High-Resolution North Atlantic Ocean Modeling: Impact of bathymetry, tides, and atmospheric forcing

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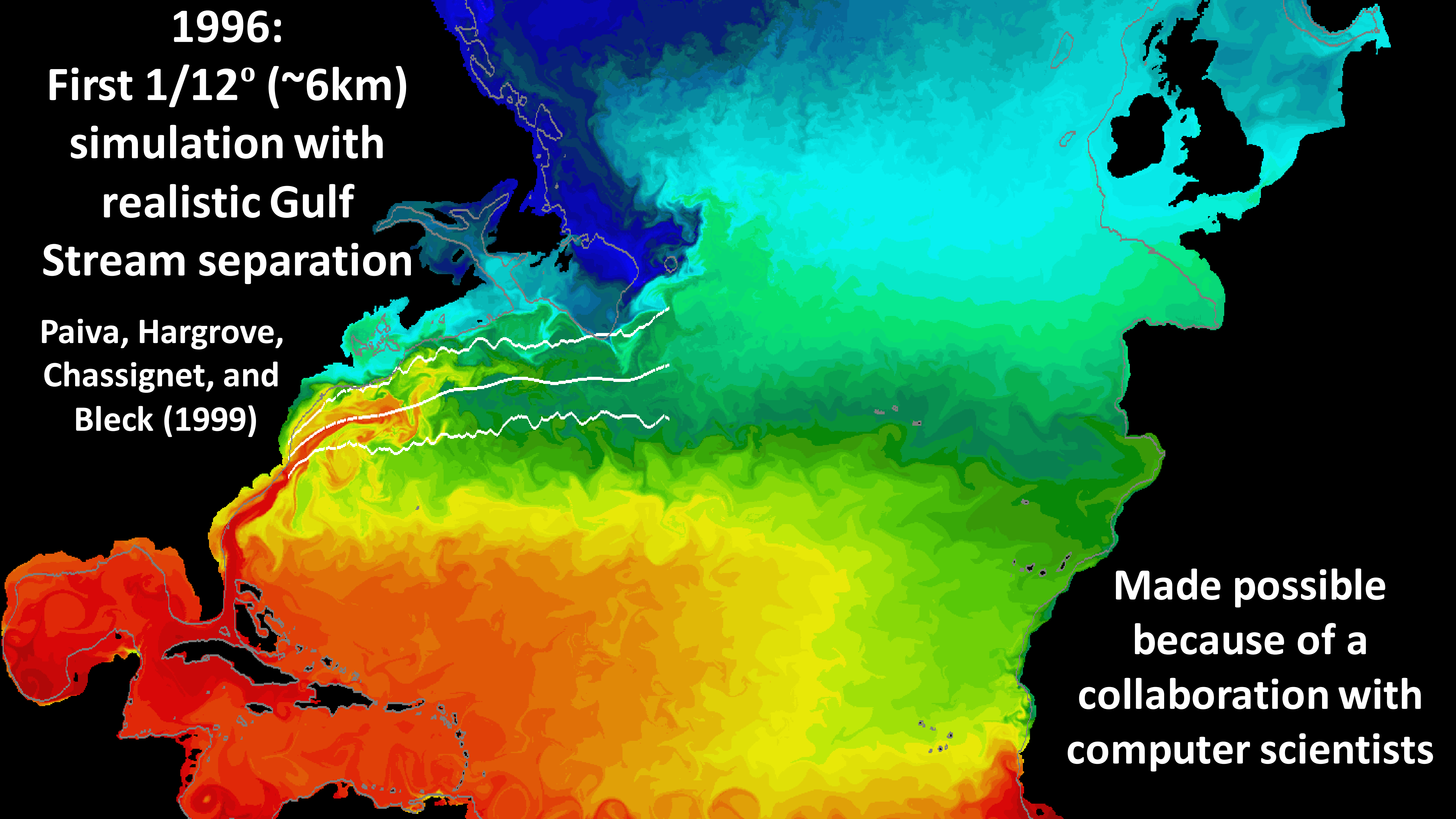
1996:
First 1/12º (~6km) simulation with realistic Gulf Stream separation

Paiva, Hargrove, Chassignet, and Bleck (1999)



Made possible because of a collaboration with computer scientists

~25 years later

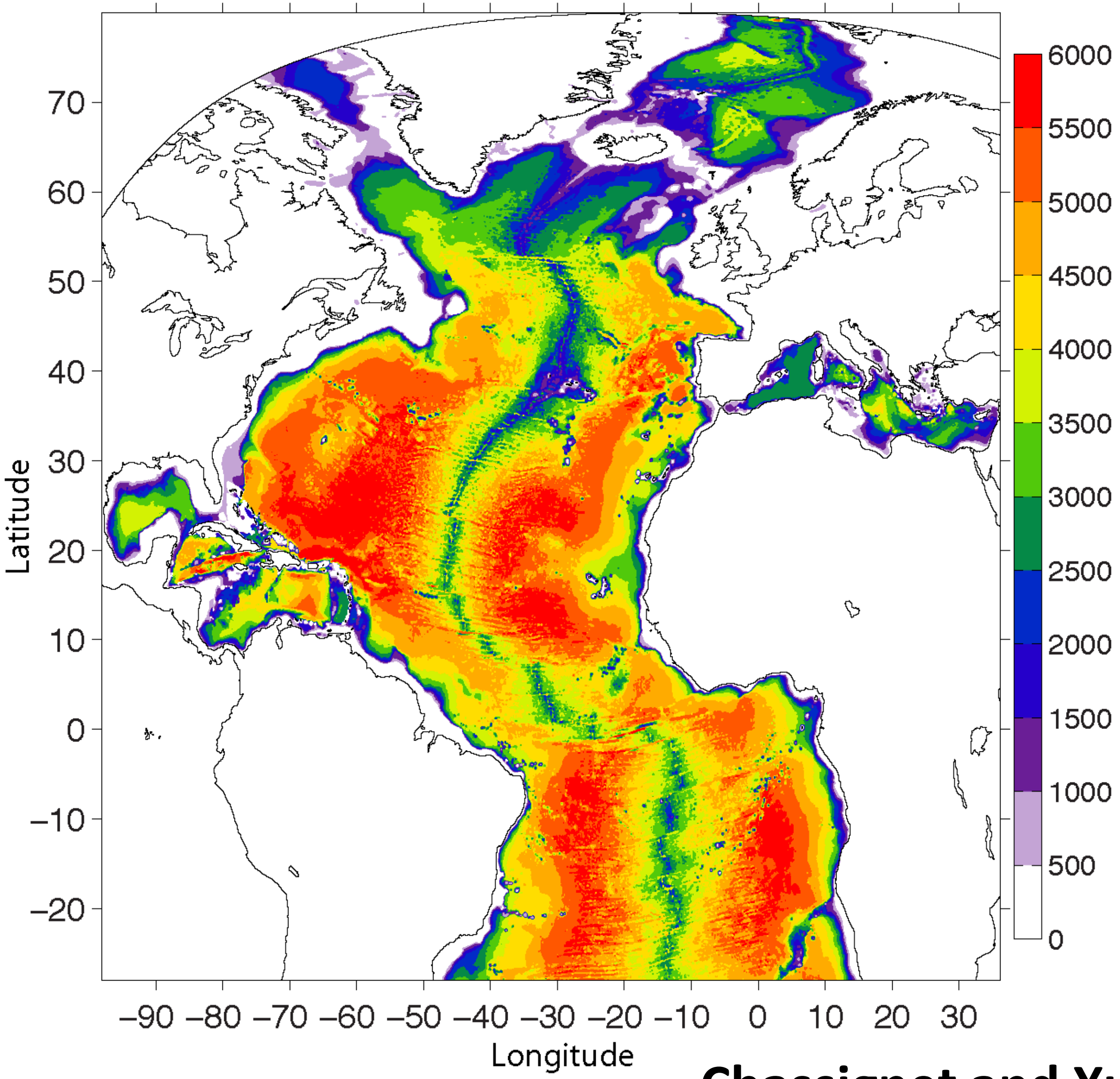
- Routine global ocean prediction at 1/12° (~6 km at mid-latitudes) (Mercator, HYCOM GOFS 3.1, BlueLINK, etc.)
- State-of-the art global ocean prediction at 1/25° (~3 km at mid-latitudes) with tides (HYCOM GOFS 3.5, Navy ESPC); prototype 1/36° MERCATOR NEMO
- Short decadal climate integration of coupled ocean-ice-atmosphere models with ocean resolution at ~1/10°
- Prototypes global and basin-scale ~1/50° simulations (~1.5 km at mid-latitudes) with tides (MITgcm, NEMO, HYCOM, ROMS)

- **Why the improvement at Δx>1/10°?**
  - First baroclinic Rossby radius of deformation is mostly resolved => good representation of baroclinic instability processes
  - Flows may exceed a critical Reynolds number (Özgökmen, Chassignet, and Paiva, 1997)
- **However, identifying the dynamics responsible for western boundary current separation and penetration continues to be a challenge** (Chassignet and Marshall, 1998)

Increasing resolution

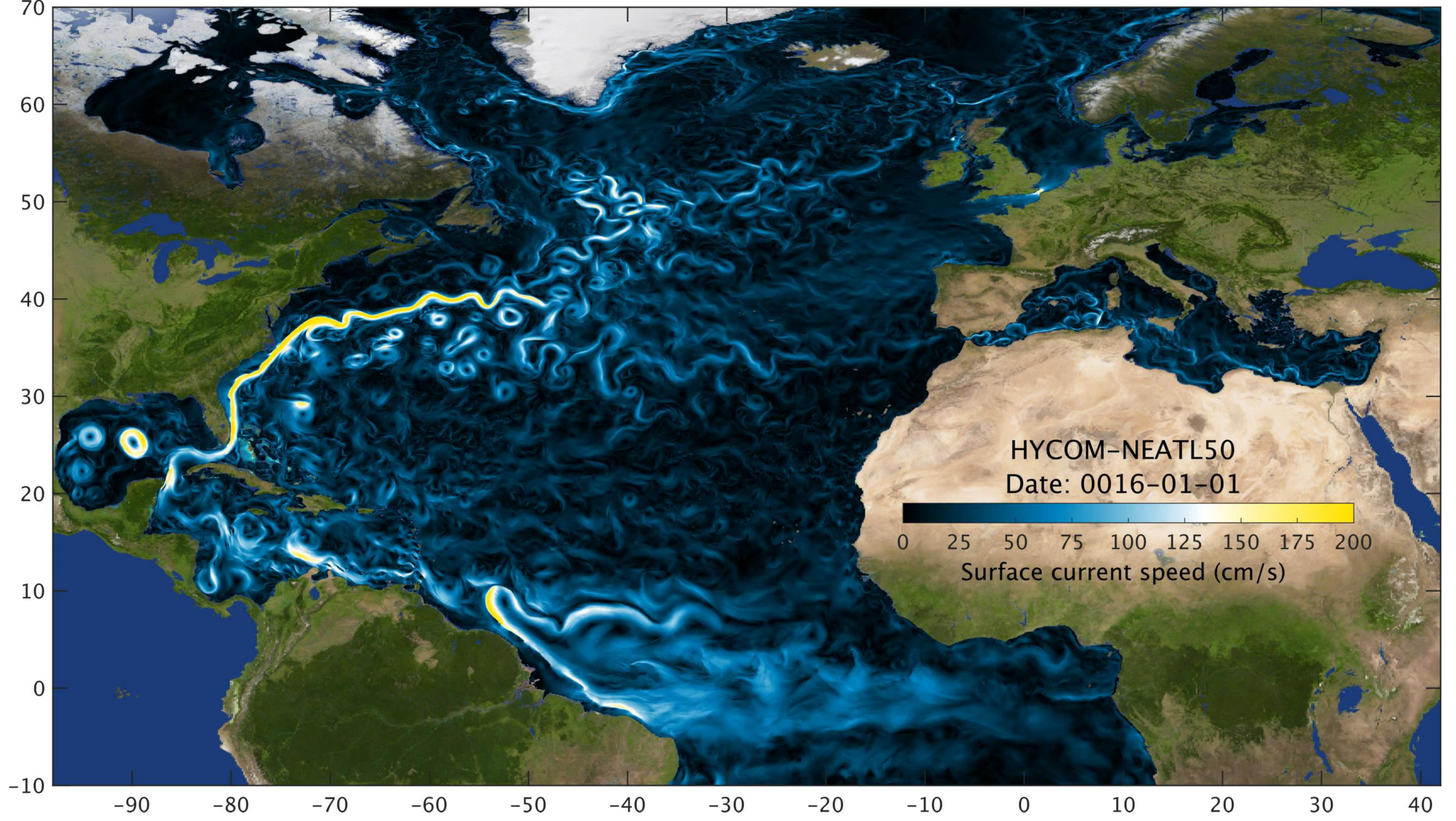
- **1/12°, 1/25°, 1/50°?**
- **What is the added value?**

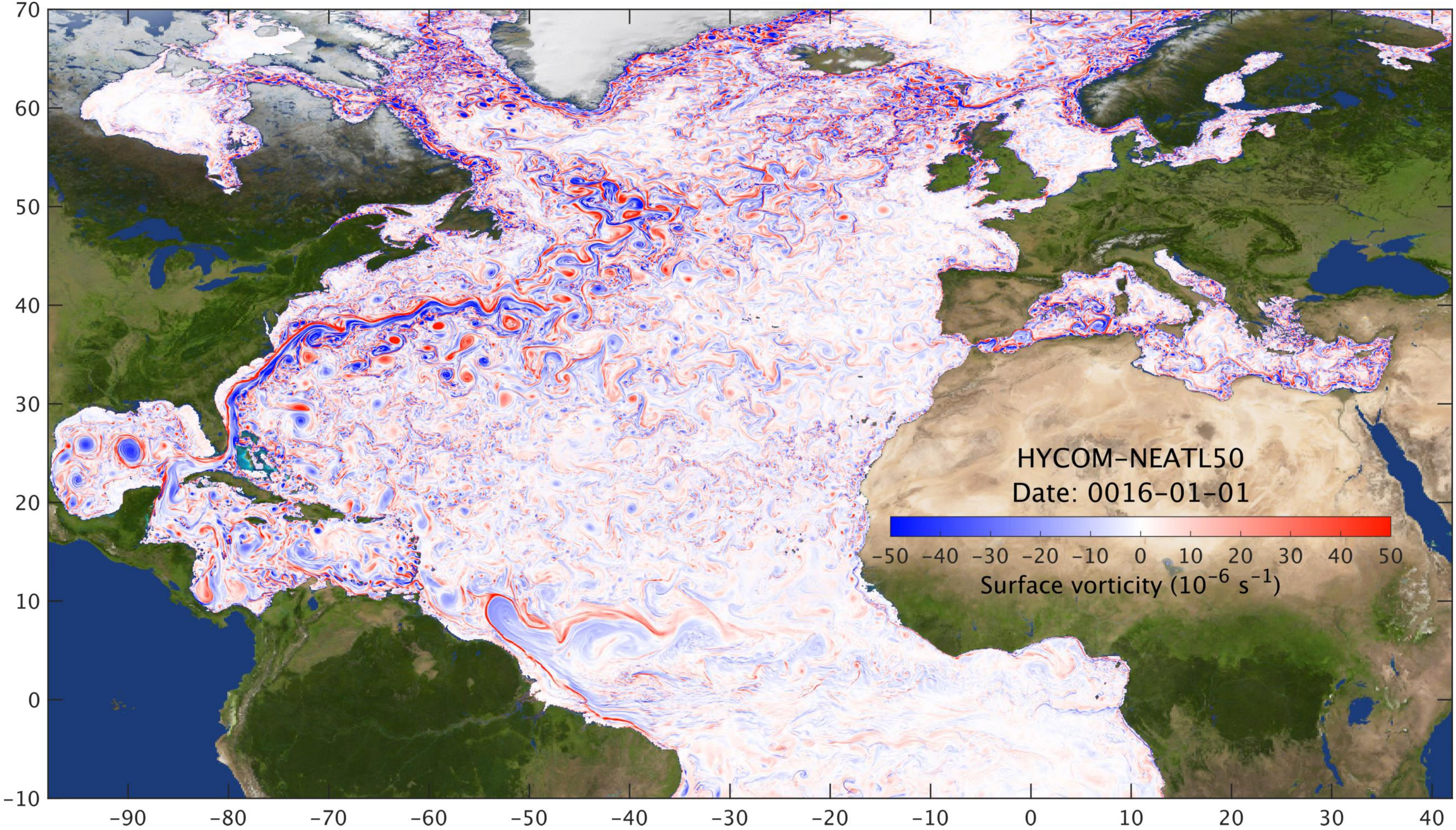
- **Identical 32 layers HYCOM configuration including topography.**
- **Closed boundaries**
- **Climatological forcing with daily variability**
- **Viscosity as a function of grid spacing (1/12° and 1/25°)**
- **Same viscosity for 1/25° and 1/50°**

