# Ocean fronts, eddies, and internal waves in numerical models and SWOT

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# Construction of the adjoint MIT ocean general circulation model and application to Atlantic heat transport sensitivity

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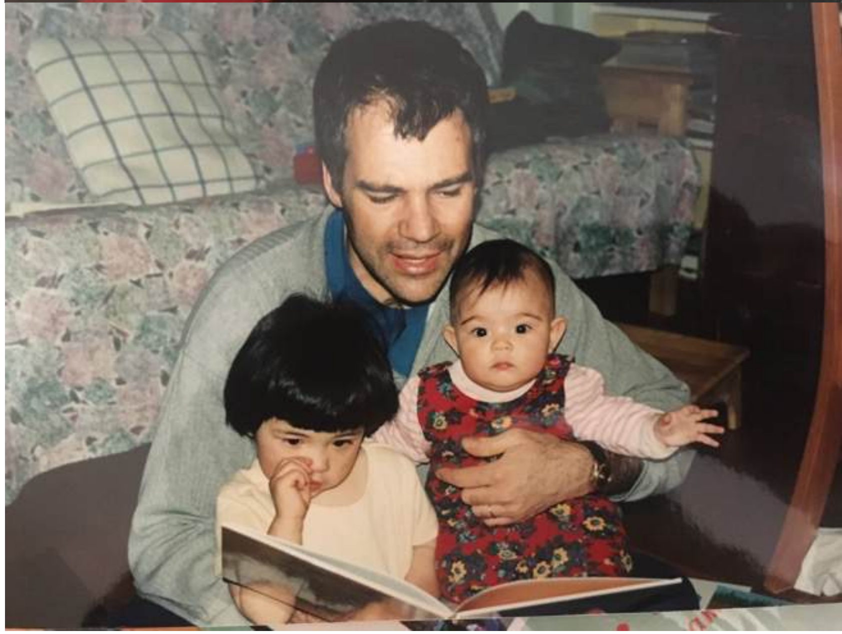
Chris Hill, and Tong Lee[2]

Center for Global Change Science, Department of Earth, Atmospheric, and Planetary Sciences,
Massachusetts Institute of Technology, Cambridge



*Journal of Marine Research*, 57, 305–334, 1999

# The importance of open-boundary estimation for an Indian Ocean GCM-data synthesis

by Kate Q. Zhang[1] and Jochem Marotzke[2]

ABSTRACT

The Indian Ocean general circulation is estimated by fitting the MIT Ocean General Circulation Model to the annual mean climatological hydrography and surface forcing, using the model and its computer-generated adjoint. Open boundary conditions are implemented to the west of the Indonesian Archipelago and near 30S. The approach simultaneously optimizes the initial conditions of the hydrographic fields, surface fluxes, and the open boundary conditions (temperature, salinity, and horizontal velocities).

Compared to previous results obtained in a closed domain, the estimated velocity field shows a

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- Hockey stick graphs (aka motivation for studying submesoscale processes)
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- An unexpected twist
- Summary and concluding remarks

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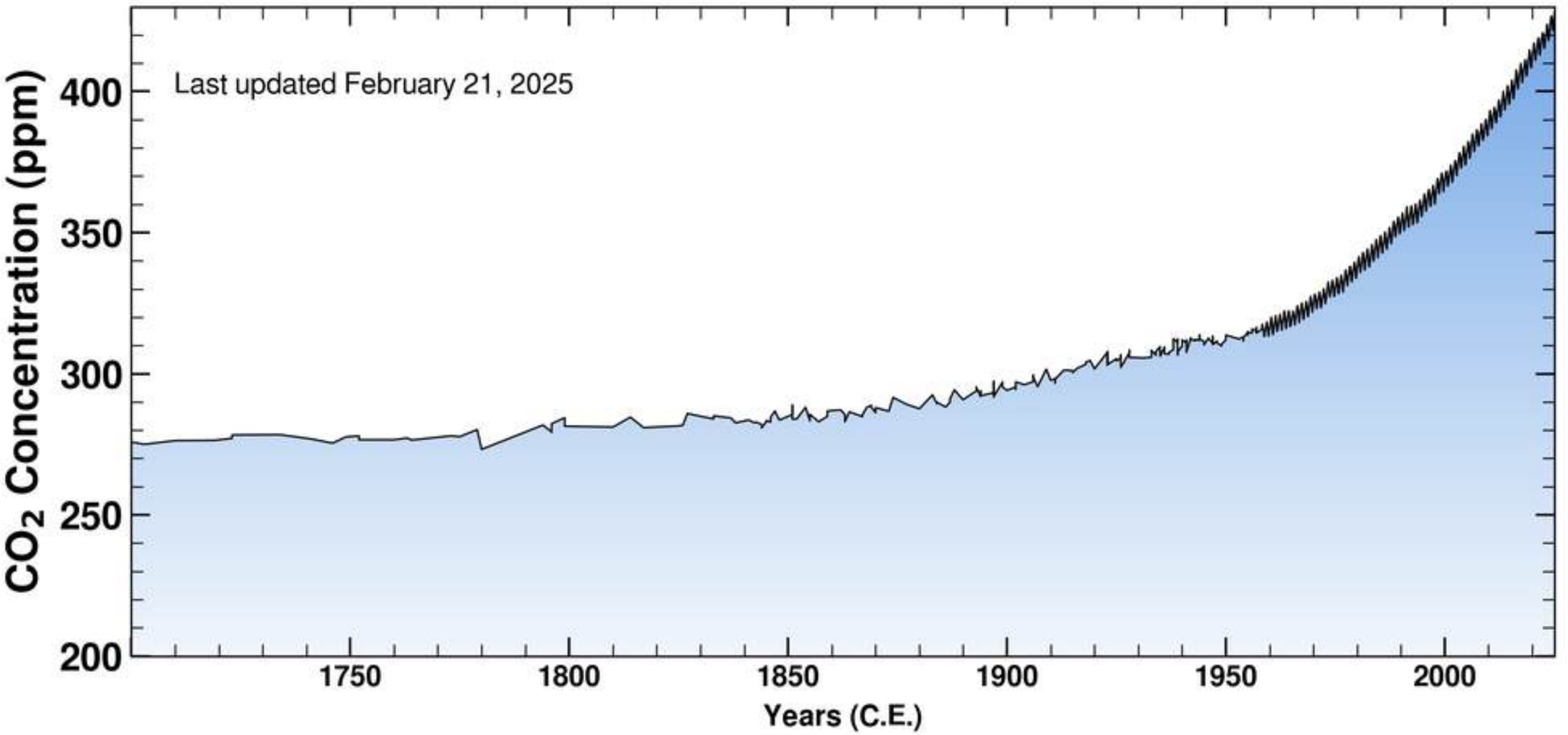
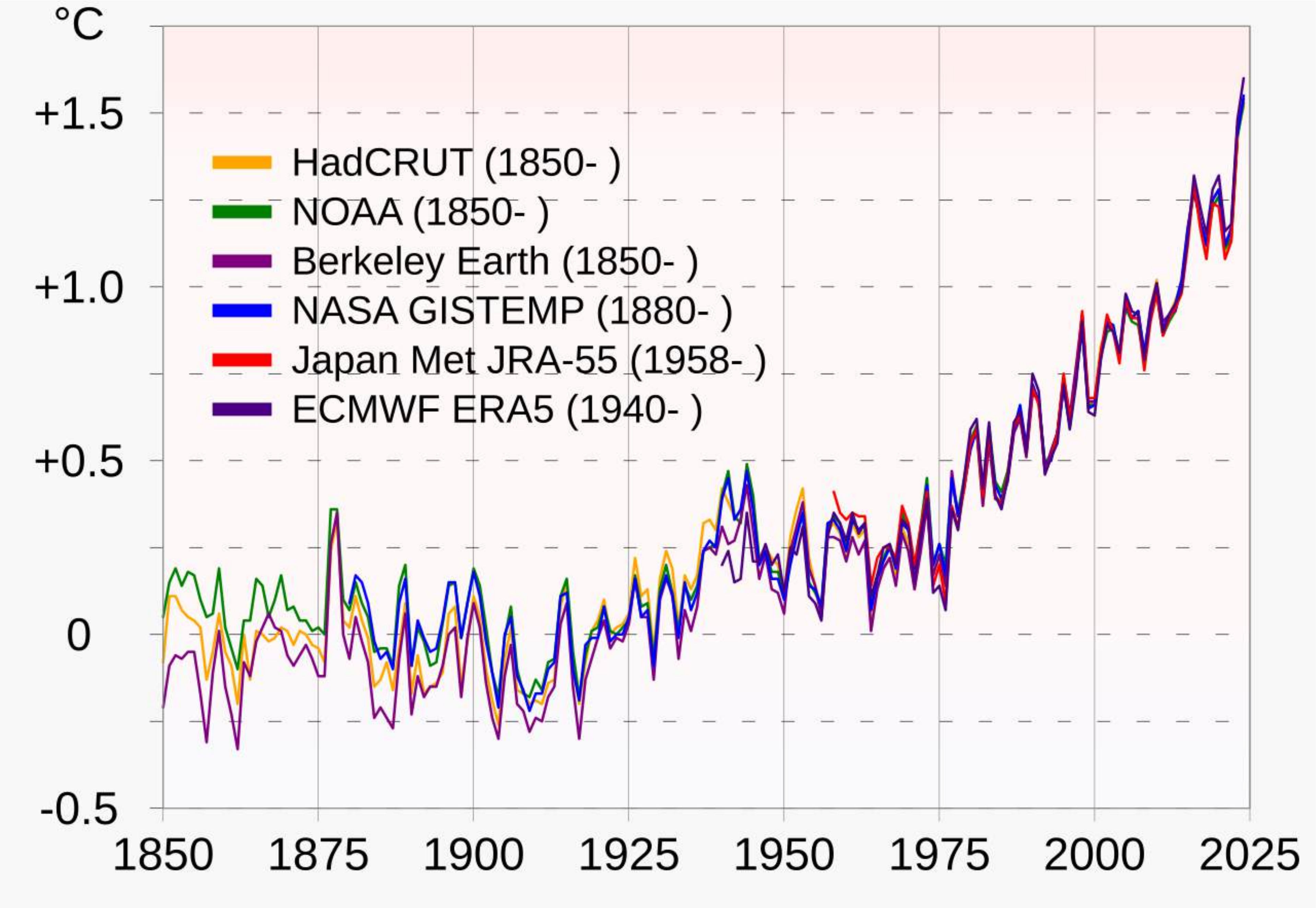
# Atmospheric carbon dioxide — ice-core data before 1958, Mauna Loa after 1958 (last week, Mauna Loa observations exceeded 430 ppm)



# Atmospheric surface temperature increase since industrial revolution

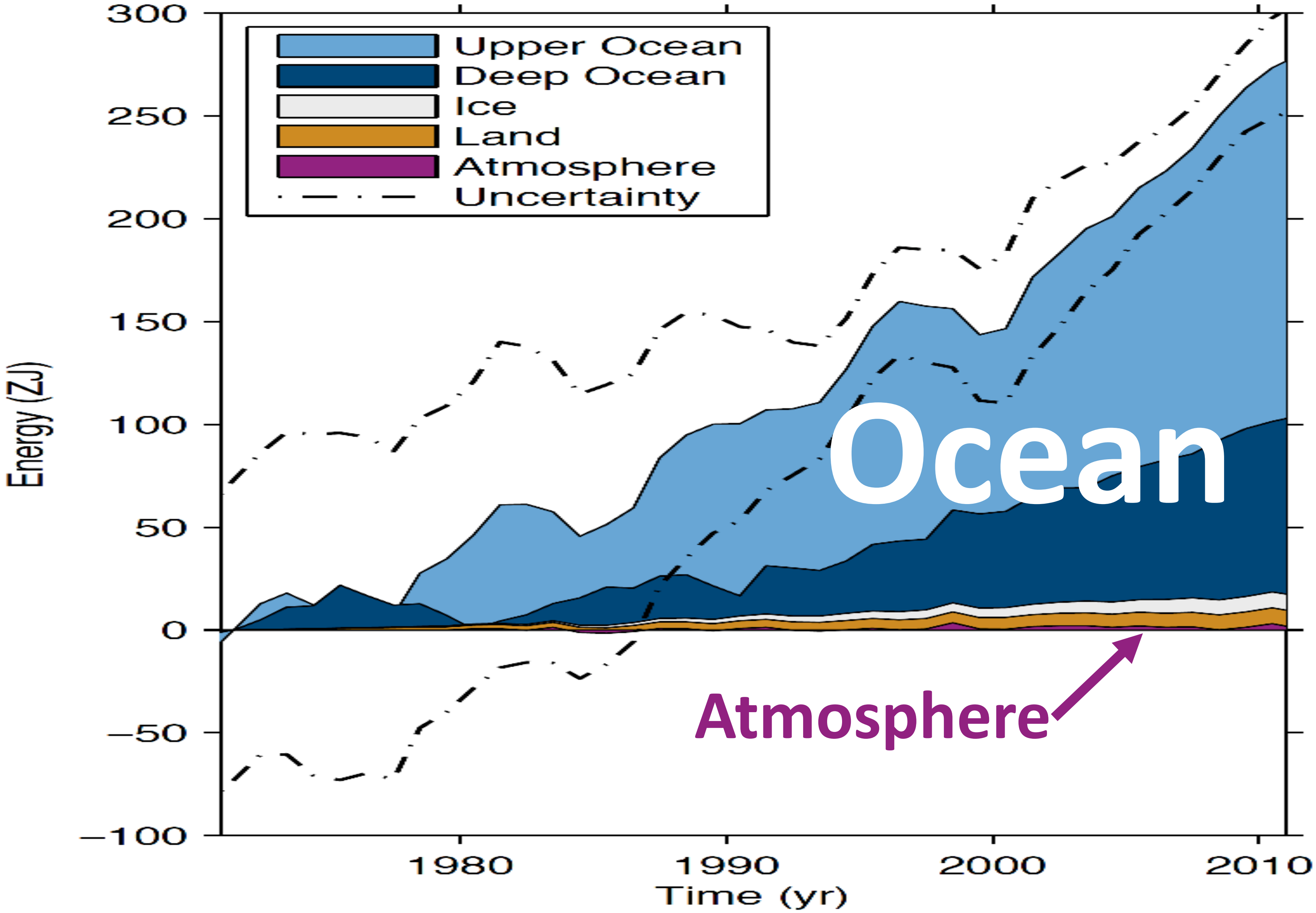



2024 was the warmest year on record, 1.5°C warmer than pre-industrial temperatures.

