From small swirls up to the global ocean circulation: how ocean eddies affect the Earth's climate

Navid Constantinou

Remark: Not to be confused with Van Gogh's "Starry Night"

RSES School Seminar
25th March 2021

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

Credit: NASA/Goddard Space Flight
Center Scientific Visualization Studio

ocean currents modelled at different horizontal resolutions

(why ocean eddies give headaches to climate scientists?)

typically used
for climate predictions
IPCC, etc…

state-of-the-art
ocean—sea-ice model

[ACCESS-OM2 ocean—sea-ice models]

ocean currents modelled at different horizontal resolutions

typically used
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state-of-the-art
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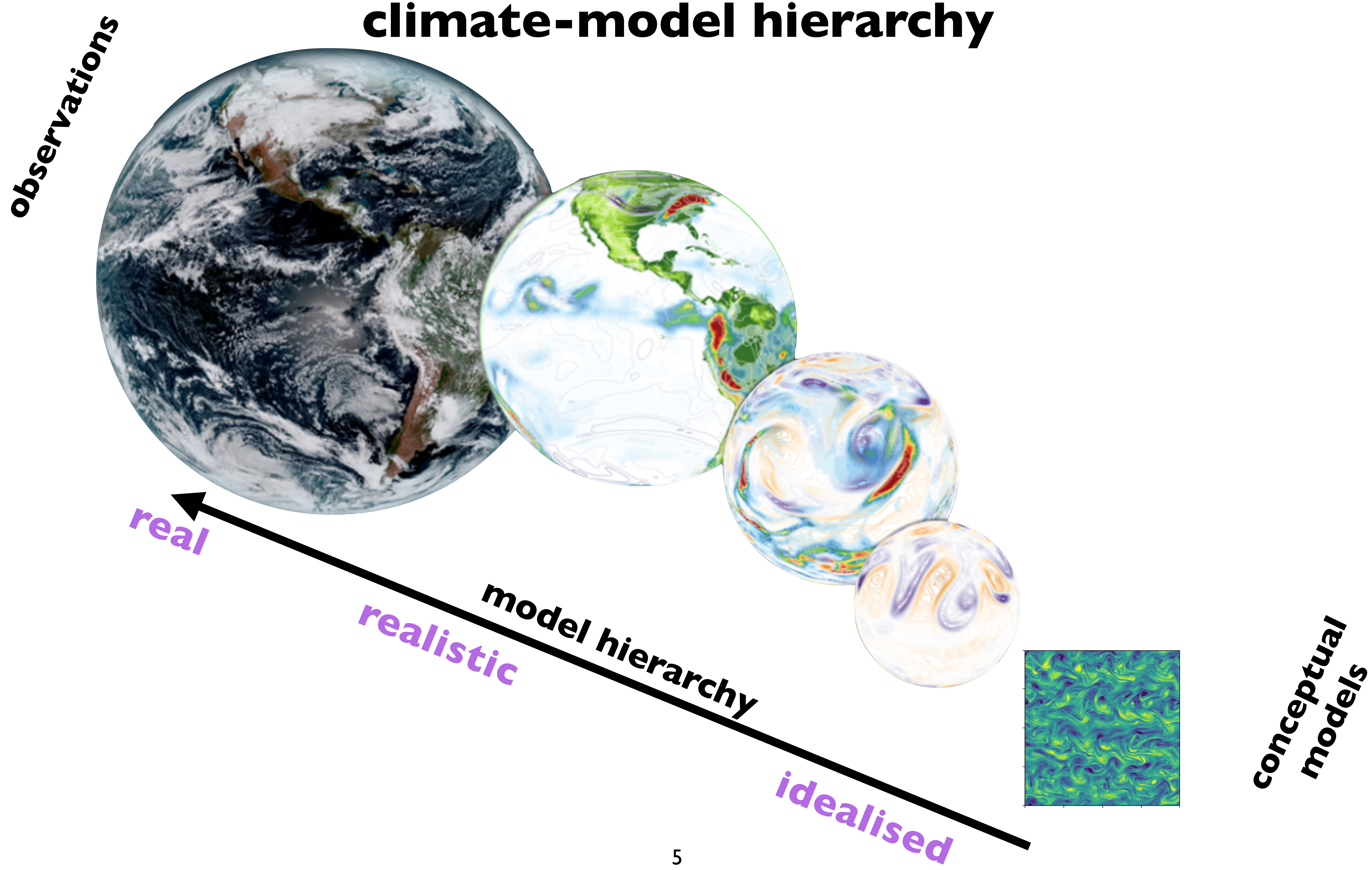
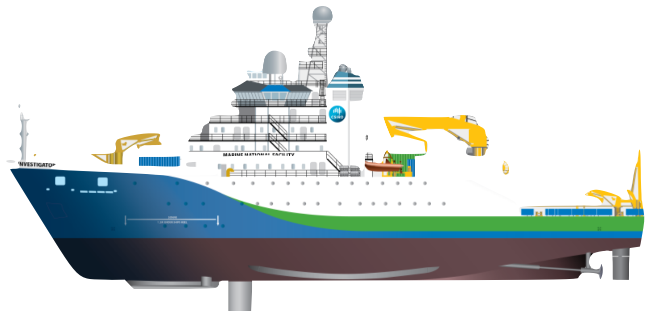
[Gogh, V., *MoMA*, 1889]

how do we deal with this issue?

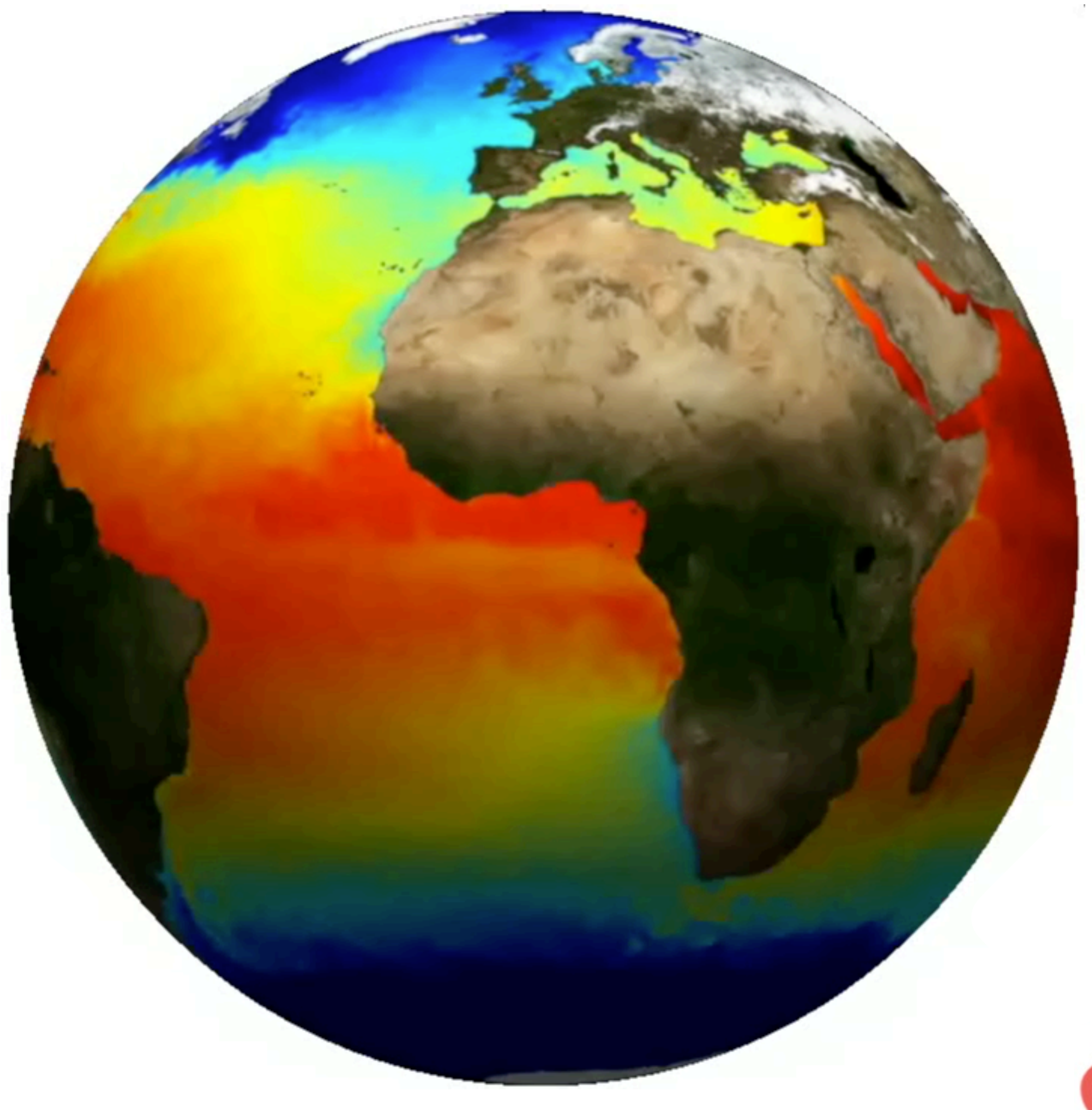
build intuition bottom-up via **climate-model hierarchy**



observe the real world
seek for patterns/underlying phenomena
discover unknown processes



Observations



[NASA's Goddard Space Flight Center]

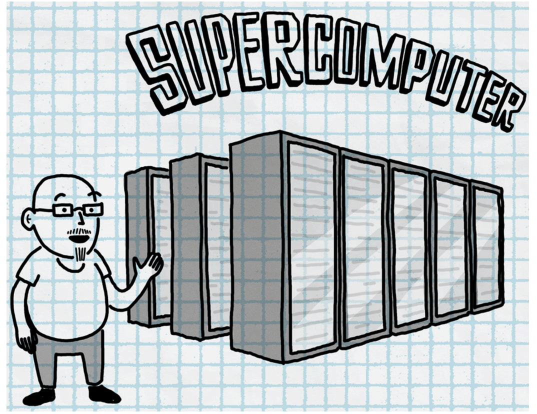
model and simulate "reality"
predict future
look for patterns/correlations

Simulation

```
import NavidsGCM

import ArgoData: Stratification
import WindReanalysis: WindStress


while GCMmodel.time < year.2100

  stepforward!(GCMmodel)
  updatevariables!(GCMstate)
  saveoutput!(GCMoutput)

end
```

netCDF

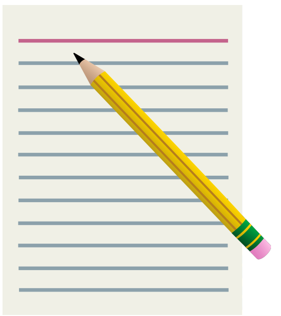
xarray



$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}\cdot\nabla\boldsymbol{u}\right) = \dots$$

$$\Gamma(x) = \int_0^\infty t^{x-1} e^t \, \mathrm{d}t$$

Theory



start from dynamical laws
(differential equations)
predict consequences
understand phenomena

reality

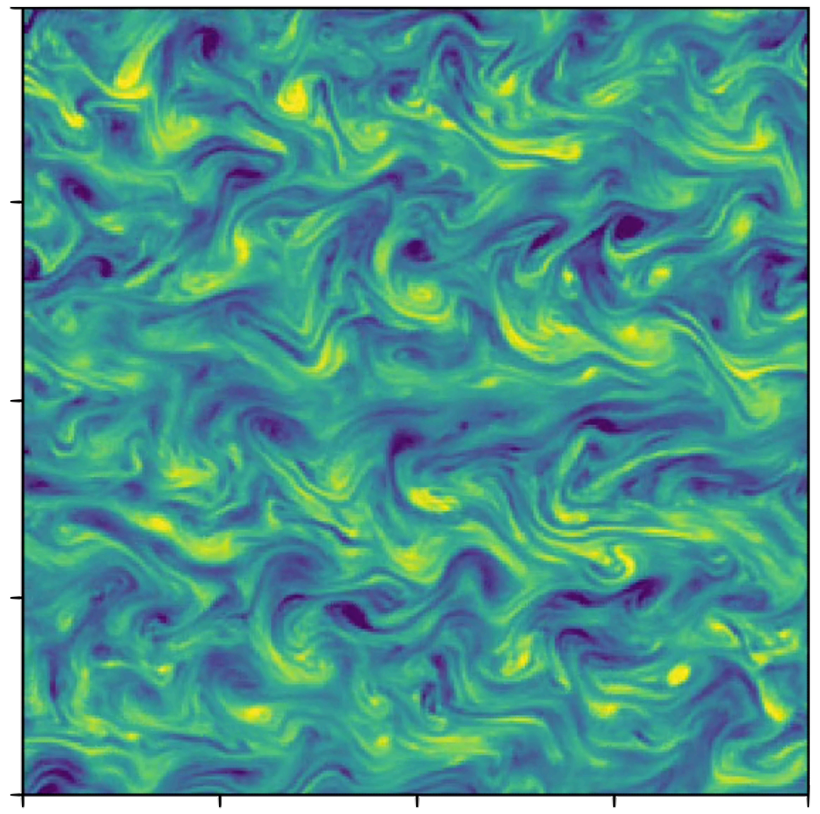
Goal: narrow the gap between theory and ~~simulation~~

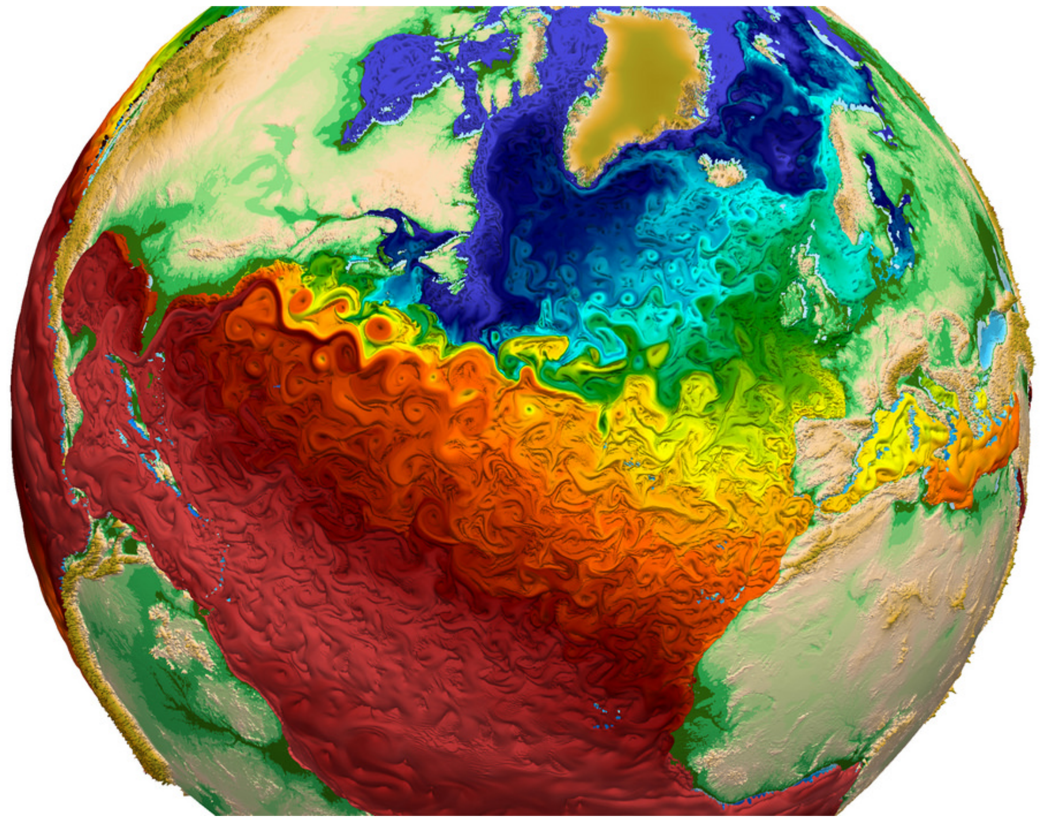
[Held 2005, BAMS]

inform climate model development
and interpretation

conceptual models

observations /
realistic models





easy to understand
and build physical intuition

closer to
reality

motivate conceptual model studies
from climate model output/observations

rest of the talk

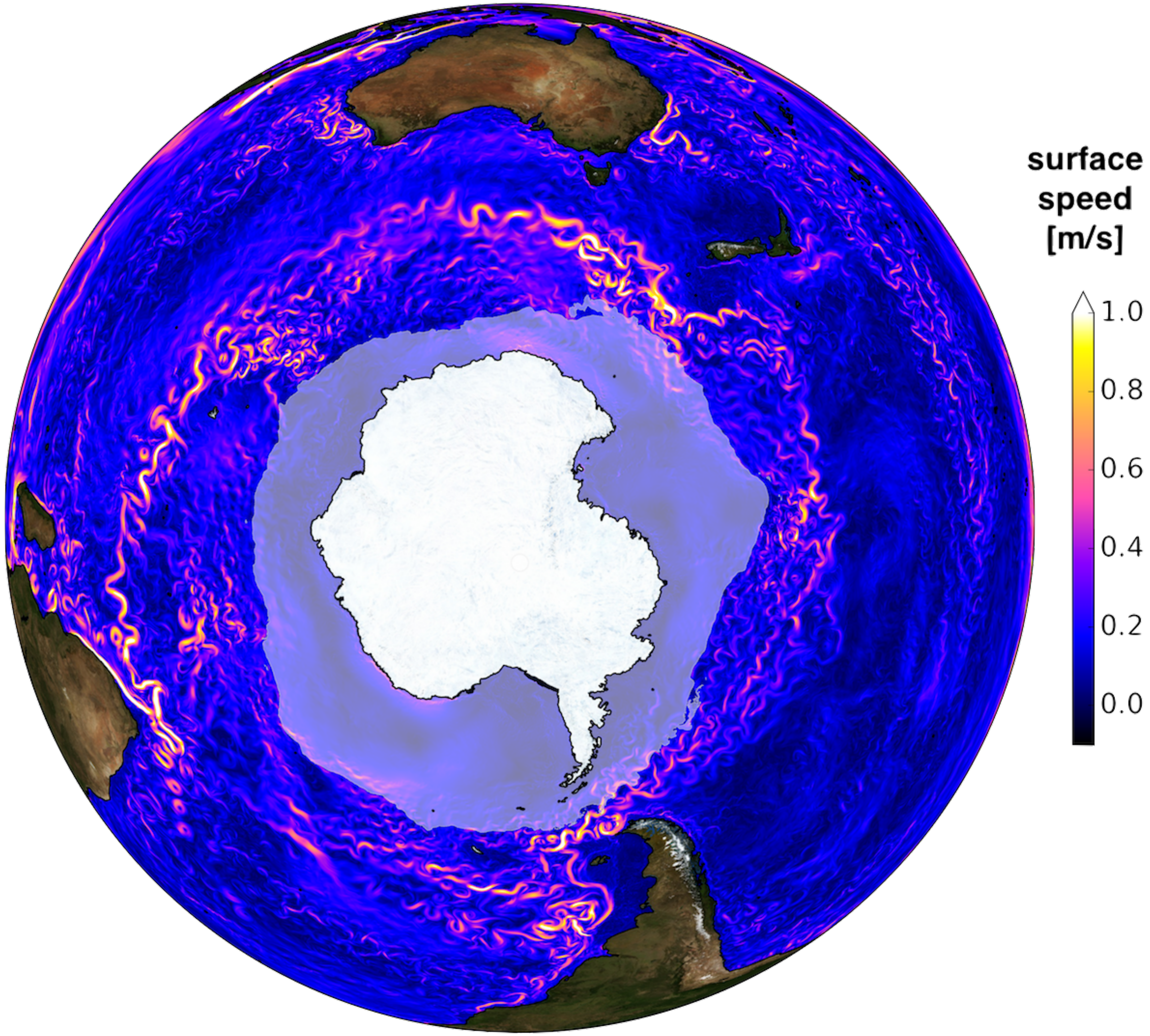
3 examples
that probe how eddies work
and how they affect the big picture (climate)

"Eddies act in mysterious ways."
[adage]

Example #1:

Southern Ocean's response to strengthening winds

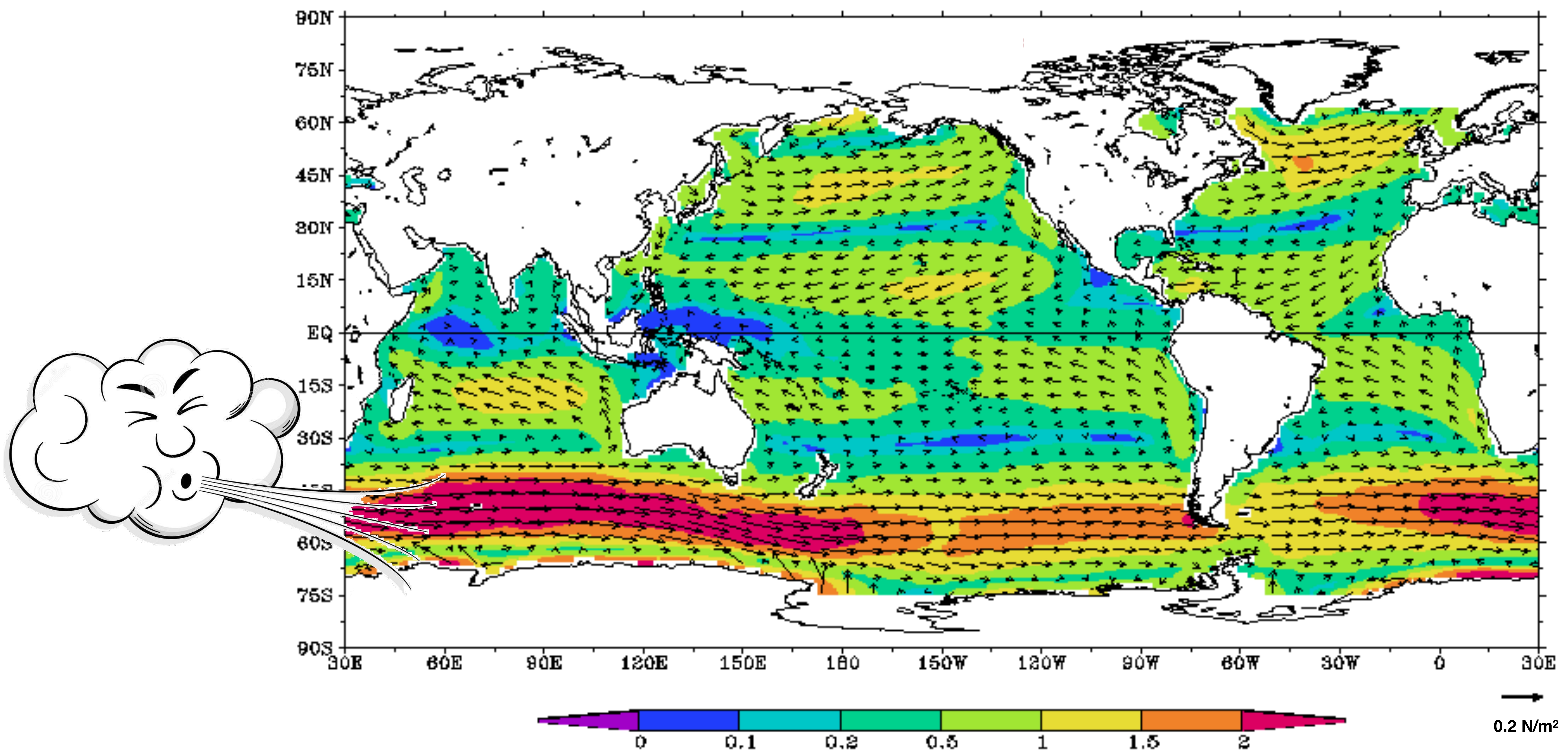
Antarctic Circumpolar Current (ACC)