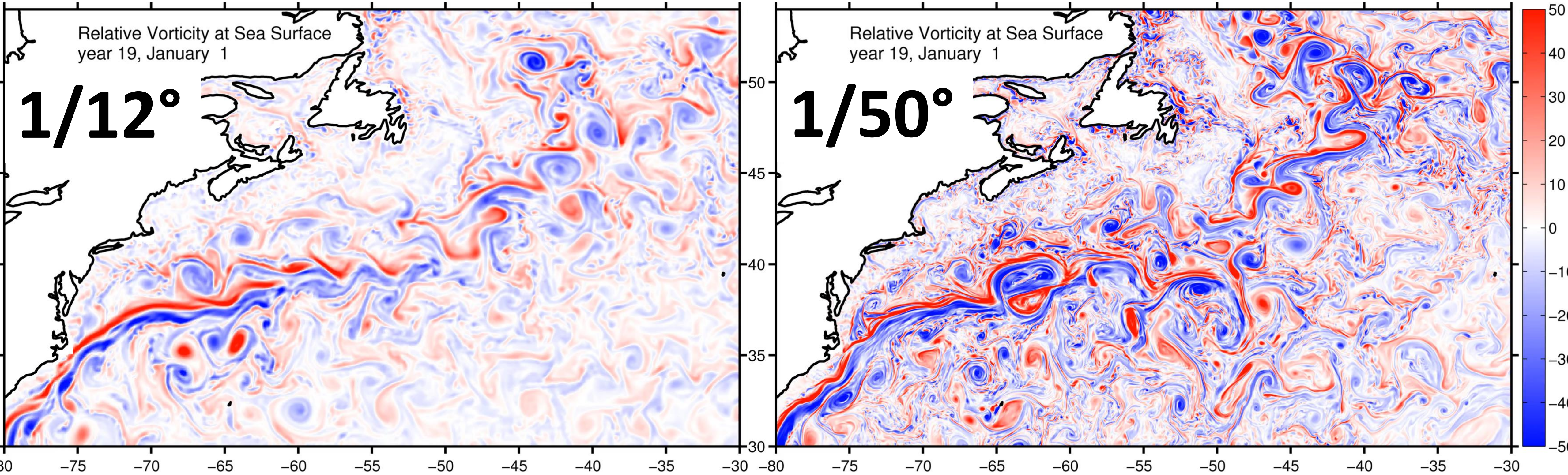


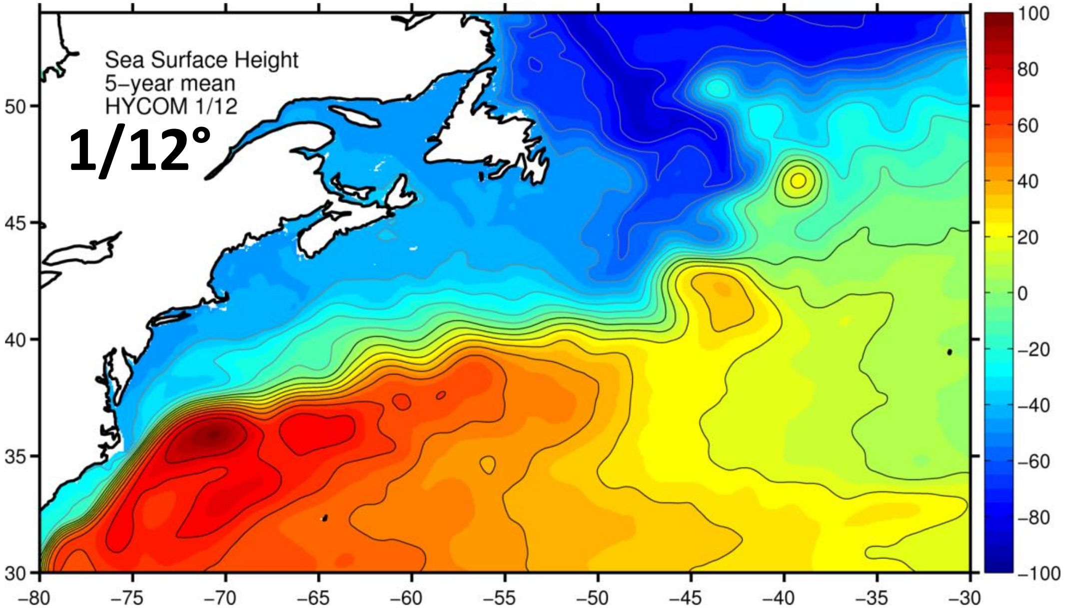
Chassignet and Xu (2017, JPO)

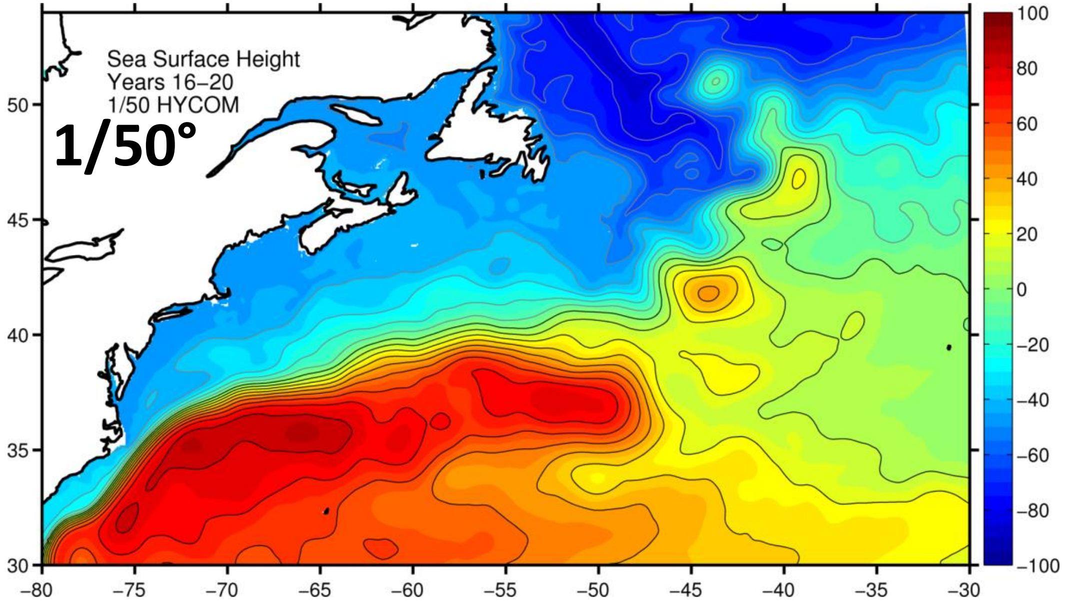
500k CPU-hours per model year for the 1/50°


HYCOM-NEATL50
Date: 0016-01-01
0 25 50 75 100 125 150 175 200
Surface current speed (cm/s)
70
60
50
40
30
20
10
0
−10
−90 −80 −70 −60 −50 −40 −30 −20 −10 0 10 20 30 40


HYCOM–NEATL50
Date: 0016–01–01
–50 –40 –30 –20 –10 0 10 20 30 40 50
Surface vorticity (10^{-6} s^{-1})
70
60
50
40
30
20
10
0
–10
–90
–80
–70
–60
–50
–40
–30
–20
–10
0
10
20
30
40

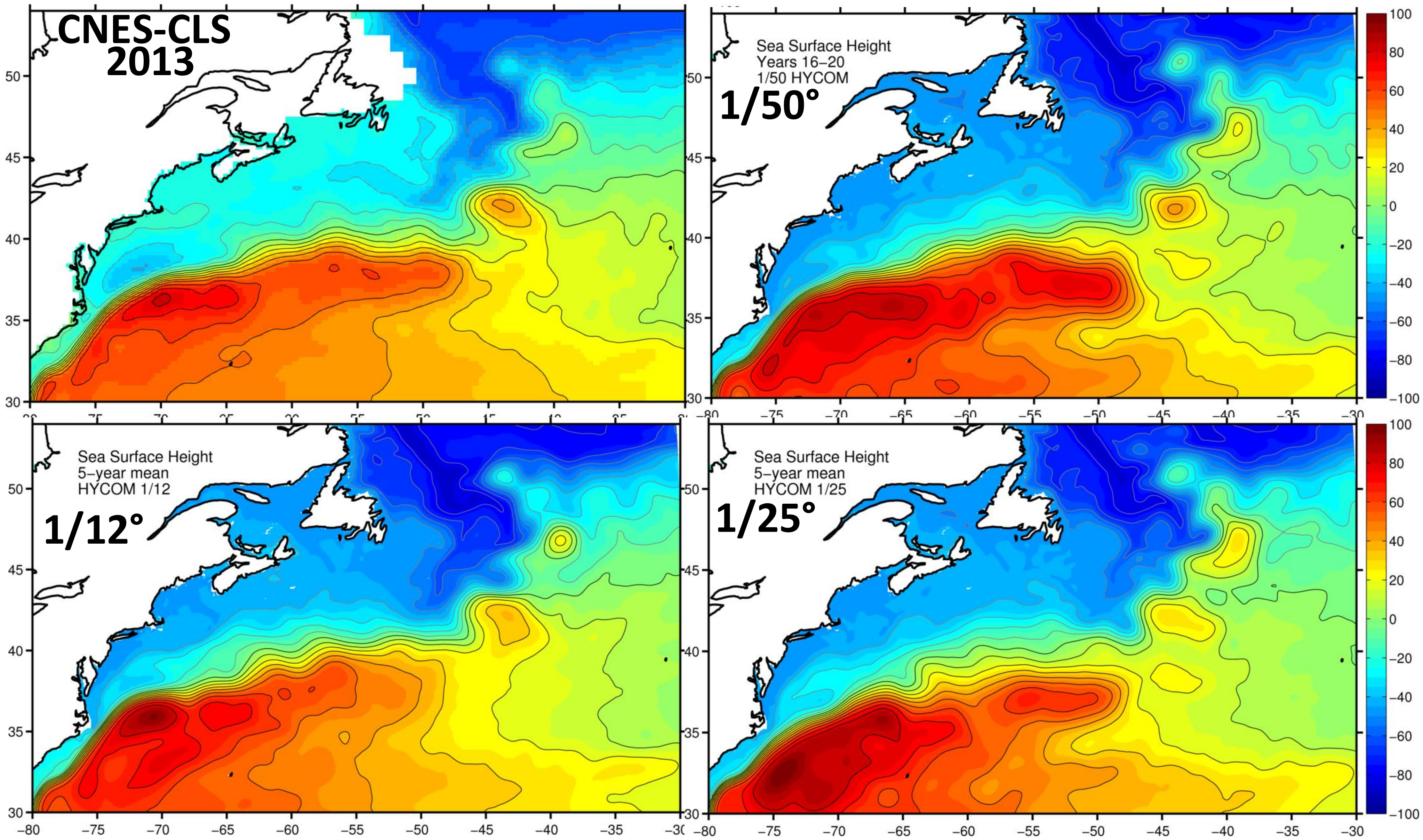




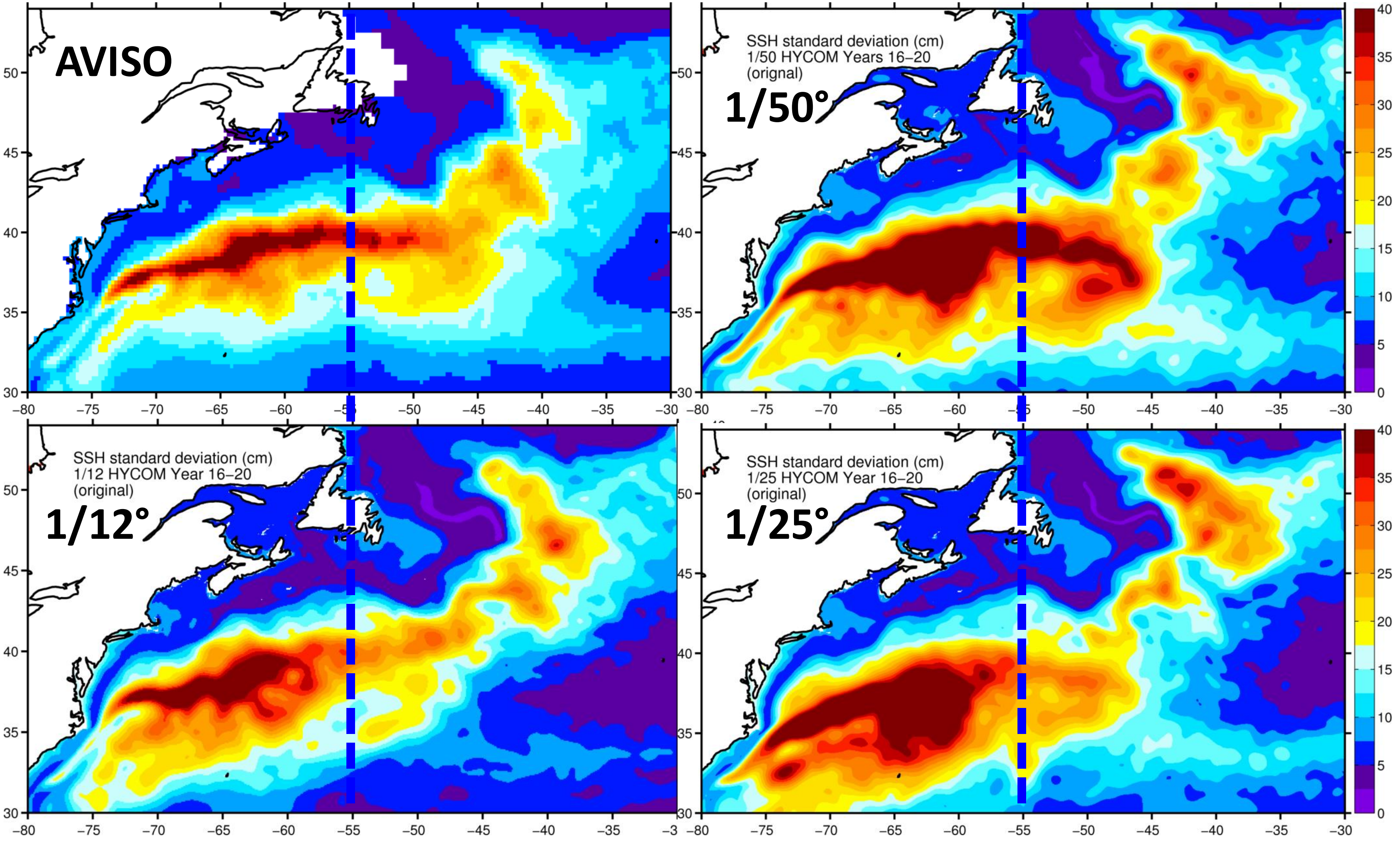


Chassignet and Xu (2017)

Mean SSH (Years 16-20)

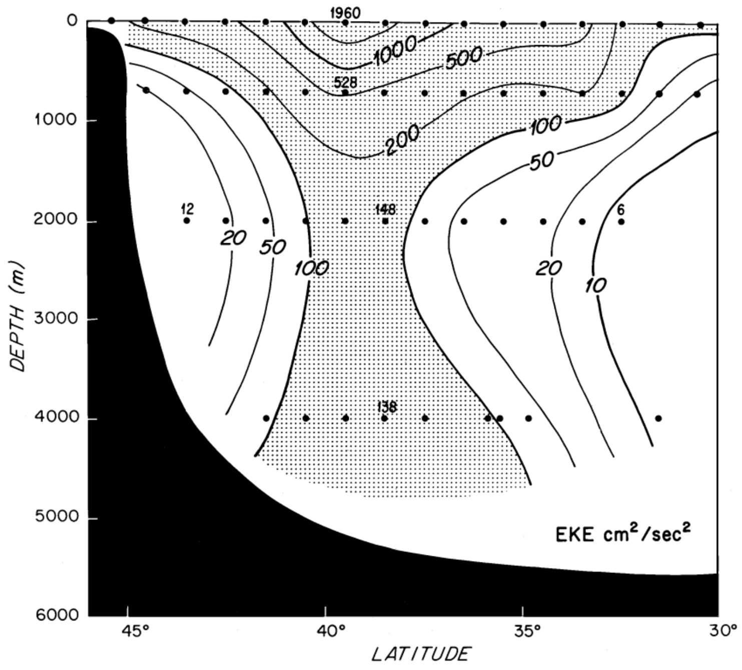


SSH variability (Years 16-20)