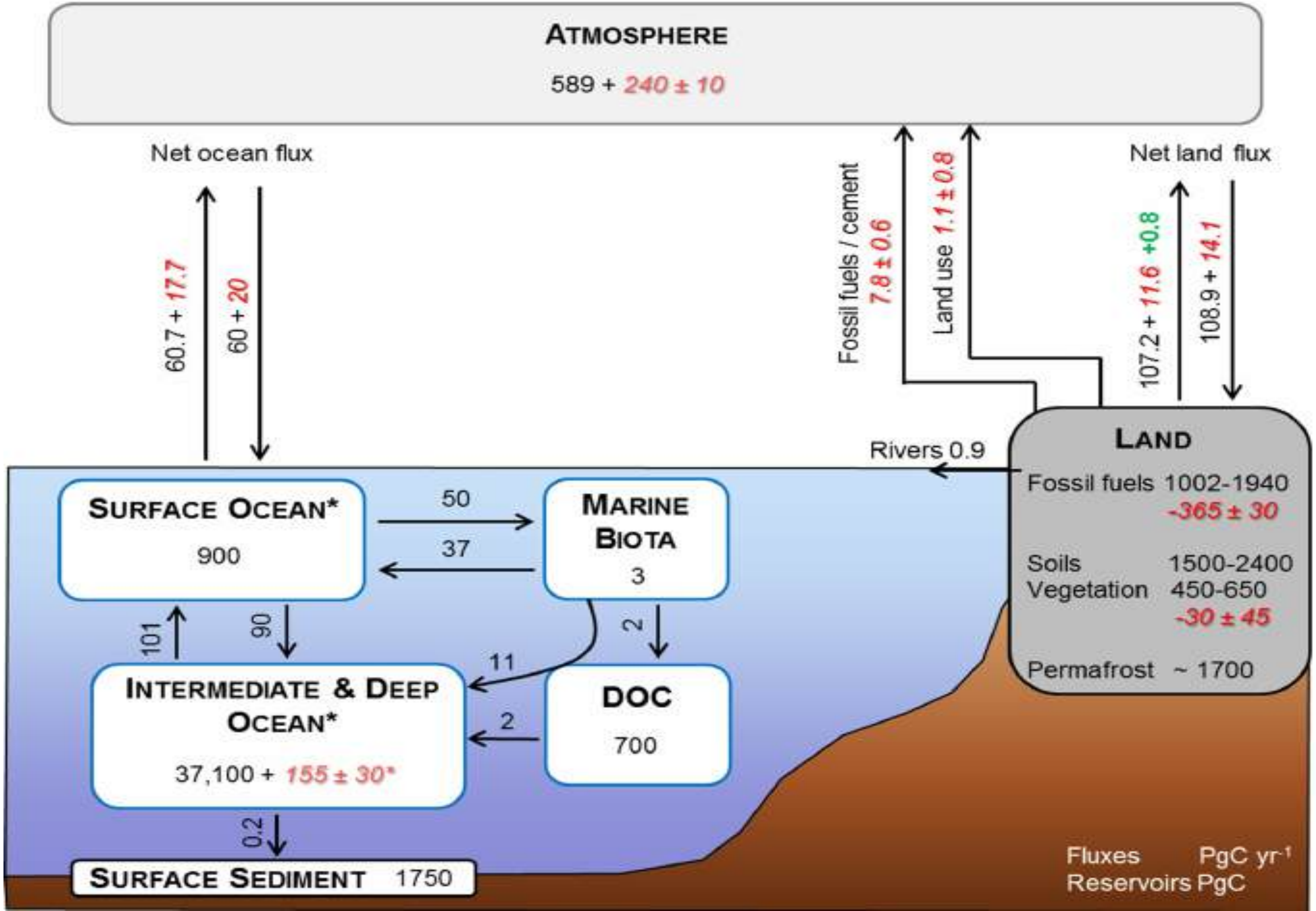
# The ocean is the climate's reservoir of heat

**1 ZettaJoule (ZJ)**
= $10^{21}$ Joules
= 67 million Hiroshima nuclear explosions

**Ocean absorbs ~7 Hiroshimas every second**



# The ocean is the largest active reservoir of carbon




The ocean contains ~90% of active carbon (~50 times more than the atmosphere) and, so far, has absorbed 30% of human-generated $CO_2$.

**Question:** Can we understand and predict the exchange of heat, freshwater, carbon, and other properties between the global ocean and the atmosphere?

**Hypothesis:** Submesoscale ocean motions (<50 km), both balanced and unbalanced, play a key role in air-sea exchanges and vertical property transports in the ocean.

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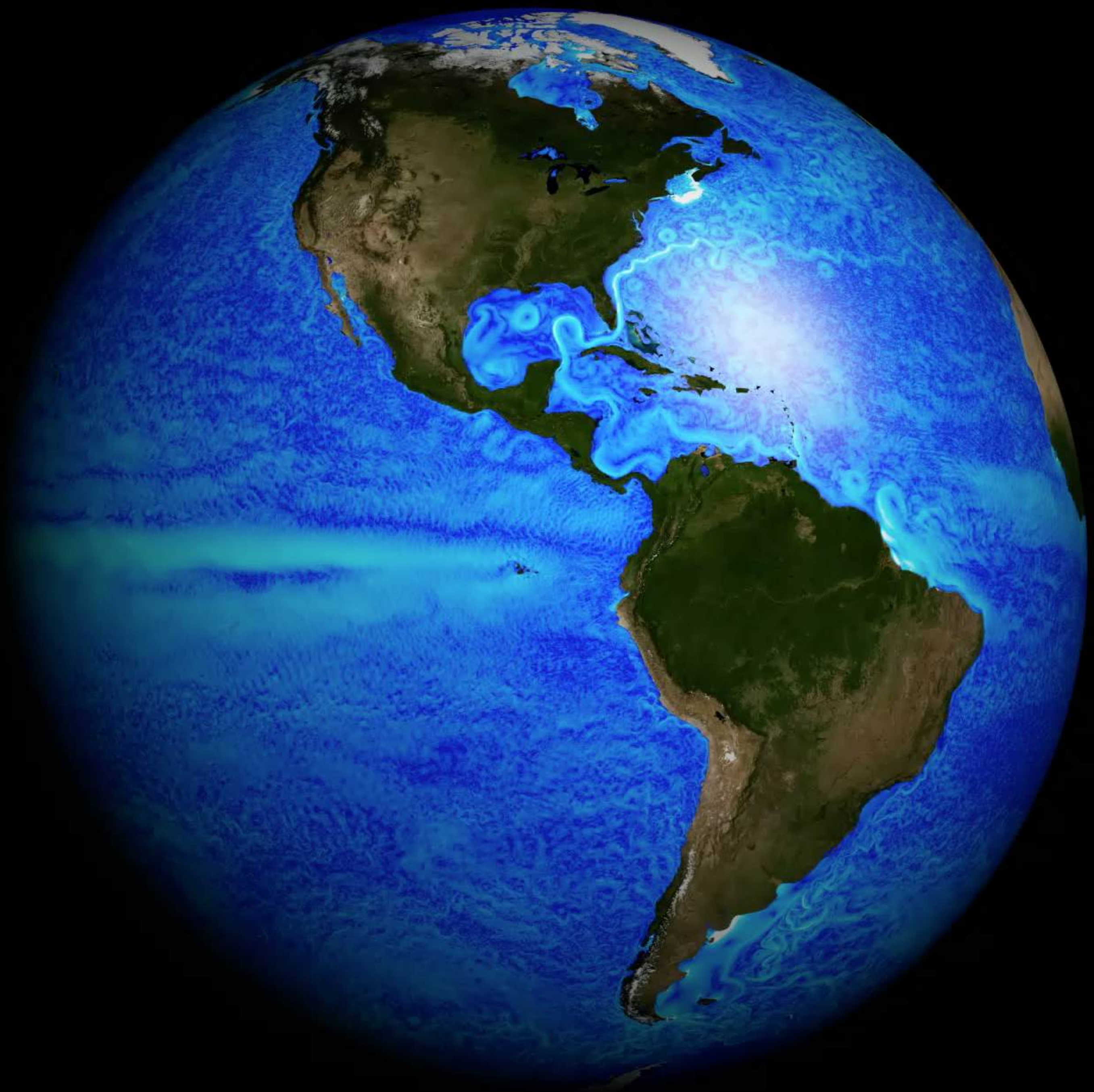
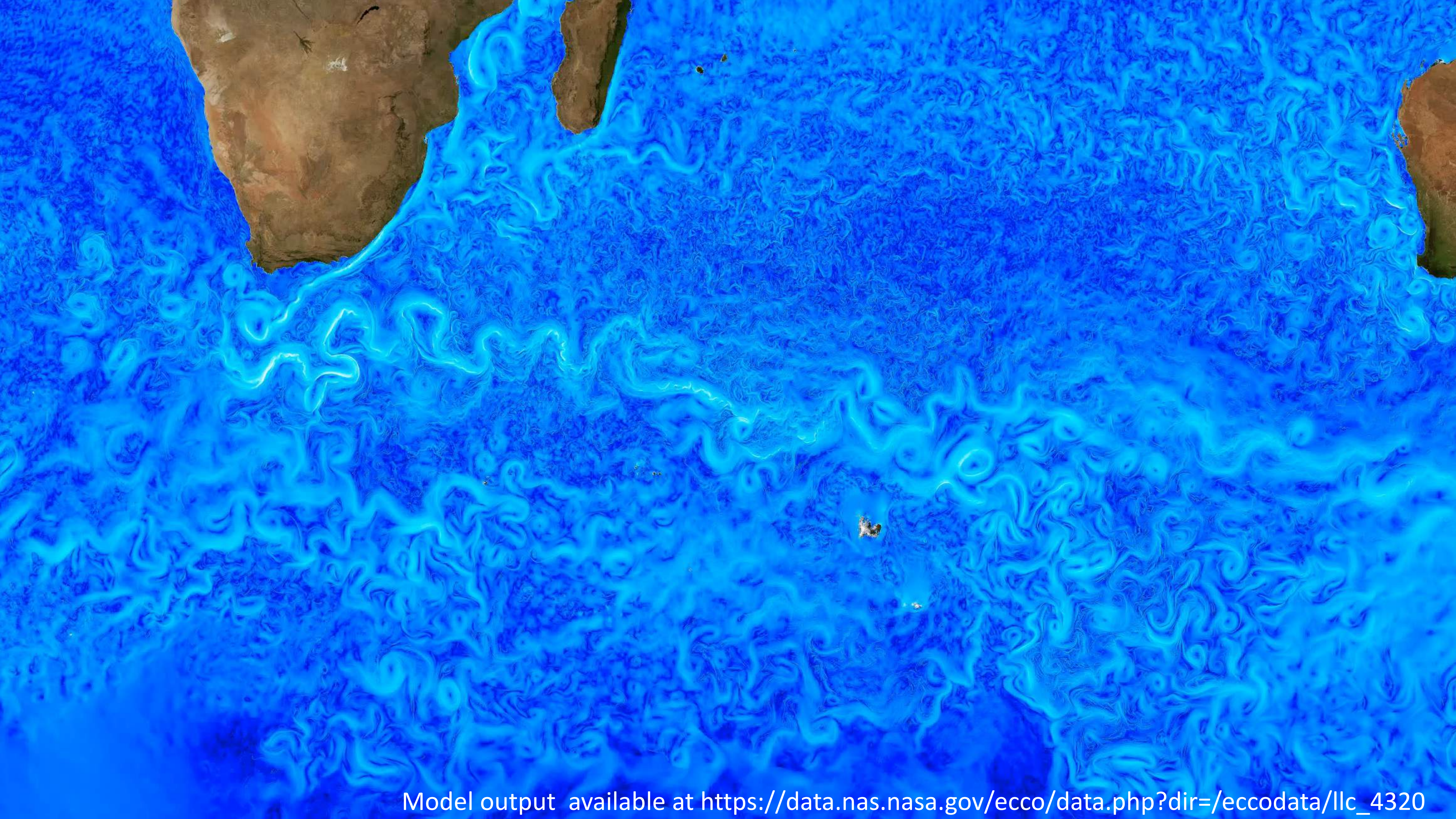


Model output available at https://data.nas.nasa.gov/ecco/data.php?dir=/eccodata/llc_4320



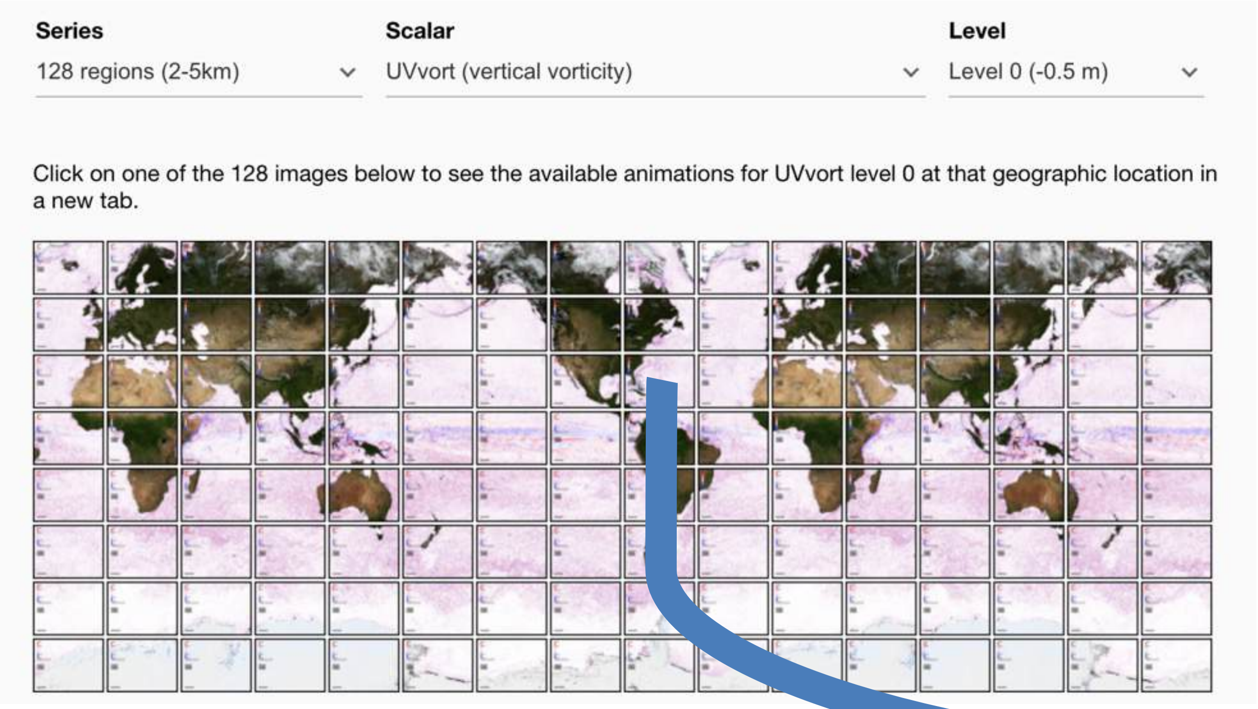
Model output  available at https://data.nas.nasa.gov/ecco/data.php?dir=/eccodata/llc_4320

