Paleoclimate Applications with CESM: Past climates inform our future

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& NCAR Paleoclimate Group :
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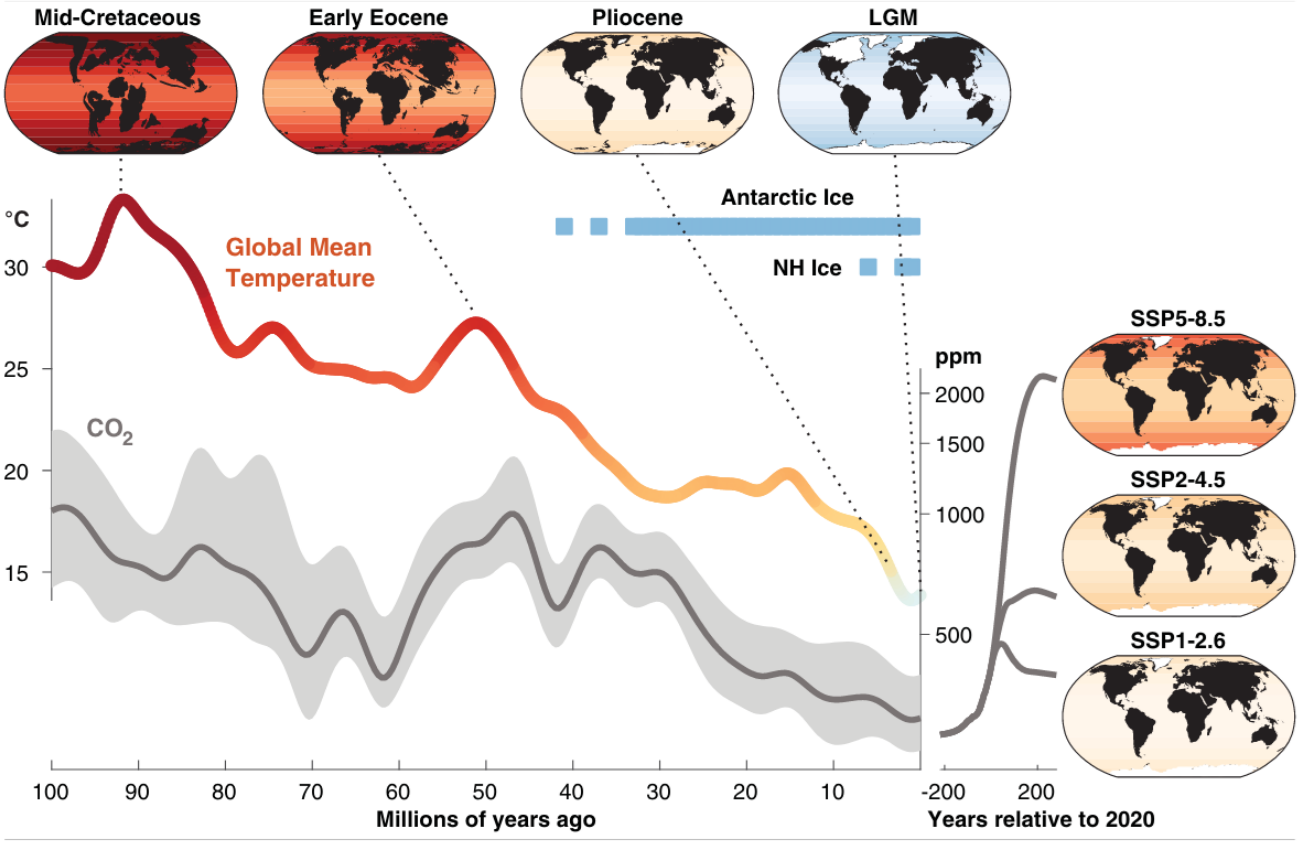
Outline

- Why do we study paleoclimates with CESM?
- What is proxy data?
- Important aspects and applications of paleoclimate simulations
  - Water isotope tracers
  - Low-resolution climate ensembles
  - High-resolution extreme weather phenomena
- How do you modify CESM for paleoclimate simulations?
- Resources for paleoclimate applications of CESM & Paleoclimate Working Group

Past climates provide only real data for future high CO_2 scenarios



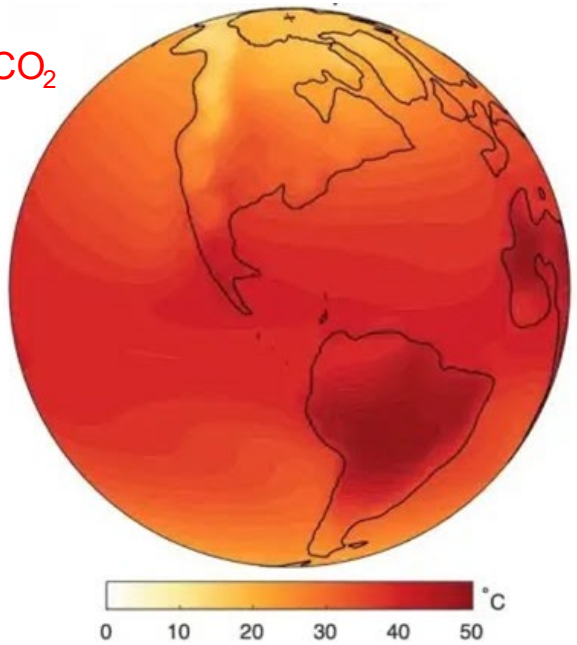
Tierney et al. (2020), *Science*

Past extreme climate states

High CO_2 (>1000 ppm)
Early Eocene Climatic Optimum (~50 Myr ago)

Elevated CO_2

Global warming

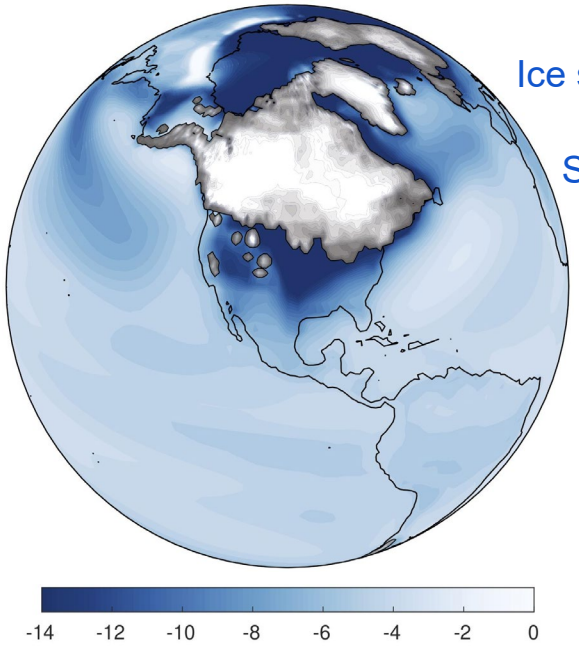


Low CO_2 (~180 ppm)
Last Glacial Maximum (~21 kyr ago)
and subsequent deglaciation

Ice sheet stability

Sea level change

Abundant
proxy records



Geologic record provides information on extreme climate states

Early Eocene Climatic Optimum (~50 Myr ago)

Coryphodon and deciduous forest ecosystem in high Arctic

Last Glacial Maximum (~21 kyr ago) and subsequent deglaciation

Woolly mammoths had most widespread distribution of any large mammal

Picture credit: D. Finnin, *American Museum of Natural History (left);* Alan Turner, *Nat'l Geographic Prehistoric Mammals (right)*

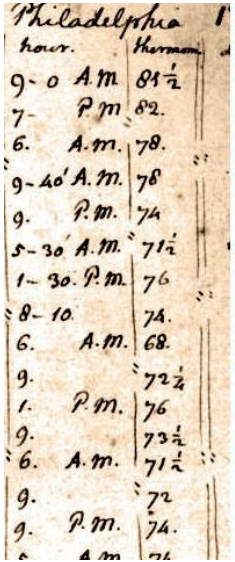
Proxies: real-world climate data beyond the record of direct measurements

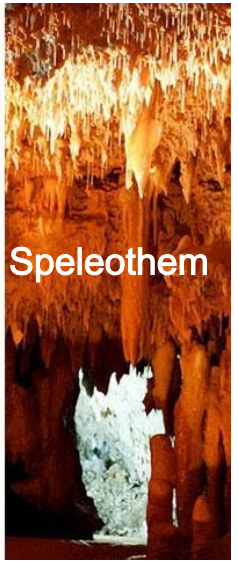
Proxies can be physical, chemical, or biological measurements related to…