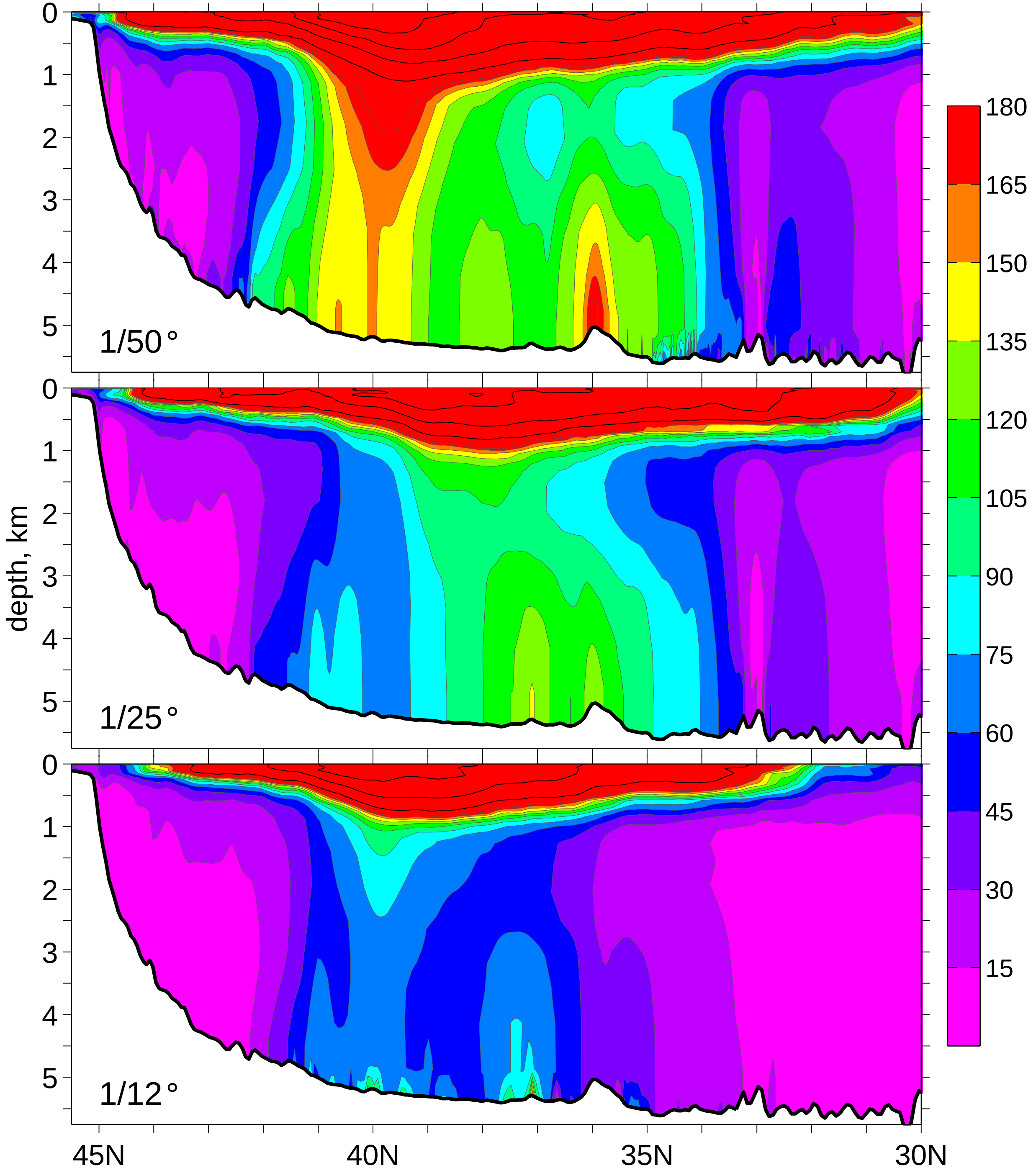


Mean Eddy Kinetic Energy at 55°W

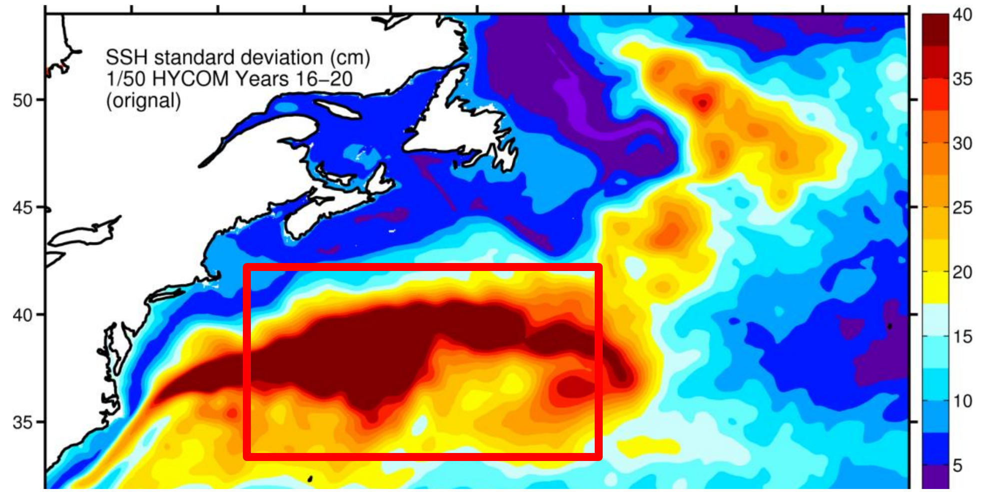
(Richardson, 1985)

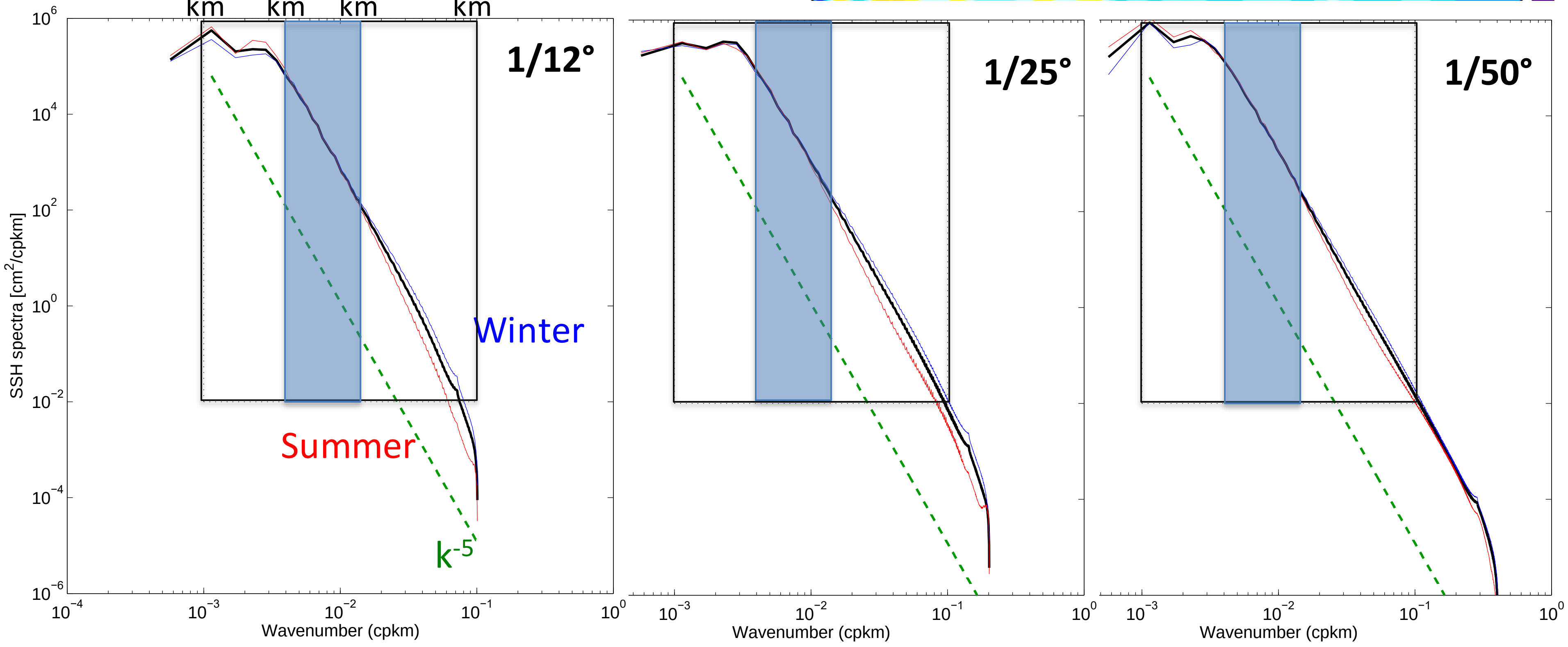


Years 16-20



SSH spectra in the North Atlantic





-5.124 (-5.223, -5.025)

-4.905 (-4.983, -4.828)

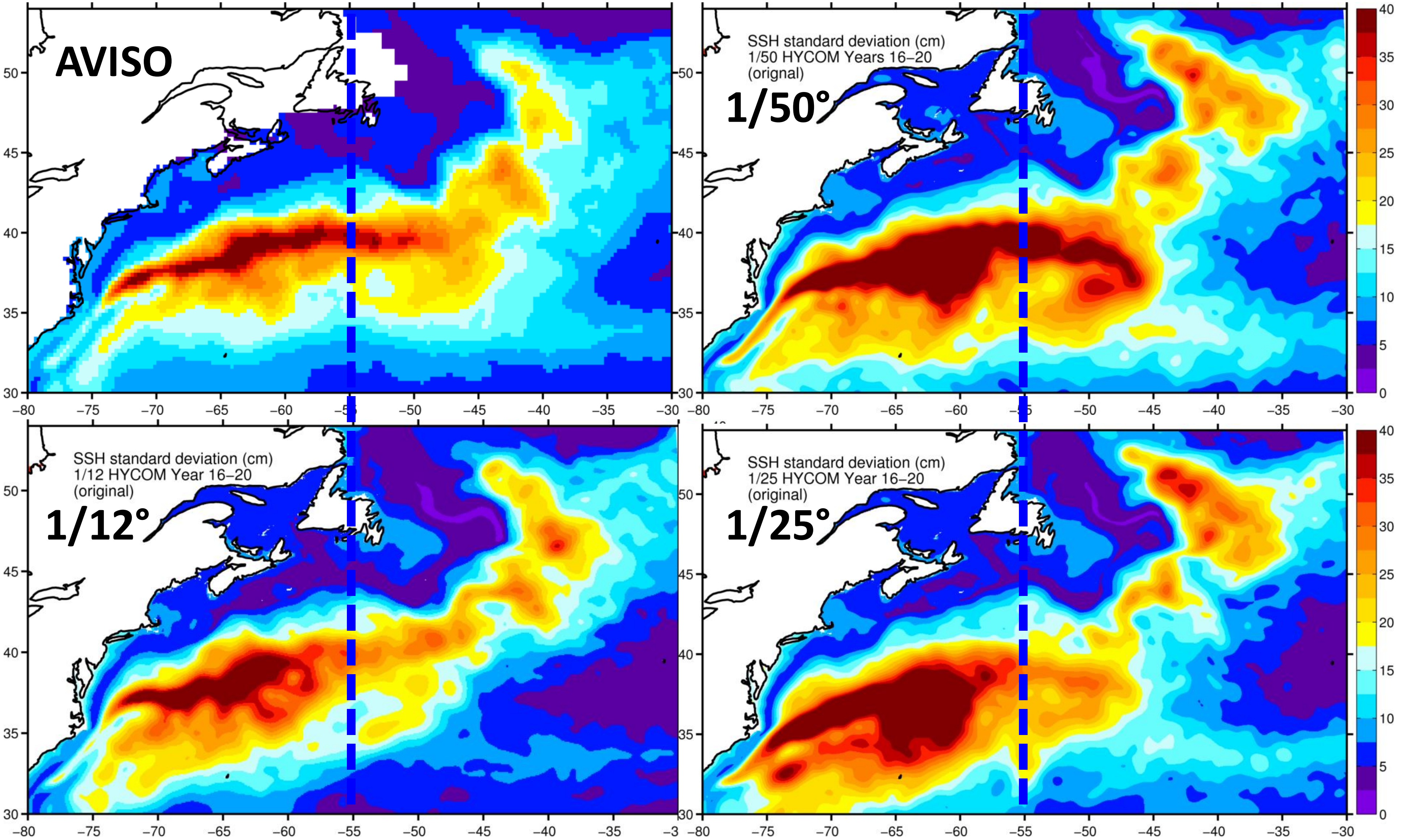
-4.962 (-5.038, -4.886)

Linear fit coefficients (with 95% confidence bounds) for horizontal scale of 70-250 km

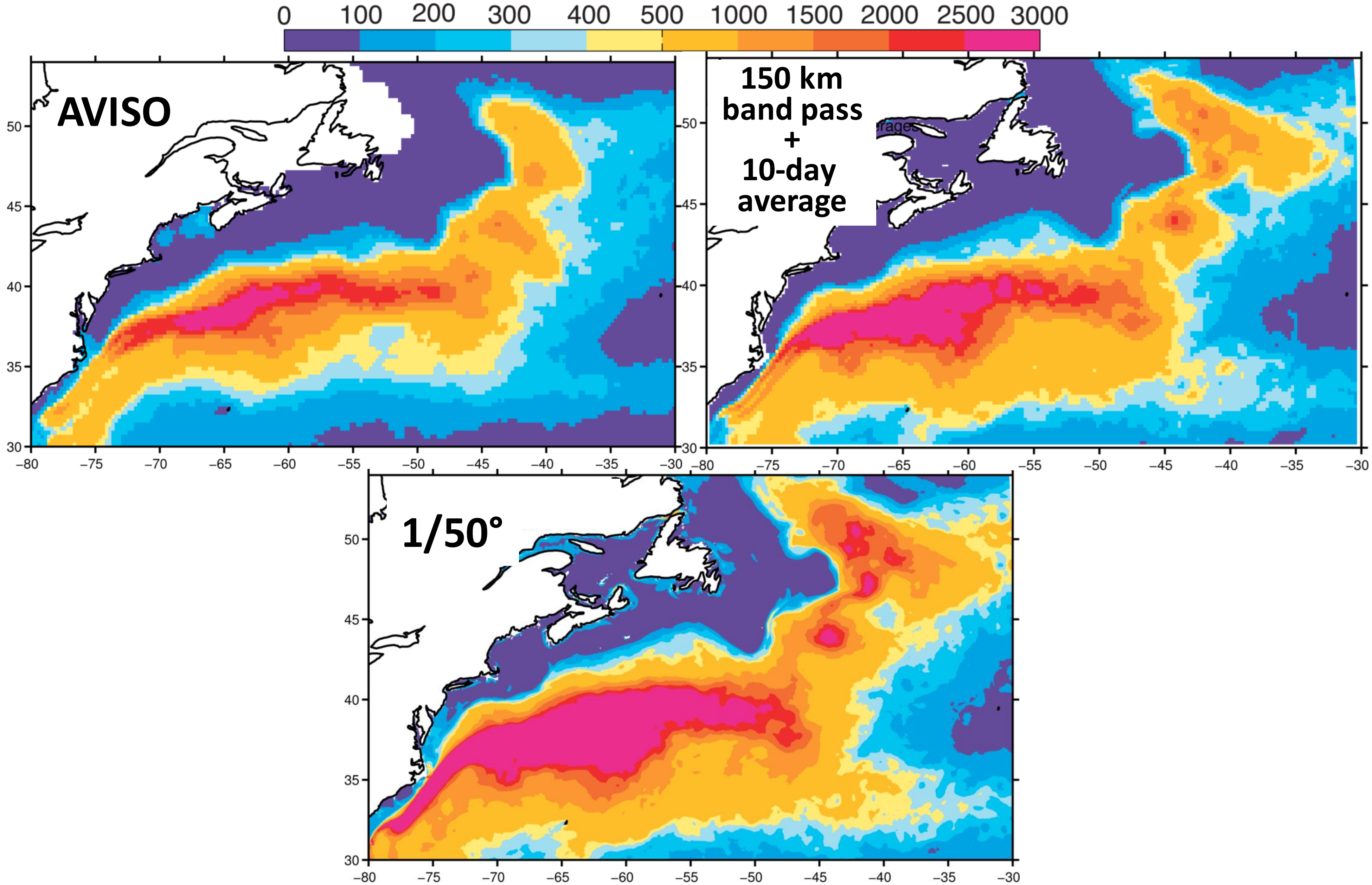
SSH wavenumber Spectrum

The results, which are independent of resolution, suggest that the SSH spectra slope is k^{-5}, in agreement with QG turbulence theory. This is in agreement with shipboard ADCP observations (Wang et al., 2010) and the latest spectra calculated from along-track satellite altimetry data with high-frequency noise corrections (Zhou et al., 2015). Seasonal dependence is most significant below 70 km.