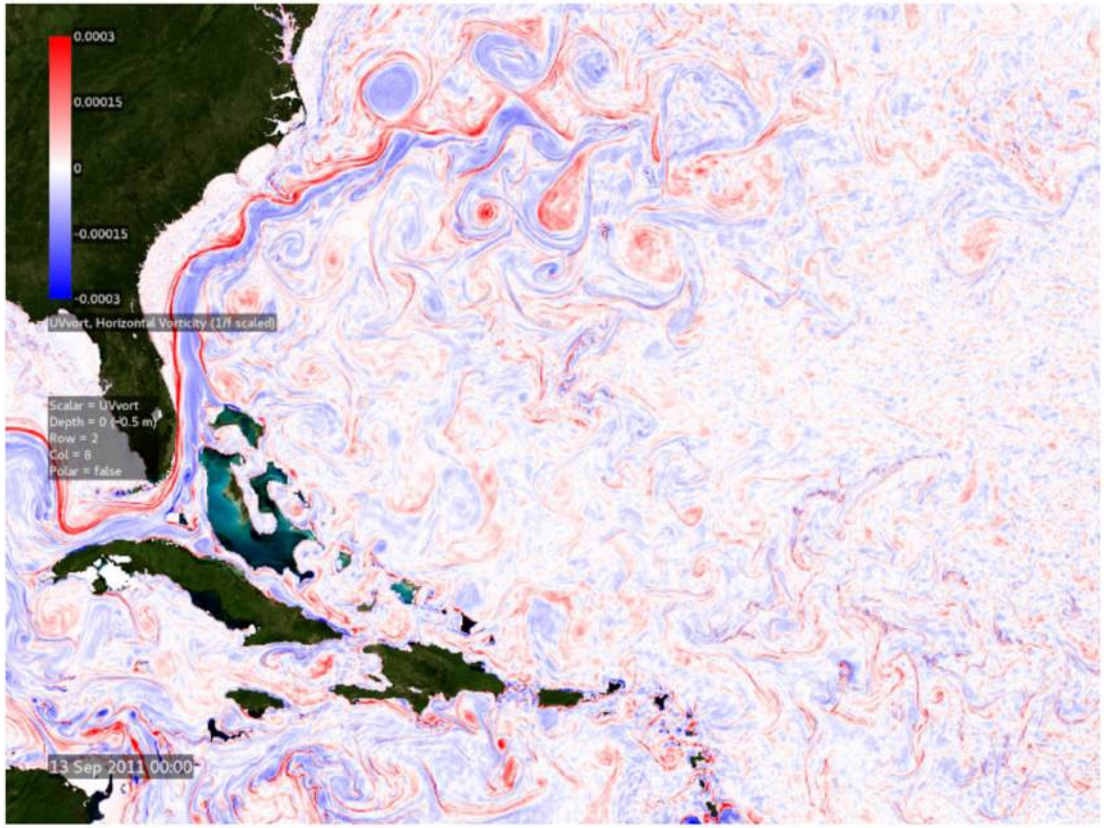

The NASA Advanced Supercomputing (NAS) Hyperwall enables interactive visualization of multi-petabyte, time-varying, multivariate data.

(Chris Henze, Bron Nelson, and others)

# Hyperwall at home (created by David Ellsworth)

https://ecco-group.org/world-of-ecco.htm



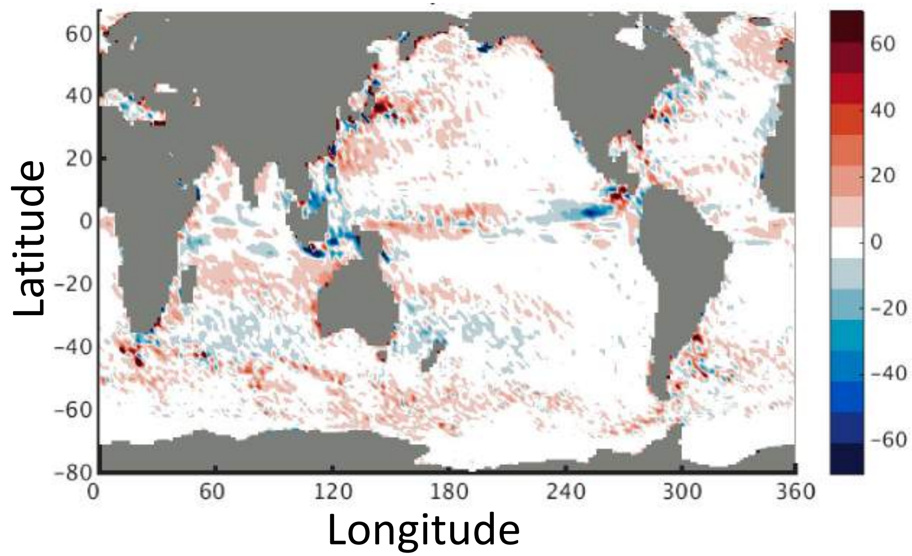




The buttons below will select a visualization of UVvort (horizontal vorticity) level 0 (depth -0.5 m) located at row 2 column 8 in the 128-region series of animations. The different buttons are for either a MP4 animation or a full size image. Animations are available for different resolutions and image sizes, and for a range of time steps. The sizes listed are for the MP4.

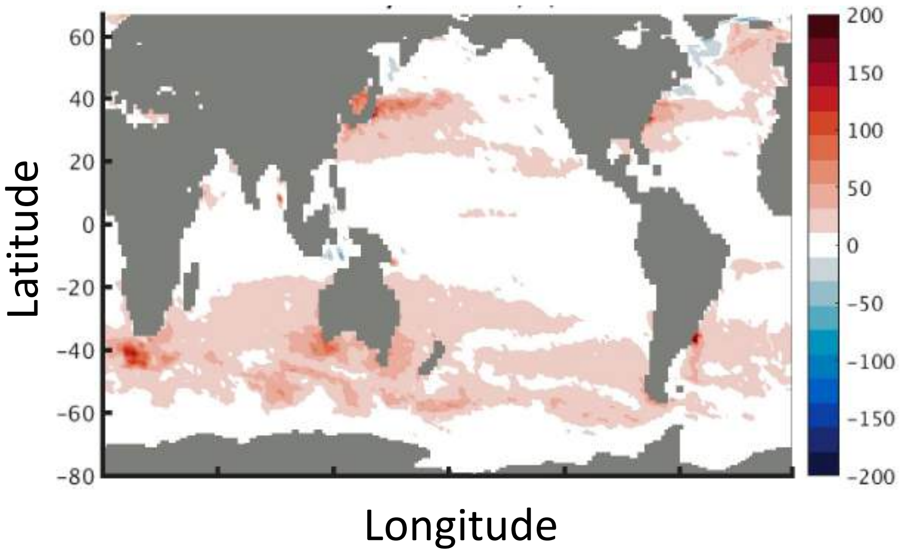
| Timestep | Animation Pixel Resolution and File Size | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 5.4 km / 800x600 | | | | 2.7 km / 1600x1200 | | | |
| 1 hour | 172 MB | Play MP4 | Download MP4 | Image | 788 MB | Play MP4 | Download MP4 | Image |
| 3 hours | 58 MB | Play MP4 | Download MP4 | Image | 313 MB | Play MP4 | Download MP4 | Image |
| 6 hours | 39 MB | Play MP4 | Download MP4 | Image | 199 MB | Play MP4 | Download MP4 | Image |
| 12 hours | 22 MB | Play MP4 | Download MP4 | Image | 110 MB | Play MP4 | Download MP4 | Image |
| 24 hours | 14 MB | Play MP4 | Download MP4 | Image | 65 MB | Play MP4 | Download MP4 | Image |

Hyperwall at home capability allows visual exploration of the hi-res simulation from a remote workstation.

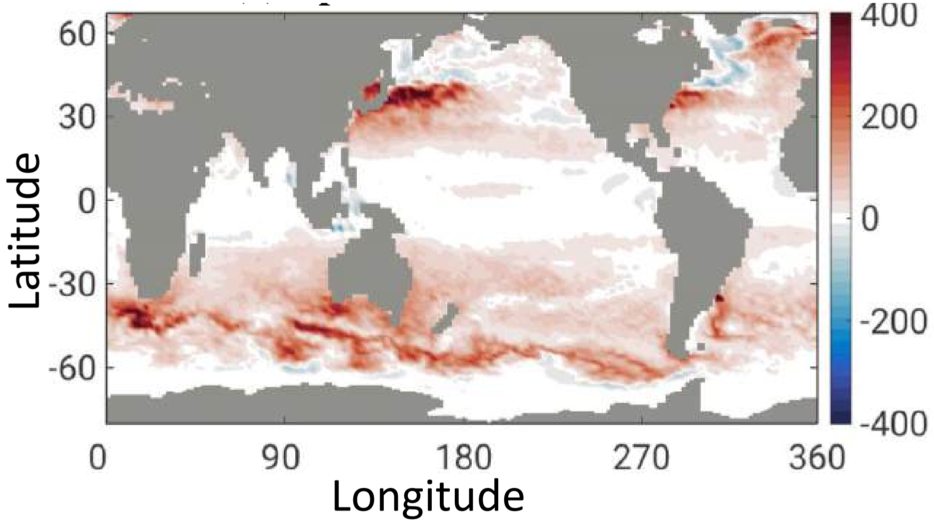
Mesoscale (>50km) vertical heat flux @ 40 m



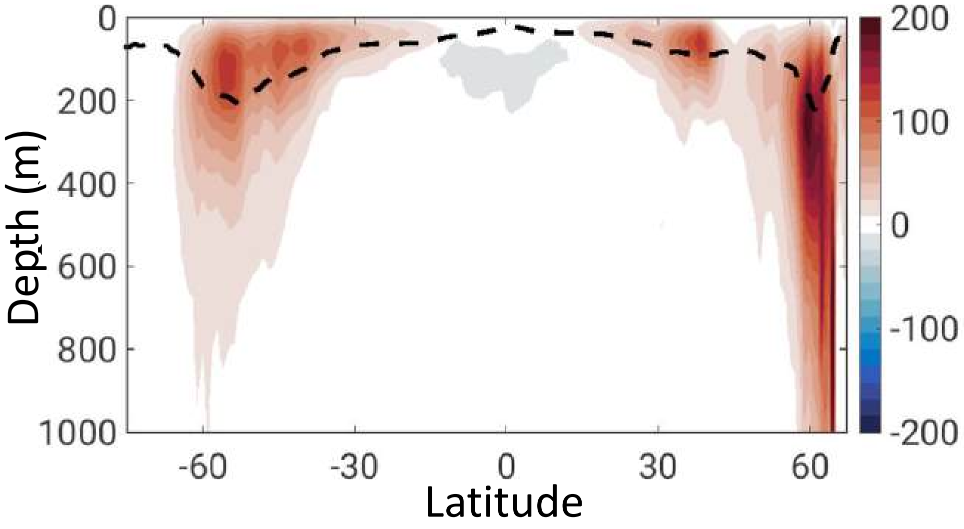

Submesoscale (<50km) vertical heat flux @ 40 m
(based on daily-mean model output)




Submesoscale (<50km) vertical heat flux @ 40 m
(based on hourly model output)




Submesoscale (<50km) zonal-mean heat flux

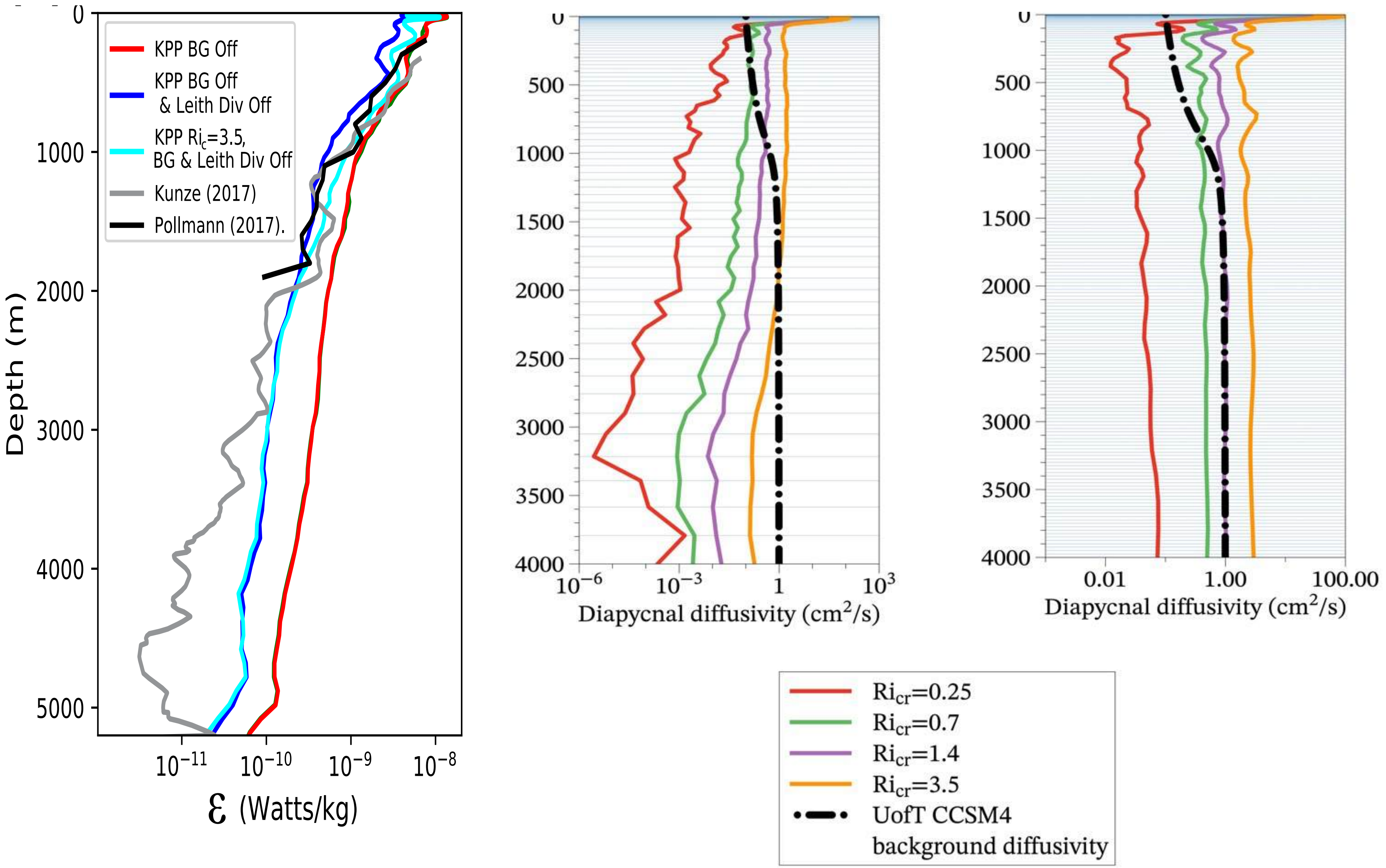



Vertical heat transport at submesoscales (<50km) is an order magnitude larger than at mesoscales (>50km).