Air temperature
Precipitation
Atmospheric CO_2

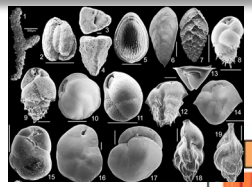
Ocean-atmosphere circulation
Ice sheets

Ocean temperature
Salinity
Sea level

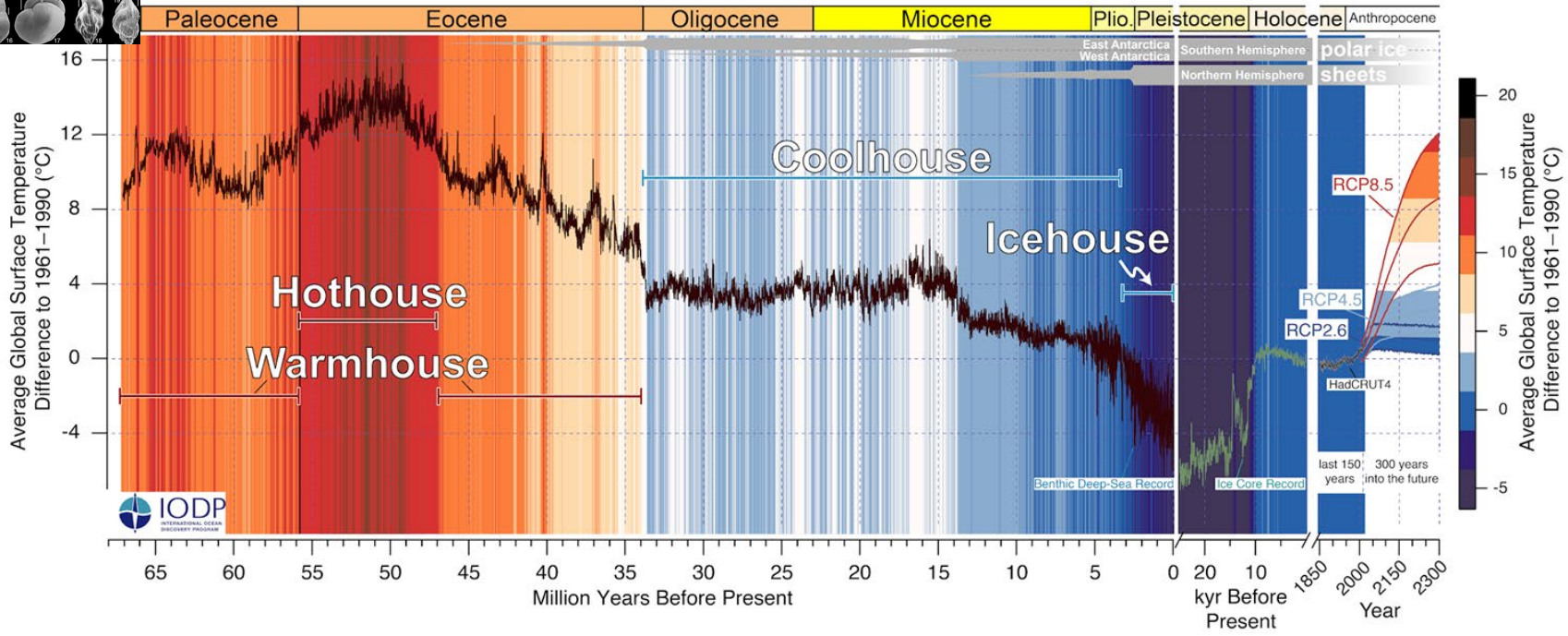




Proxy reconstruction of past global surface temperature



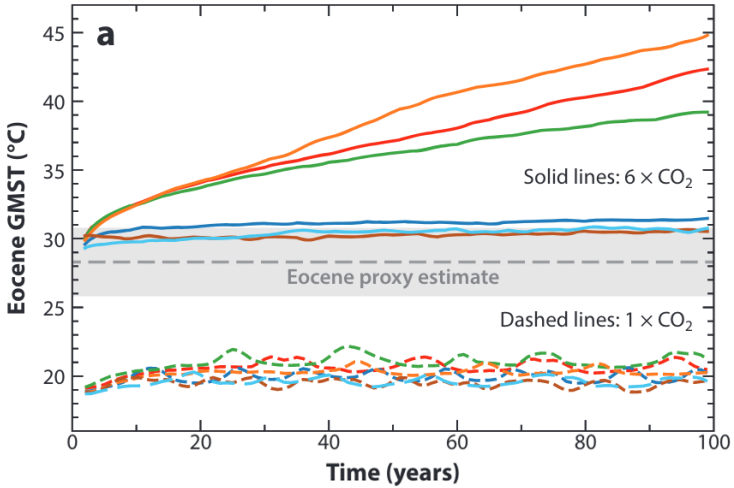
Benthic foraminifera



Past climates provide out-of-sample testing of modeled processes

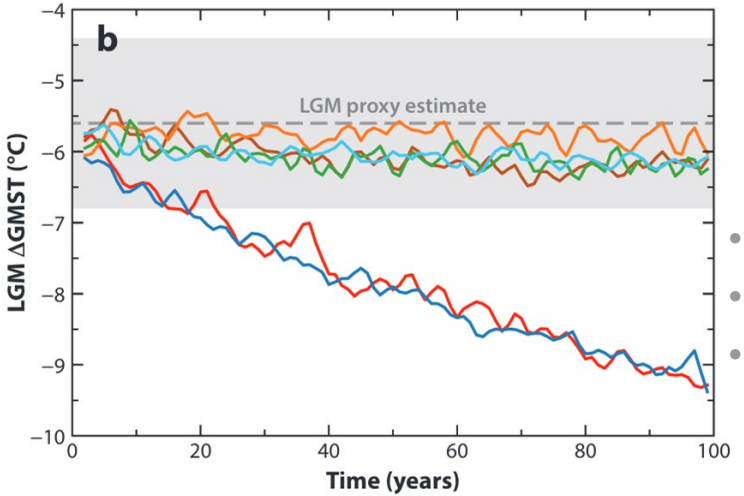
CESM2 overestimates past extreme warming & cooling, adjustments to the cloud schemes bring temperatures to the range of proxies

Early Eocene (55 Ma)



Boundary layer turbulence & convection processes most important

Last Glacial Maximum (21 ka)

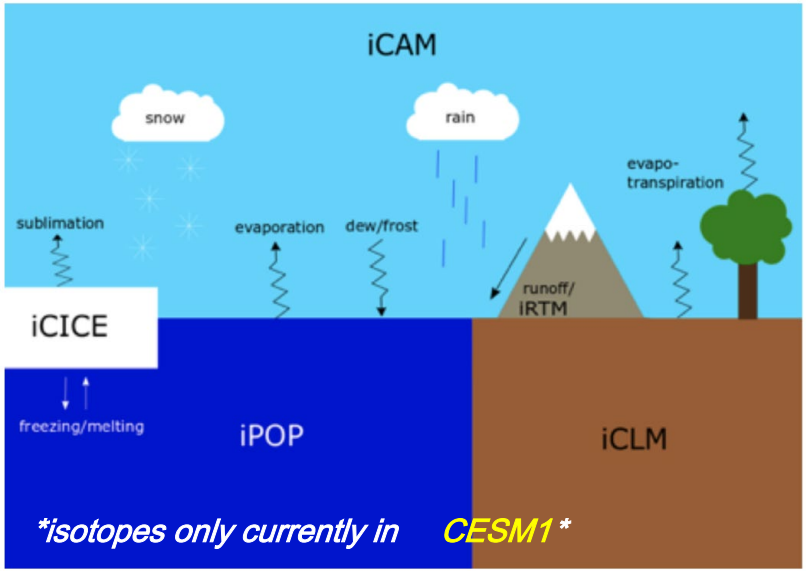


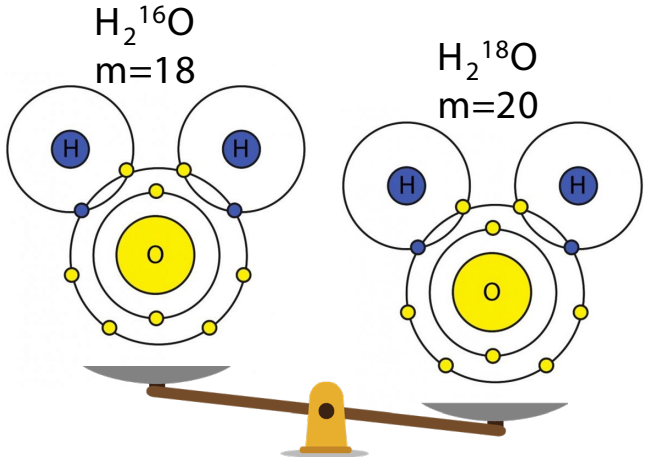
- Remove limiter on cloud ice #
- Increase # time steps in cloud microphysics
- Enhance damping of the asymmetrical mixing → weaken BL turbulence → longer lasting low-level clouds

Ice nucleation & cloud microphysics schemes are most fix

Water isotope tracers throughout the hydrologic cycle of CESM1 (iCESM1)

- Proxy isotope ratios integrate ambient temperature & isotope ratios of source water that formed them
- Water isotope tracers help erode the "language barrier" that exists between climate models and proxy data





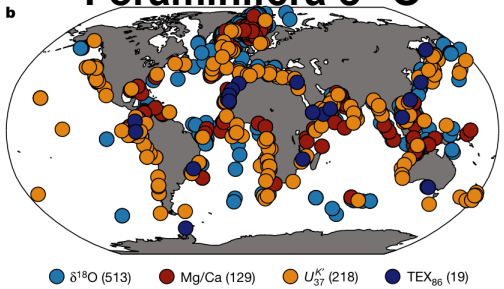
Speleothems, ice cores, foraminifera

Water isotope tracers vastly improve proxy-model comparisons

$$\delta^{18}O = \left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} - 1 \right) \times 1000\,‰$$

How much colder was the ocean during the Last Glacial Maximum compared to present day?