[sea-surface speed ACCESS-OM2 sea-ice-ocean model at 0.1° resolution]

winds drive the Antarctic Circumpolar Current

GODAS Wind Stress, 1982-2004 Annual

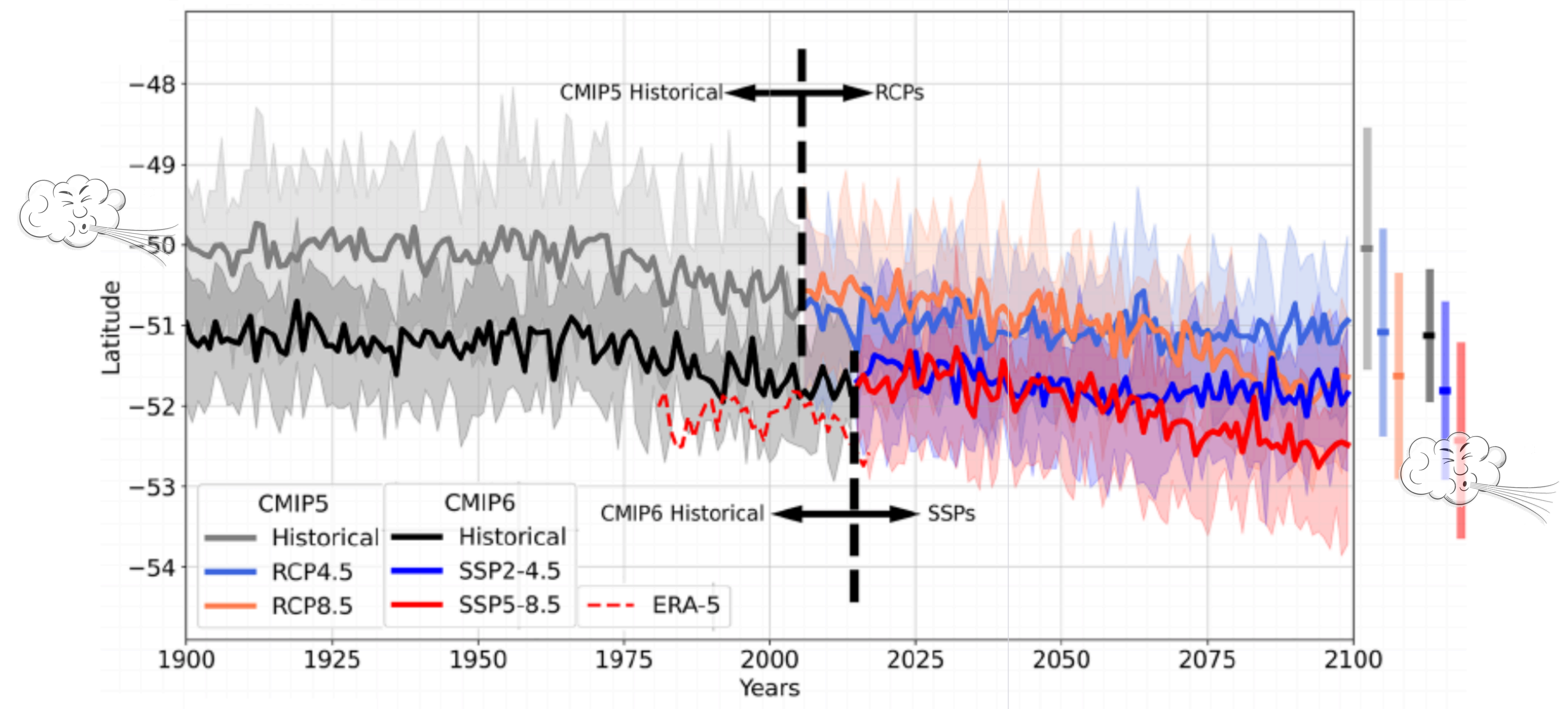


Climate Prediction Center

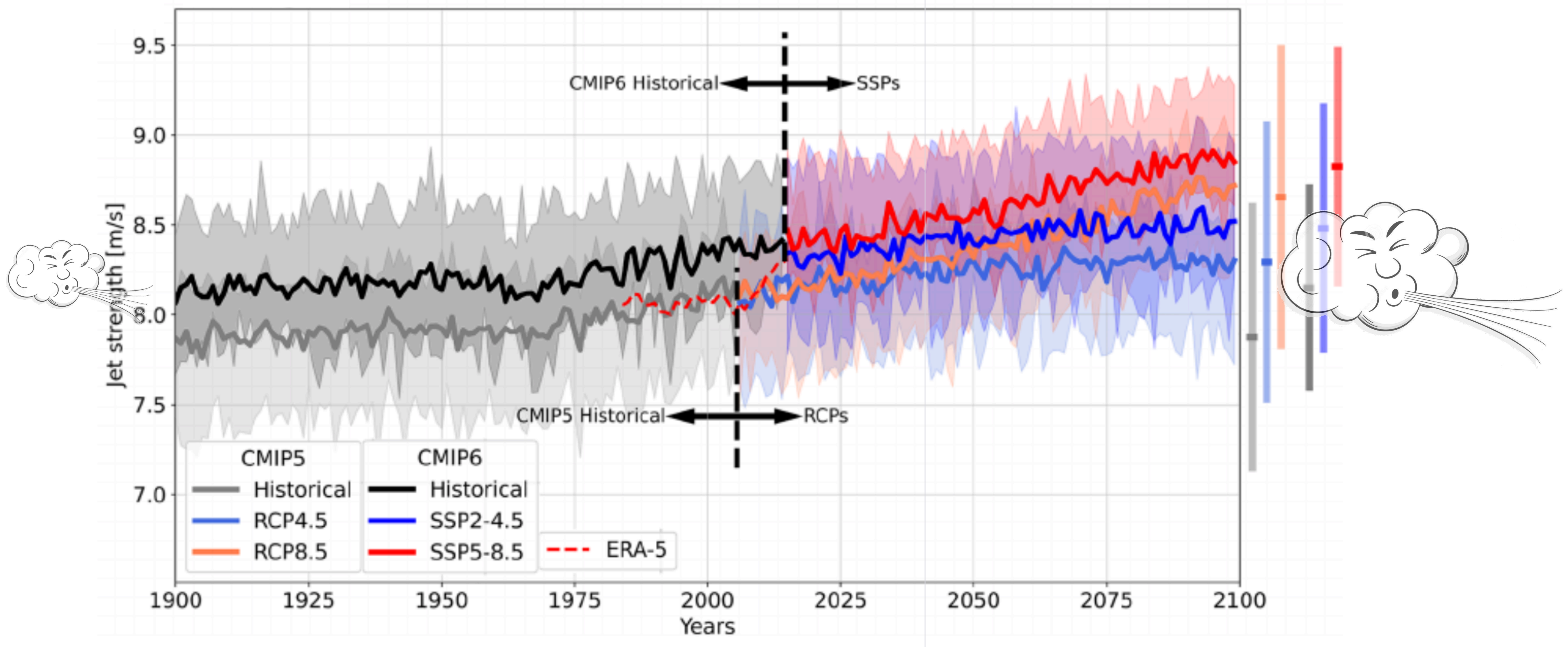
strong westerly winds blow over the Southern Ocean transferring momentum through wind stress at the surface

winds over Southern Ocean are getting stronger

winds peak location



winds peak strength



how will the
Antarctic Circumpolar Current
respond?

does doubling the winds imply
double ACC the transport?
not always — “eddy saturation”

[Goyal et al. GRL 2021]

what's *eddy saturation*?

the time-mean strength of a current
is ***relatively insensitive*** to wind stress strength

$\Longrightarrow$ extra work done by increasing wind goes into ***eddies***

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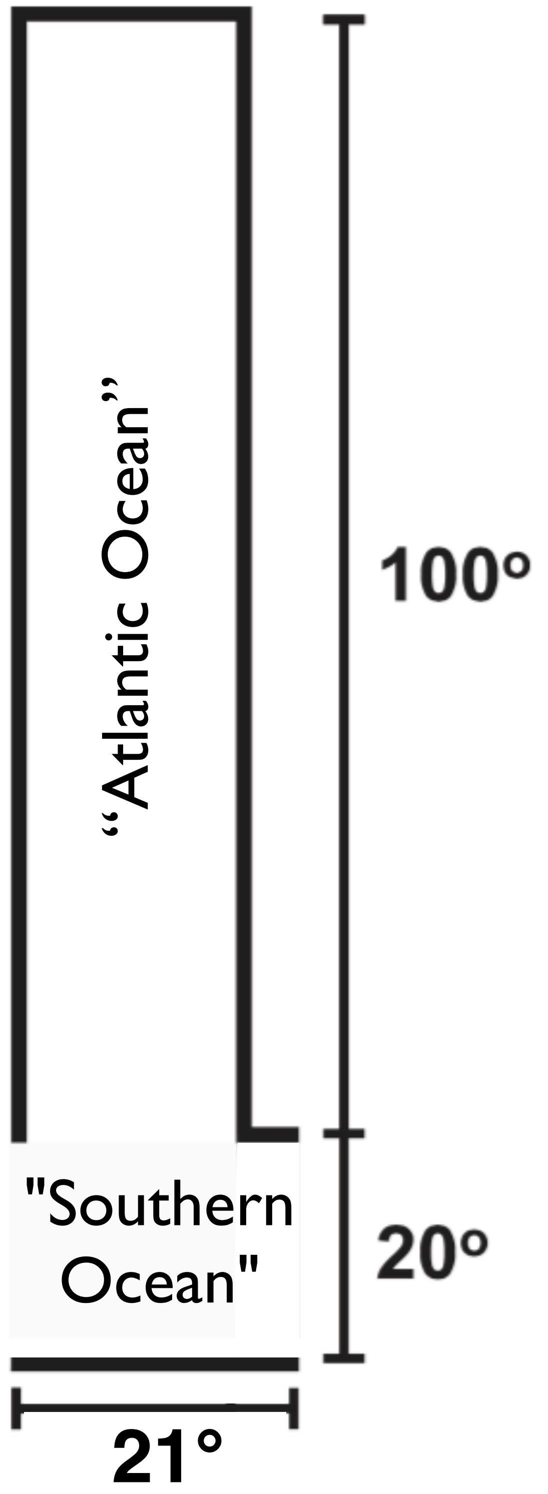
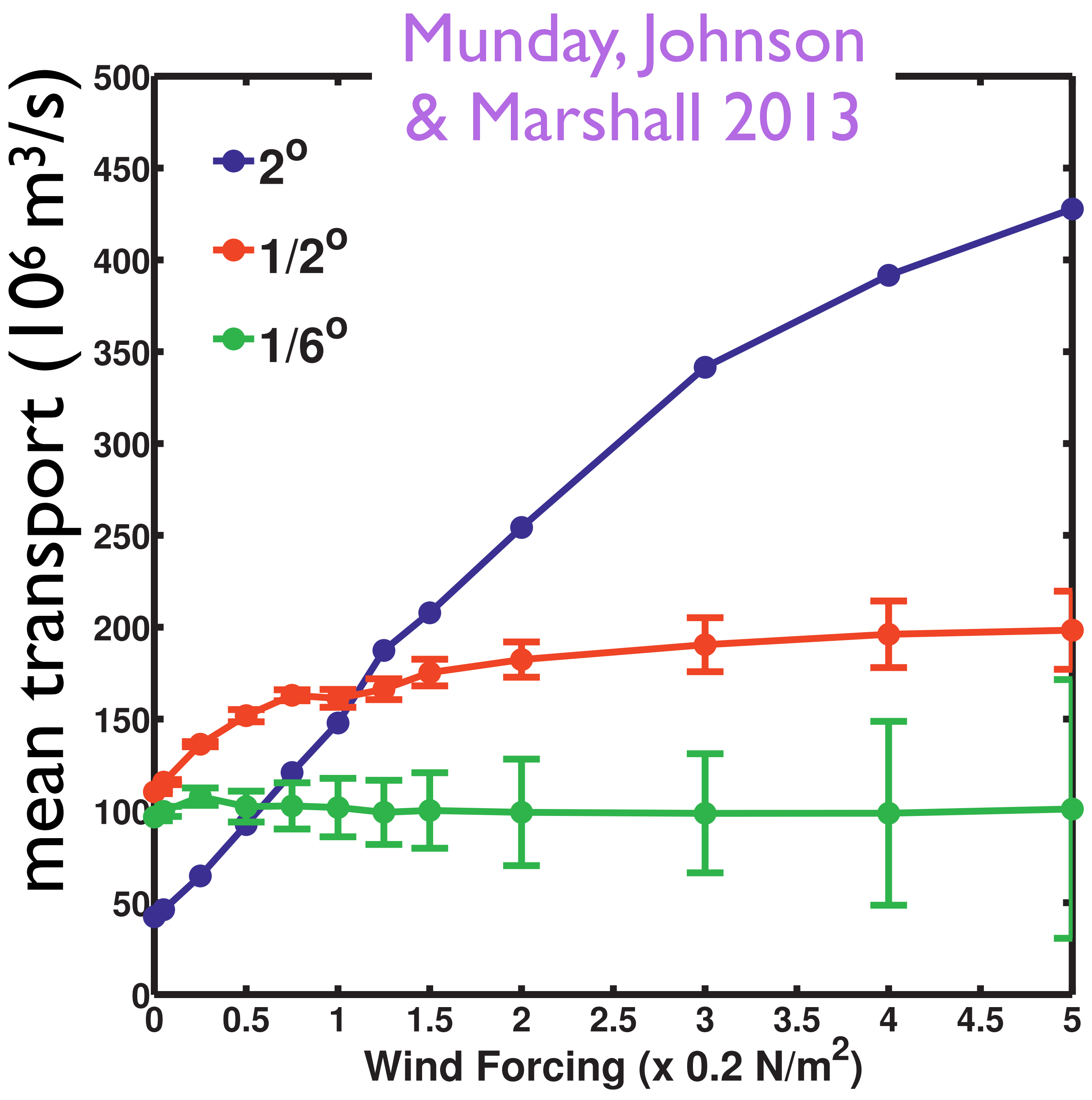




transport =
a "measure" of the strength of the current
(volume per unit time carried by current)

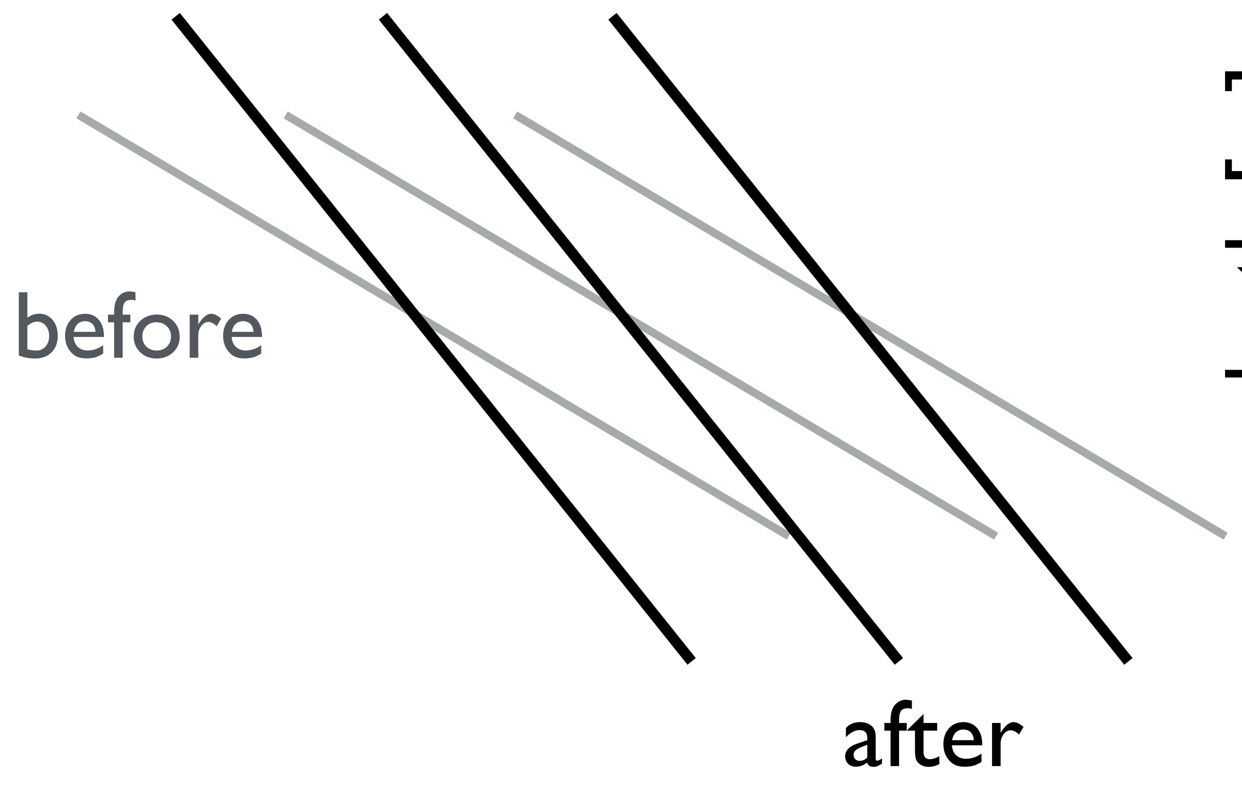
Eddy saturation is seen in
eddy-resolving "ocean models".
(some hints also in obs.)

higher resolution $\longrightarrow$ eddy saturation "emerges"

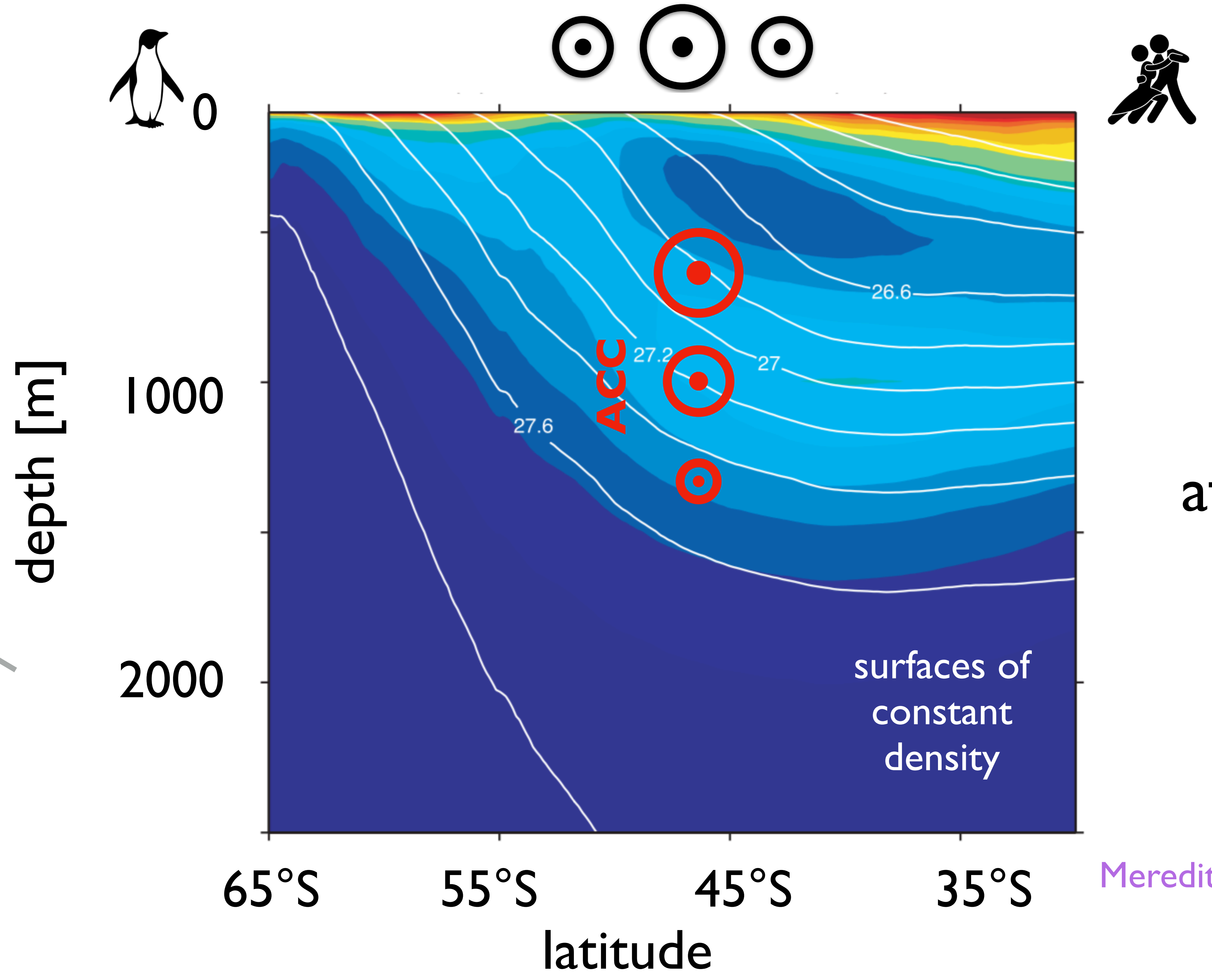
[Other examples: Hallberg & Gnanadesikan 2001, Tansley & Marshall 2001, Hallberg & Gnanadesikan 2006, Hogg et al. 2008, Nadeau & Straub 2009, 2012, Farneti et al. 2010, Meredith et al. 2012, Morrison & Hogg 2013, Abernathey & Cessi 2014, Farneti et al. 2015, Nadeau & Ferrari 2015, Marshall et al. 2017.]

the textbook explanation: how eddies lead to eddy saturation?

