Australian
National University

"From little things big things grow": how small-scale ocean turbulence affects the global ocean circulation 🌊 and climate 🌎

Navid Constantinou

Visualization using output from the MIT/JPO project
Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2)

SGEAS, Nov 2023

Credit: NASA/Goddard Space Flight Center
Scientific Visualization Studio

presentation outline

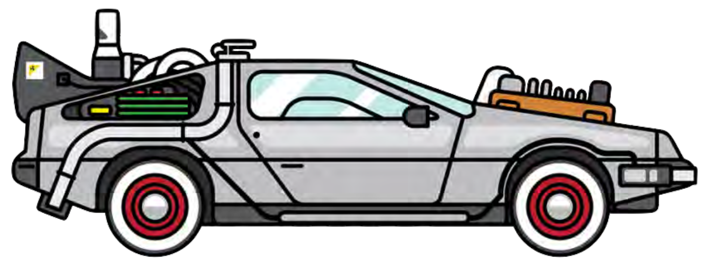
overview **I.** climate problem, why is it so hard?
(how do the little things affect the big picture)

past **II.** how ocean's mesoscale eddies shape
the decadal variability of upper-ocean heat content and climate

Constantinou and Hogg, *J. Climate*, 2021
doi:10.1175/JCLI-D-20-0962.1

ongoing & future **III.** a new ocean model fast enough
to resolve mesoscales eddies in climate projections!

future **IV.** disentangling ocean decadal variability
from underlying climate change

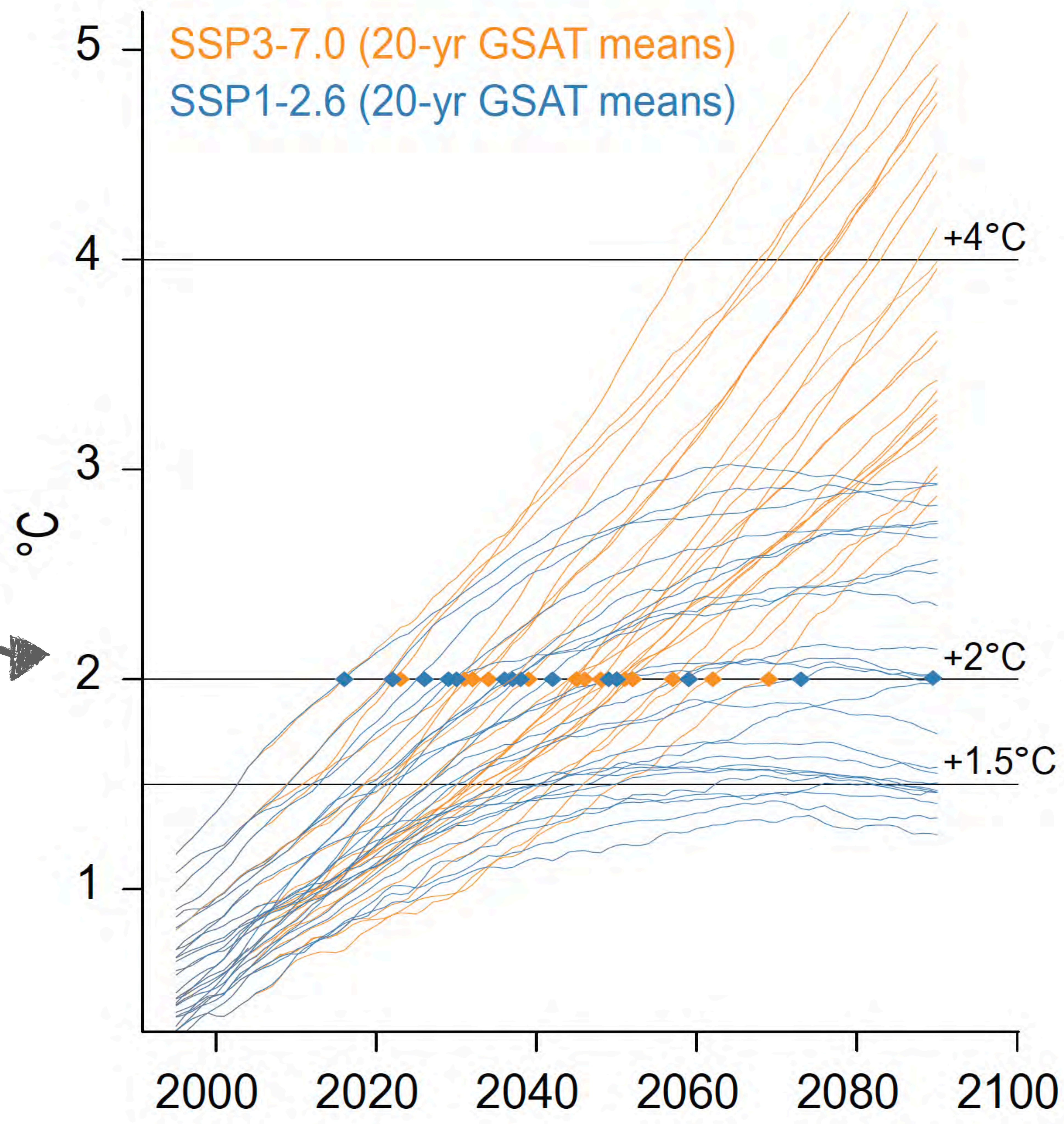


I.

🌏 climate problem, why is it so hard?
(how do the little things affect the big picture)

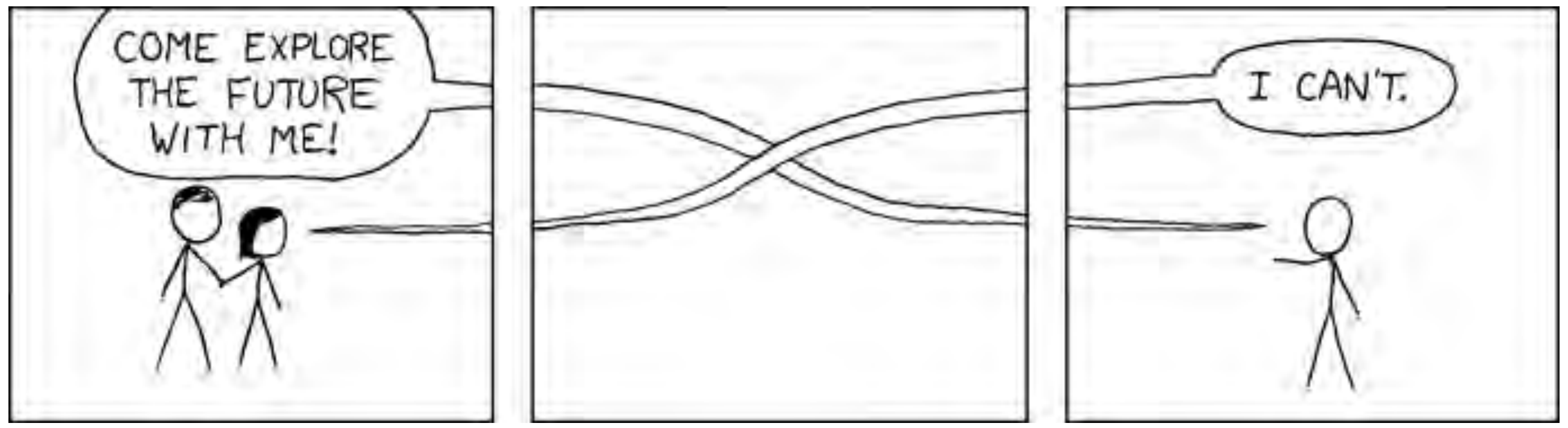
predictions of future warming are *uncertain*

2°C threshold



High-emissions (SSP3-7.0)
and
low-emissions (SSP1-2.6)
scenarios in CMIP6

IPCC AR 6 Working Group I



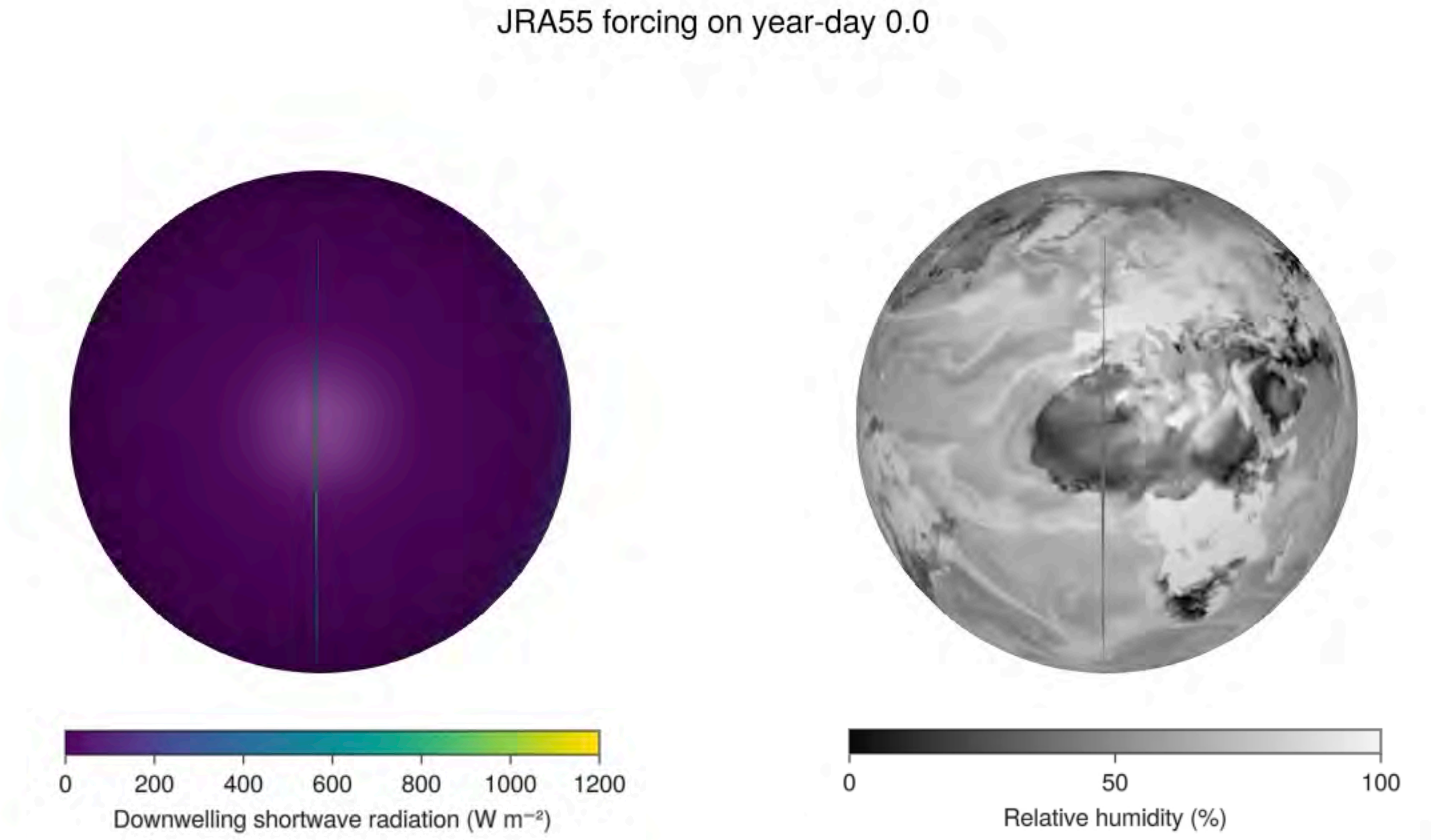
[xkcd.com/338]

I.

why is climate prediction so hard?

The Earth system is ***strongly*** forced
but very close to equilibrium

Climate change signal: ~3-5 W/m²
Instantaneous solar flux: ~1300 W/m²



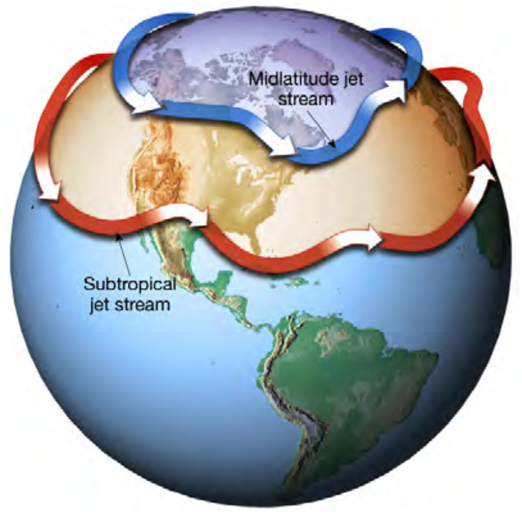
Earth system models redistribute these fluxes across all components
(atmosphere, ocean, land, ice, trees, etc)

I.

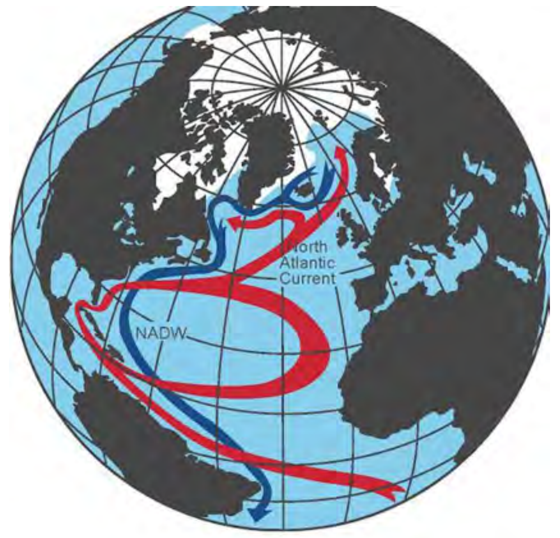
why is climate prediction so hard?

Interconnections among many processes

Some things we can't resolve..!
Other things we don't even know the equations!



atmosphere



ocean

clouds

trees

[made by Claire Yung]

ice-ocean interactions

air-sea exchanges

. . .

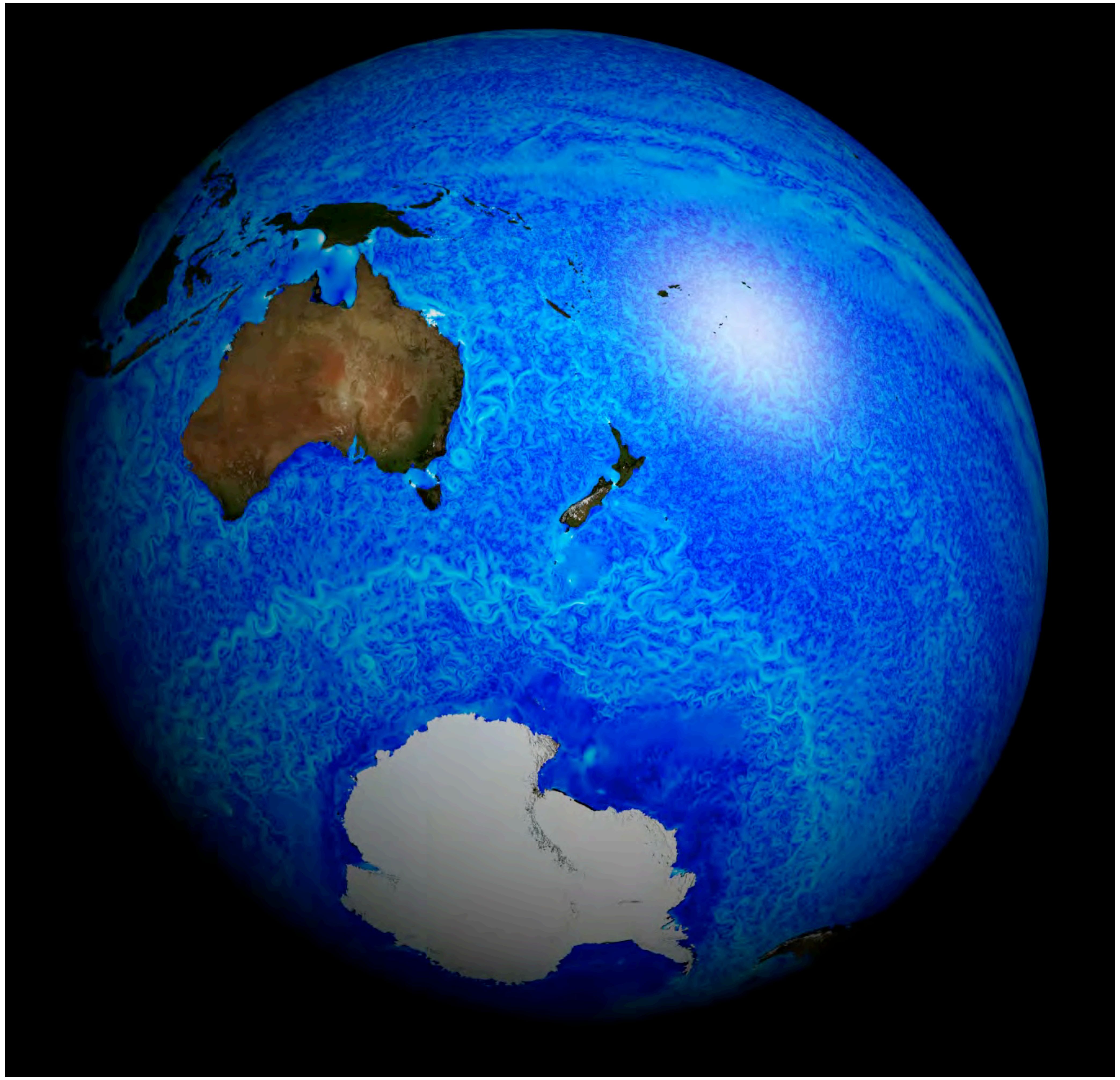
many more processes

Approximate models for many processes (parameterisations) dominate the uncertainty of climate projections

I.

🌊 ocean: processes at many scales interact

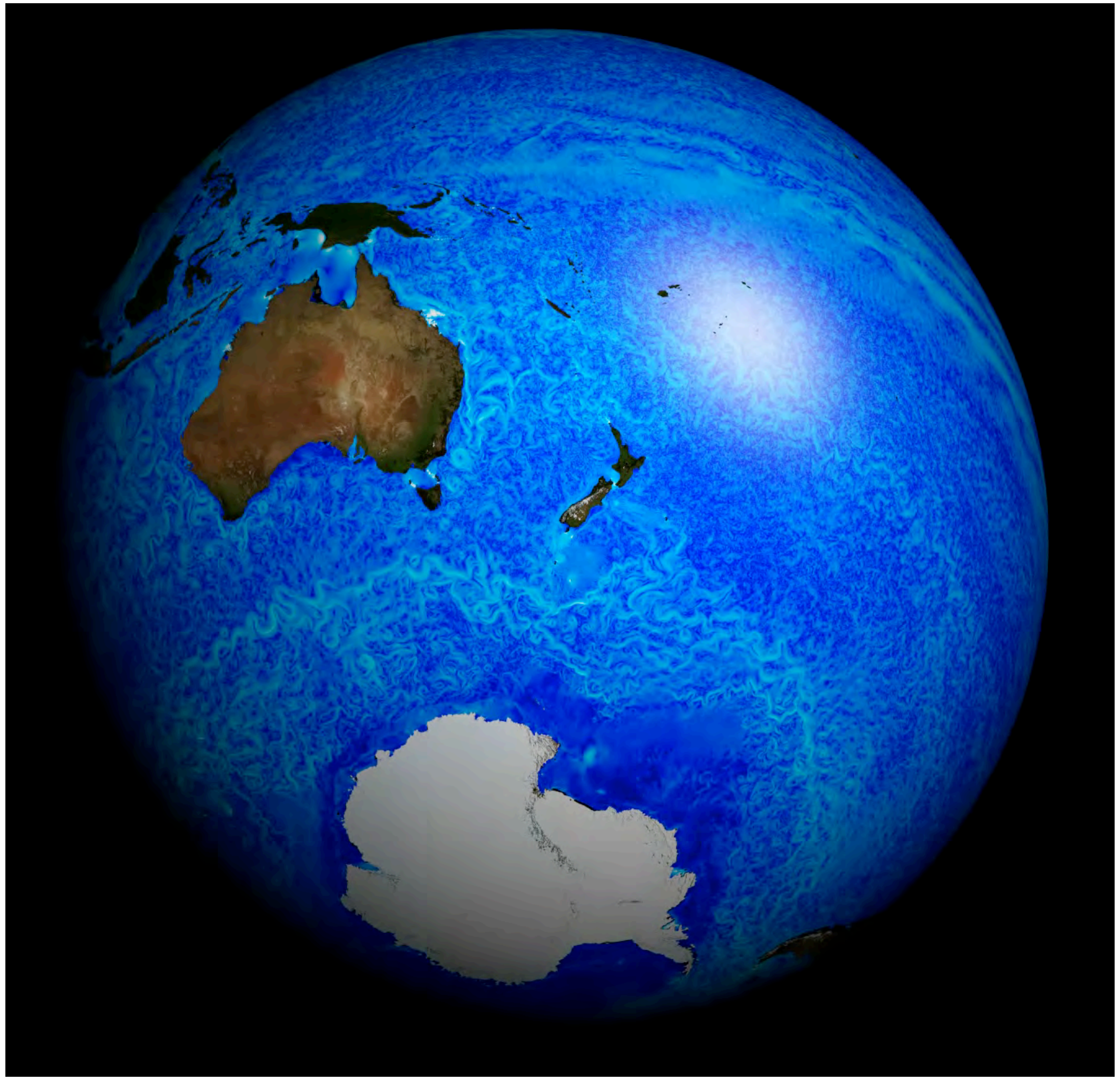
turbulence	~1-100 metres ~minutes
eddies	~200 km ~months
currents	~1000 km ~years-decades
overturning circulation	~10.000km ~centuries



LLC4320 sea surface speed animation
by Henze and Menemenlis (NASA/JPL)
1/48th degree, 90 vertical levels
(biggest ocean simulation ever run…
until very recently — hold on to your chairs 🪑)

🌊 ocean: processes at many scales interact

turbulence	~1-100 metres ~minutes
eddies	~200 km ~months
currents	~1000 km ~years-decades
overturning circulation	~10.000km ~centuries



LLC4320 sea surface speed animation
by Henze and Menemenlis (NASA/JPL)
1/48th degree, 90 vertical levels
(biggest ocean simulation ever run…
until very recently — hold on to your chairs 🪑)