Foraminifera $\delta^{18}O$



Seawater temperature

Seawater $\delta^{18}O$

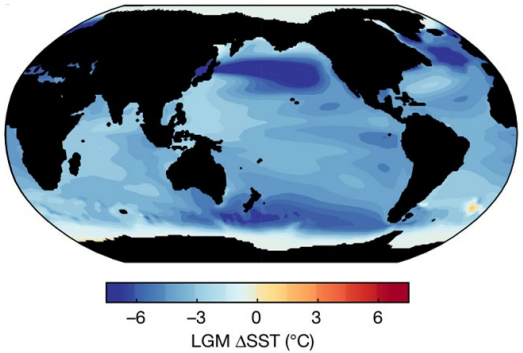
+

Estimate of seawater $\delta^{18}O$

Consider global ice volume, ocean circulation, P-E balance

=

Seawater temperature



Tierney et al. (2020), *Nature;* Brady et al. (2019), *JAMES*

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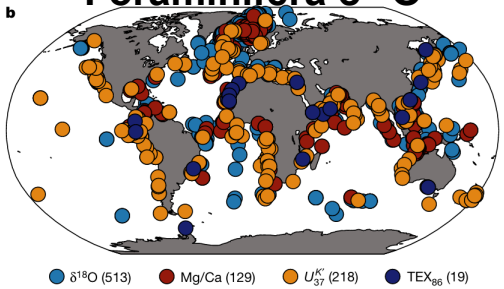

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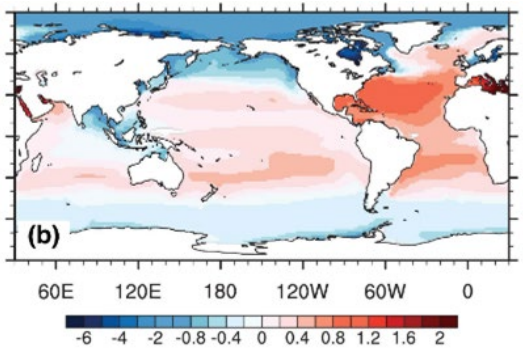
Seawater $\delta^{18}O$ from iCESM



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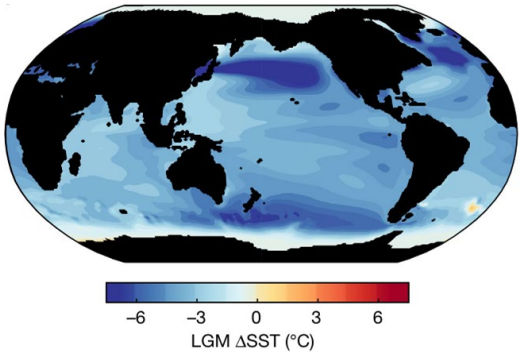
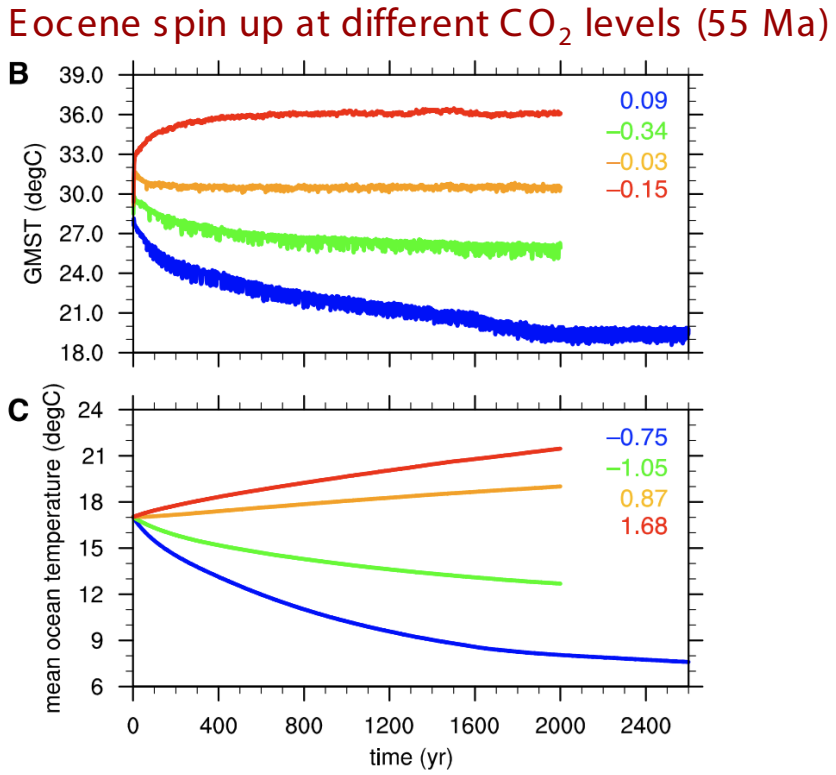


Tierney et al. (2020), *Nature;* Brady et al. (2019), *JAMES*

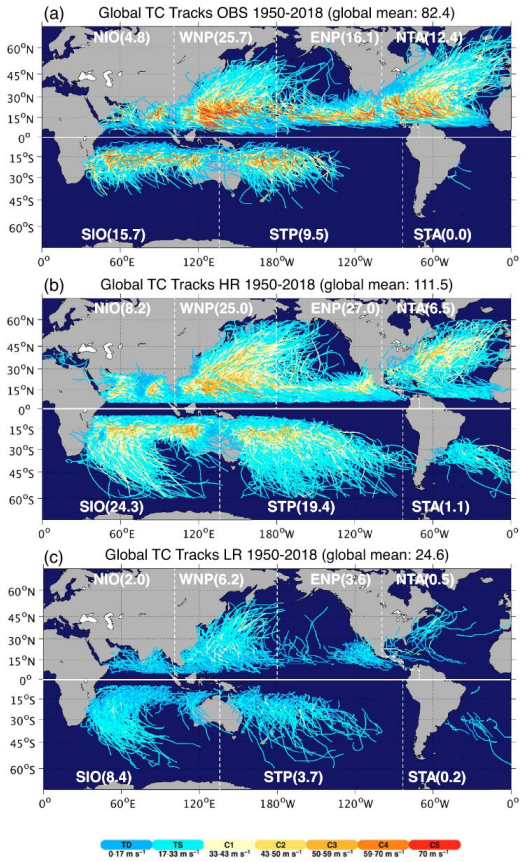
Ensembles of low resolution, long simulations used to assess uncertainty

- Low horizontal grid resolution (≥100 km) enables running many simulations that capture uncertainty in boundary conditions and forcings
- Long model spin up (>1000 years) required for climate states far from modern day

