Climate Science in a Changing Climate

Abigail Bodner

Department of Earth, Atmospheric, and Planetary Science

Department of Electrical Engineering and Computer Science

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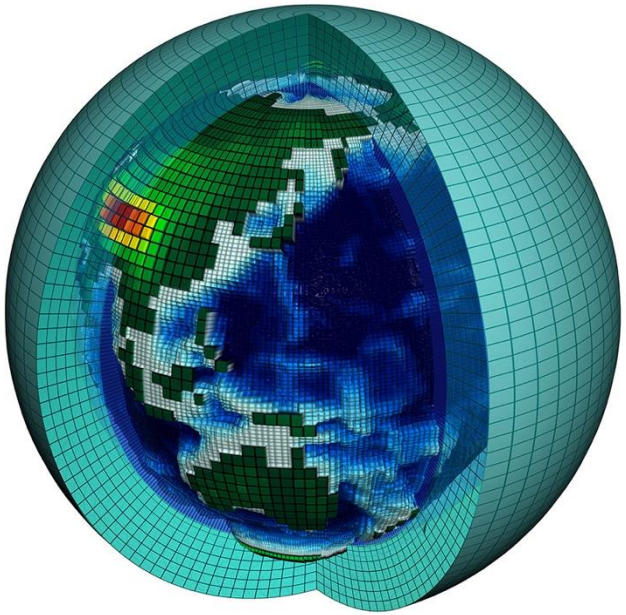

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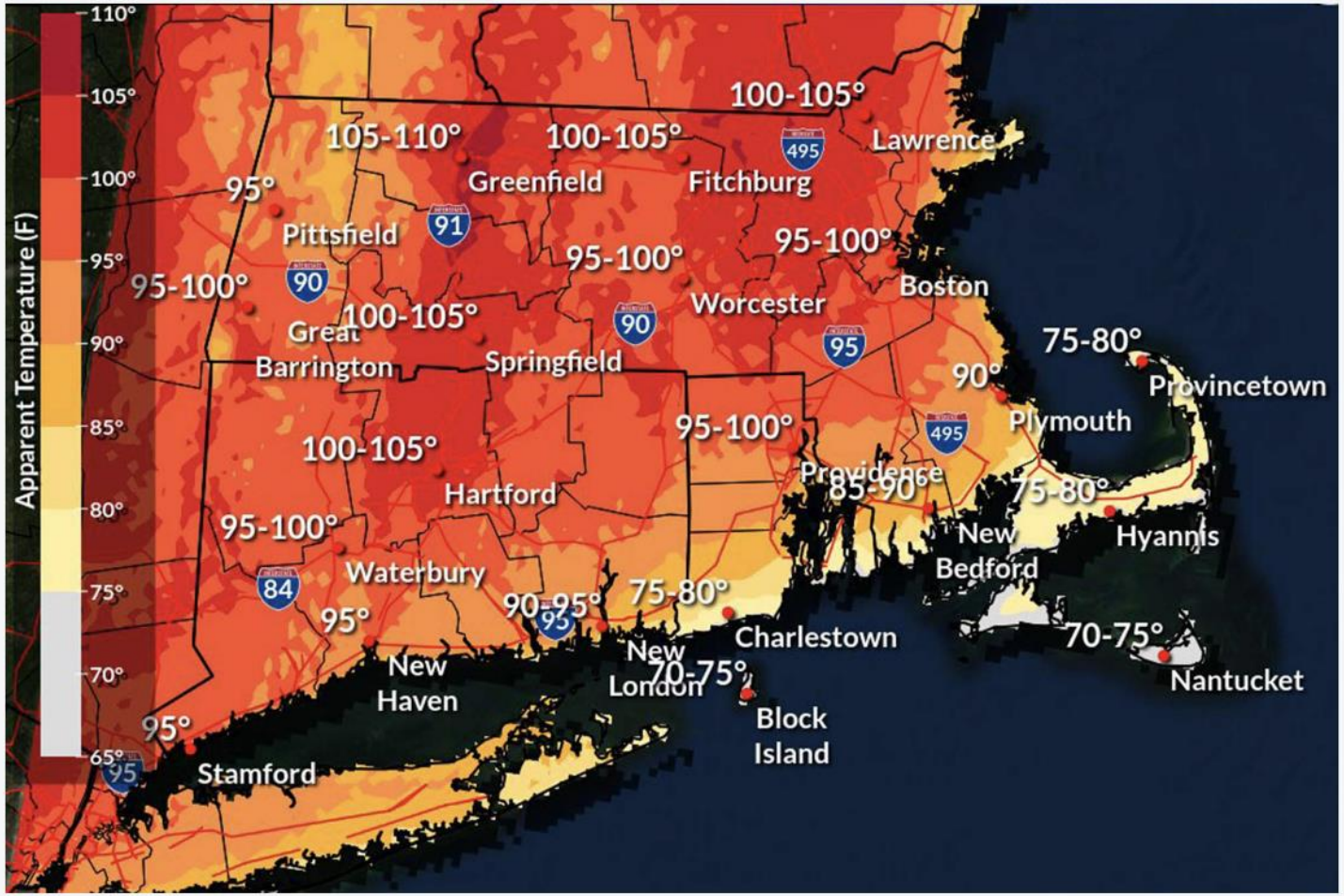
As Boston Braces for First Heat Wave of Season, BU Opens Cooling Stations for Students

Plus, tips for staying safe when the temperature soars



Boston's first heat wave of the season is expected to arrive on Tuesday with heat indices anticipated to reach between 95 and 105 degrees over the next four days. Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

The Impossible Fight to Stop Canada's Wildfires

Canada's worst wildfire season ever has put unprecedented strain on the country's firefighters. Tens of thousands of people have been displaced, with millions more choking on toxic wildfire smoke. Next summer could be far worse.

PHOTOGRAPH: DARREN HULL/GETTY IMAGES

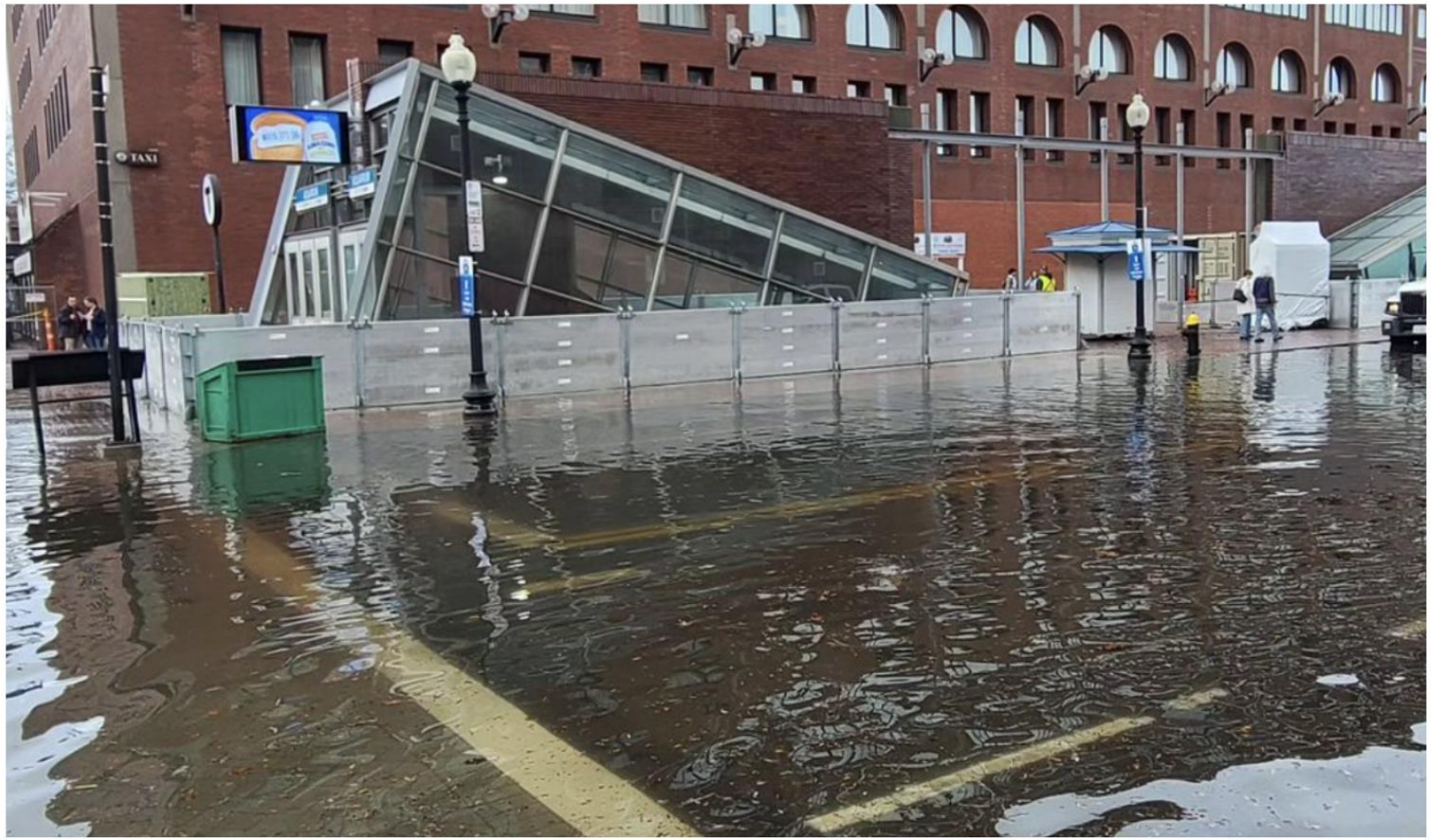
Photos: Smoke from Canada wildfires blankets Northeast

By Tuesday evening, New York City had the most polluted air in the world with an air quality index rating of 196. On Saturday, the city's AQI rating was 15.

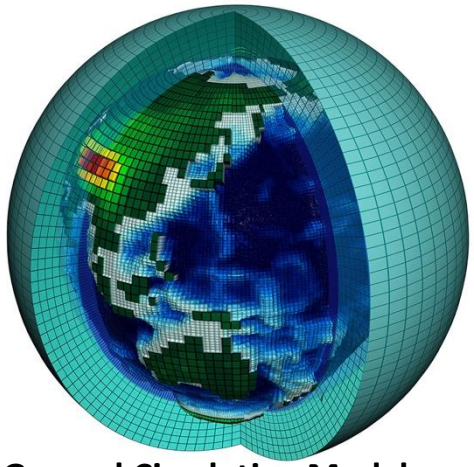
Smoke from the hundreds of wildfires in eastern Canada has drifted into the United States, casting a sky of smog over New York City and triggering air alerts across the northeast. *Maansi Srivastava/The New York Times*

Photos: Smoke from Canada

For the second time in less than one week, Boston experienced a significant storm event that caused flooding throughout the city on January 13, 2024. During this event, the late morning high tide was the fourth highest water level ever recorded at the Boston NOAA tide gauge.



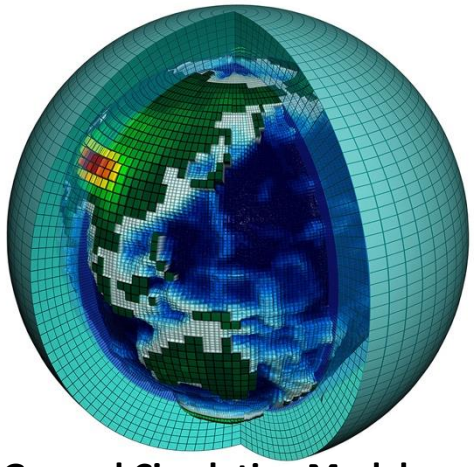
Flood barriers are deployed at Aquarium Station on the Blue Line on January 13, 2024 (Photo by David Weaver)



General Circulation Model

Global Climate Change

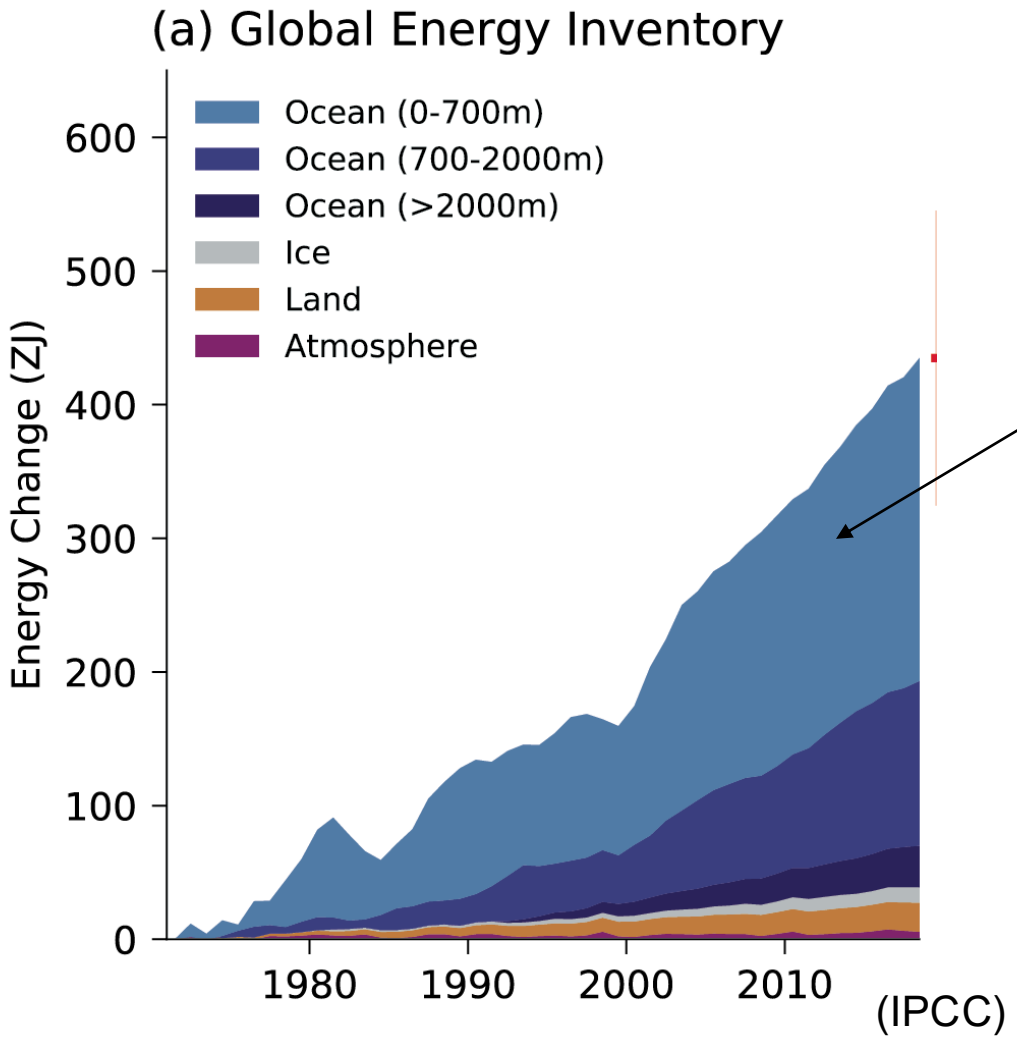
Global Climate Change



General Circulation Model

IPCC

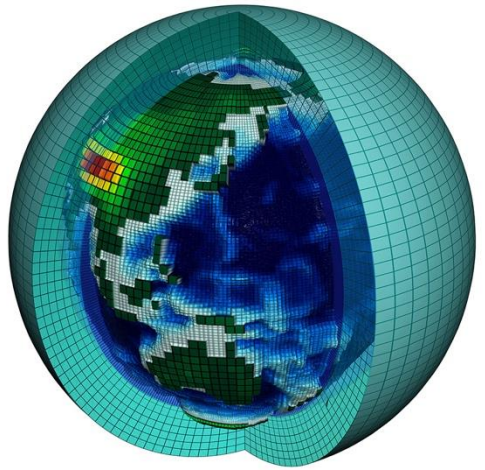
The upper ocean is an important control on climate

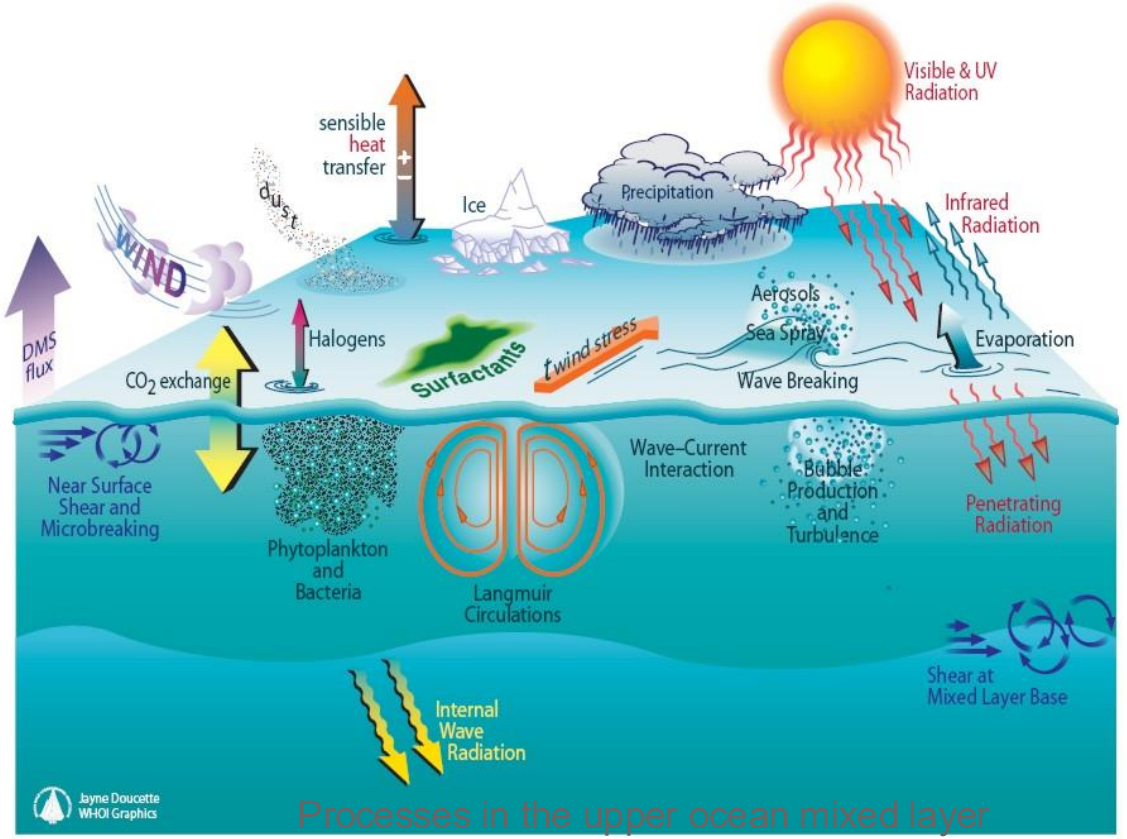


Most of the heat is in the upper ocean!

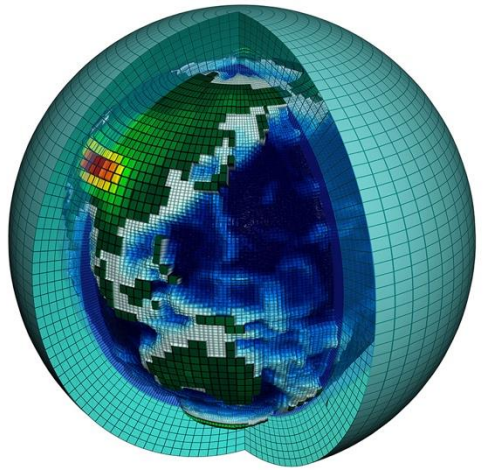
Ocean Mixed Layer

- Mixing and turbulence controls atmosphere-ocean interactions
- Accurate representation of fluxes is crucial for climate simulations
- Small, fast and complex processes
- Unresolved in General Circulation Models





Ocean Mixed Layer



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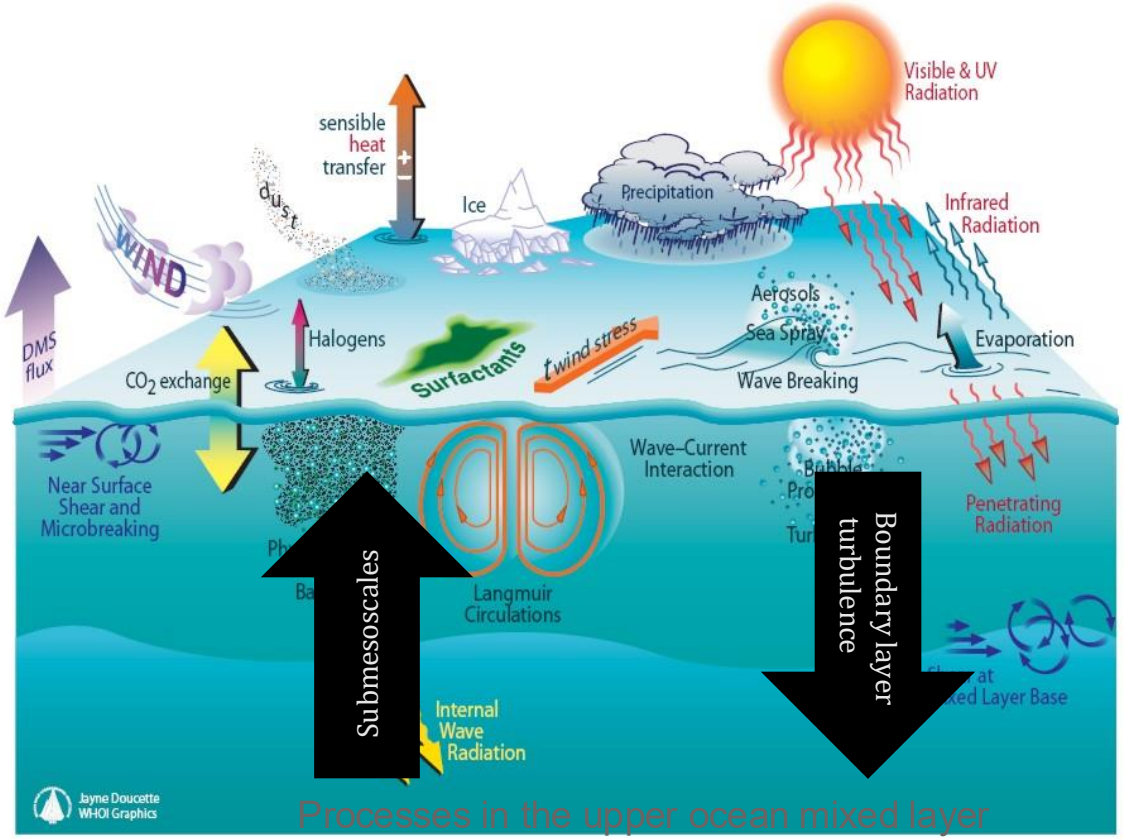
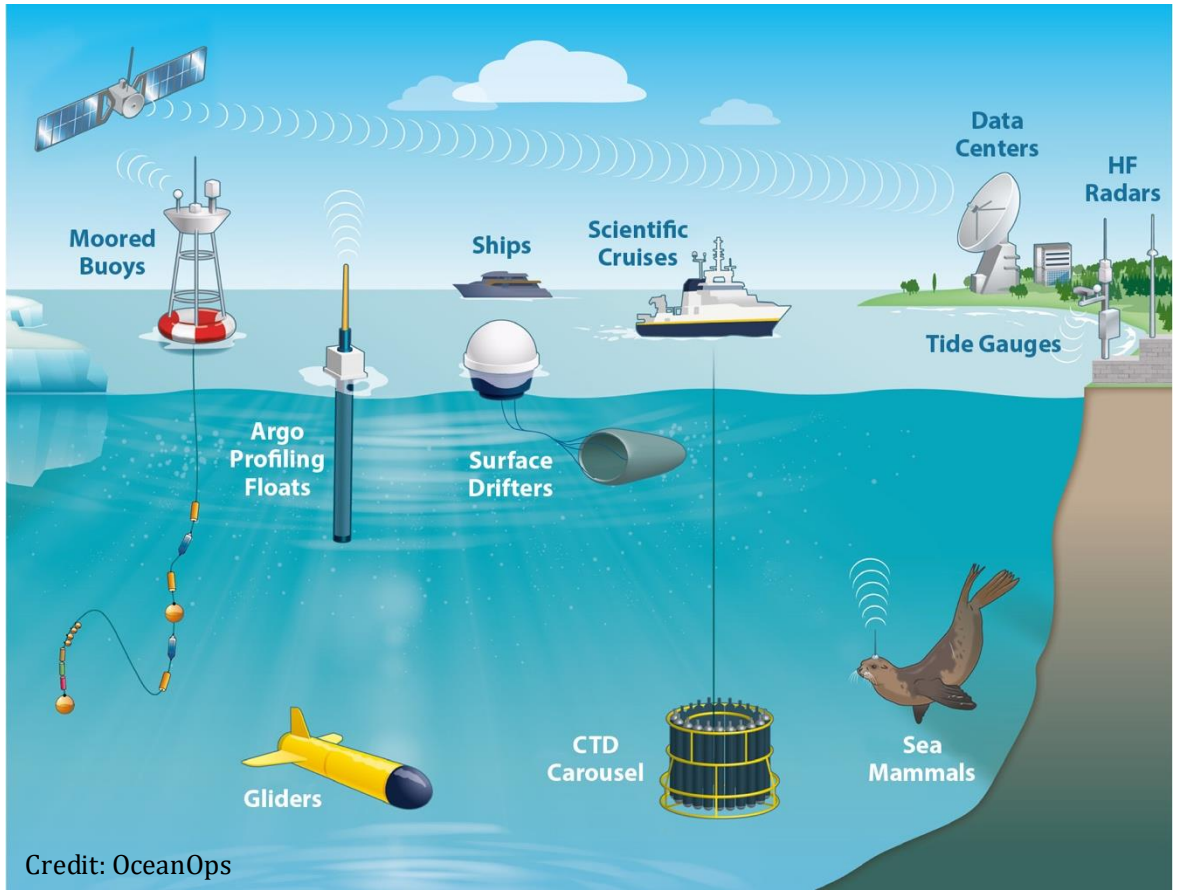
Vertical fluxes $\overline{w'b'}^z$