II.

how ocean's mesoscale eddies 🌀 shape the decadal variability of upper-ocean heat content and climate

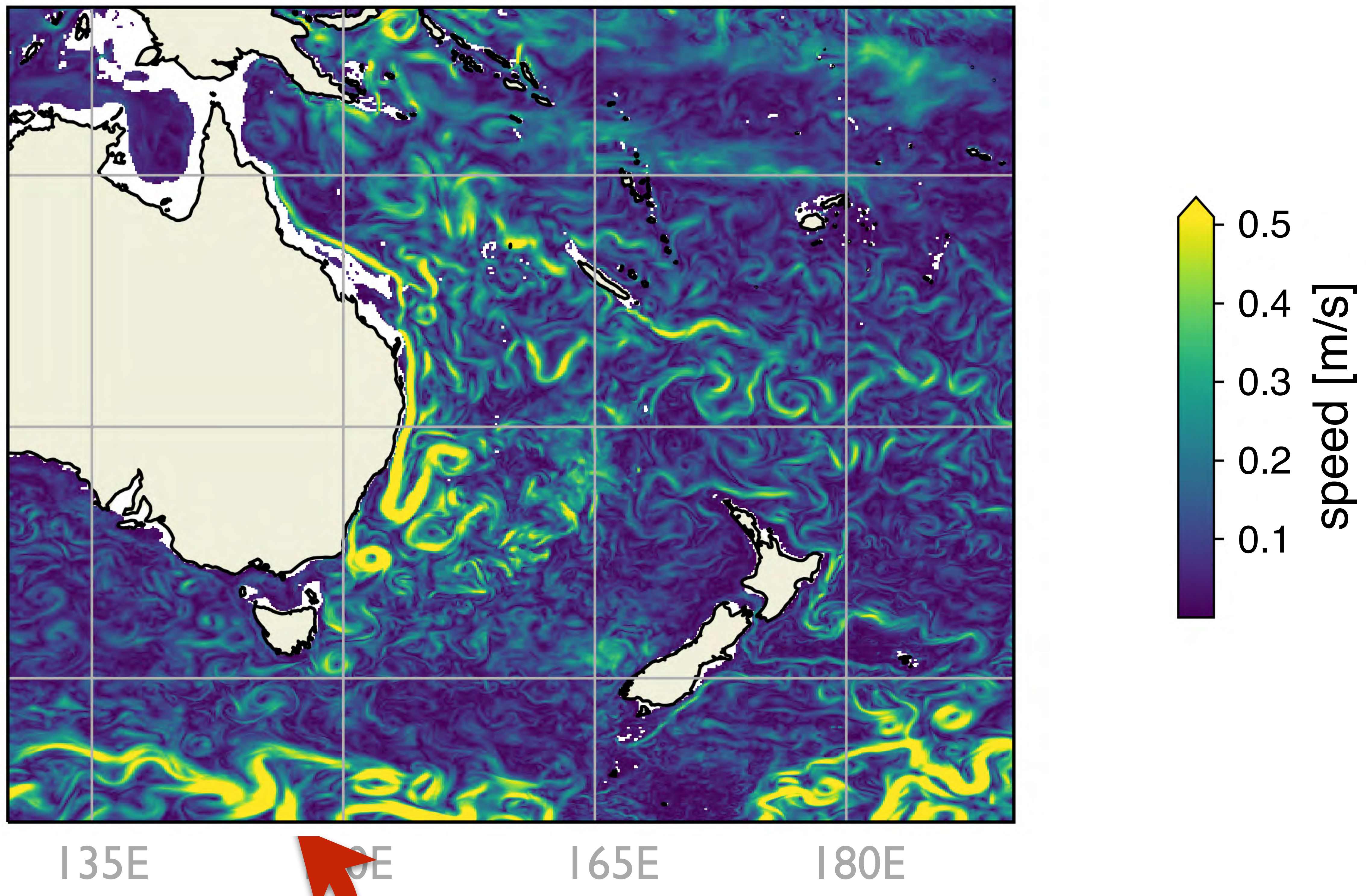
Constantinou and Hogg, *J. Climate*, 2021
doi:10.1175/JCLI-D-20-0962.1

II.

climate models typically used for climate projections *do not* resolve the ocean's mesoscale 🌀

lateral resolution

0.10°



state-of-the-art
global ocean—sea-ice model
unfortunately, too expensive
for climate projections!

[ACCESS-OM2 global ocean—sea-ice model, Kiss et al., *Geosci. Model Dev.* 2020]

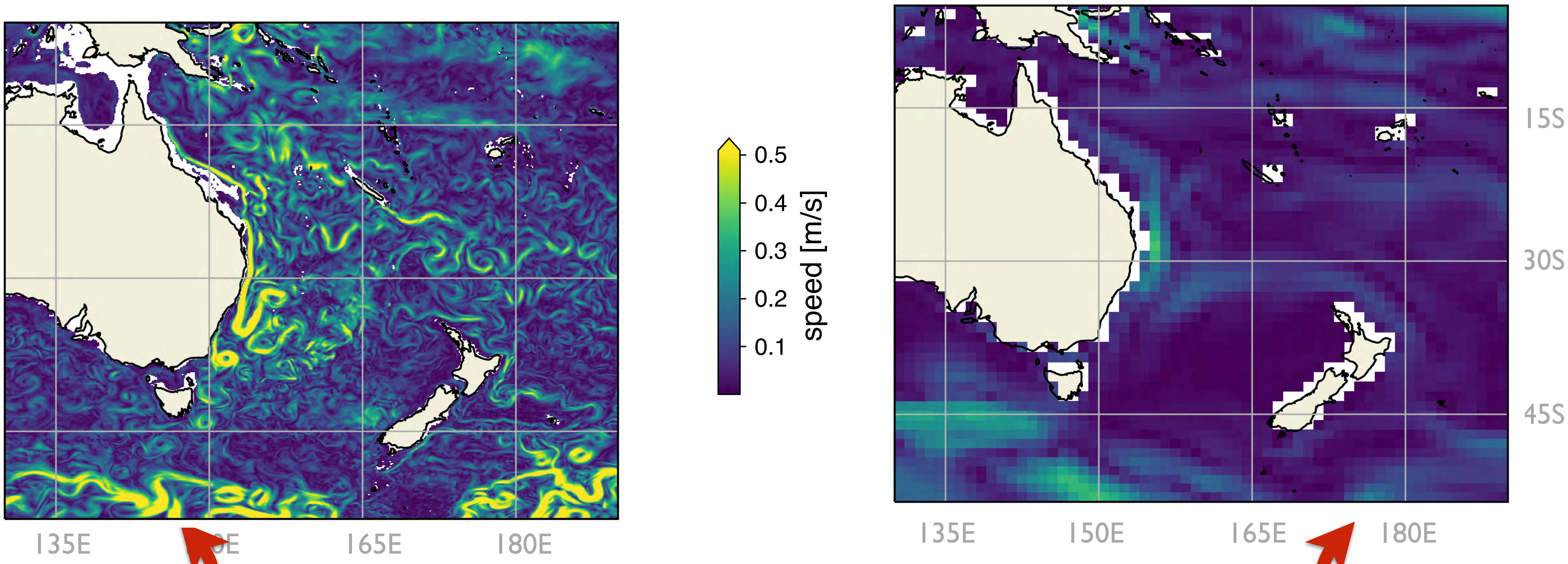
II.

climate models typically used for climate projections *do not* resolve the ocean's mesoscale 🌀

lateral resolution

0.10°

1°



state-of-the-art
global ocean—sea-ice model
unfortunately, too expensive
for climate projections!

typically used
by IPCC, etc…

[ACCESS-OM2 global ocean—sea-ice model, Kiss et al., *Geosci. Model Dev.* 2020]

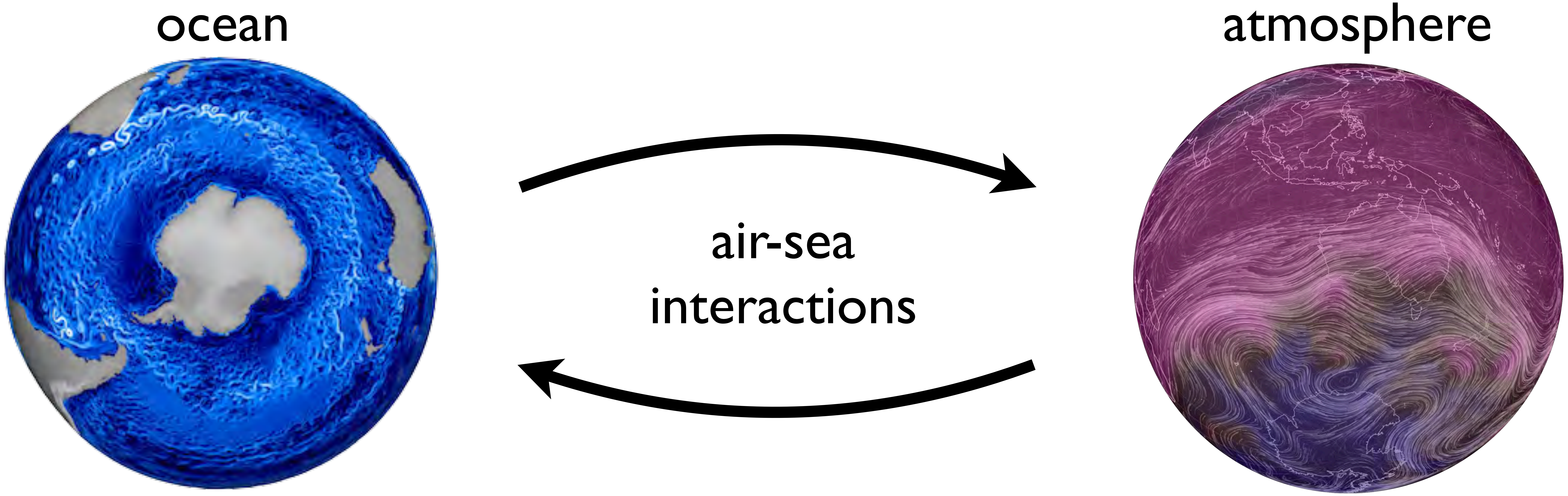
climate models typically used for climate projections
do not resolve the ocean's mesoscale 🌀

state-of-the-art
global ocean—sea-ice model

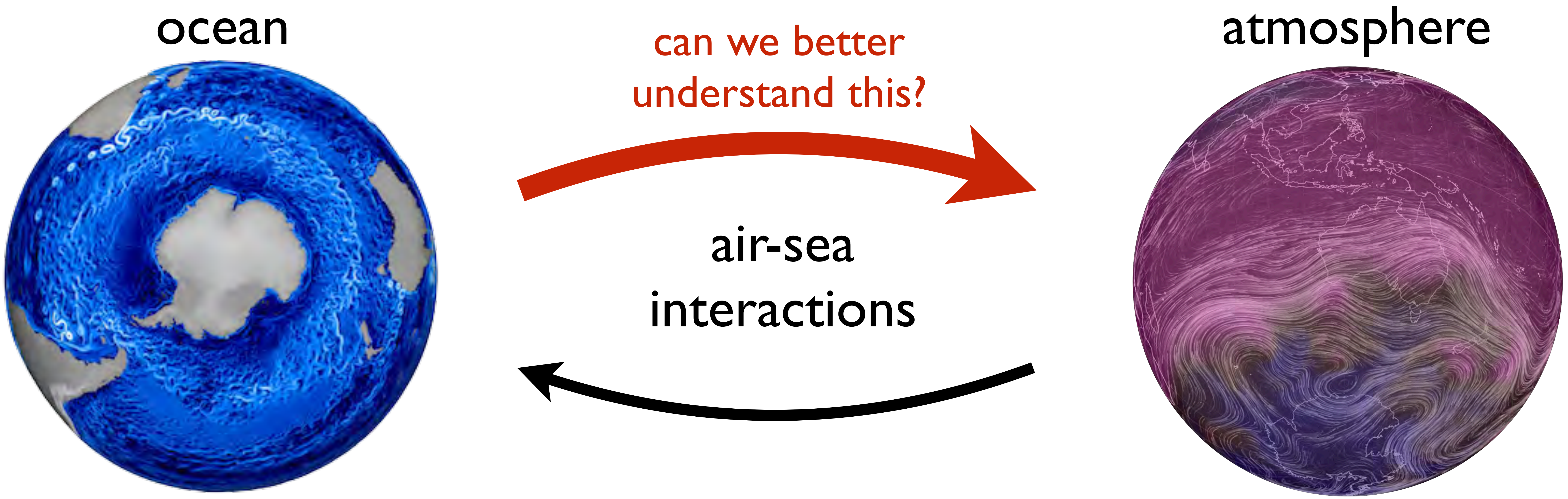
are the details (ocean eddies 🌀) really important?

typically used
by IPCC, etc…

[Gogh, V., *MoMA*, 1889]


ocean
atmosphere
air-sea
interactions

II.

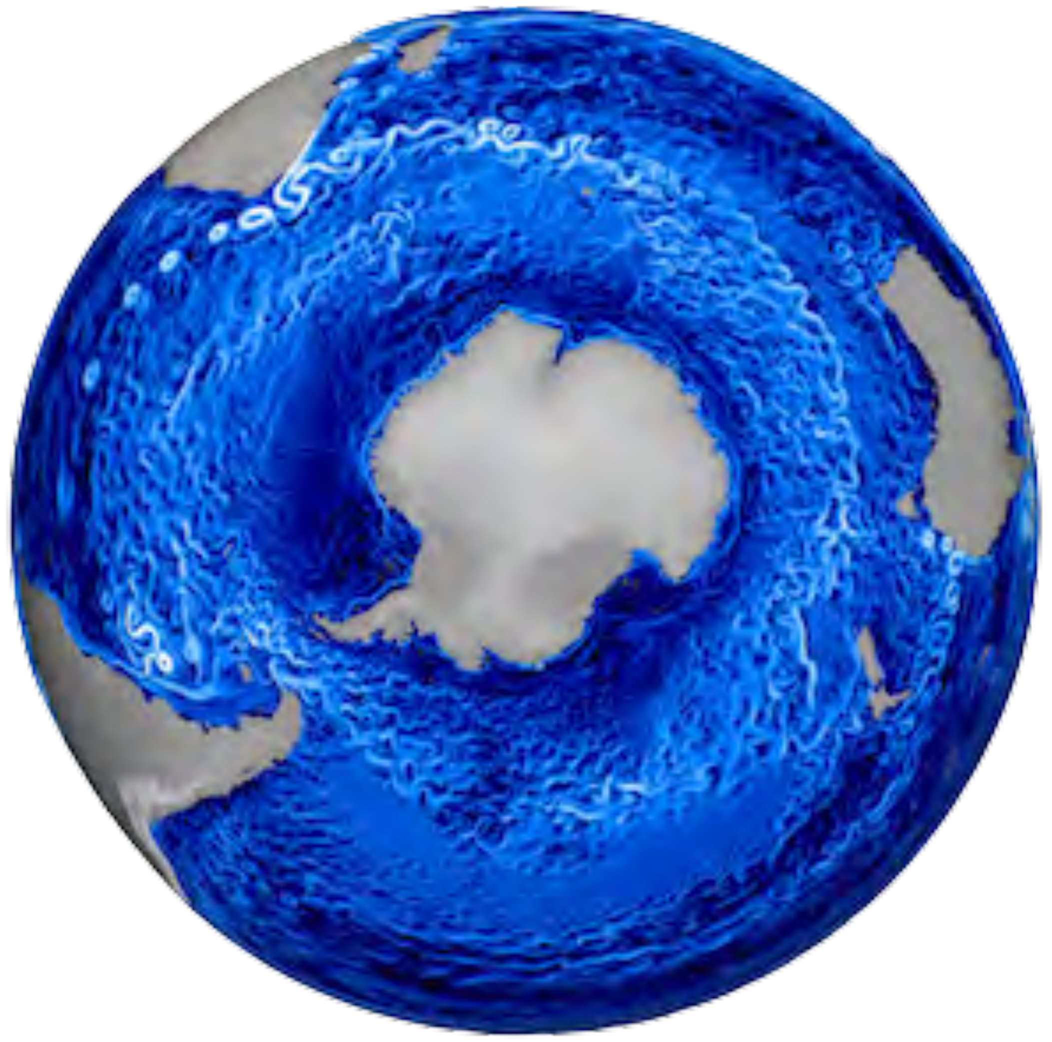

ocean
can we better
understand this?
air-sea
interactions
atmosphere

II.

atmosphere "feels" the upper-ocean's heat content

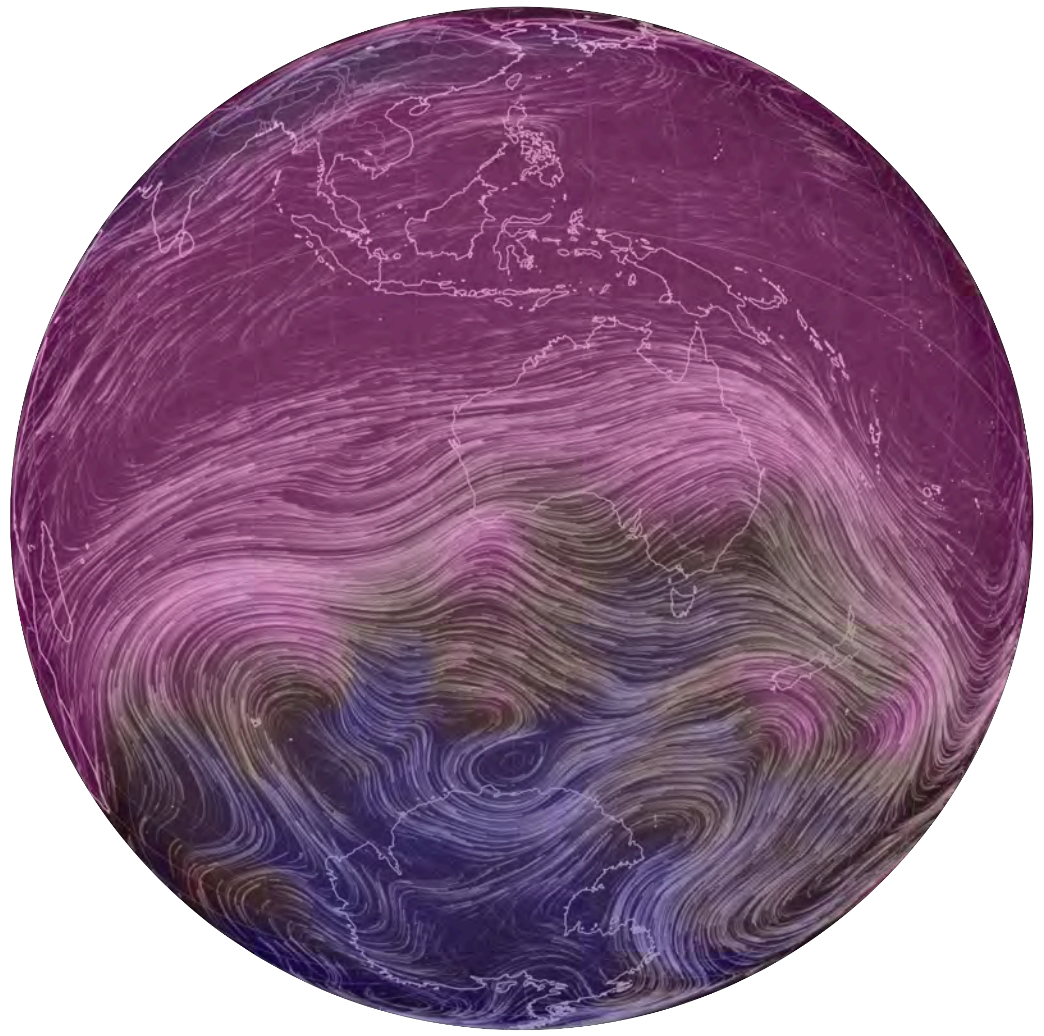
ocean

ocean eddies 🌀
~50-200km
~1-3 months



can we better understand this?