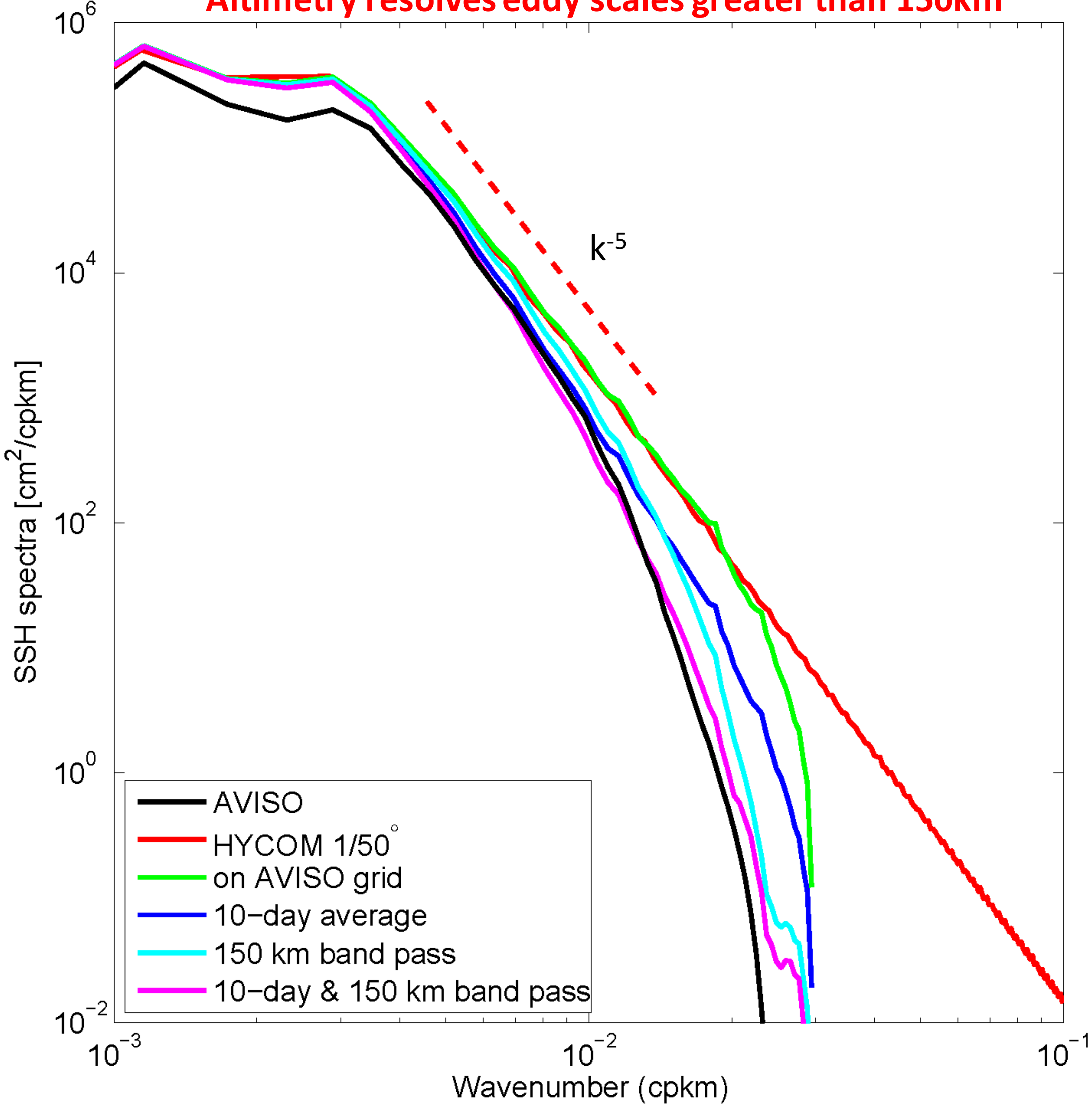
SSH variability (Years 16-20)



Impact of averaging on EKE



Altimetry resolves eddy scales greater than 150km



Increased horizontal resolution

- ⇒ Horizontal resolution of ~1/10^o led to a significant improvement in western boundary current separation
- ⇒ Possible regime shift at 1/50^o when the submesoscale (~10 km) is resolved and the nonlinear effects of the submesoscale eddies intensifies the midlatitude jet and increases its penetration eastward

Chassignet and Xu (2017, JPO)

Three major discrepancies when comparing to observations

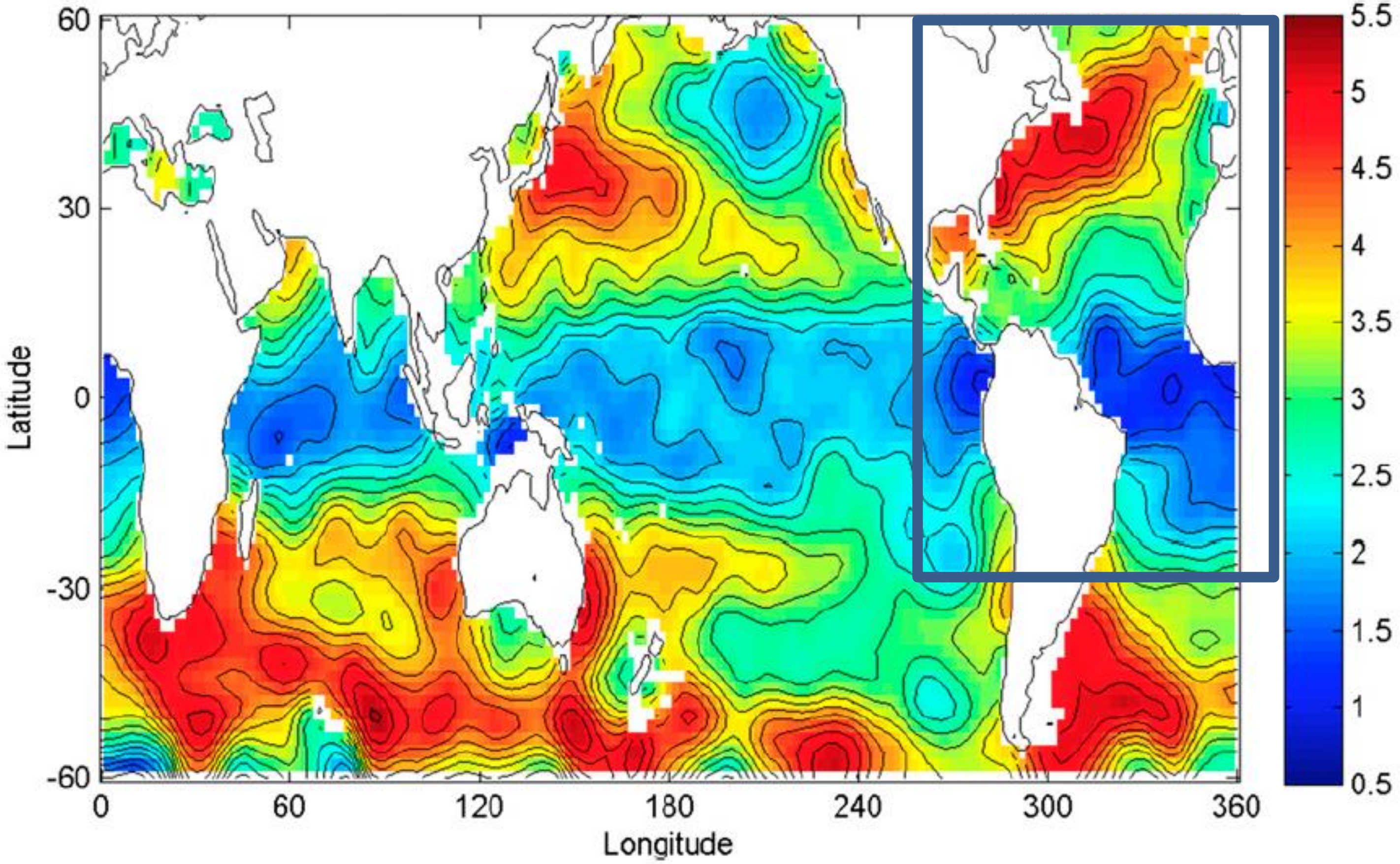
#1: No variability in the SSH wavenumber spectral slope between high/mid-latitudes and the equator.

#2: High EKE around the New England Seamount Chain

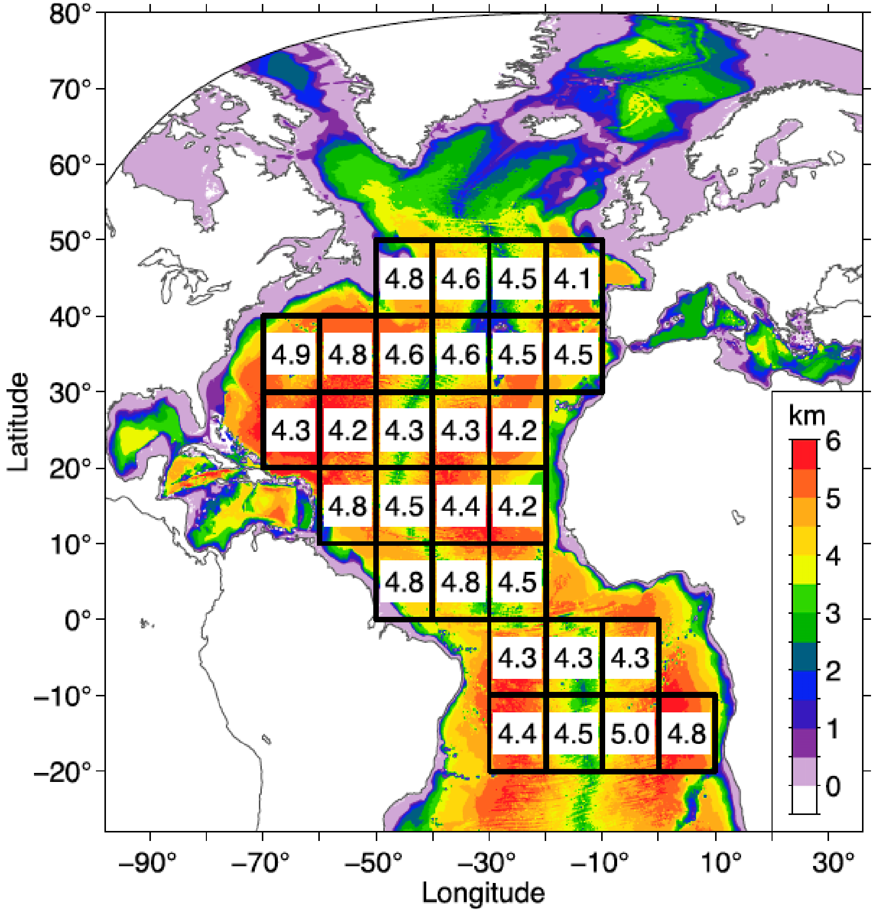
#3: High EKE upstream the New England Seamount Chain

Discrepancy #1: Observed vs. modeled SSH spectra slopes

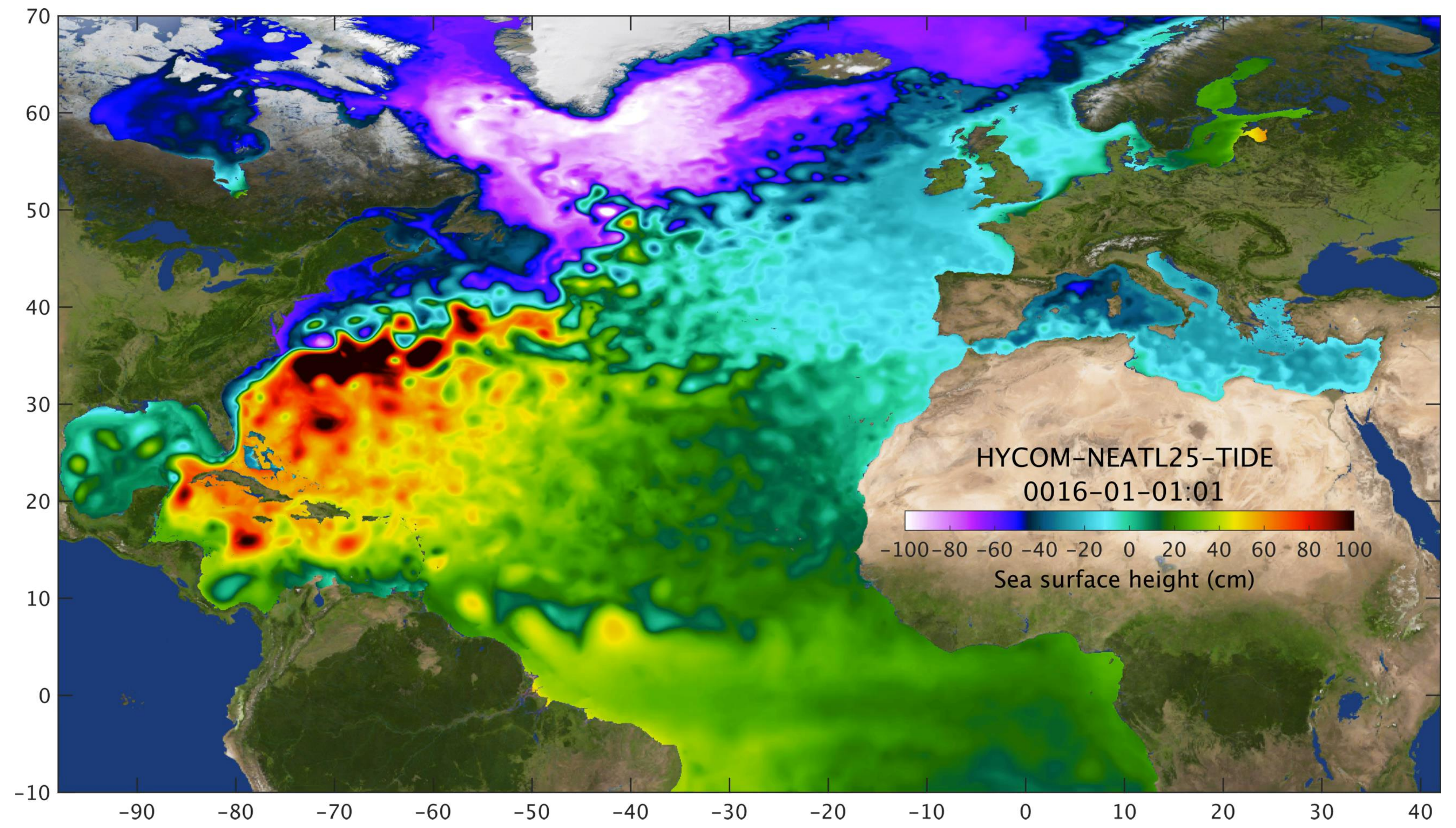
Observations: Zhou et al. (2015)

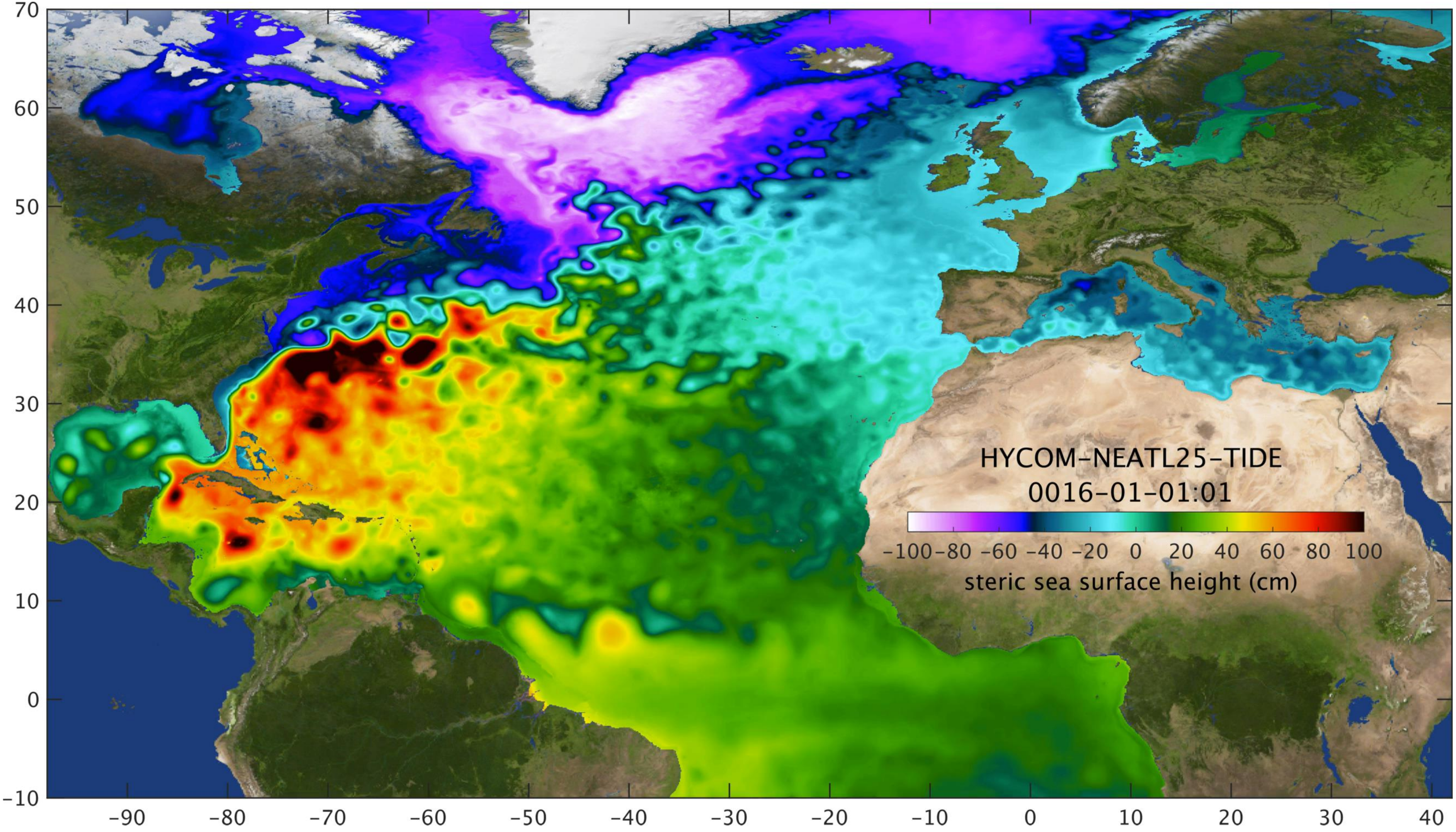


Model: Chassignet & Xu (2017)