wind increase slopes the isopycnals

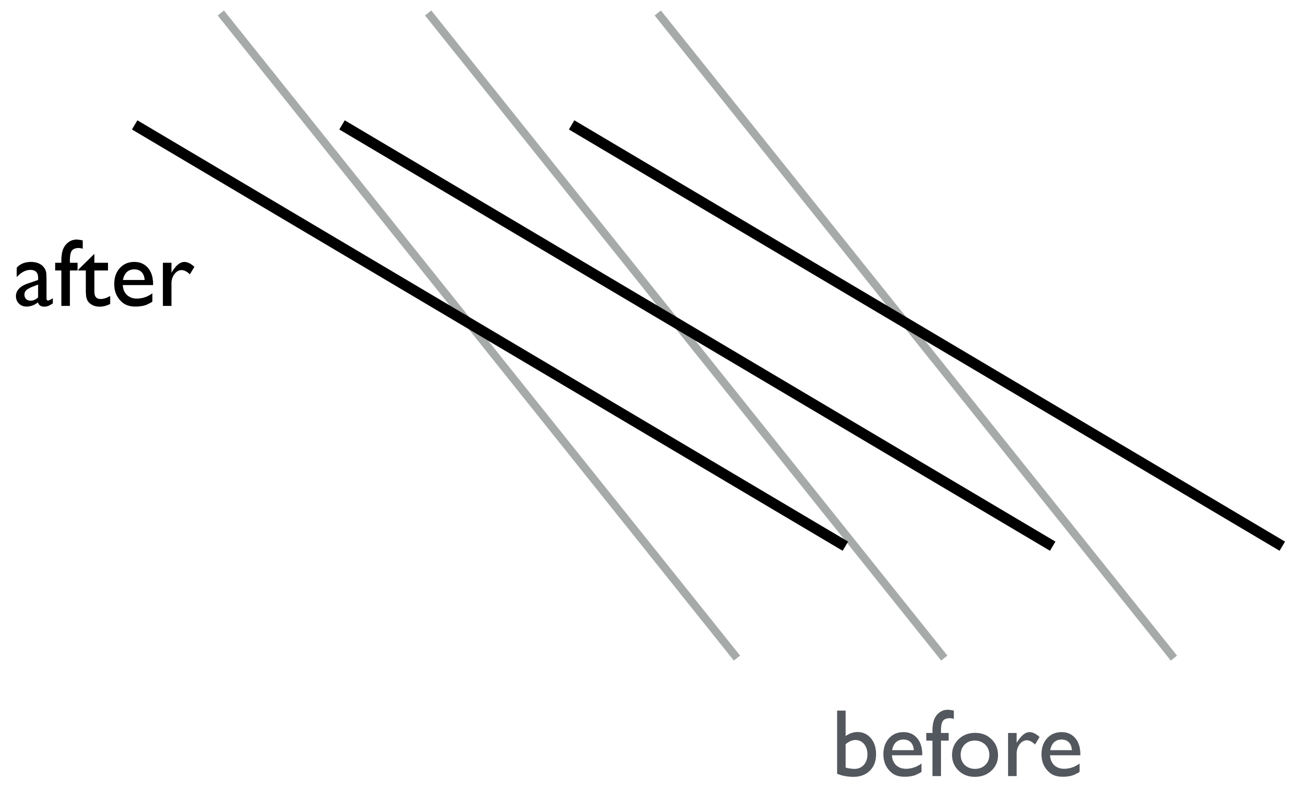


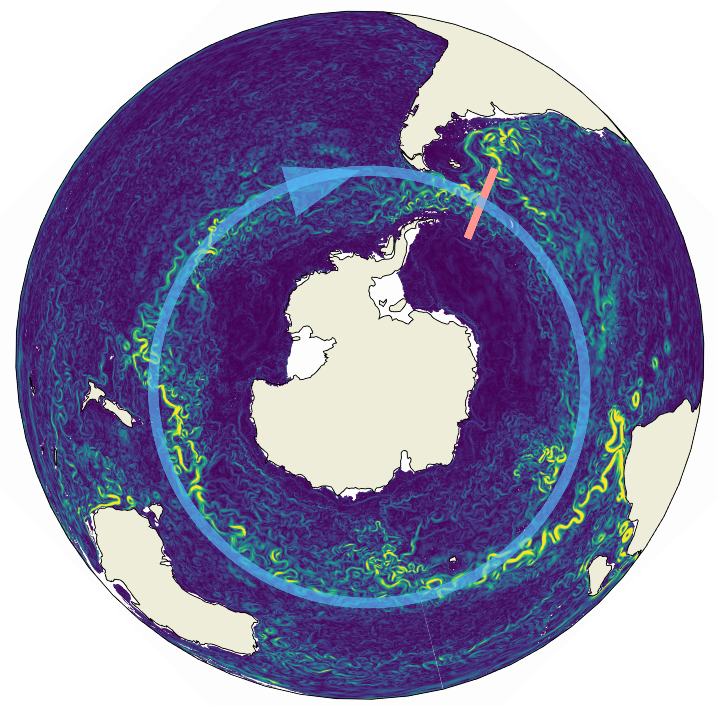
westerly winds



Meredith et al. 2012

baroclinic eddies restratify isopycnals





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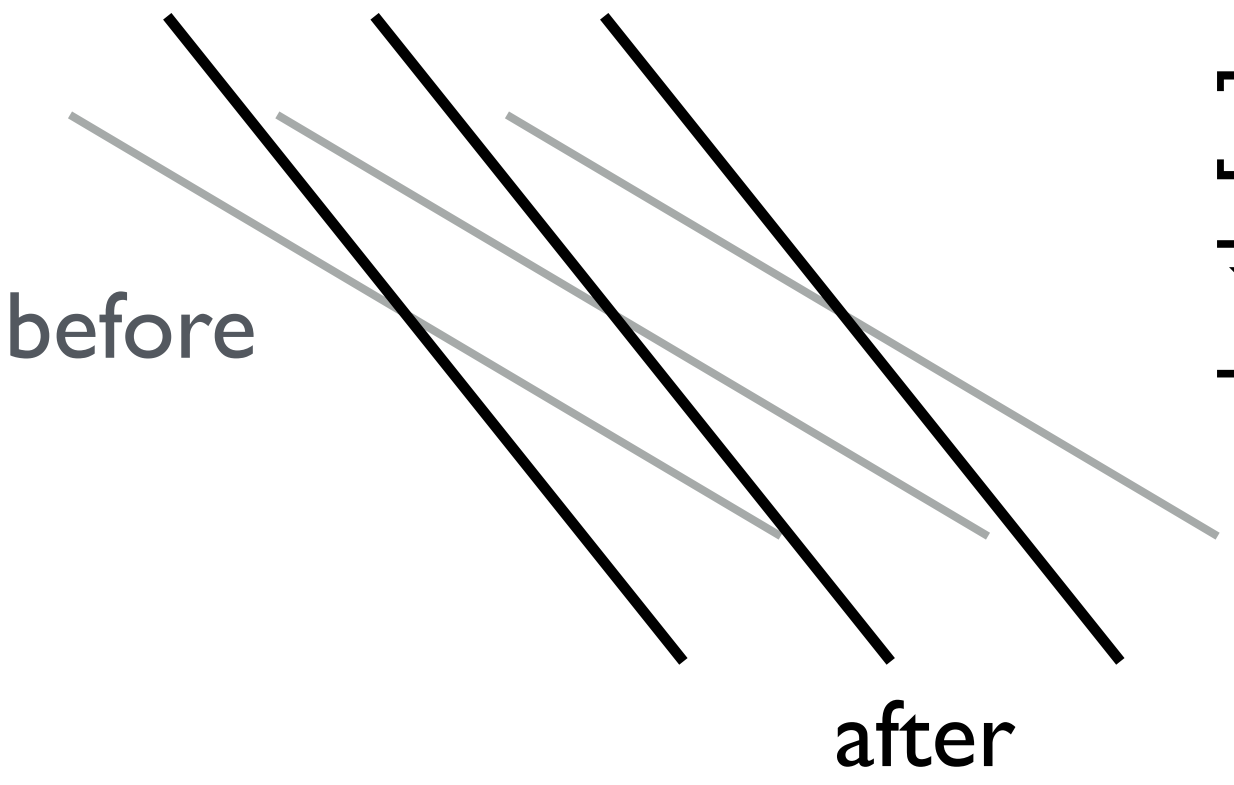
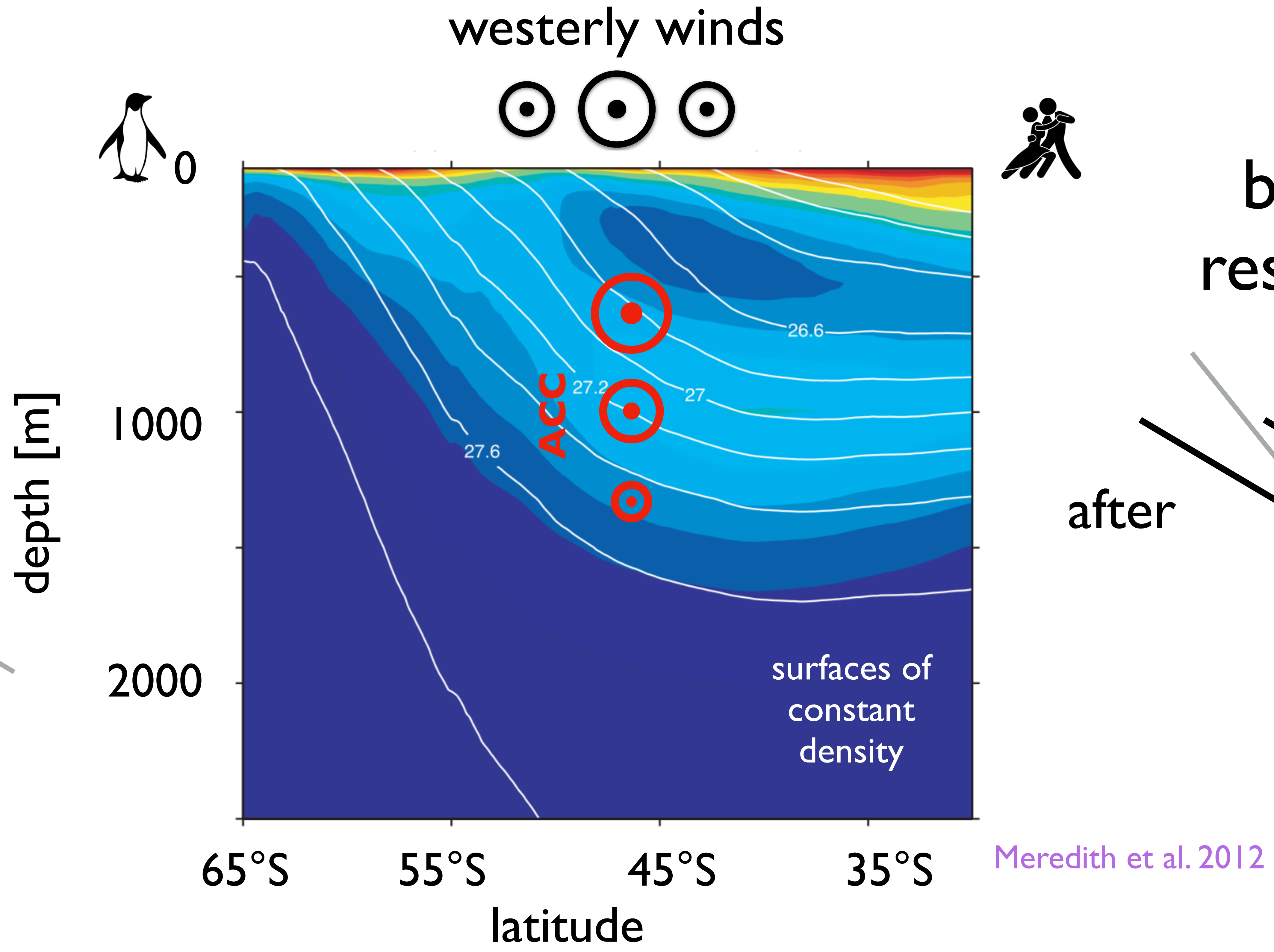
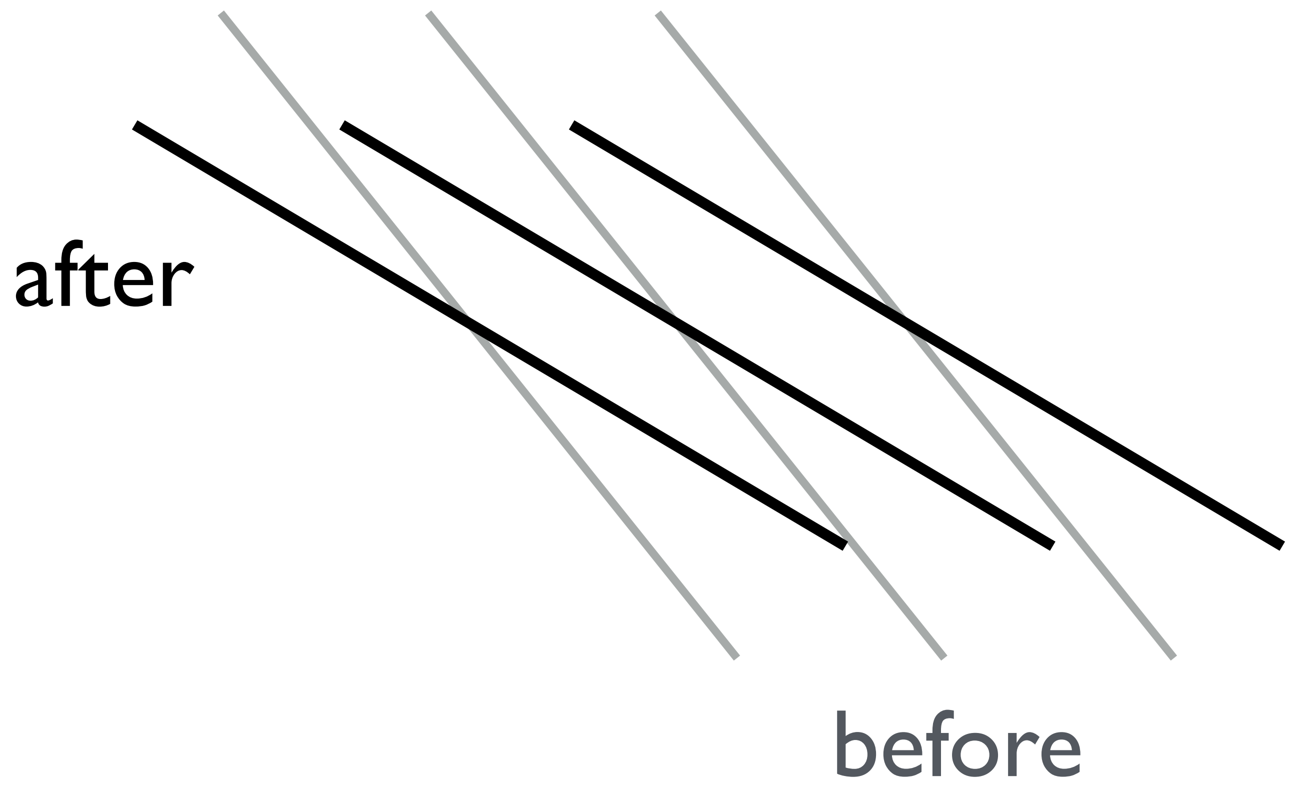




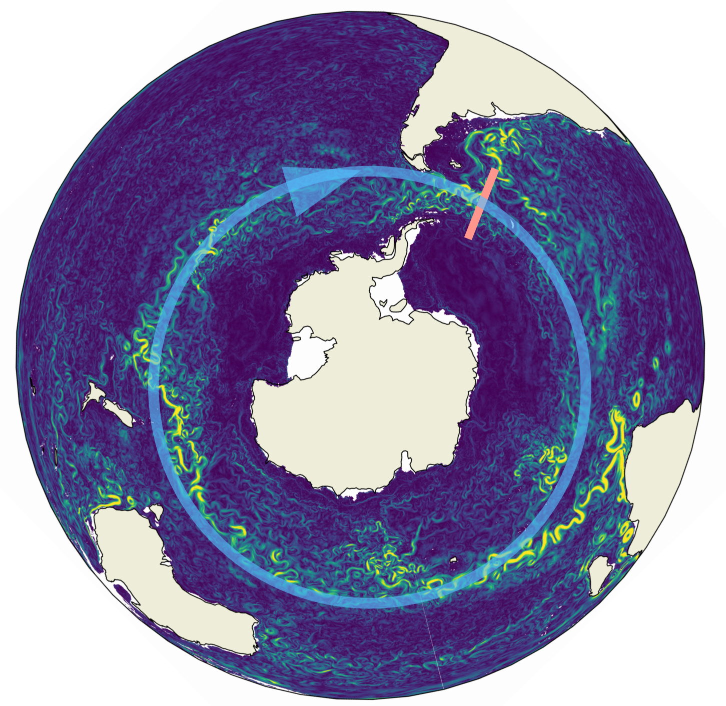
baroclinic eddies
restratify isopycnals



Explanation crucially ***relies on density varying with depth***.

[in technical terms: "baroclinic"]

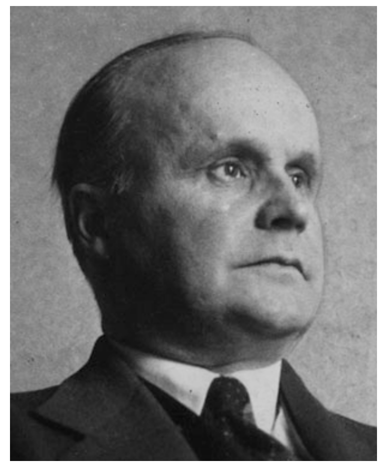
Role of bathymetry?



role of bathymetry I

Momentum balance in the Southern Ocean is
"*applied at the bottom [...] where ridges lie.*"

W.H. Munk

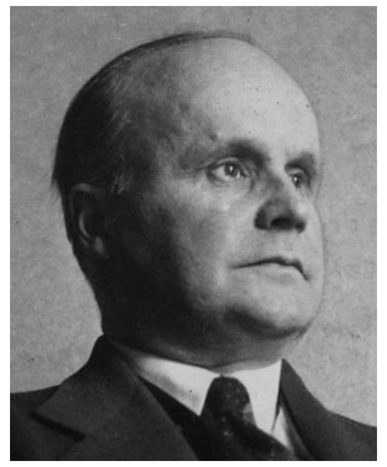


E. Palmén

Munk & Palmén (1951)

topographic form stress

role of bathymetry I

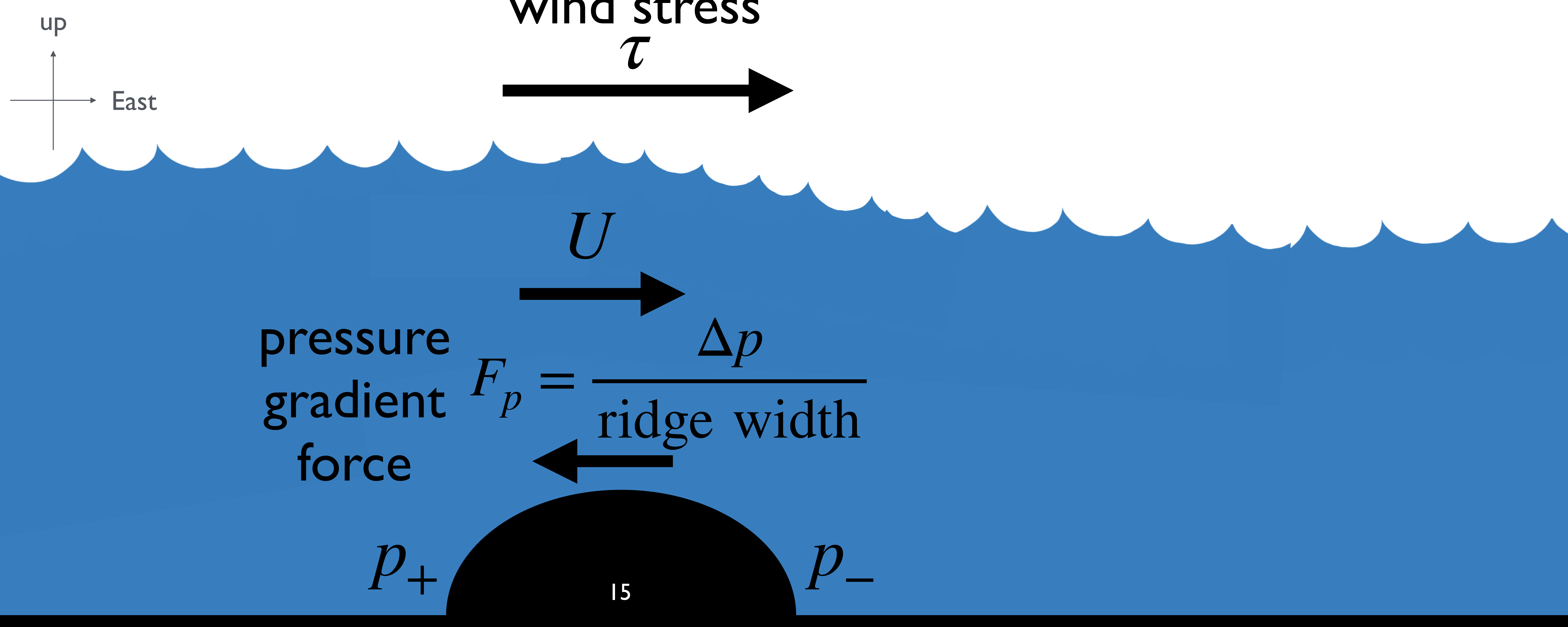


Munk & Palmén (1951)

Momentum balance in the Southern Ocean is "*applied at the bottom [...] where ridges lie.*"

topographic form stress

wind stress

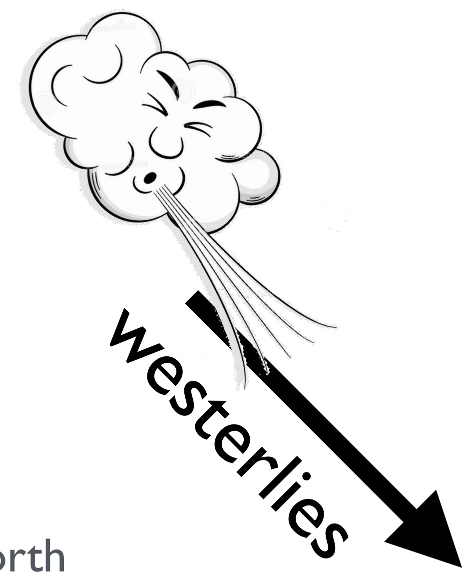


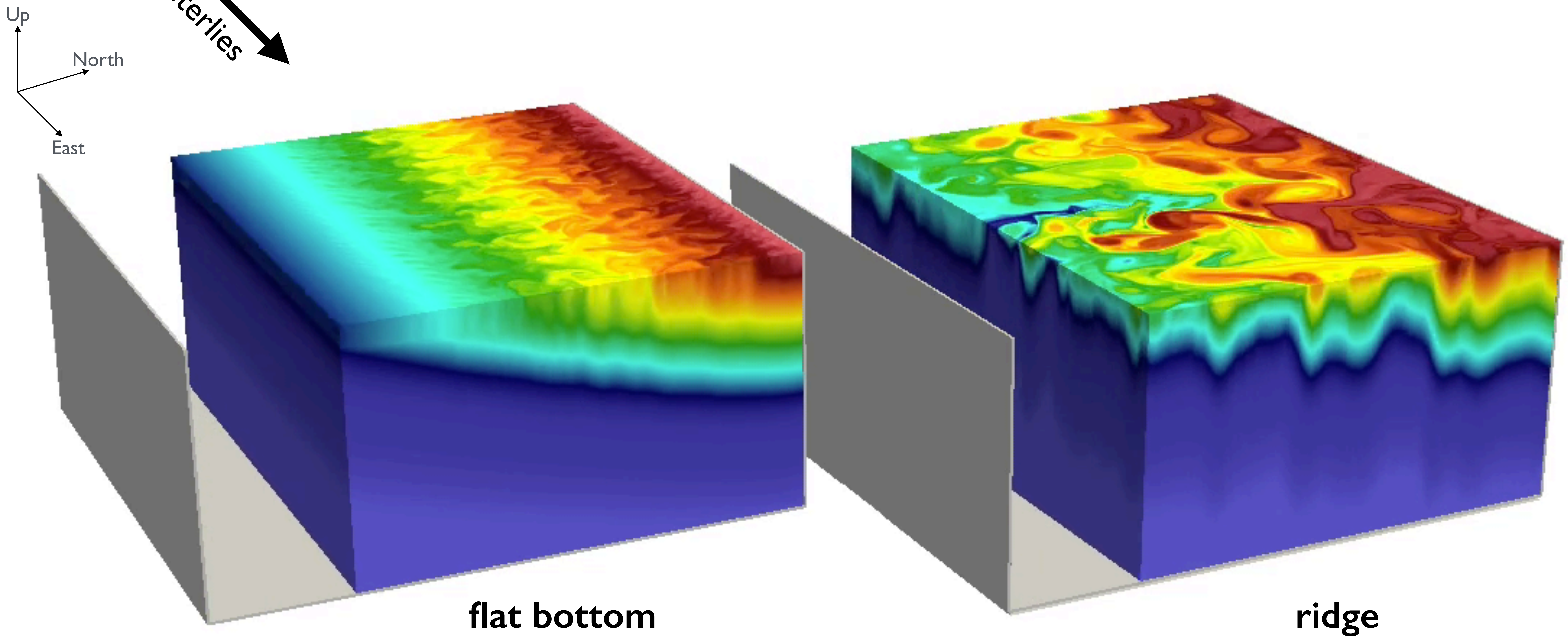
$$F_p = \frac{\Delta p}{\text{ridge width}}$$

role of bathymetry II

Bathymetry enhances *in situ*
eddy growth via
“baroclinic instability”

Abernathey & Cessi (2014)
[See also Youngs et al. (2017)]





flat bottom

ridge

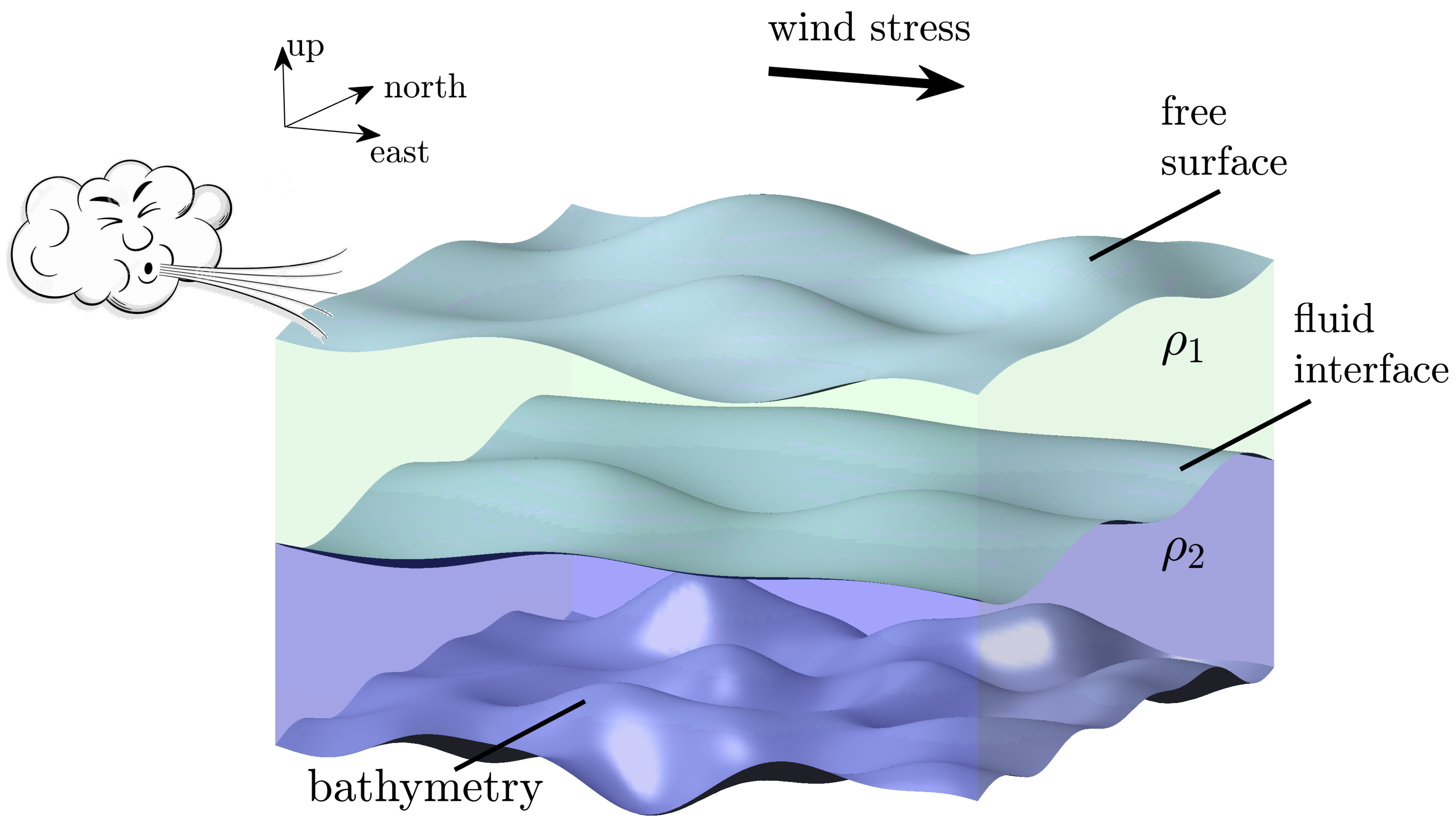
http://vimeo.com/55486114

equilibration ~100 yr
isosurfaces of potential temperature
colours from 0 ^{o}C to 8 ^{o}C

what's the plan

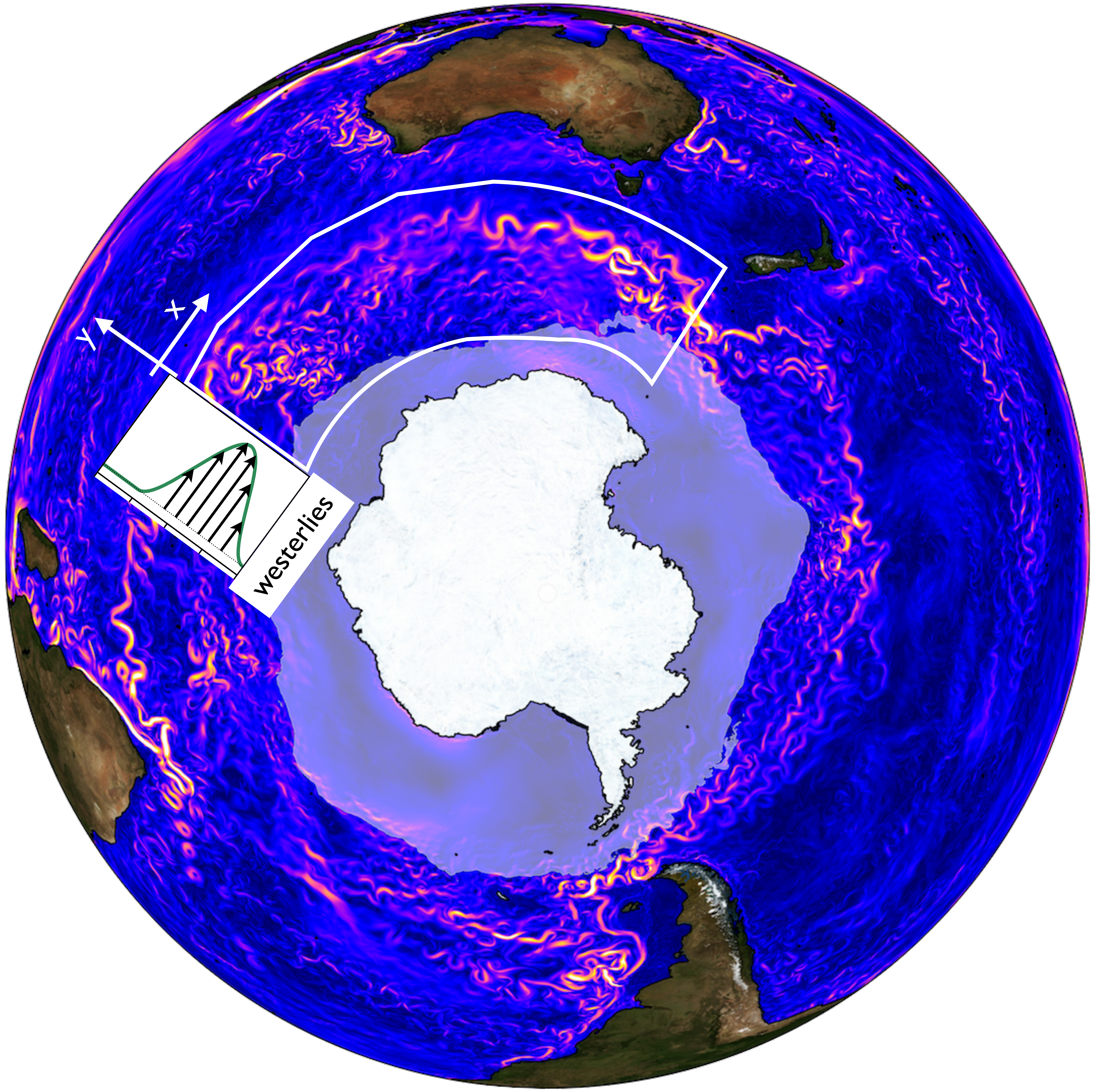
Assess the role of
barotropic (depth-independent) versus **baroclinic** (depth-varying)
dynamics for establishing "eddy saturated" ocean states.