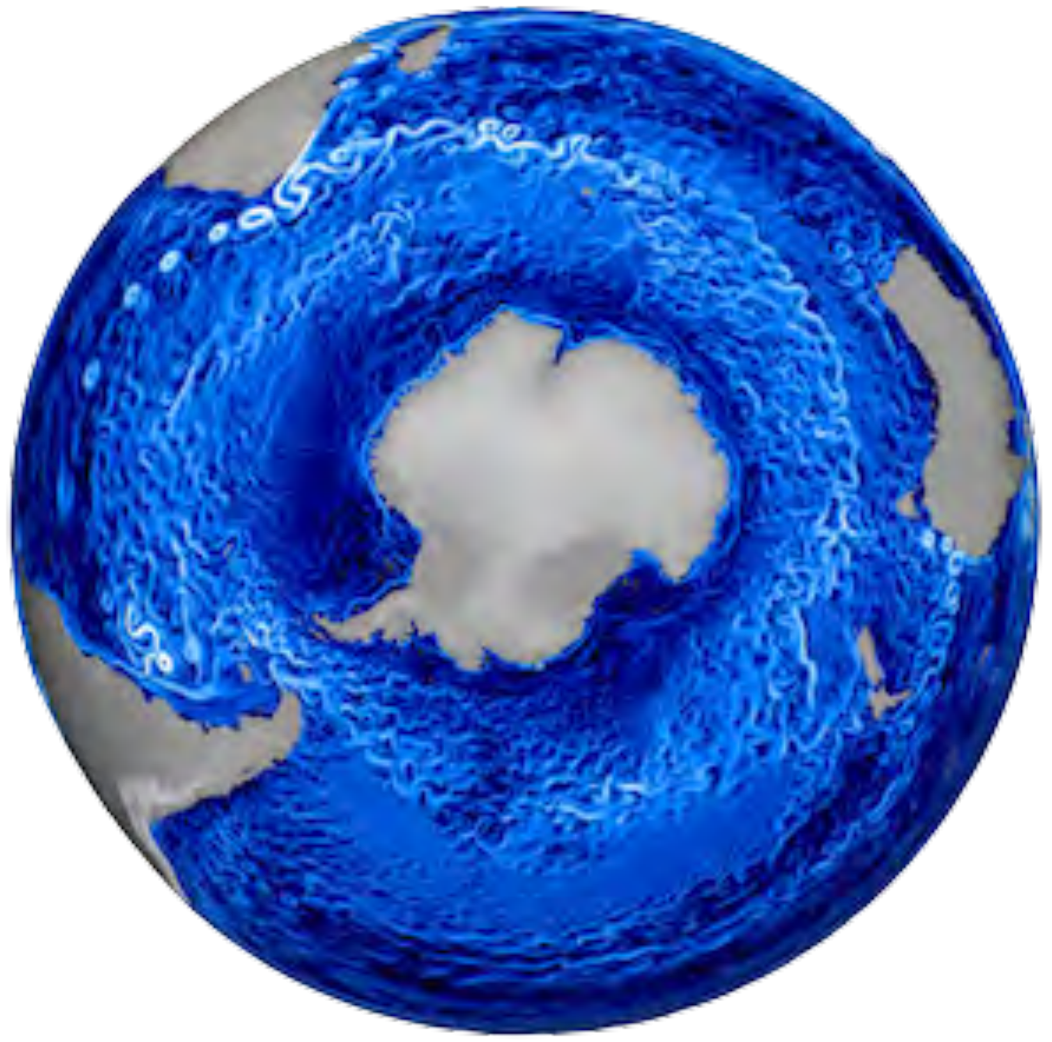
atmosphere



atmosphere "feels" the upper-ocean's heat content

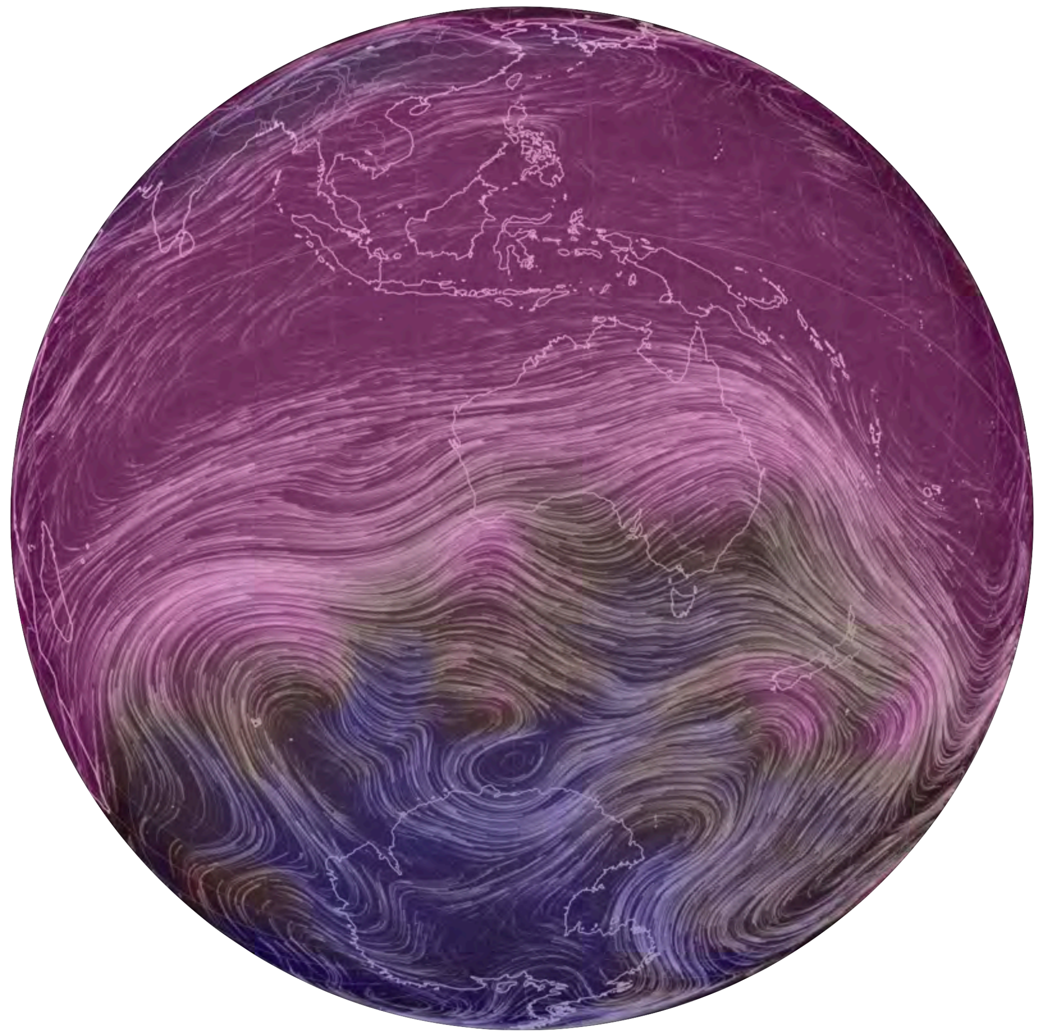
ocean

ocean eddies 🌀
~50-200km
~1-3 months



can we better understand this?

atmosphere



can ocean intrinsic variability (ocean eddies) feed back on the atmosphere? (and thus on climate)

can ocean eddies lead to **large-scale, decadal** patterns of upper-ocean heat content?

an ocean eddy

"Does the flap of ~~a butterfly's wings~~ in Brazil set off an ~~tornado in Texas~~?"

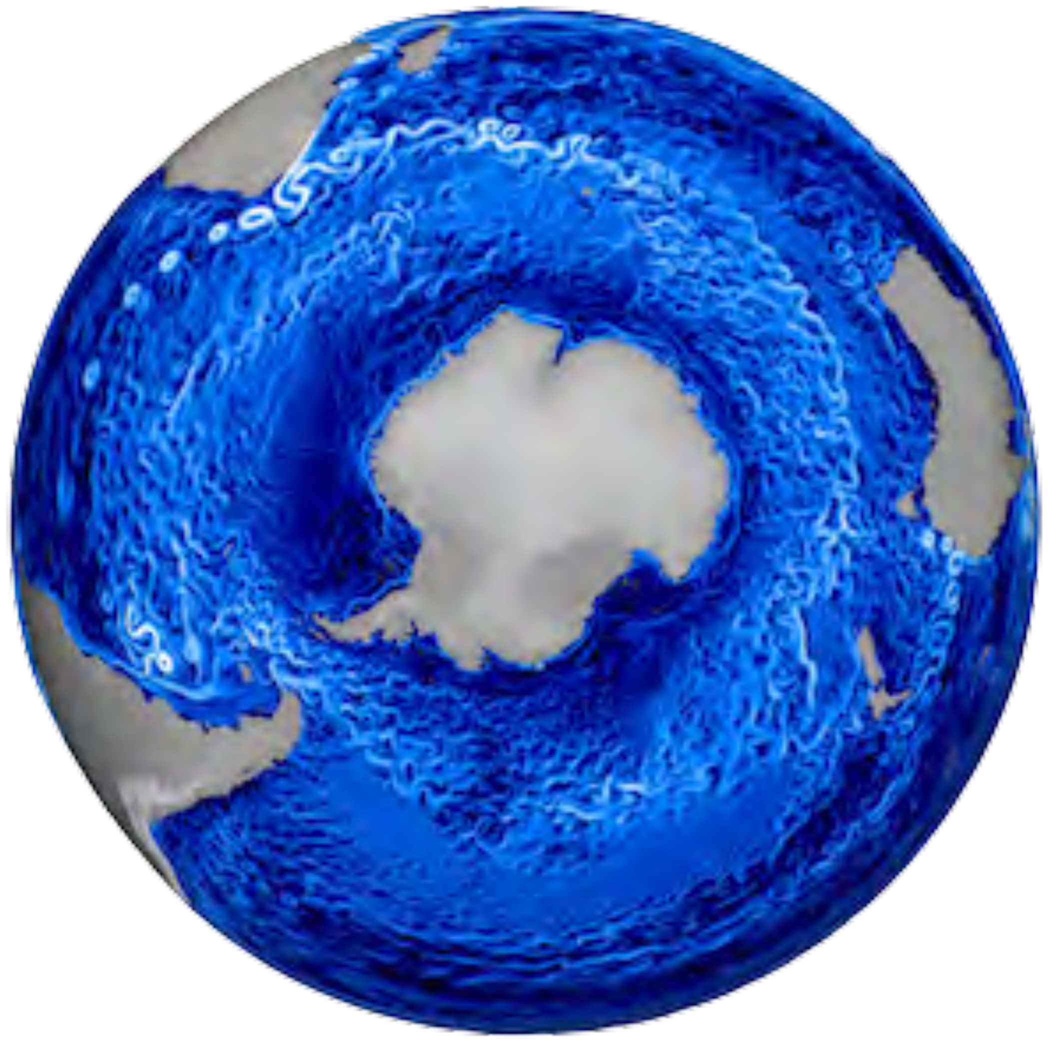
El Niño

[Ed Lorenz, Philip Merilees]

atmosphere "feels" the upper-ocean's heat content

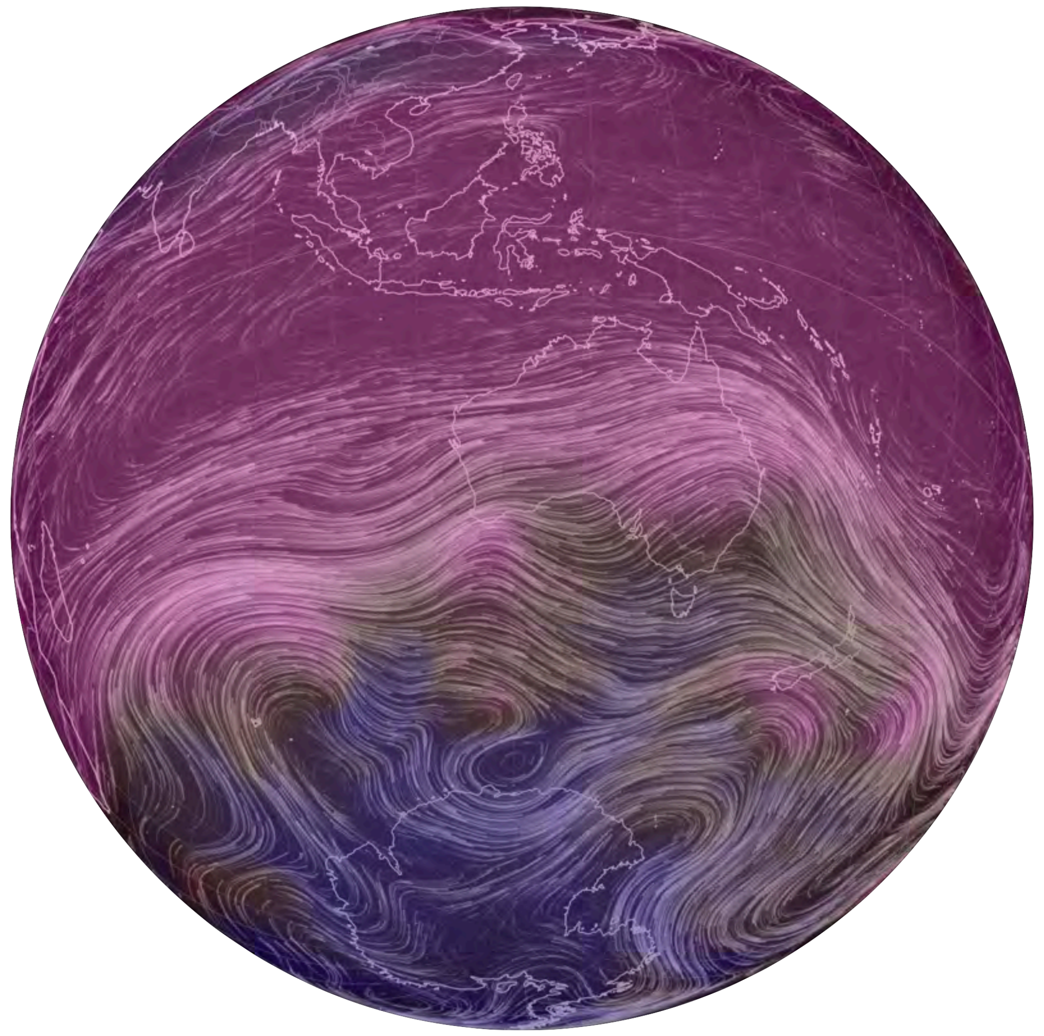
ocean

ocean eddies 🌀
~50-200km
~1-3 months



can we better understand this?

atmosphere



but there is an issue here! 🚨

how do we disentangle the role of ocean eddies 🌀
in shaping *decadal* patterns of upper-ocean heat content?

upper-ocean heat content's response due to

atmosphere-forced variability

oceanic intrinsic variability 🌀

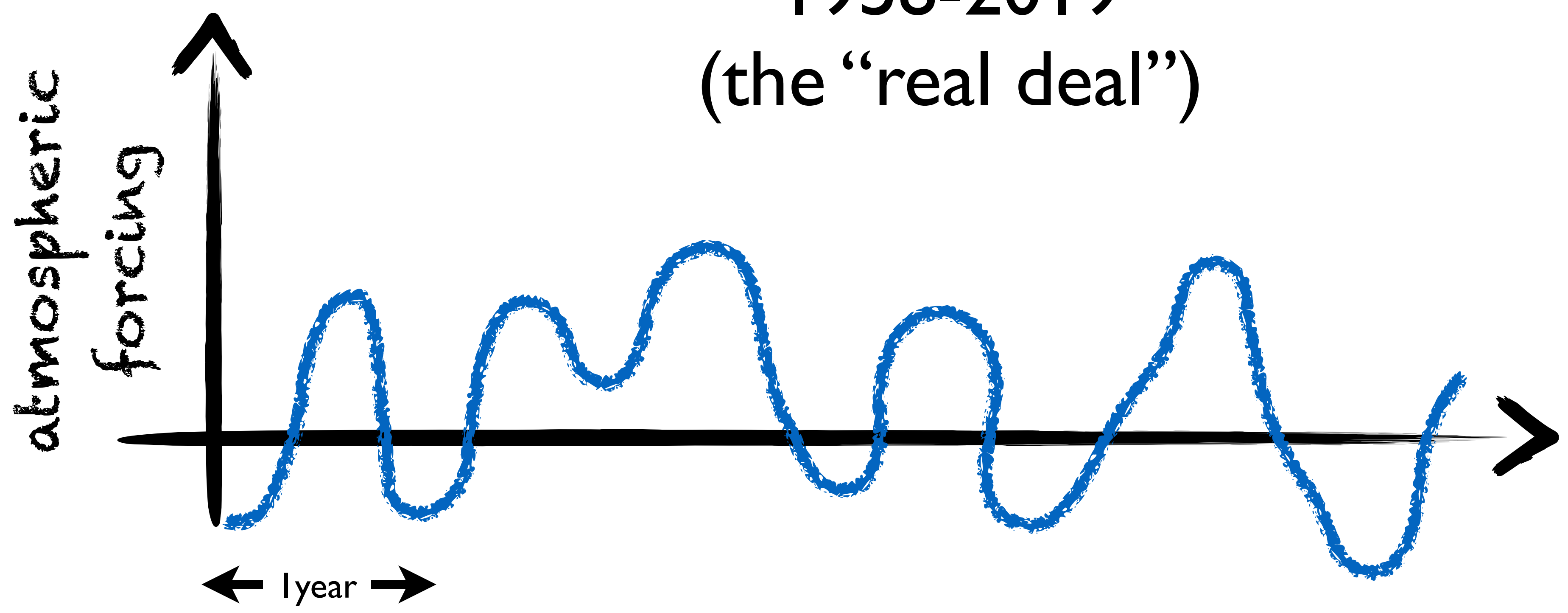
disentangle the role of the atmosphere and ocean dynamics 🌀

ACCESS-OM2 global ocean-sea ice model [Kiss et al. 2020]

driven by JRA55 reanalysis [Tsujino et al. 2018]

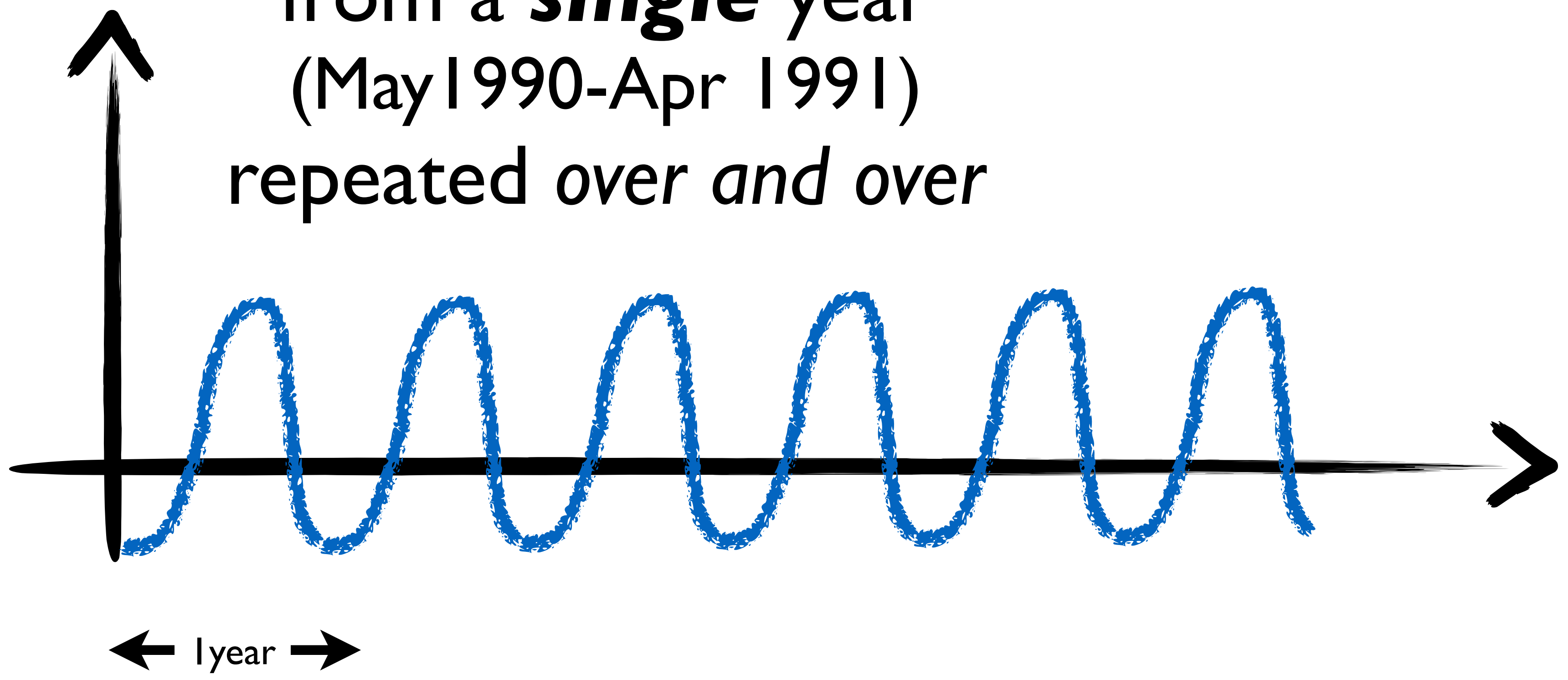
inter-annual forcing
IAF

realistic atmosphere
1958-2019
(the "real deal")



repeat-year forcing
RYF [Stewart et al. 2020]

realistic atmosphere
from a ***single*** year
(May1990-Apr 1991)
repeated *over and over*



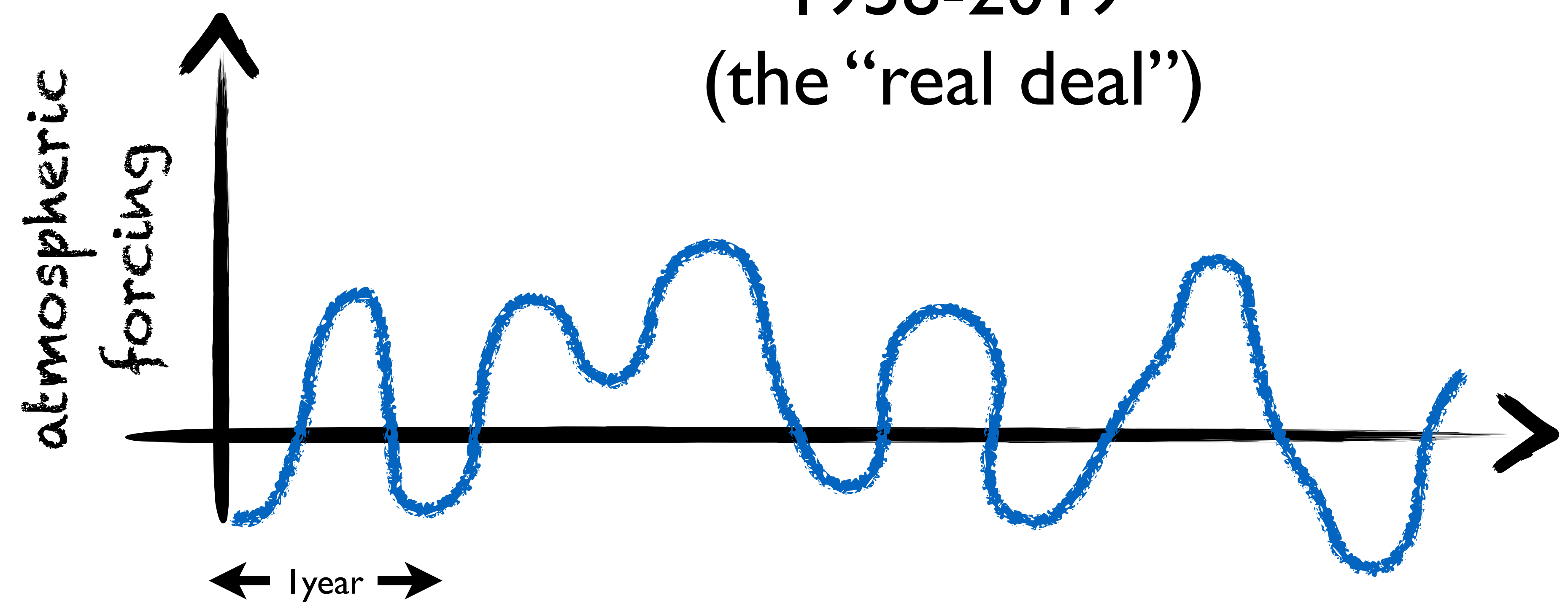
disentangle the role of the atmosphere and ocean dynamics 🌀