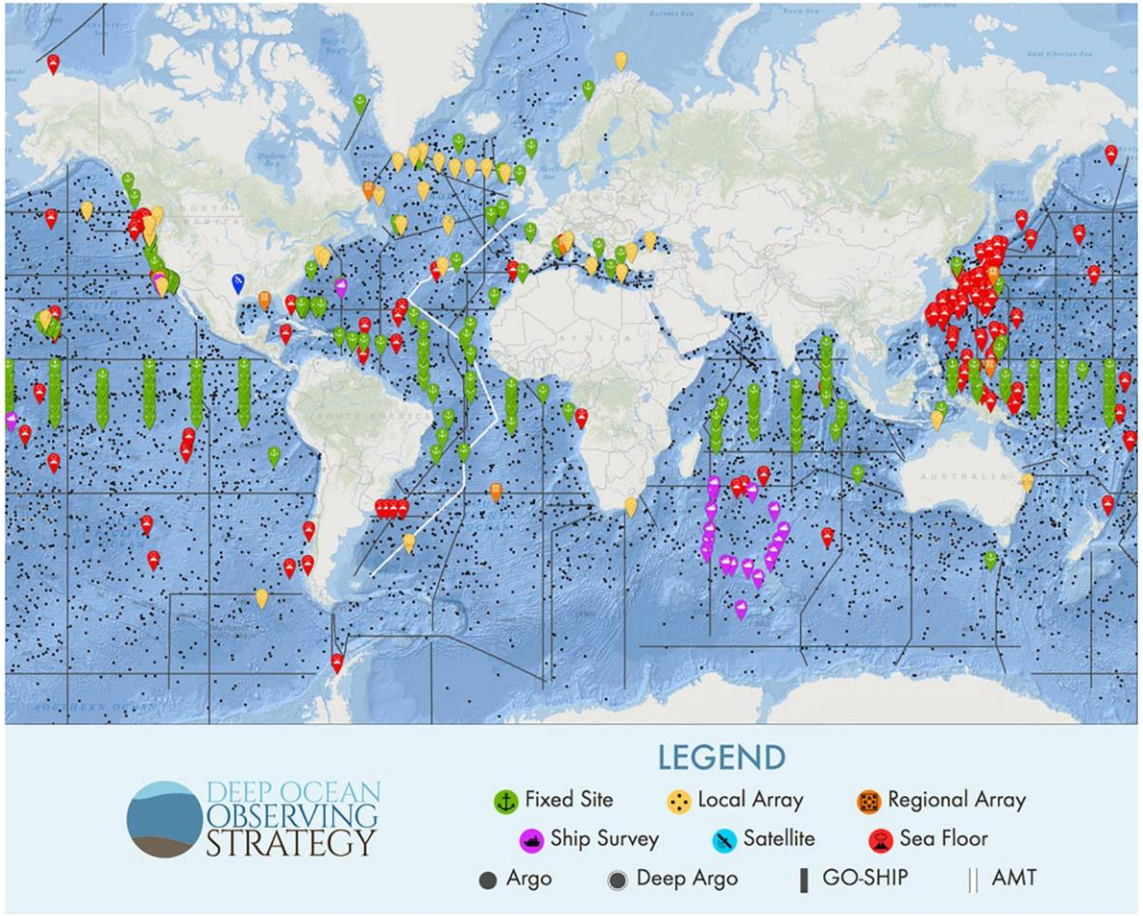
Processes in the upper ocean mixed layer

Submesoscale flows O(1km)
Boundary layer turbulence O(1m)

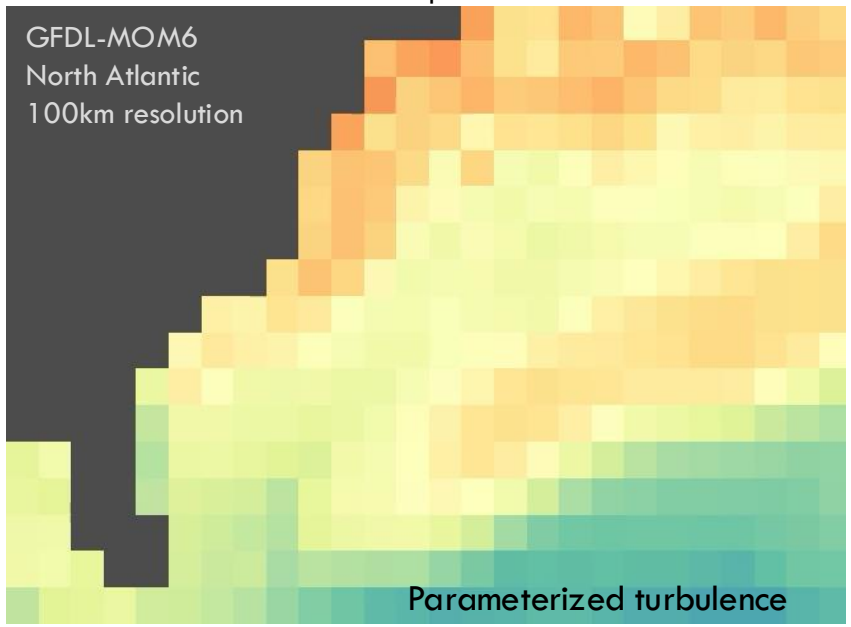
Limited observational data



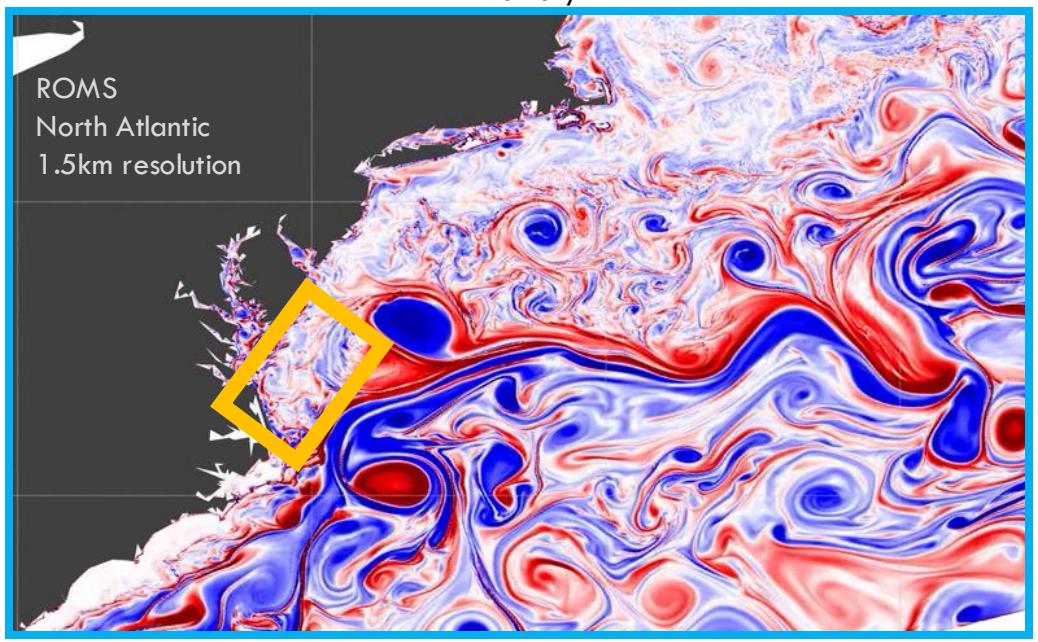
Credit: OceanOps

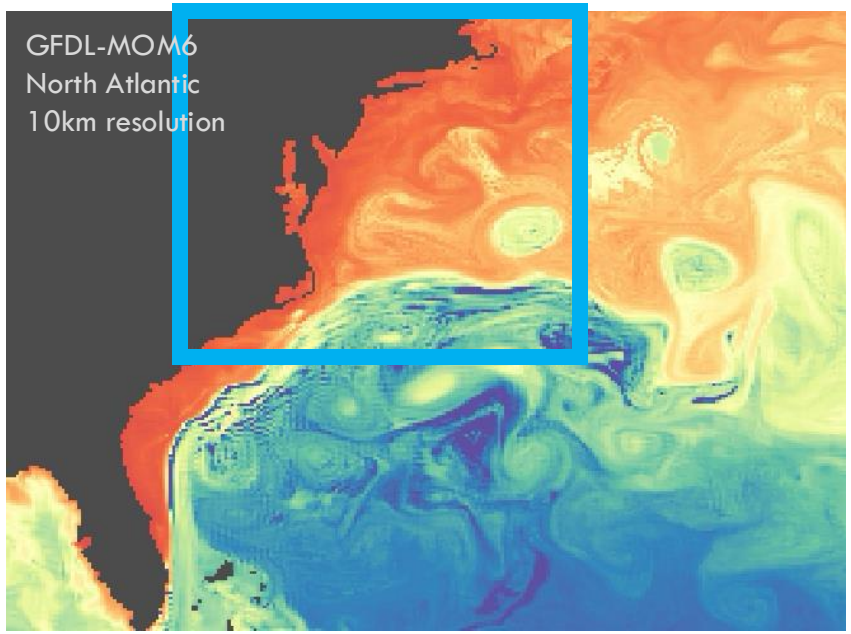


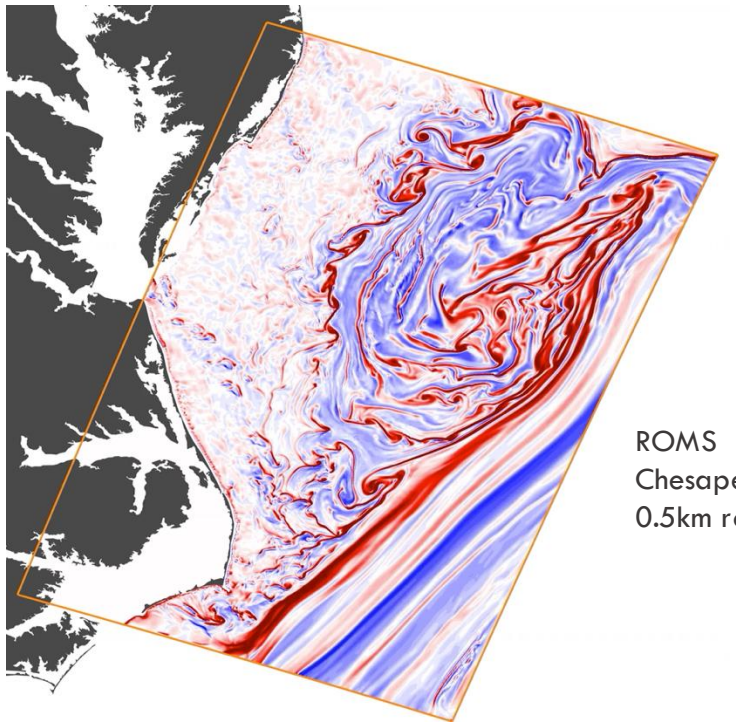
Sea surface Temperature



Vorticity





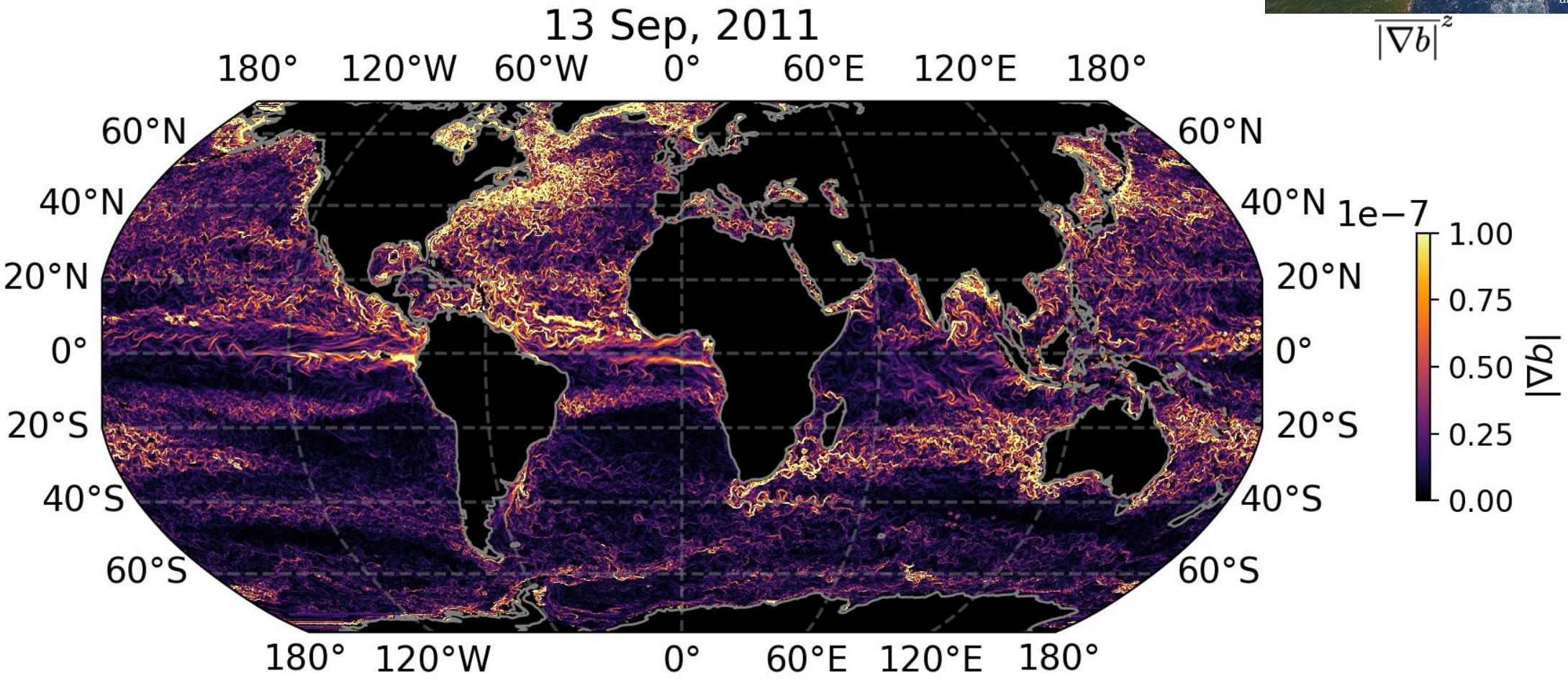


Courtesy of Julius Busecke

Courtesy of Jacob Wenegrat

Challenges in studying the upper ocean

$\overline{|\nabla b|}^z$



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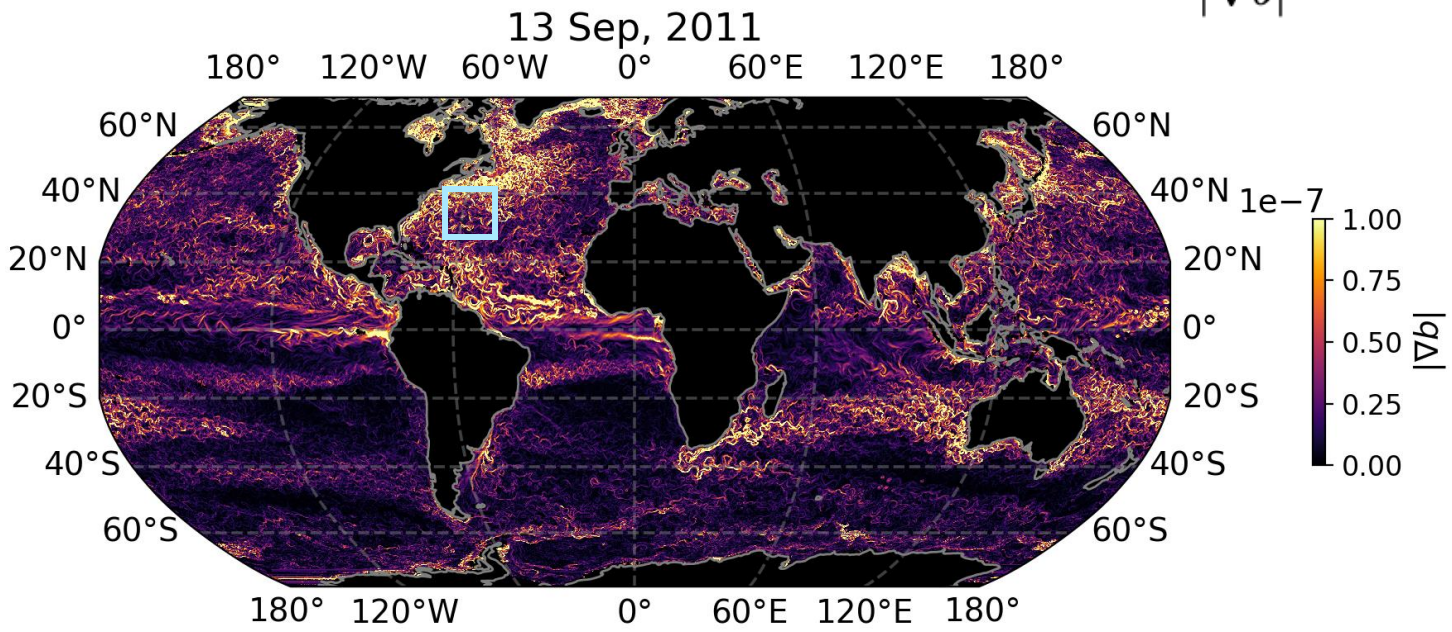
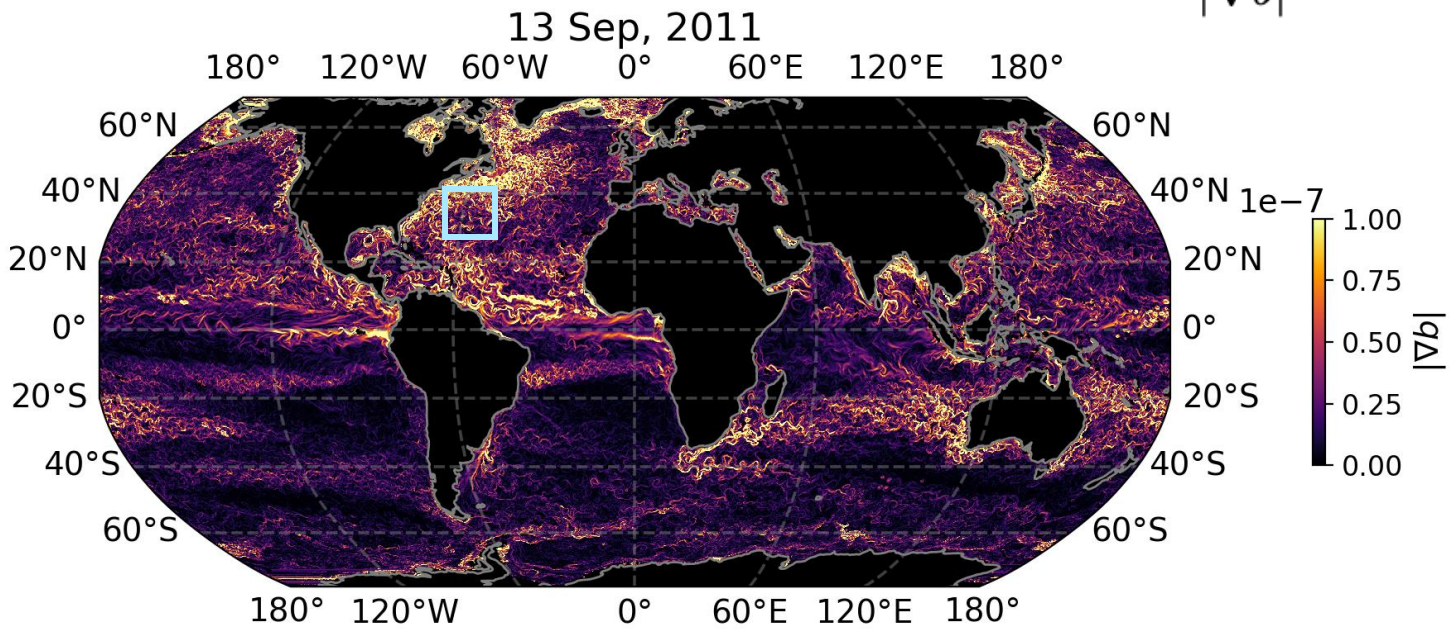


Challenges in studying the upper ocean

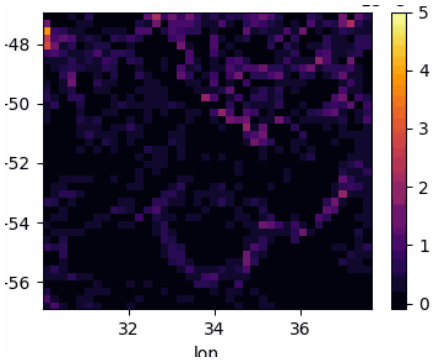
$$\overline{|\nabla b|}^z$$

vertical fluxes

$$\overline{w'b'}^z \propto \overline{|\nabla b|}^z$$



"truth" from high-res model



Challenges in studying the upper ocean

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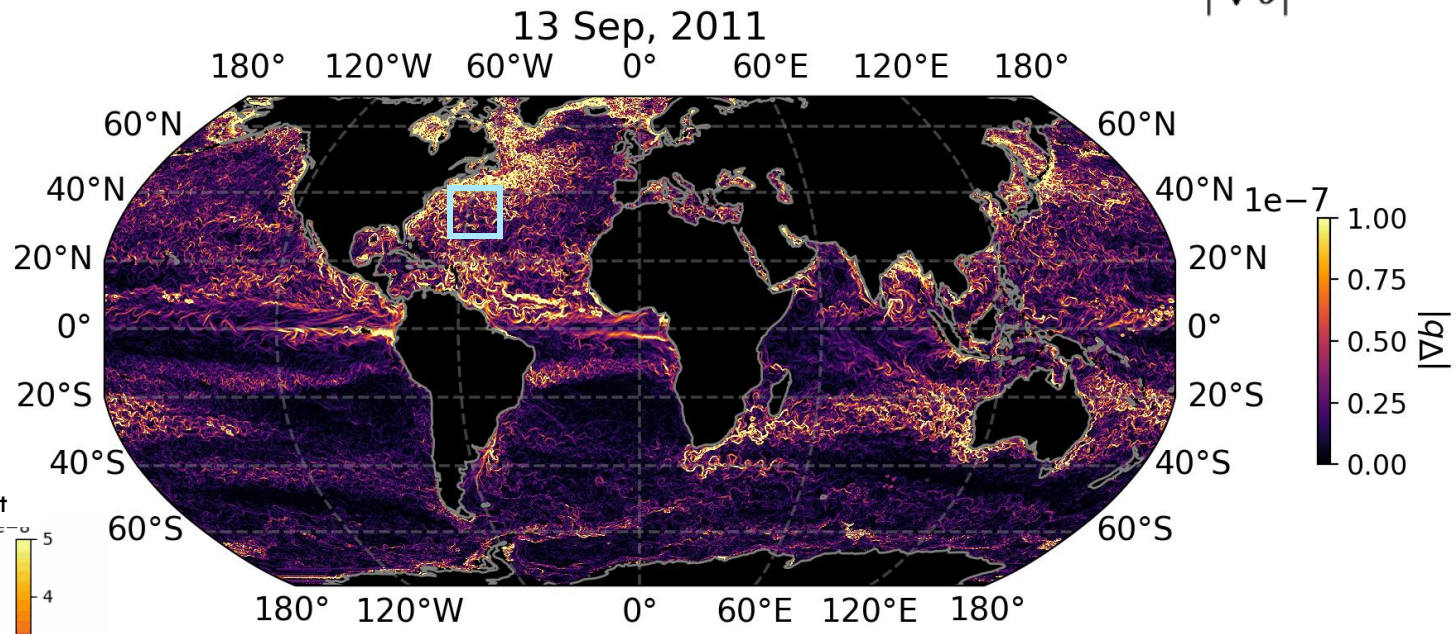
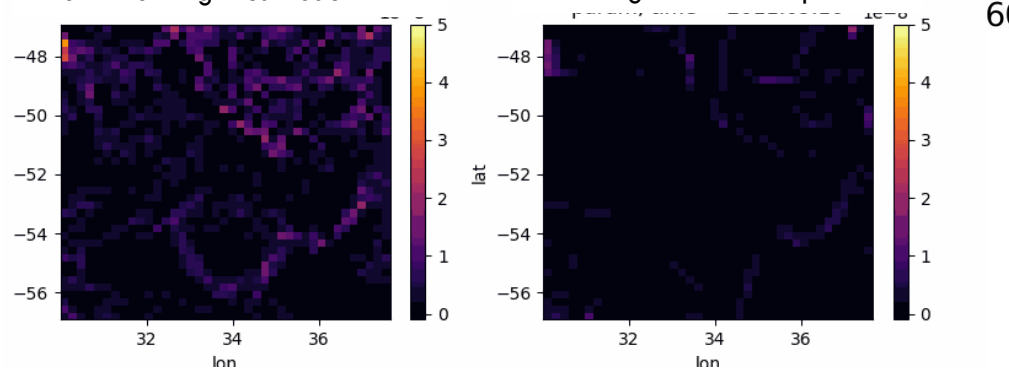


"truth" from high-res model

What global models predict



Mixed layer eddy parameterization
(Fox-Kemper et al 2008, 2011)

The submesoscale parameterization

MITgcm-llc4320 (horizontal resolution $1/48^o$ ~2km)

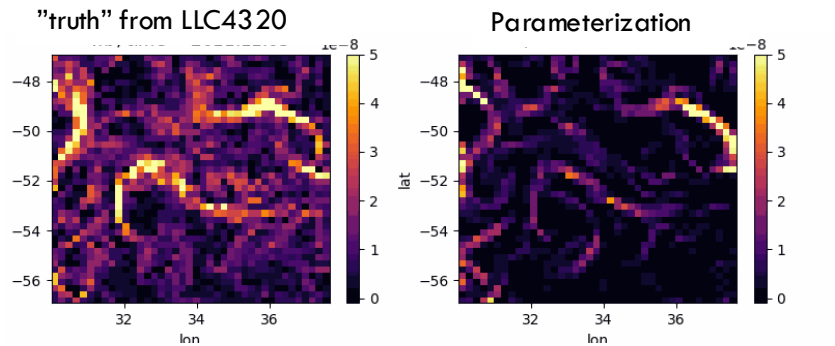
Bodner, & Fox-Kemper (2020).