A model with varying number of fluid layers



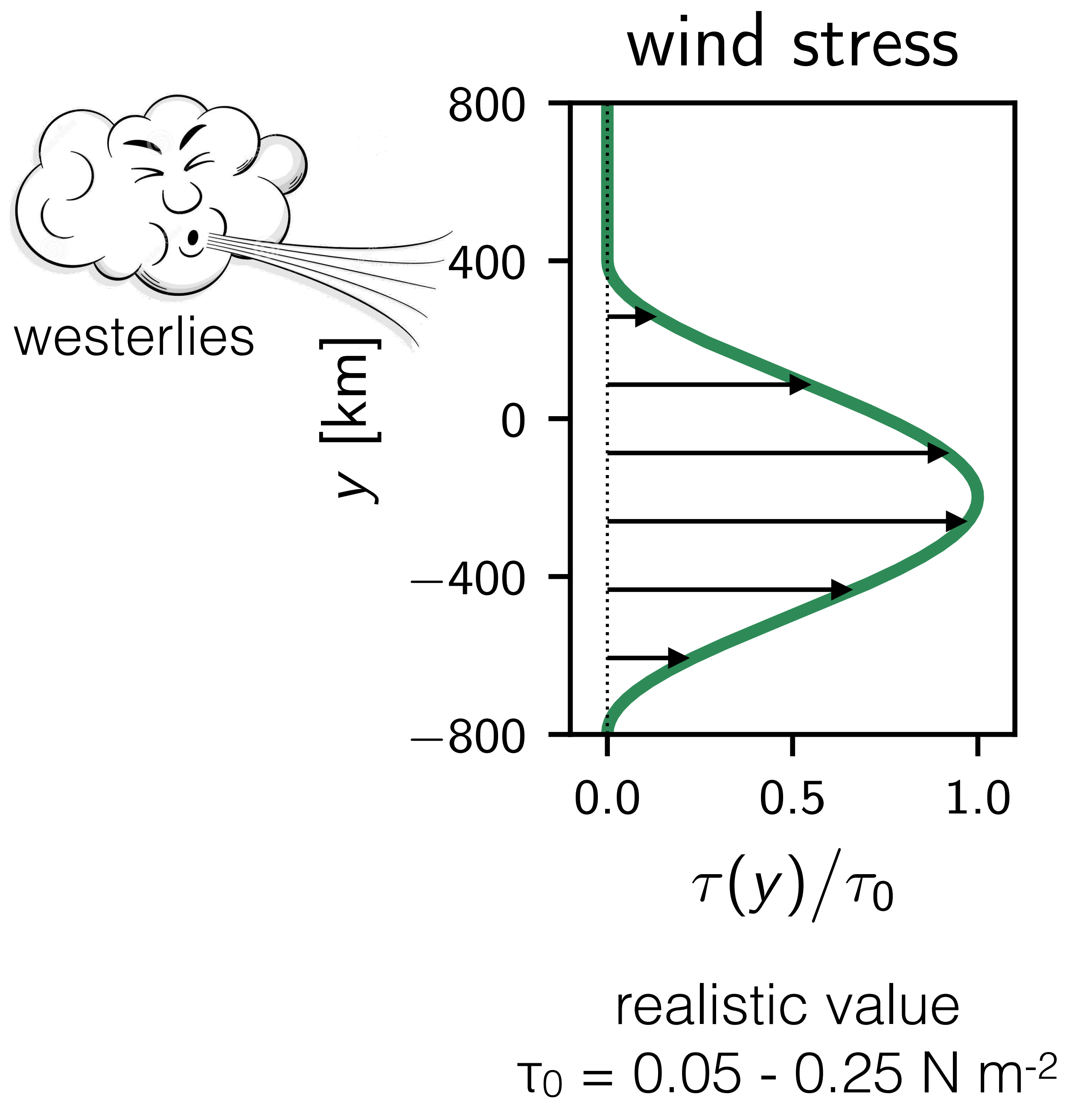
the "spherical-cow"-version of the Southern Ocean

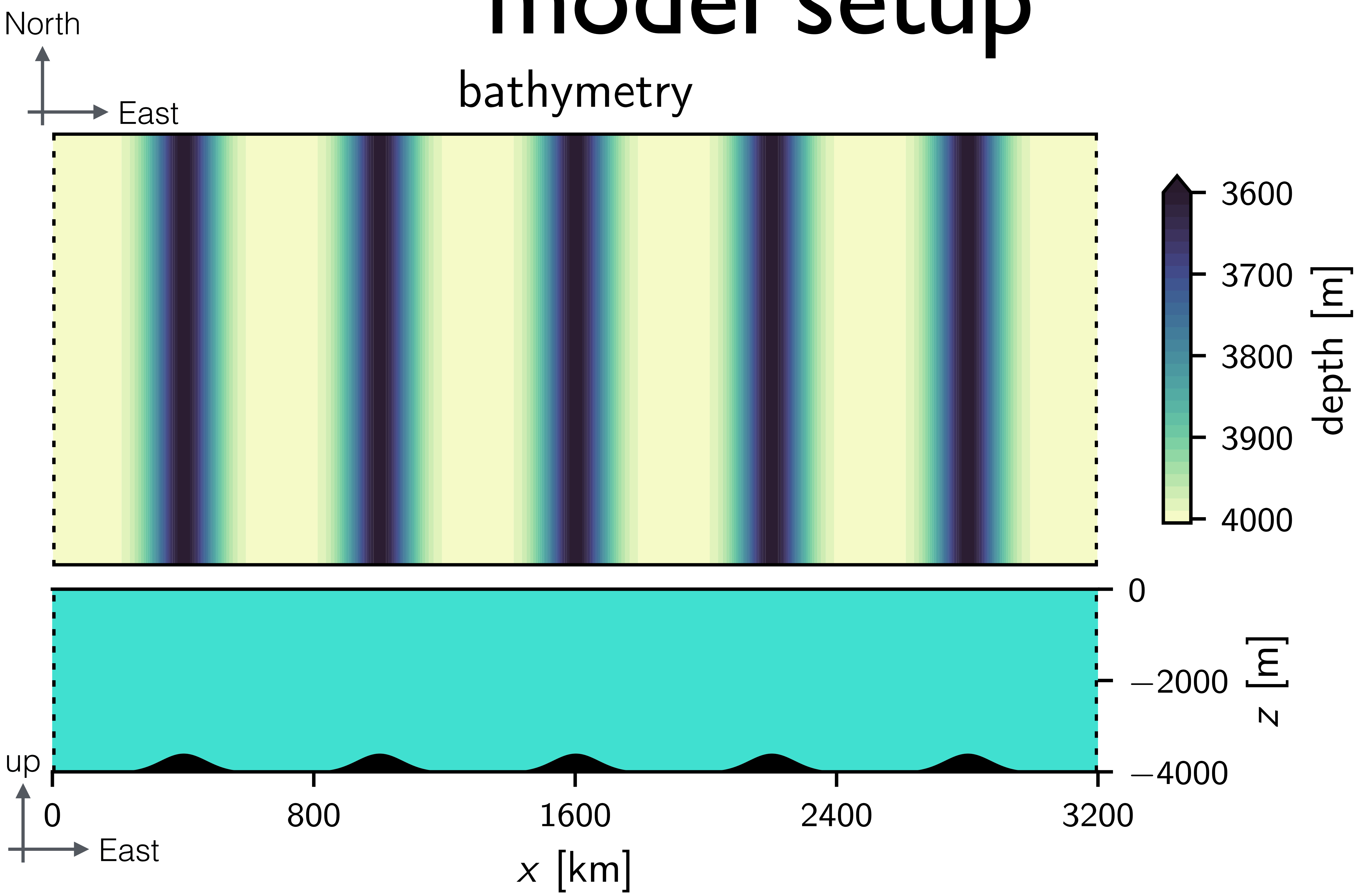
a sector of the
Antarctic Circumpolar Current
(ACC)



[sea-surface speed ACCESS-OM2
sea-ice-ocean model at 0.1° resolution]

model setup

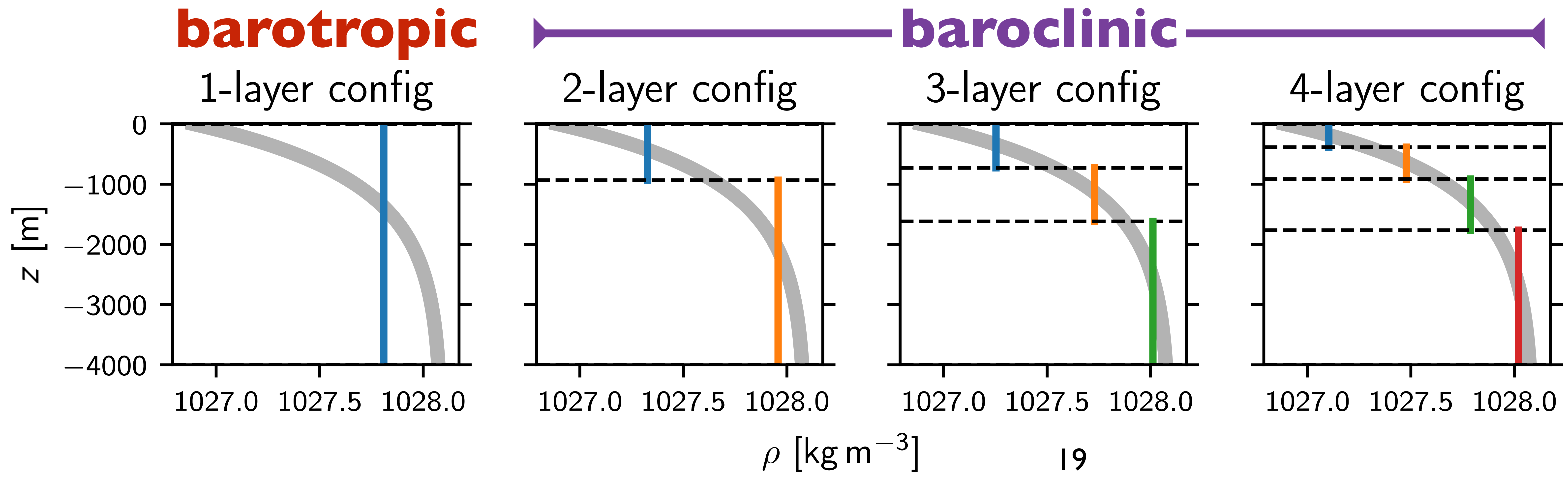




GFDL's MOM6 model
primitive equations
isopycnal coordinates
Boussinesq approximation

Southern Ocean
parameter values

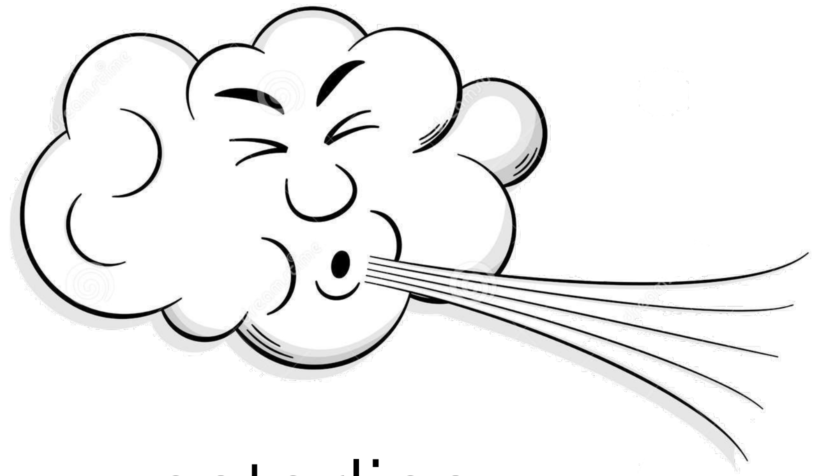
no diapycnal motions
no buoyancy forcing



layered approximations

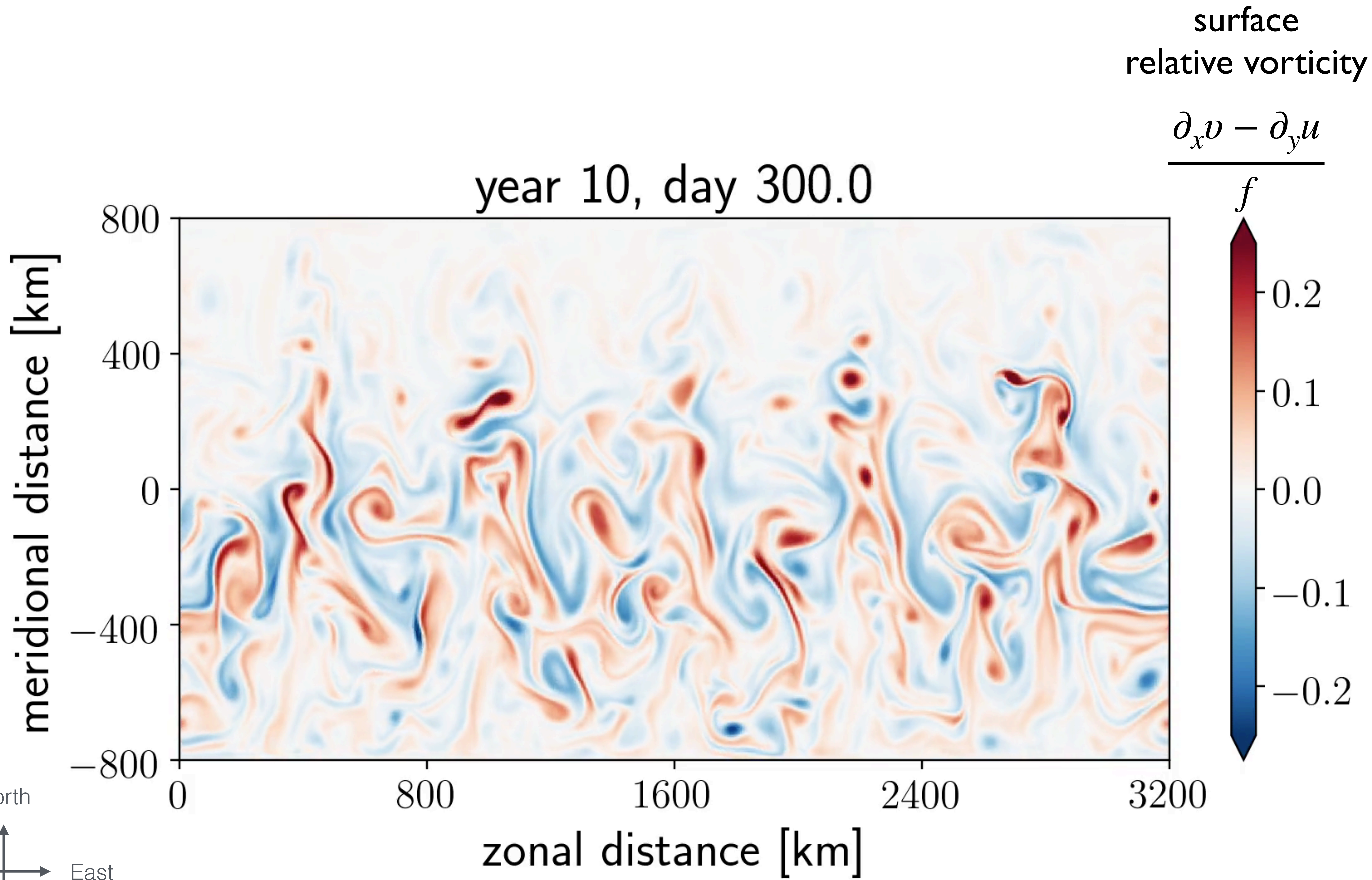
[C & Hogg *GRL* 2019]

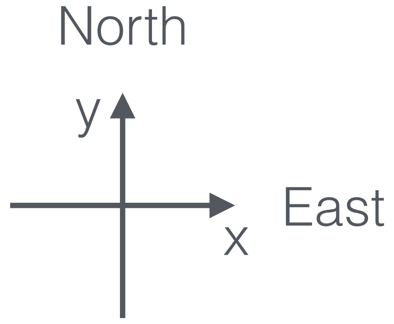
the "spherical-cow"-version of the ACC

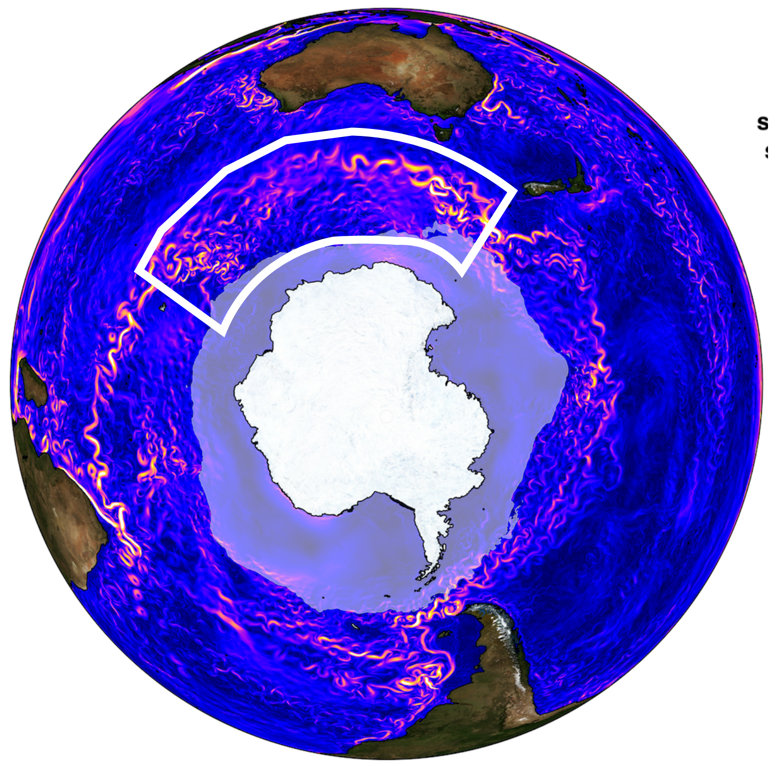


westerlies

τ_0=0.2 N/m^2





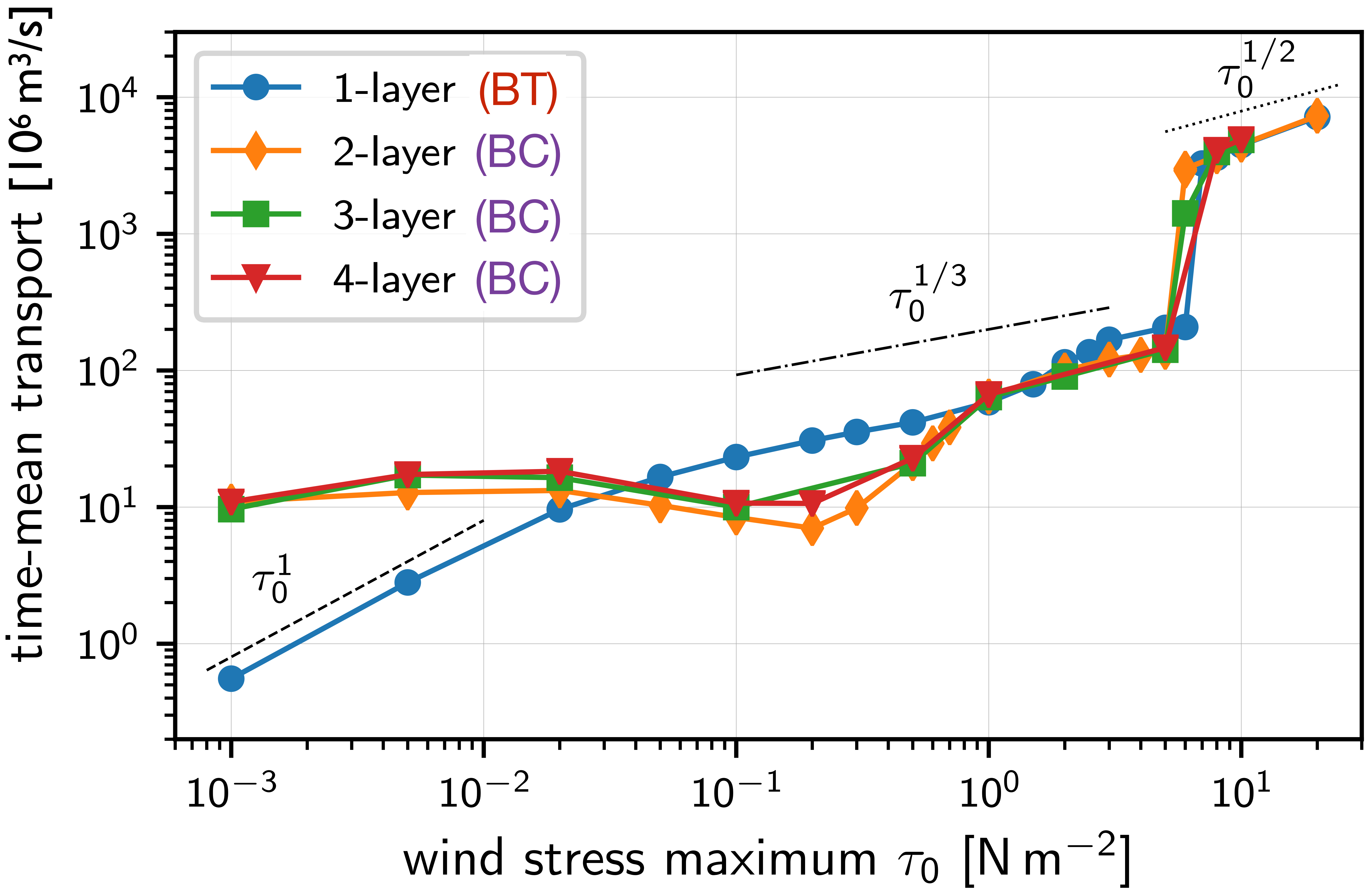


note: standing meander & eddies

[C & Hogg *GRL* 2019]

vary the wind stress amplitude τ_0
and see how the time-mean zonal transport changes

mean ACC transport Vs wind stress

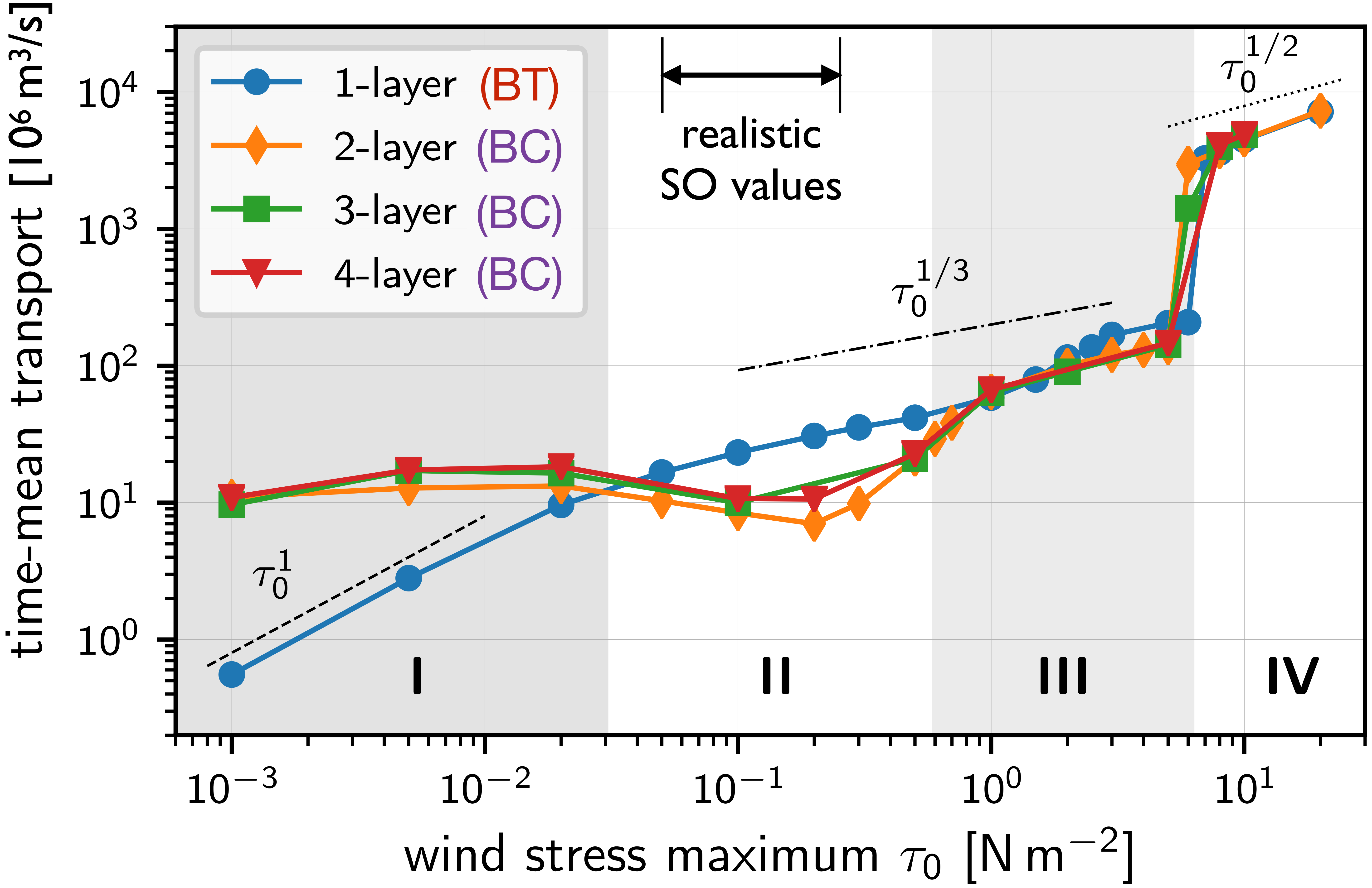


>3-layer configurations are the same as 2-layers

(as fas as the mean zonal transport is concerned)