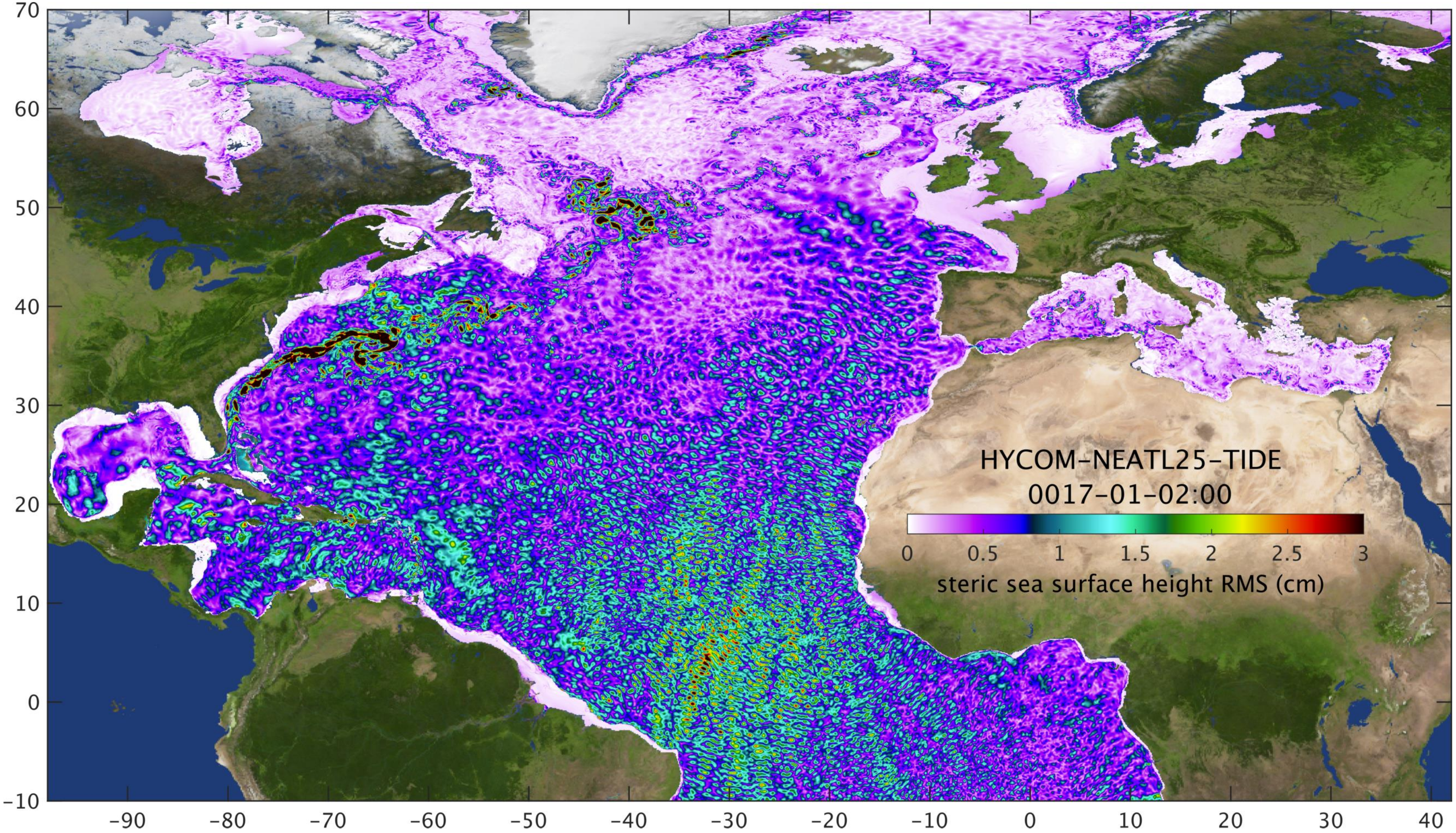


The SSH wavenumber slope in the equatorial Atlantic Ocean is much flatter (on the order of −0.5 to −1) than in the Gulf Stream region (on the order of −5). These values of −0.5 to −1 near the equator are much flatter than either values predicted by QG or SQG turbulence theories. **SURFACE SIGNATURE OF INTERNAL TIDES IS MISSING**

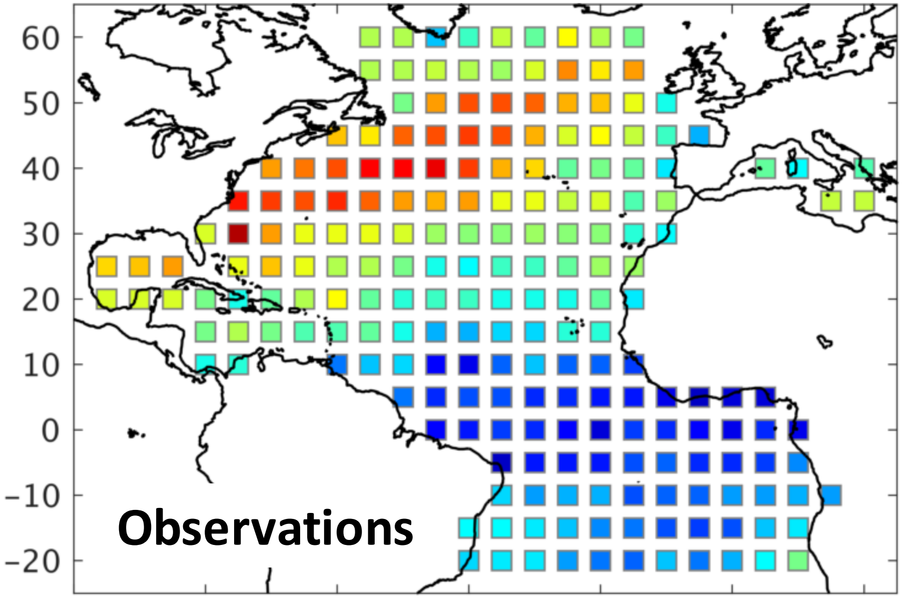

HYCOM-NEATL25-TIDE
0016-01-01:01
-100
-80
-60
-40
-20
0
20
40
60
80
100
Sea surface height (cm)
70
60
50
40
30
20
10
0
-10
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40

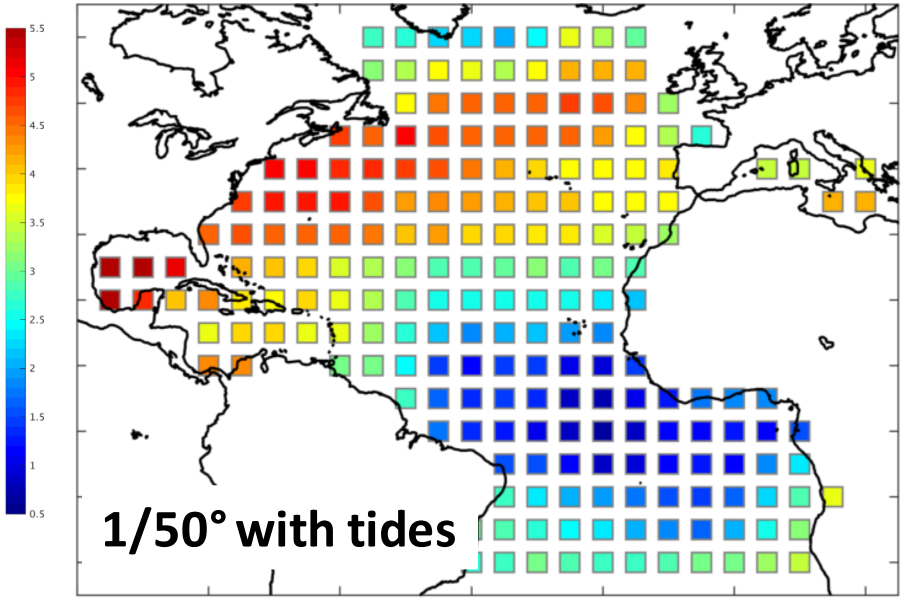

HYCOM-NEATL25-TIDE
0016-01-01:01
-100
-80
-60
-40
-20
0
20
40
60
80
100
steric sea surface height (cm)
70
60
50
40
30
20
10
0
-10
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40

RMS of steric SSH based on 1 day of hourly outputs

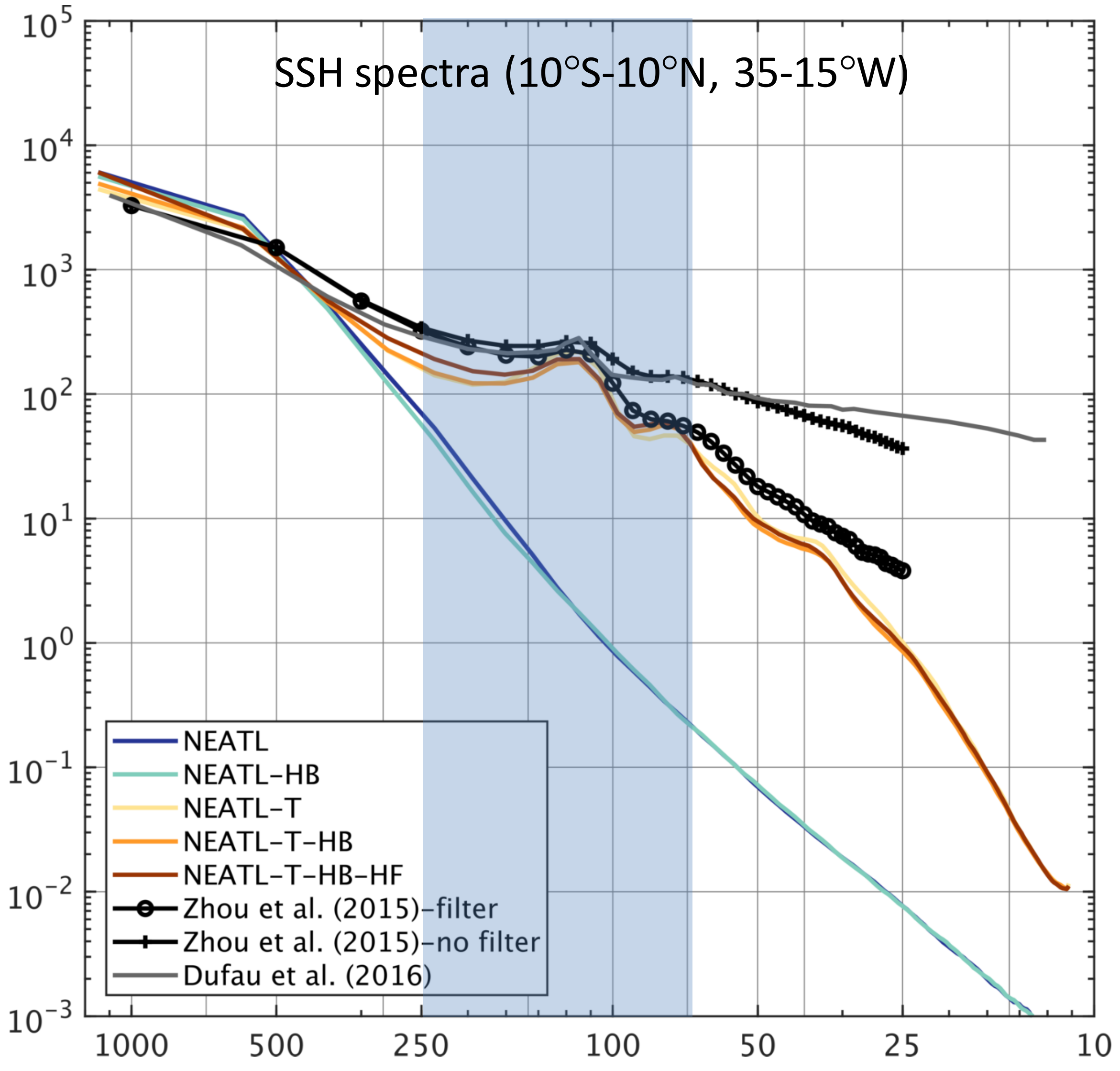


SSH Spectra near the Equator

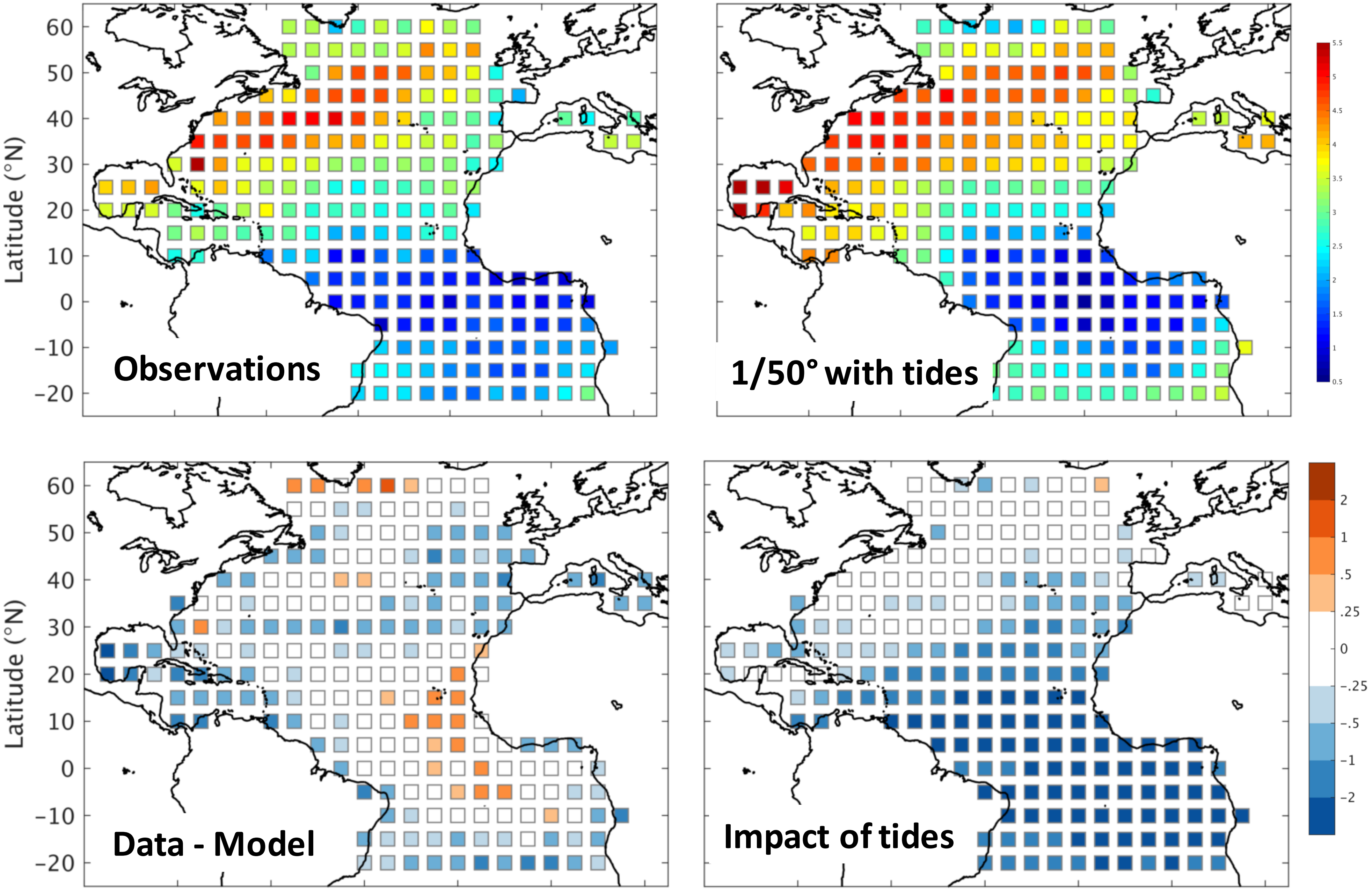




Xu, Chassignet, Wallcraft, Arbic, Buijsman, and Solano (2022)



Internal tides flattens the slope within the mesoscale range.