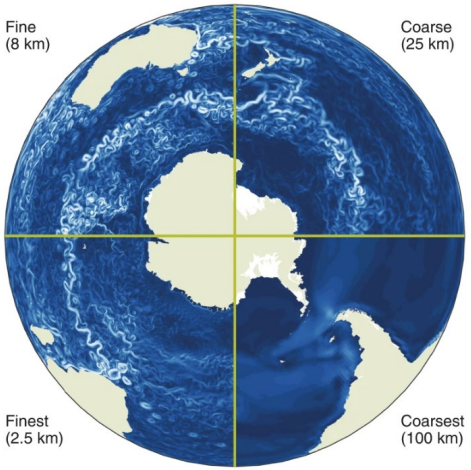


Tierney et al. (2020), *Science*

Higher grid resolution improves CESM simulations of extreme precipitation



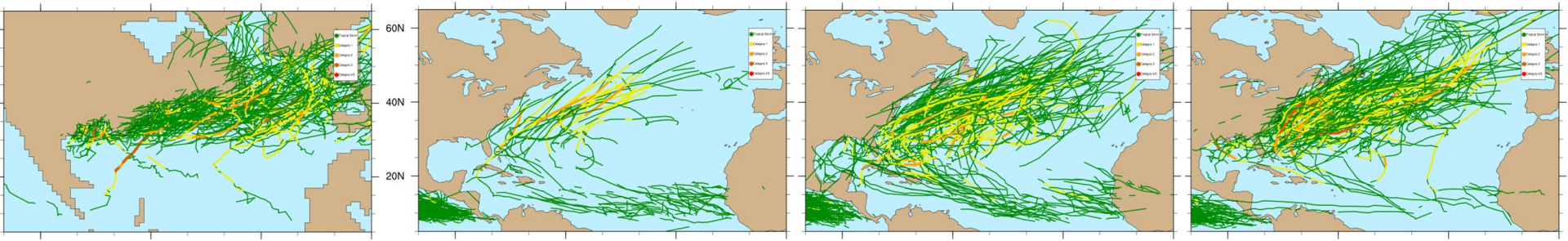
- Higher grid resolution (<100 km) enhances CESM simulations and relies less on parameterizations
- iCESM1.3 includes 25 km atm/land, 10 km ocn/sea ice
- Paleoclimate can leverage low and high resolution CESM



Chang et al. (2020), *JAMES* (left);
Hewitt et al. (2022), *Nature Clim. Chan.* (right)

High-resolution enables past-to-future assessment of rainfall extremes

- Tropical cyclones extend farther poleward at high CO_2
- Deep tropics become more hostile for tropical cyclone development at high CO_2 (*Eocene & RCP8.5)*
- More CAT3 and stronger hurricanes in warm climates



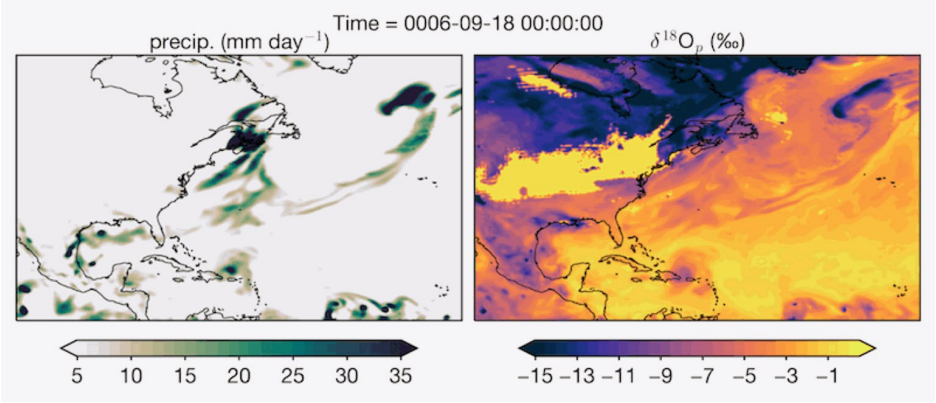
Eocene ***Last Glacial Maximum*** ***Preindustrial*** ***RCP 8.5 (@2100)***

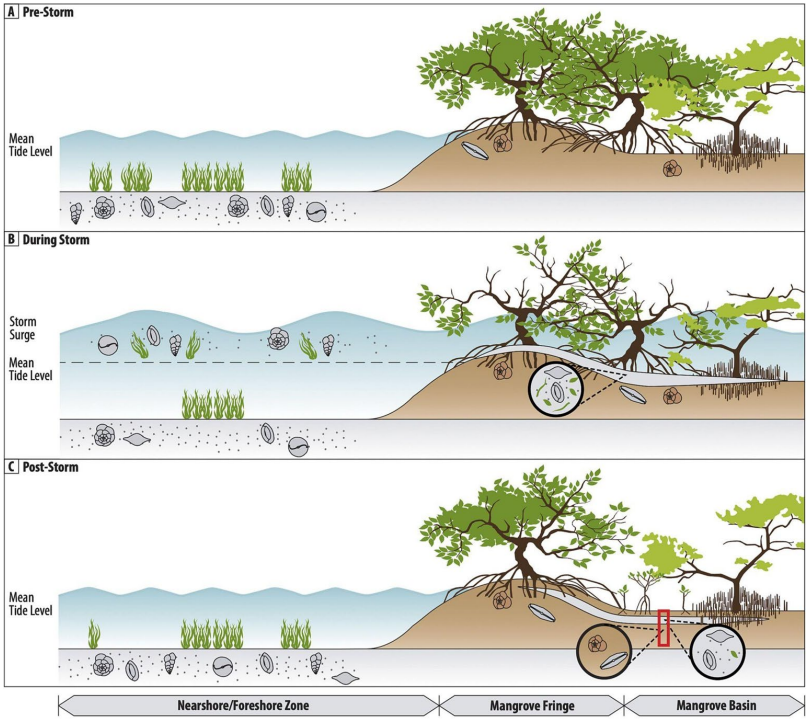
Otto-Bliesner et al. (*in preparation*)

High-resolution proxy records enable the study of paleotempestology

Proxy reconstructions can provide strong evidence for past changes in extreme precipitation events (e.g., tropical cyclones)

Rate & $\delta^{18}O$ of Precipitation

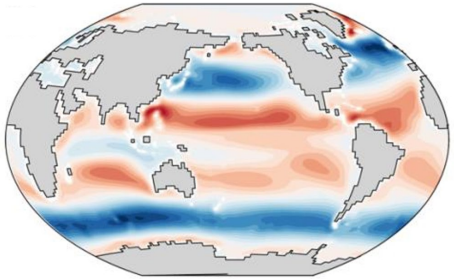




Joyce et al. (2023), *Marine Geology*

Designing a paleoclimate simulation is highly interdisciplinary

"Out-of-box" default preindustrial CESM case



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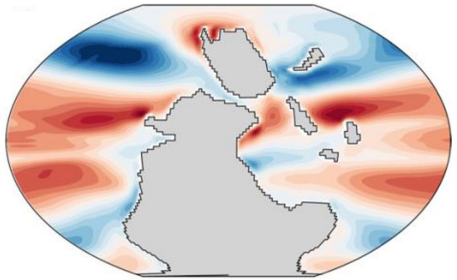
Paleoclimate CESM case



Macarewich & Poulsen (2022), *Paleoceanography & Paleoclimatology*

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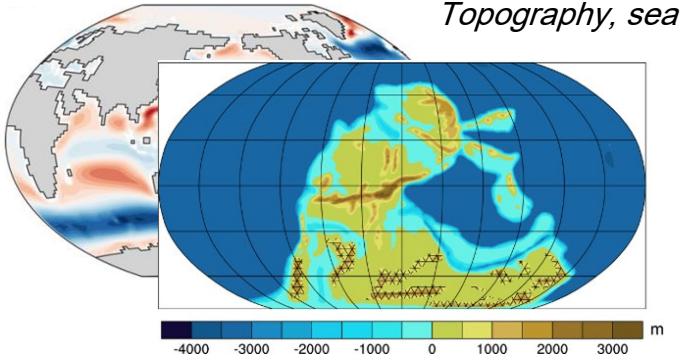
Paleogeography

Topography, sea level, bathymetry



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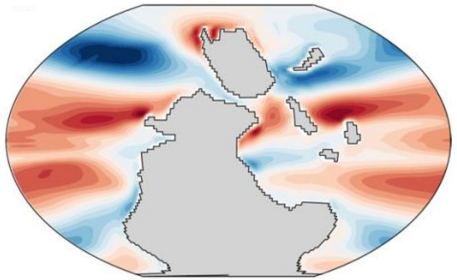

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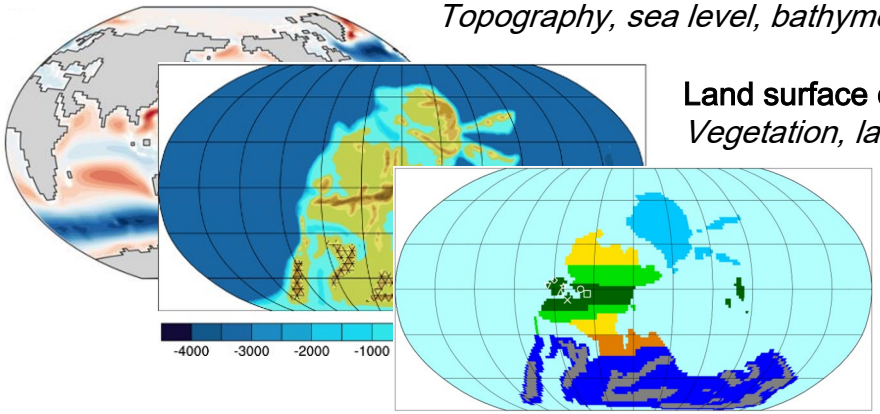
Topography, sea level, bathymetry