Note that submesoscale heat fluxes are up-gradient, not down-gradient as is often assumed in climate-model vertical mixing parameterizations.

**(Su et al., 2018; 2020)**

# Dissipation and vertical diffusivity




Internal-wave admitting ocean simulations can also be used for dissipation and vertical diffusivity studies.

**Skitka et al, 2024**
**Momeni et al, 2024**

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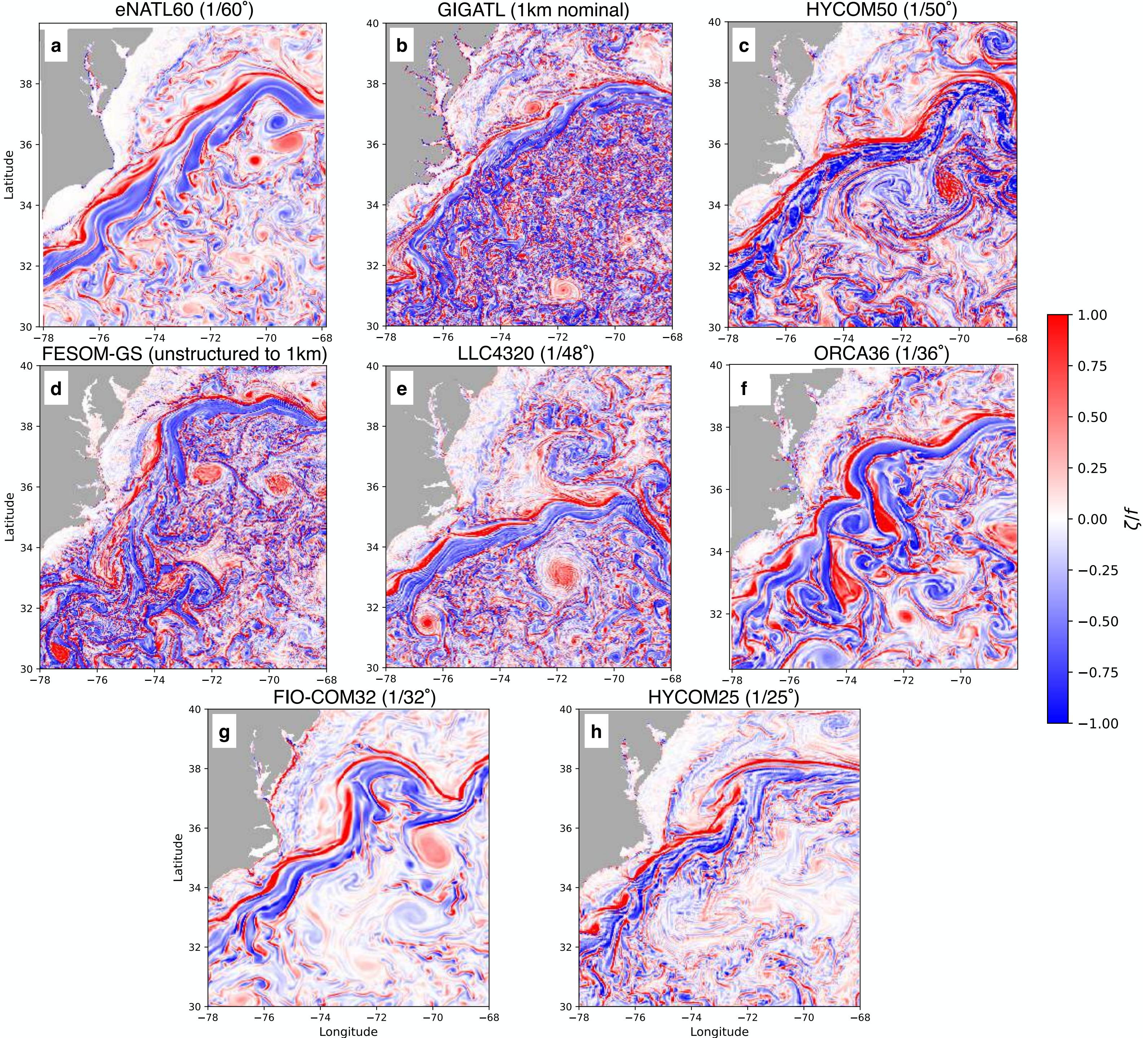
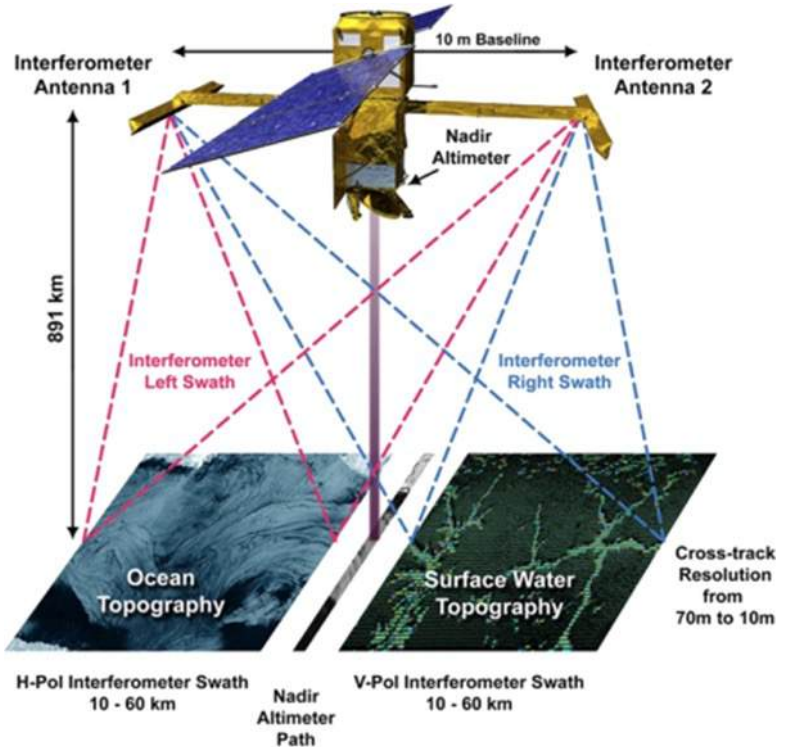
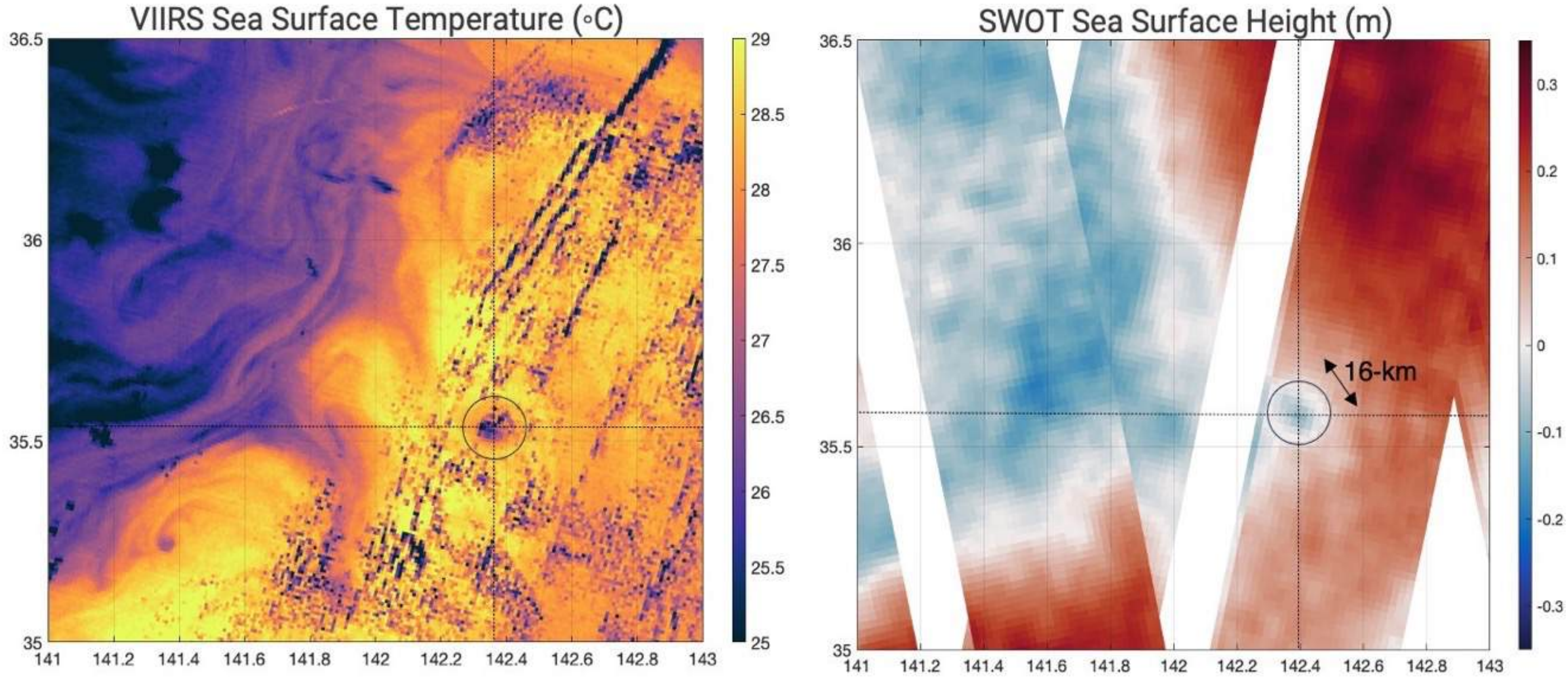



Surface relative vorticity in Gulf Stream region scaled by local Coriolis parameter for 8 high resolution simulations (Uchida et al. 2002)

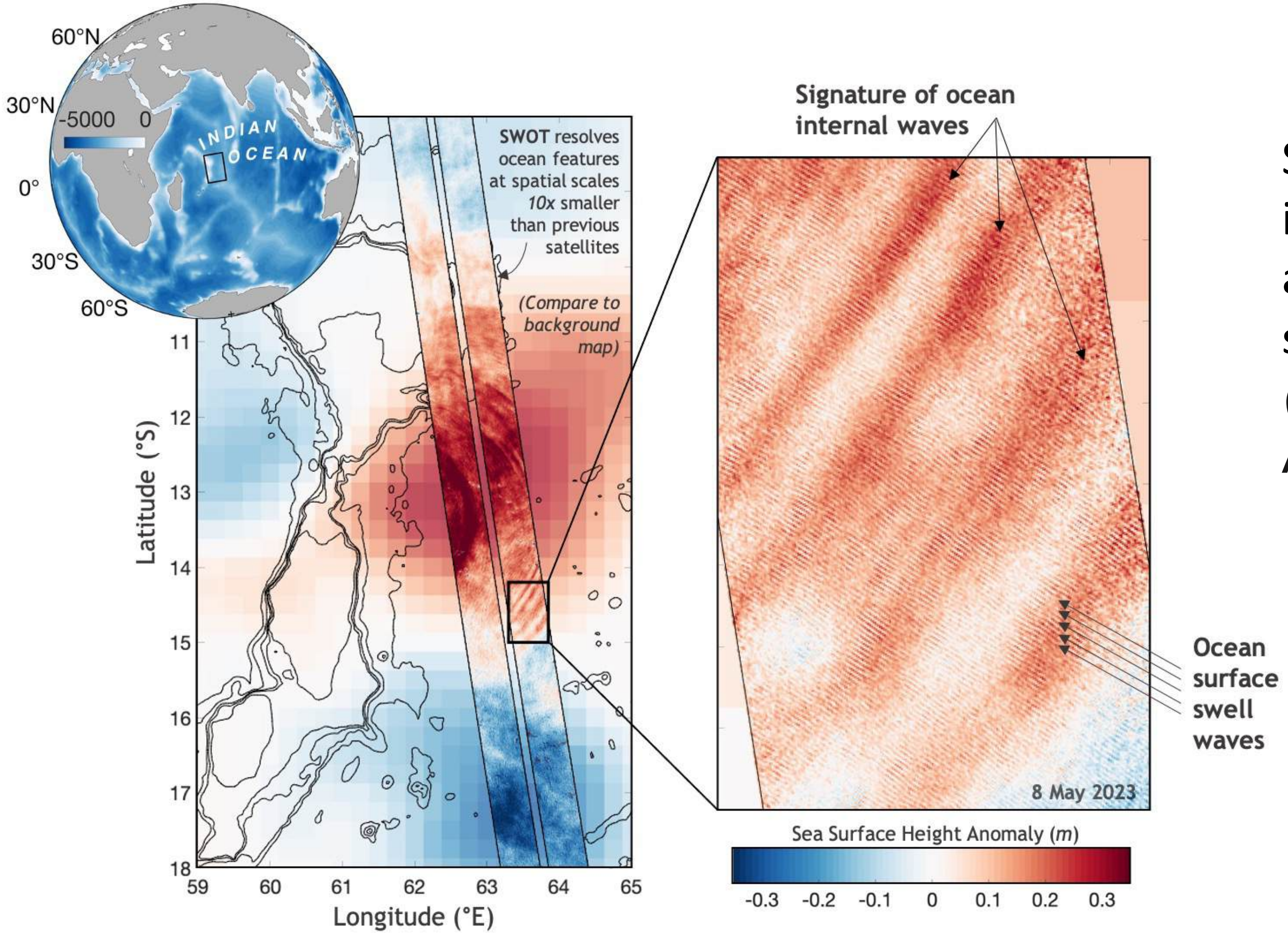
# The surface Wave and Ocean Topography (SWOT) mission.