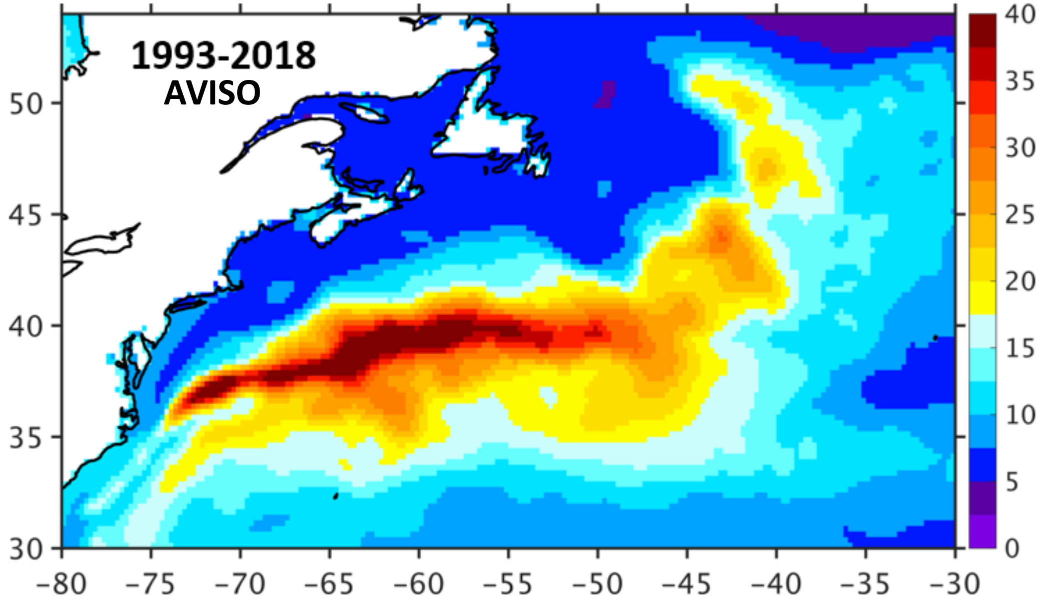


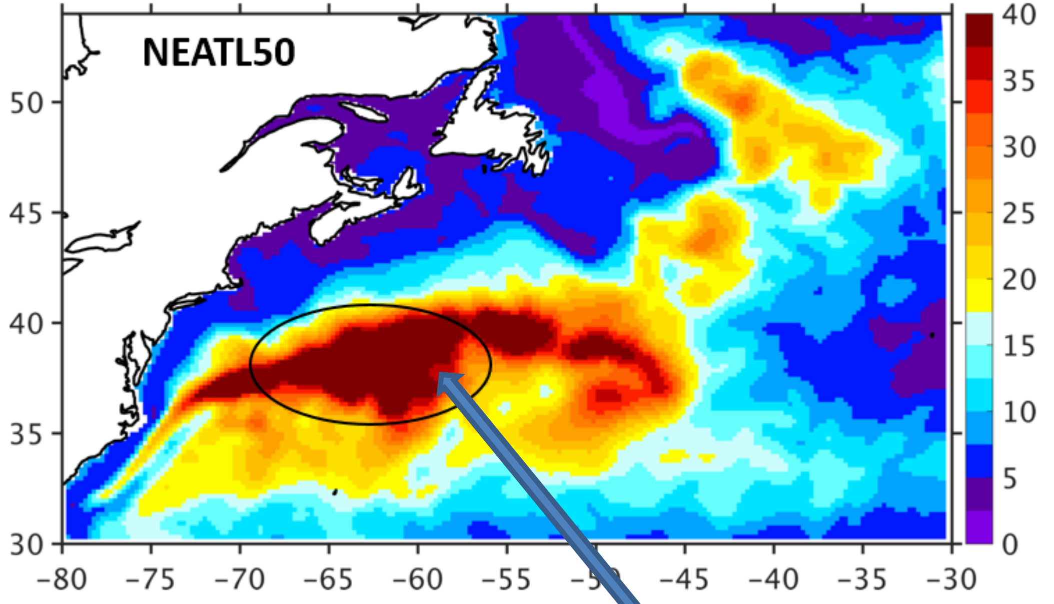
Xu, Chassignet, Wallcraft, Arbic, Buijsman, and Solano (2022)

Conclusion #1: Tides

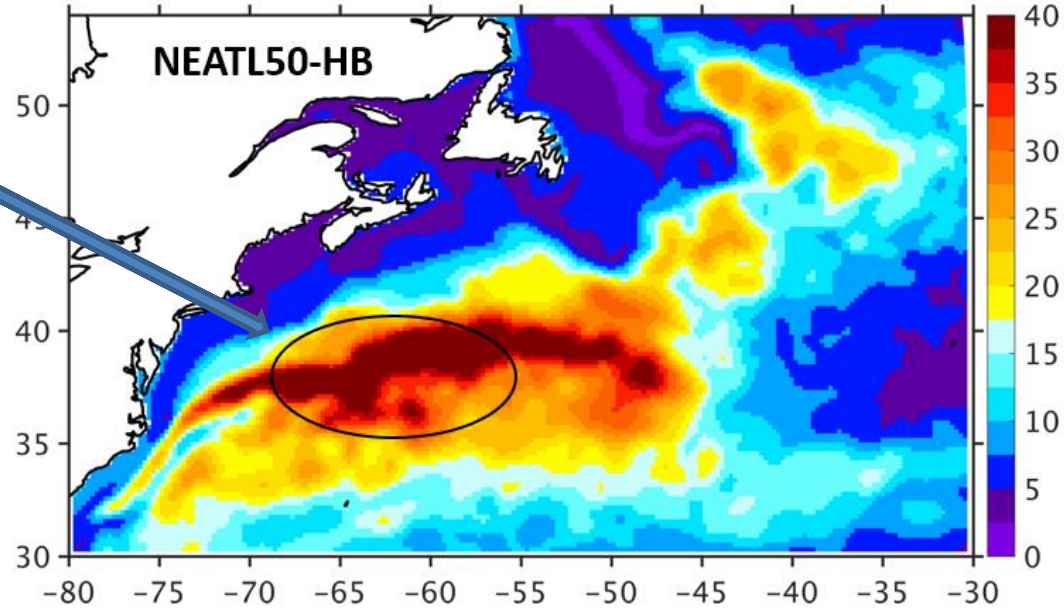
Internal tides flattens the slope within the mesoscale range and explains the difference between non-tidal ocean models and observations (Xu et al., 2022, JGR).

