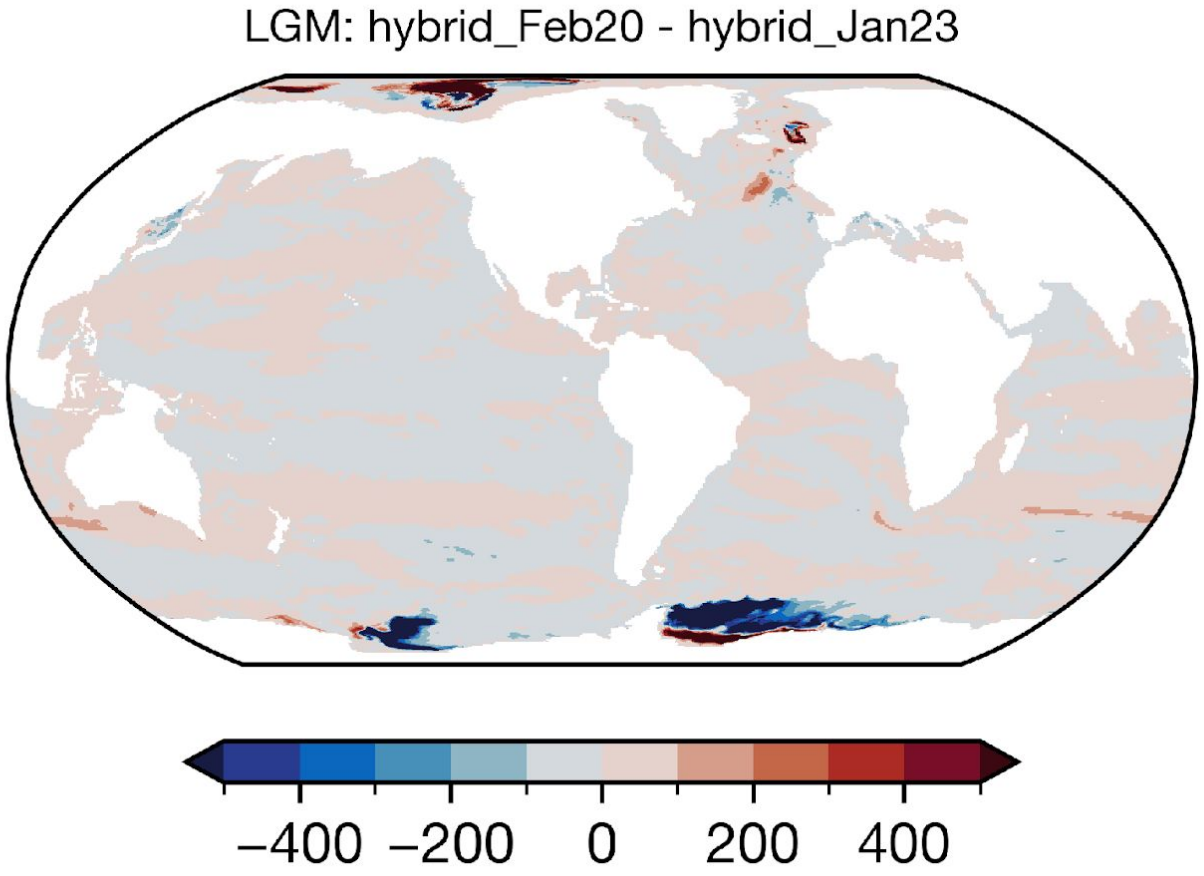
Global Mean Ocean Temperature



Sensitivity to HYCOM1 coordinate targets (comparing two versions from Ian)



MLD



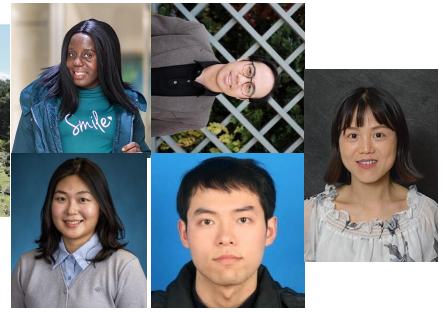
CESM1(CAM5) is the most popular model for paleoclimate research