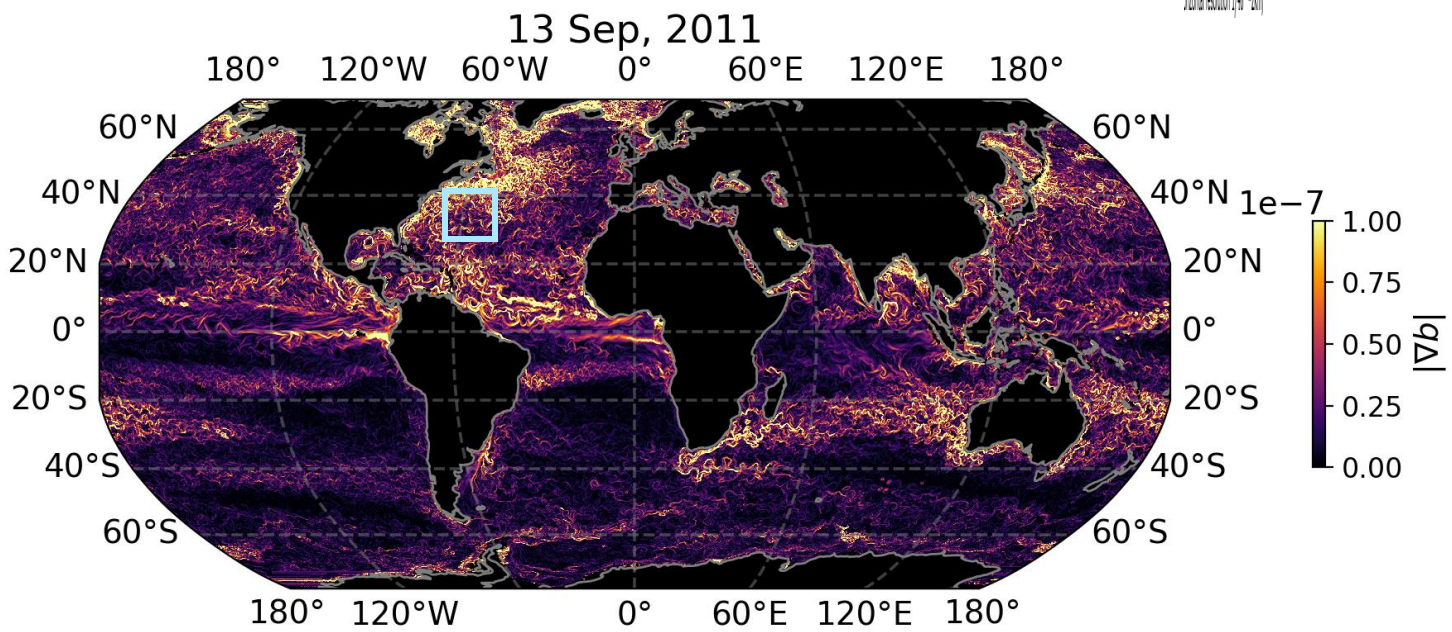
Bodner, et al. (2023)

vertical fluxes

Mixed layer eddy parameterization
(Fox-Kemper et al 2008, 2011)

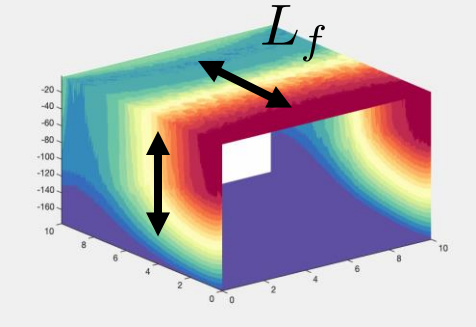
$$\overline{w'b'}^z \propto$$ horizontal resolution $1/48^o$ ~2km





Frontal width rescaling factor

L_f



What determines frontal width?

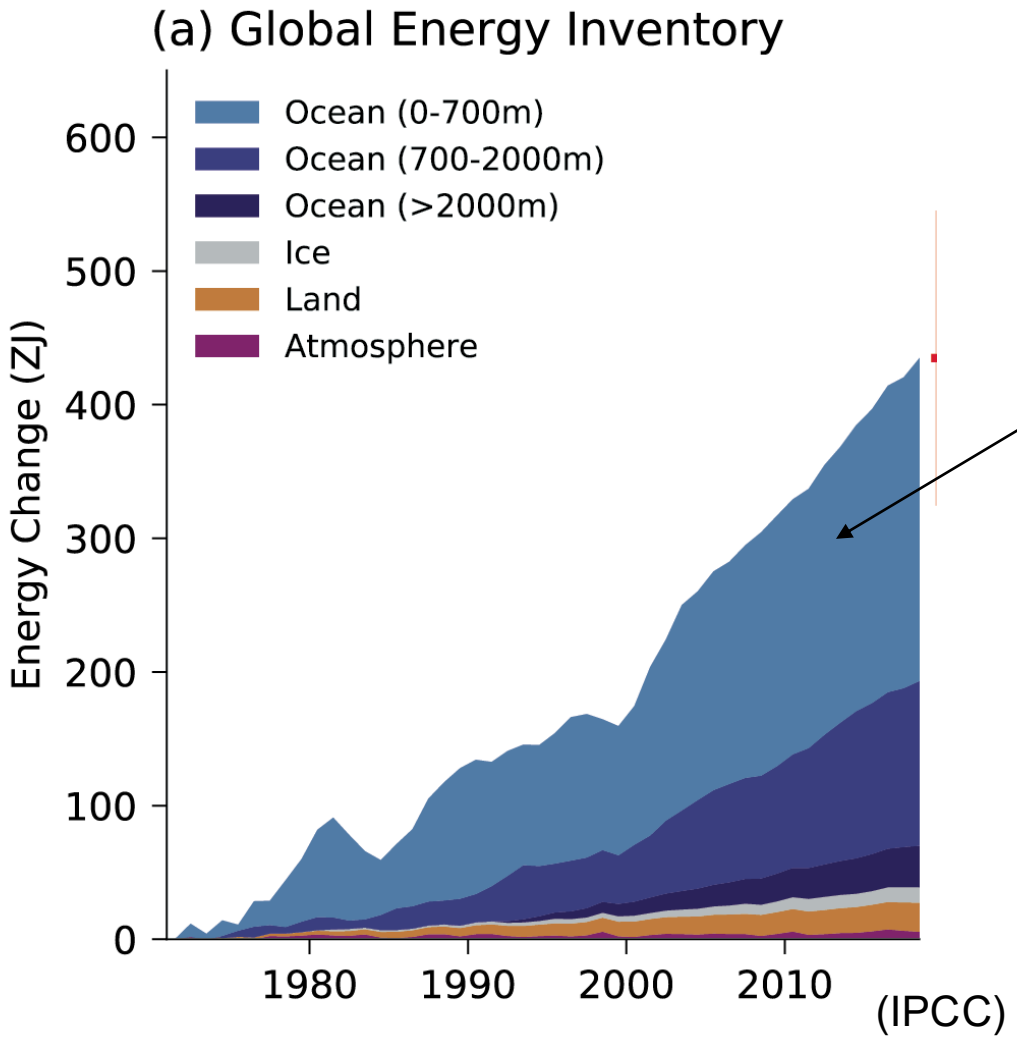
Turbulent parameters

$\vec{u_*}, w_*$ $h_{\mathbf{BL}}$

Improved theory

$$L_f = C_f \cdot \frac{(m_* u_*^3 + n_* w_*^3)^{\frac{2}{3}}}{f^2} \cdot \frac{1}{h}$$

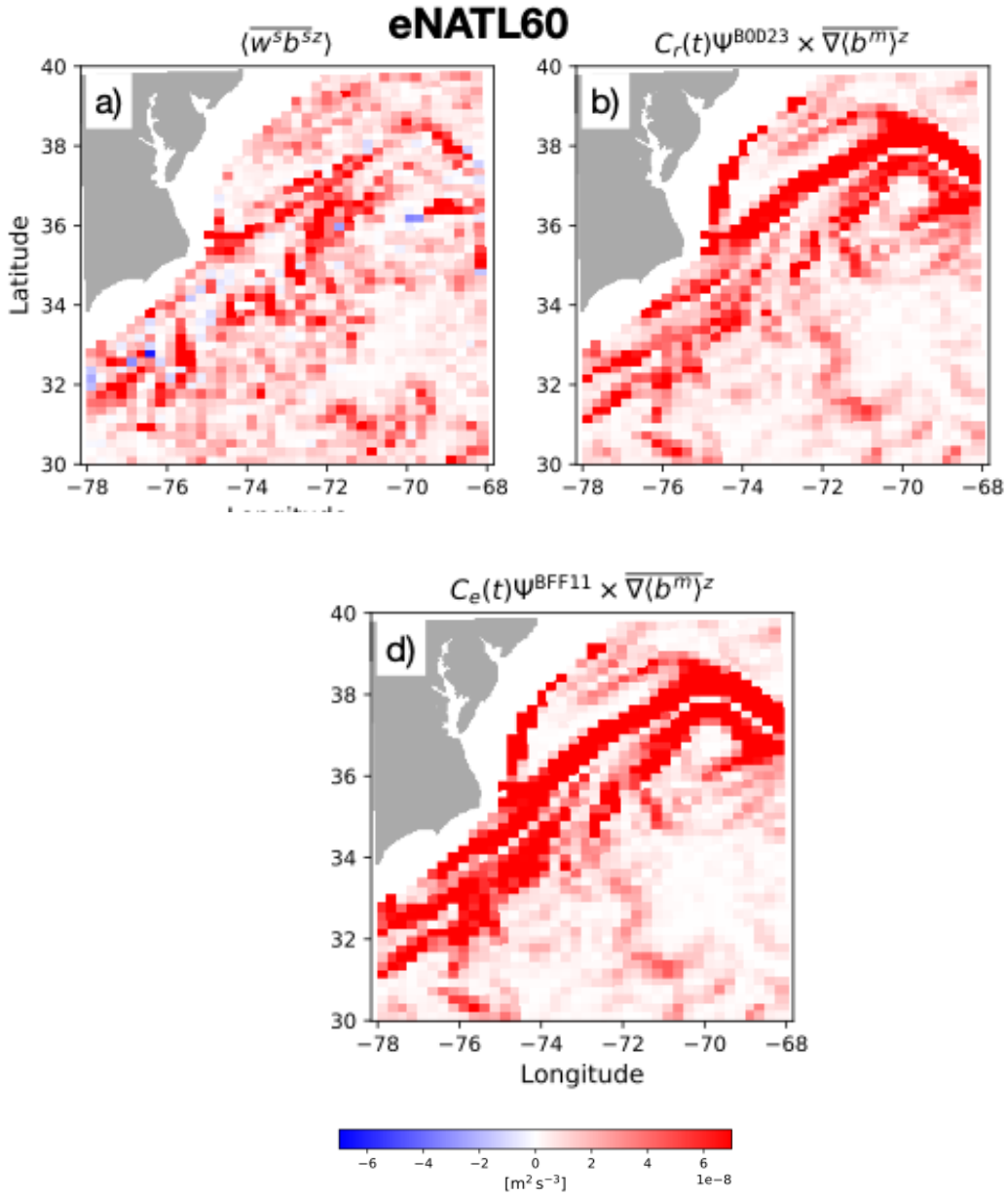
What is the impact of upper ocean turbulence on climate?



Most of the heat is in the upper ocean!

New parameterization estimates stronger submesoscale fluxes

Uchida, Bodner et al (under review, GRL)



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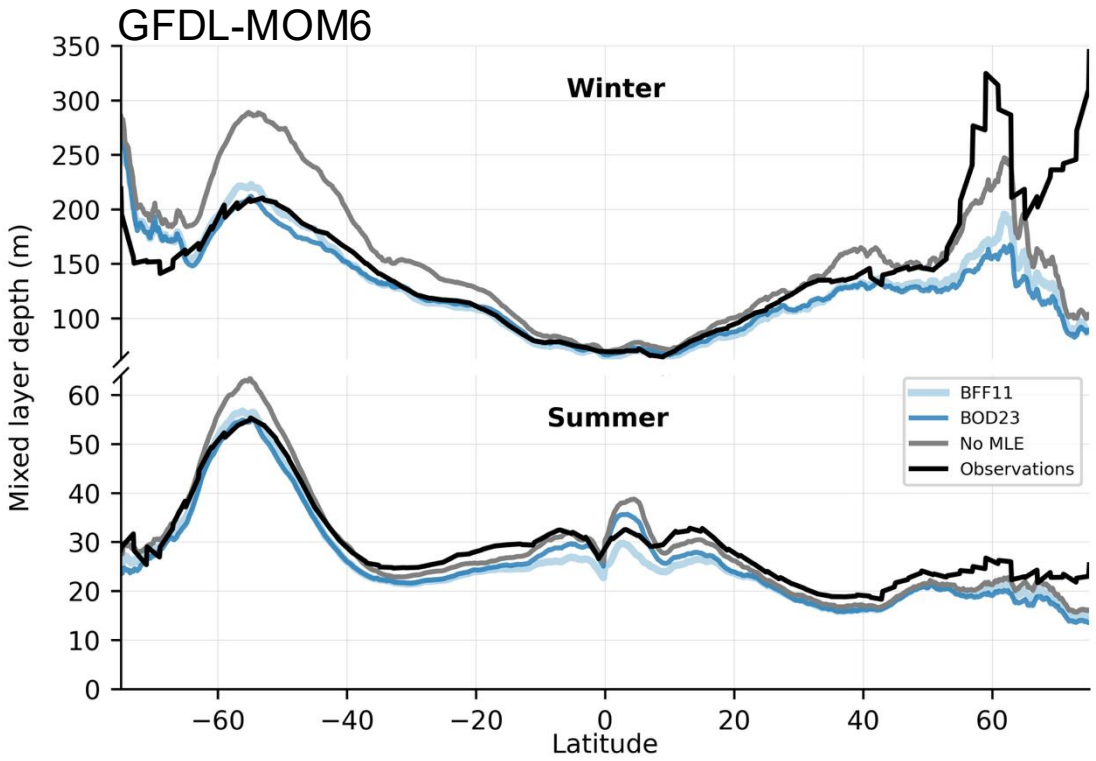
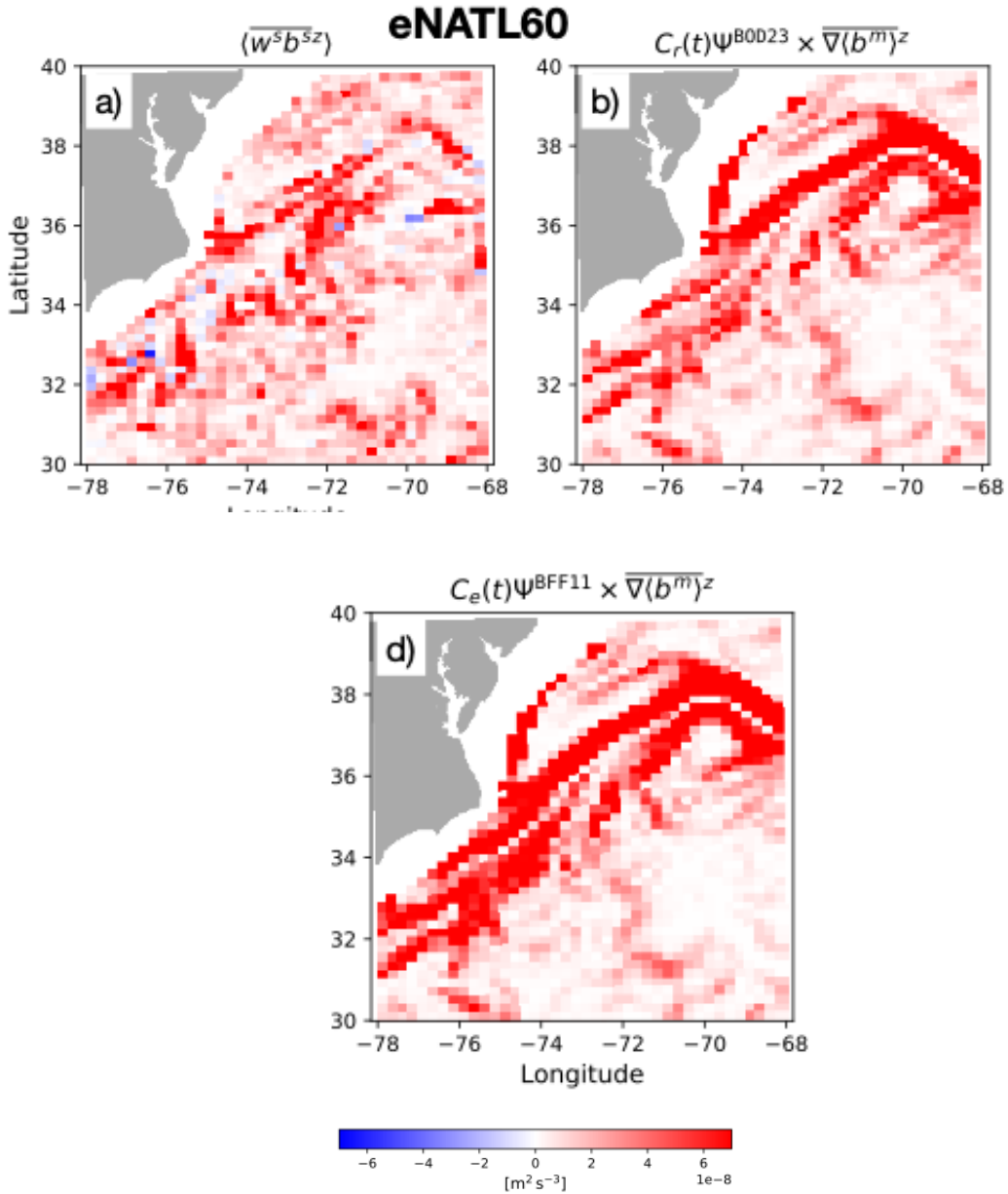


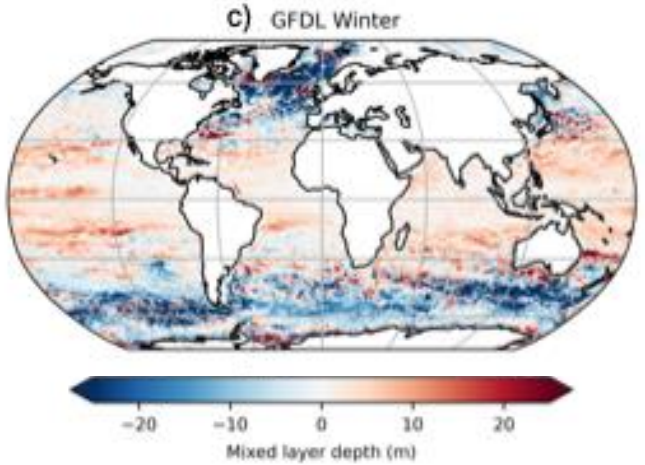
differences in zonal mean MLD are smaller than the biases that arise without any MLE representation