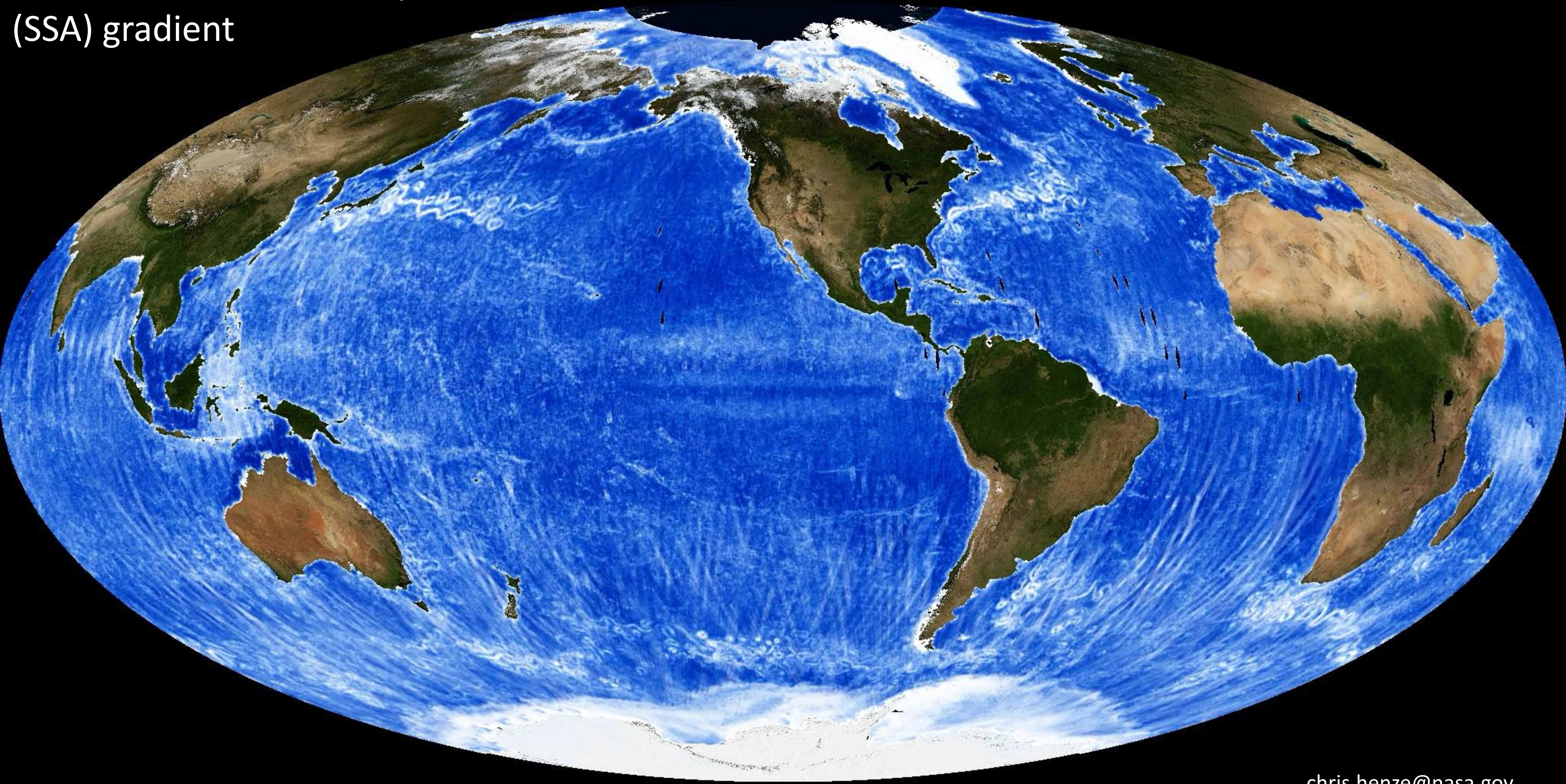

Launched December 2022. Carries a Synthetic Aperture Radar (SAR) Ka-band Radar Interferometer (KaRIn).

SWOT can observe submesoscale processes that cannot be observed with nadir altimetry (courtesy Matt Archer, JPL).



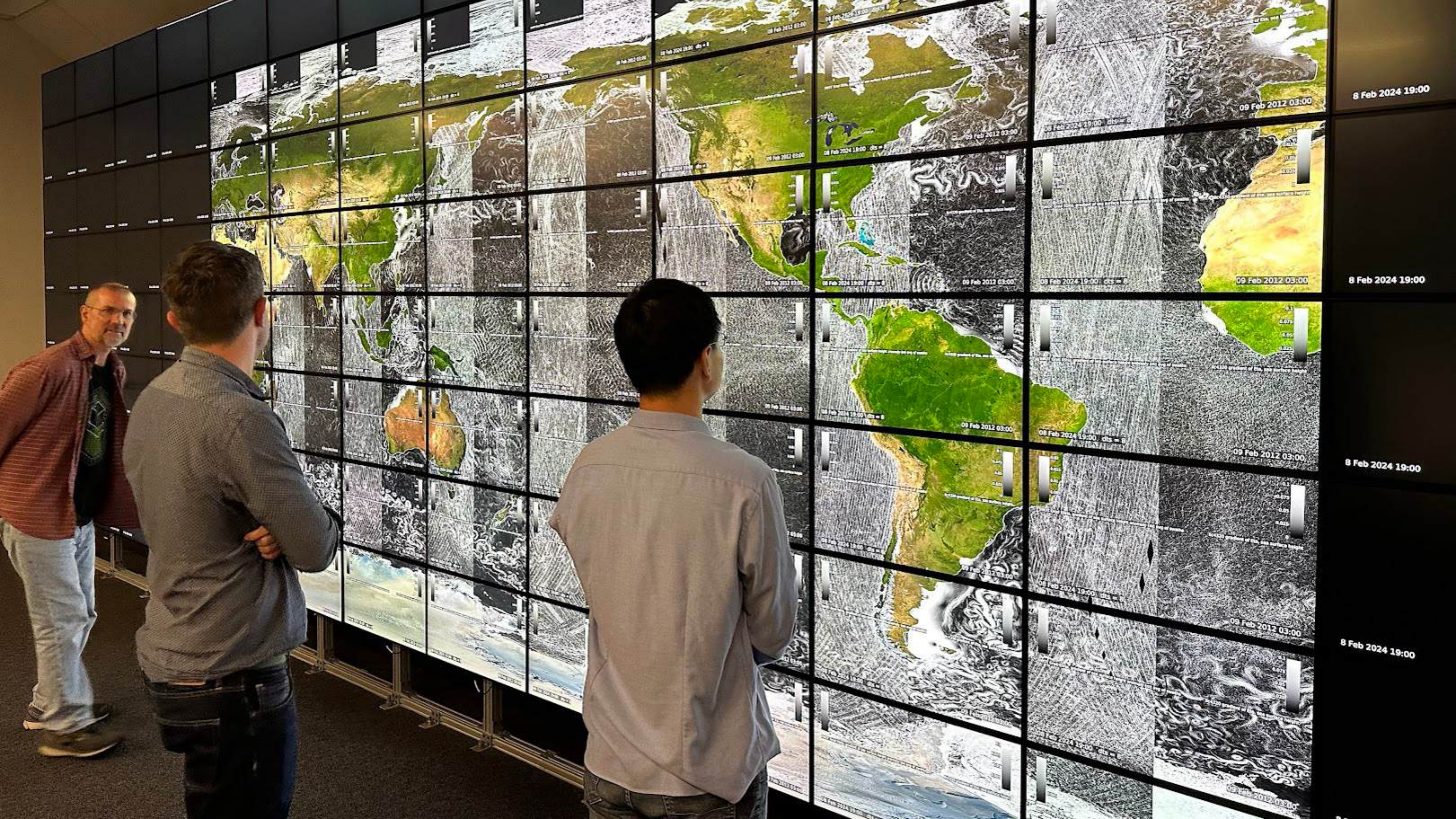

SWOT observes internal waves and surface swell as well (courtesy Matt Archer, JPL).