Macarewich
U Mich

Song
CUG, China

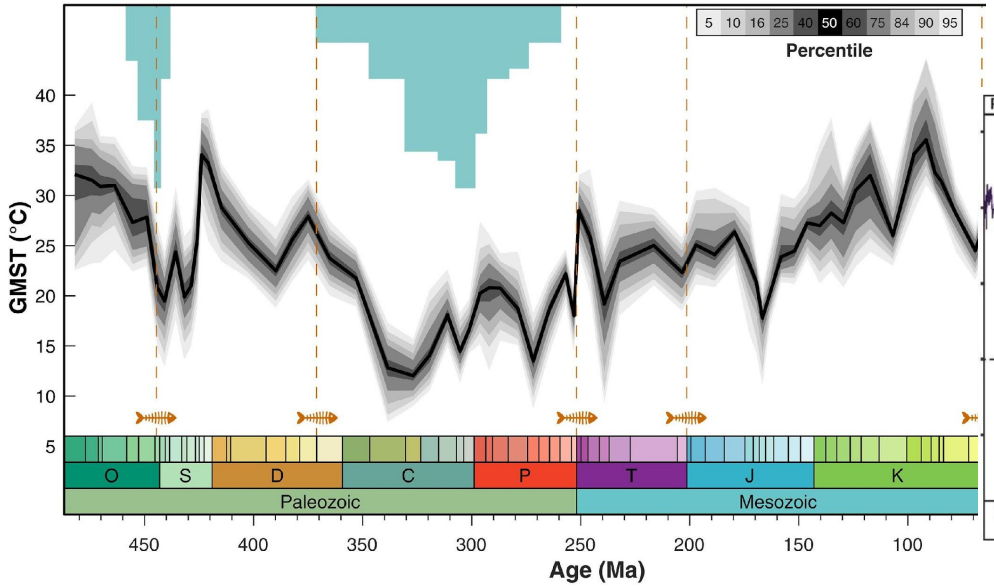
Saar
U Oregon

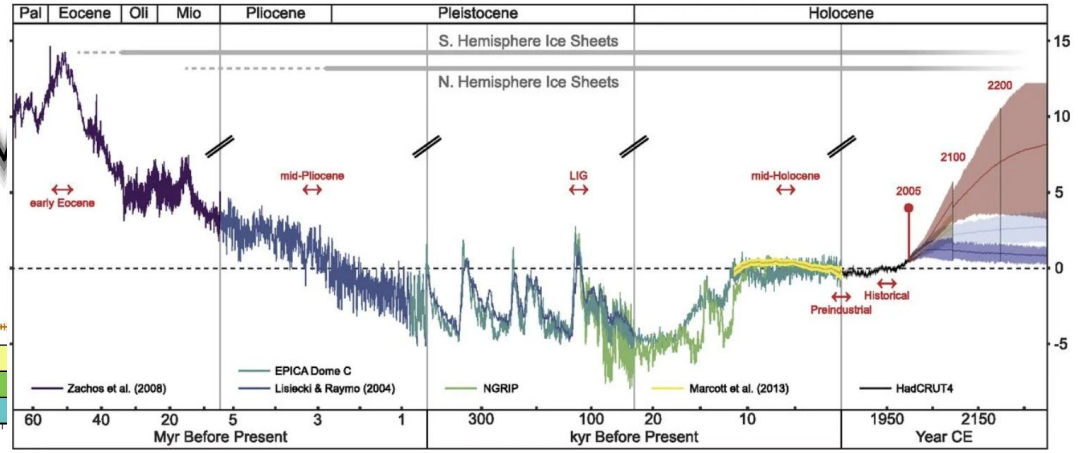
Ladent
U Mich



Nadoya, Lee, Acosta, Zhu, Liu
U Conn, U Mich, Purdue, NCAR

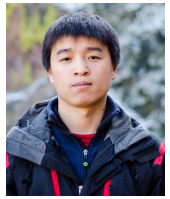
Schnaubelt
U Conn





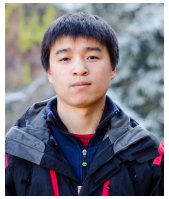
- Hu Group (China): 54 time-slices of past 540 million yrs
- Timmerman Group (South Korea): transient simulation of the last 2 million years
- PALMOD Group (Germany): transient deglaciation with ice sheets & carbon cycle