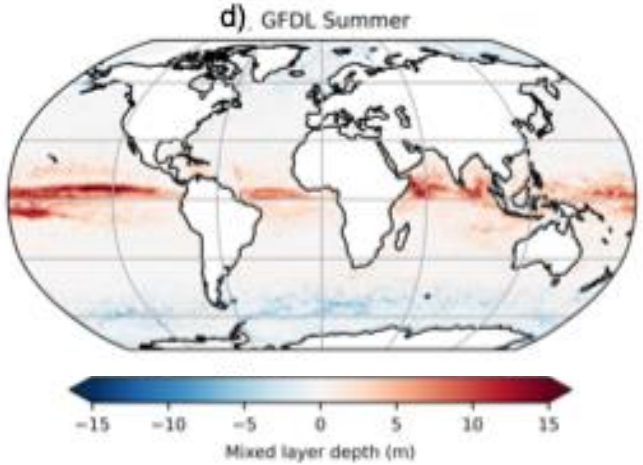


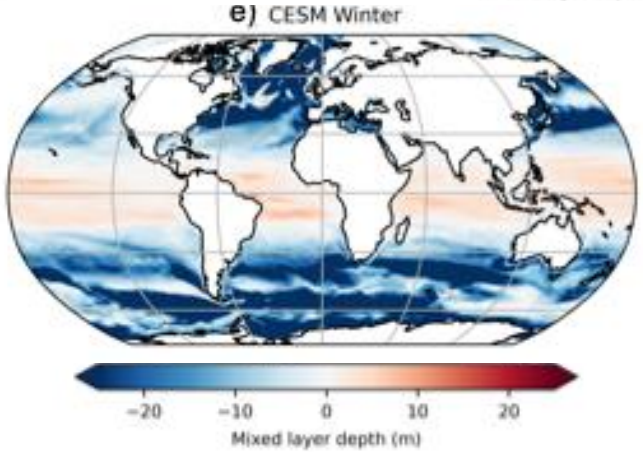
GFDL-MOM6 CESM-MOM6 BLOM

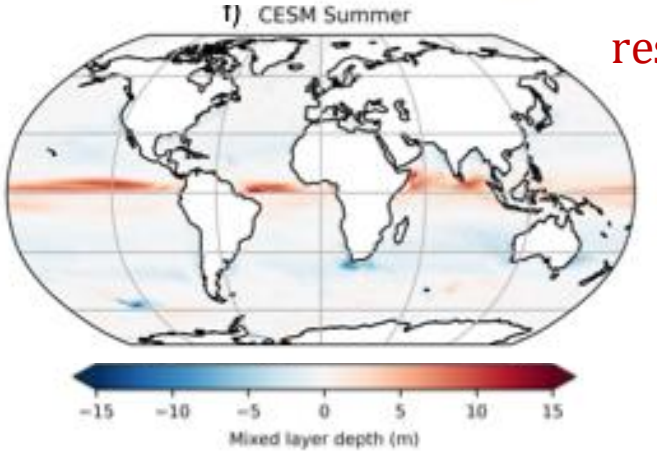
Mixed layer depth

Results from Bodner23 minus results from Fox-Kemper 2011



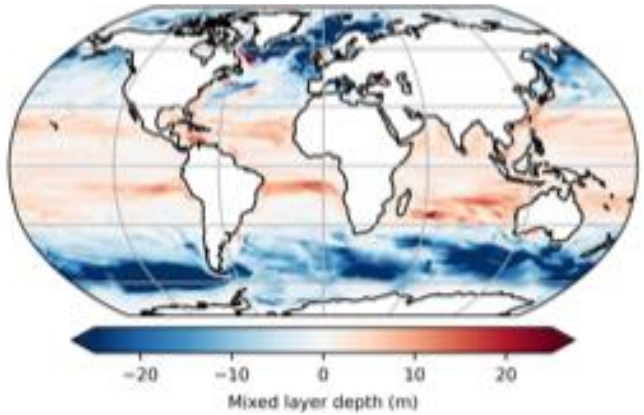


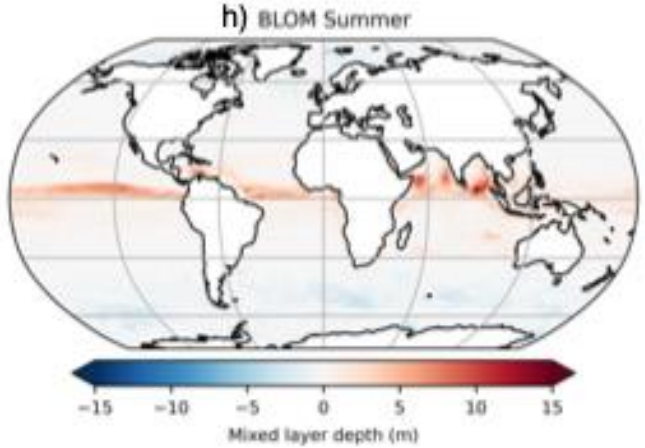




BOD23 reduces restratification

BOD23 Increases restratification

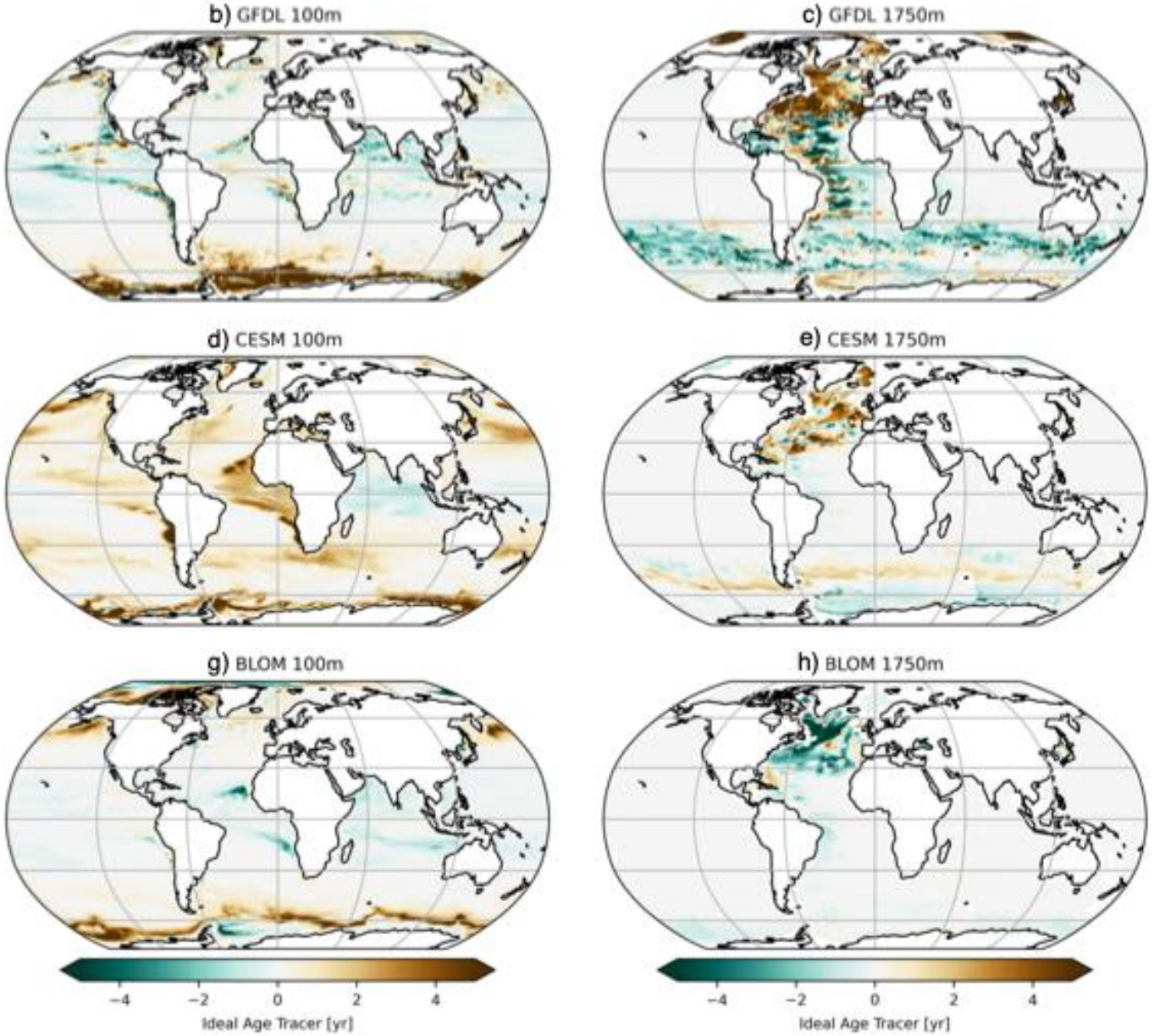




Results from Bodner23 minus
results from Fox-Kemper 2011

GFDL-MOM6 CESM-MOM6 BLOM

Ideal Age



BOD23 reduces ventilation

BOD23 increases ventilation

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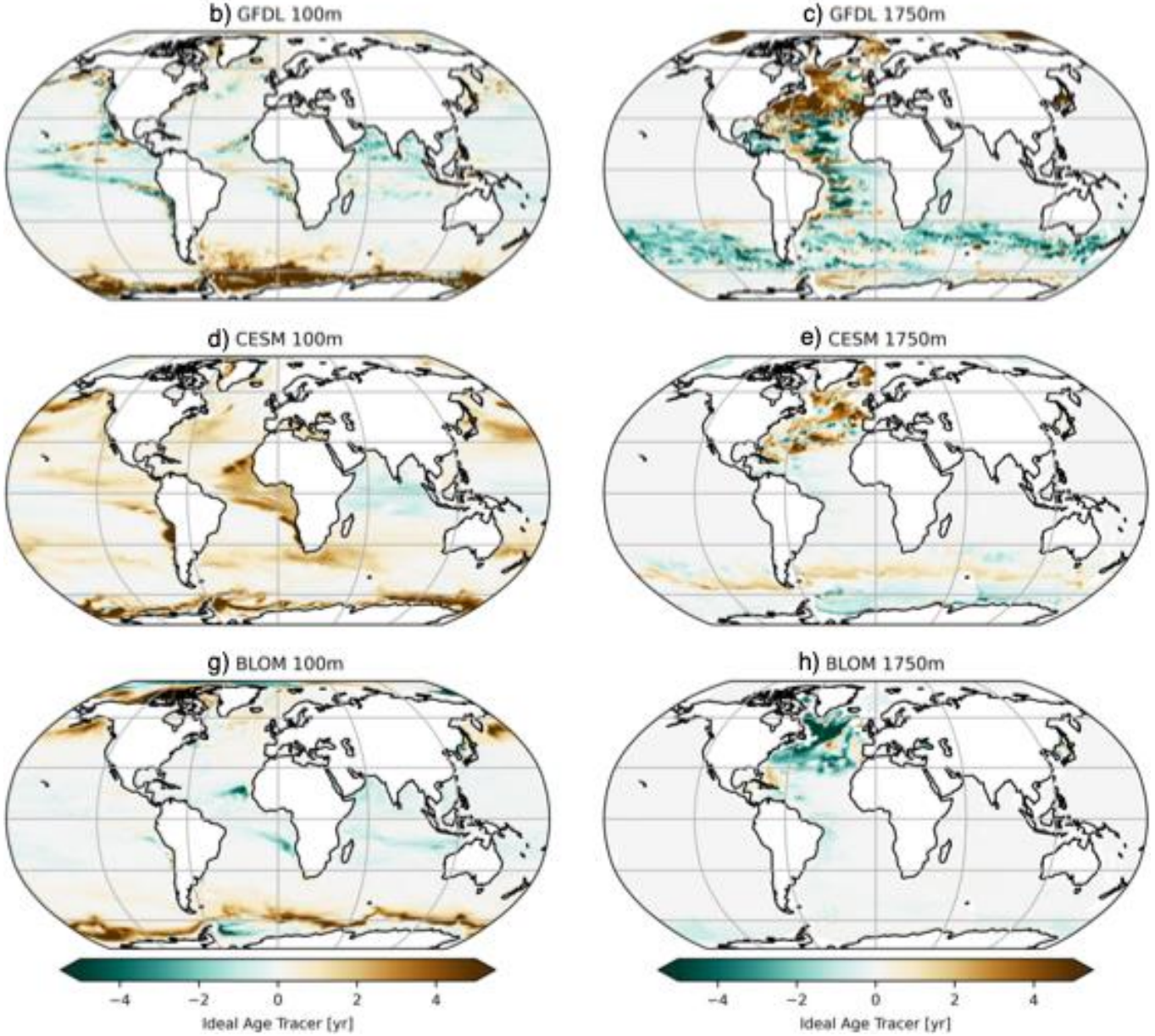
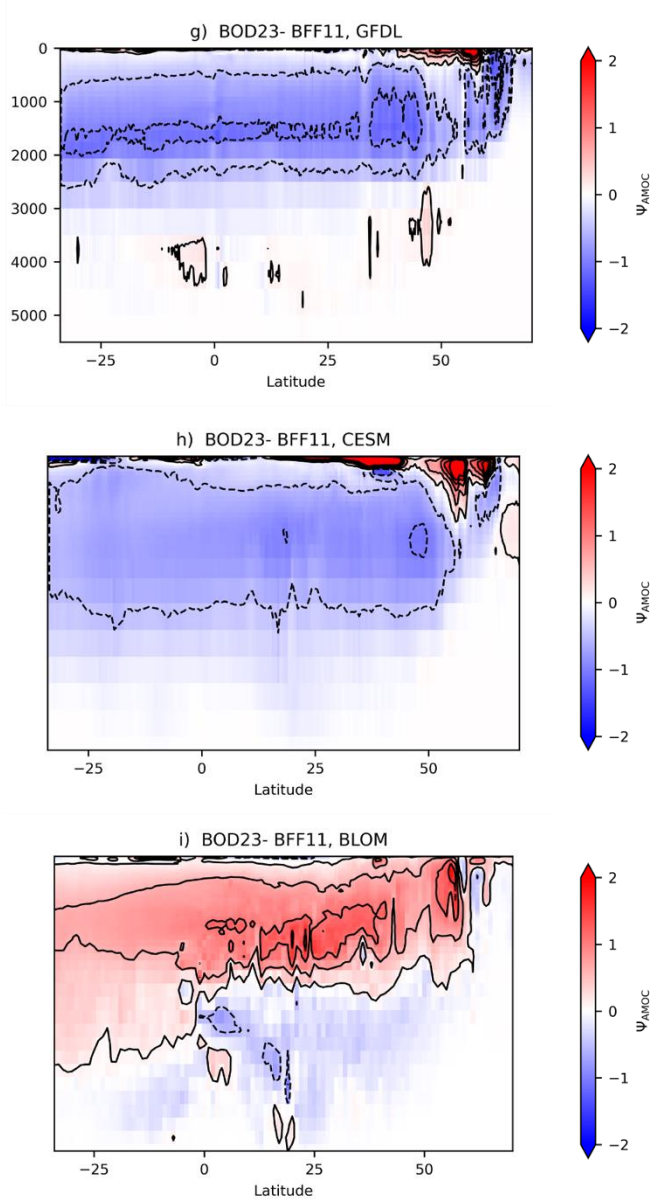


AMOC



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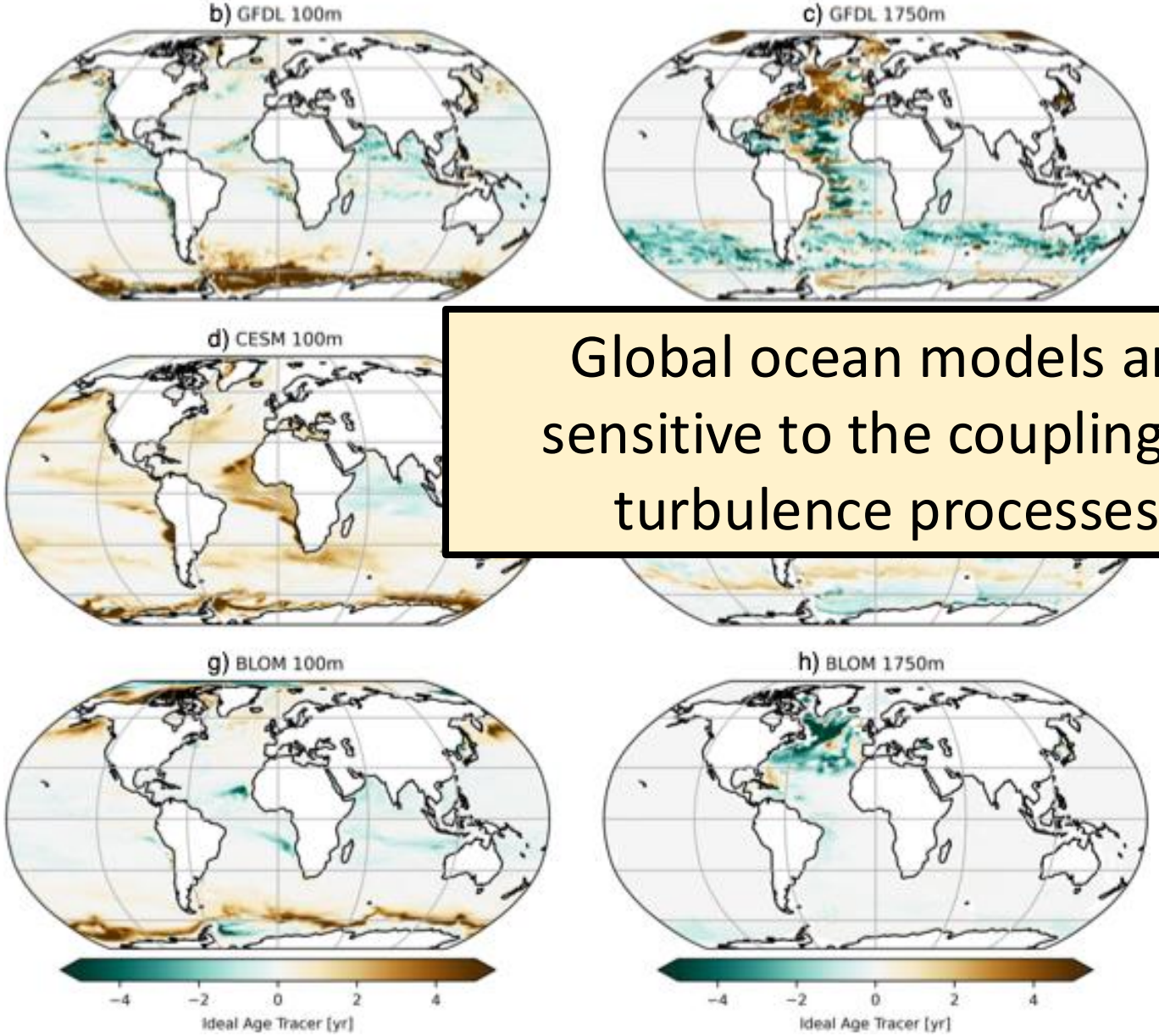

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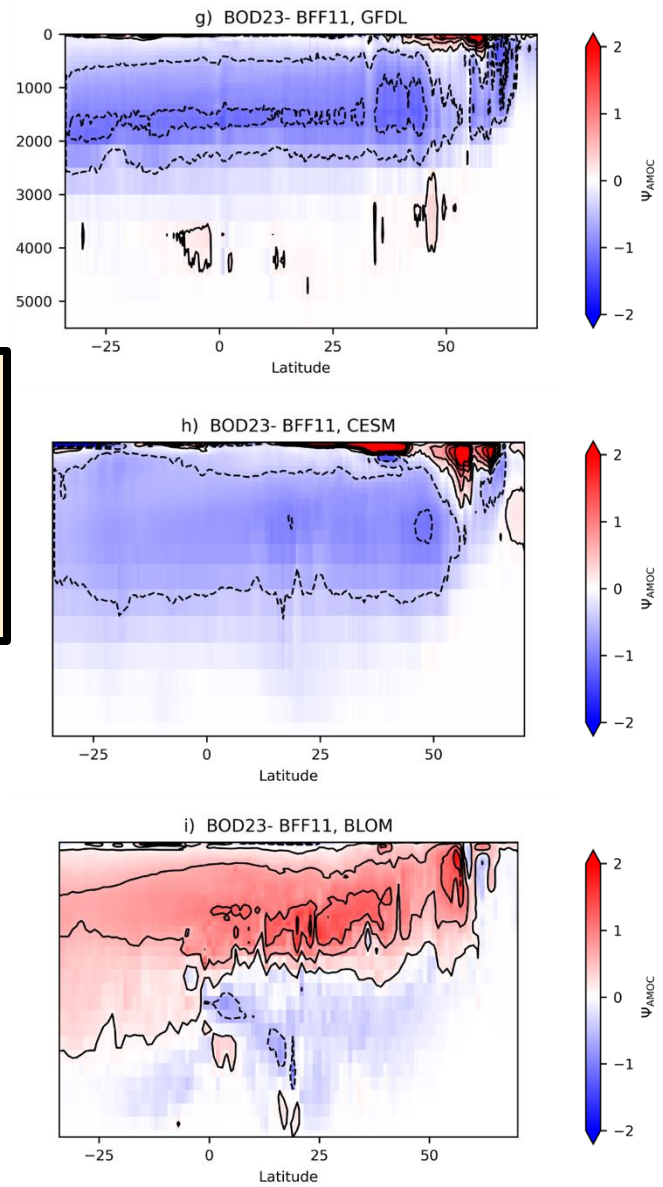
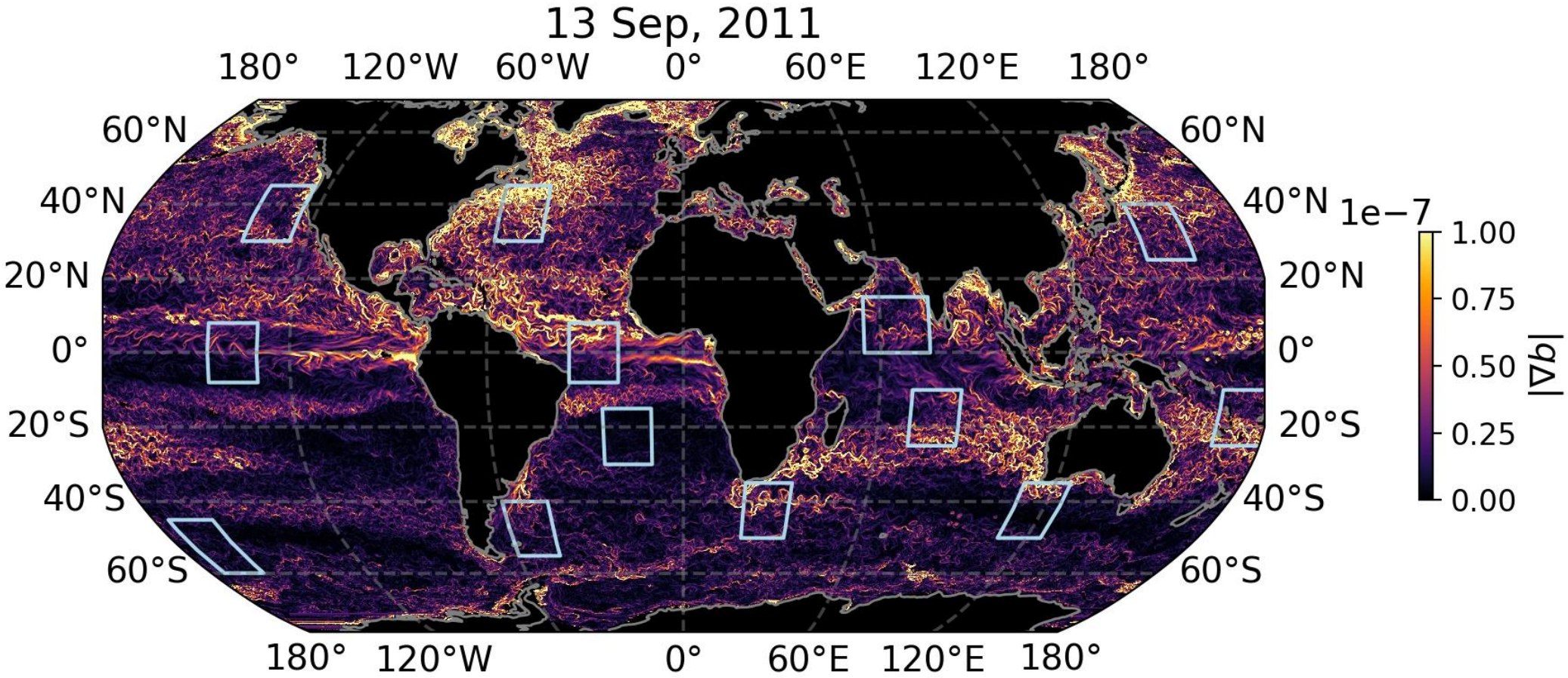


Global ocean models are sensitive to the coupling of turbulence processes

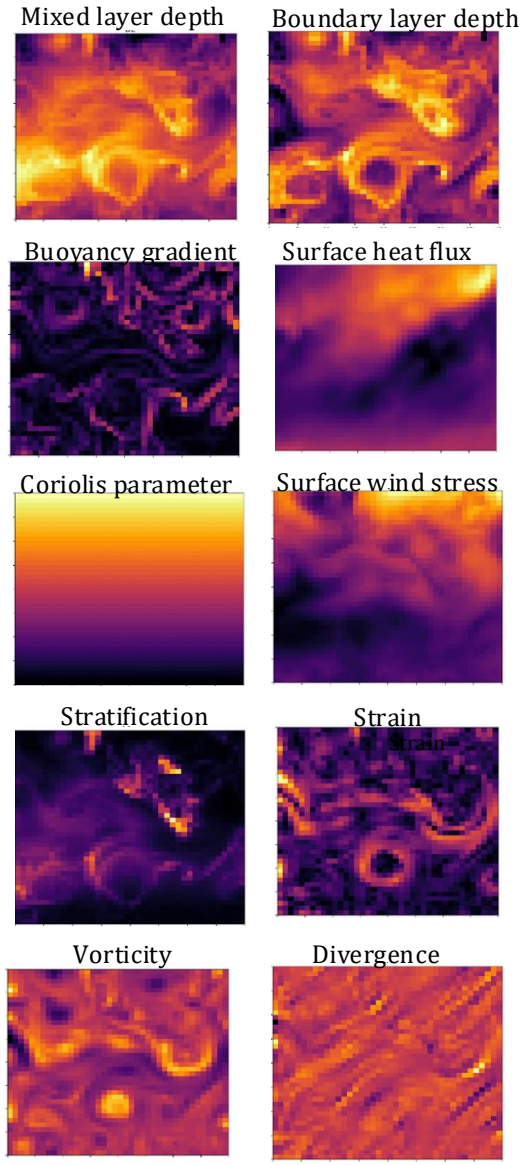
Data-driven submesoscale parameterization

MITgcm-llc4320 (horizontal resolution $1/48^o$ ~2km)



Bodner, Balwada, Zanna (in press, JAMES)

Data-driven submesoscale parameterization



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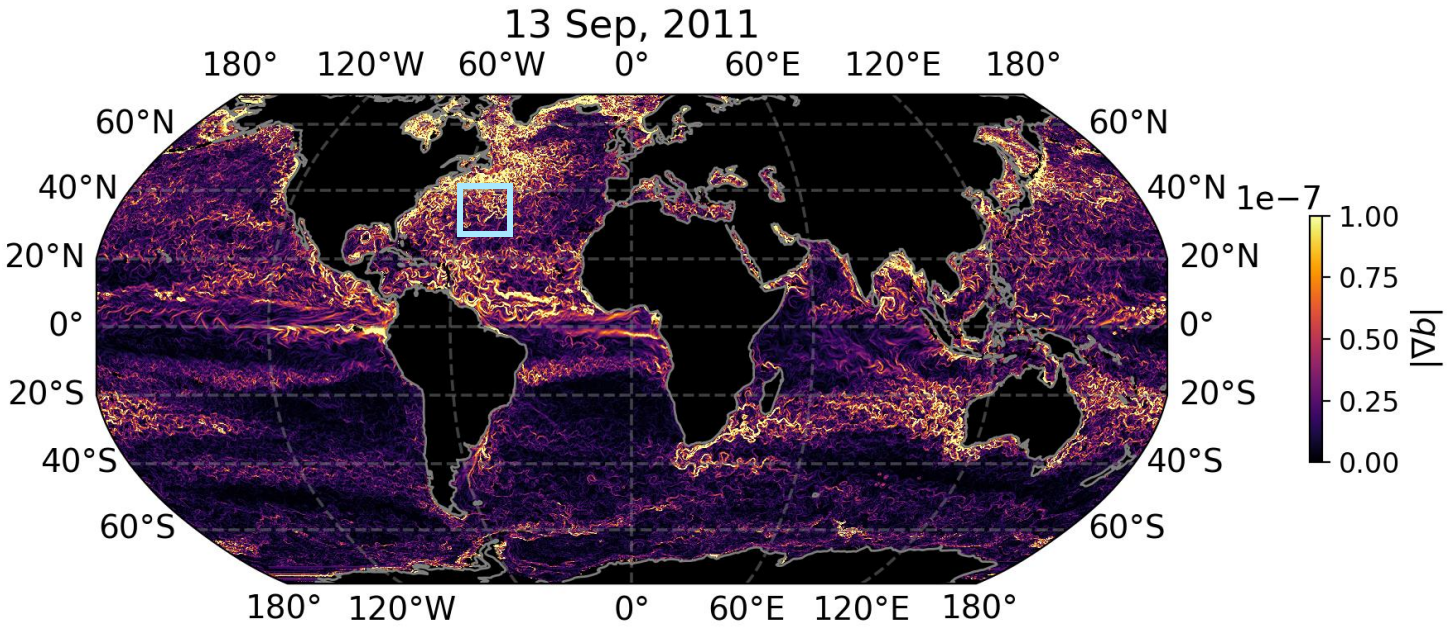
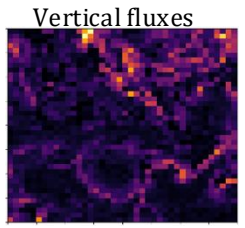