ACCESS-OM2 global ocean-sea ice model [Kiss et al. 2020]

driven by JRA55 reanalysis [Tsujino et al. 2018]

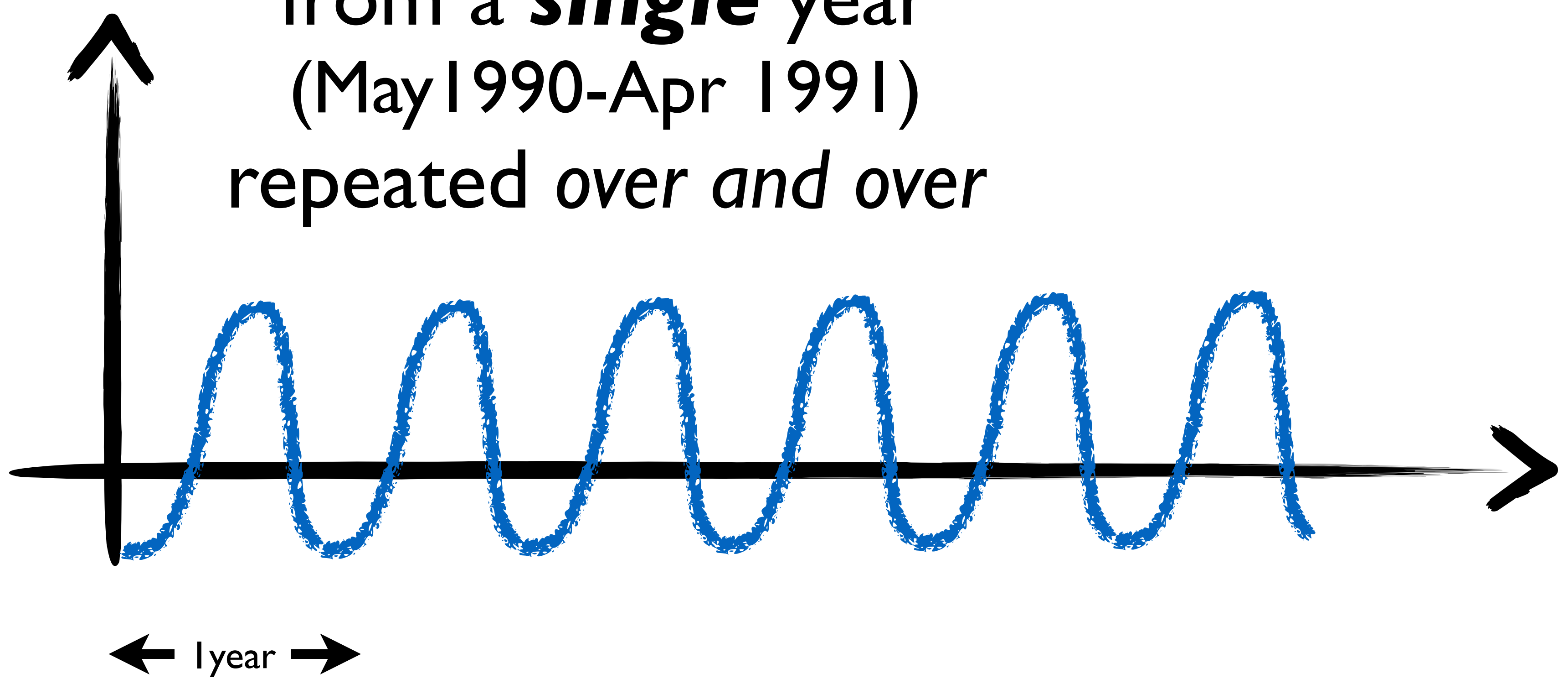
inter-annual forcing **IAF**

realistic atmosphere
1958-2019
(the "real deal")



repeat-year forcing **RYF** [Stewart et al. 2020]

realistic atmosphere
from a ***single*** year
(May1990-Apr 1991)
repeated *over and over*



Variability at timescales longer than 1 year *cannot* be due to the atmosphere.
It ***has to be due to the ocean.***

what's upper-ocean heat content?

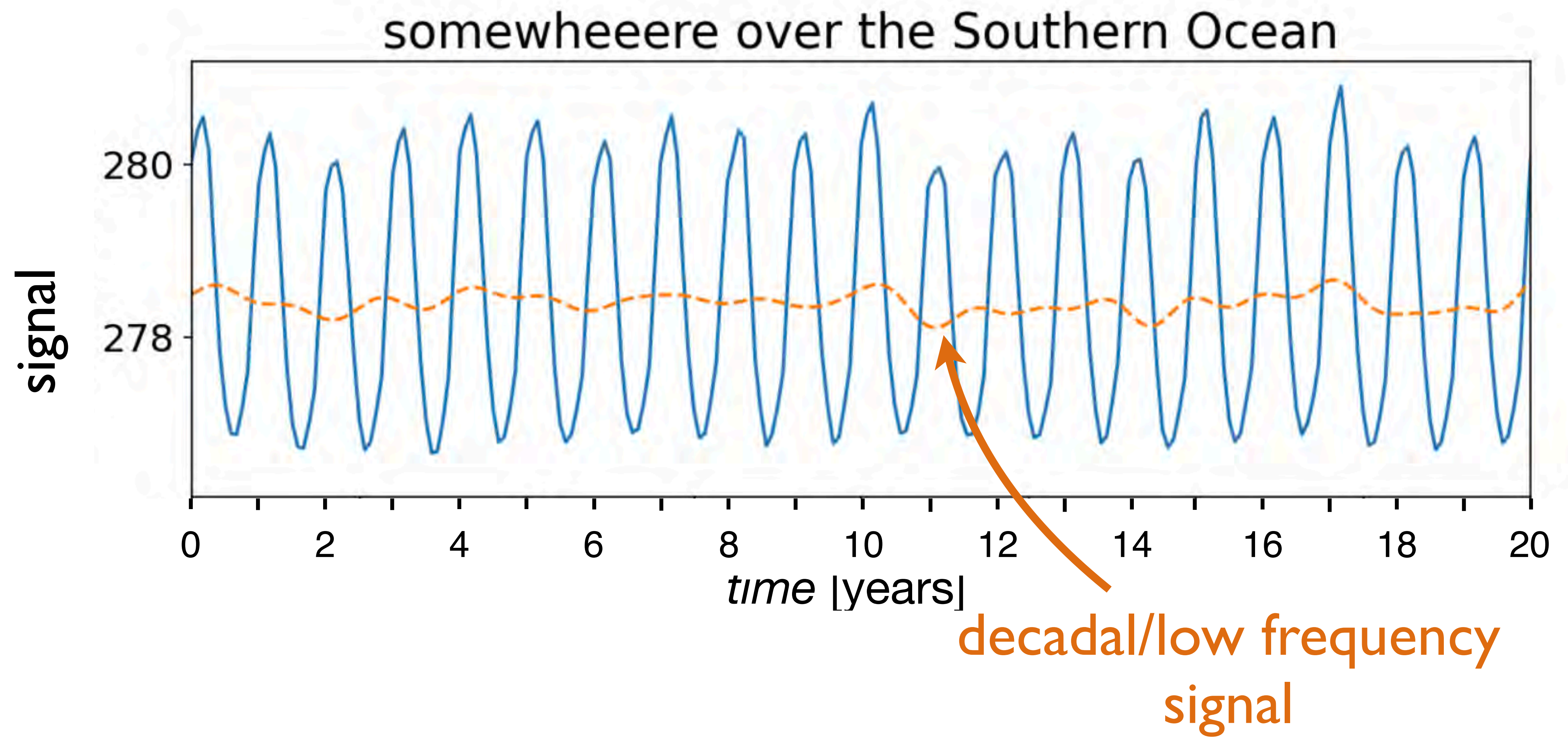
heat at top-part of ocean $= \text{UOHC}(\text{lon}, \text{lat}, t) = \int_{-50\,m}^{\text{SSH}} \rho_0\, C_p\, T(\text{lon}, \text{lat}, z, t)\, \text{d}z$

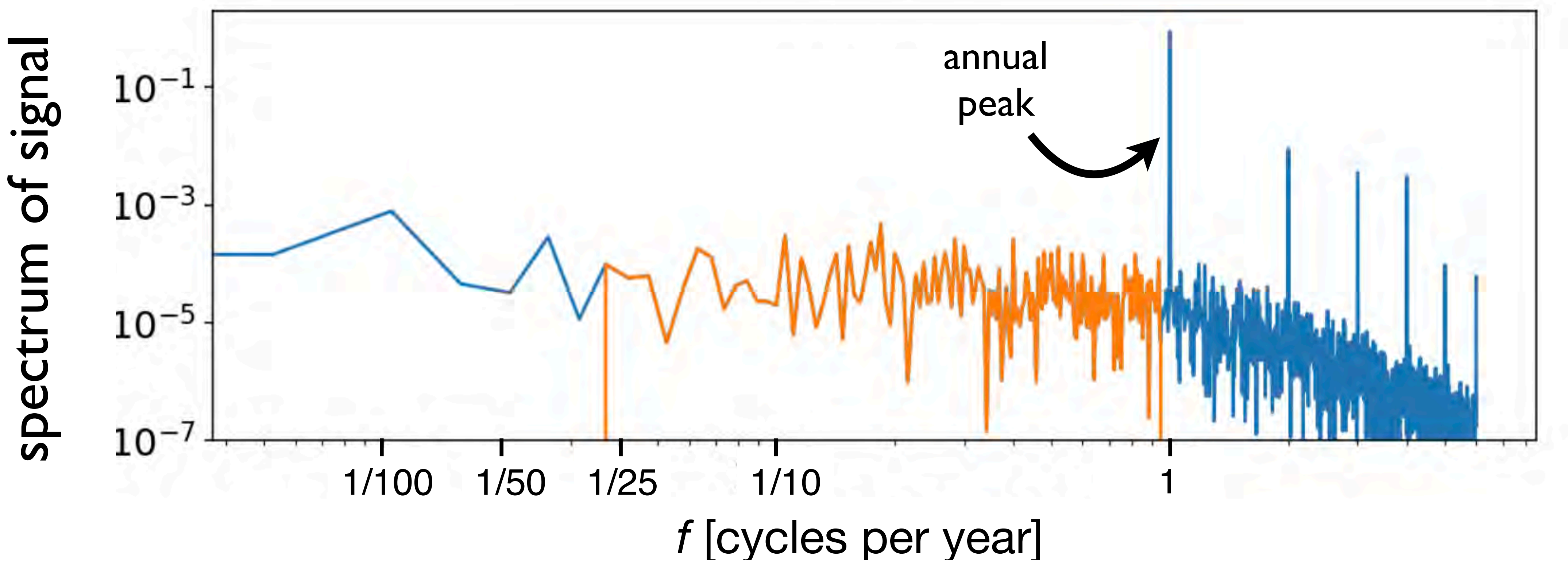
sea-surface height

upper ocean

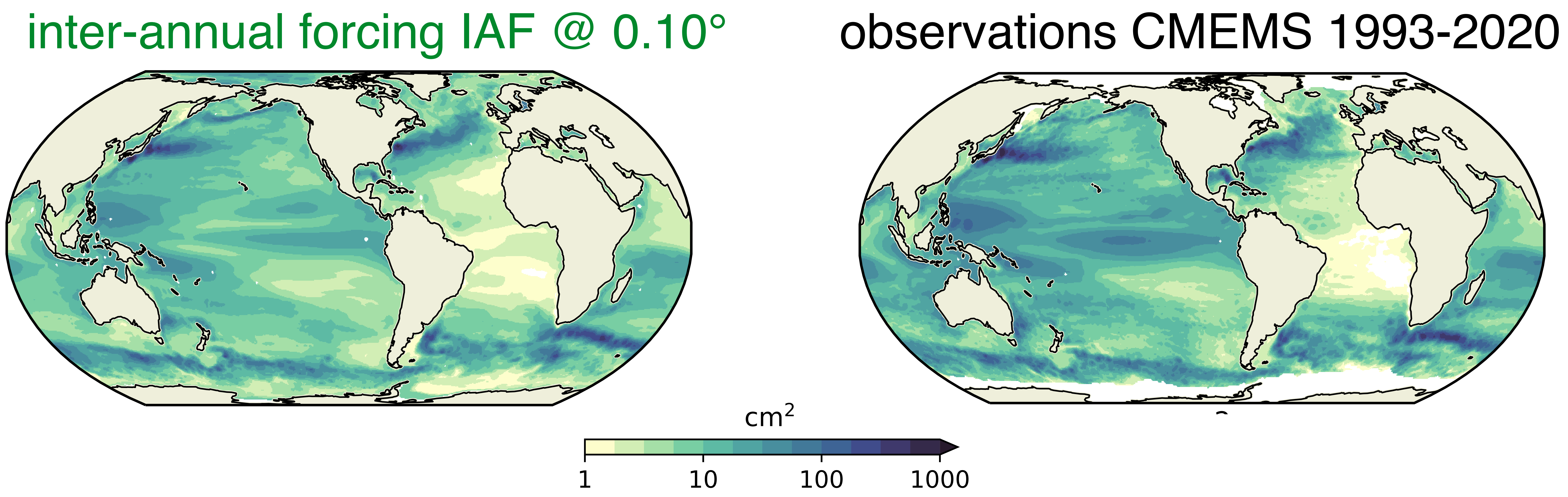
what's low frequency/decadal?

"low frequency" / decadal 👉 the part of the signal that varies at 1.5 years ≤ timescales ≤ 25 years





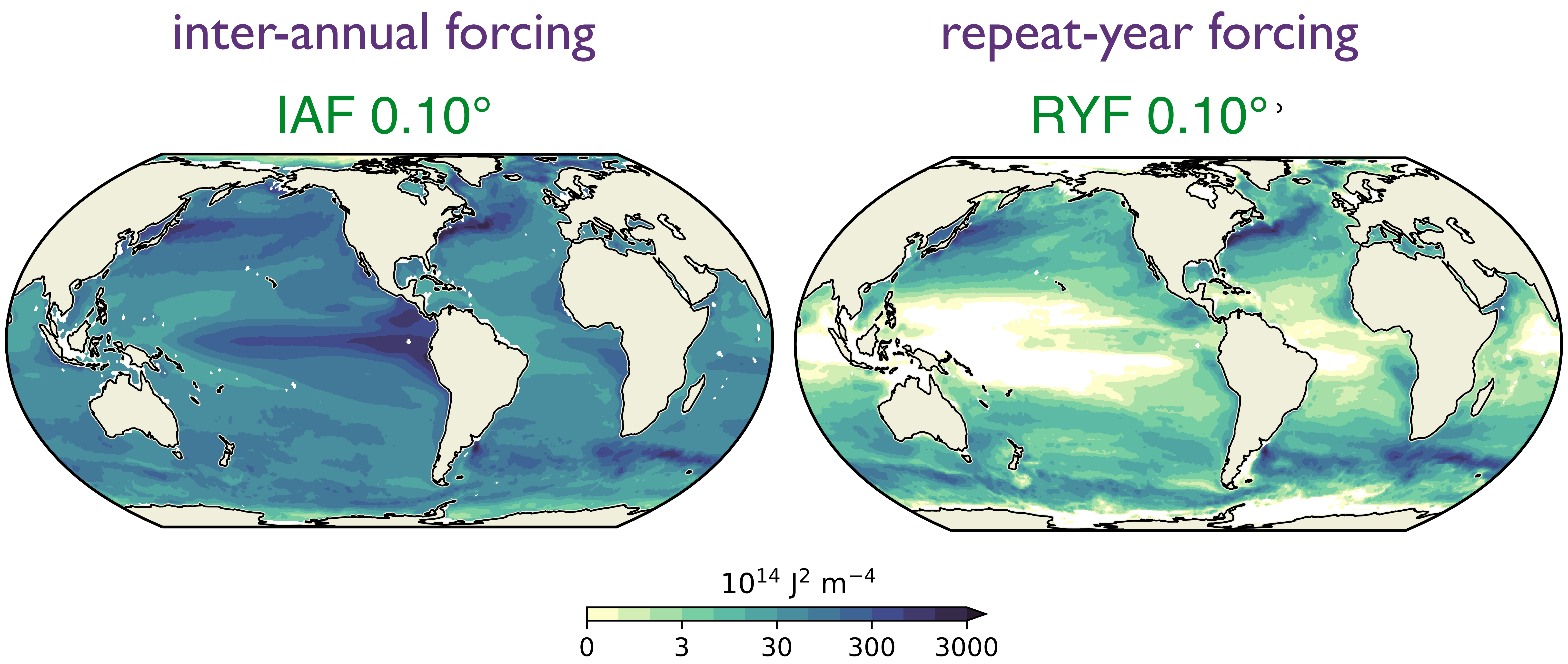
benchmark the model: compare low-frequency variance of sea-surface height with observations



good representation of low-frequency sea-surface height variance ✔

(for more comparisons with observations 👉 Kiss et al., 2020)

low-frequency upper-ocean heat content variance
what's the ocean's intrinsic part into this?



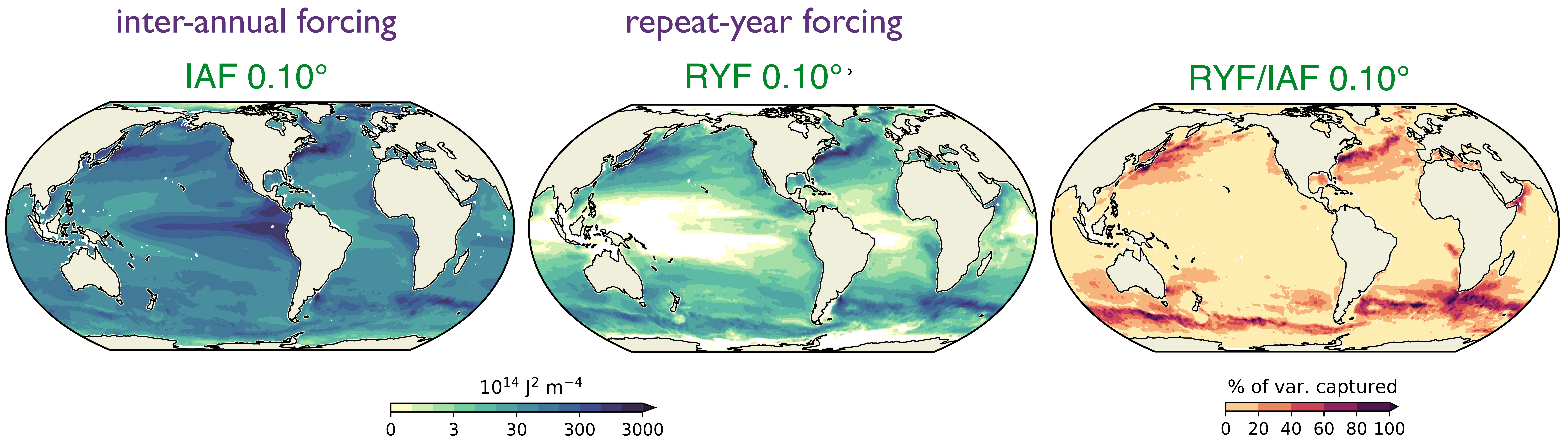
ocean's intrinsic variability:

doesn't show up in the tropics

aligns with regions of high eddy activity

[Constantinou & Hogg, *JCli*, 2021]

low-frequency upper-ocean heat content variance
what's the ocean's intrinsic part into this?



in regions where eddies are prominent
up to ~80-90% of variability comes from ocean's intrinsic dynamics

[Constantinou & Hogg, *JCli*, 2021]

II.

low-frequency upper-ocean heat content variance with eddies or without eddies?