[C & Hogg *GRL* 2019]

mean ACC transport Vs wind stress



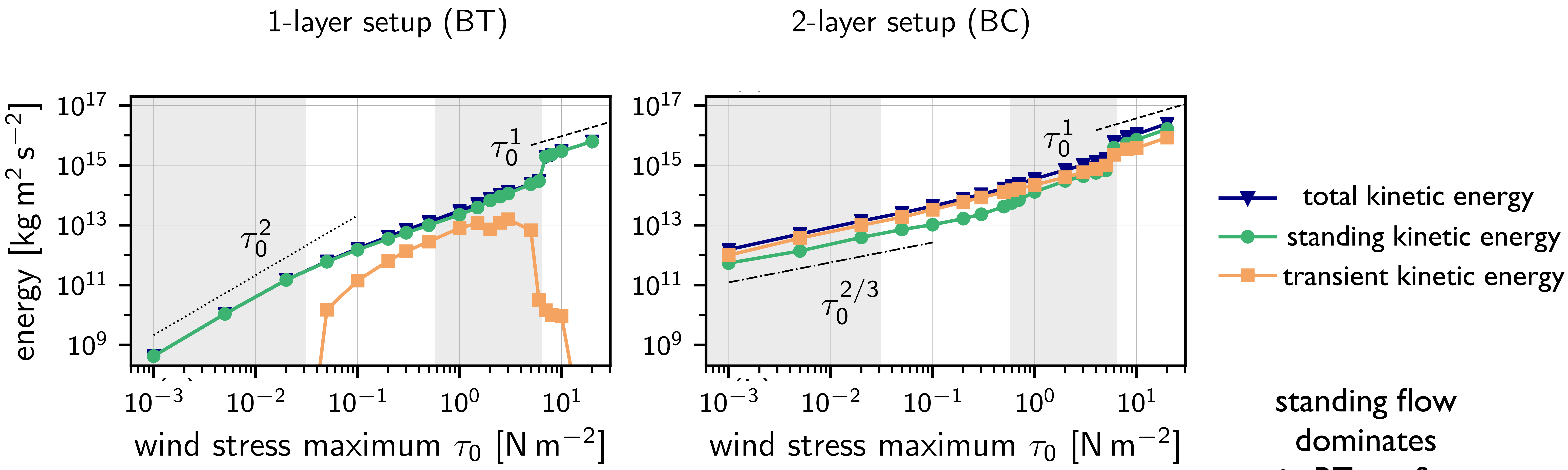
four distinct flow regimes

Barotropic shows saturation II & III

Baroclinic shows saturation I, II & III

[C & Hogg *GRL* 2019]

standing–transient kinetic energy decomposition



BT config
has transients
only in II & III

standing flow
dominates
in BT config;

transient flow
dominates in BC

Barotropic shows saturation II & III
Baroclinic shows saturation I, II & III

[C & Hogg *GRL* 2019]

depth-integrated time-mean zonal momentum balance

wind stress (WS) $=$ topographic form stress (TFS) $+$ bottom drag (BD)

$$\propto p_{\text{bot}} \frac{\partial h_{\text{bot}}}{\partial x}$$

[C & Hogg *GRL* 2019]

depth-integrated time-mean zonal momentum balance

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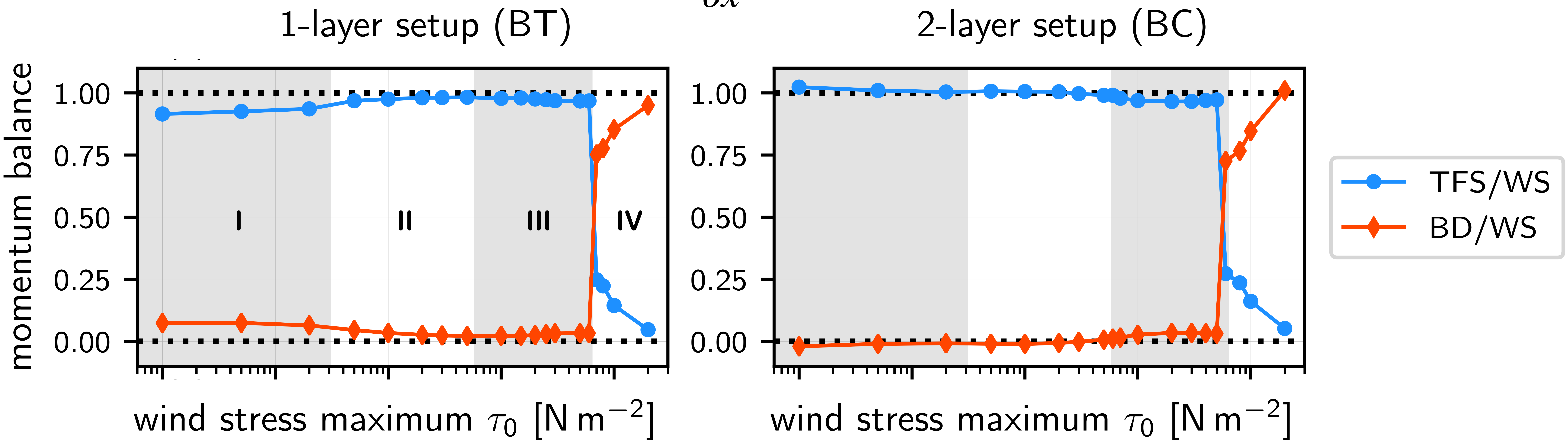
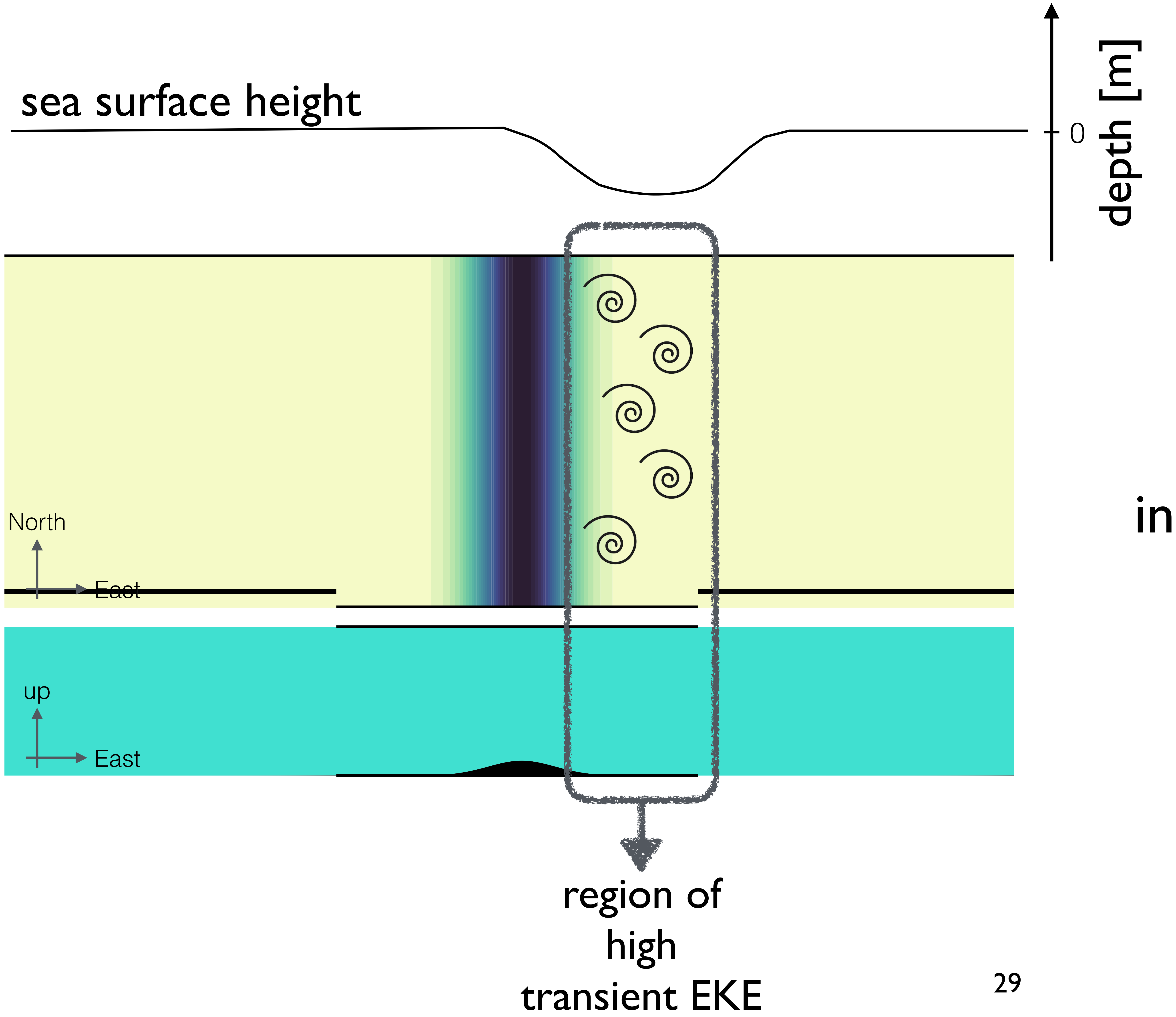


Almost *all* momentum is balanced by topographic form stress

(except when flow transitions to "upper branch")

[C & Hogg *GRL* 2019]

how time-varying eddies lead to time-mean topographic form stress?



transient eddies appear downstream of topography

↓

have an asymmetric signature on SSH

↓

induce asymmetric time-mean pressure upstream & downstream the ridge

↓

topographic form stress

[C & Hogg *GRL* 2019]

Should I take anything home?

proposal:

eddy saturation occurs due to
transient eddies shaping the standing flow
to produce topographic form stress that balances the wind stress
(*regardless* of the process from which transient eddies originate)

"Spherical-cow" conceptual setups help us build understanding

[C & Hogg *GRL* 2019]

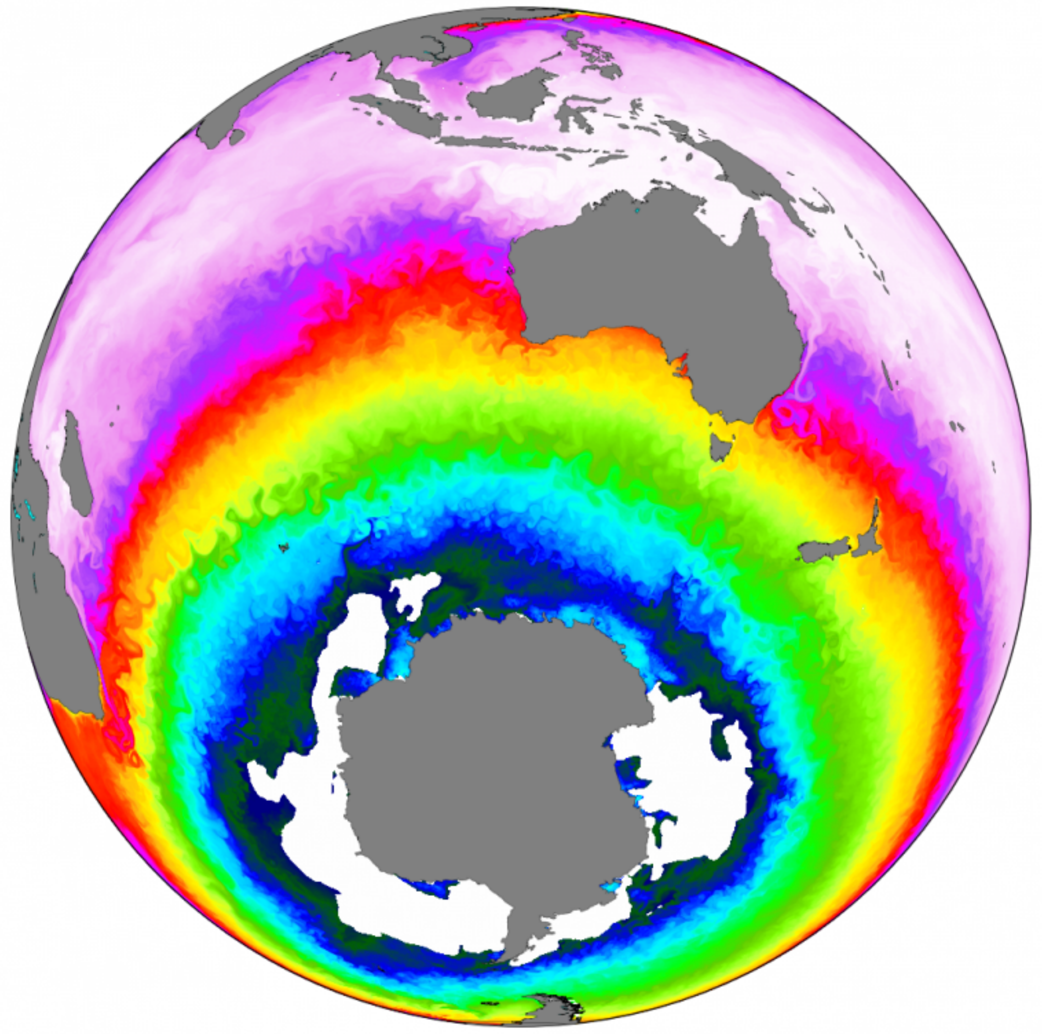
what's next?

Keep climbing up the model-hierarchy ladder…

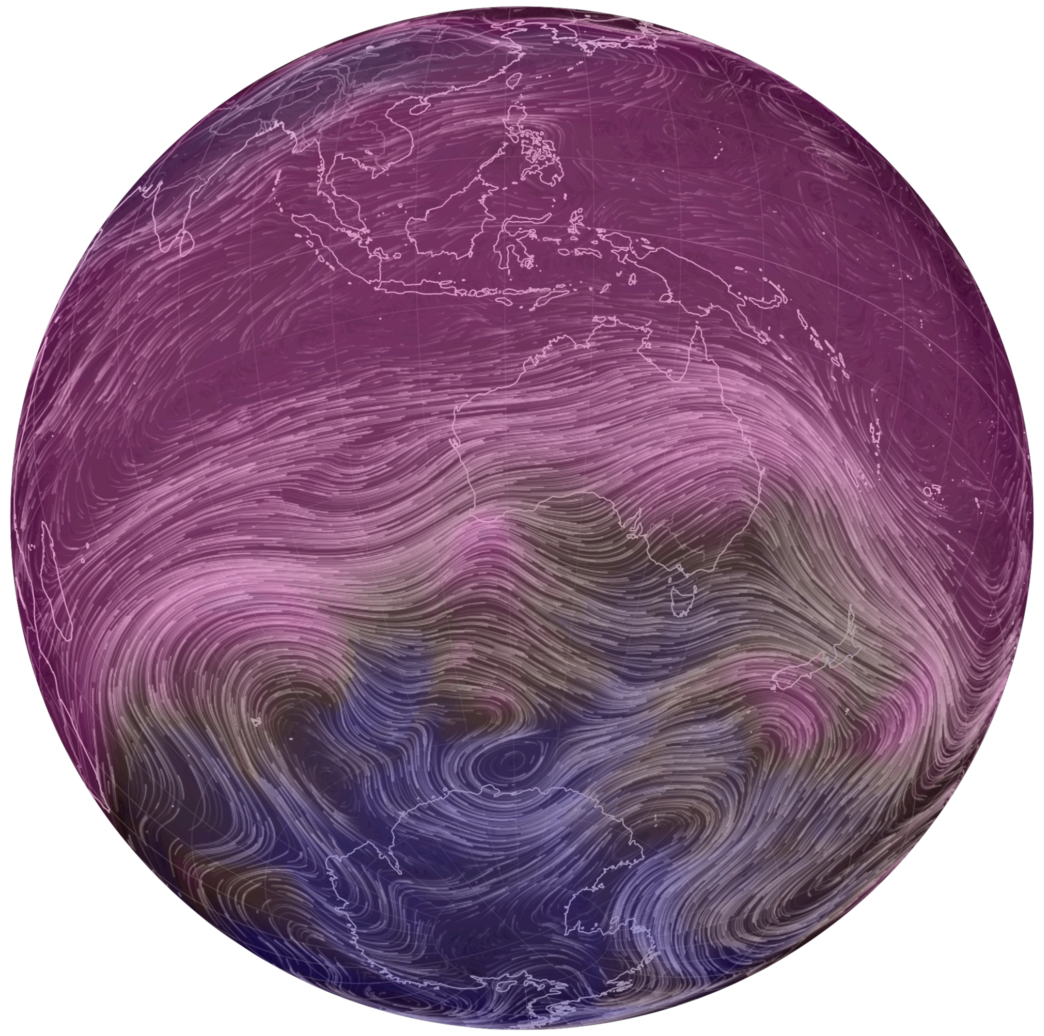
Connect to real world

Example #2:

ocean



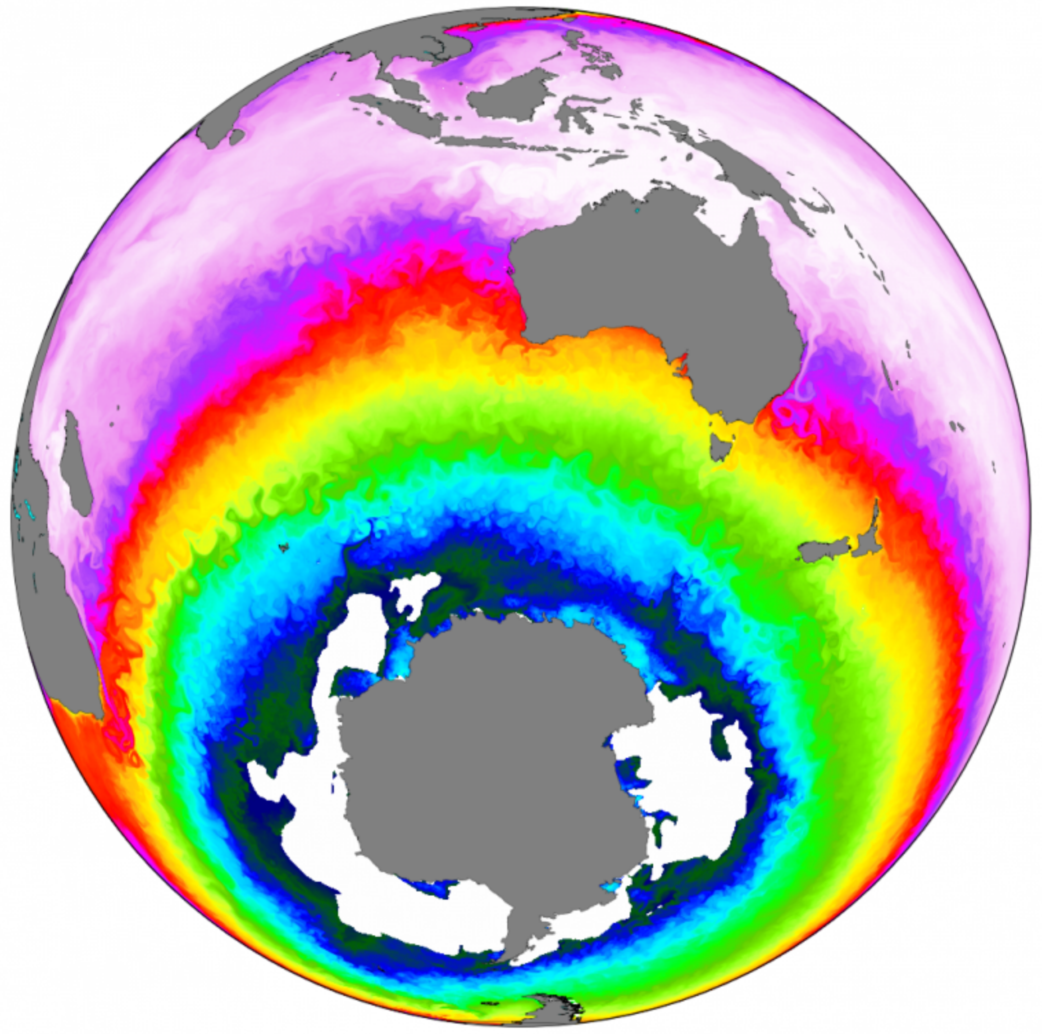
atmosphere



air-sea
interactions

climate

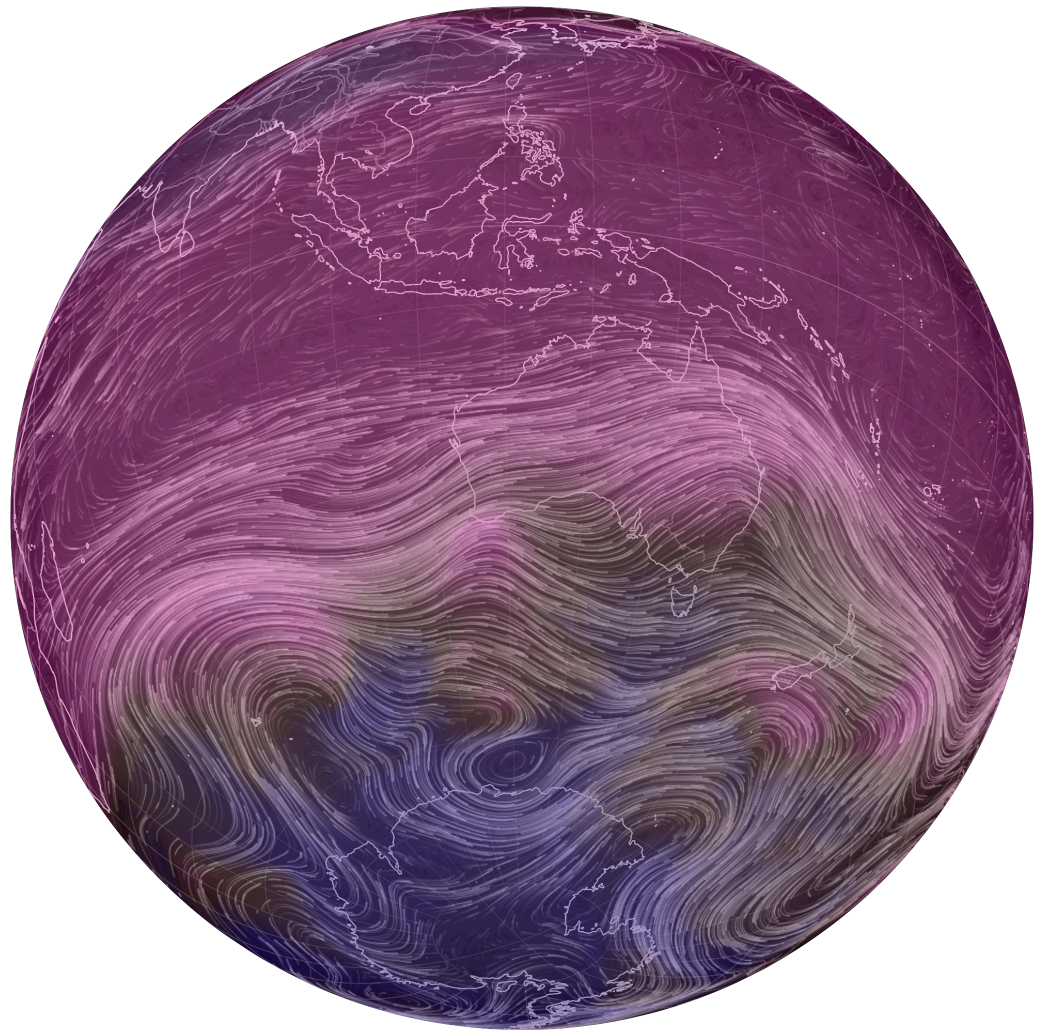
ocean



can we better understand this?