Land surface cover
Vegetation, land ice, rivers



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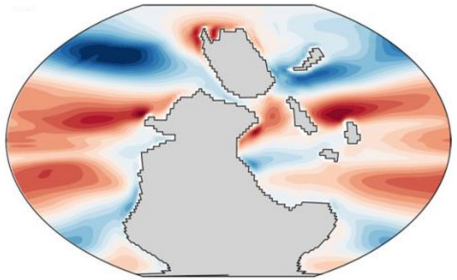

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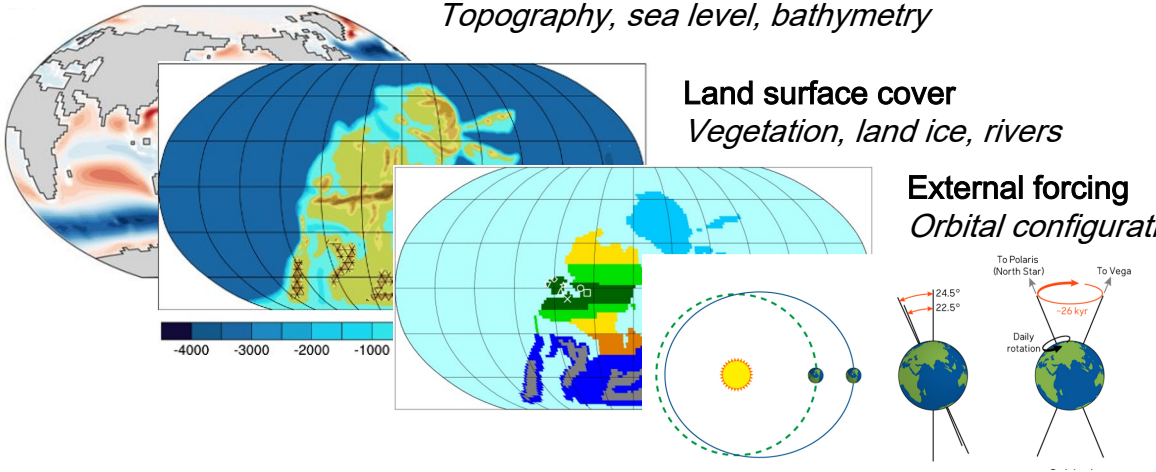
External forcing
Orbital configuration, solar luminosity



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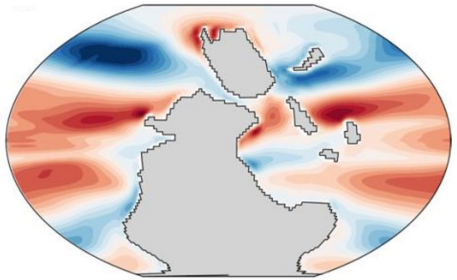

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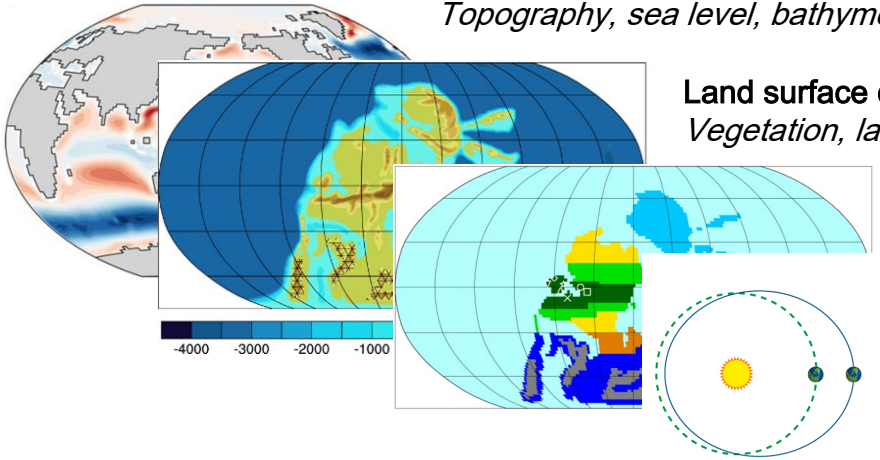

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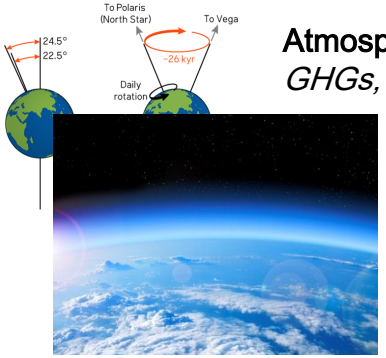
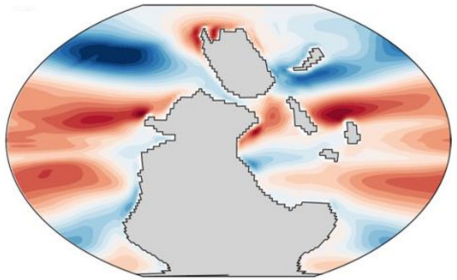


Atmospheric composition
GHGs, aerosols

Paleoclimate CESM case



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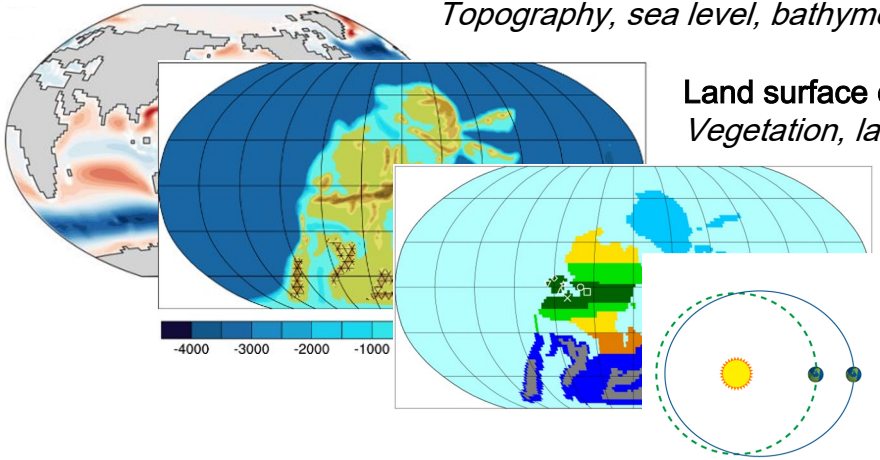

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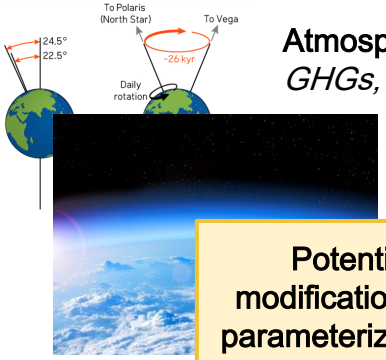
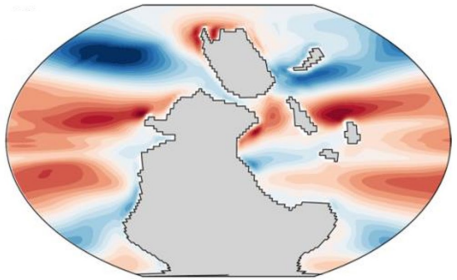


Atmospheric composition
GHGs, aerosols

Potential modifications to parameterizations

Paleoclimate CESM case



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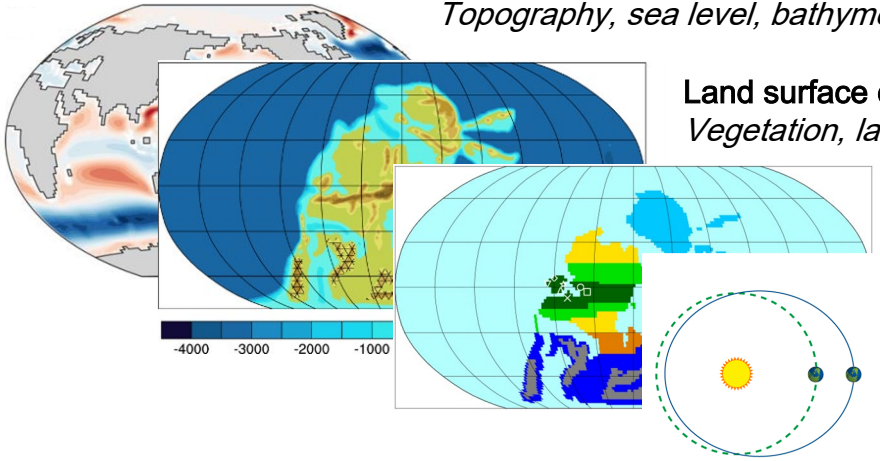