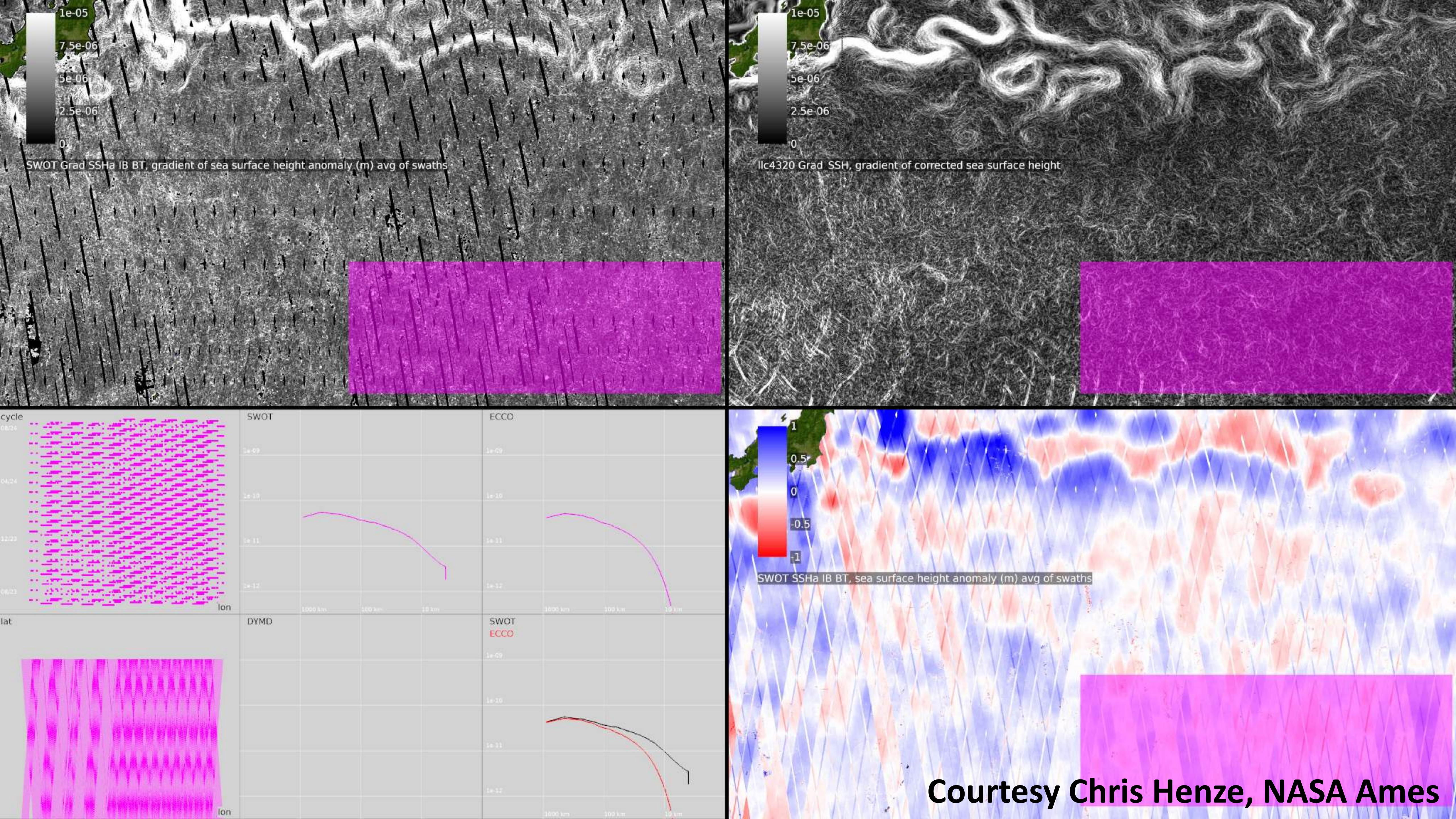
# SWOT Sea Level Anomaly (SSA) gradient



NASA Ames mirror of L2 and L3 SWOT data: /export1/nmccurdy/public/swot

chris.henze@nasa.gov
nina.mccurdy@nasa.gov

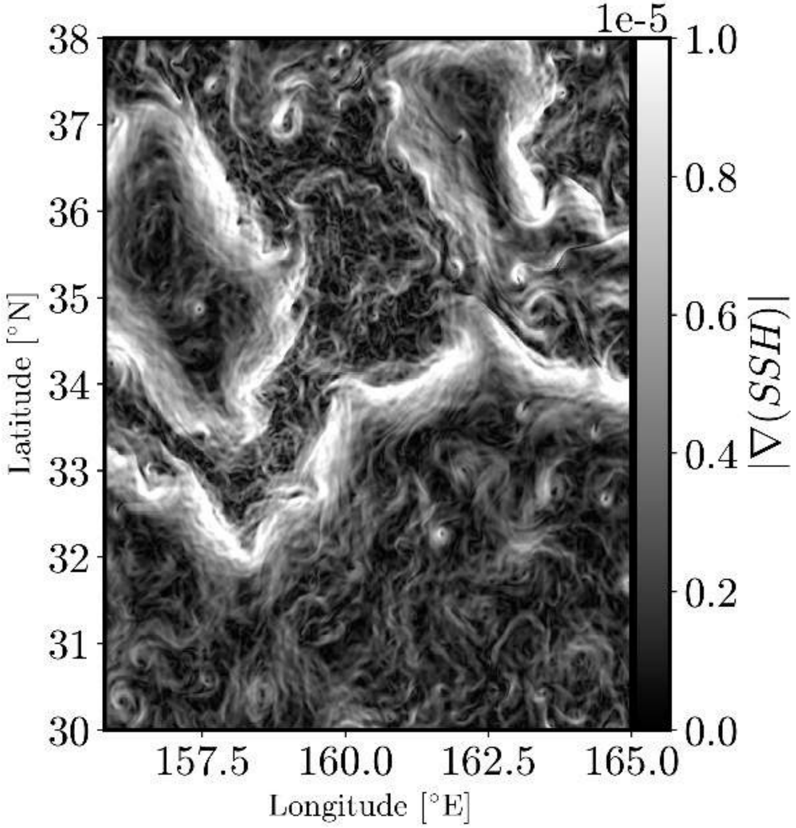

8 Feb 2024 19:00
09 Feb 2012 03:00
8 Feb 2024 19:00
09 Feb 2012 03:00
8 Feb 2024 19:00
8 Feb 2024 19:00



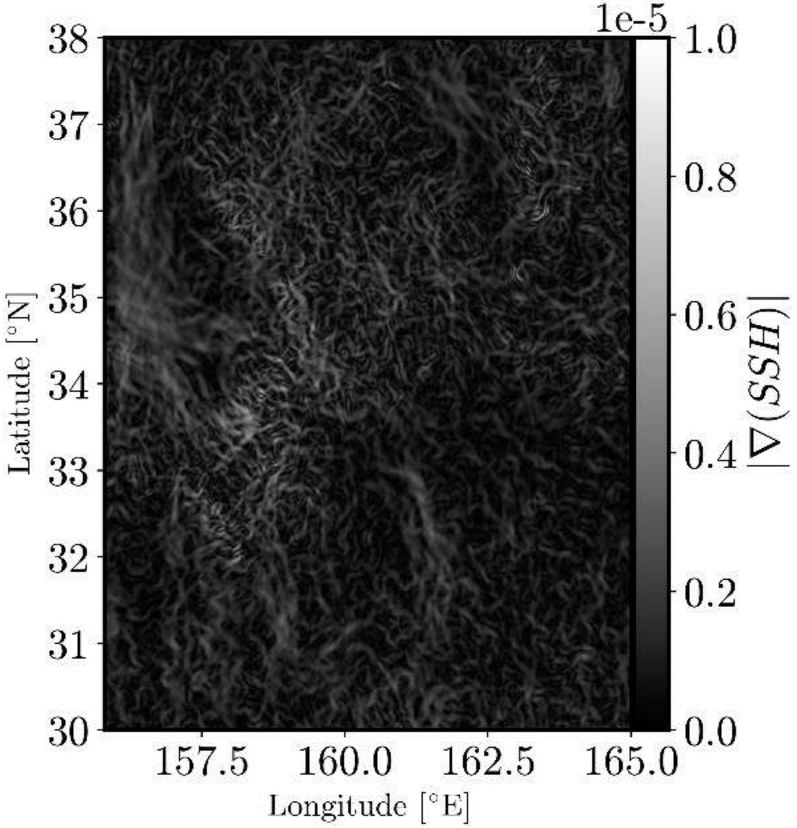

Courtesy Chris Henze, NASA Ames

# Dynamical filter used to separate balanced from unbalanced motions

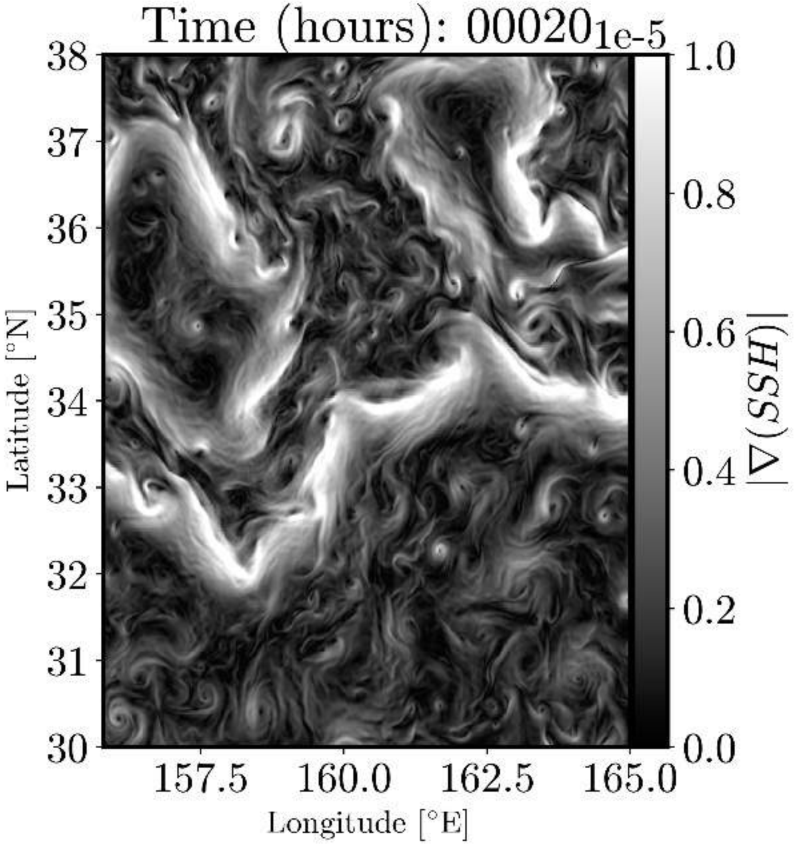
**Unfiltered SSH gradients**




**SSH gradients associated to IGWs**

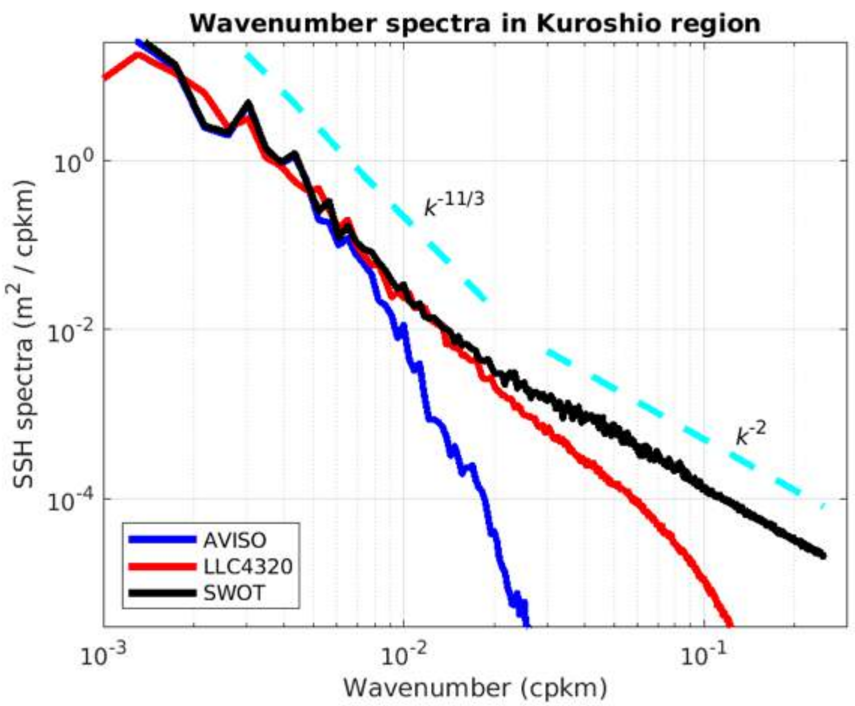


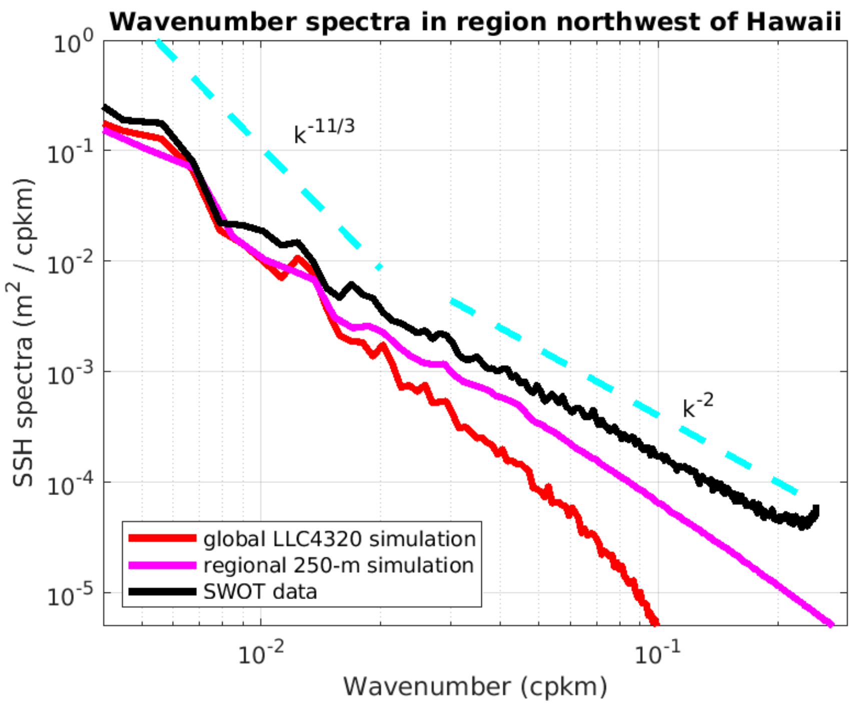

**SSH gradients associated to BMs**




Courtesy Hector Torres, JPL

# SWOT high-wavenumber signals confront our models with a need for improvement




The wavenumber spectra in global high-resolution models capture more high-wavenumber activity than gridded AVISO products made from nadir altimetry, and lie close to the SWOT spectrum down to about 50 km.

However, the SWOT spectrum has more energy than the global models at high wavenumbers.

What is this  high-wavenumber energy? Internal waves? Something else? Whatever it is, it is missing from even the highest-resolution global models.

Our regional simulations (Thakur et al. 2022) feature much finer horizontal and vertical grid spacing than global LLC4320, and they include remotely generated internal waves (from global LLC4320) at their lateral boundaries. The regional models come closer to the SWOT data but are still insufficiently energetic at high wavenumbers.

So, what is missing? Do we need to improve the global models that serve as boundary conditions? Do we need even higher resolution in the regional models? Larger supercomputers would help!

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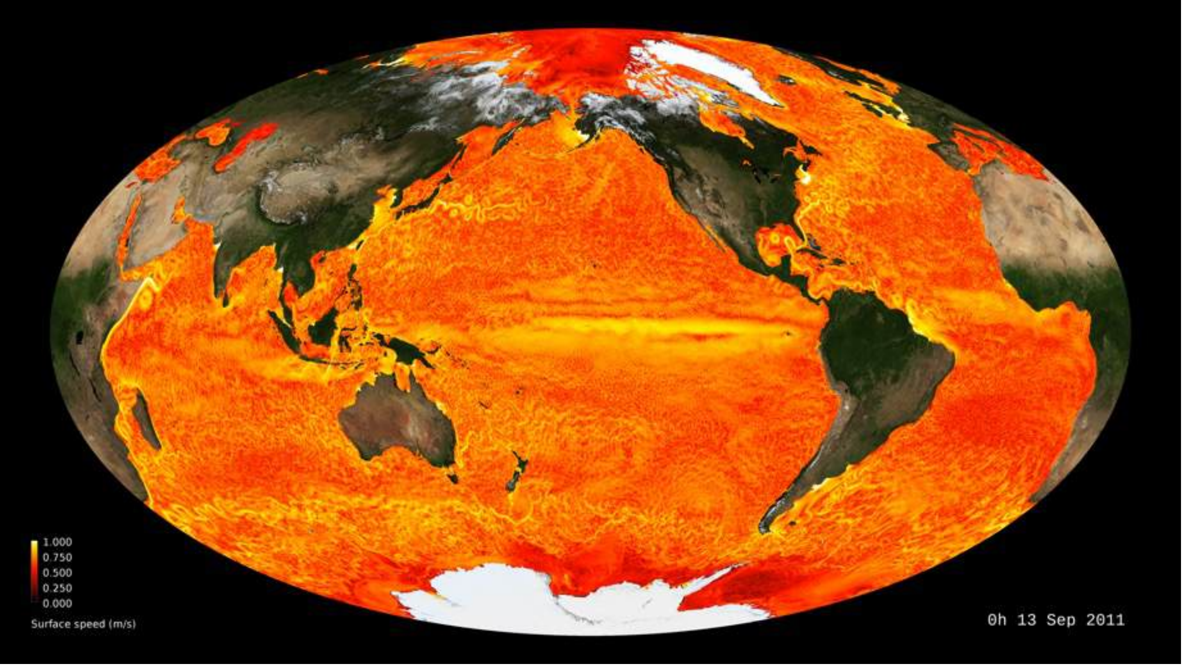
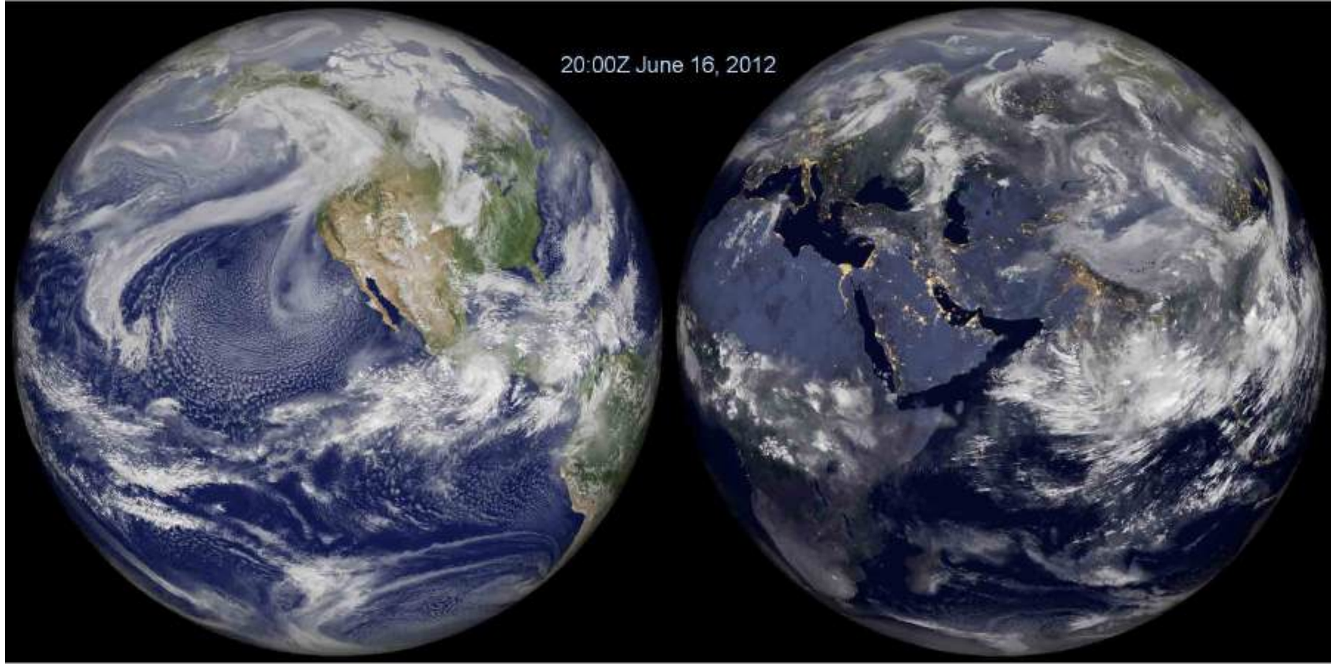



Map of surface current speed from a 1/48° global-ocean and sea ice simulation carried out using the MITgcm. Importantly this simulation includes both atmospheric and tidal forcing and it admits submesoscale eddies and internal waves.

Preliminary work started in October 2012, with successful integration 1/48-deg simulation started in January 2014.

Over 200 science publications make use of output from this simulation, especially for SWOT pre-launch studies.

Global, cloud-resolving simulation with GEOS, carried out with horizontal grid spacing of 1.5-km. Up to one year ago, this was the highest resolution atmospheric simulation carried out with any US global model.

Explicit cloud-resolving simulations provide valuable insight on the ‘grey-zone’ of physics parameterizations, where sub-grid scale processes are partially resolved.

This engineering demonstration led to rapid development of the infrastructure of GEOS to support high-resolution global downscaling applications for climate and weather.