Given a set of relevant variables: predict vertical fluxes directly computed from data



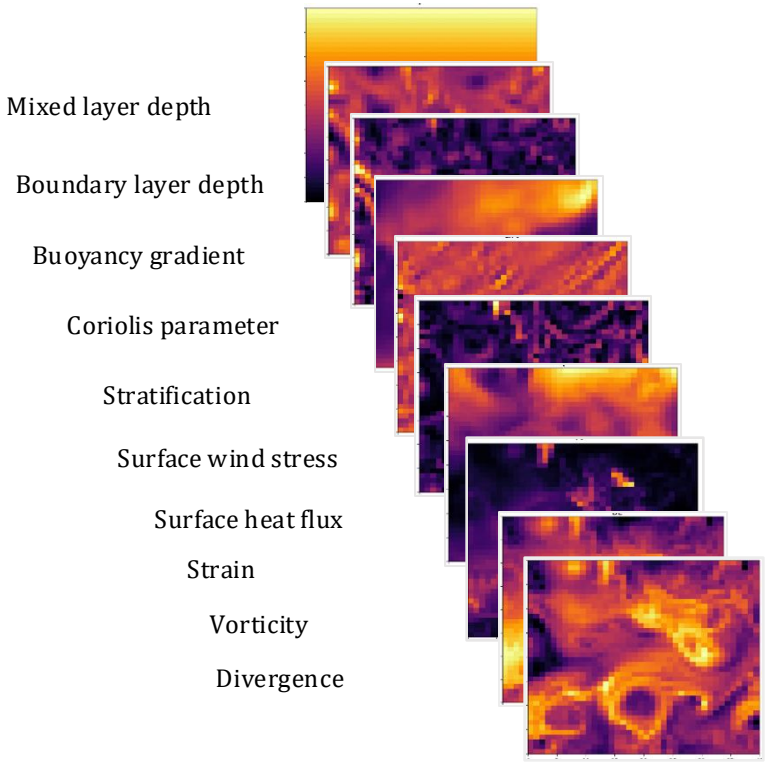
Bodner, Balwada, Zanna (in press, JAMES)

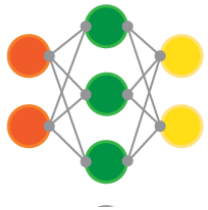
Data-driven submesoscale parameterization

MITgcm-llc4320 (horizontal resolution $1/48^o$ ~2km)

Inputs

Variables resolved by General Circulation Models



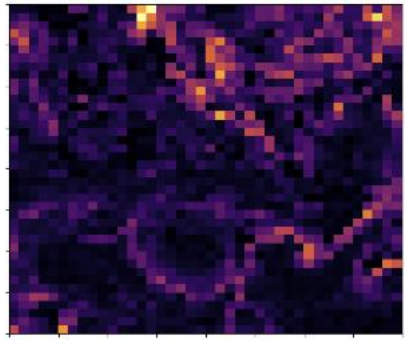


Fully Convolutional Neural Network

Output

Submesoscale vertical buoyancy fluxes

$$\overline{w'b'}$$



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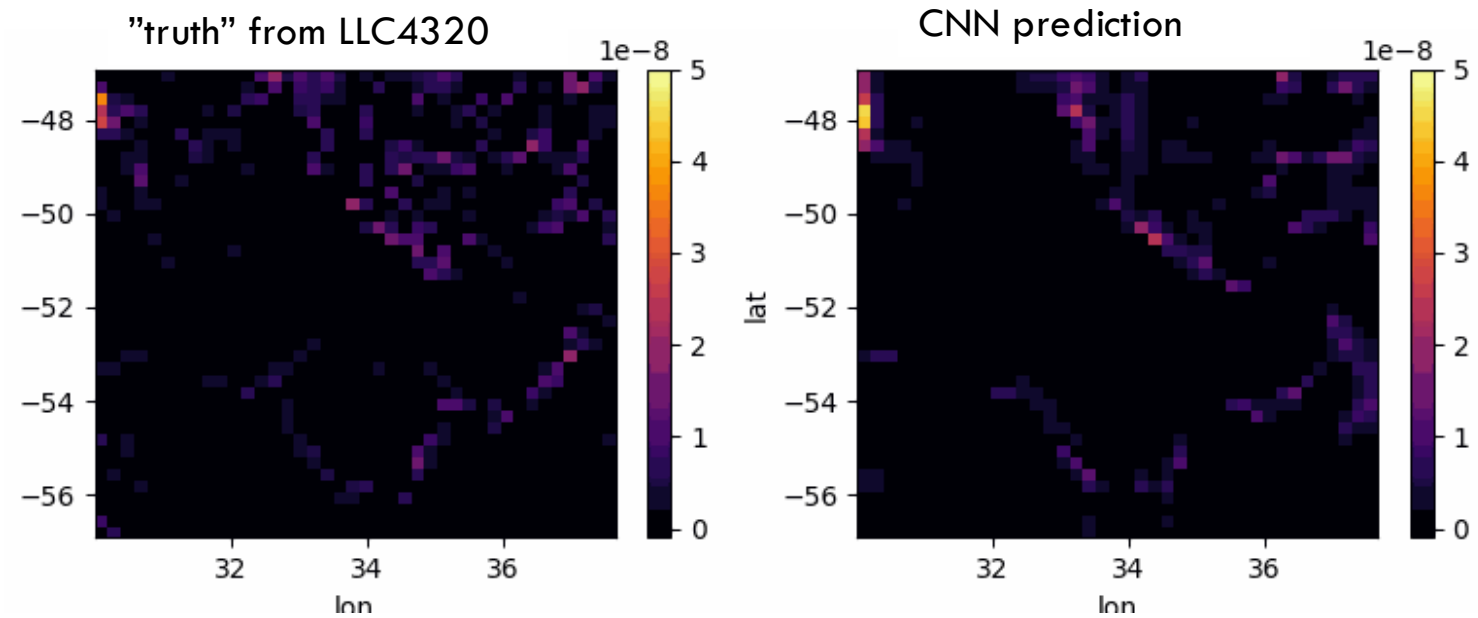
Bodner, Balwada, Zanna (in press, JAMES)

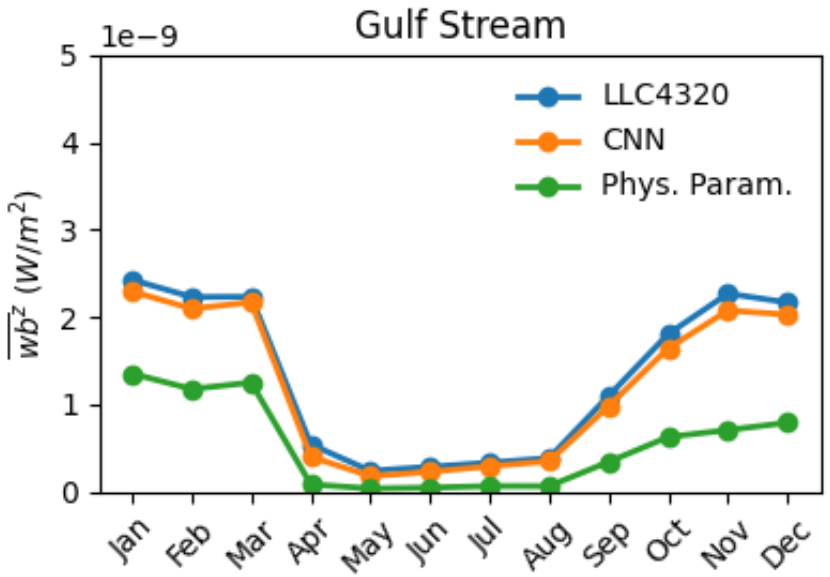
Prediction on unseen data

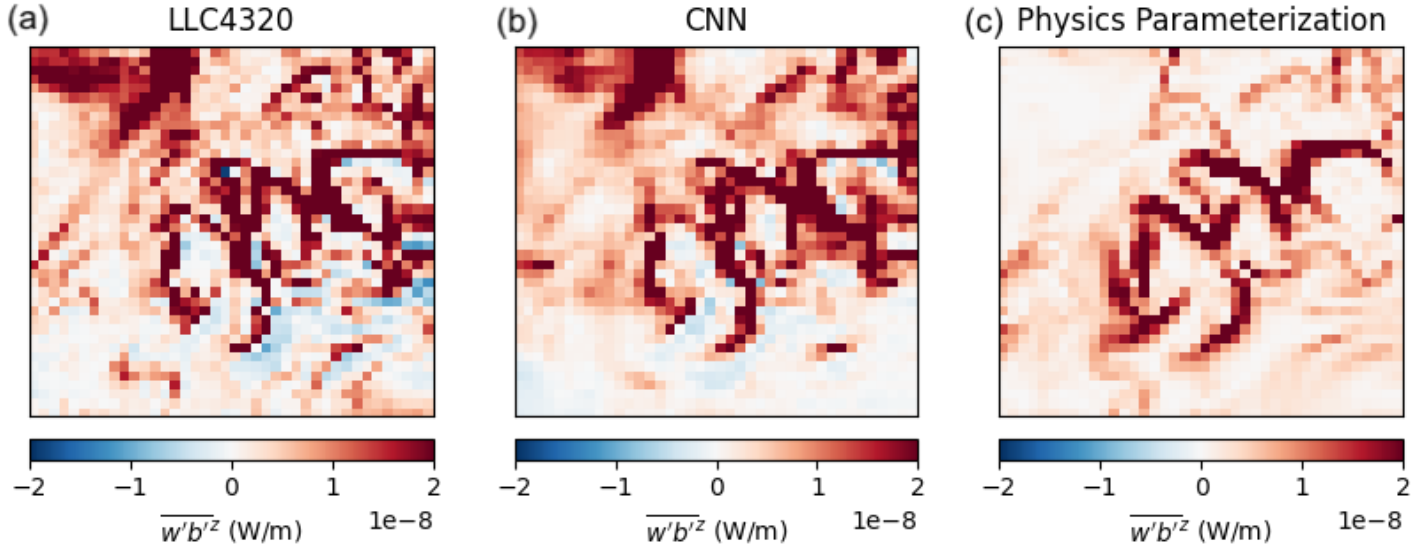
- The CNN captures the overall structure, including negative fluxes

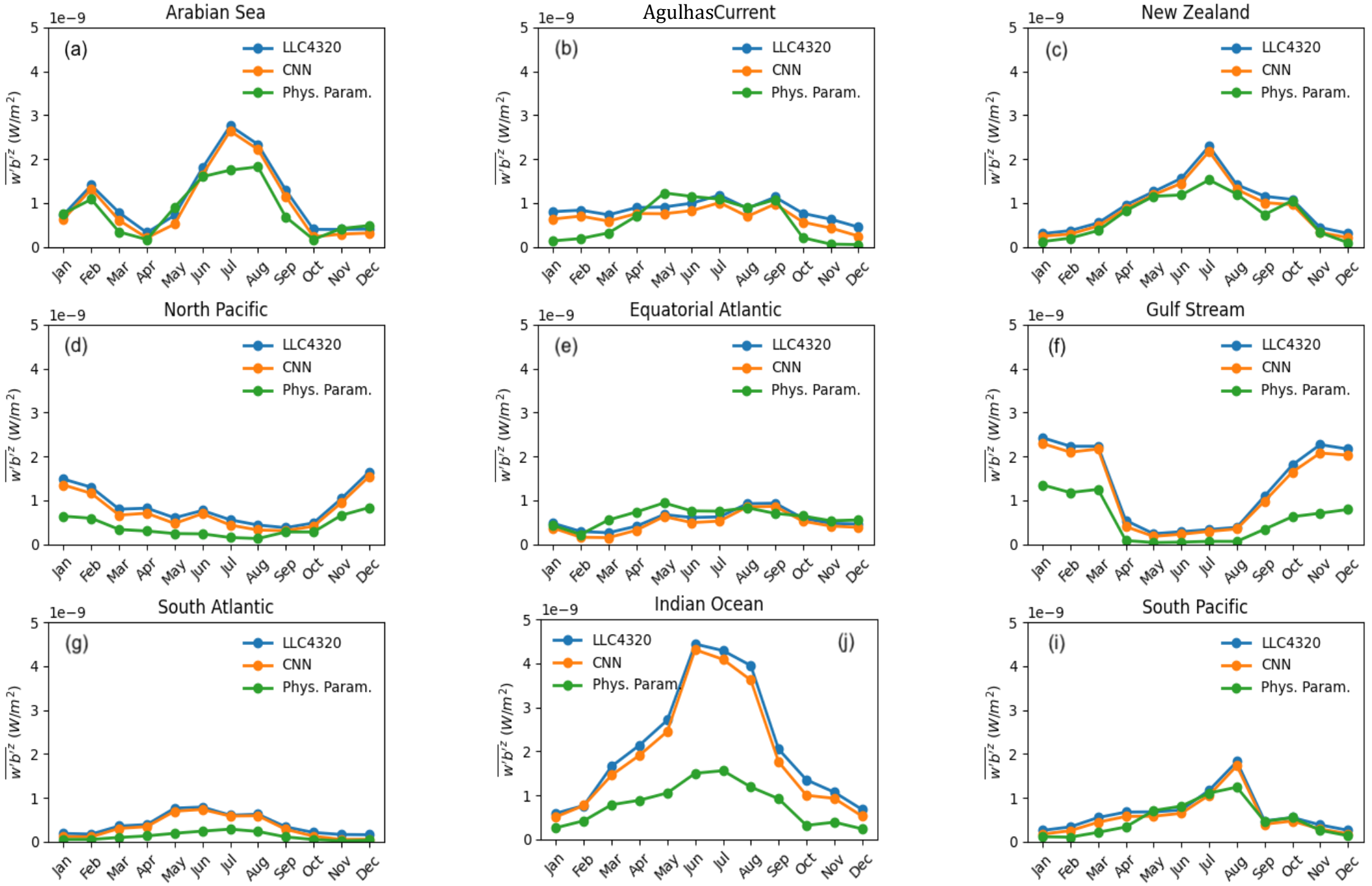


Prediction on unseen data

- The CNN captures the overall structure, including negative fluxes
- the CNN predictions outperforms the physics-based parameterization, particularly during months of strong submesoscale fluxes.






Arabian Sea
AgulhasCurrent
New Zealand
North Pacific
Equatorial Atlantic
Gulf Stream
South Atlantic
Indian Ocean
South Pacific
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(j)
(i)
LLC4320
CNN
Phys. Param.
1e−9
$\overline{w'b'^z}$ (W/m^2)
Jan
Feb
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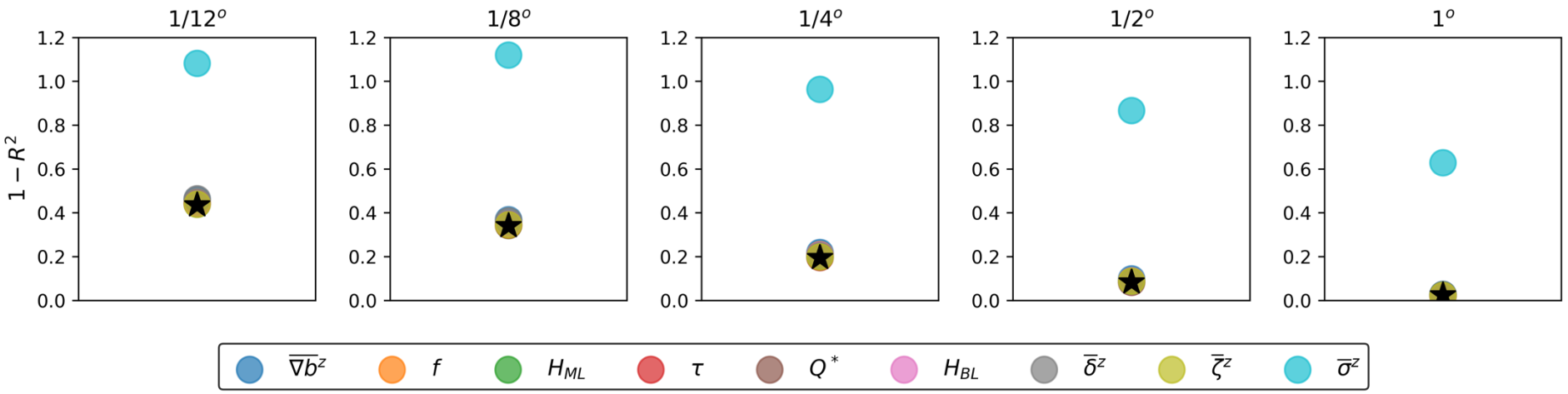
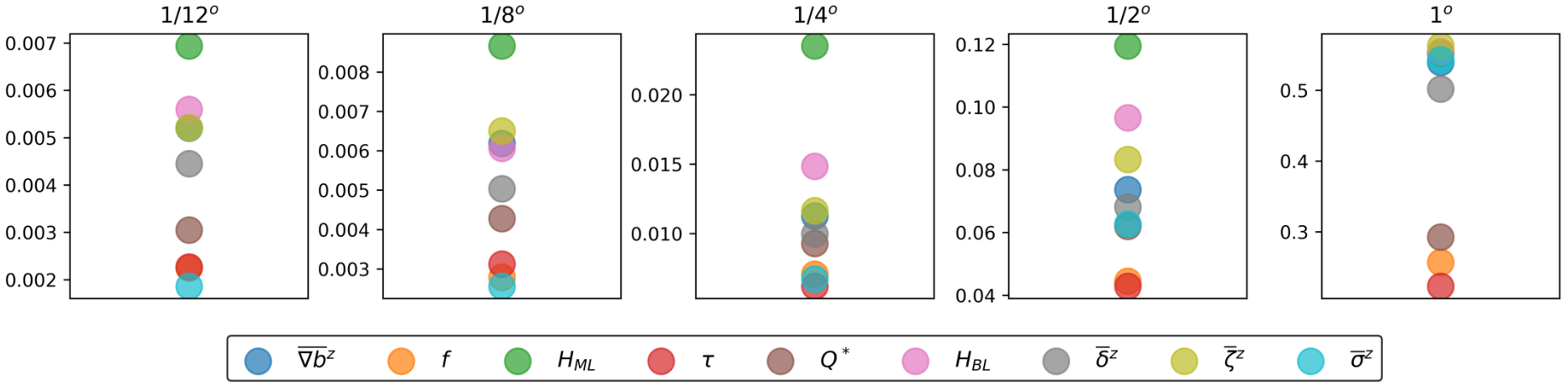
Oct
Nov
Dec

But why so good?

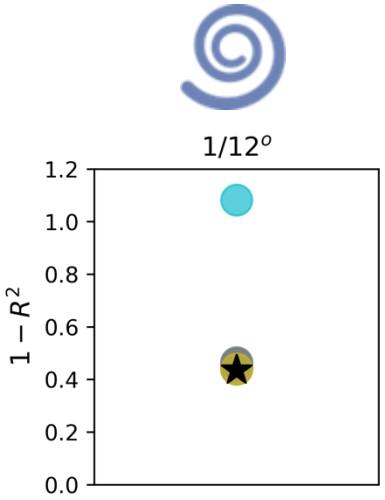


Remove input feature

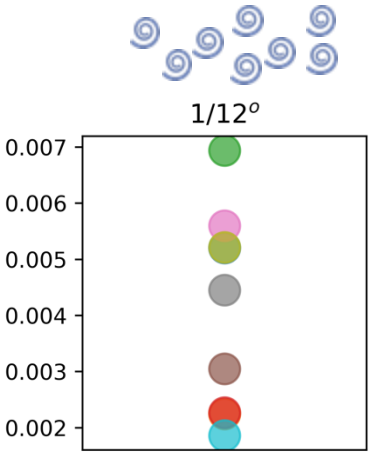


Sensitivity (gradients) relative to input feature

But why so good?

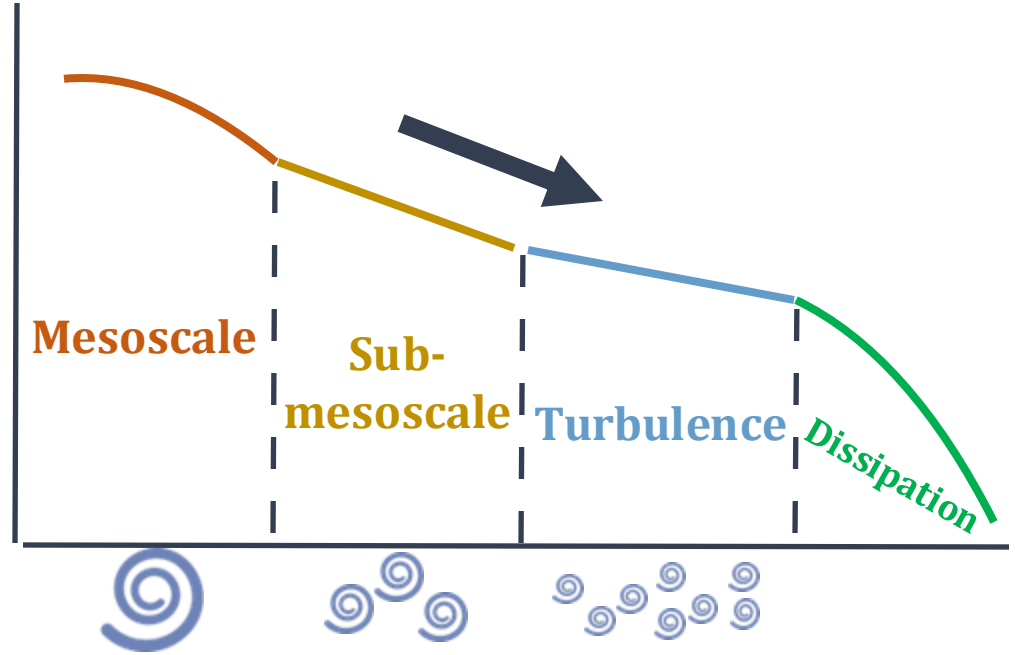


Remove input feature



Sensitivity (gradients) relative to input feature

Multiscale interactions determine submesoscale flux!

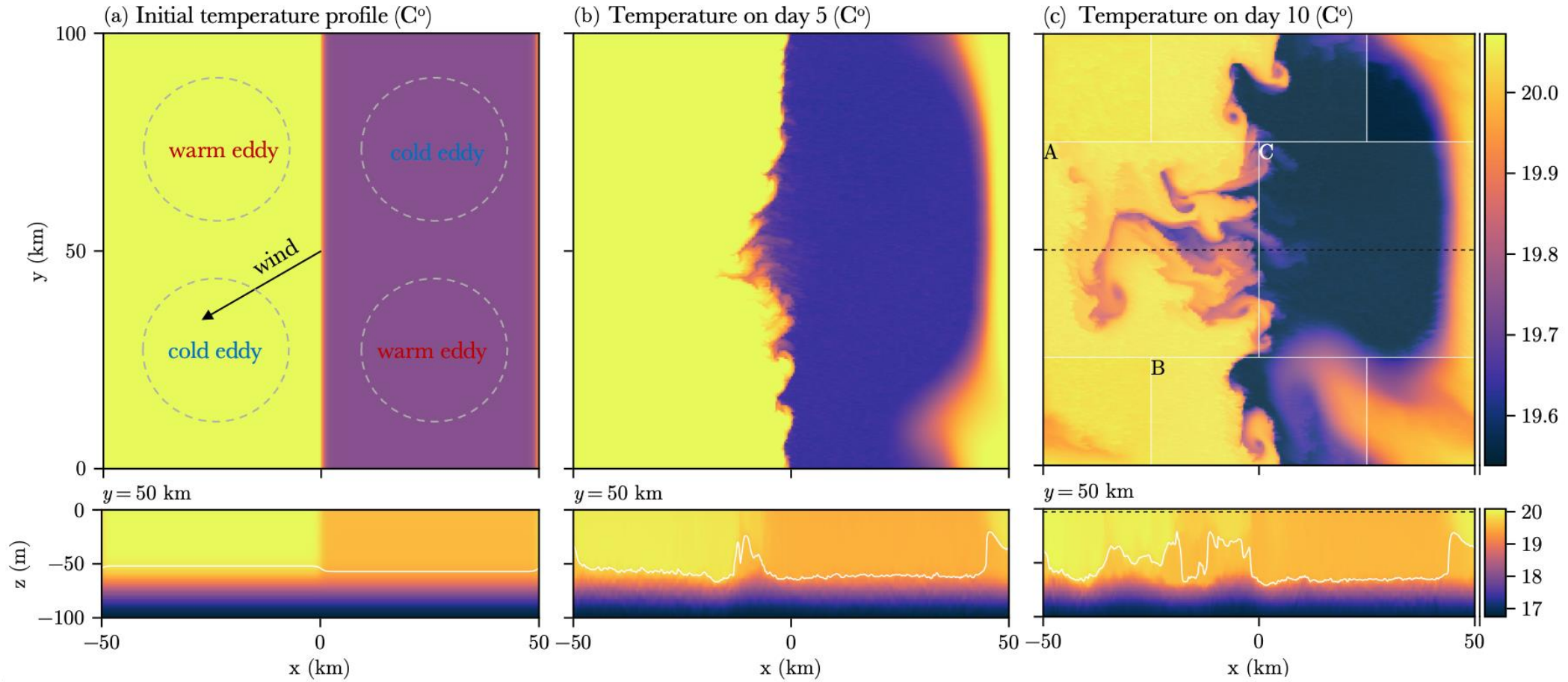


Pushing the limit of multiscale modeling


Sarah Snider


Shirui Peng


Simone Silvestri



Peng, Bodner & Silvestri (In prep.)