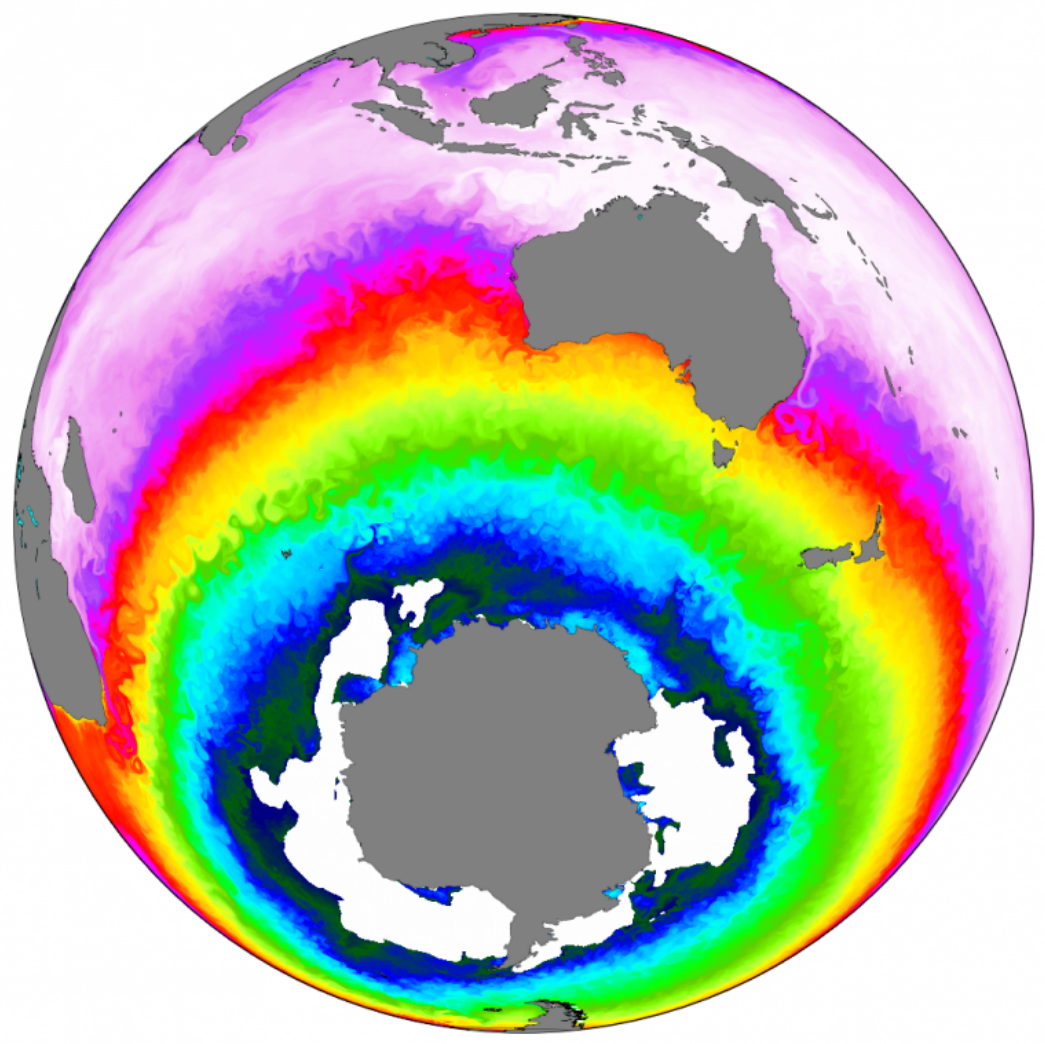
air-sea interactions

atmosphere



climate

ocean



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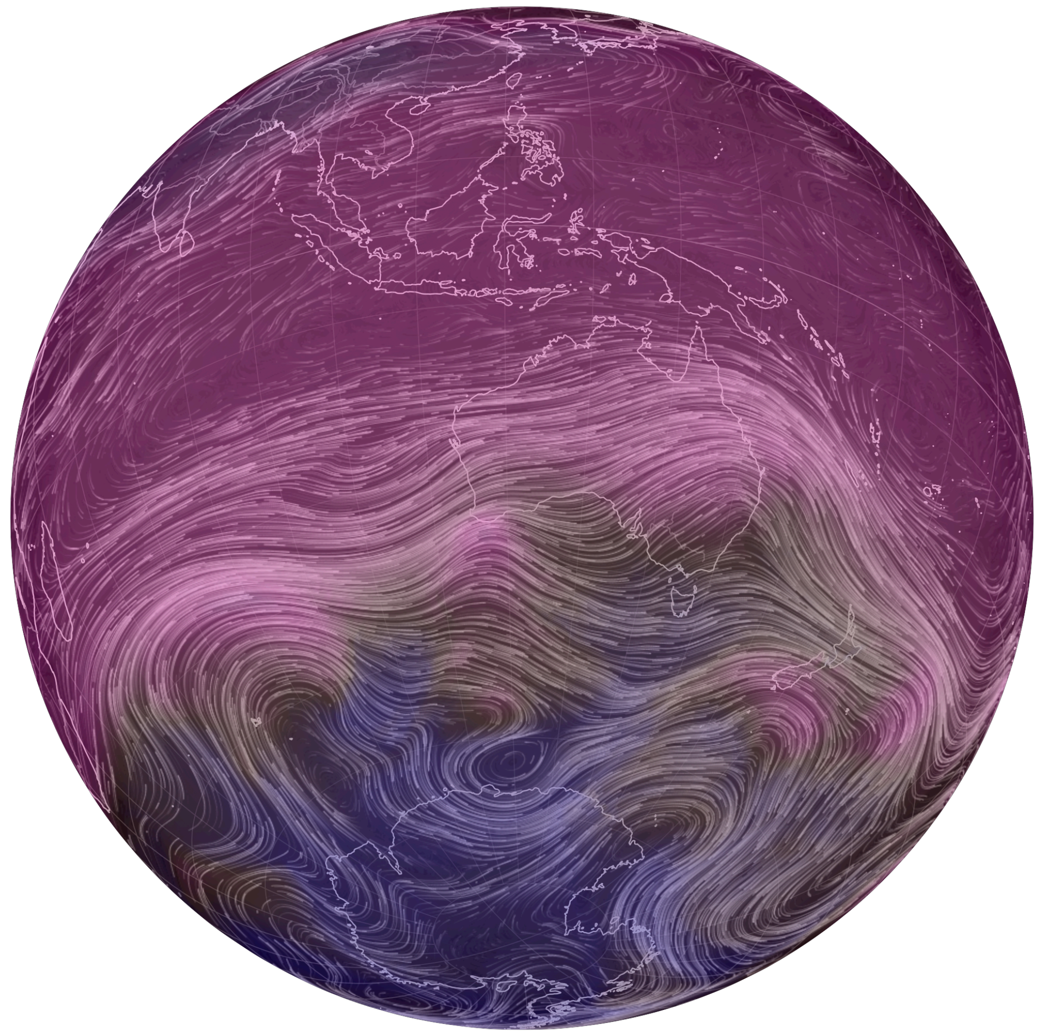


atmosphere "feels" the ocean's upper-layer ocean heat content

Can ocean dynamics feed back on the atmosphere?
(and thus on the climate)

Ocean eddies lead to **large-scale, multi-annual (decadal) patterns** of upper-ocean heat content?

an ocean eddy

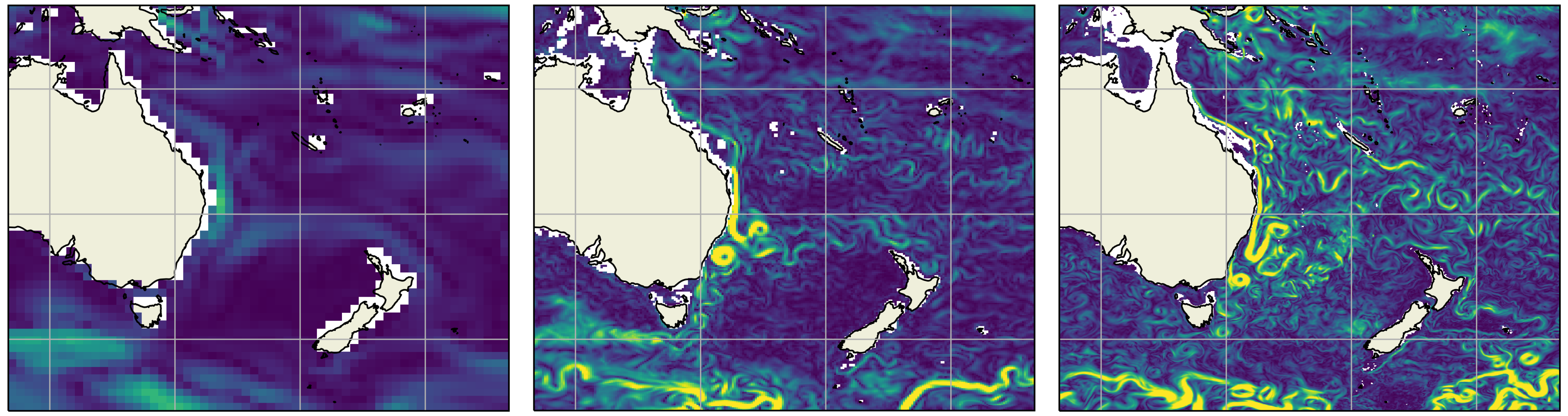
"Does the flap of ~~a butterfly's wings~~ in Brazil
set off an ~~tornado in Texas~~?"

El Niño

how do we probe the role of ocean dynamics?

ACCESS-OM2 ocean models
@ 3 horizontal resolutions

1° 0.25° 0.10°



JRA55 reanalysis
[Tsujino et al. 2018]

IAF

driven with
realistic
atmosphere
1958-2019

(the "real deal")

RYF

driven with
realistic
atmosphere
from a ***single*** year
May1990-Apr 1991
repeated over and over and over…
[Stewart et al. 2020]

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ACCESS-OM2 ocean models
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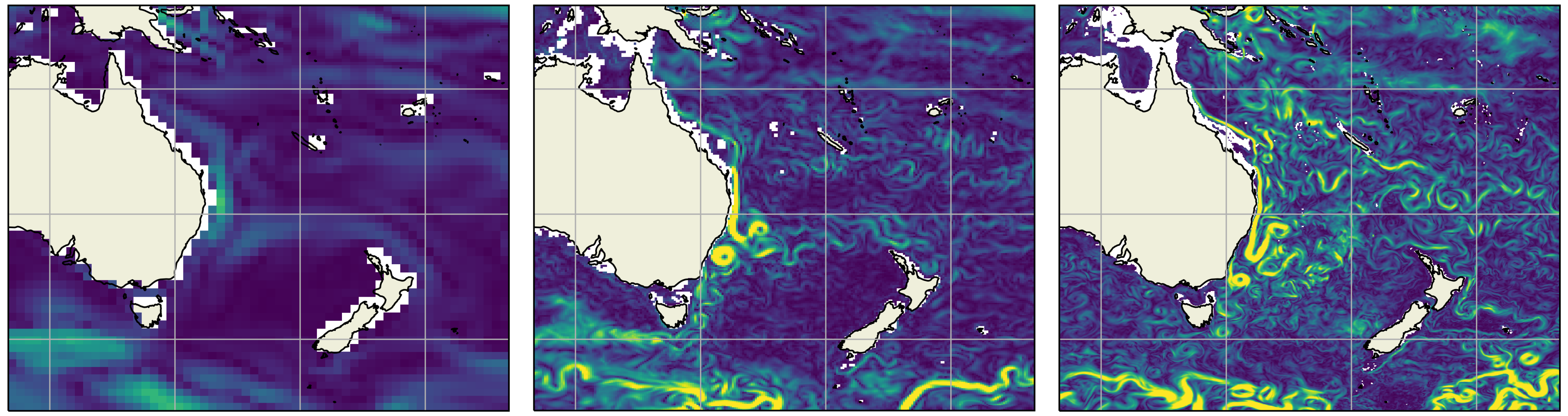

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[Stewart et al. 2020]

Boring
weather! zzZZ

yeah right..
But this way
we are sure that any
decadal signal we find
it comes from
ocean dynamics!

what do we look at?

$$\mathscr{H}(\mathrm{lon}, \mathrm{lat}, t) = \rho_0 c_p \int_{-50\,m}^{\mathrm{SSH}} T(\mathrm{lon}, \mathrm{lat}, z, t)\, \mathrm{d}z$$

sea-surface height

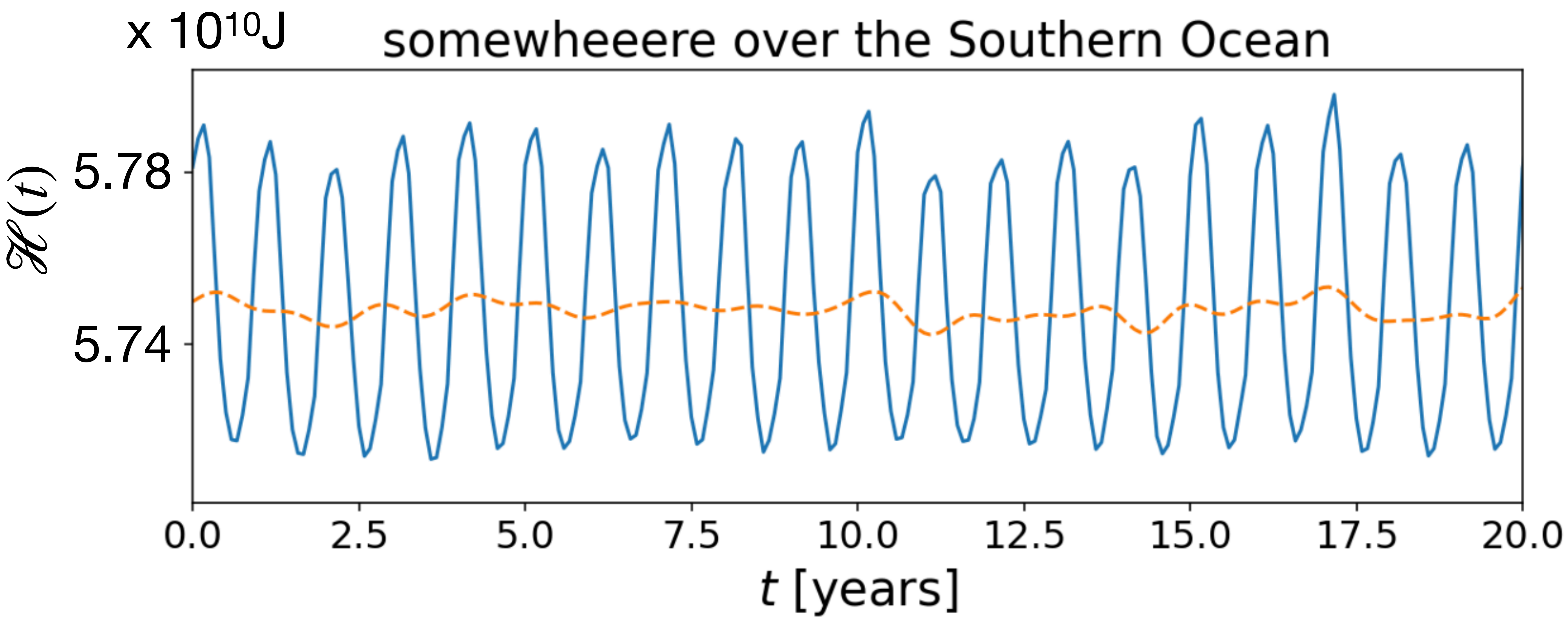
temperature

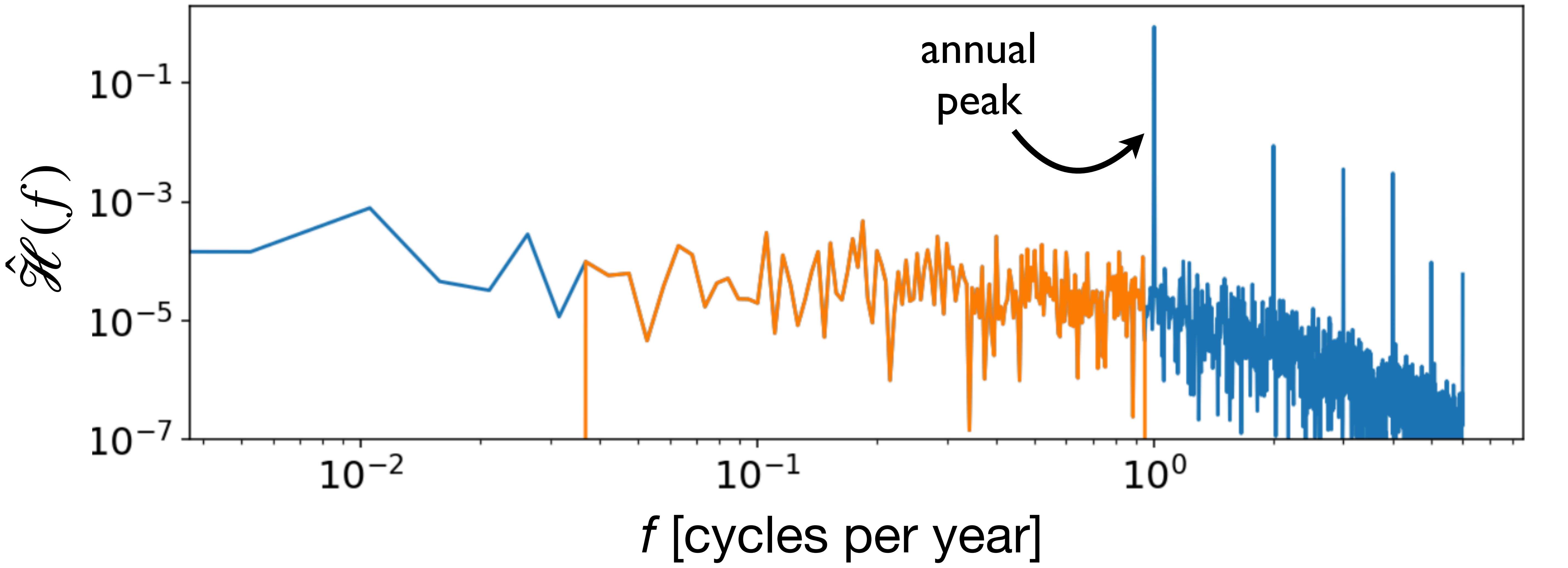
frequency decomposition:

$$\hat{\mathscr{H}}(\mathrm{lon}, \mathrm{lat}, f) = \int \mathscr{H}(\mathrm{lon}, \mathrm{lat}, t)\, \mathrm{e}^{2\pi i f t}\, \mathrm{d}t$$

"low frequency" or decadal:

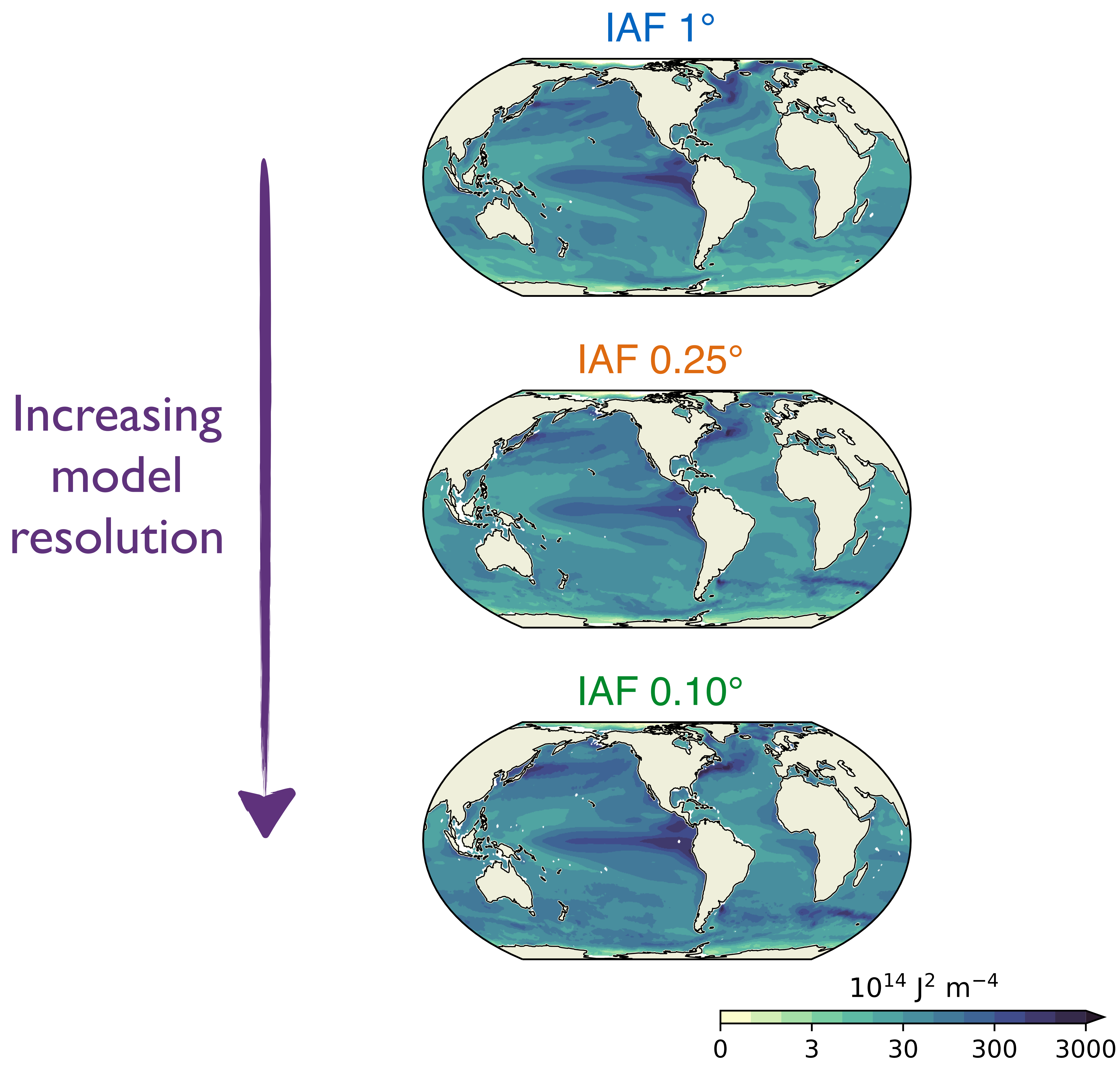
$\hat{\mathscr{H}}_{\mathrm{LF}}$ for $(25 \text{ years})^{-1} \leq f \leq (1.5 \text{ years})^{-1}$