Discrepancy # 2: Higher EKE around the NESMC



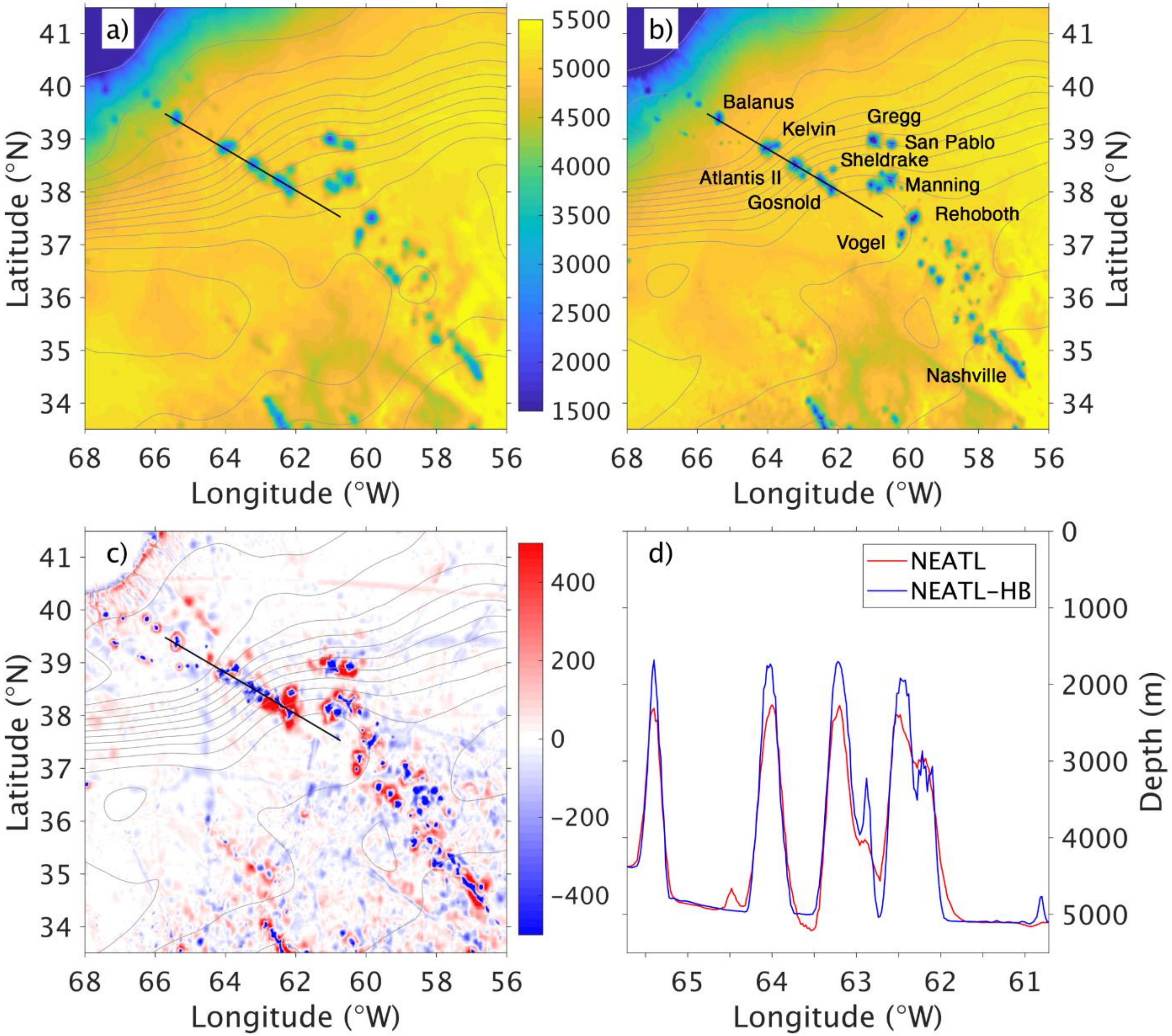


Bathymetry resolution = 6 km

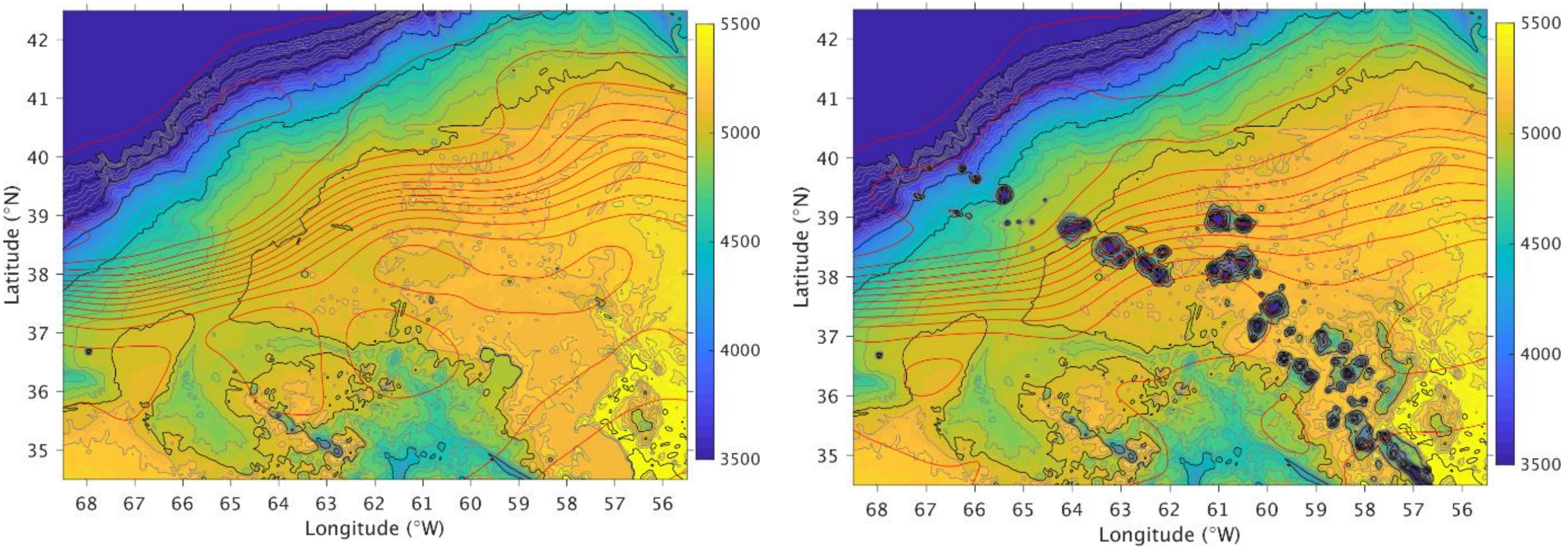


Bathymetry resolution = 1.5 km

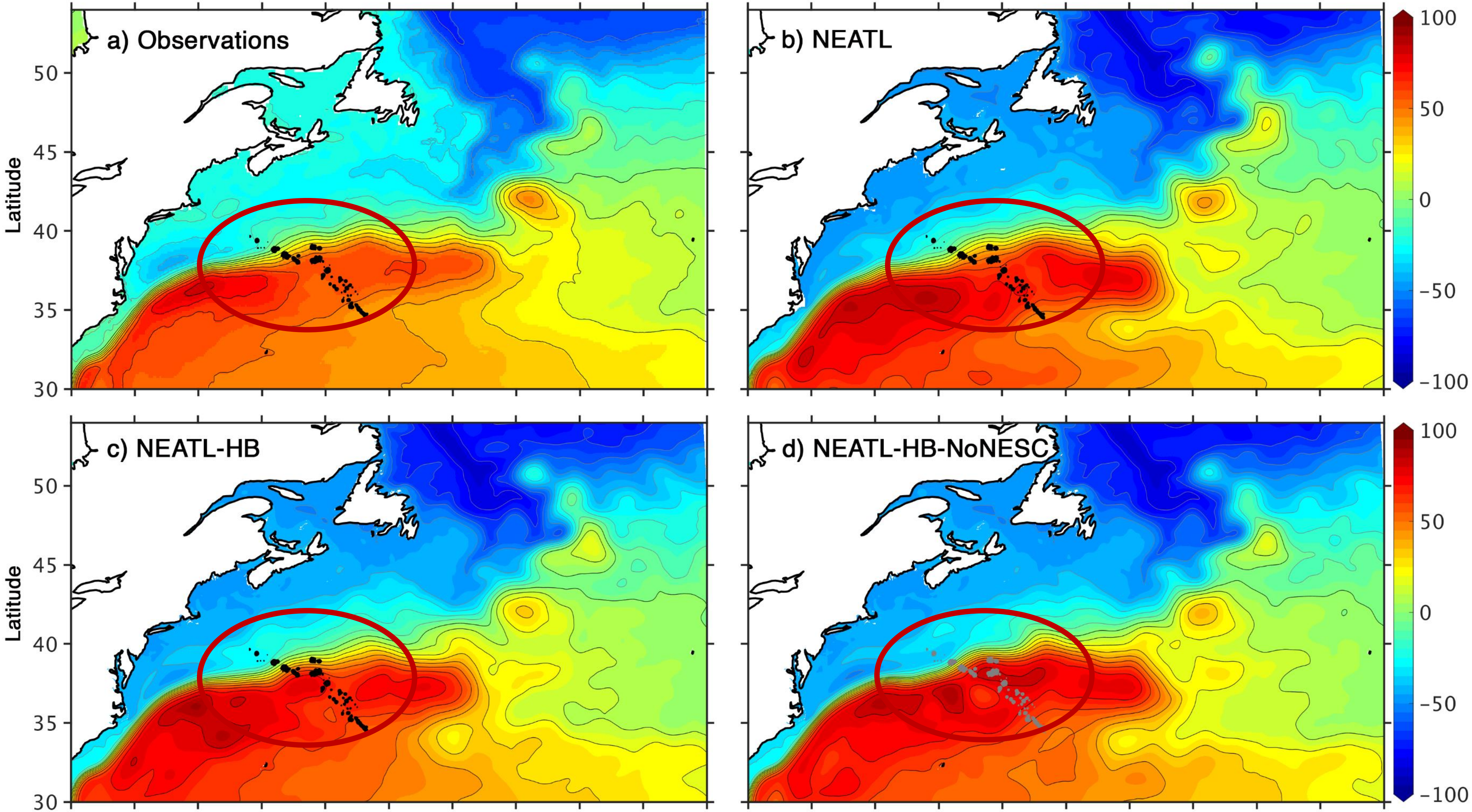
Difference in bathymetry

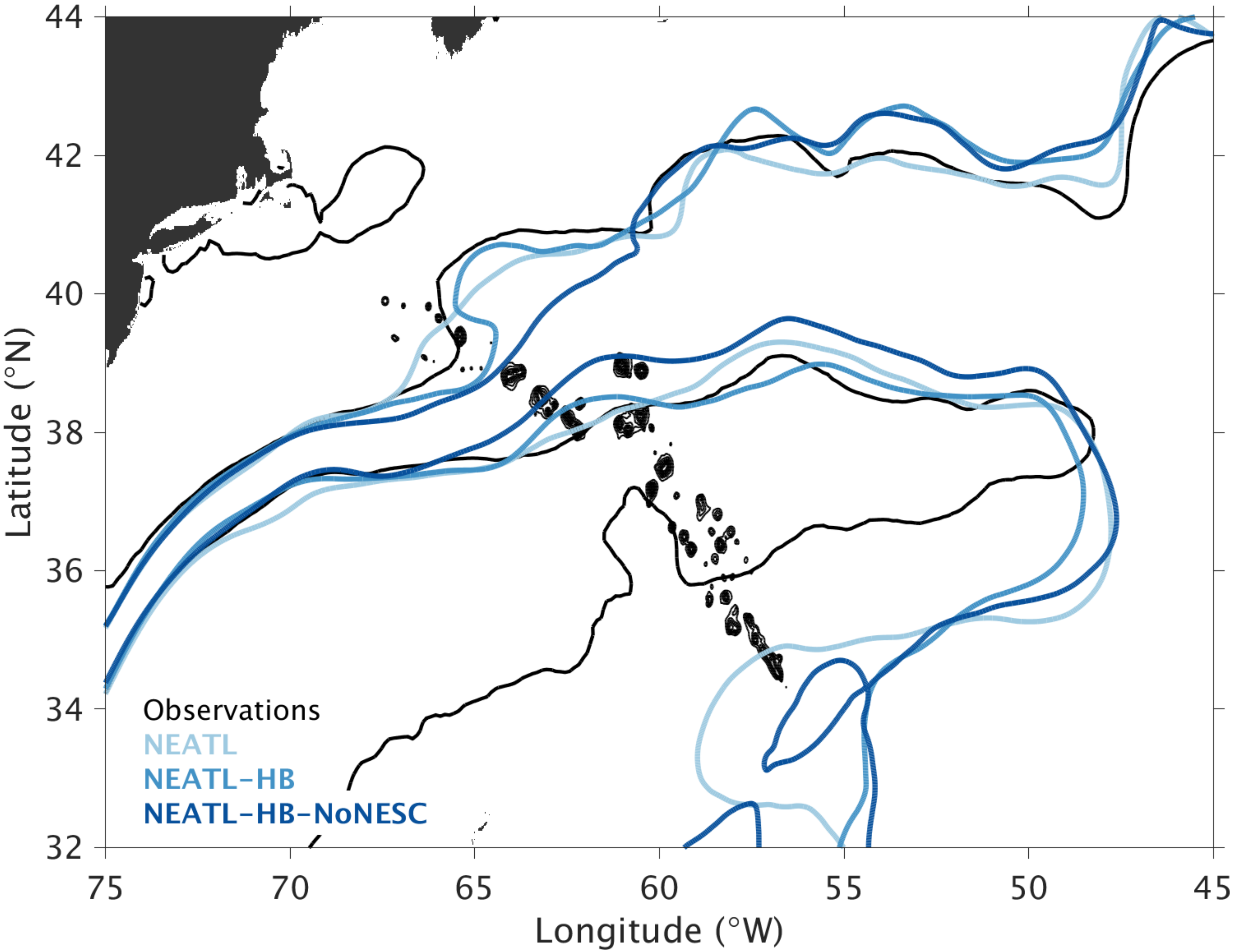


Removal of the New England Seamount Chain

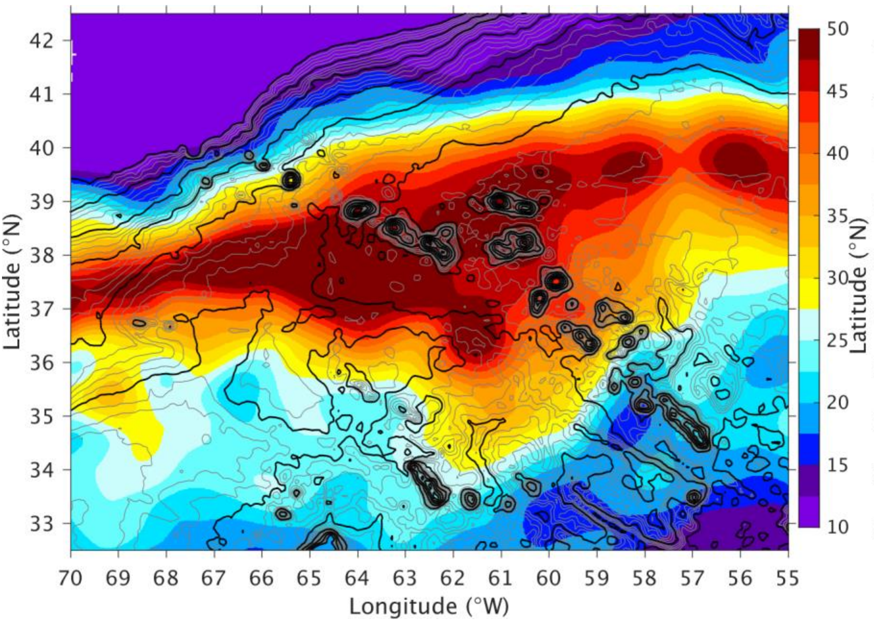


Bathymetry impact on mean sea surface height

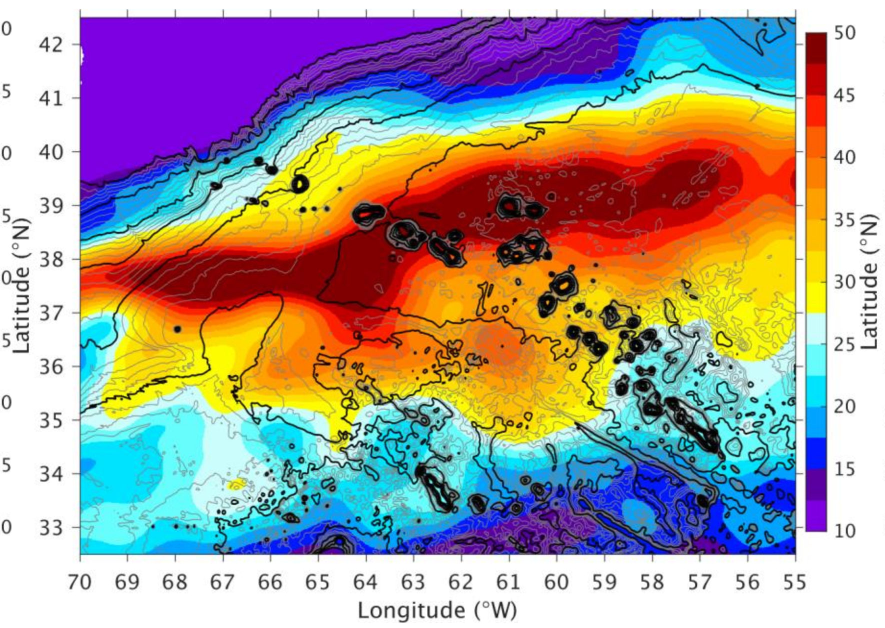



Latitude (°N)
Longitude (°W)
44
42
40
38
36
34
32
75
70
65
60
55
50
45
Observations
NEATL
NEATL-HB
NEATL-HB-NoNESC

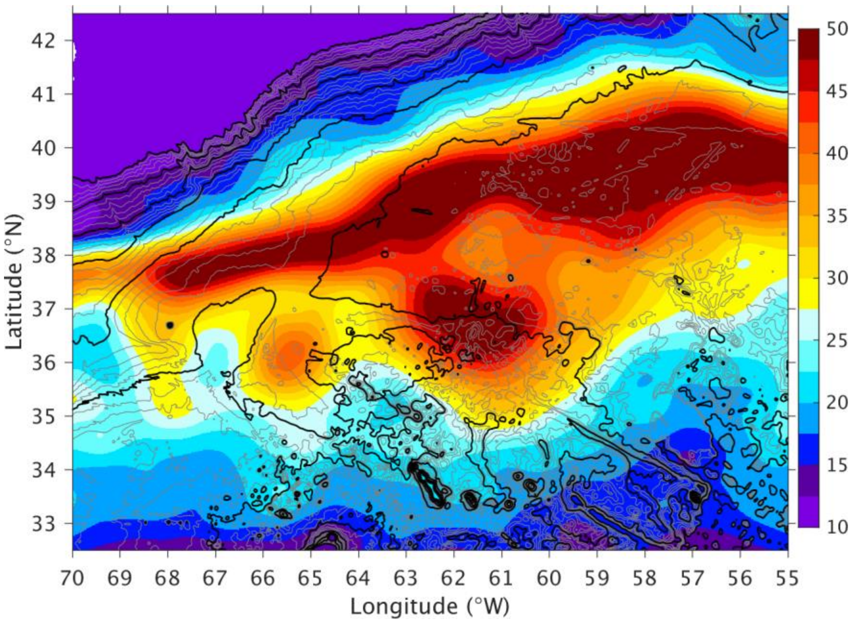
Eddy Kinetic Energy



Coarse bathymetry



Fine bathymetry



No NESC

- **Clear impact of the New England Seamount Chain on the Gulf Stream pathway and variability**
- **Can we quantify/document this impact? => Idealized studies**

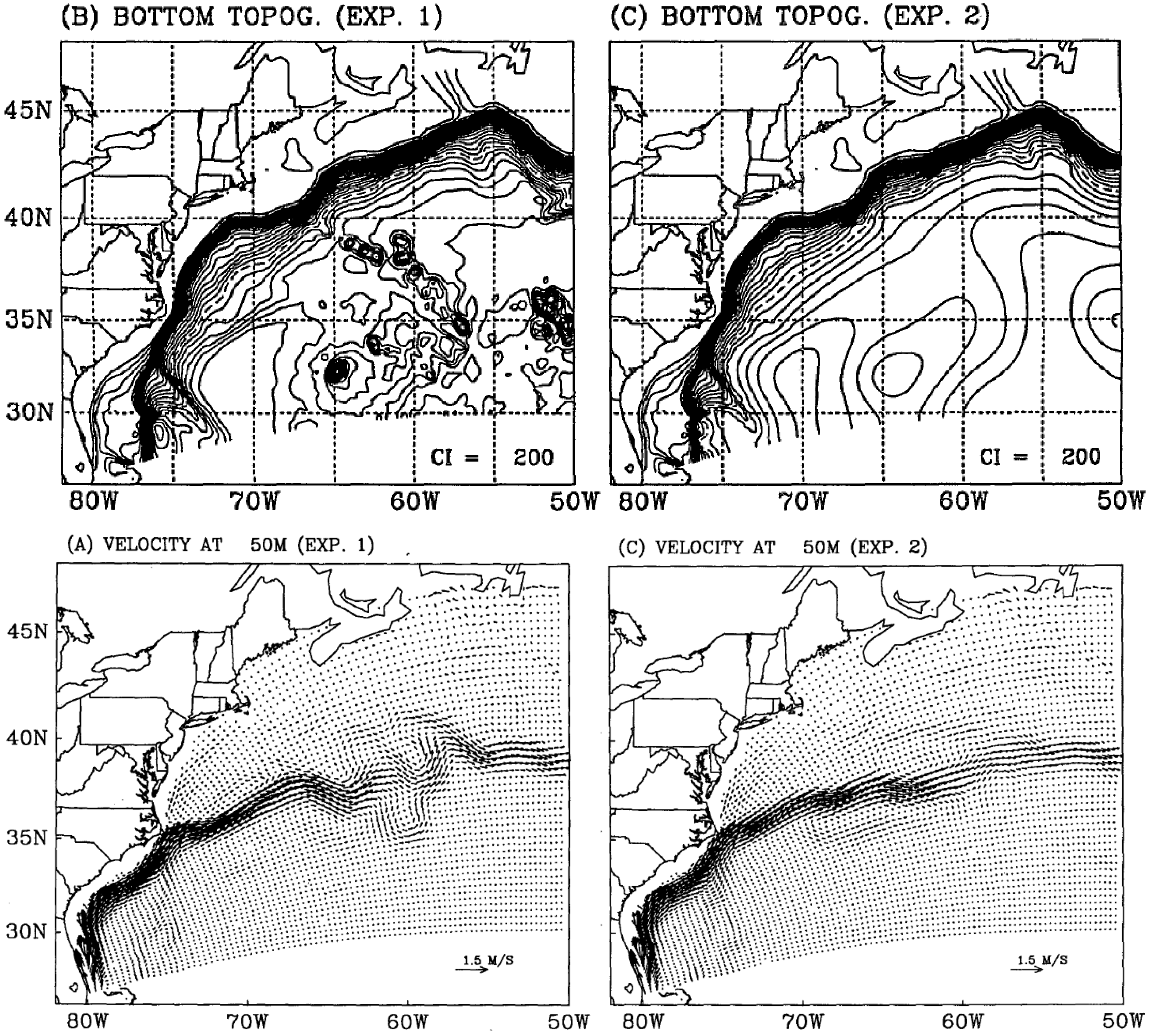
Ezer (1994)

Princeton Ocean Model: **Δx~15 km**

Smooth topography (terrain-following coordinates)

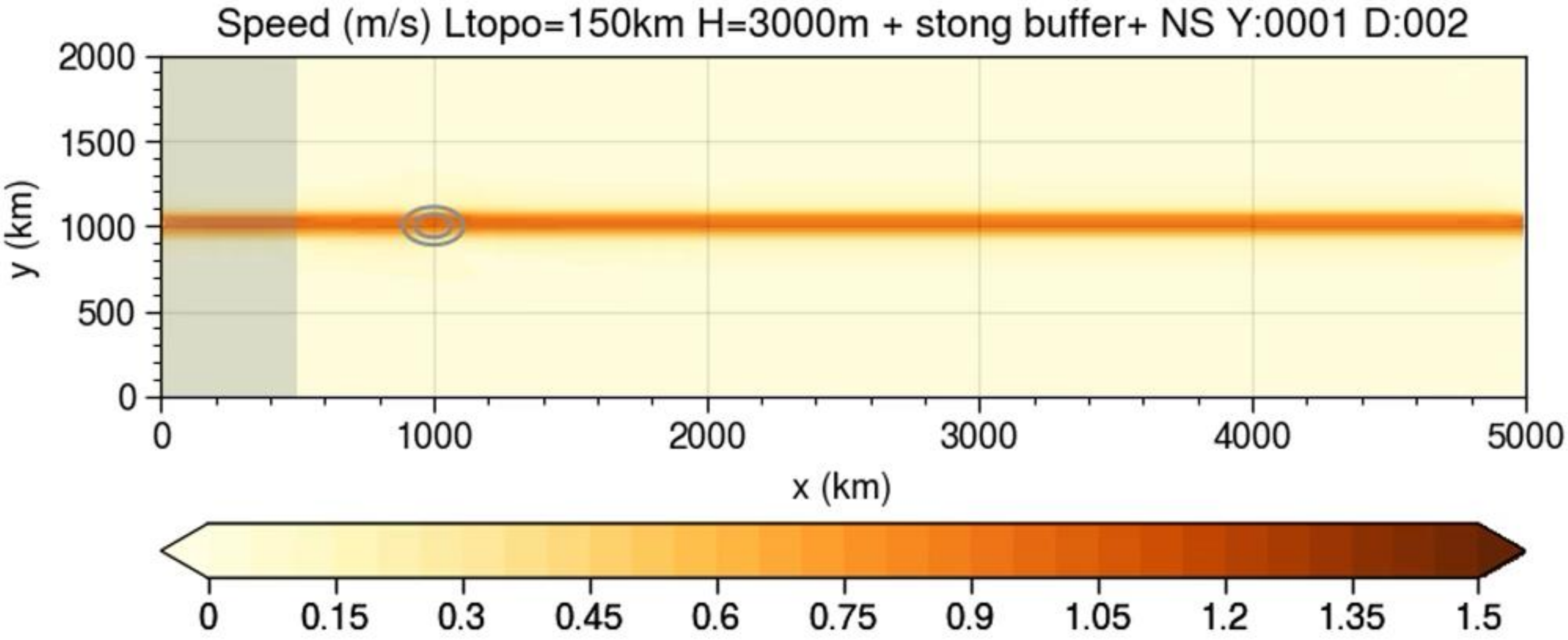
Because of grid spacing and smoothing, the seamounts are not well defined and are more like a ridge