Zhu
U Mich



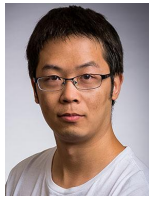
Feng
NCAR

Zhu
UW-Madison

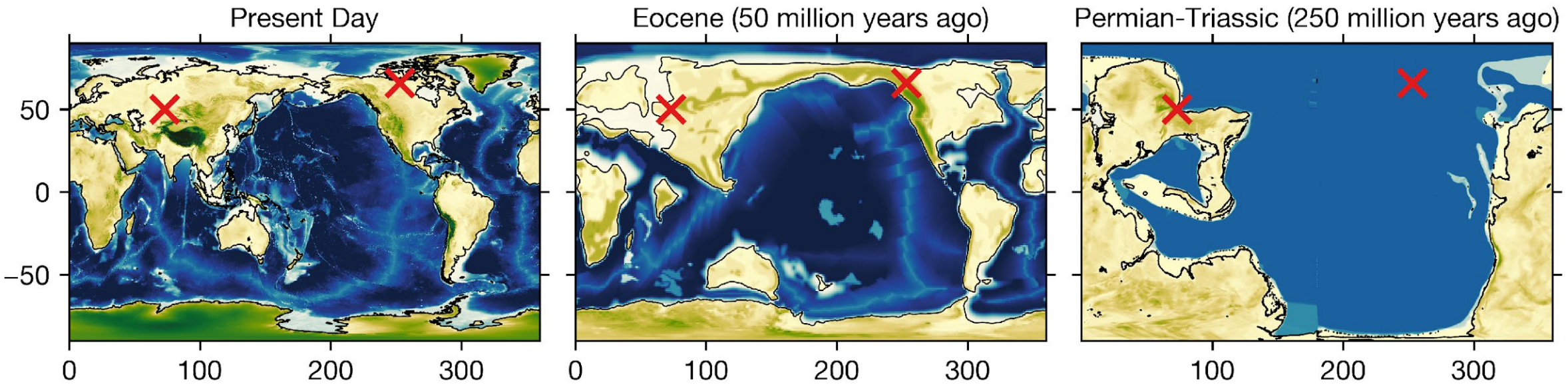


Tabor
NCAR

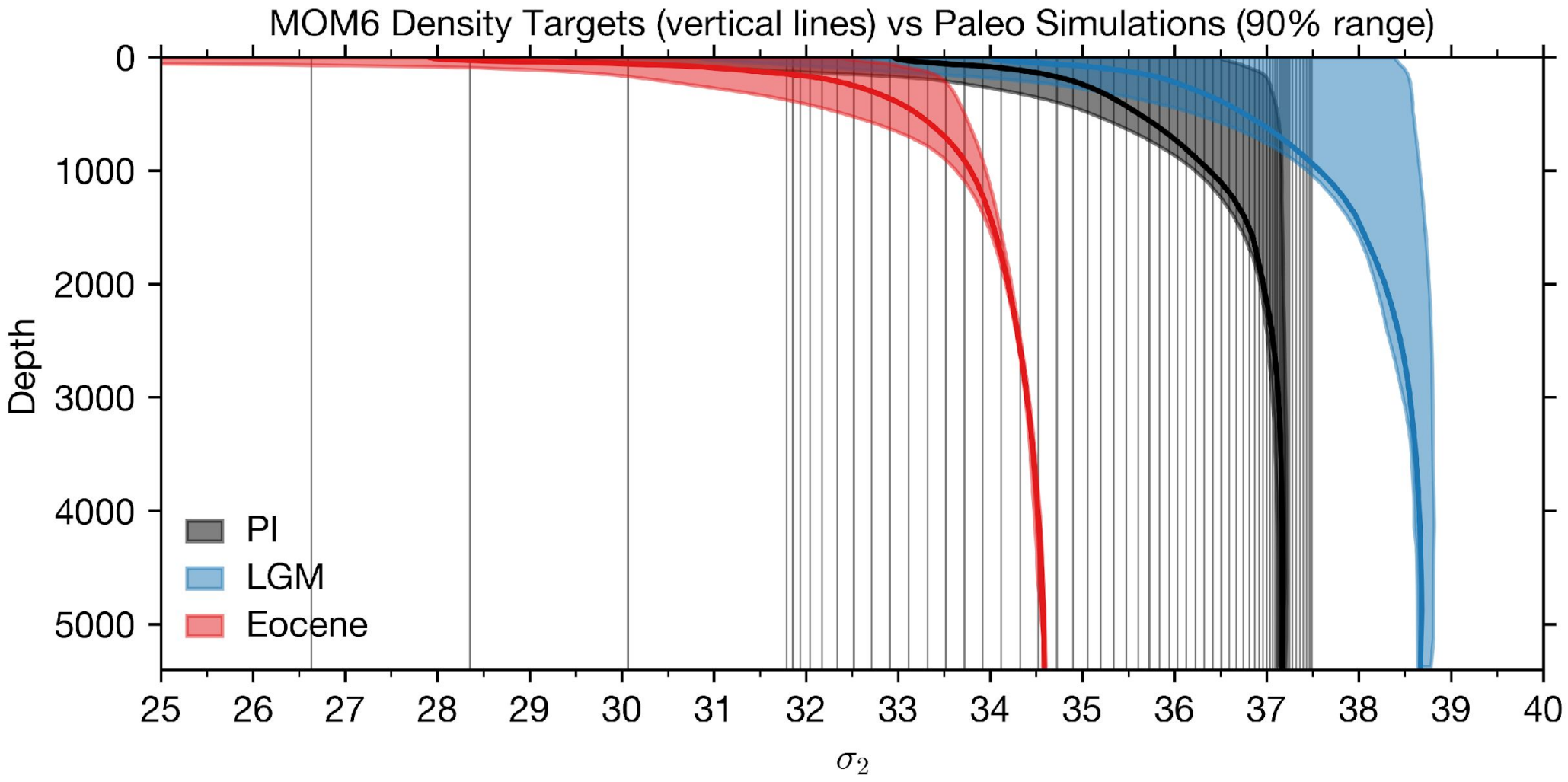
He
OhioSU



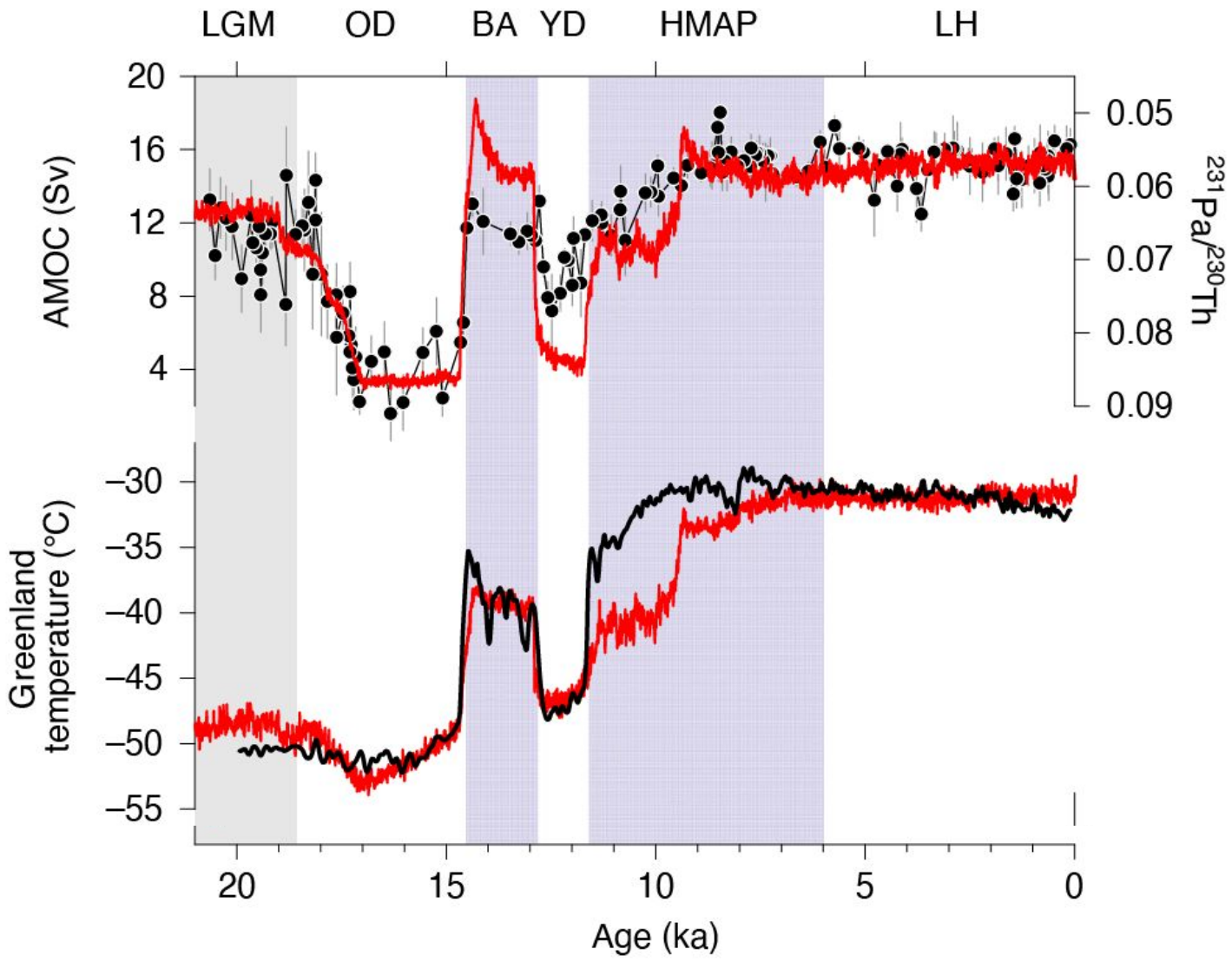
Challenges: How to develop ocean grid for MOM6?



Challenges: How to develop and evaluate the vertical coordinates?



Challenges: How to use hybrid coordinates in transient simulations with large, abrupt changes?



Liu, Otto-Bliesner, He, Brady, et al., 2009, Science
He & Clark, 2022, Nature Climate Change

Summary

- CESM3 LGM simulations show
  - Realistic glacial temperatures, supporting its climate sensitivity
  - A shallower (& weaker) AMOC, agreeing well with proxy data and theory
  - Some dependence on choices/details of MOM6 vertical coordinates over the deep-water formation region

- For successful paleo-applications of CESM-MOM6, we need
  - Tools and scientific considerations for grid and vertical coordinate development and evaluation
  - A coarser resolution for faster throughput

Thank you!

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Sensitivity to vertical coordinates? Z* vs HYCOM1

LGM AMOC 2 Sv stronger with hybrid vertical coordinate