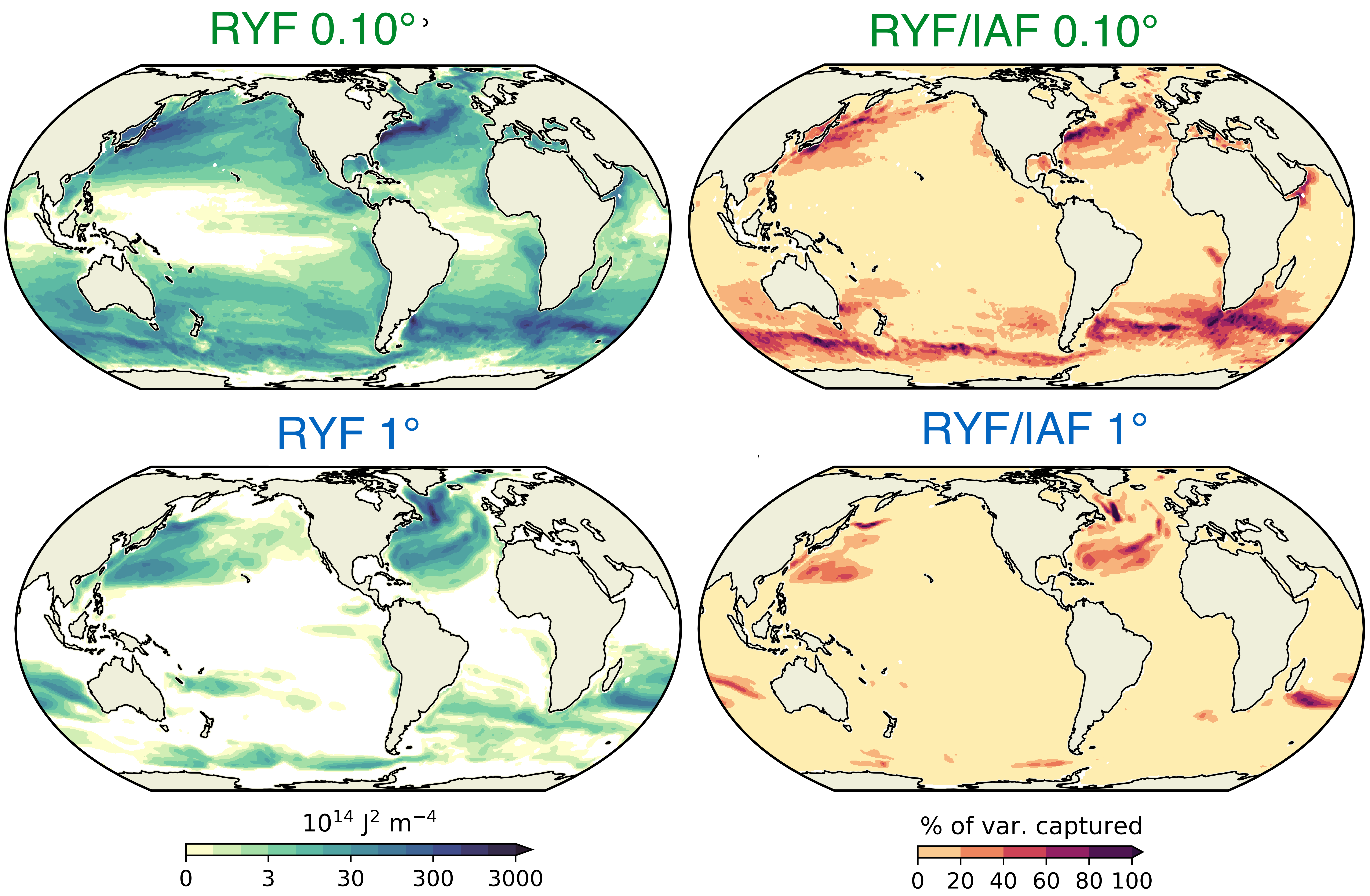
rich in eddies 🌀

(state-of-the-art)

parametrizes eddies 🌀

(IPCC)

repeat-year forcing



[Constantinou & Hogg, *JCli*, 2021]

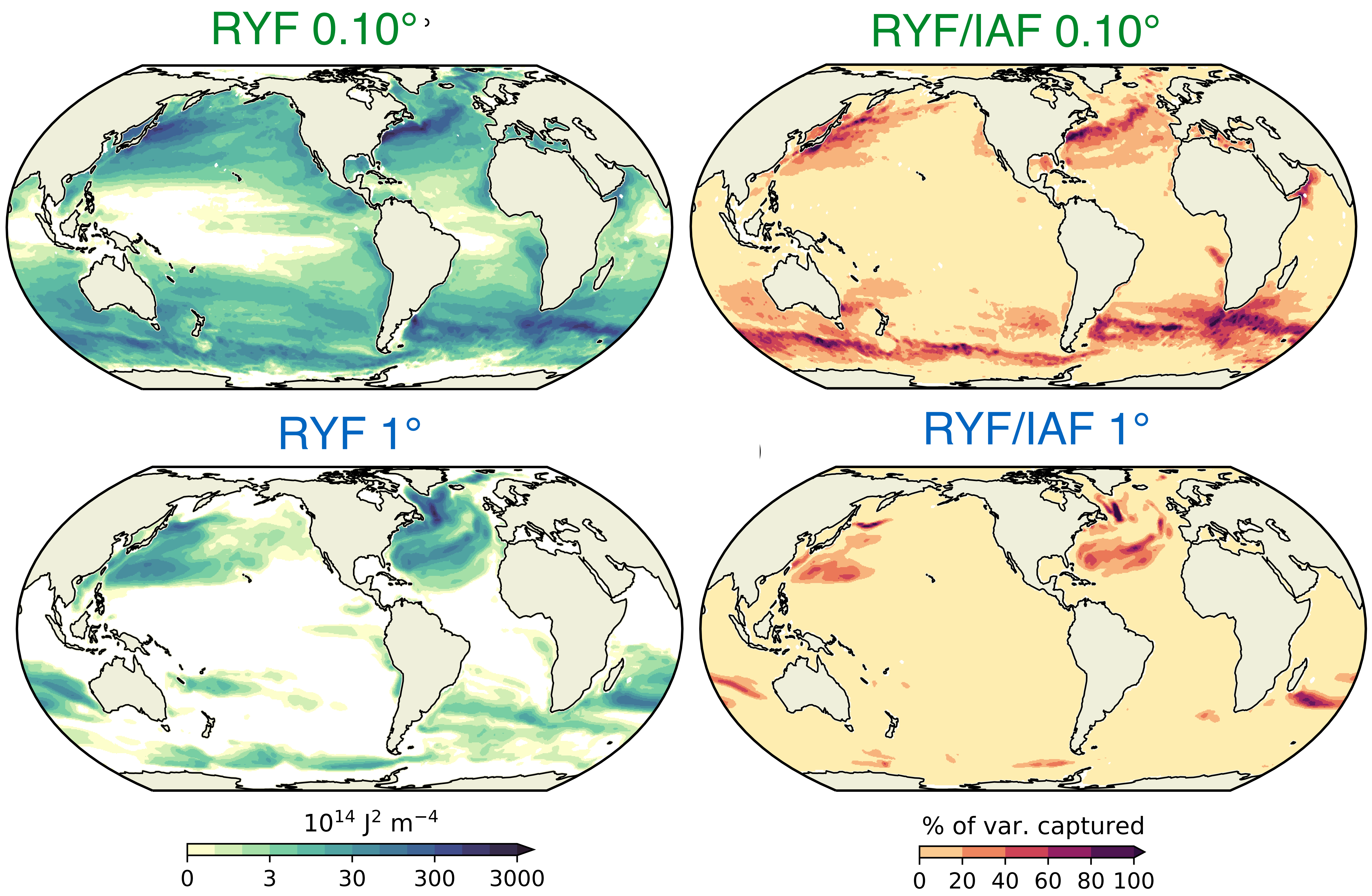
low-frequency upper-ocean heat content variance with eddies or without eddies?

repeat-year forcing

low-frequency variance
due to oceans' intrinsic dynamics
@ mid-latitudes
increases
with model resolution

patterns of variability?

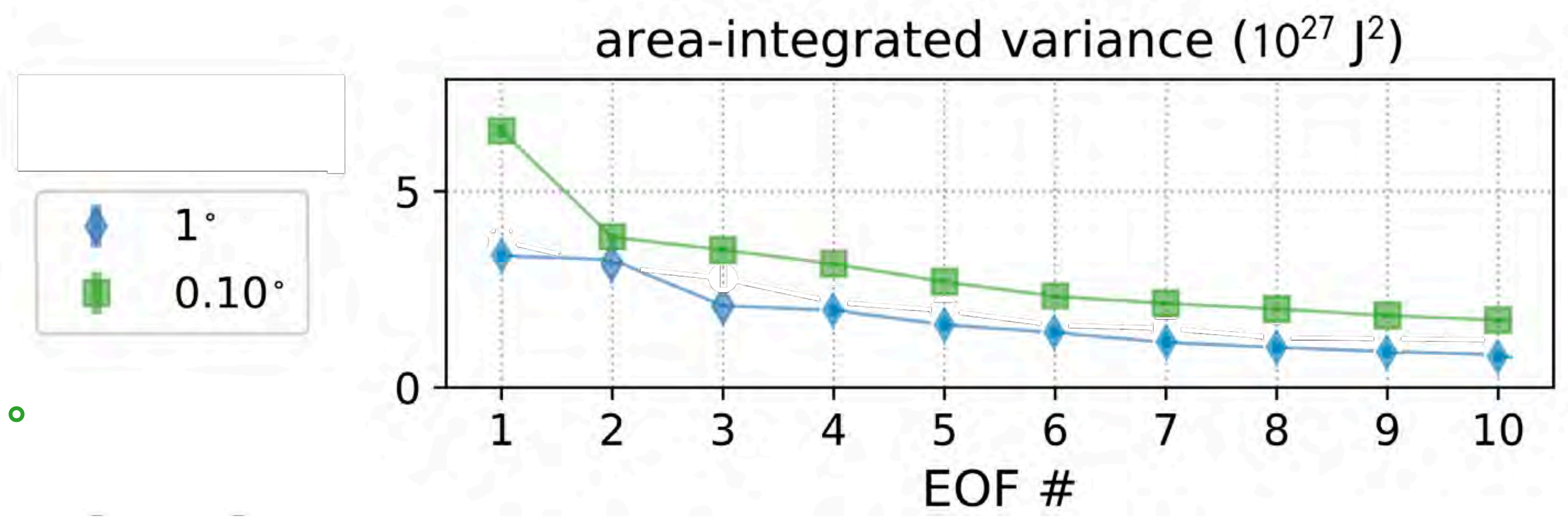
are they the
same across resolutions?



[Constantinou & Hogg, *JCli*, 2021]

II.

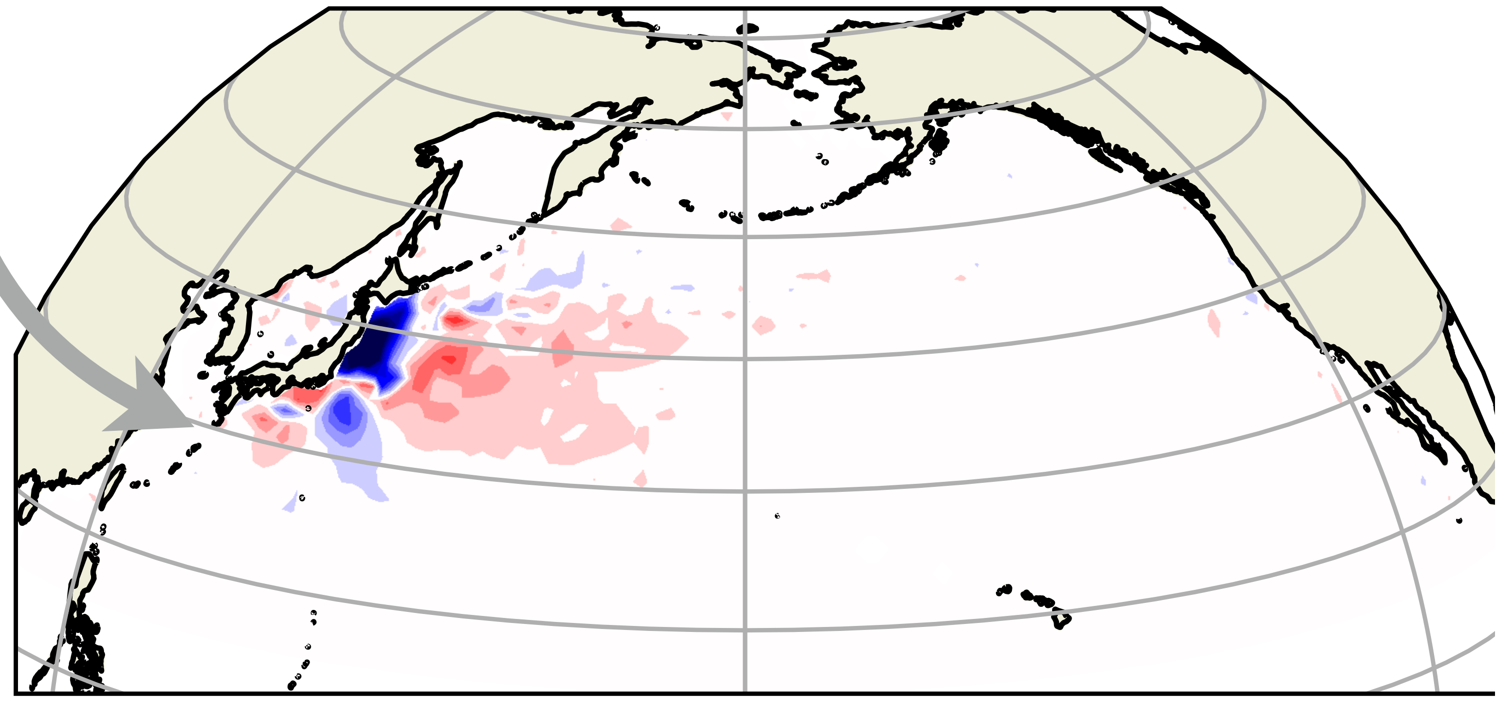
EOF analysis of low-frequency upper-ocean heat content from repeat-year forcing @ North Pacific

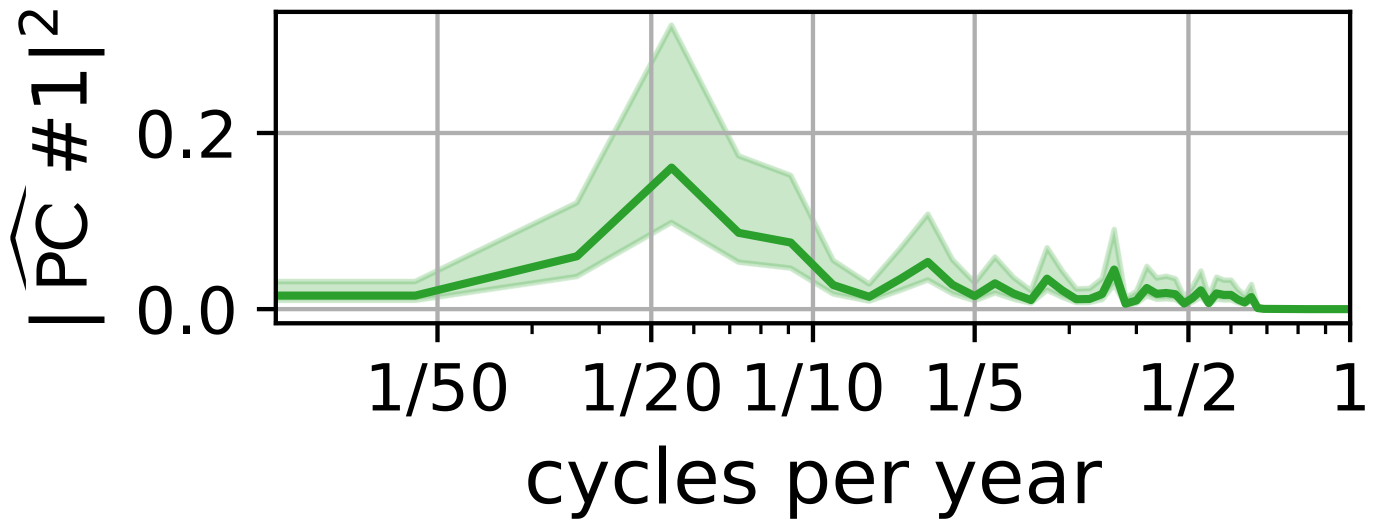


eddy-rich ocean has very different imprint on the atmosphere…

RYF 0.10°

EOF #1, 4.9% var.



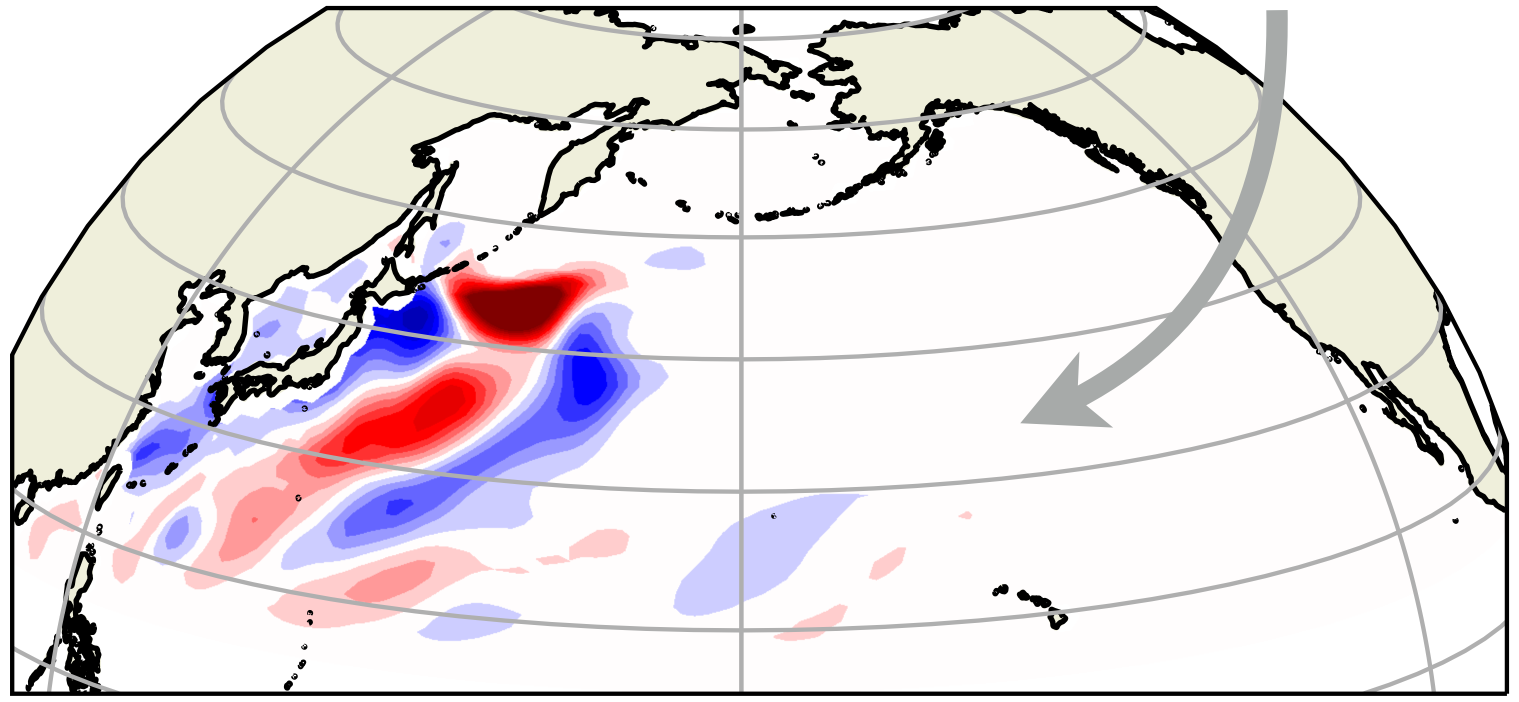


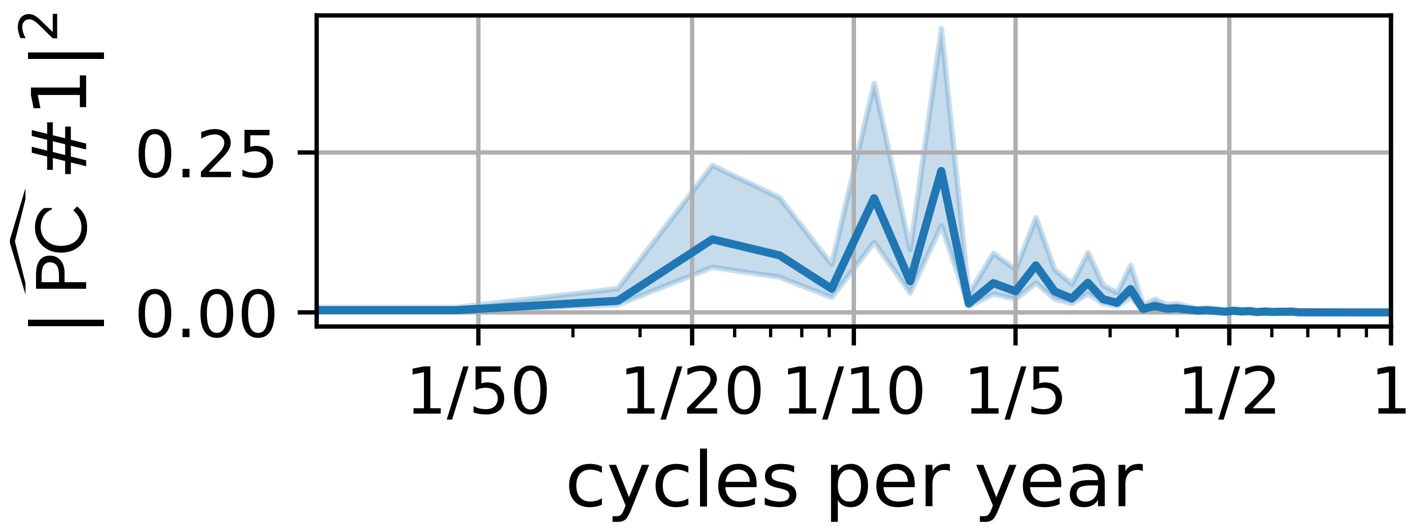
IPCC

RYF 1°

EOF #1, 11.7% var.

the "IPCC atmosphere" feels this ocean at decadal timescales





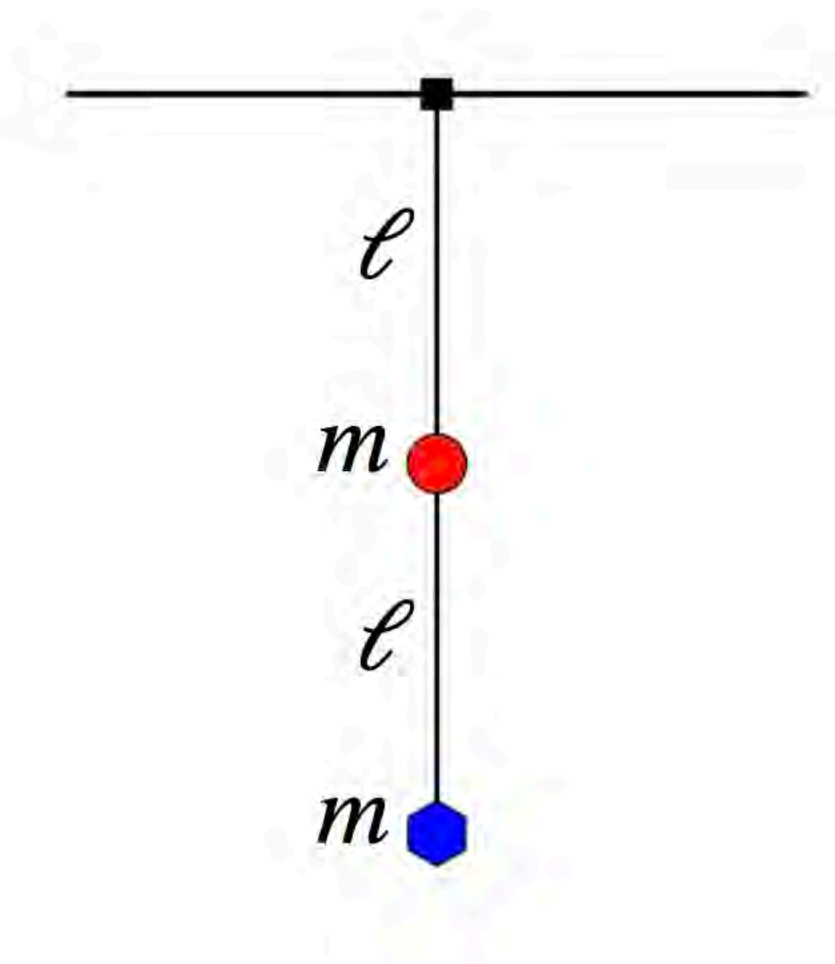
~ timescales of various decades
climate modes of variability (PDO, NAO,…)