# GEOS/ECCO Coupled Model (Simulation 2/2020-4/2021)

Atmosphere+Infrastucture (GEOS GCM)

- Recent GEOS AGCM, including interactive aerosol model + aerosol-cloud interaction
- Horizontal Grid: Cubed Sphere, C1440, approximately 6–7 km grid spacing
- Vertical Grid: Hybrid eta-pressure, 72 levels, approximately 8 levels inside boundary layer, 30 above tropopause
- MAPL (Modeling, Analysis and Prediction Layer) interface to ESMF infrastructure

Ocean (MITgcm/ECCO)

- MITgcm, Hydrostatic primitive equations for velocity, potential temperature and salinity, with an implicit free surface
- Includes tidal forcing
- KPP vertical mixing of Large et al. (1994), non-local term disabled
- Horizontal Grid: Latitude-Longitude-polar-Cap 2160 (LLC2160), approximately 2–4 km grid spacing
- Vertical Grid: 90 levels, 1m resolution near surface, ~300m resolution at 5000m depth

Sea Ice

- Sea Ice Thermodynamics of CICE4.0;
- Sea Ice Advection (each ice thickness category separately) in MITgcm

Atmosphere-Ocean Interface

- "Skin layer" of Price, et al., 1978
- Implicit backward surface flux calculation assures absolute conservation of energy and water across the interface

# GEOS/ECCO Coupled Model Output – Visualizations

**(Nina McCurdy, David Ellsworth, and others)**

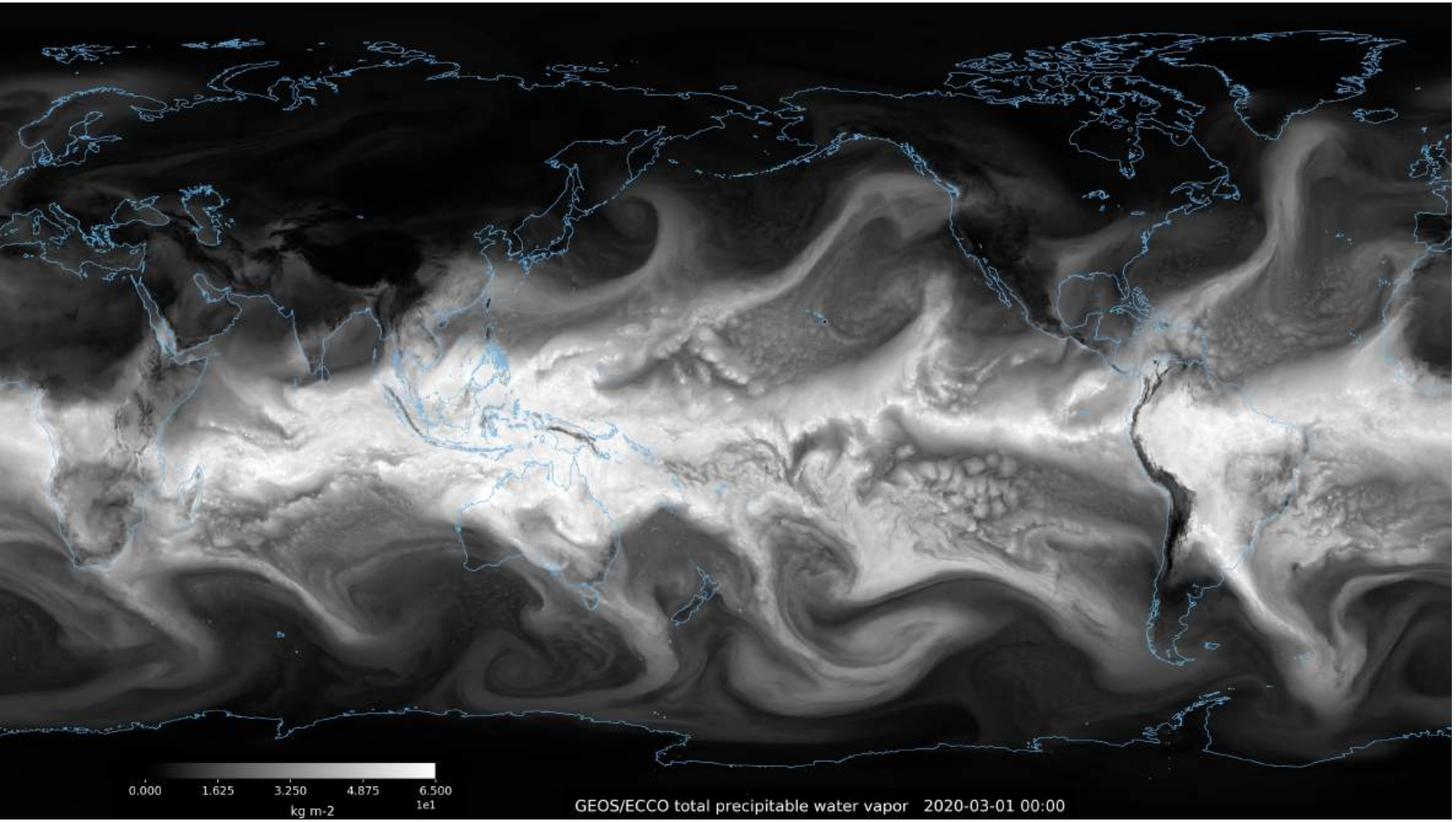
Field-by-field animations of GEOS Atmosphere-related output (interpolated to a lat/lon grid):
https://data.nas.nasa.gov/geoseccoviz/geoseccovizdata/c1440_llc2160/GEOS

Field-by-field animations of MITgcm Ocean-related output (interpolated to a lat/lon grid):
https://data.nas.nasa.gov/geoseccoviz/geoseccovizdata/c1440_llc2160/MITgcm/

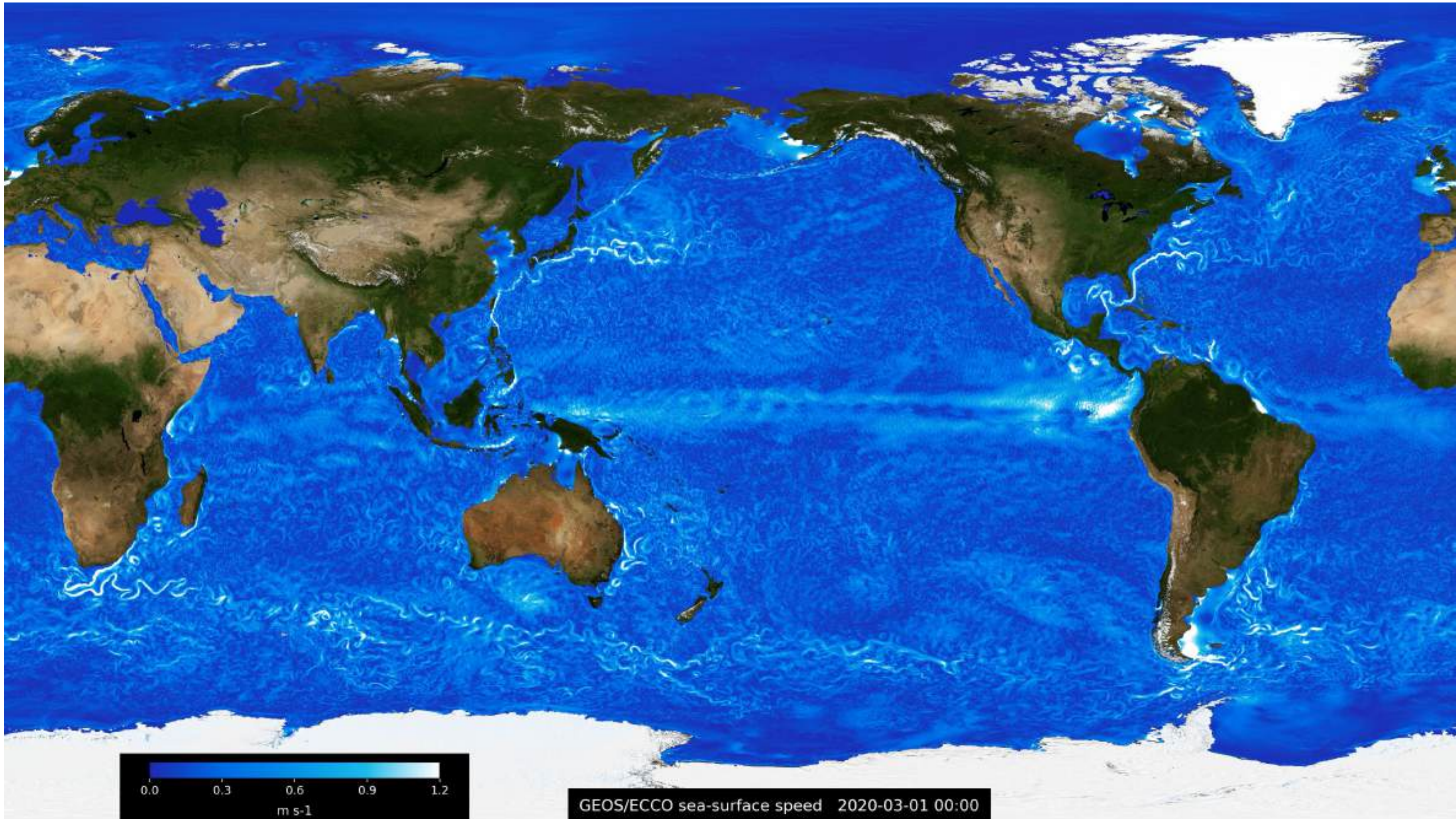
Additional selected fields with native grid visualizations:
https://data.nas.nasa.gov/viz/data.php?dir=/vizdata/nmccurdy/DYAMOND_c1440_llc2160/native_grid

Additional regionally-focused animations:
https://portal.nccs.nasa.gov/datashare/g6dev/WebGL/geos_dyamondv2.html

# 1/16° GEOS water vapor

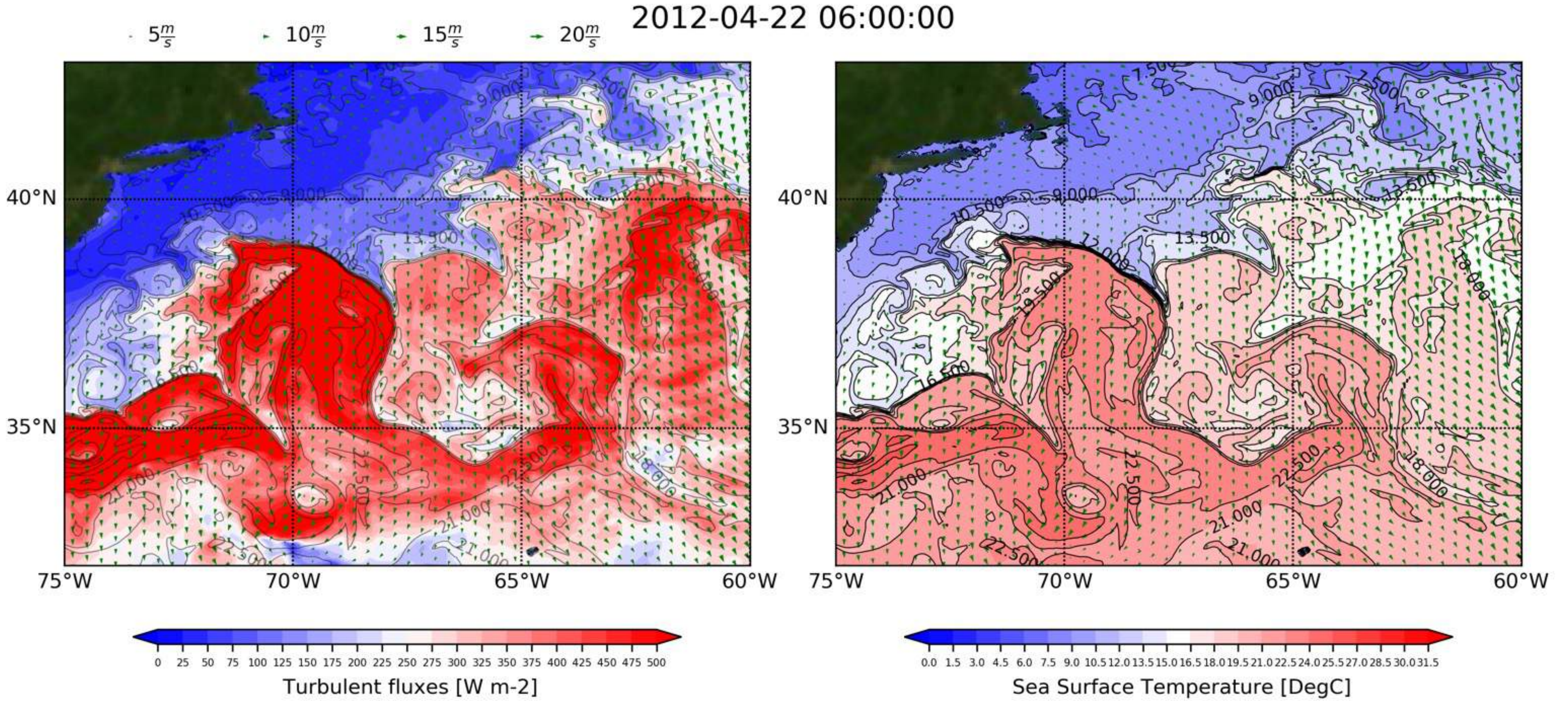


# 1/24° ECCO surface speed



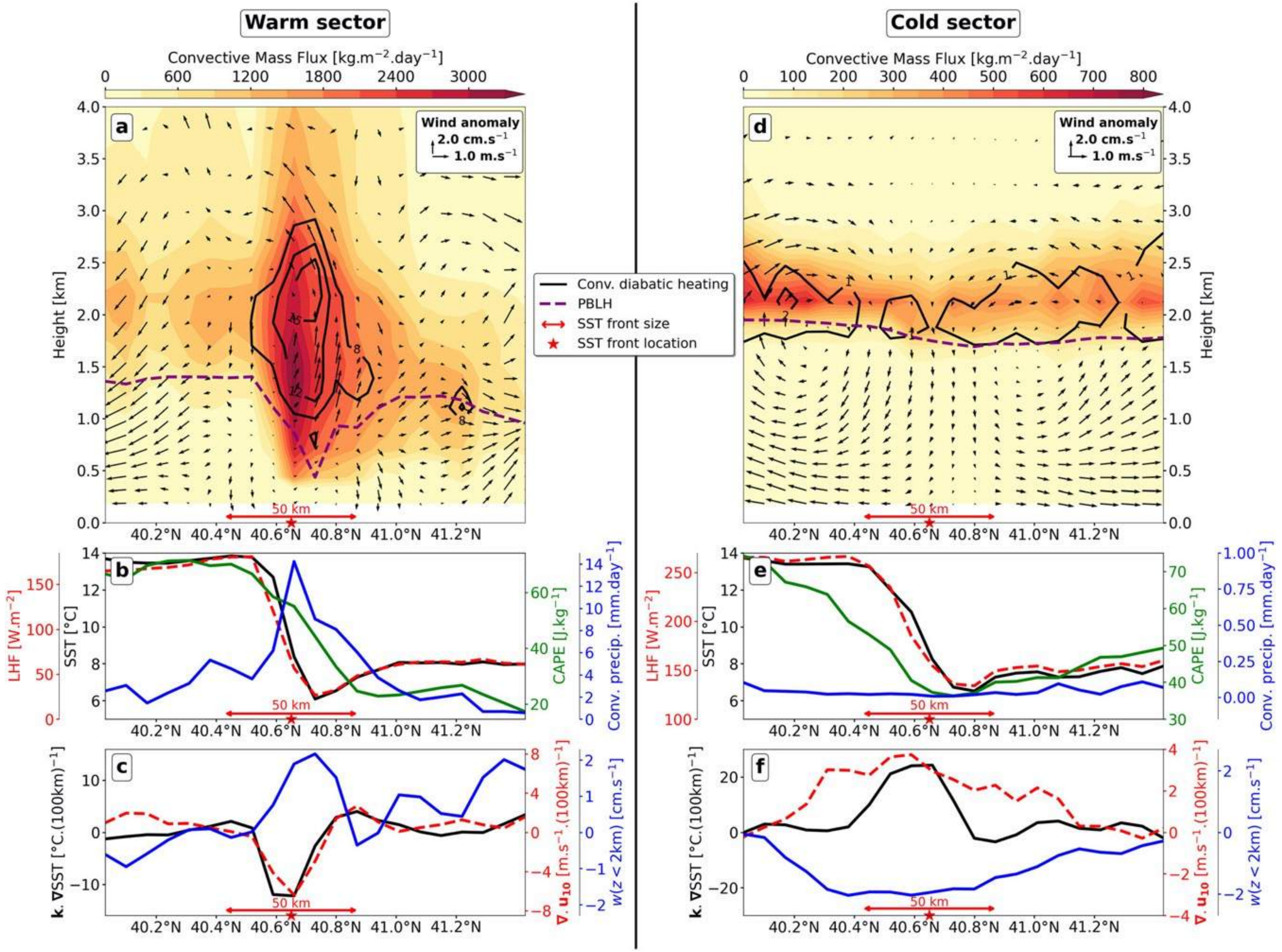
**Ocean eddies observed by SWOT explain 30 to 50% of moisture supply from ocean to atmosphere. As such, these eddies are a significant driver of the global hydrological cycle.**

One key factor is the spatial resolution of ocean eddies and associated currents. High-resolution ocean currents from SWOT observations, combined with microwave and infrared Sea Surface Temperature (SST) images, enable reconstruction of SST fronts around mesoscale eddies, which are critical to the estimation of latent heat fluxes at the air-sea interface and therefore of moisture supply to the atmosphere.