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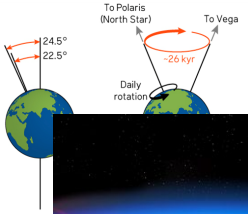
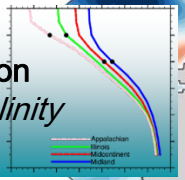


Atmospheric composition
GHGs, aerosols

Potential modificati… parameteri…

Initialization
Temp-Salinity



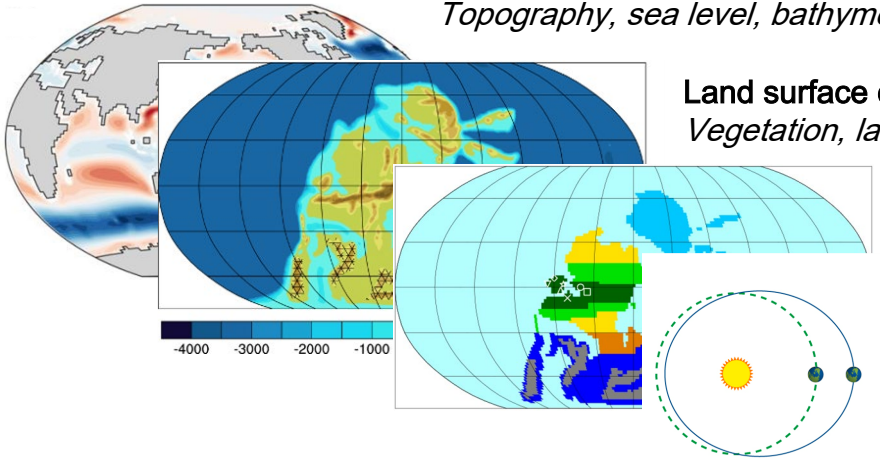
Paleoclimate CESM case

Different types of paleo expertise needed for each step, collaboration is highly valuable

Macarewich & Poulsen (2022), *Paleoceanography & Paleoclimatology*

After some debugging… you've got a deep-time paleo simulation!!!

"Out-of-box" default preindustrial CESM case



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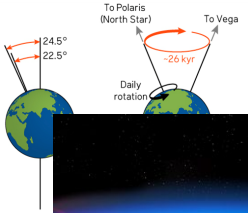

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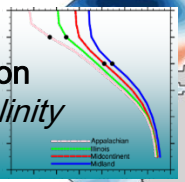


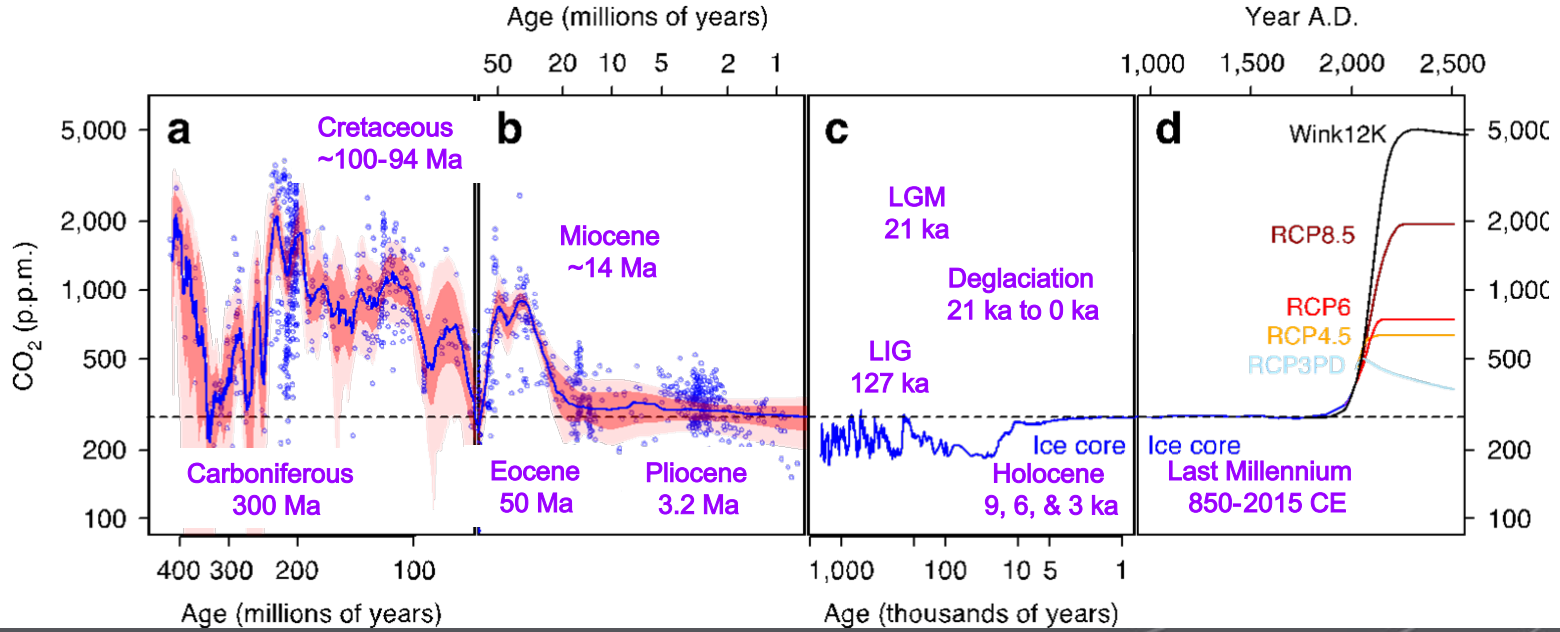
Paleoclimate CESM case

Summary of Paleoclimate with CESM

- Paleo is used in the development and assessment of CESM
- Isotope capability in CESM1.3 is critical for proxy-model integration
- Paleo requires low-res, long simulations and leverages high-res for studying past weather extremes
- Paleo relies on interdisciplinary expertise of colleagues at universities to help design boundary conditions & forcings for CESM

Resources: Paleoclimate with CESM & Paleoclimate Working Group

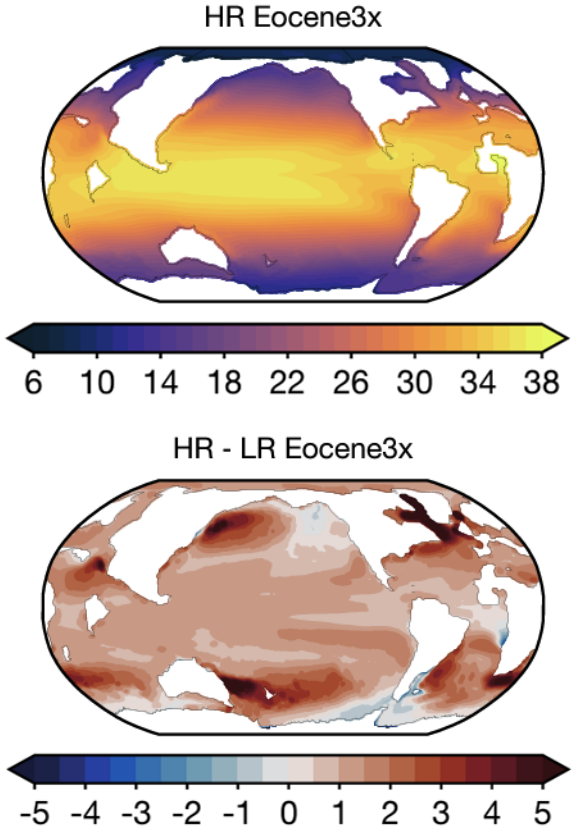
- Start from available CESM simulations before creating a new one (DeepMIP, PlioMIP, PMIP)
- Subscribe to Paleoclimate mailing list: cesm-paleoclimate@ucar.edu
- Post & engage with Paleoclimate section of DiscussCESM forum
- Attend Paleoclimate Working Group meetings in winter and summer