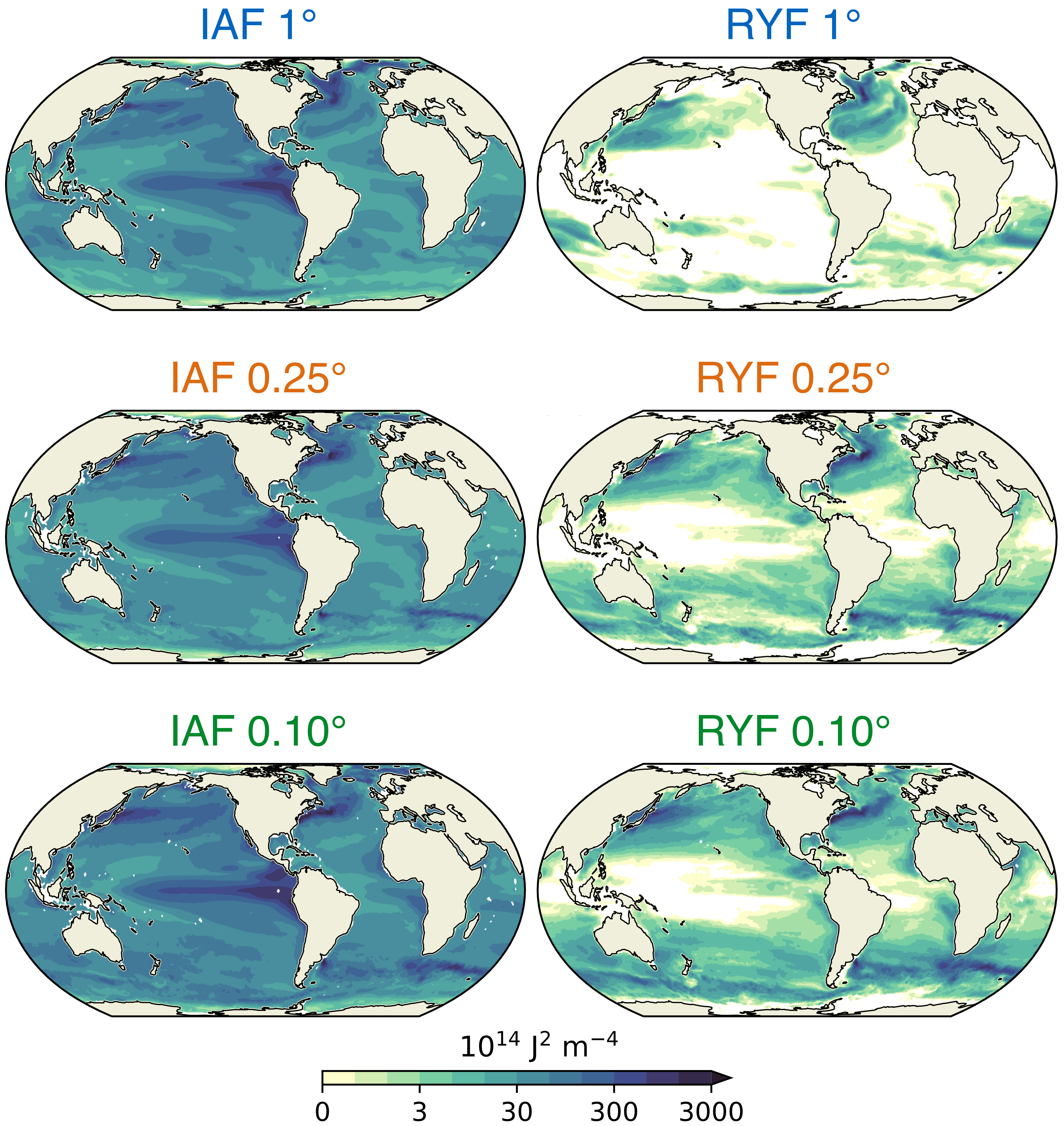
upper-ocean heat content
low-frequency variance

upper-ocean heat content low-frequency variance



[C & Hogg *J Climate* 2021 (in review)]

upper-ocean heat content low-frequency variance

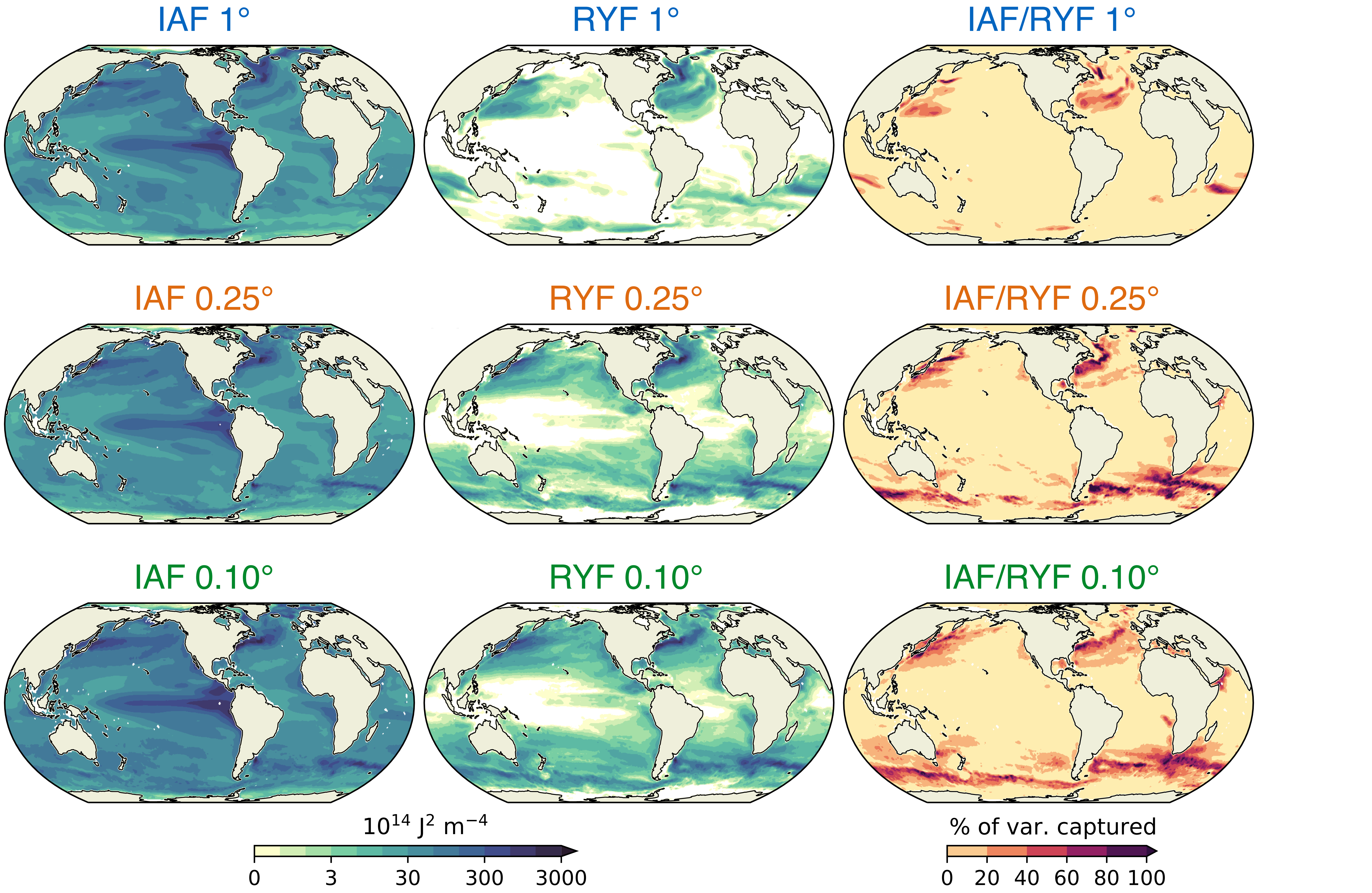


Increasing model resolution

[C & Hogg *J Climate* 2021 (in review)]

upper-ocean heat content
low-frequency variance

Increasing model resolution



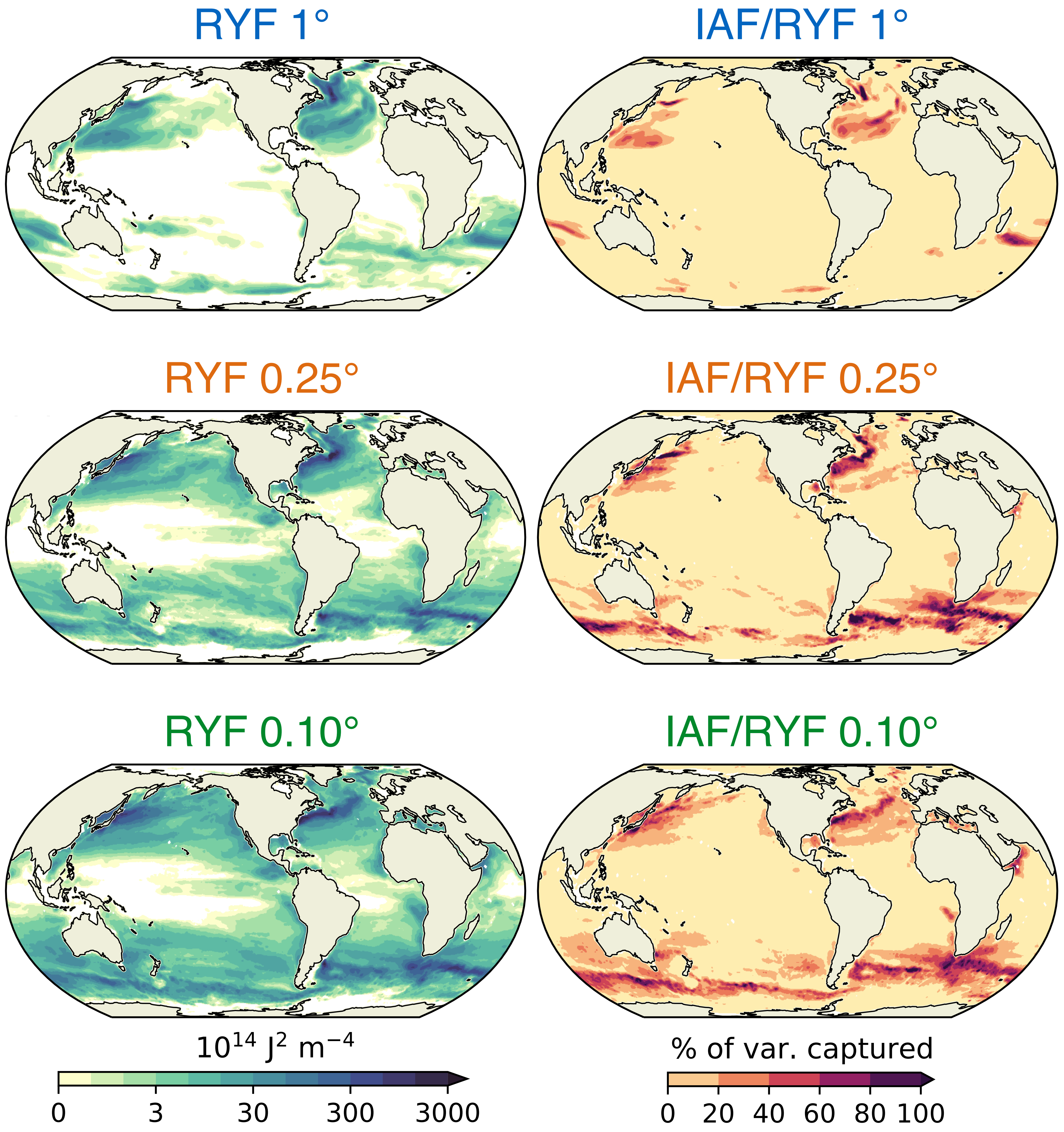
[C & Hogg *J Climate* 2021 (in review)]

upper-ocean heat content low-frequency variance

LF variance
@ mid-latitude
increases
with model resolution

patterns of variability?

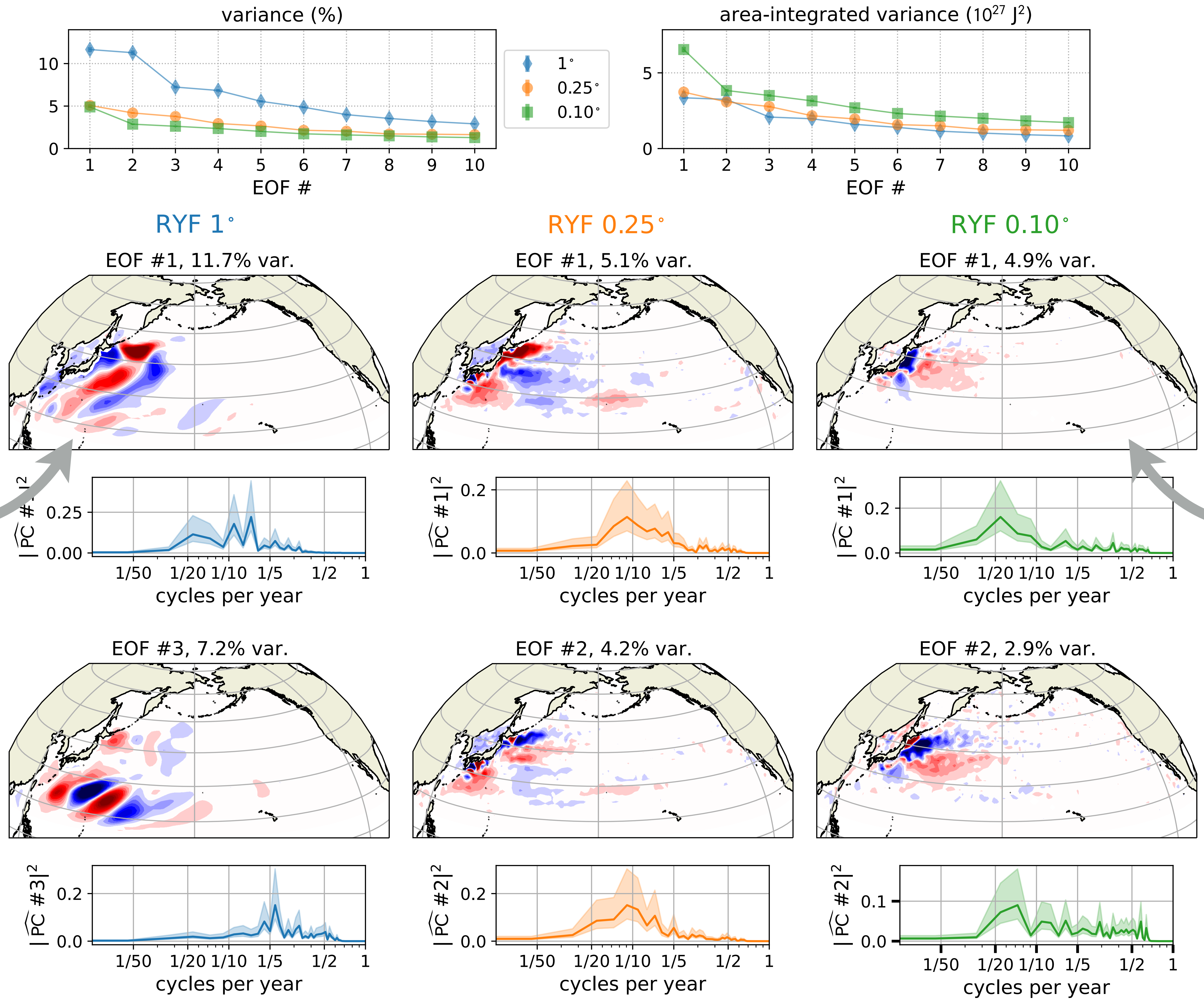
are they the
same across resolutions?



[C & Hogg *J Climate* 2021 (in review)]

EOF analysis of LF upper-ocean heat content from RYF experiments @ North Pacific

The “IPCC” atmosphere feels this ocean at inter-annual timescales



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

principal component power spectra peaks shift to longer timescales

[C & Hogg *J Climate* 2021 (in review)]

Should I take anything home?

An atmosphere sitting on top of
higher-resolution ocean feels:

more upper-ocean heat content variance
at decadal timescales

+

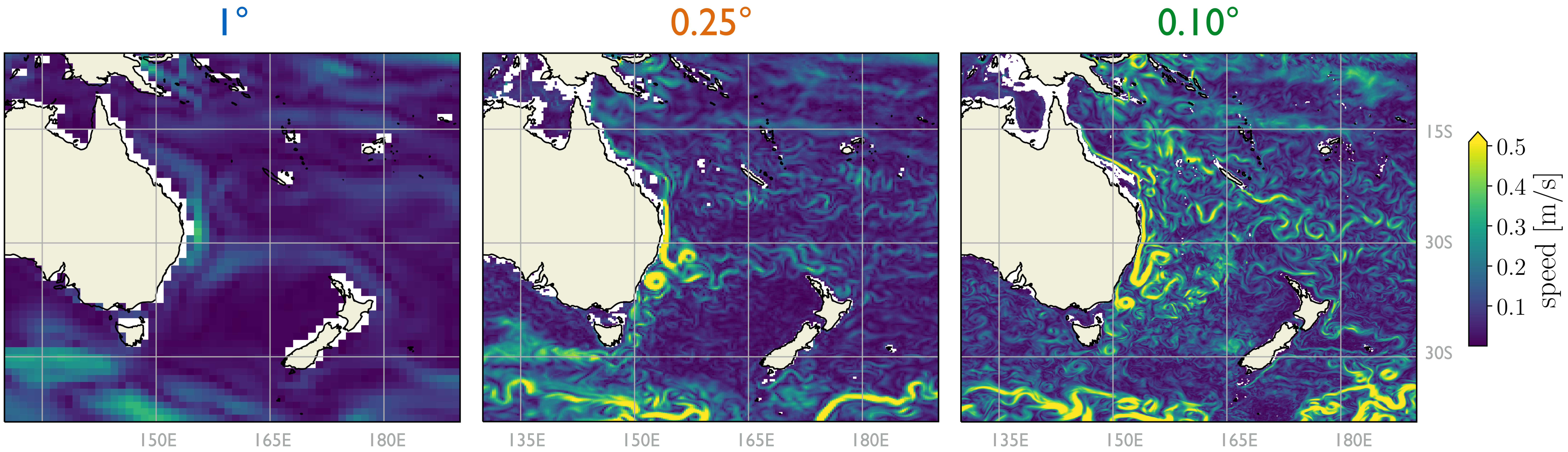
very different patterns of decadal variability
(that reflect more the eddy-active regions)

corollary:

Community should move towards climate
models with higher-resolution oceans

Example #3

How can we encapsulate the effect
of the small-scale features on the "big picture"?



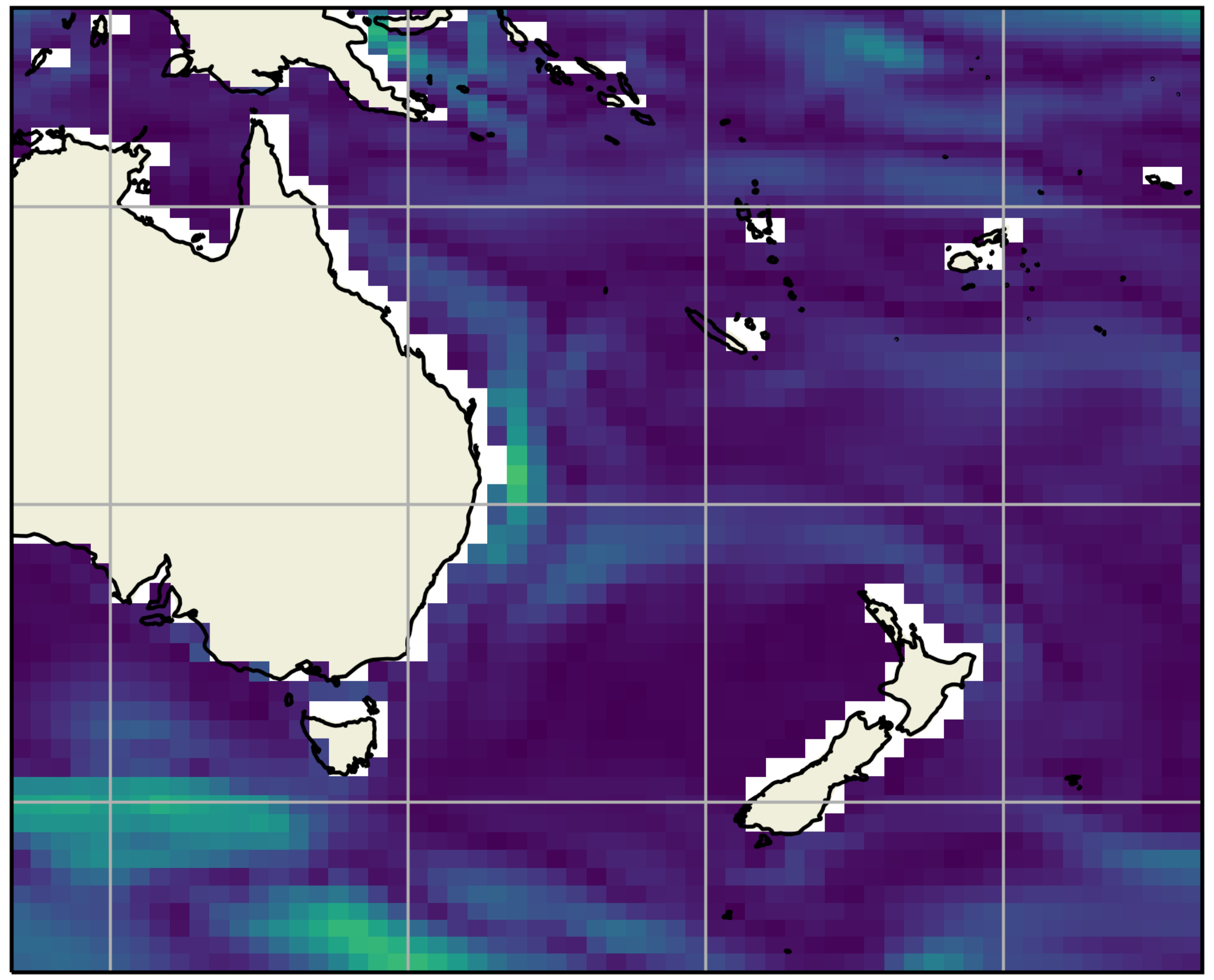
Can we make the 1° model feel the effect of the flow details
that it's been missing when compared to the **0.10°** model?

[in technical terms: "eddy parameterisation"]

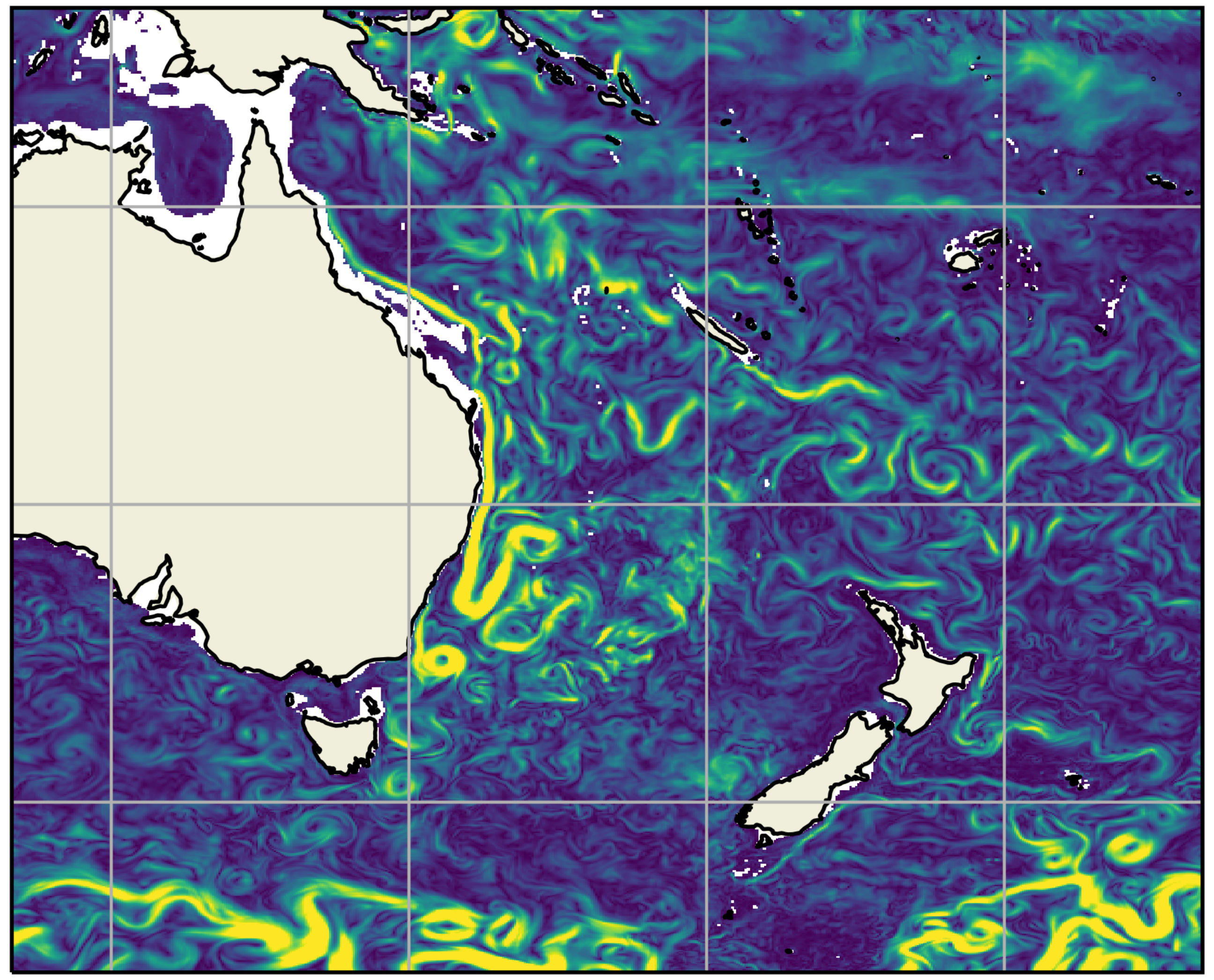
(Eddy) Parameterisations

How can we encapsulate the effect
of the small-scale features on the "big picture"?