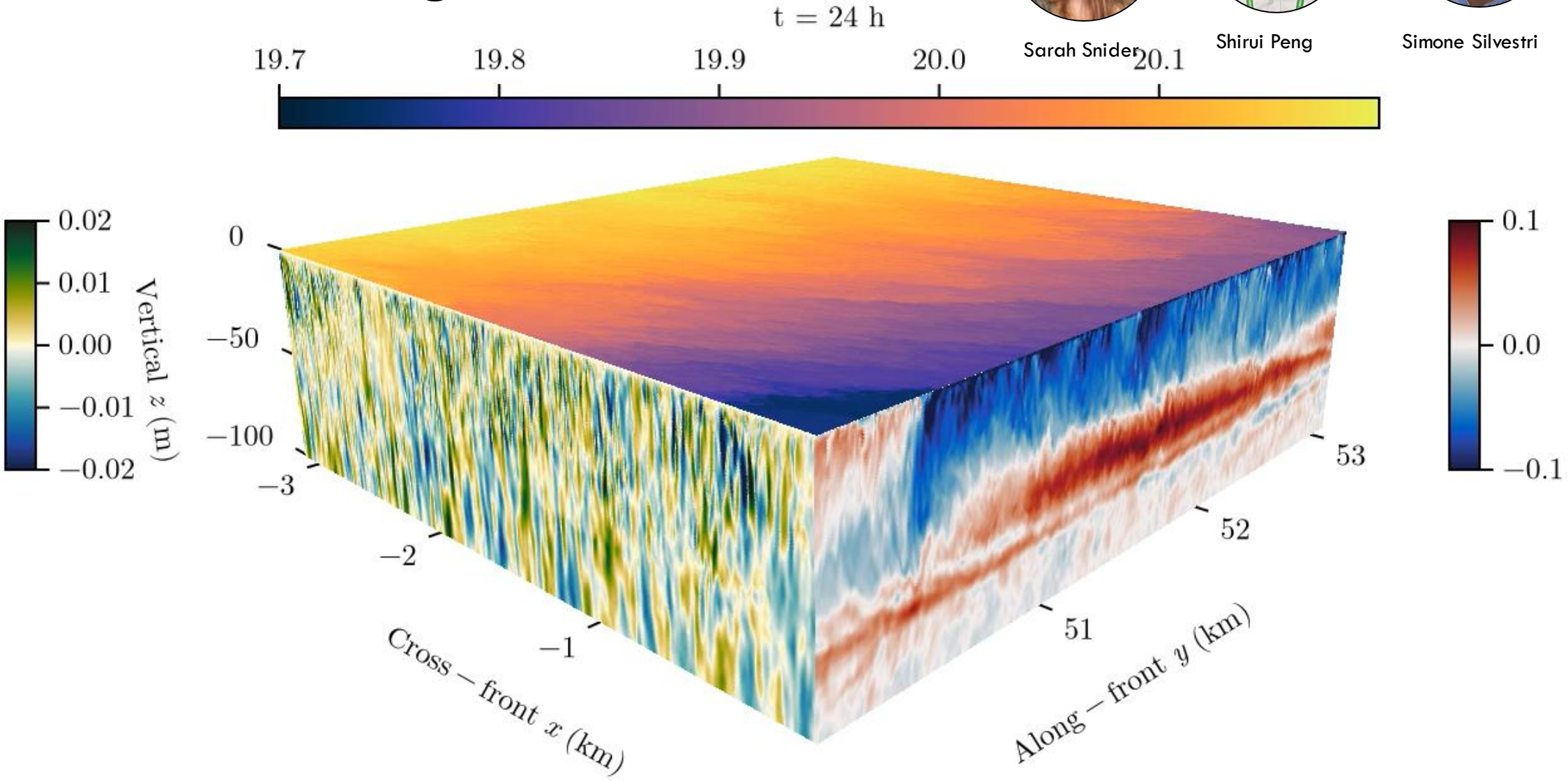
Oceananigans.jl

Pushing the limit of multiscale modeling

Sarah Snider

Shirui Peng

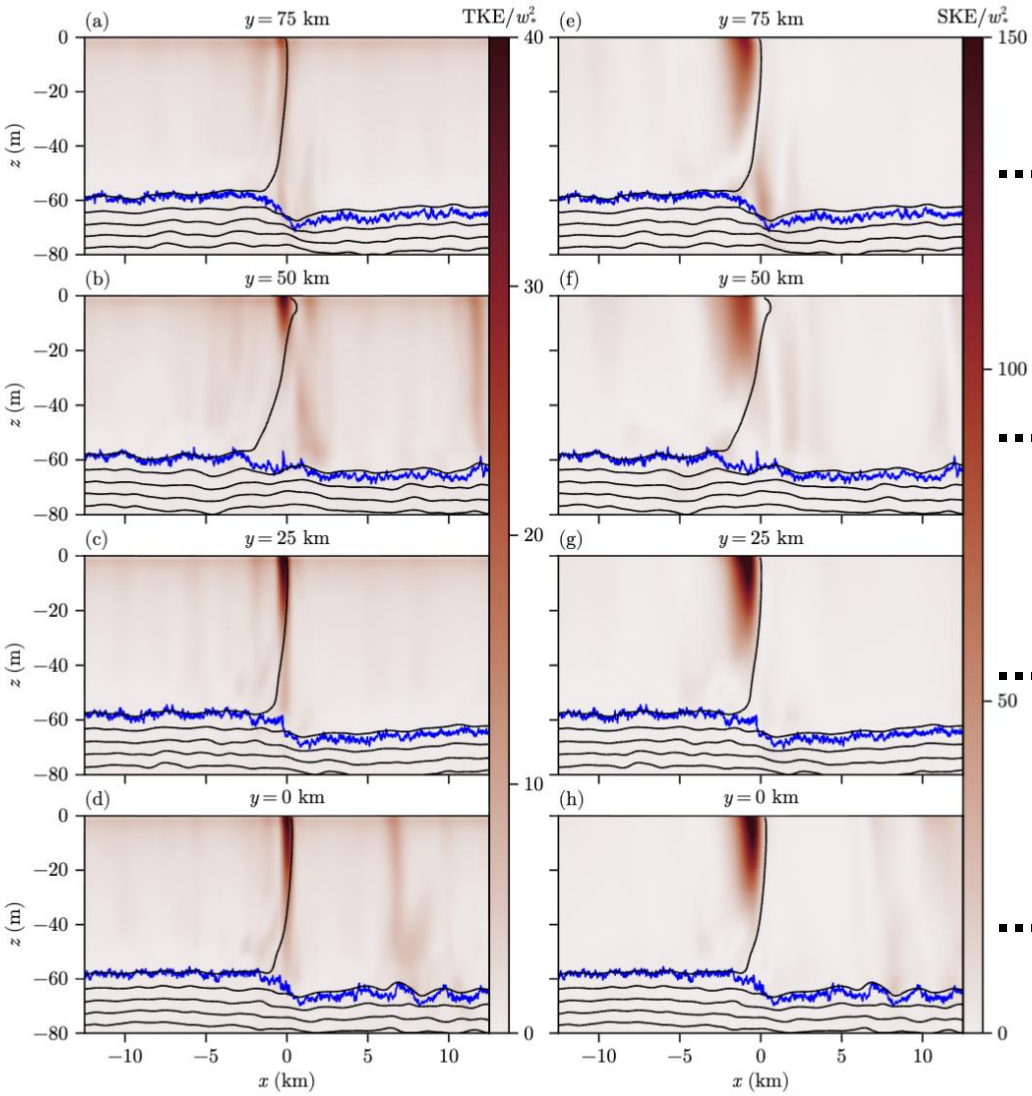
Simone Silvestri



$$\epsilon = \underbrace{-\overline{\boldsymbol{u}'w'}\frac{\partial \overline{\boldsymbol{u}}_s}{\partial z}}_{\text{Langmuir shear production(LSP)}} \underbrace{-\overline{\boldsymbol{u}'w'}\frac{\partial \overline{\boldsymbol{u}}_g}{\partial z}}_{\text{Geostrophic shear production (GSP)}} \underbrace{-\overline{\boldsymbol{u}'w'}\frac{\partial \overline{\boldsymbol{u}}_a}{\partial z}}_{\text{Ageostrophic shear production (AGSP)}} \underbrace{+ -\overline{w'b'}}_{\text{Vertical buoyancy production(VBP)}}$$

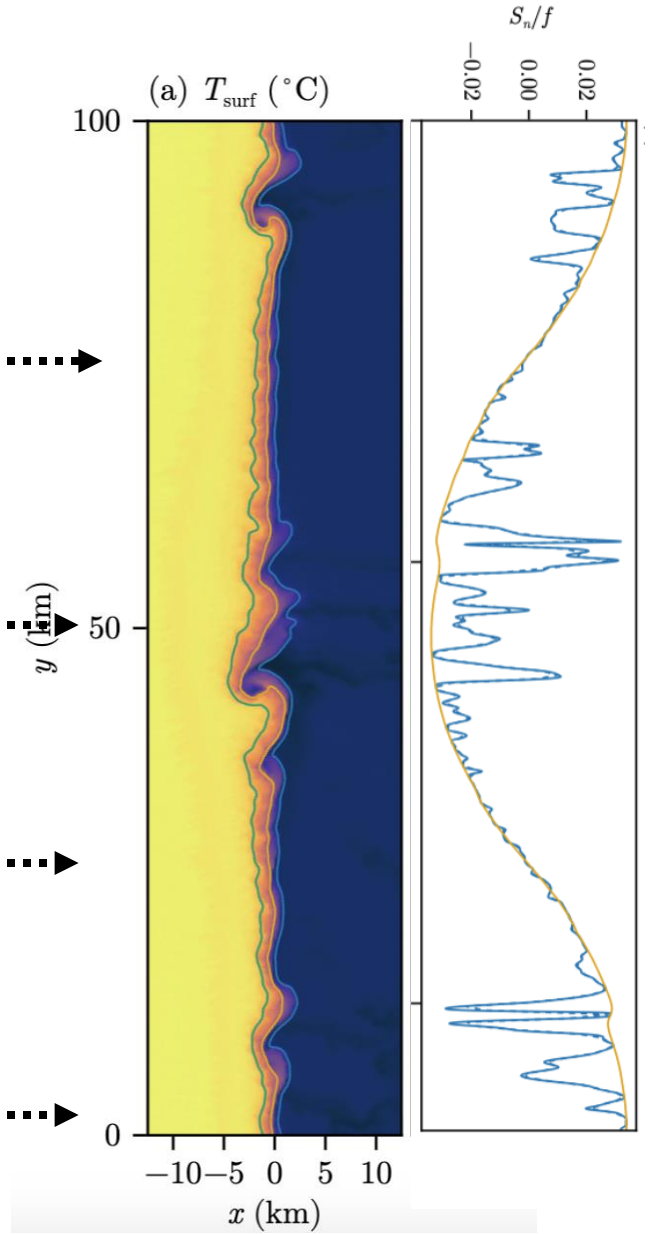
Dissipation

Turbulence across scales affects kinetic energy



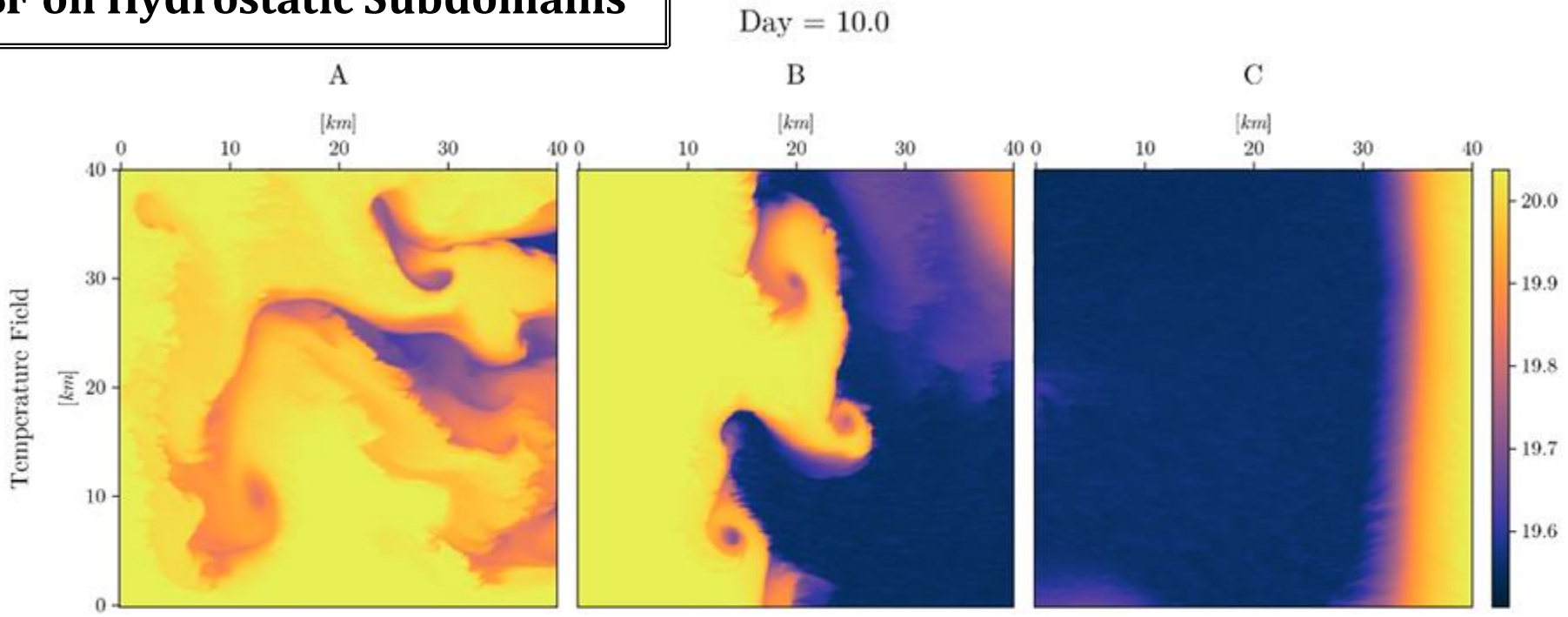
TKE SKE

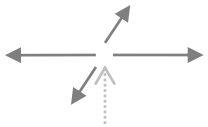
Peng, Bodner & Silvestri (In prep.)



Peng, Bodner & Silvestri (In prep.)