(Strobach et al.. 2022)

# Ocean submesoscale fronts induce diabatic heating and convective precipitation within storms




Example of submesoscale-induced convection in the GEOS/ECCO simulation at 153°E in Kuroshio region.

The fields are averaged over five days (Dec. 16 to Dec. 21) for a–c southerly winds and d–f northerly winds

(Vivant et al., 2025)

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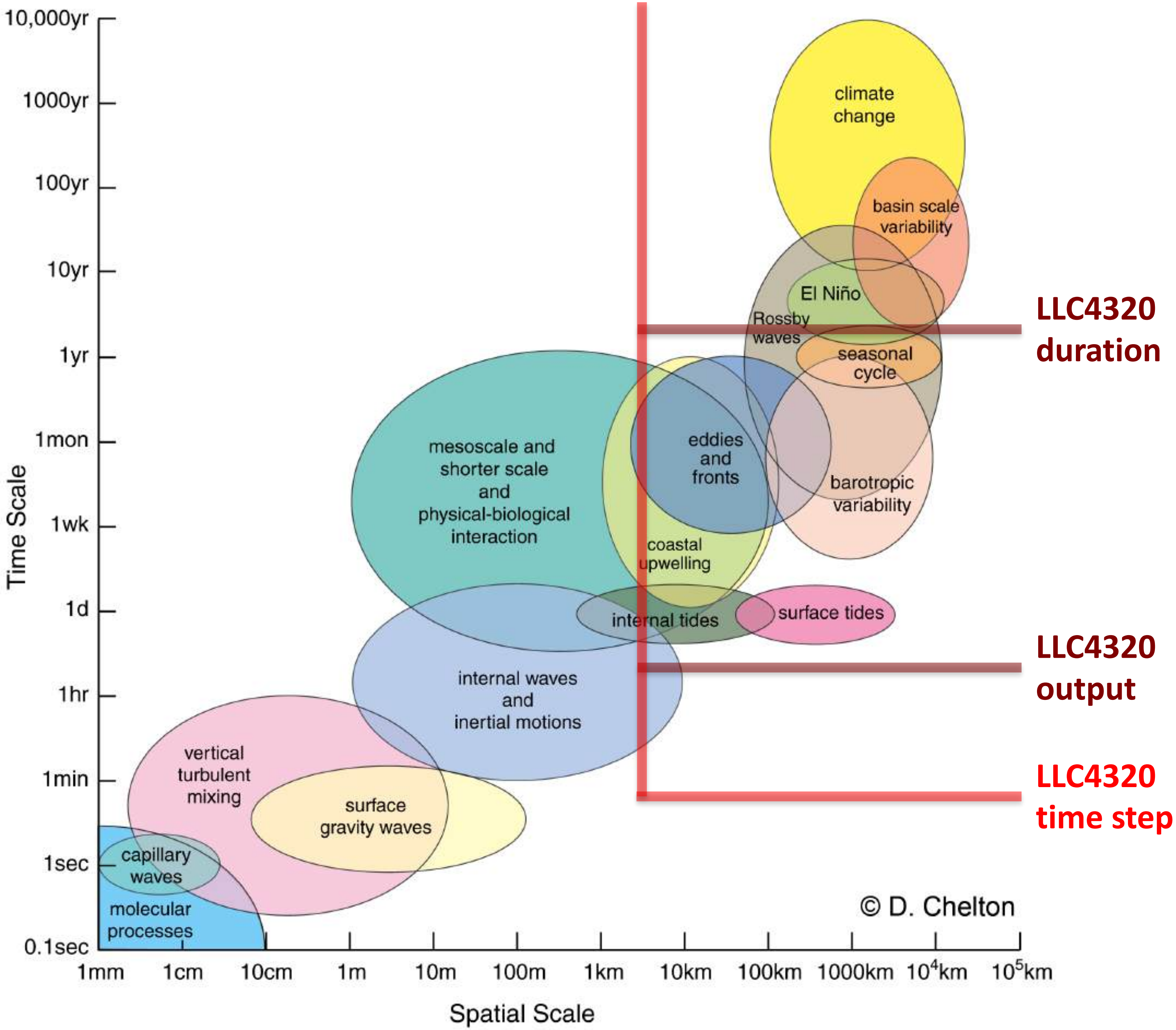
10,000yr
1000yr
100yr
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1yr
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1min
1sec
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Time Scale
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1cm
10cm
1m
10m
100m
1km
10km
100km
1000km
$10^4$km
$10^5$km
Spatial Scale
climate change
basin scale variability
El Niño
Rossby waves
seasonal cycle
eddies and fronts
barotropic variability
mesoscale and shorter scale and physical-biological interaction
coastal upwelling
internal tides
surface tides
internal waves and inertial motions
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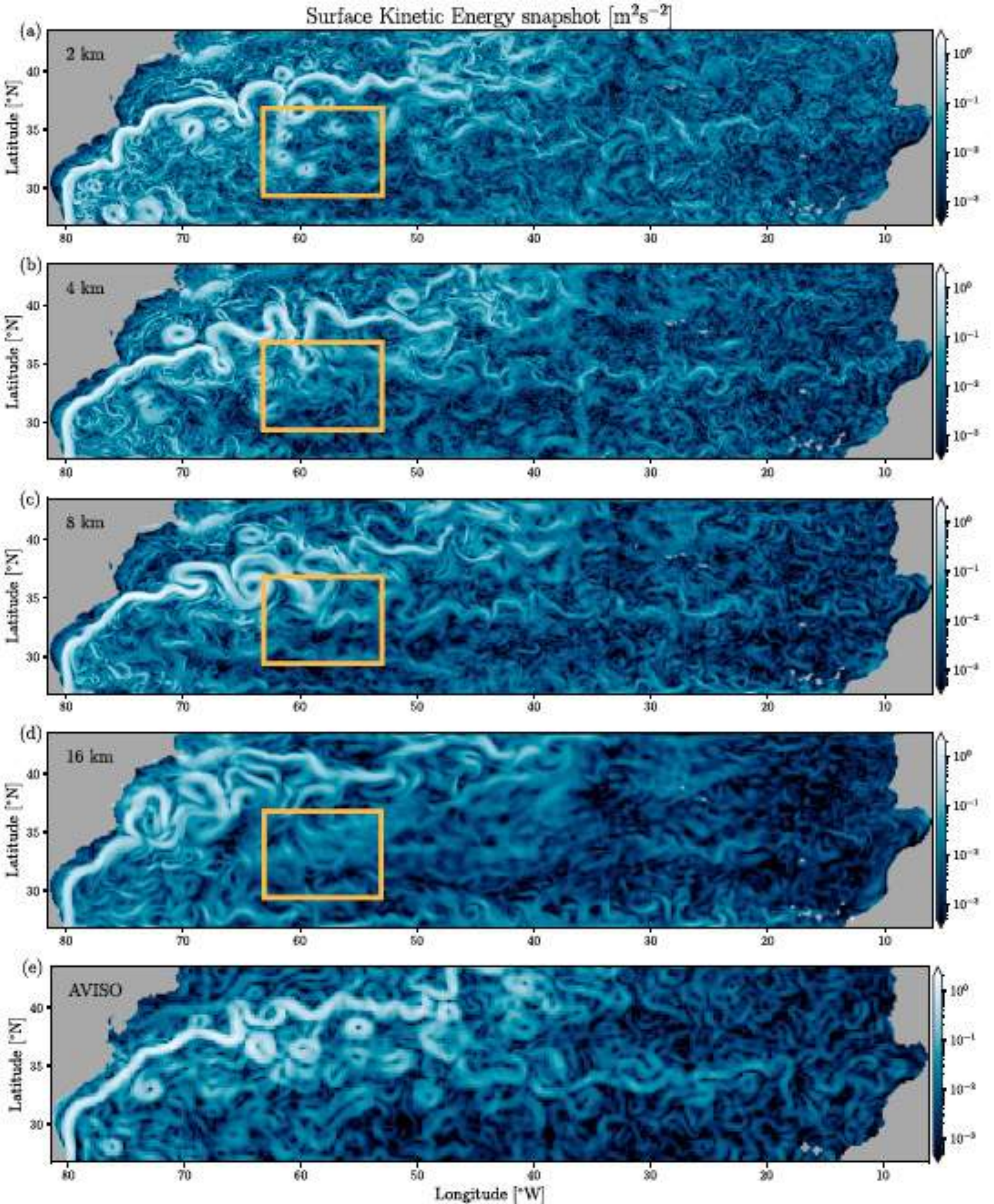
© D. Chelton
LLC4320 duration
LLC4320 output
LLC4320 time step




2-km grid spacing

4-km grid spacing

8-km grid spacing

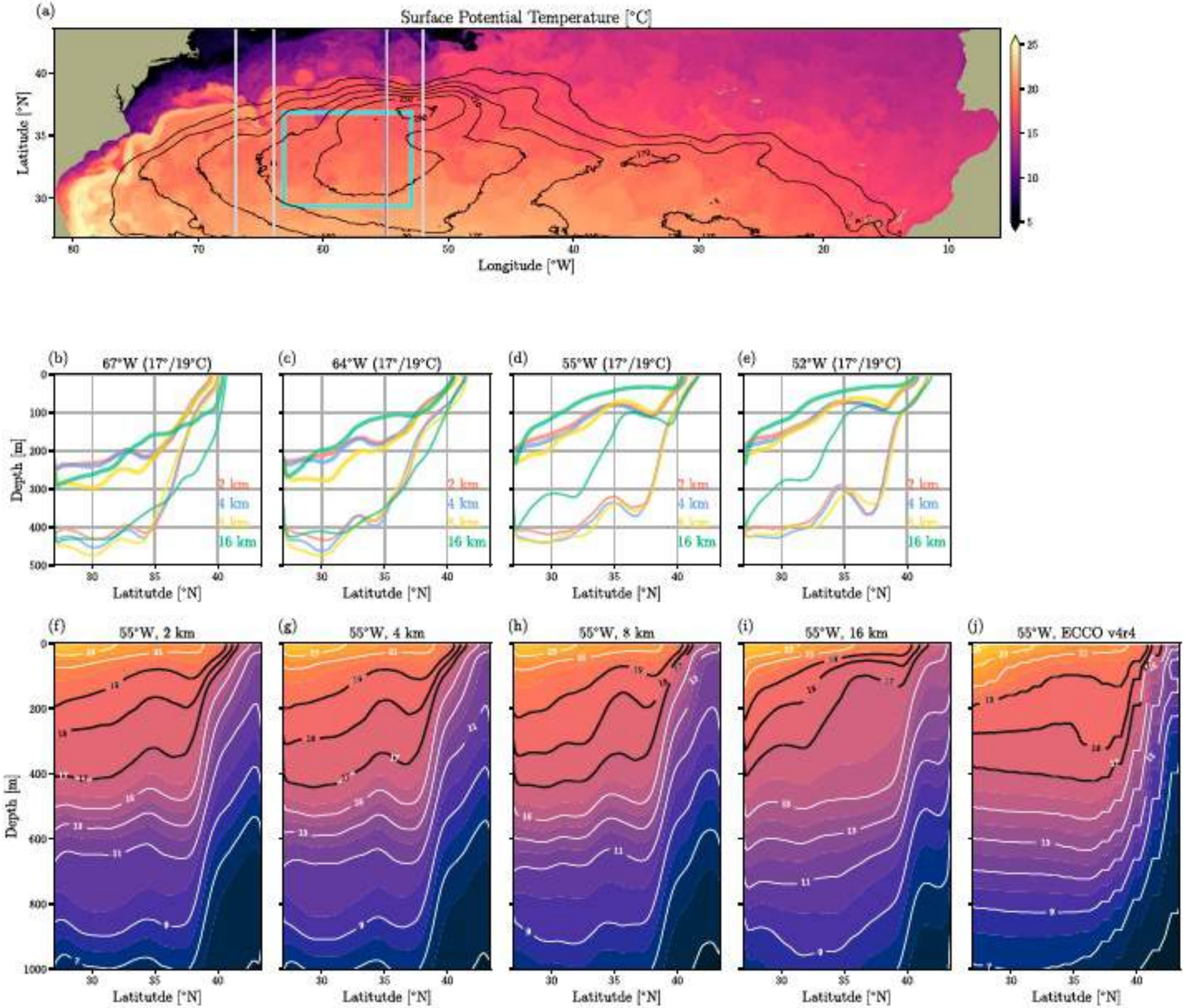
16-km grid spacing

AVISO

# Do Submesoscales Affect the Large-Scale Structure of the Upper Ocean?

(Sinha et al., 2023)

Carry out 50-year regional simulations to equilibrate upper ocean.




The equilibrium stratification of the thermocline changes drastically as the grid spacing is refined from 16 to 8 km and mesoscale eddies are fully resolved.

The thermocline stratification remains largely unchanged, however, between the 8-, 4-, and 2-km runs.

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**Question:** Can we understand and predict the exchange of heat, freshwater, carbon, and other properties between the global ocean and the atmosphere?

(or is climate the other dismal science, incompletely observed, and unboundable in its potentially important pieces?)

A key responsibility of our generation is to start and maintain key climate-quality time series that can be used by future generations to better understand, predict, and control the Earth's climate.

**Hypothesis:** Submesoscale ocean motions (<50 km), both balanced and unbalanced, play a key role in air-sea exchanges and vertical property transports in the ocean.

Almost certainly yes, but there are surprises, e.g., the study of Sinha et al. (2023).

What resolution or model parameterizations are sufficient for climate simulations with descriptive and predictive skill?