1°



0.10°



$$\rho_{1^\circ}\frac{\partial \boldsymbol{u}_{1^\circ}}{\partial t} + \ldots = -\nabla p_{1^\circ} + \ldots$$

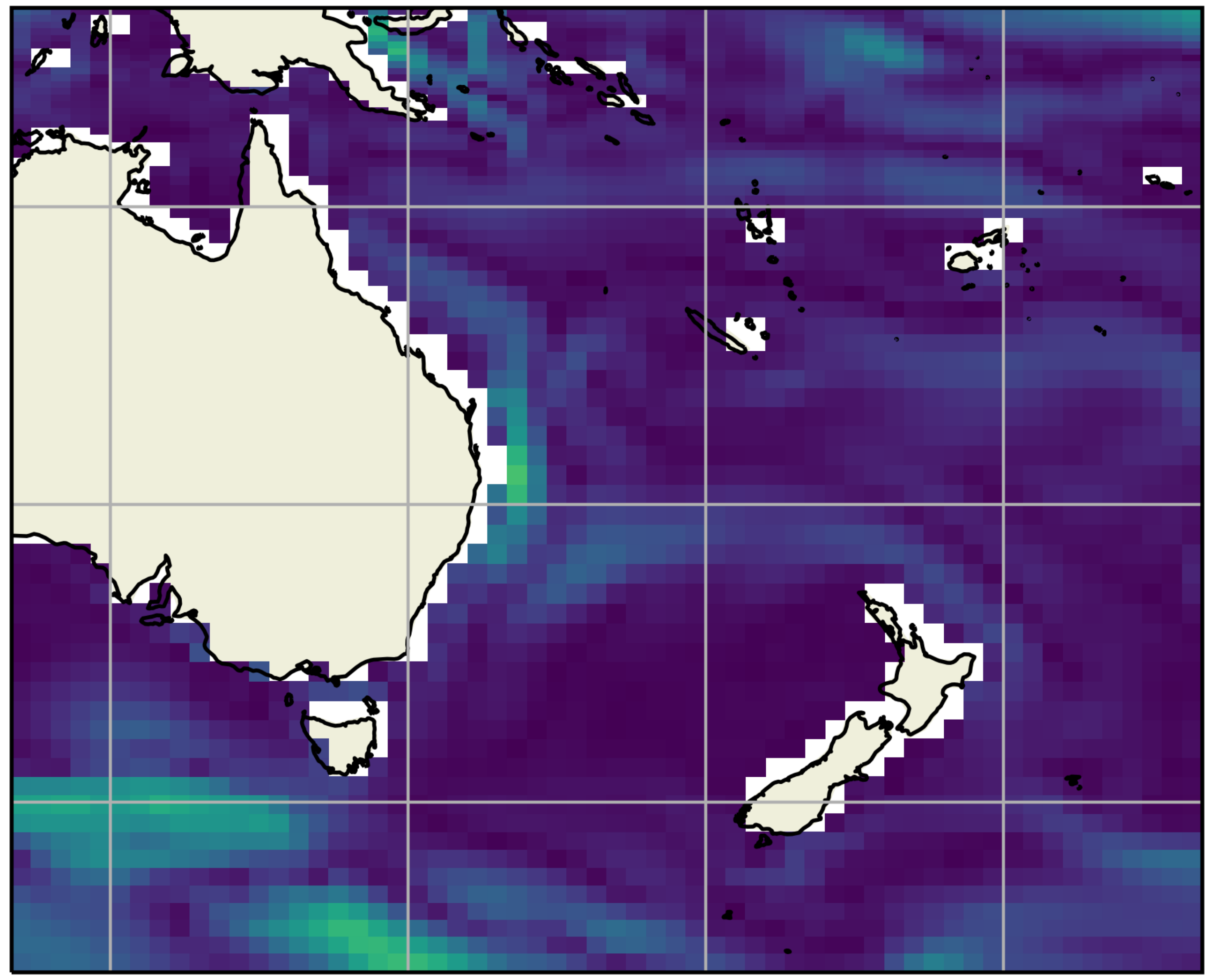
$$\rho_{0.10^\circ}\frac{\partial \boldsymbol{u}_{0.10^\circ}}{\partial t} + \ldots = -\nabla p_{0.10^\circ} + \ldots$$

Same eqs; different variables

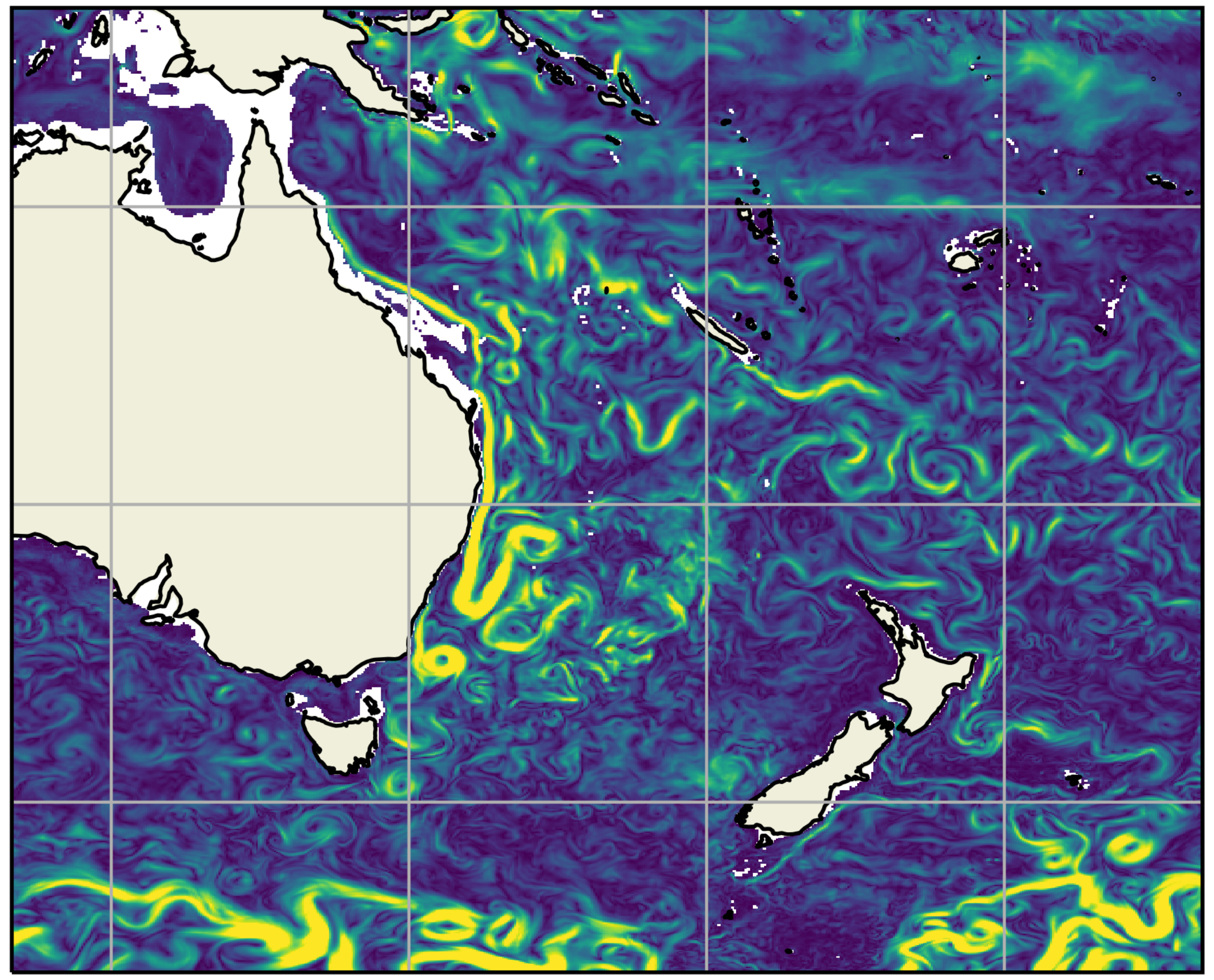
(Eddy) Parameterisations

How can we encapsulate the effect
of the small-scale features on the "big picture"?

1°



0.10°



$$\rho_{1^\circ}\frac{\partial \boldsymbol{u}_{1^\circ}}{\partial t} + \ldots = -\nabla p_{1^\circ} + \ldots + \mathscr{F}(\boldsymbol{u}_{1^\circ}, p_{1^\circ}, \ldots)$$

a parameterisation

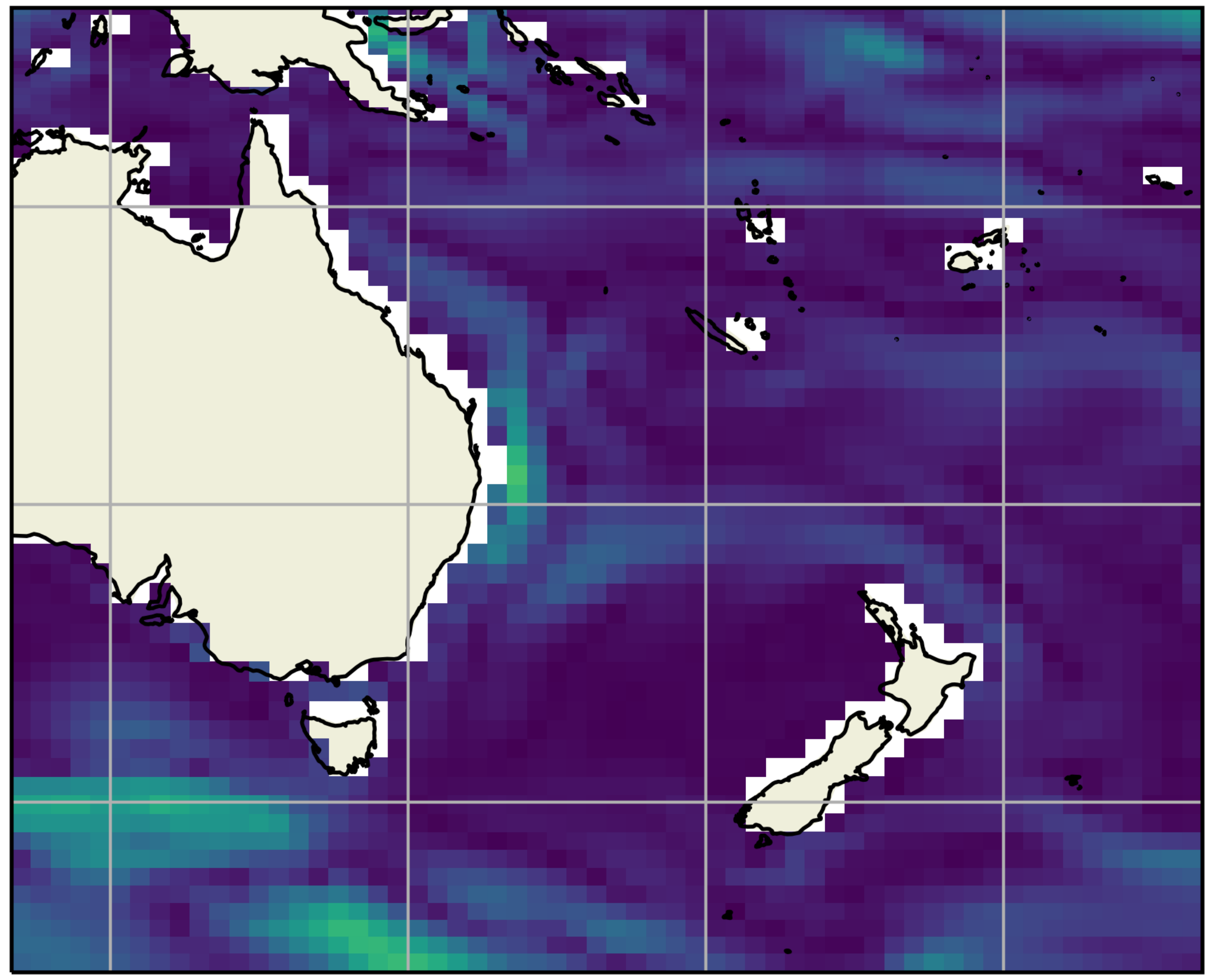
(depends only on the model variables)

$$\rho_{0.10^\circ}\frac{\partial \boldsymbol{u}_{0.10^\circ}}{\partial t} + \ldots = -\nabla p_{0.10^\circ} + \ldots$$

(Eddy) Parameterisations

How can we encapsulate the effect
of the small-scale features on the "big picture"?

1°



Physics-based parameterisations

Mesoscale eddies [Gent & McWilliams 1990]
Mixed-Layer Scheme
Convective Adjustment
Submesoscale restratification
…

Often they work 'OK'; sometimes not as good.

$$\rho_{1^\circ}\frac{\partial \boldsymbol{u}_{1^\circ}}{\partial t} + \ldots = -\nabla p_{1^\circ} + \ldots + \mathscr{F}(\boldsymbol{u}_{1^\circ}, p_{1^\circ}, \ldots)$$

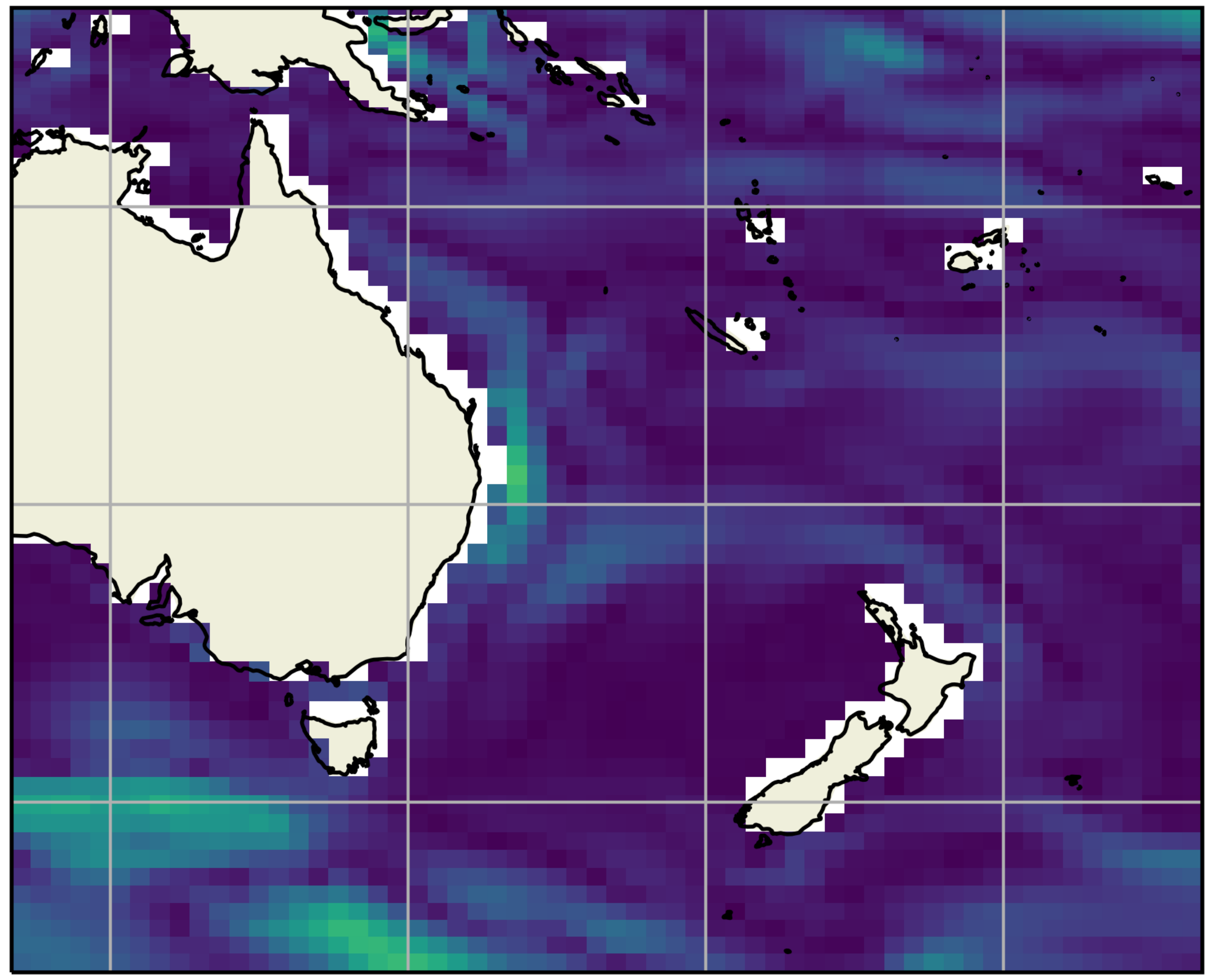
a parameterisation

(depends only on the model variables)

(Eddy) Parameterisations

How can we encapsulate the effect
of the small-scale features on the "big picture"?

1°



Physics-based parameterisations

Mesoscale eddies [Gent & McWilliams 1990]
Mixed-Layer Scheme
Convective Adjustment
Submesoscale restratification
…

Could we make them better?

$$\rho_{1^\circ}\frac{\partial \boldsymbol{u}_{1^\circ}}{\partial t} + \ldots = -\nabla p_{1^\circ} + \ldots + \mathscr{F}(\boldsymbol{u}_{1^\circ}, p_{1^\circ}, \ldots)$$

a parameterisation

(depends only on the model variables)

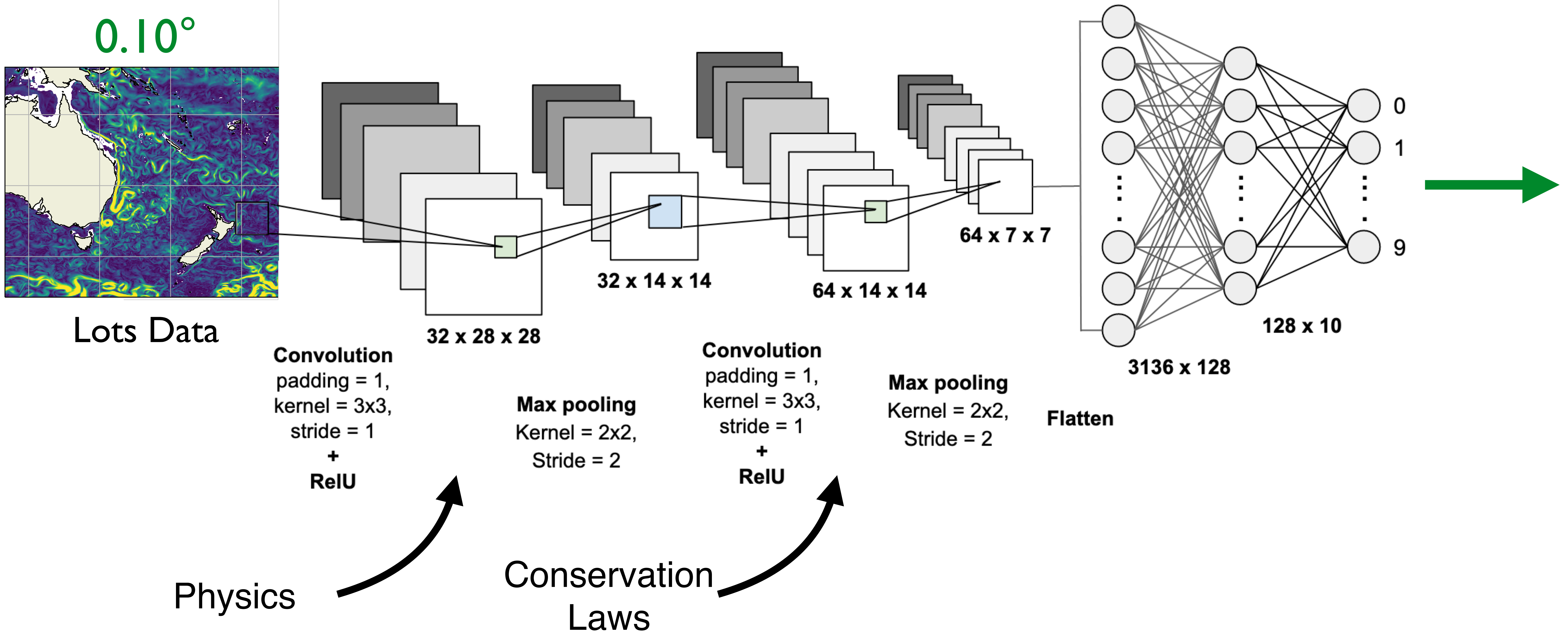
(Eddy) Parameterisations

Physics + Lots of Data = Physics-aided Machine Learning

[C, ARC DE2021]

(Eddy) Parameterisations

Physics + Lots of Data = Physics-aided Machine Learning



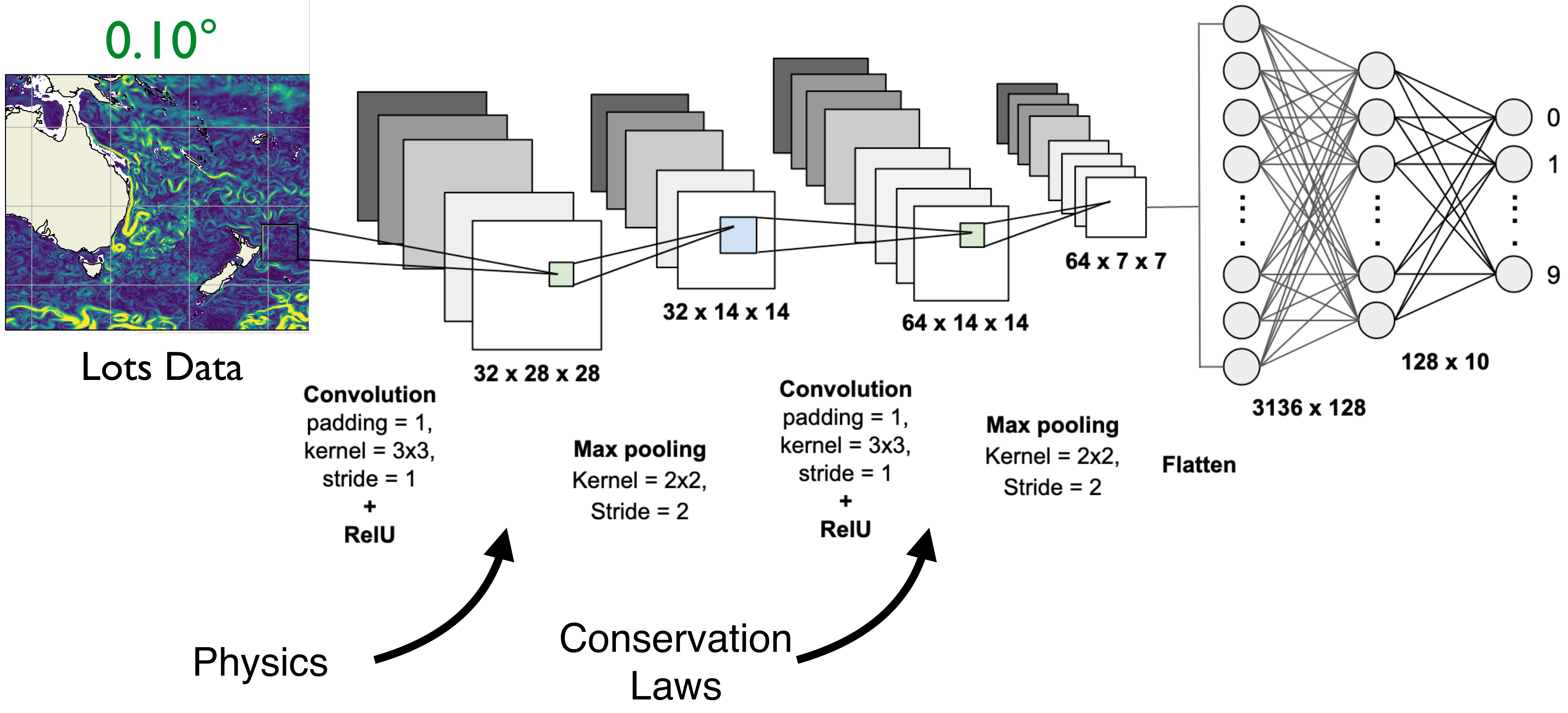
$\mathscr{F}(\boldsymbol{u}_{1^\circ}, p_{1^\circ}, \ldots)$

a Machine Learning parameterisation

[C, ARC DE2021]

(Eddy) Parameterisations

Physics + Lots of Data = Physics-aided Machine Learning

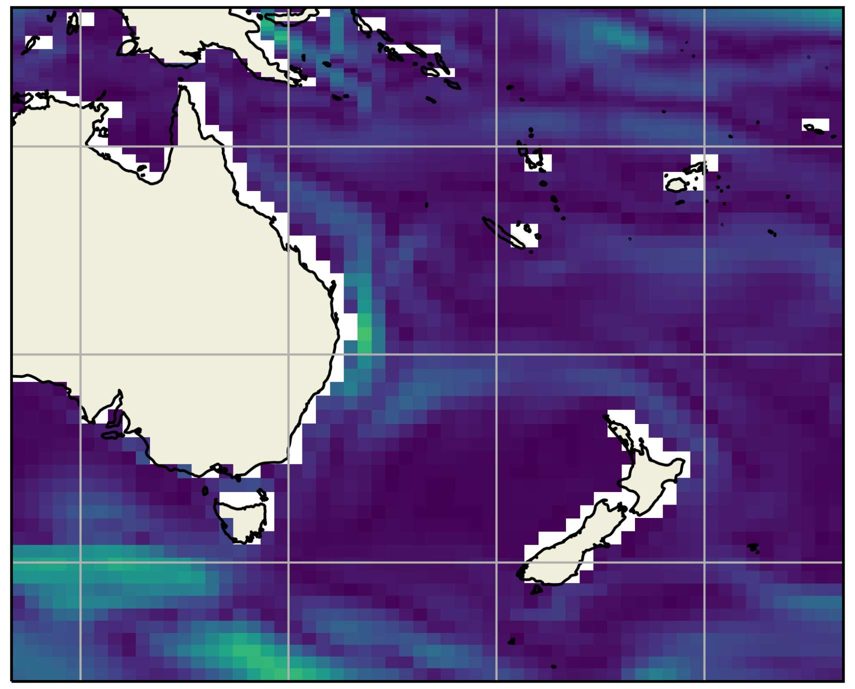


$\mathscr{F}(\boldsymbol{u}_{1^\circ}, p_{1^\circ}, \ldots)$

a Machine Learning parameterisation

plug it in

1°



[C, ARC DE2021]

Should I take anything home?

Not quite yet — just hold on to your chair!

Let's sum up

example #1 "Spherical-cow" conceptual setups help us build understanding

example #2 Higher resolution ocean feedback very differently onto the atmosphere compared to the "laminar" 1° typically used for climate predictions.

(Ramifications for decadal climate predictions, El Niño, Interdecadal Pacific Oscillation, North Atlantic Oscillation,…)

example #3 Community should move towards coupled climate models with higher oceanic resolution ***or find better ways to parameterise the unresolved processes.***

"Indeed, eddies act in mysterious ways.
Rest assured that at RSES we are doing our best to demystify them."
[by an anonymous research fellow]