Extra Slides

Ocean eddies help warm high latitudes in hot house climates

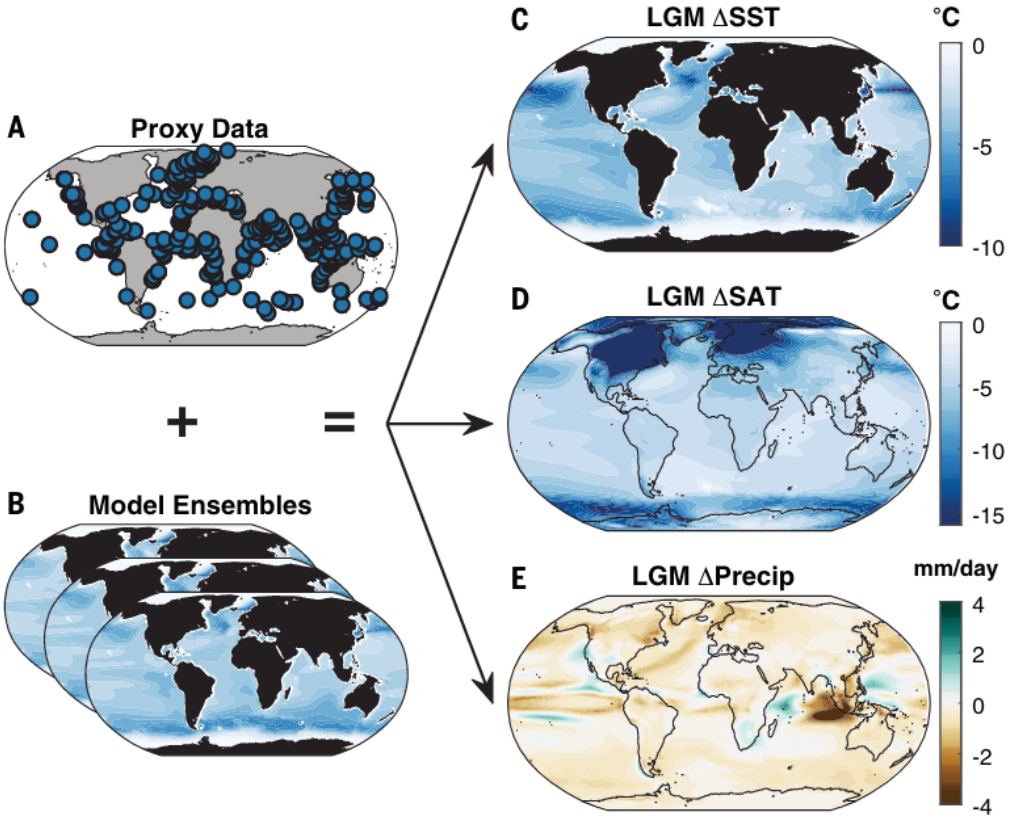
Higher resolution warms the high-latitudes in Eocene and helps with “equable climate problem”, likely due to resolved ocean eddies



Simulation ensembles assess uncertainty & improve paleoclimate reconstructions

Inexpensive, low-resolution (≥100 km) simulations can build ensembles of past climate states that capture range of uncertainty in boundary conditions and forcings

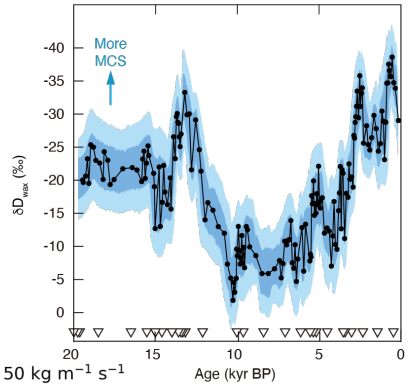
Data assimilation can be used to produce climate field reconstructions that leverage the strengths of climate models and proxy data

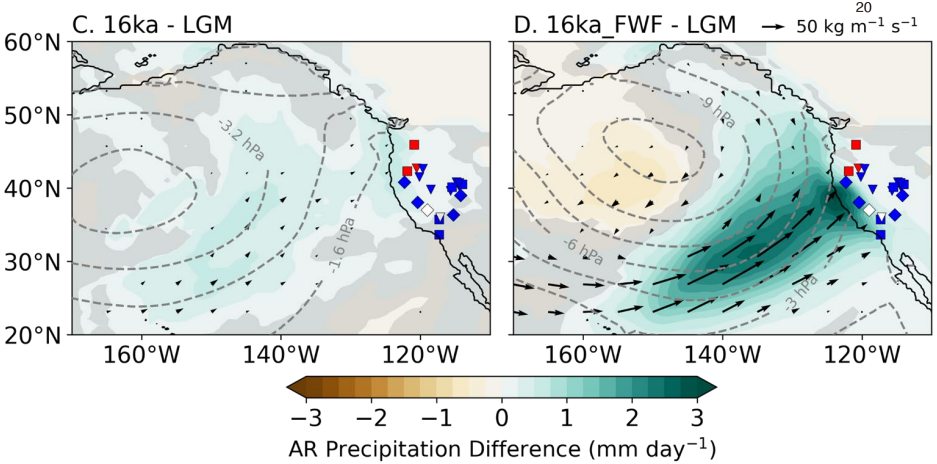


Tierney et al. (2020), *Science*

Modern precipitation extremes are used to learn about paleotempestology

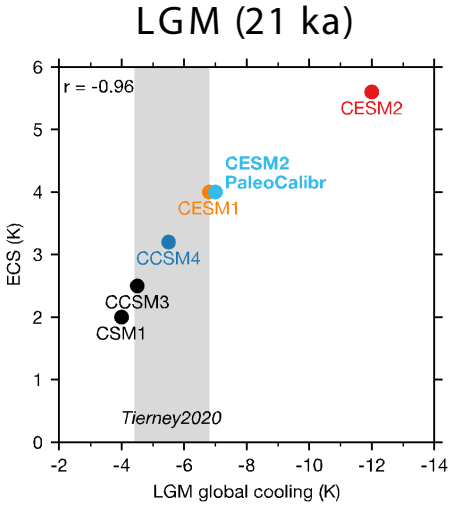
High and variable-res (<<100 km) simulations can be used to study weather phenomena & reduce model bias