"IPCC atmosphere" experiences shorter timescales

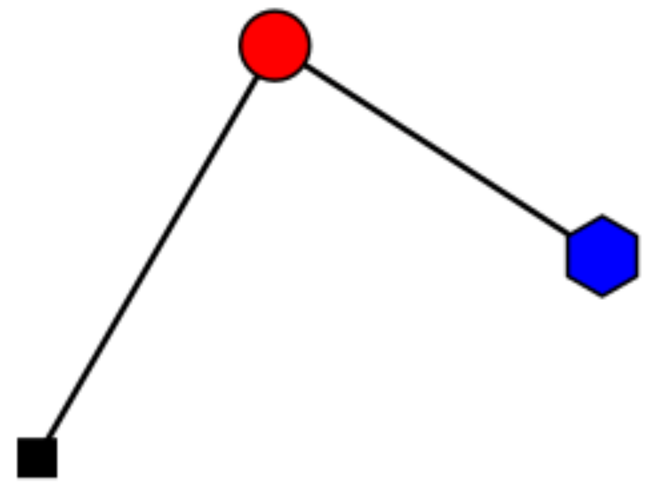
[Constantinou & Hogg, *JCli*, 2021]

II.

a small digression — the double pendulum

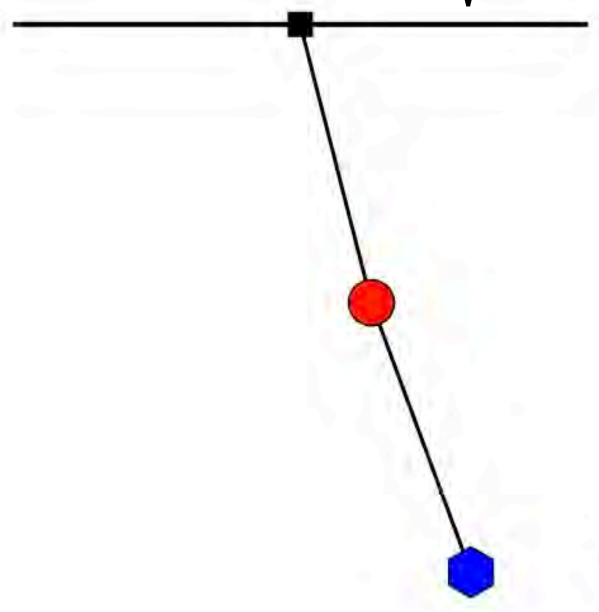


initialised randomly

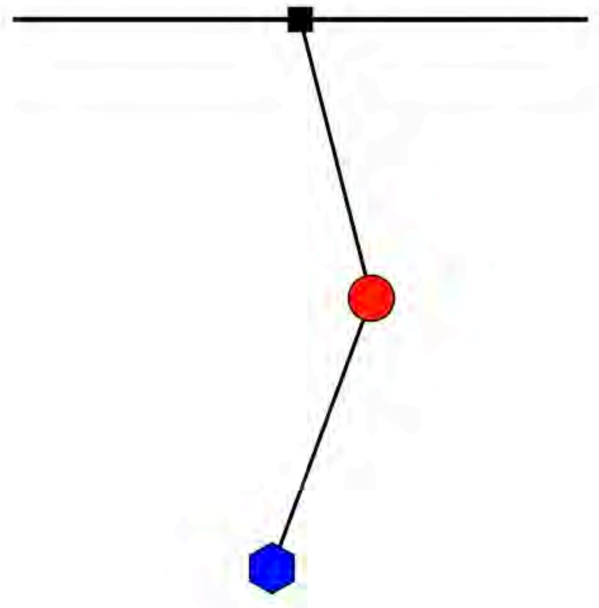


two normal modes

$$\omega_1 = \sqrt{2-\sqrt{2}}\sqrt{\frac{g}{\ell}}$$



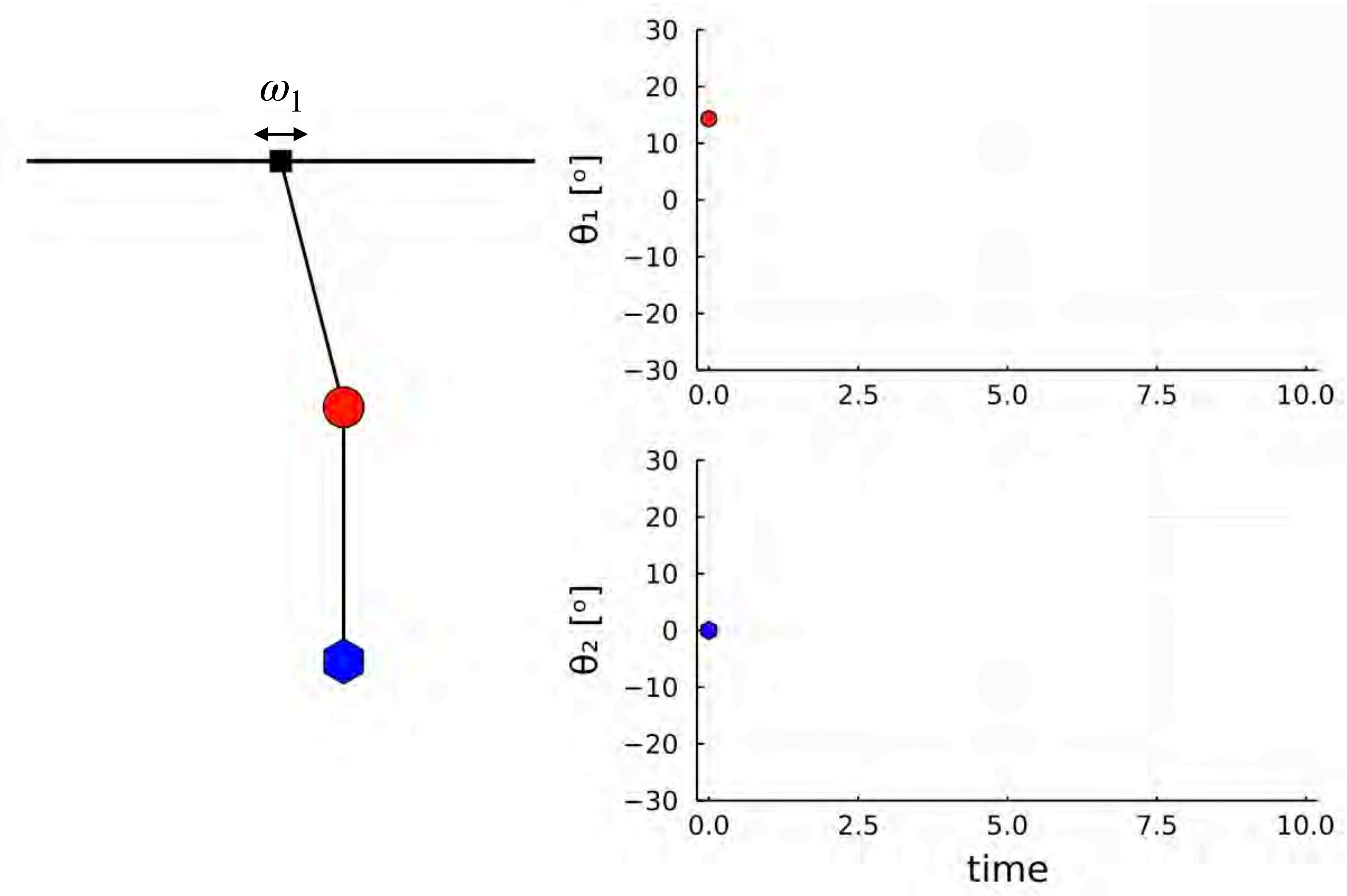
$$\omega_2 = \sqrt{2+\sqrt{2}}\sqrt{\frac{g}{\ell}}$$



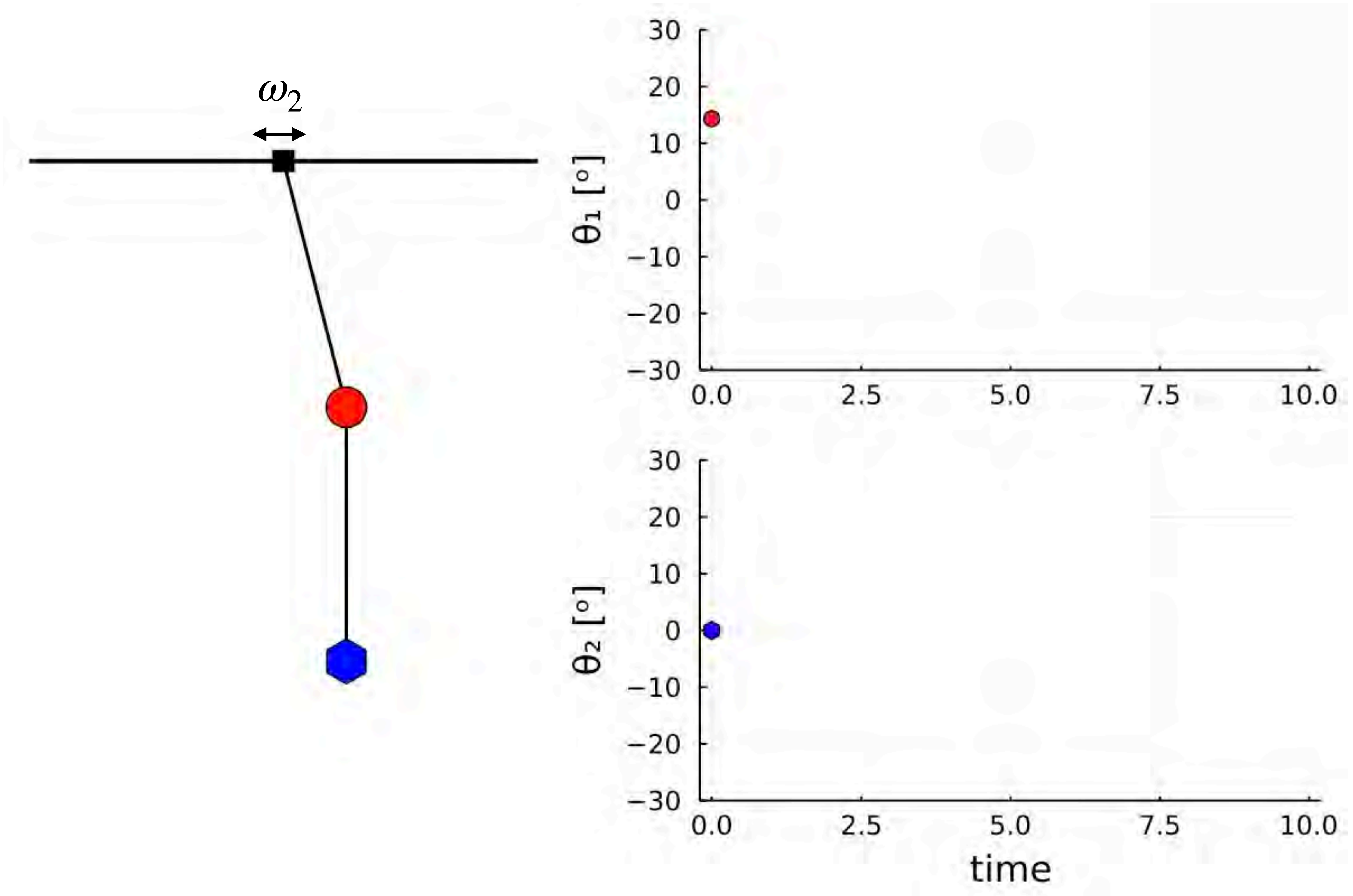
github.com/navidcy/double_pendulum

a small digression — the double pendulum
forcing + dissipation

forcing with normal-mode frequency $f_0 \cos(\omega_1 t)$
+ damping



forcing with normal-mode frequency $f_0 \cos(\omega_2 t)$
+ damping



nudge w/ normal-mode frequency 👉🏼

👉🏼 normal mode comes out

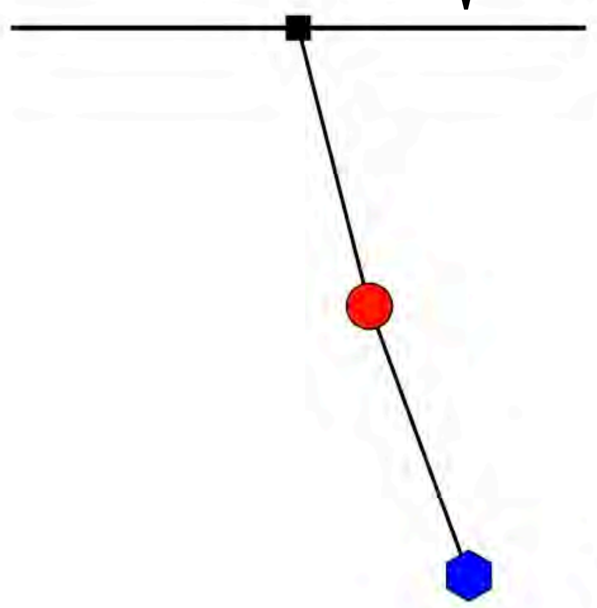
II.

the double pendulum
— a very loose analogy —

decadal climate modes of variability

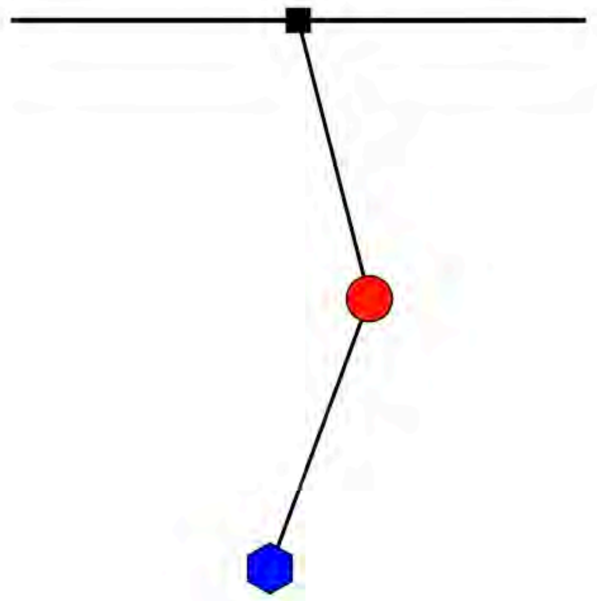
e.g. ,
North Atlantic oscillation

$$\omega_1 = \sqrt{2-\sqrt{2}}\sqrt{\frac{g}{\ell}}$$

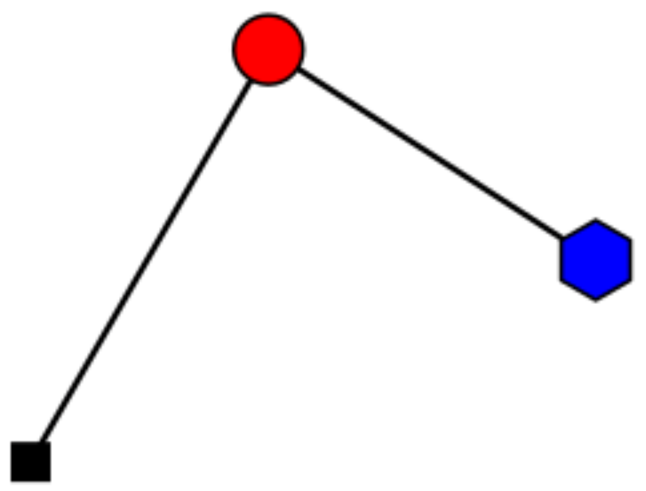


Pacific Decadal oscillation

$$\omega_2 = \sqrt{2+\sqrt{2}}\sqrt{\frac{g}{\ell}}$$



climate



ocean’s nudging on atmosphere

forcing, e.g., $f_0 \cos(\omega t)$

(for any ω)

anything to take home? 🧳

atmosphere on top of eddy-resolving ocean feels:

more upper-ocean heat content variance
at decadal timescales

&

very *different* patterns of decadal variability
(that reflect more the eddy-active 🌀 regions)

a "nudge" from the ocean at the appropriate frequency
may excite decadal climate modes of variability (PDO, NAO, …)

II.

anything to take home? 🧳

atmosphere on top of eddy-resolving ocean feels:

more upper-ocean heat content variance
at decadal timescales

&

very *different* patterns of decadal variability
(that reflect more the eddy-active 🌀 regions)

a "nudge" from the ocean at the appropriate frequency
may excite decadal climate modes of variability (PDO, NAO, …)

better parameterize the ocean's mesoscale 🌀
or move towards climate models that resolve the 🌀

Oceananigans

a new ocean model fast enough
to resolve mesoscales eddies in climate projections

III.

CLiMA
CLIMATE MODELING ALLIANCE

climate modelling v2.0

Caltech

JPL
Jet Propulsion Laboratory
California Institute of Technology

MIT

ANU

…building a ***new Earth system model***
that leverages recent advances in the computational and data sciences
to learn directly from a wealth of Earth observations from space and the ground.

Calibrate the whole climate model including all parameterizations leveraging as much data as possible


Andre Souza


Chris Hill


Sid Bishnu


Simone Silvestri


Greg Wagner


Raffaele Ferrari


Jean-Michel Campin


Navid Constantinou


John Marshall

Ocean Model Dev Team


Grace O'Neil


Xin-Kai Lee


M. G.


Ali Ramadhan


Ulyana Piterbarg


Adeline Hillier


Valentin Churavy

Oceananigans is the ocean core of Clima's Earth System model

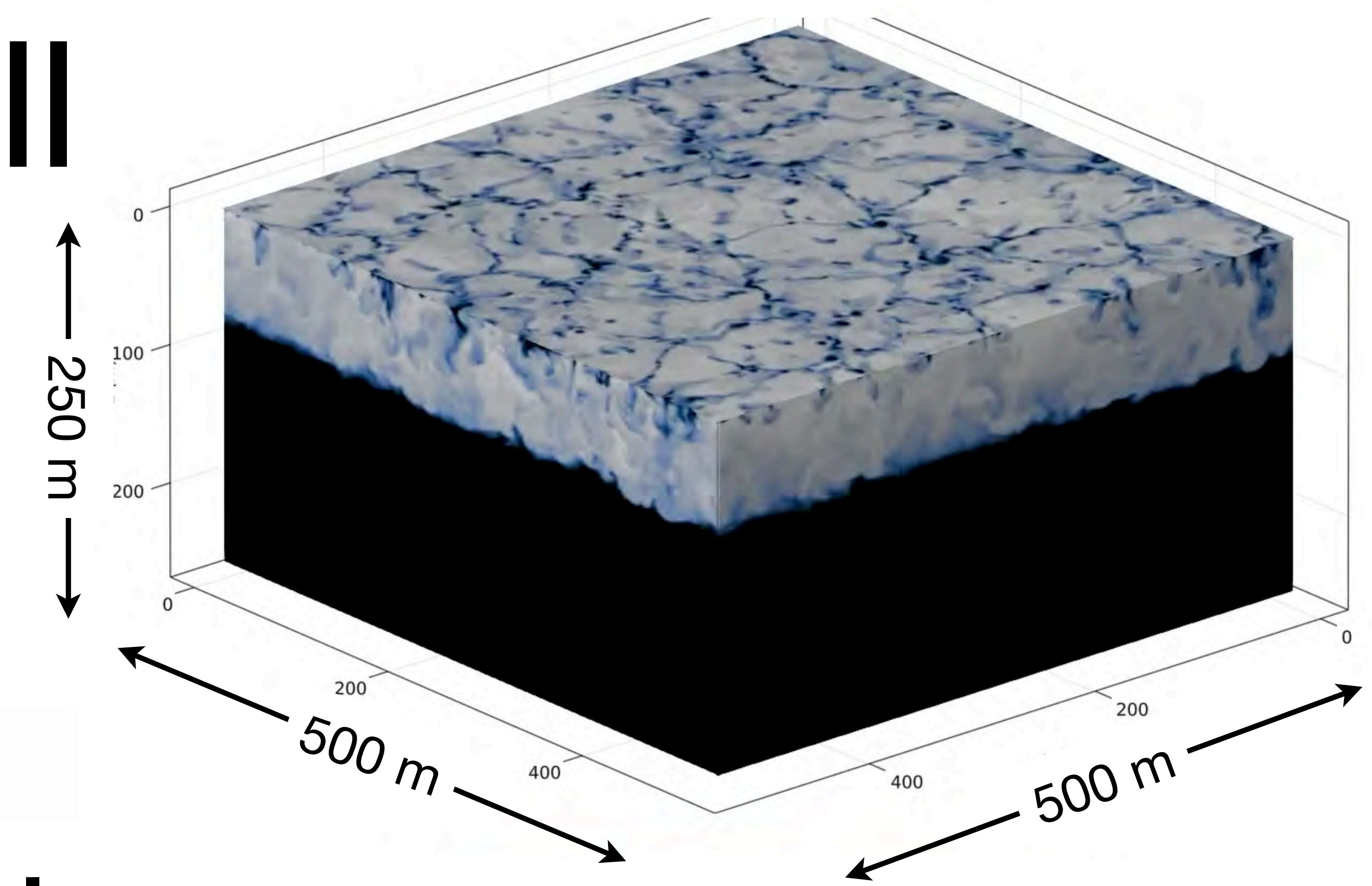
GitHub

julia

Oceananigans in a nutshell

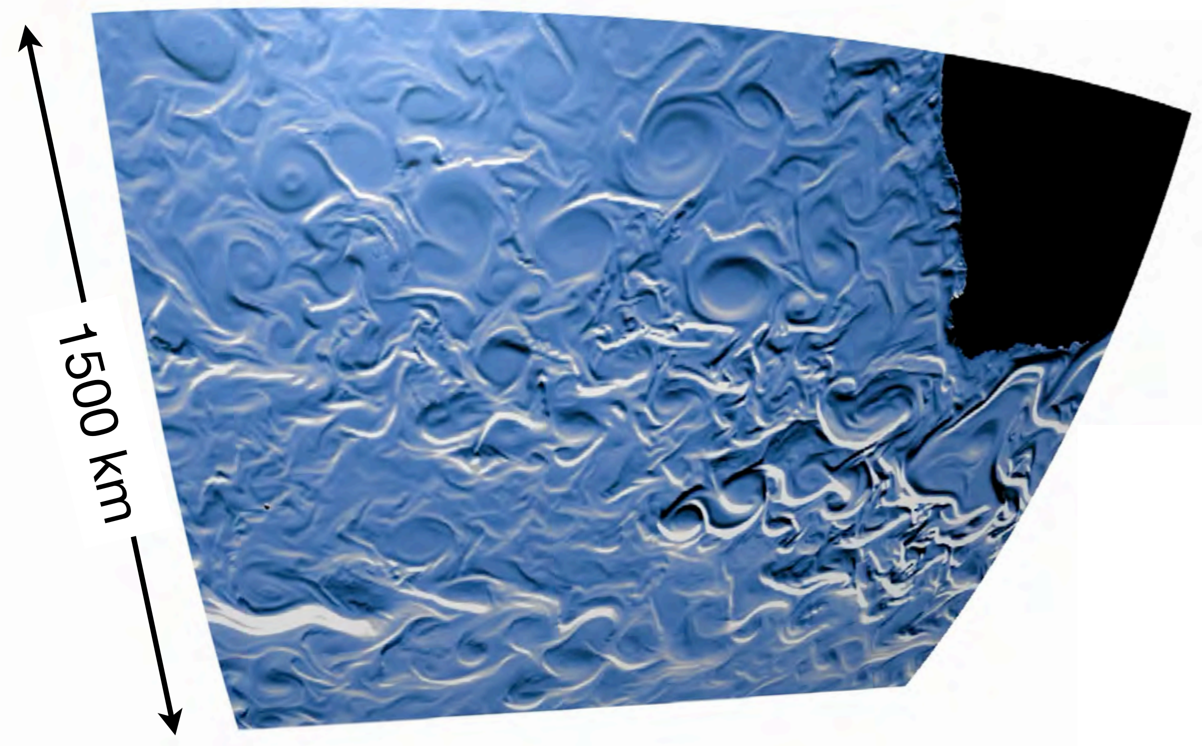
- Software for ocean-flavored fluid dynamics using finite-volume numerical methods
- Fast: written from scratch for GPUs
- Friendly: uses the Julia programming language
  - *Simple simulations are easy*
  - *Complex, creative simulations are possible*
- Flexible
  - *Companion packages for biogeochemistry, sea ice, ocean-sea-ice coupled simulations*