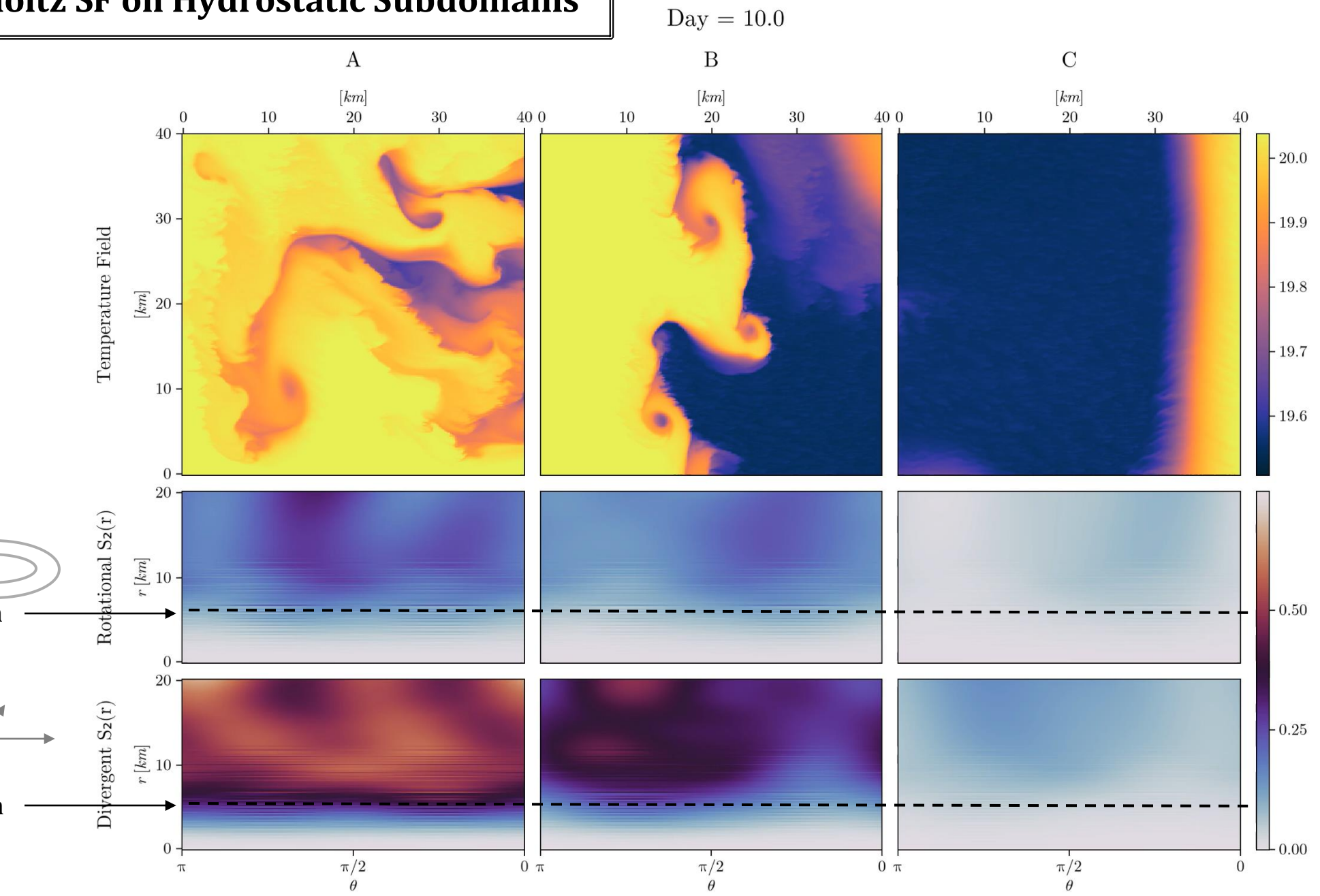
Helmholtz SF on Hydrostatic Subdomains





Sarah Snider

Helmholtz SF on Hydrostatic Subdomains



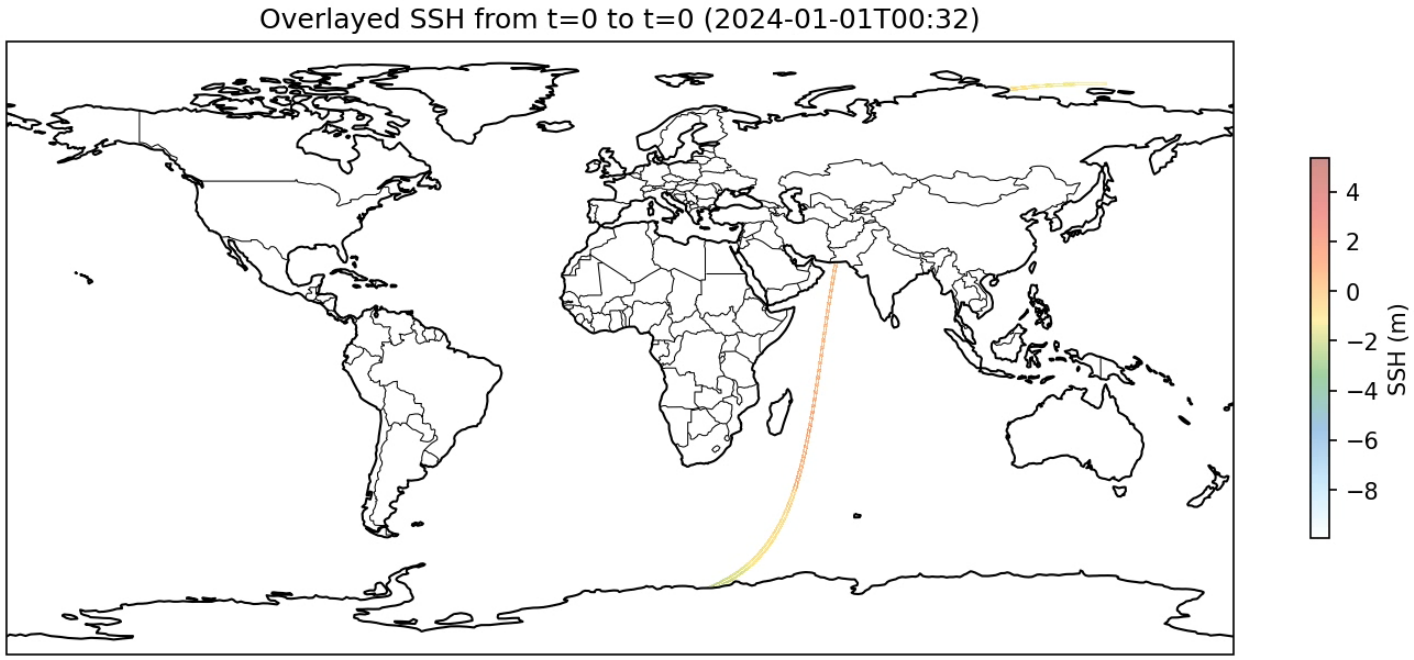
Sarah Snider

Harnessing real-world data

Anshul Agarwal

Yidongfang Si

Bianca Champenois

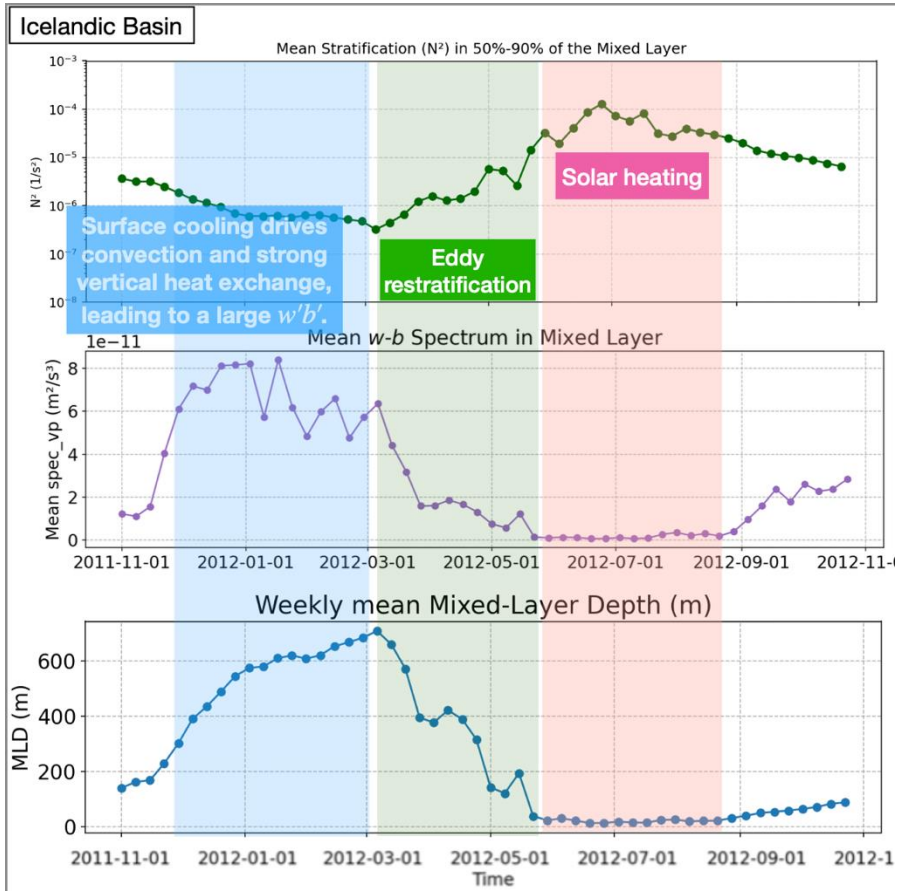


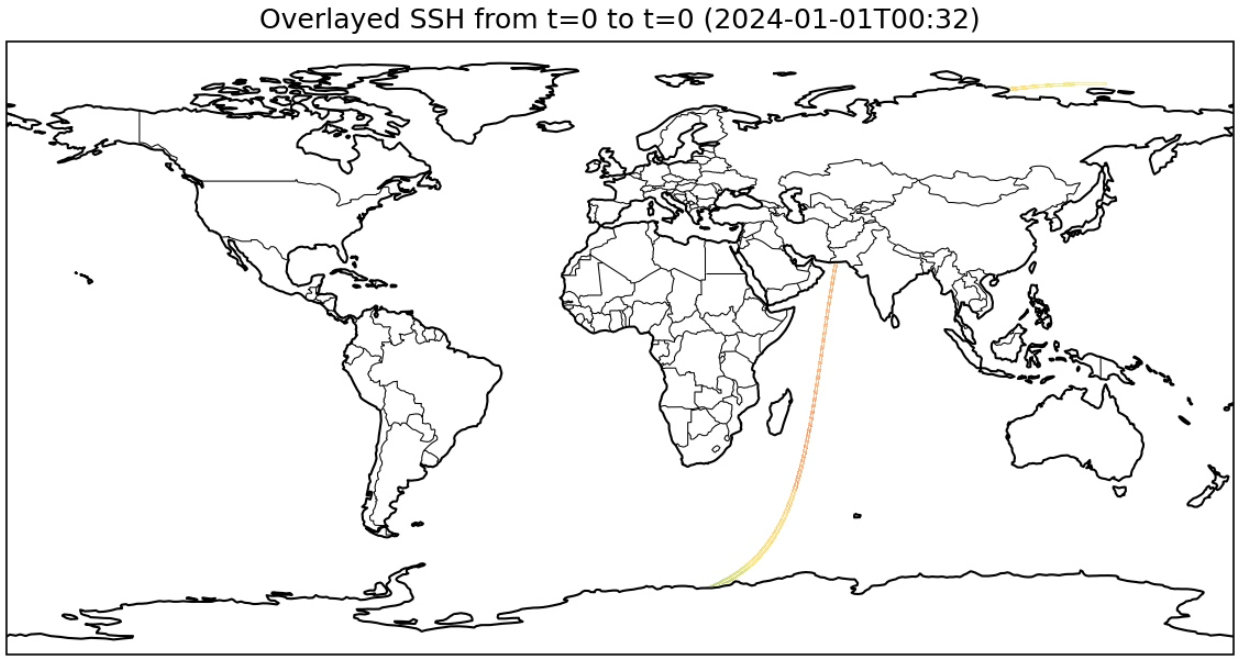
Harnessing real-world data

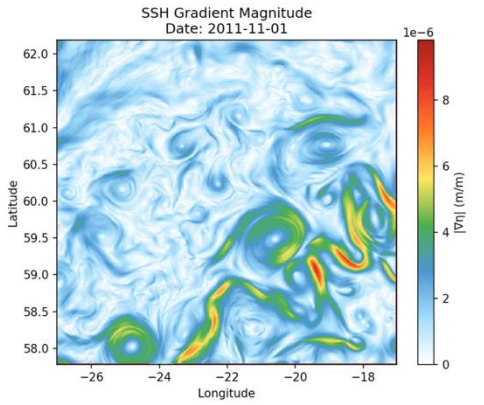

Anshul Agarwal


Yidongfang Si


Bianca Champenois







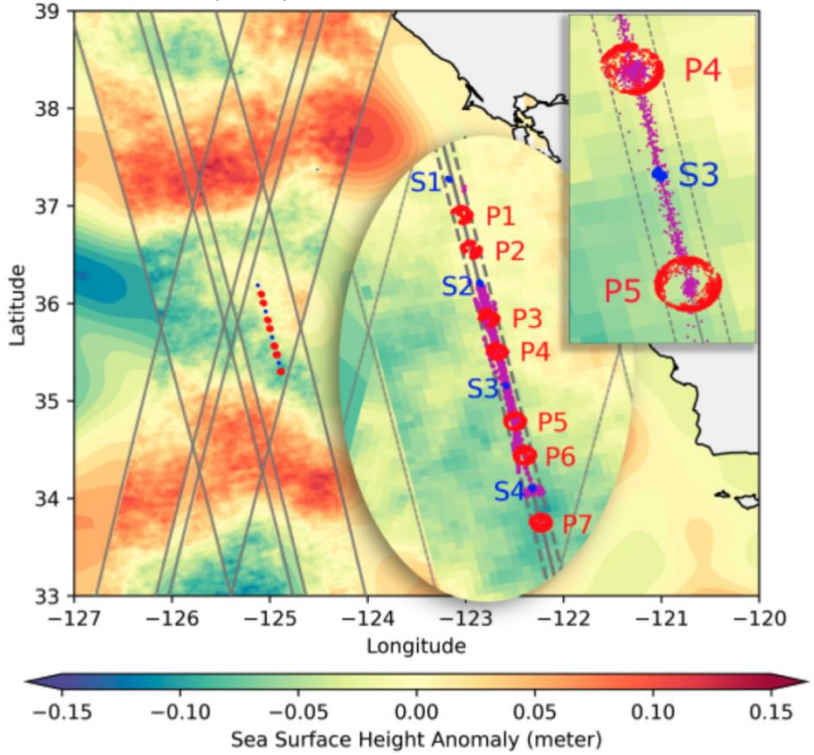
Harnessing real-world data

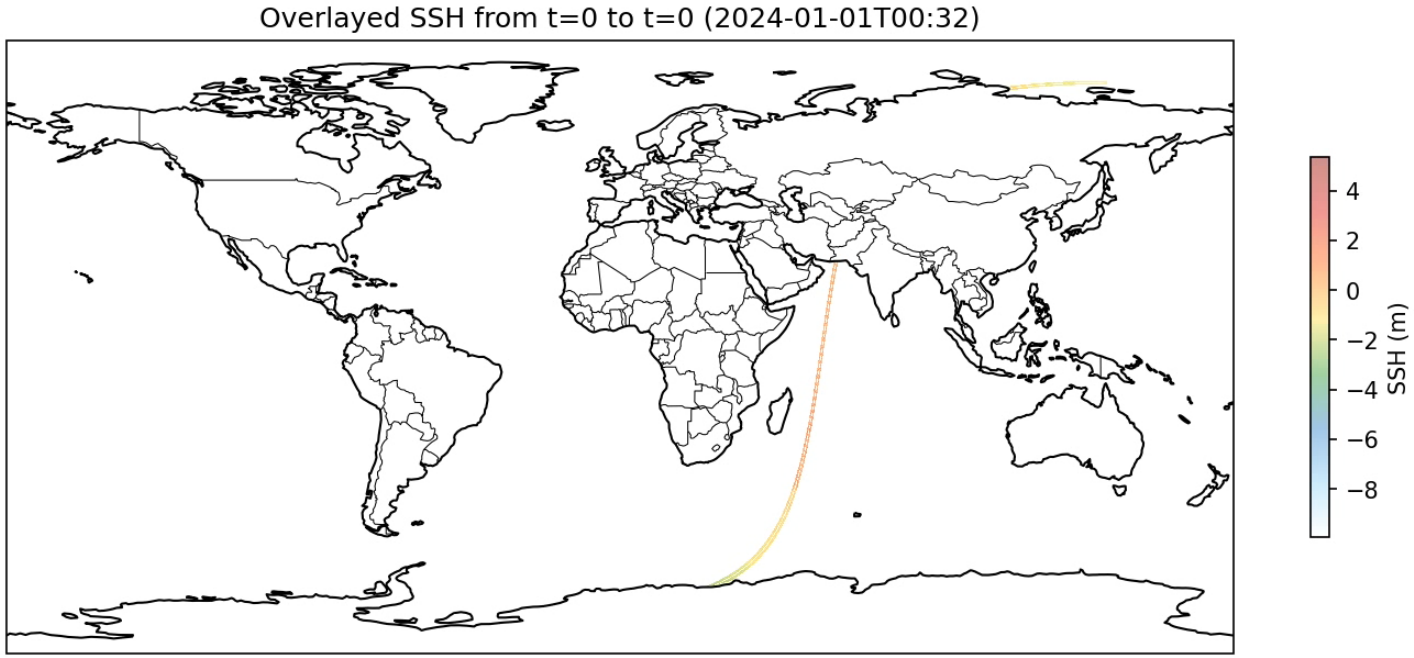

Anshul Agarwal

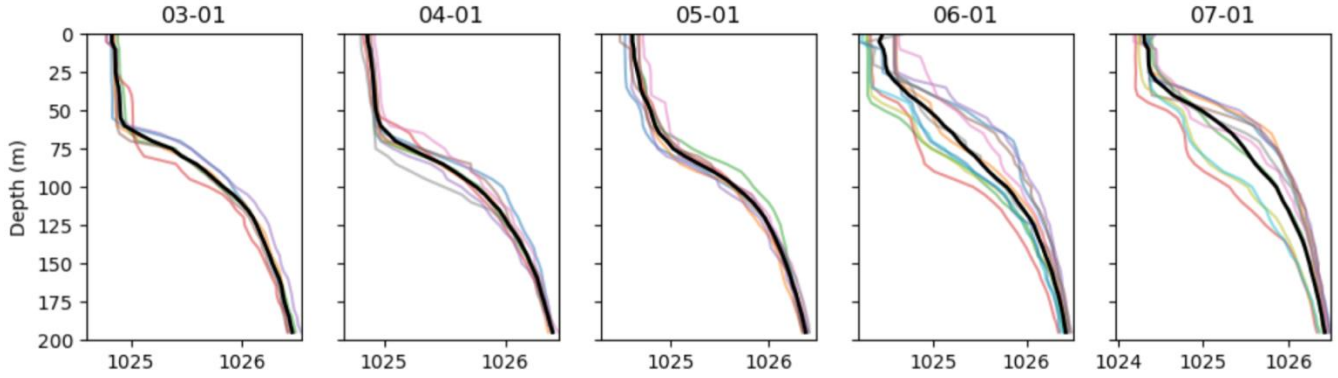

Yidongfang Si


Bianca Champenois

Wang et al (2025)

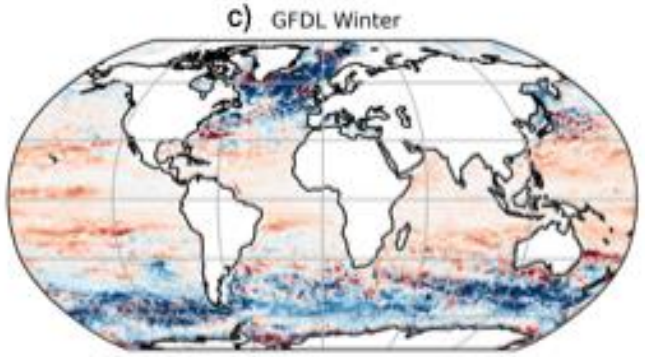


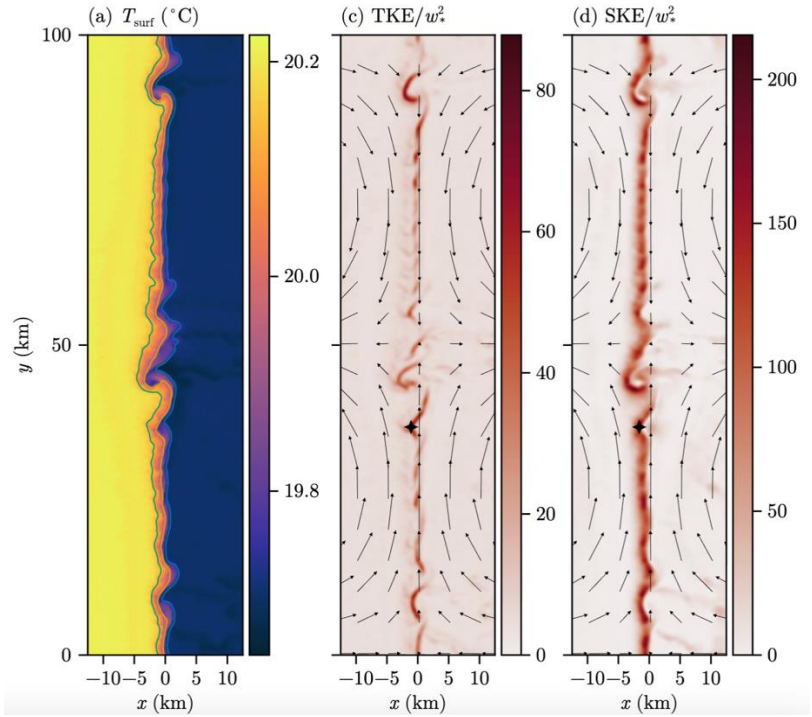




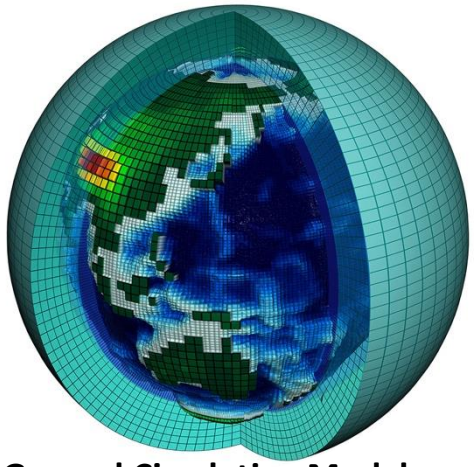
Summary

- Turbulence in the upper ocean plays a key role in the ocean heat and energy budgets
- Global ocean models are sensitive to the coupling of turbulent processes in the upper ocean
- Ongoing analysis of idealized simulations and observations to further understanding of multiscale nature





Global Climate Change



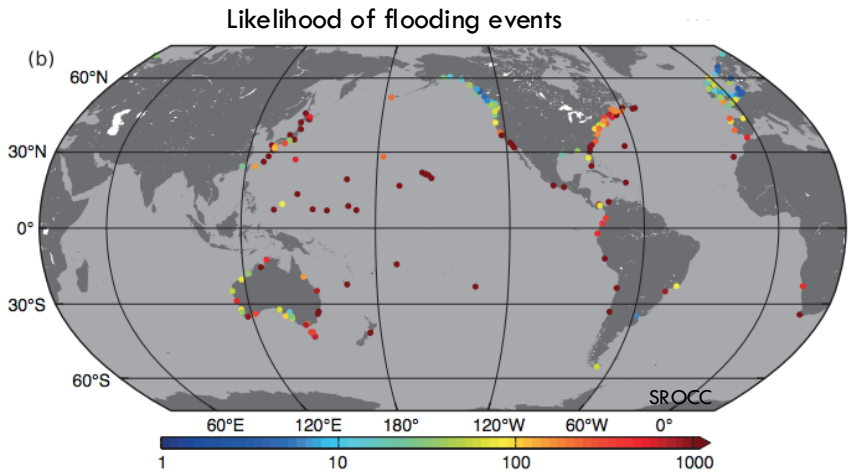
General Circulation Model

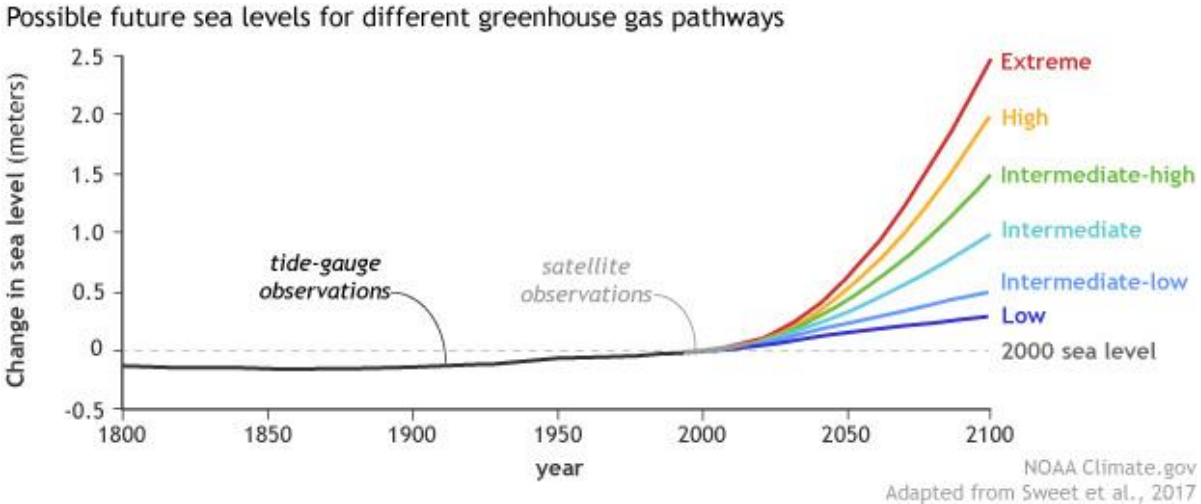
IPCC

Sea Level

Global

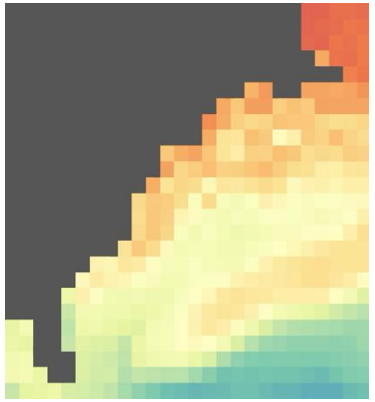
driven by thermal expansion and ice melt

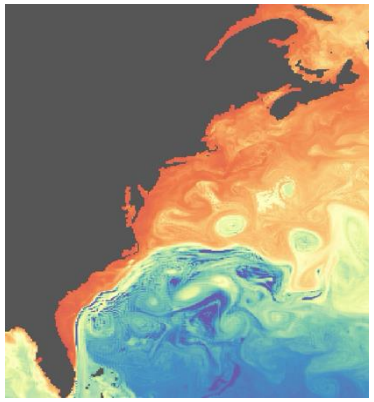


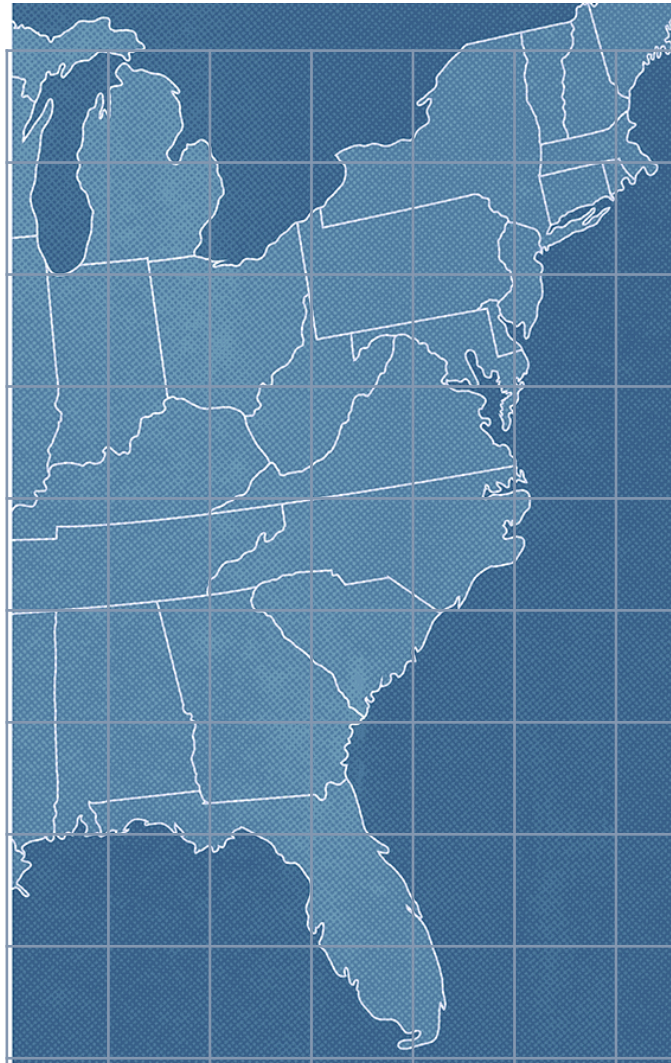


Regional

driven by local flow dynamics



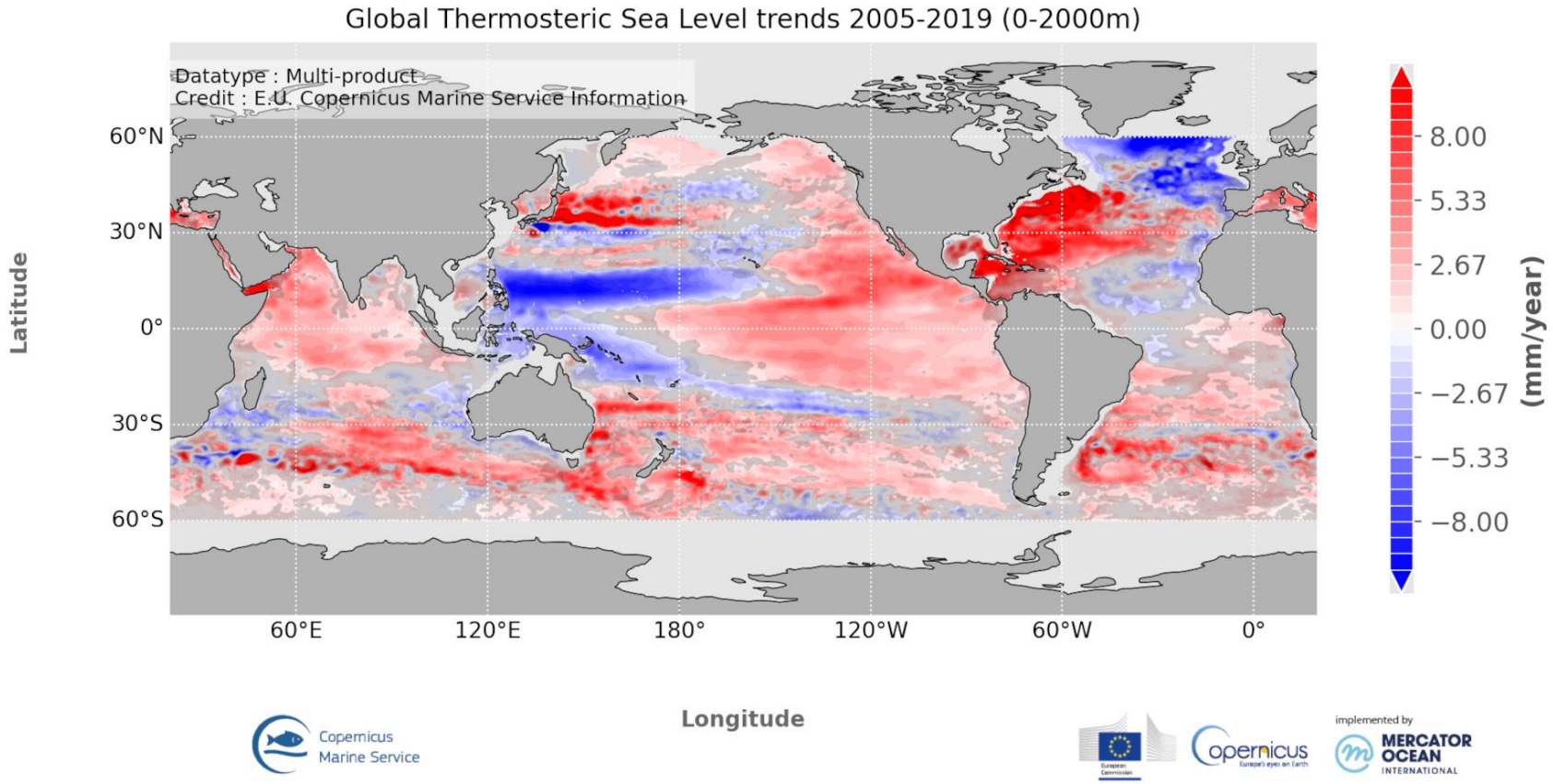




Sea Level

Linking global and local sea level budgets in climate models

Accounting for effects on heat and energy



Terms that are associated with turbulence

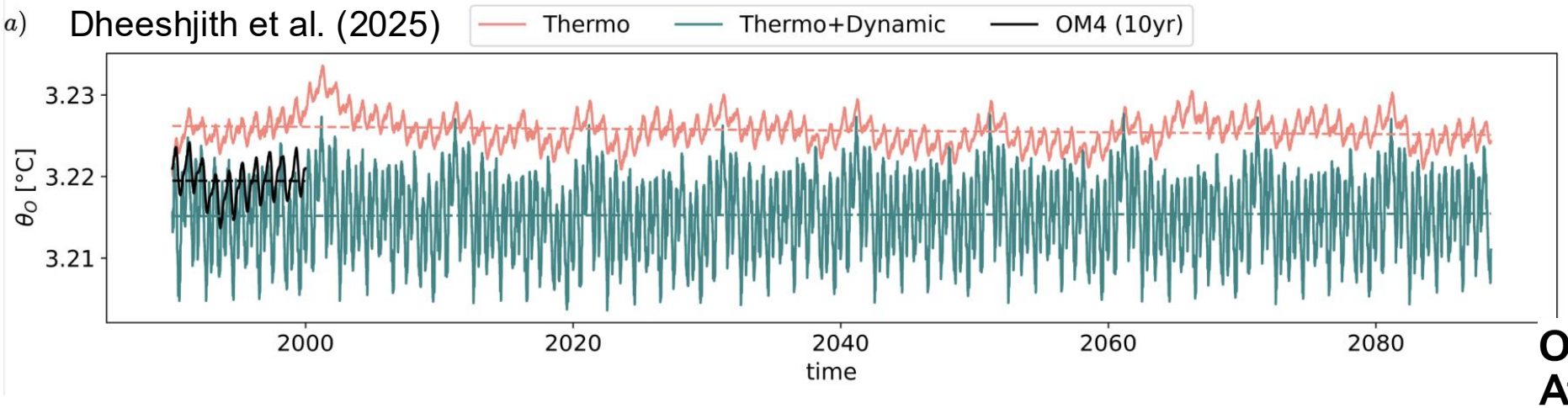
$$\frac{\partial \zeta_\rho}{\partial t} = \sum_{c\in\{\theta,S\}} \left\{ -\frac{1}{\rho_r} \int_{-H}^{0} \frac{\partial \rho}{\partial c} \left[-\mathbf{u}\cdot\nabla c + \nabla\cdot(\kappa\nabla c) + \frac{1}{\rho_r}\frac{\partial Q^c}{\partial z} \right] dz \right\}.$$