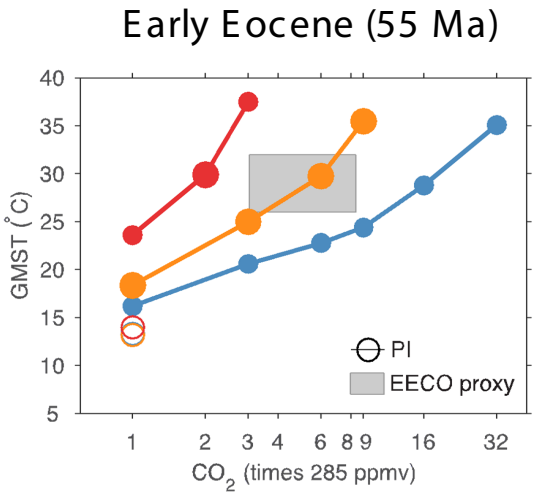


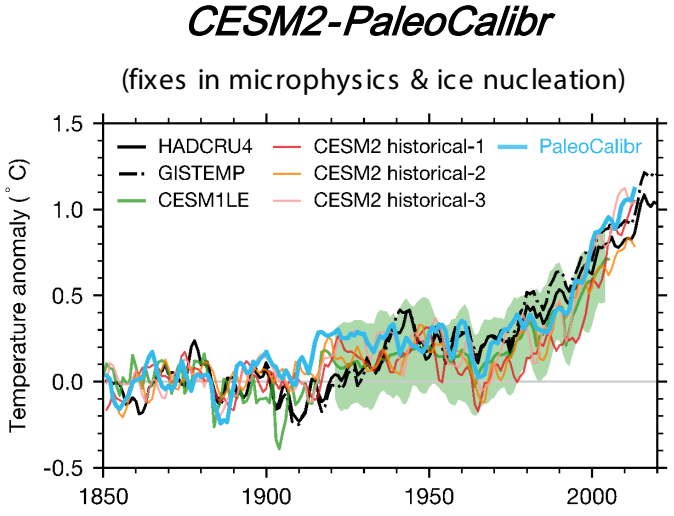


Past climates provide out -of-sample testing of modeled processes

CESM2 overestimates past extreme warming & cooling

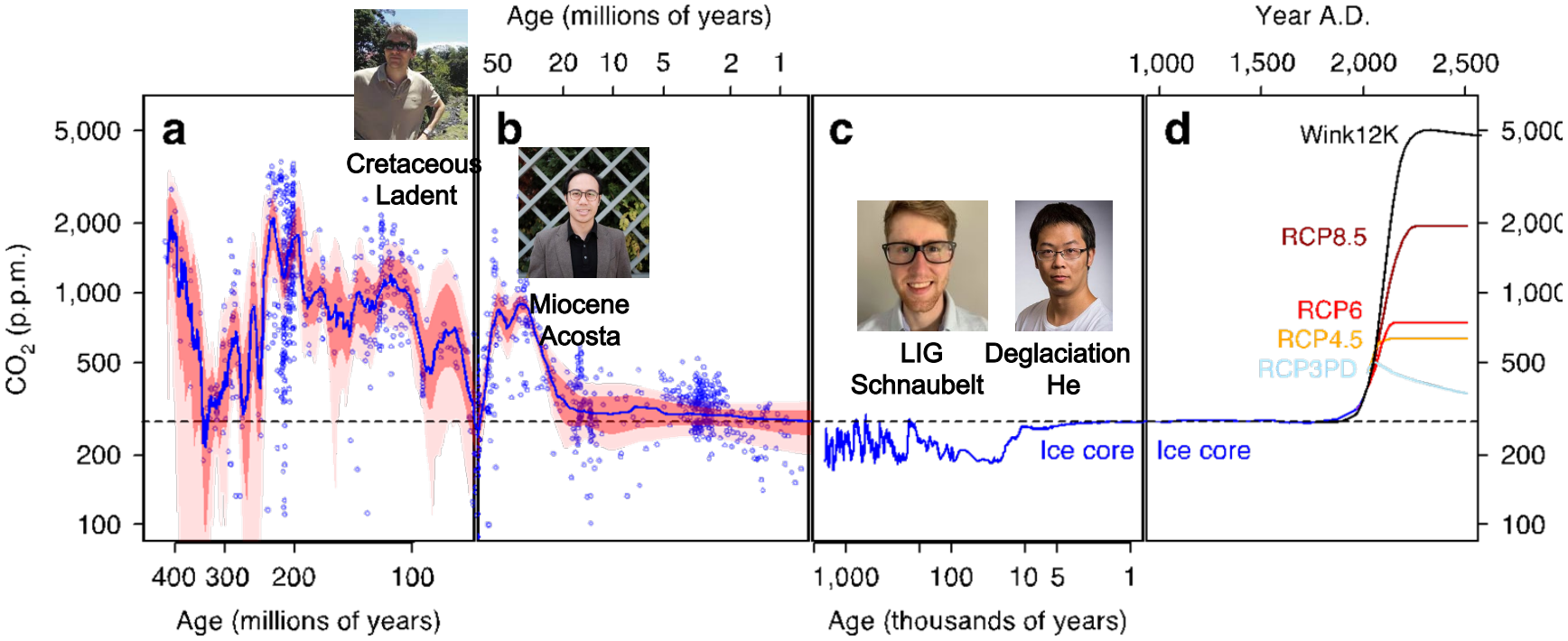






Brady et al., 2013, JC *Otto-Bliesner et al., 2006, JC* *Shin et al., 2003, Clim. Dyn.* *Zhu et al., 2017, GRL*
Zhu et al., 2019, Sci. Adv *Zhu, et al., 2020, Nat. Clim. Change* *Zhu et al., 2021, GRL* *Zhu, et al., 2022, JAMES*

Available iCESM1 simulations & early career researchers



Cretaceous
Ladent

Miocene
Acosta

LIG
Schnaubelt

Deglaciation
He

Carboniferous
Macarewich

Eocene
Zhu

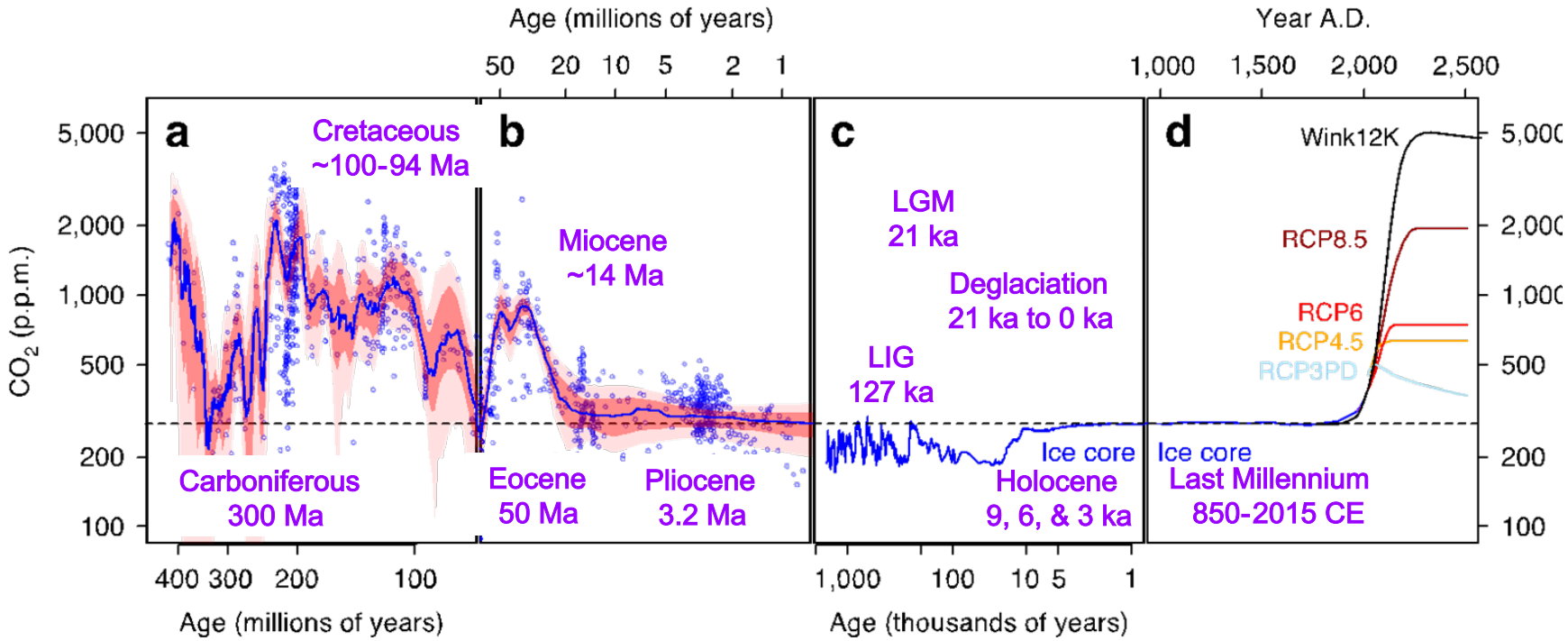
Pliocene
Feng

LGM
Zhu

Holocene
Zhu,

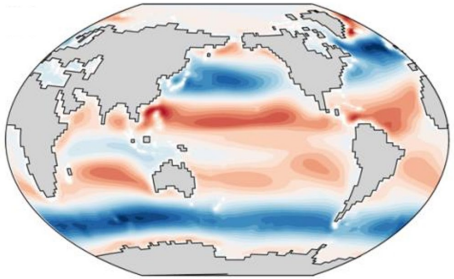
Last Millennium
Stevenson

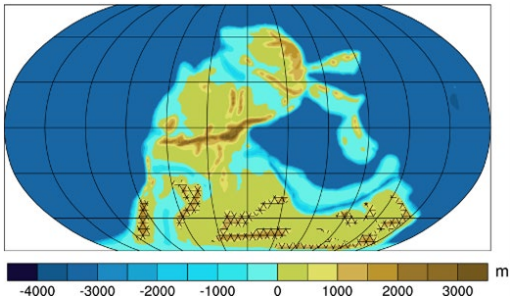
Resources: Many available paleoclimate simulations to use



Designing a paleoclimate simulation is highly interdisciplinary

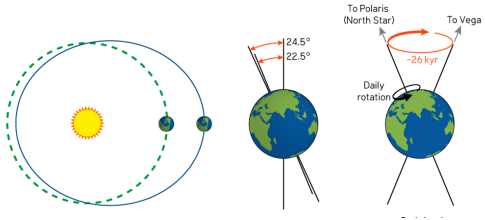
"Out-of-box" default pre-industrial case



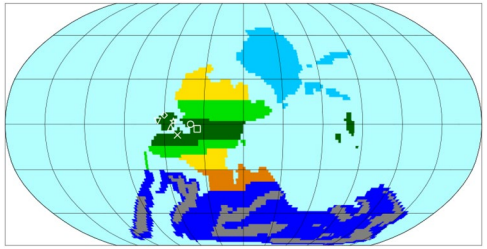


Paleogeography
Topography, sea level, bathymetry

External forcing
Orbital configuration, solar luminosity



Atmospheric composition
GHGs, aerosols



Land surface cover
Vegetation, land ice, rivers

Potential modifications to default parameterizations

Deep-time paleoclimate case