LES



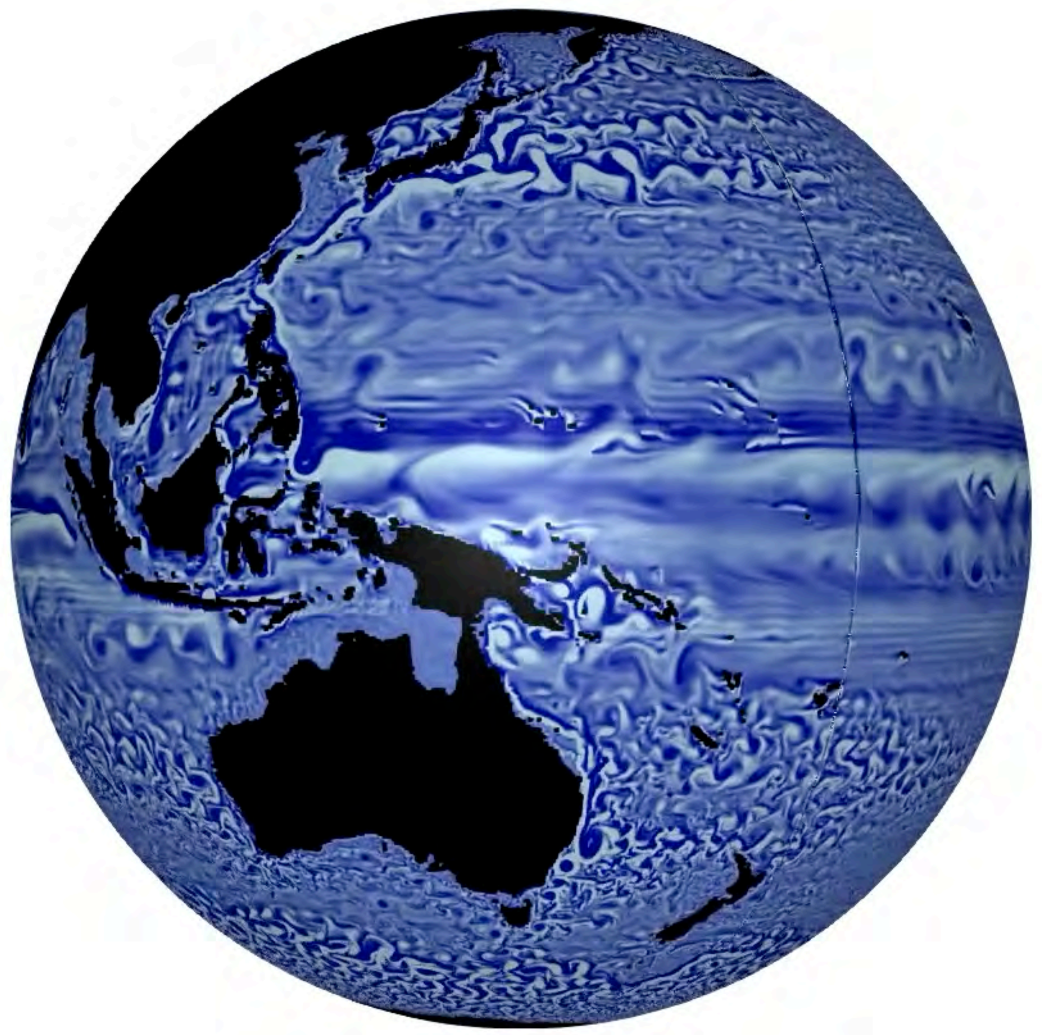
Non-hydrostatic Model

regional



Hydrostatic free-surface Model

global



Hydrostatic free-surface Model

III.

what's all the fuss about GPUs?

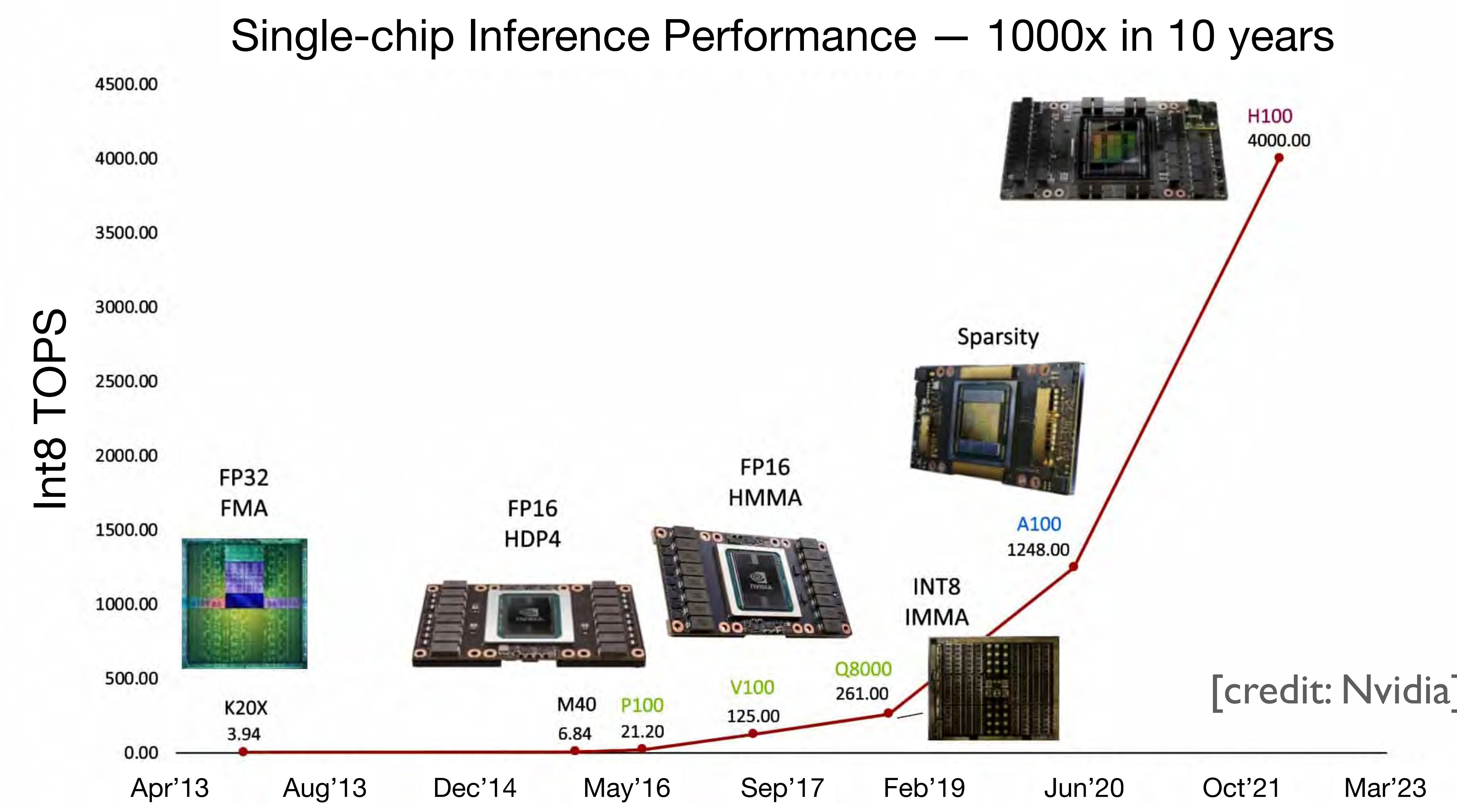
NVIDIA

CPUs: "The free lunch is over"

[Moore's law is dead;
we ain't getting 2x speedup
every 2 years anymore…]

GPUs are the future of scientific computing

- Cost: 1 GPU = 10 CPUs
- Performance: 1 GPU = 100-400 CPUs
- Cost savings: 10x-40x?



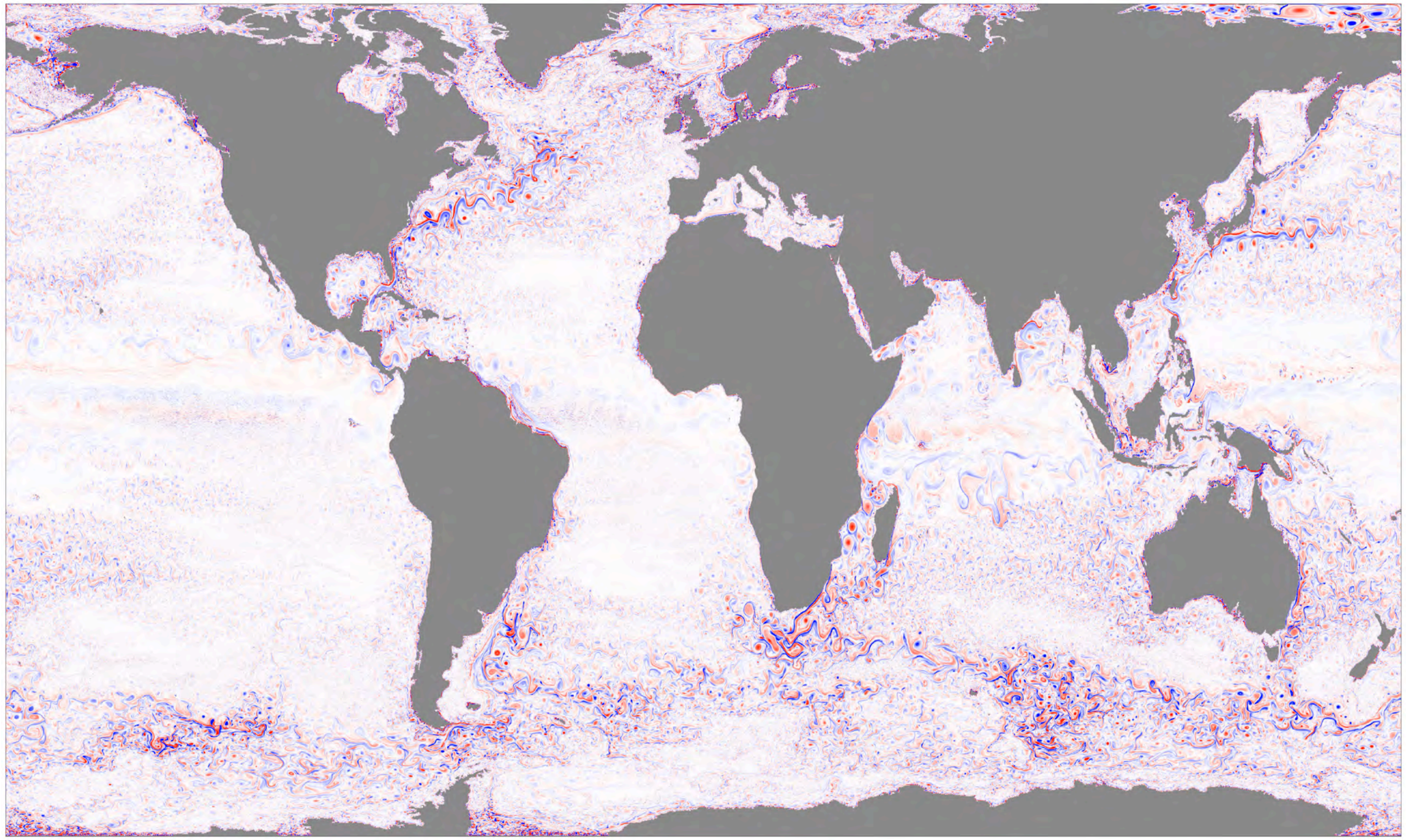
[credit: Nvidia]

GPUs are mostly optimized for AI,
which has substantial overlap with climate!

III.

Oceananigans achieves breakthrough performance

"it's fast and cheap!"



near-global (75°S–75°N) ocean simulation at 1/12° horizontal resolution, 48 vertical levels

[Scaling & Performance results at Silvestri et al., 2023, arXiv:2309.06662]

1/4th degree:

10 Simulated Years per Day on **4** GPUs

- state-of-the-art is 10 SYPD on ~2000 CPUs

1/12th degree:

10 Simulated Years per Day on **64** GPUs

1/48th degree:

0.2 Simulated Years per Day on **128** GPUs

- state-of-the-art is 0.05 SYPD on ~70,000 CPUs

Oceananigans is easy to use

Designed for scripting and interactive use

(feels like Python; runs like FORTRAN)

```
julia> using Oceananigans

julia> grid = RectilinearGrid(size=(5,5,5),extent=(1,1,1))
5×5×5 RectilinearGrid{Float64, Periodic, Periodic, Bounded} o
n CPU with 3×3×3 halo
├── Periodic x ∈ [0.0, 1.0)  regularly spaced with Δx=0.2
├── Periodic y ∈ [0.0, 1.0)  regularly spaced with Δy=0.2
└── Bounded  z ∈ [-1.0, 0.0] regularly spaced with Δz=0.2

julia> model = HydrostaticFreeSurfaceModel(; grid);

julia> simulation=Simulation(model, Δt=1.0, stop_time=10);
```

"... I have never experienced getting a useful calculation done as easily as I was able to do with Oceananigans. It not only has a sophisticated interface, but it is remarkably fast..."

Linux magazine

Designed so "code reads like a paper"

try changing CPU() to GPU()

```
using Oceananigans
using GLMakie

grid = RectilinearGrid(CPU(),
                       size = (64, 64),
                       x = (-5, 5),
                       y = (-5, 5),
                       topology = (Bounded, Bounded, Flat))

model = NonhydrostaticModel(grid=grid, tracers=:c, advection=WENO())

gaussian(x, y) = exp(-(x^2 + y^2))
set!(model, c=gaussian)

c = model.tracers.c

∇c² = ∂x(c)^2 + ∂y(c)^2
∇c² = Field(∇c²)
compute!(∇c²)
```

Initial conditions

Diagnostics

III.

Oceananigans is flexible

- From the laboratory to the planetary scales!
- Some packages that use or “plug-in” to Oceananigans:

➡ **OceanBioME** (biogeochemistry or “BGC”, applicable to carbon dioxide removal)

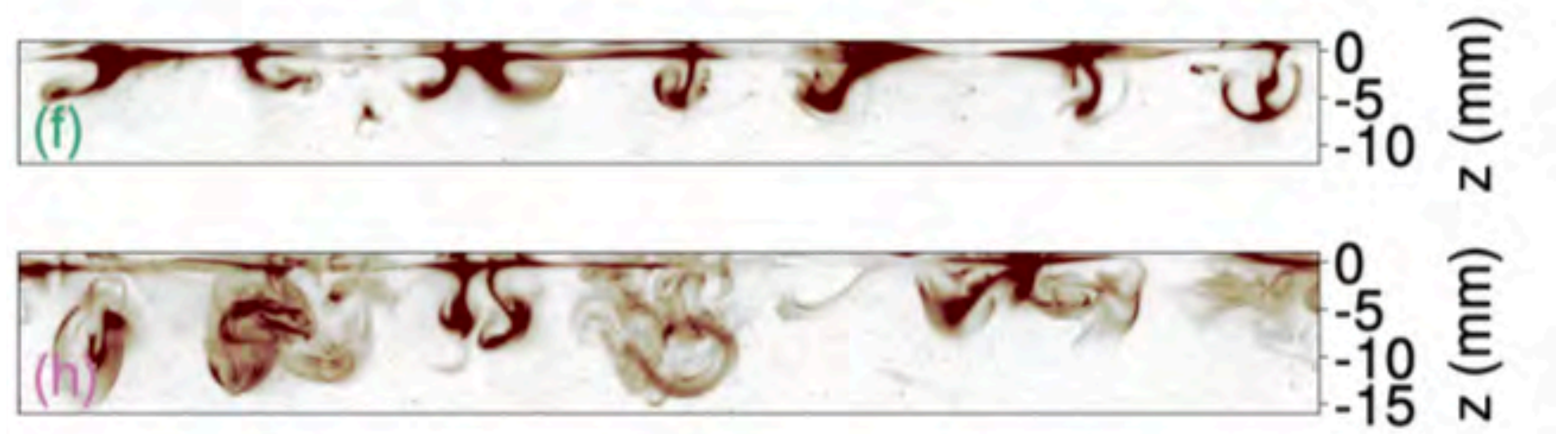
➡ **ClimaOceanBiogeochemistry** (BGC for climate prediction)

➡ **ClimaSeaIce** (sea ice model for ClimaOcean)

➡ **ClimaOcean** (coupled ocean-sea-ice simulations)

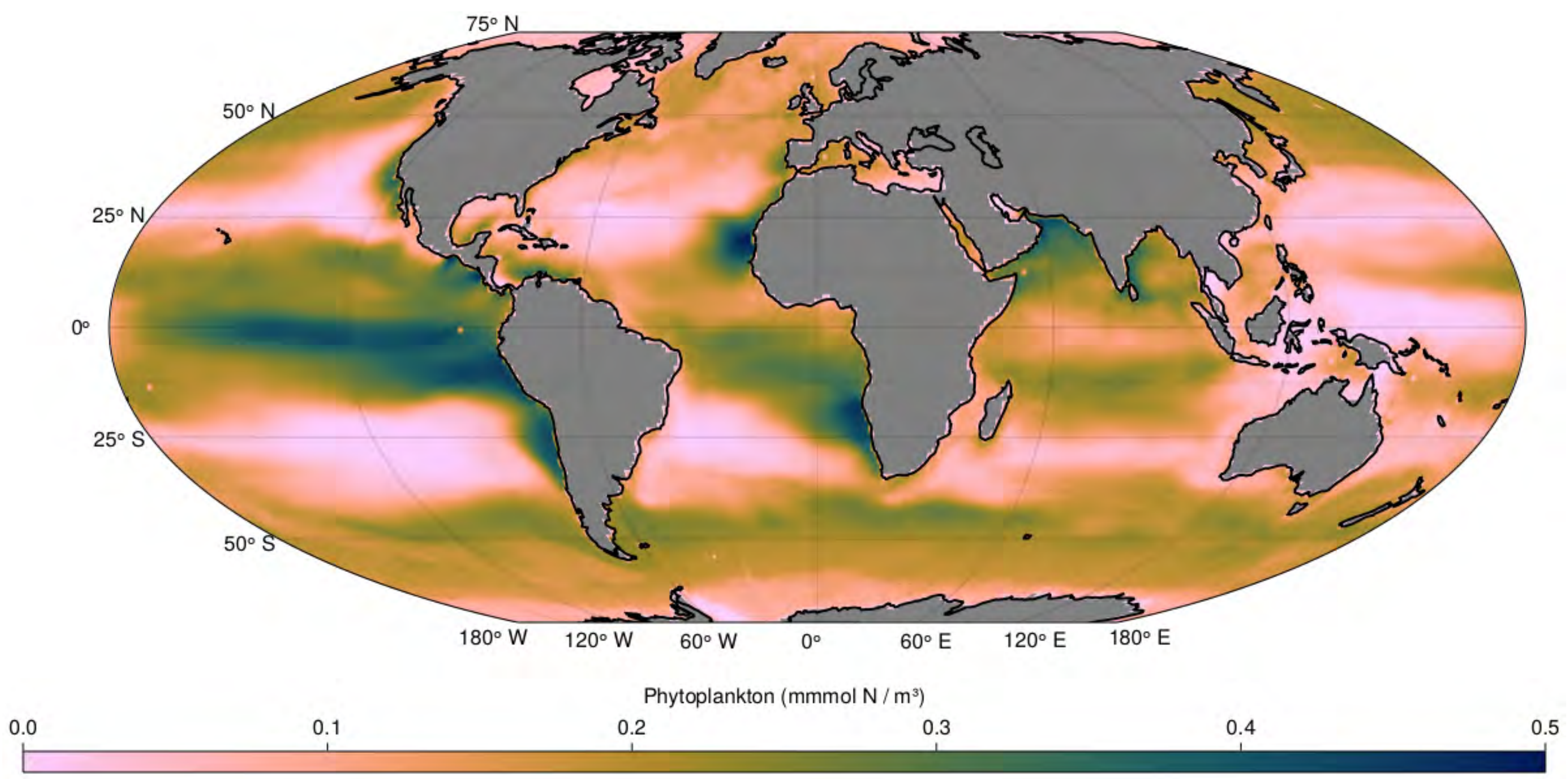
Oceananigans direct numerical simulation