Bodner, Piecuch, Steinberg (in prep)

Developing new tools for multiscale ocean physics

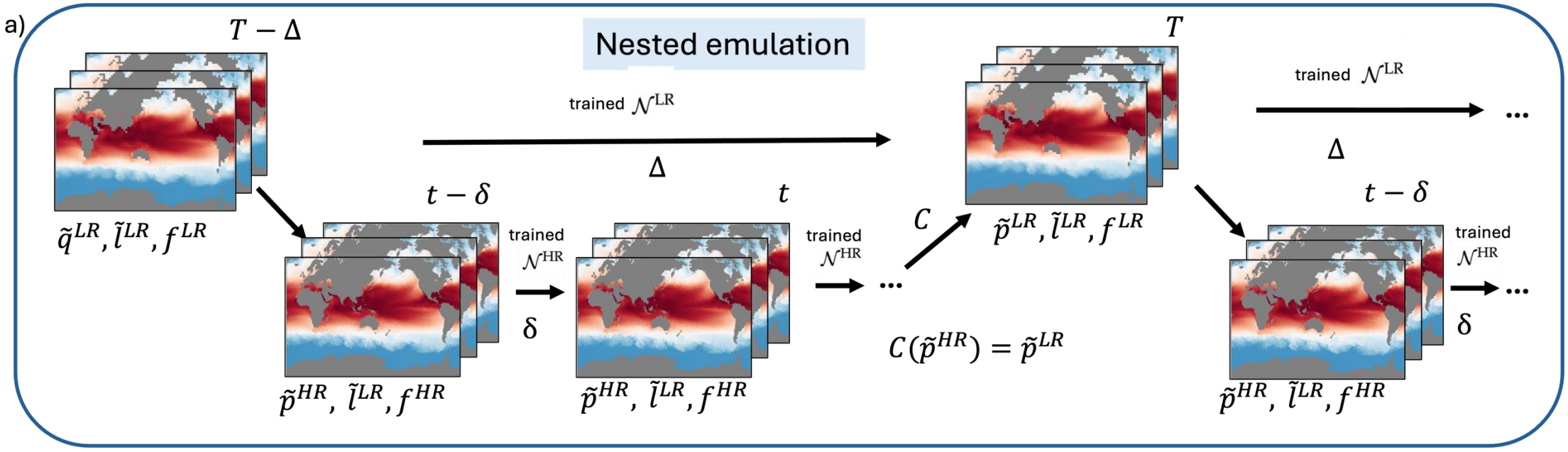
Cody Cruz

a) Dheeshjith et al. (2025)

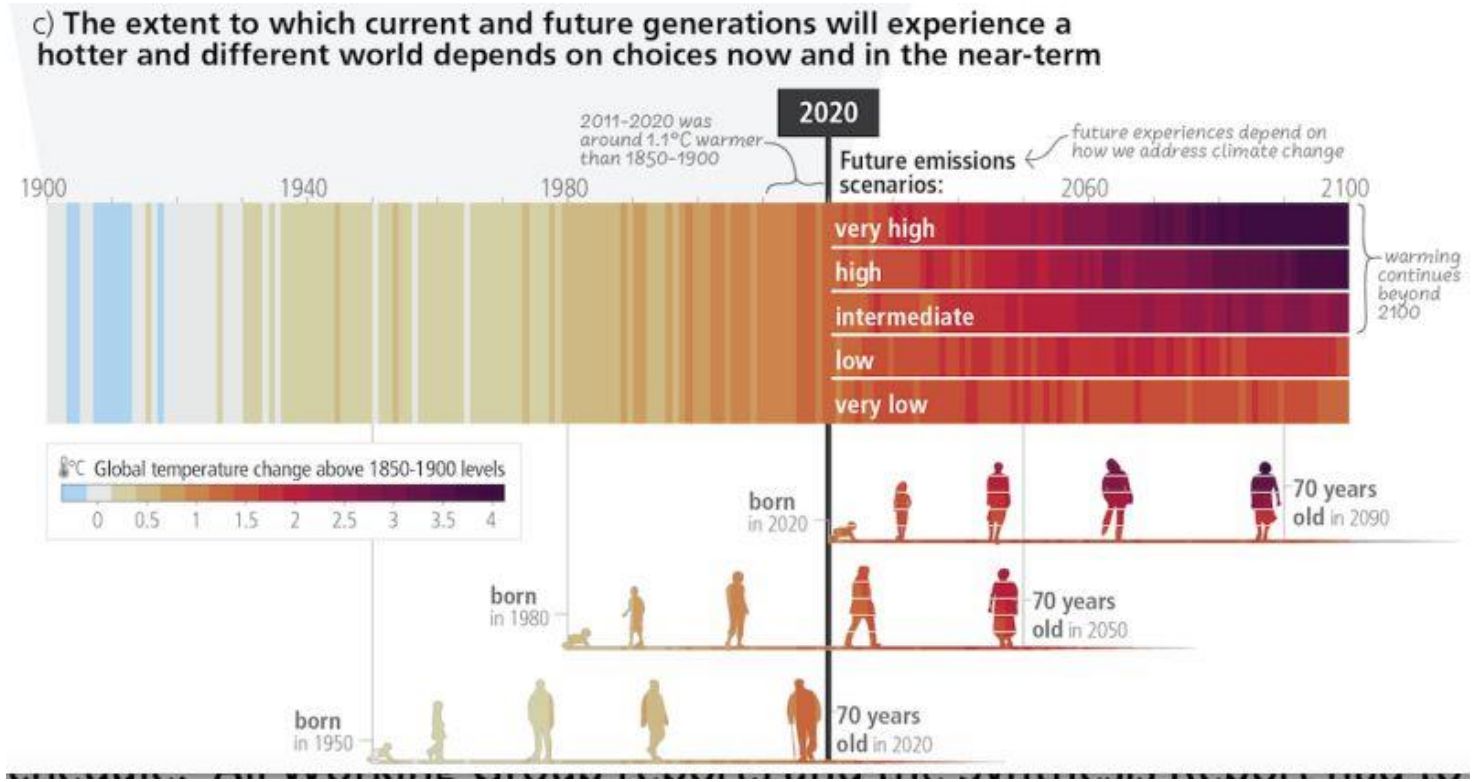


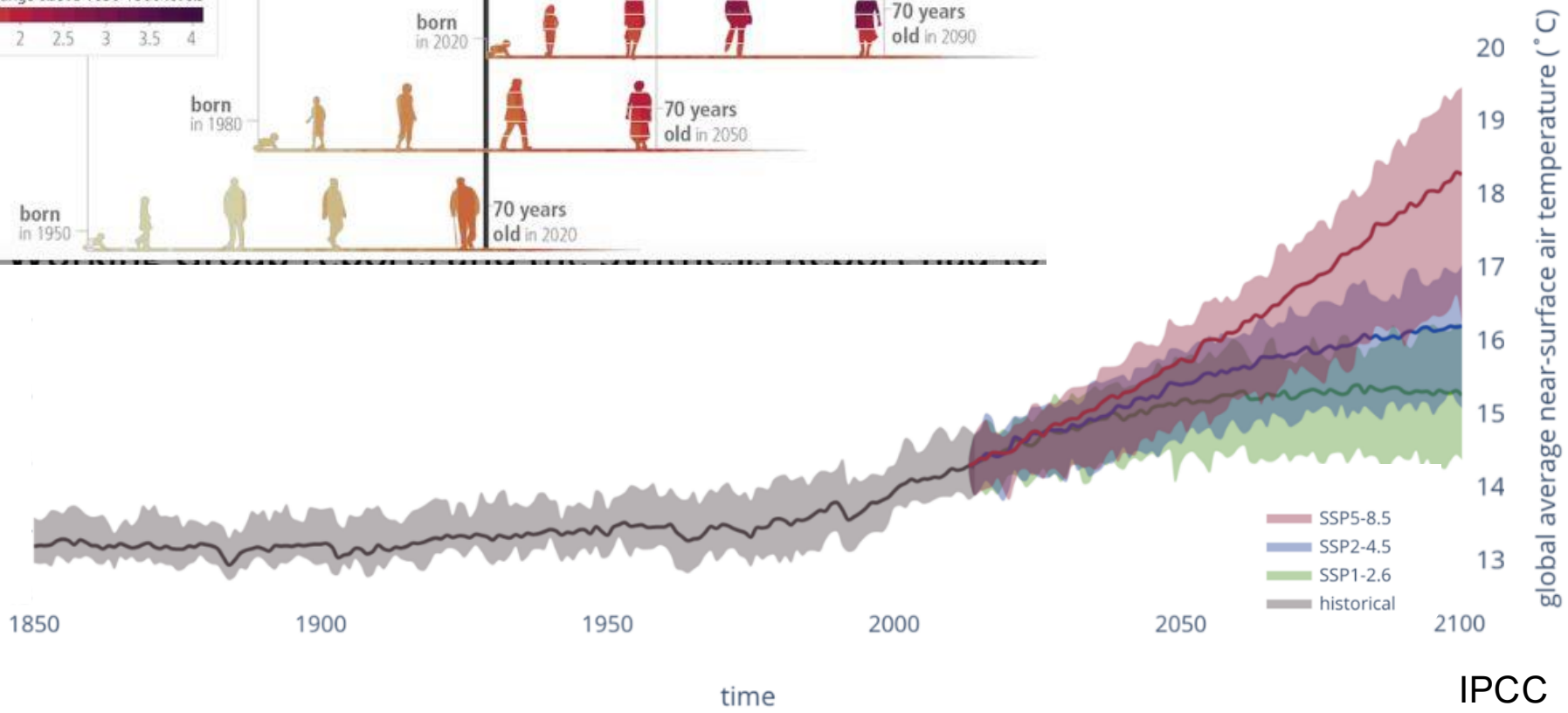
M²LInES

Open Athena



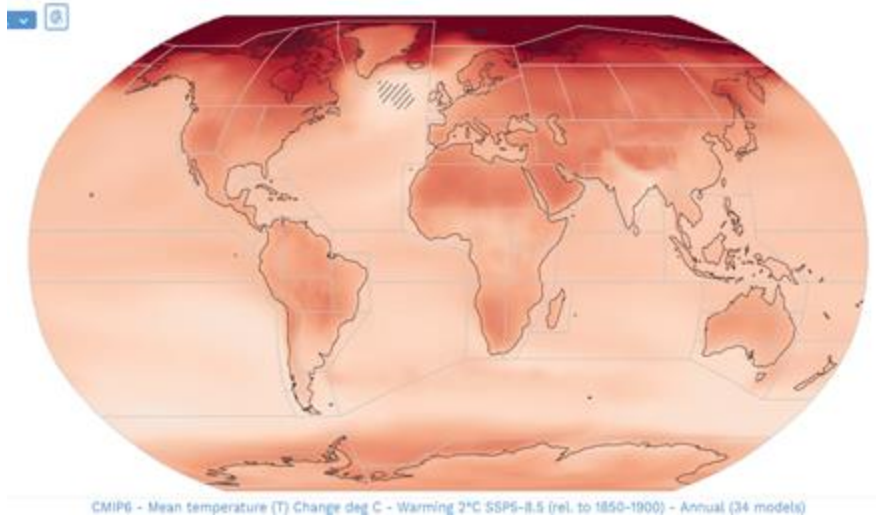
Global Climate Change





IPCC

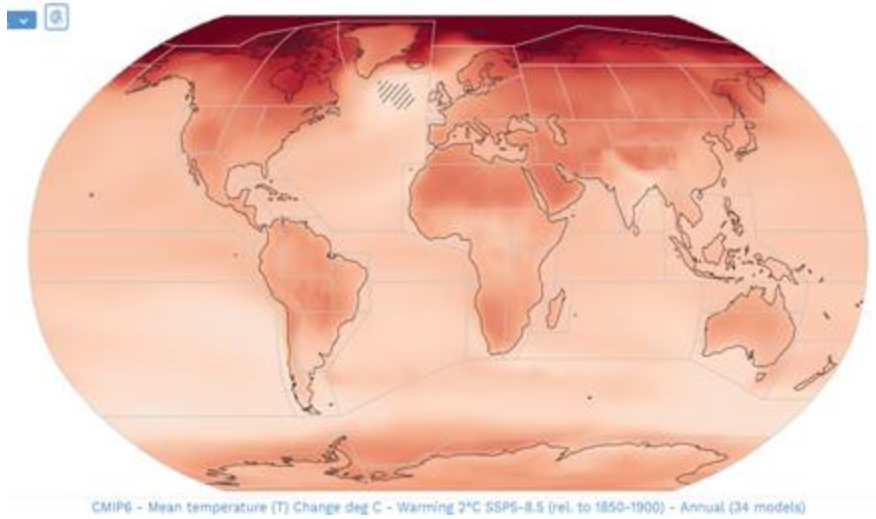
Global Climate Change



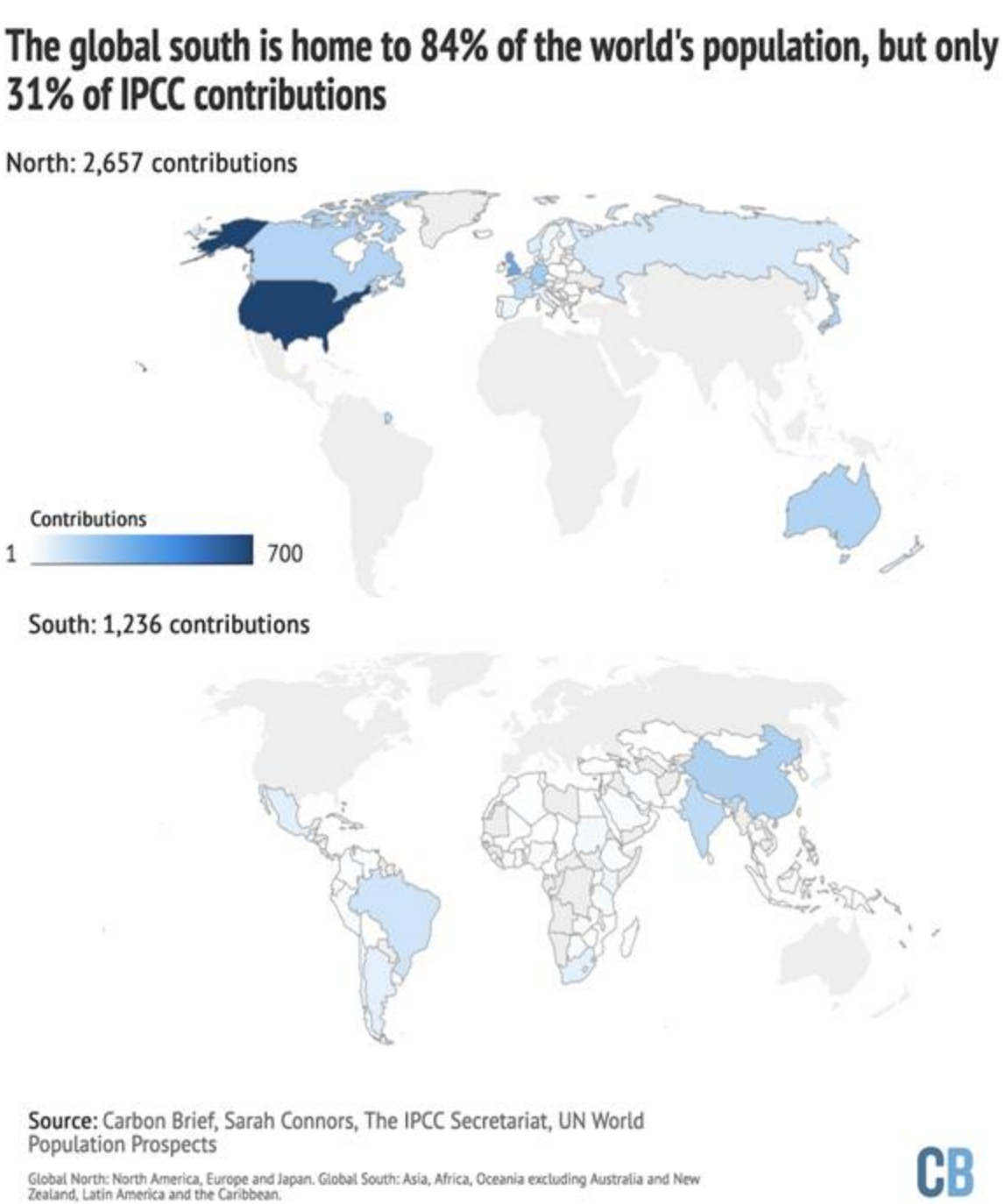
Surface temperature warming - IPCC Atlas

IPCC

The existing climate science research community severely underrepresents the global population that will be impacted by climate change.



Surface temperature warming - IPCC Atlas



500+ volunteers & organizers
400+ teaching assistants
5000+ interactive students
10,000+ conference registrants
1400+ talks/posters
100+ countries
13 languages of instructional support

$1.2M raised

neuromatch is a global movement!

March 2020: NMC1

May 2020: NMC2

May/June 2020: incorporation, 501c3

July 2020: NMA2020

November 2020: NMC3

July 2021: NMA2021

December 2021: NMC4

July 2022: NMA2022

Today

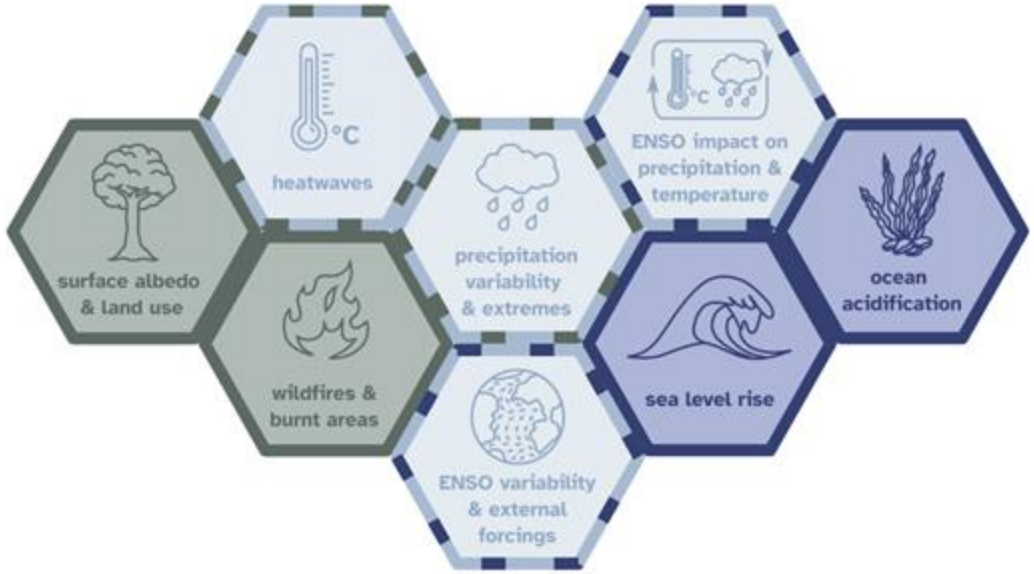
We seek to make science accessible to everybody, everywhere by removing barriers to education, networking, and knowledge sharing.

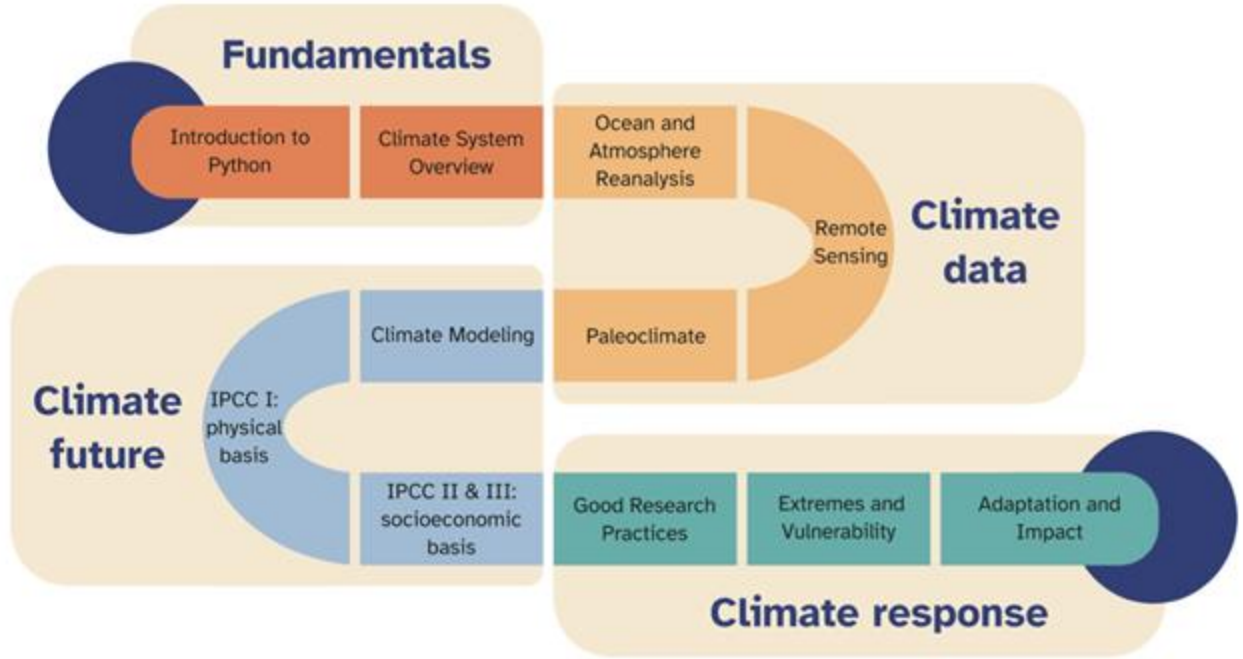
Climatematch Academy

neuromatch academy

neuromatch

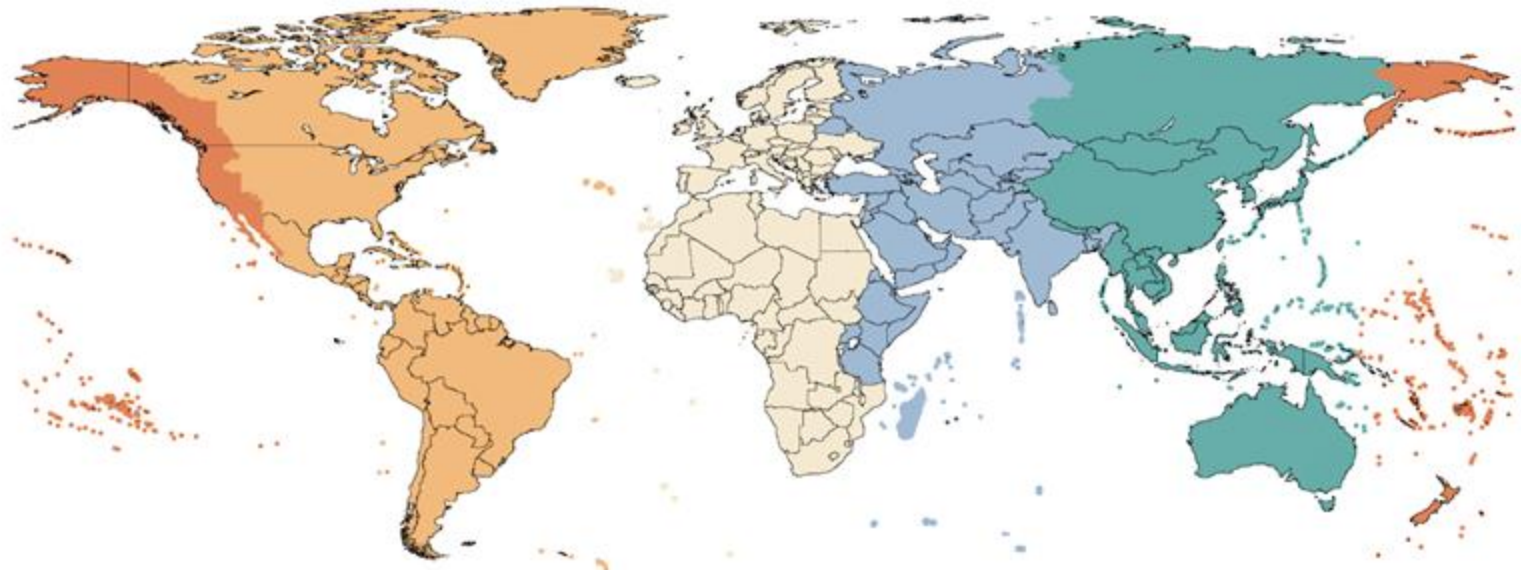
Hundreds of volunteers!!





neuromatch

Climatematch Academy



Concluding remarks

- The impacts of climate change must simultaneously account for both global and local phenomena
- Novel computational and theoretical approaches make progress towards required multiscale view
- New opportunities for research and outreach are enabled by engaging with local communities