Laboratory experiment [Veron and Melville 2001]



[Wagner et al, JFM, 2023]

Oceananigans + OceanBioME



[Strong-Wright, Chen, **Constantinou**, et al, *JOSS*, 2023]

Oceananigans

@navidcy contributor #4

- leading the cubed sphere grids to enable fully global simulations on Earth 🌎 and aquaplanets 🪐
- user interface design: making simple science easy and complex science possible
- contributing in extensive documentation 📜
- contributing towards OMIP configuration
  (=CMIP for ocean models)
- contributor for biogeochemistry package OceanBioME 🌊 🦠 🌿
  (biogeochemistry companion package)

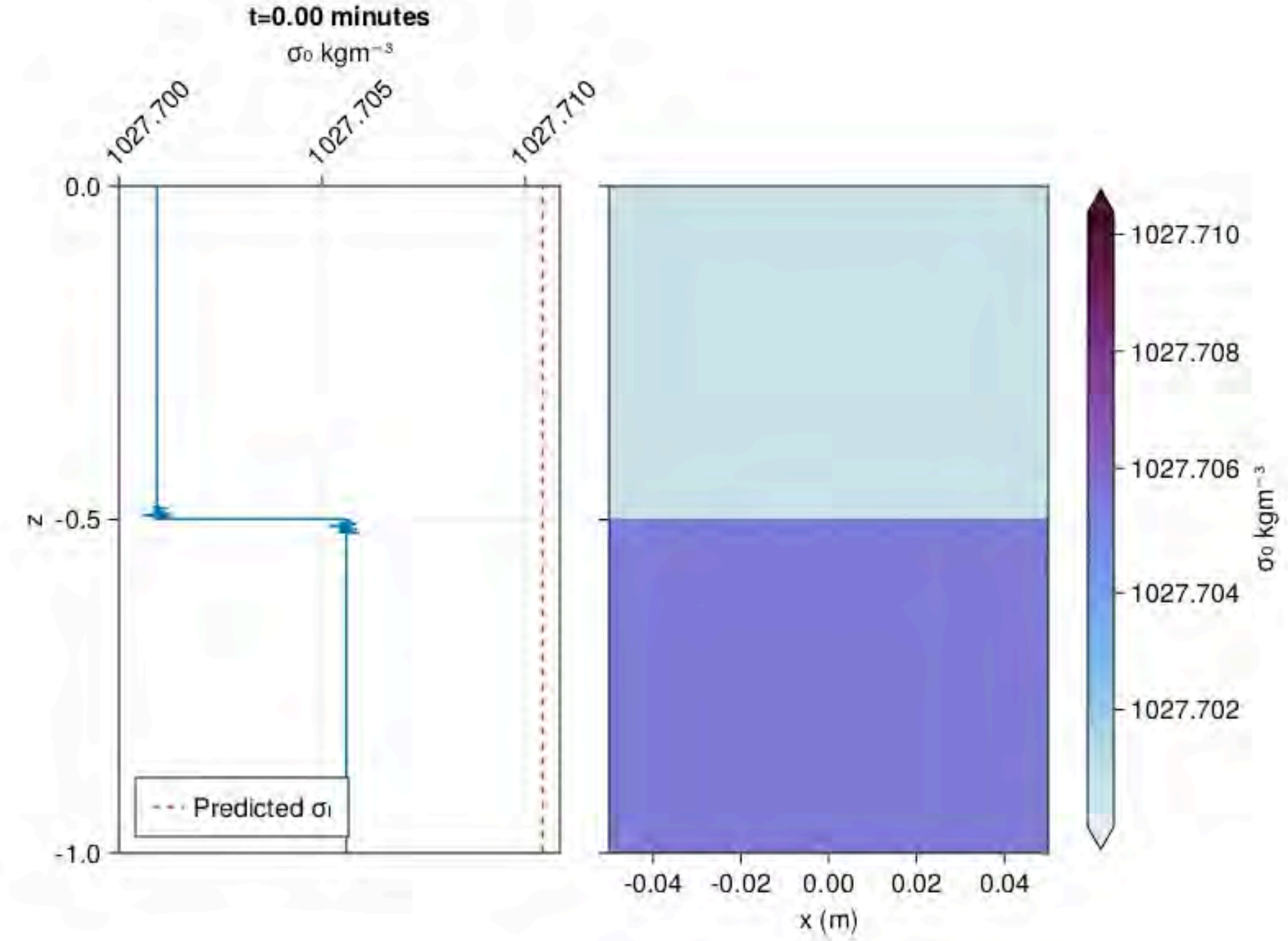
Elise Palethorpe
Honours, ANU
(w Navid)

A new multigrid pressure solver for CliMA's ocean model

III.

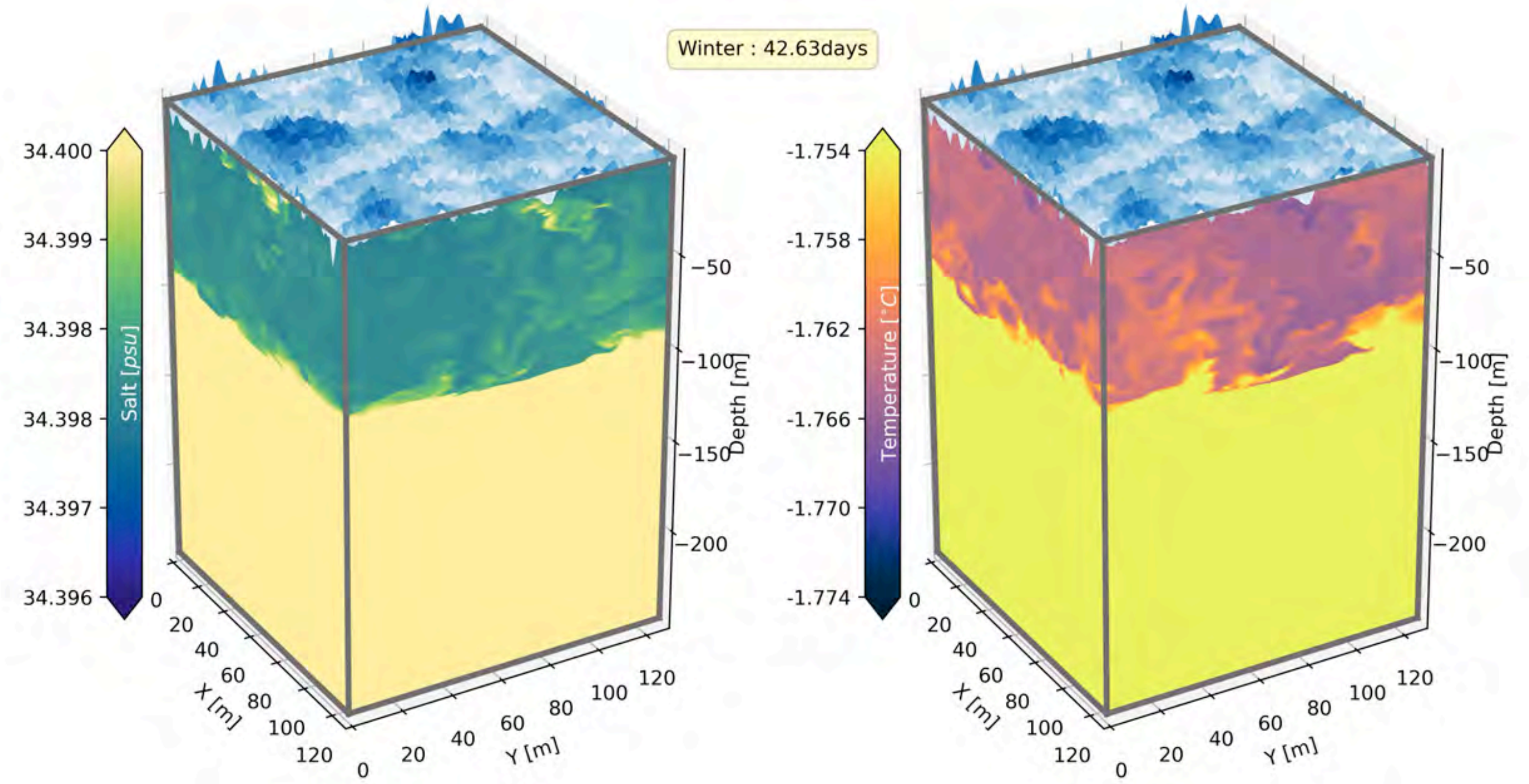
people have started using Oceananigans in Australia

Josef Bisits
PhD student
UNSW



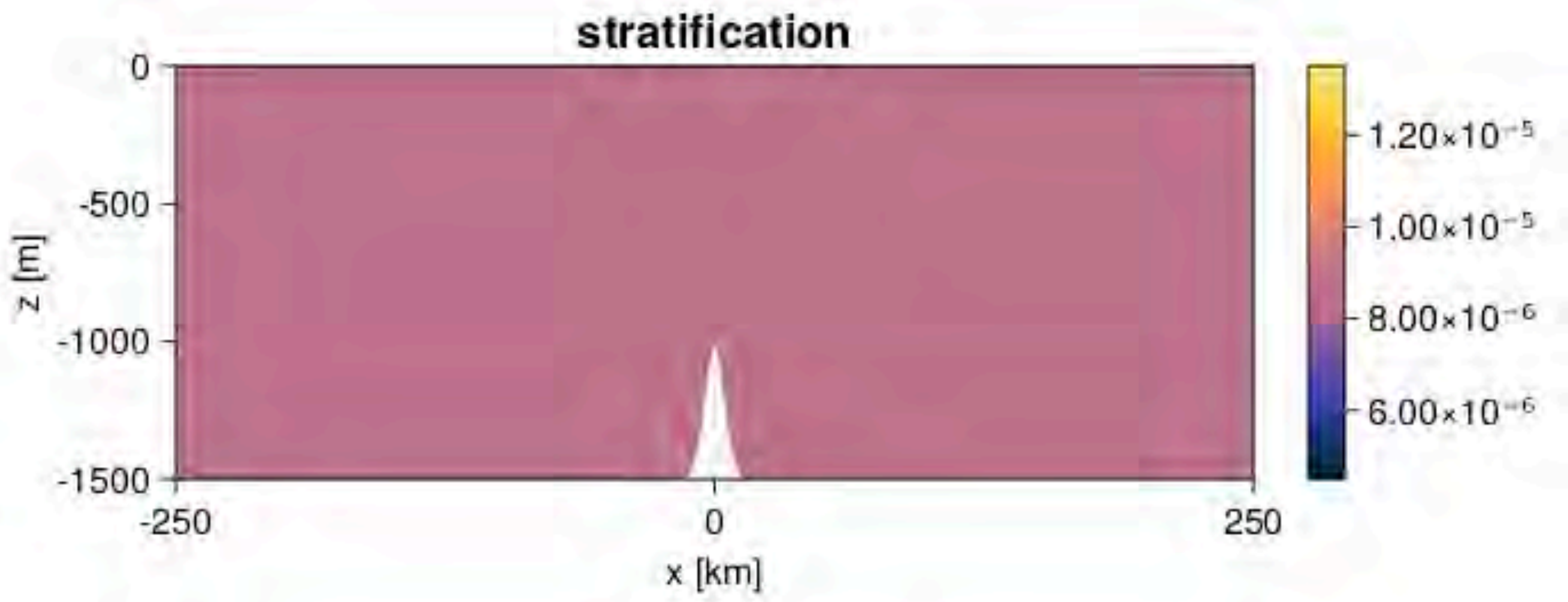
direct numerical simulation
of cabelling instability

Ankit Bhadouriya
PhD student
UniMelb



large-eddy simulations
of ocean's mixed layer under sea ice

Daniel Johnston
Researcher
ANU



tidal mixing and
topographic-induced drag

Clima's Earth System Model + Parameterisations

Why is climate hard?

Interconnections among many processes

Some things we can't resolve..!

Other things we don't even know the equations!

increasing resolution helps!

We will *always* need to parameterise some things…

Calibrate the whole climate model including all parameterizations
leveraging as much data as possible

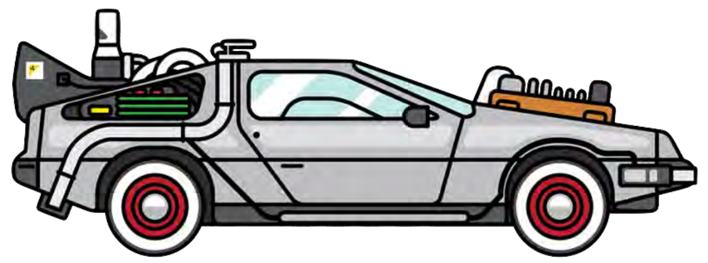
👉 use ensemble-based methods (Ensemble Kalman Inversion)

[Iglesias et al, *Inverse Problems*, 2013; Dunbar et al, EnsembleKalmanProcesses.jl: Derivative-free ensemble-based model calibration, *JOSS*, 2022] *“a model that requires 50x less resources opens up a multitude of possibilities”*

— adage

IV.

disentangling ocean decadal variability from underlying climate change

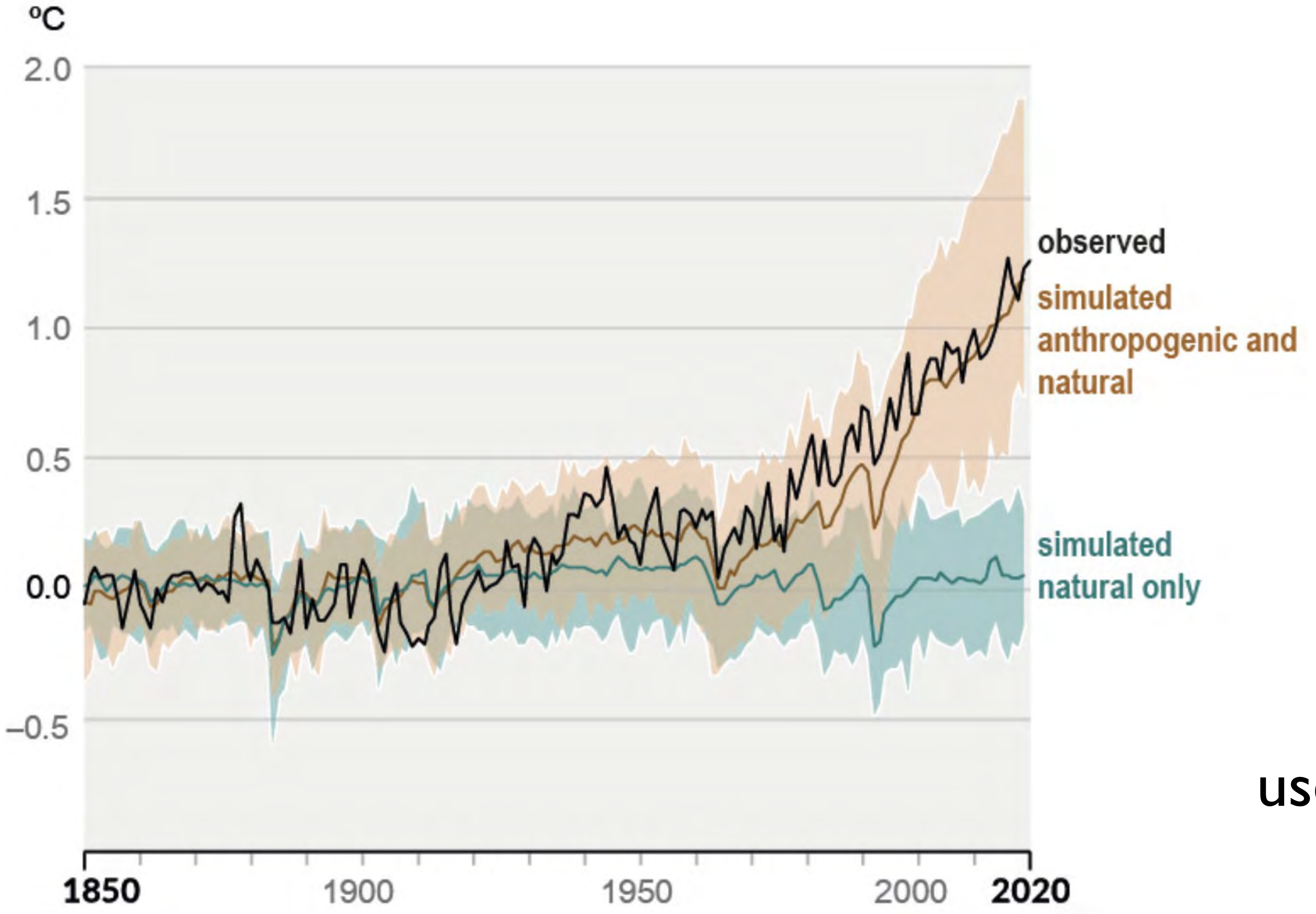


IV.

moving forward — future plans

research

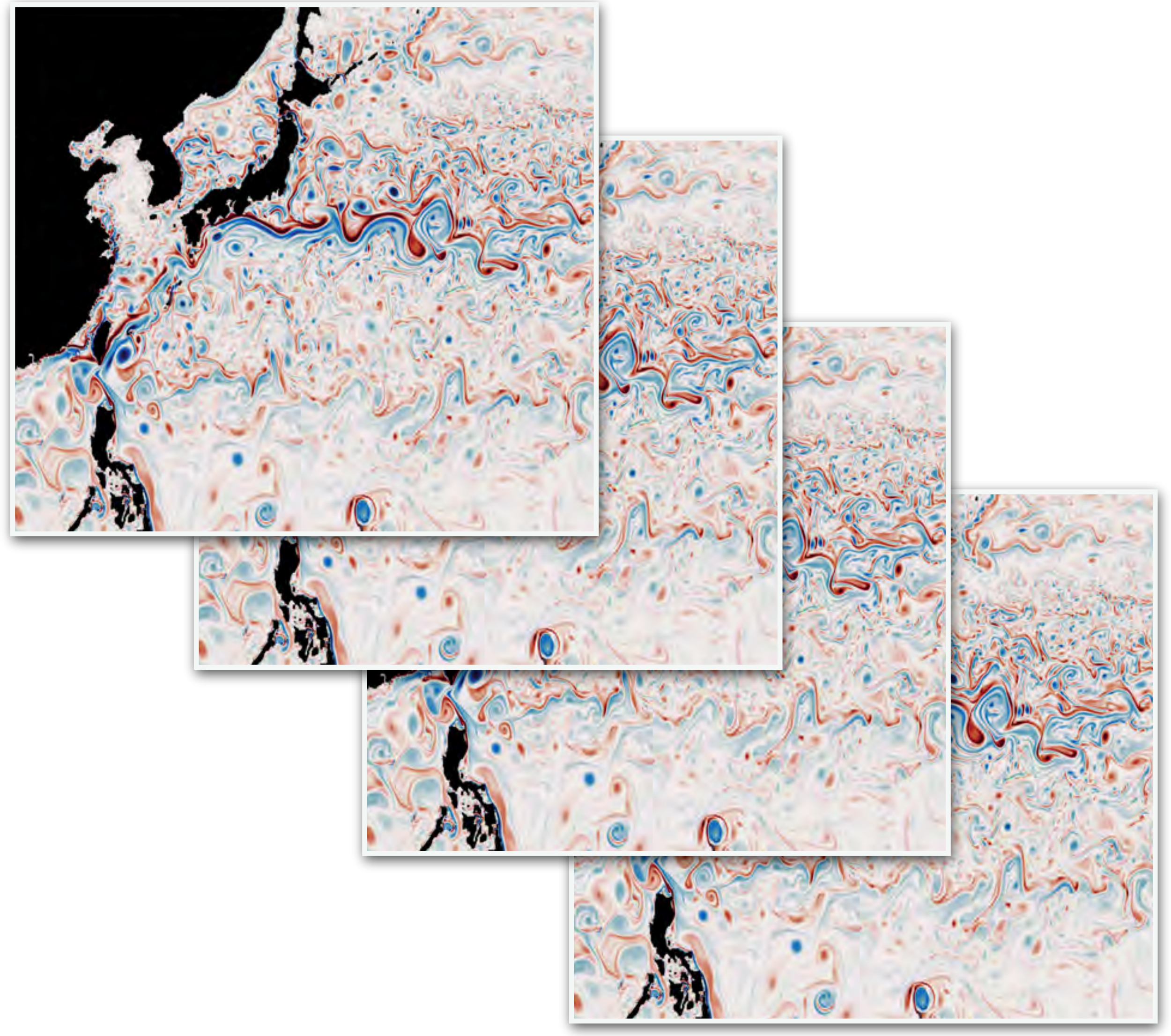
Ensembles of climate simulations are essential to disentangle natural from climate-change variability



[IPCC AR6 WG I SPM]

w/ Oceananigans we get "*50 at the price of 1*"

👉 it's feasible to *routinely* perform ensembles of eddy-resolving ocean simulations



. . .

use **ensembles** of *eddy-resolving* global ocean simulations to understand ocean's role in climate change

DP24; lead CI with Nicola Maher and Andy Hogg

IV.

moving forward — future plans

research

Climate projections that resolve ocean's mesoscale 🎉

Paleoclimate eddy-resolving simulations

Real-time regional ocean modelling
for carbon dioxide removal purposes

IV.

moving forward — future plans

research

Climate projections that resolve ocean's mesoscale 🎉

Paleoclimate eddy-resolving simulations

Real-time regional ocean modelling
for carbon dioxide removal purposes

Please fill in *your (ambitious) project*:

We can now for the first time ask ____________________
and use *modern* climate modelling tools to answer this
by doing ________________ and _______________ .

IV.

moving forward — future plans

software

CliMA CLIMATE MODELING ALLIANCE

Open-source software builds community

GitHub

COSIMA Consortium for Ocean—Sea Ice Modelling in Australia

Annual Workshop, November 2022, Hobart

Leading the coordination of open-source repository (`cosima-recipes`)
with tutorials and examples for analysing model output

“From little things big things grow”

by

Paul Kelly

small eddies	👉	large-scale patterns
short-lived eddies	👉	decadal climate variability
young undergraduates	👉	climate scientists
students	👉	government/policy makers
small communities	👉	global communities

thank you