⇒ deflection to the south consistent with PV conservation



Idealized HYCOM channel configuration

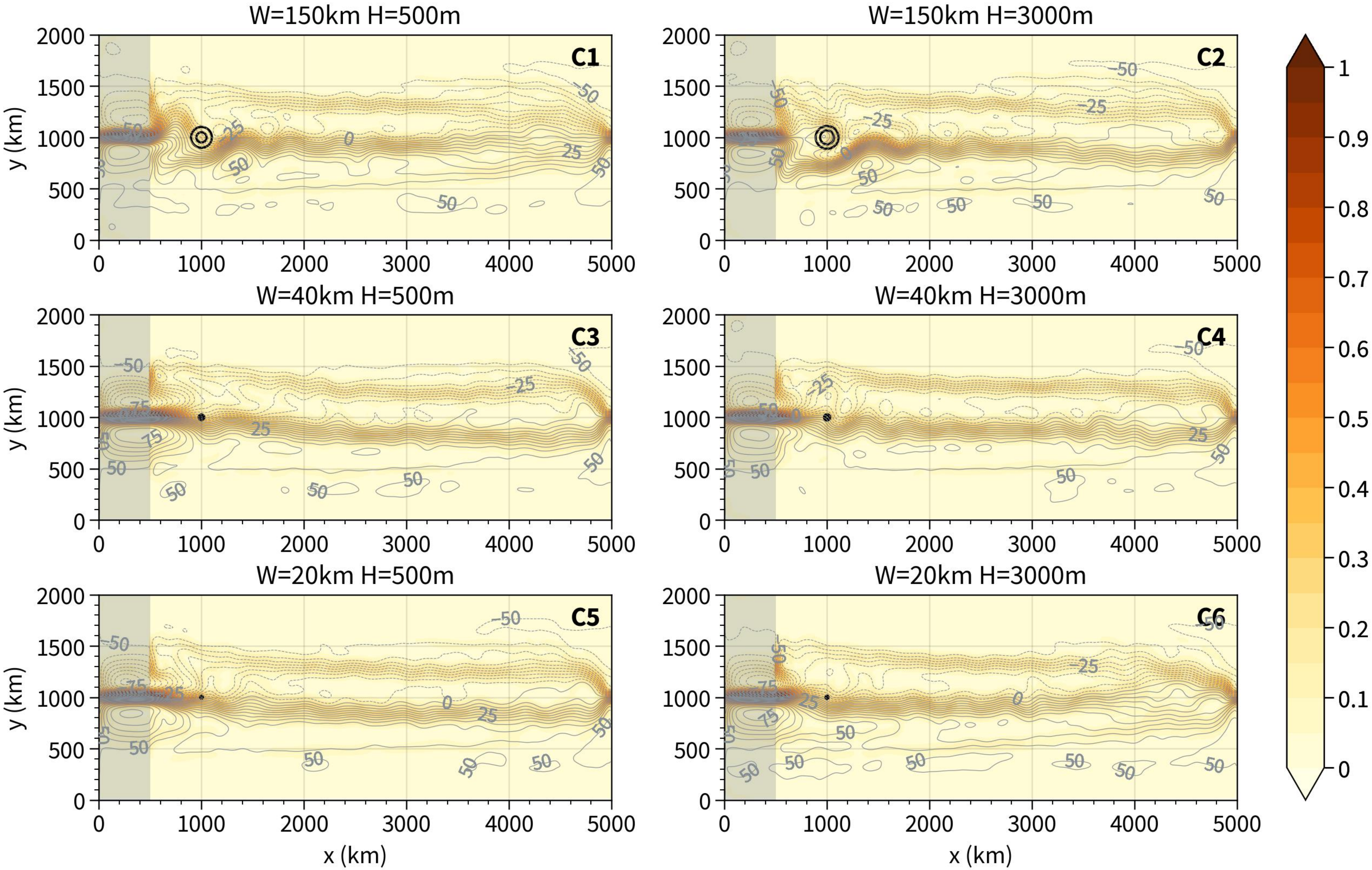
$H = h_{max}\, e^{(x-x_0)/2W^2}$



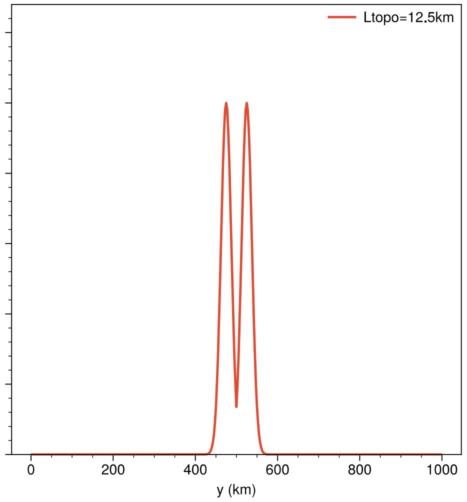
Speed (m/s) Ltopo=150km H=3000m + stong buffer+ NS Y:0001 D:002

2 layers (1000 m and 4000 m); 800 m interface displacement, .8 m/s jet

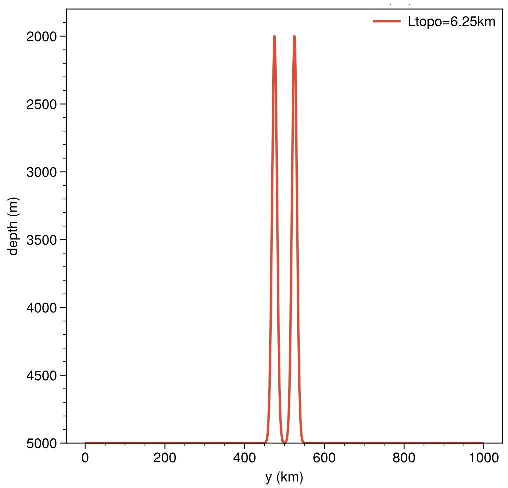
Δx=10km

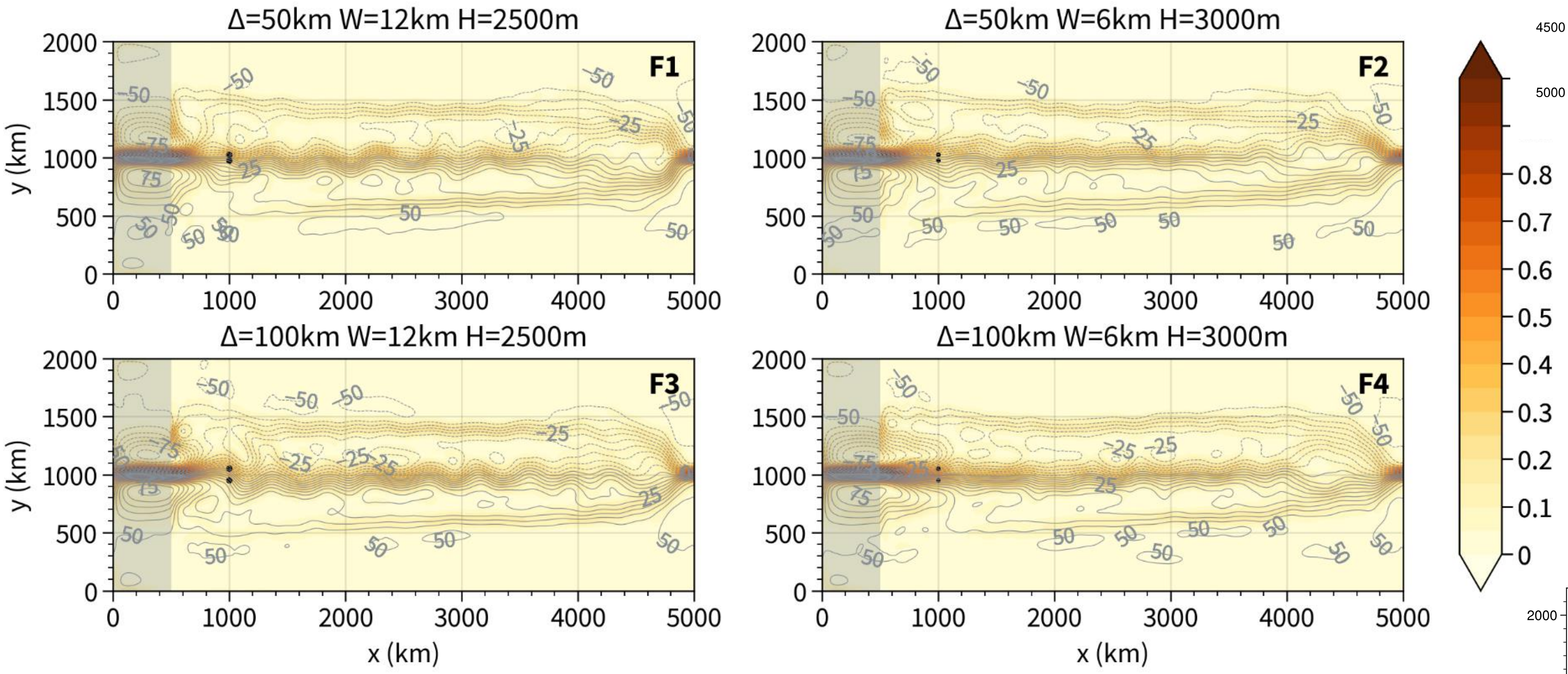

W=150km H=500m
C1
W=150km H=3000m
C2
W=40km H=500m
C3
W=40km H=3000m
C4
W=20km H=500m
C5
W=20km H=3000m
C6
y (km)
x (km)
0
500
1000
1500
2000
3000
4000
5000
-50
-25
0
25
50
-75
75
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

2-year mean

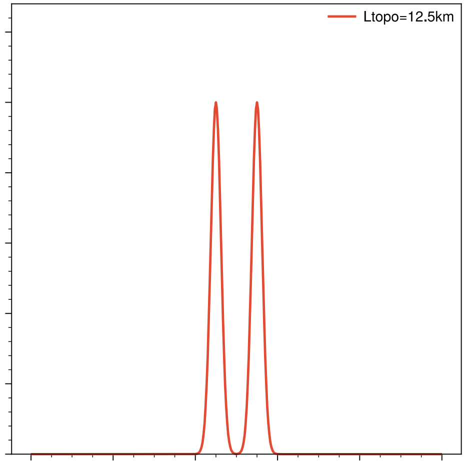


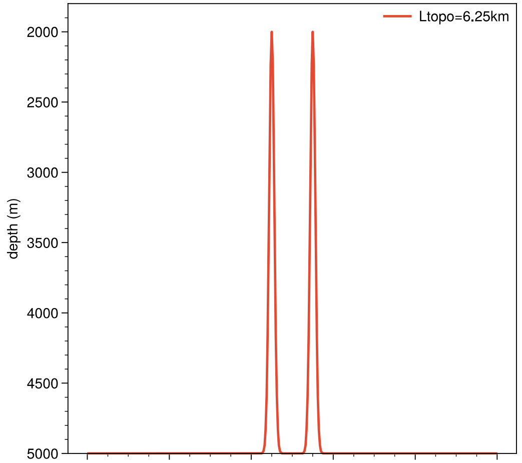
2-year mean SSH and upper velocity



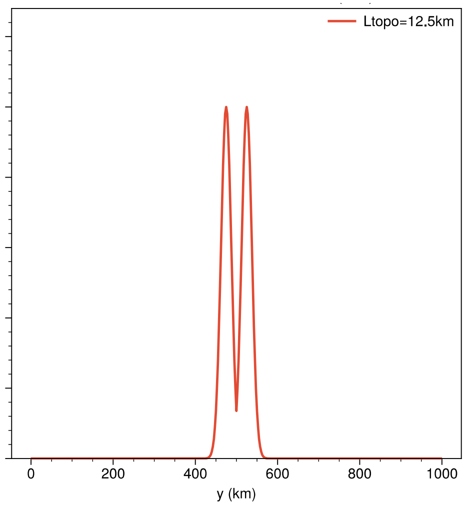


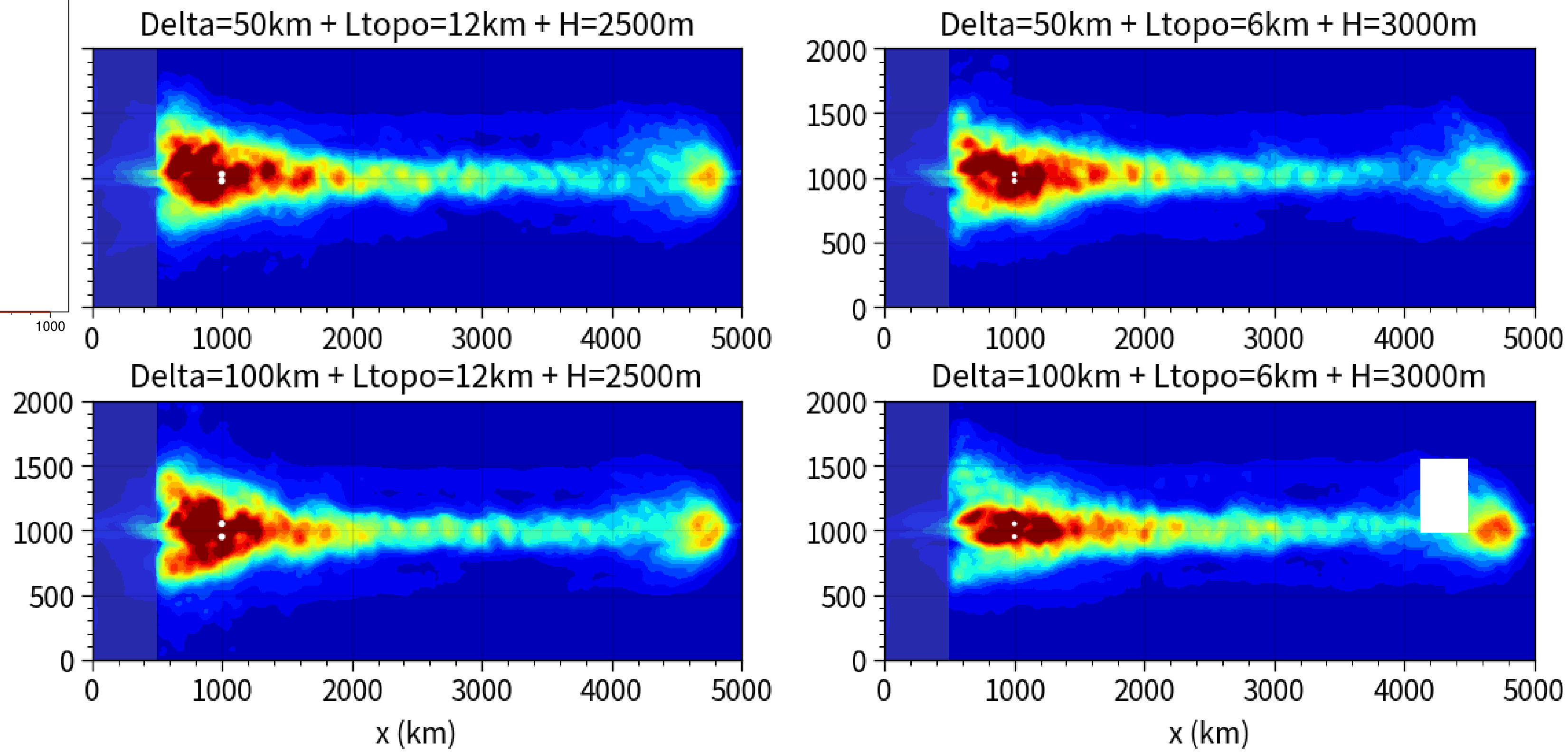
Δx=1km

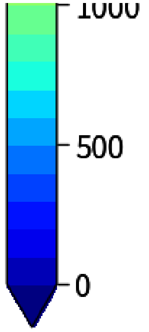


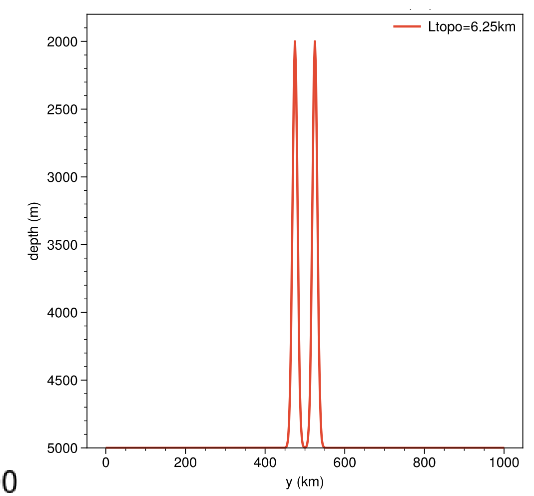


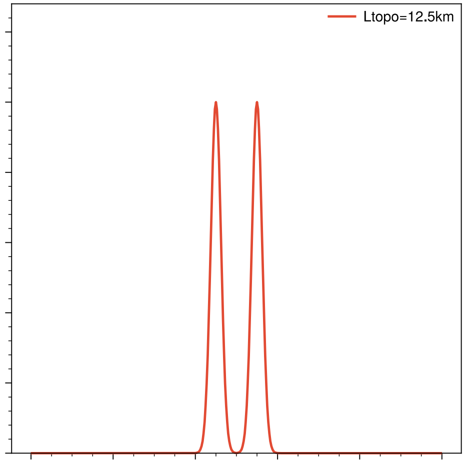
Reduced EKE with narrow seamounts

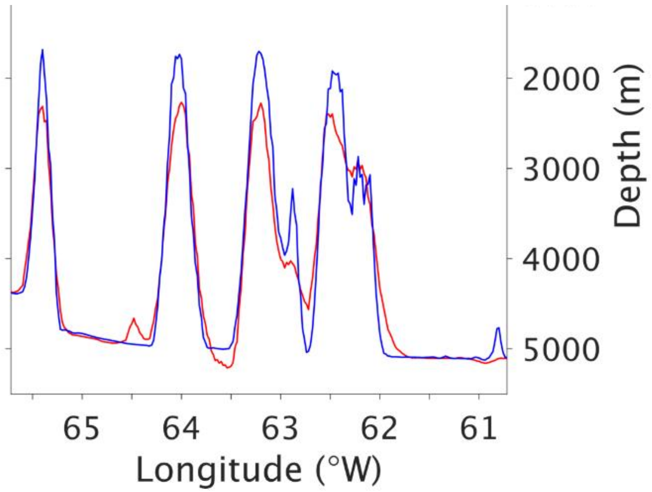


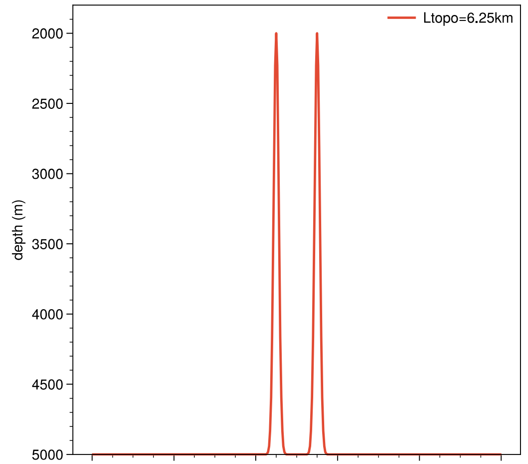






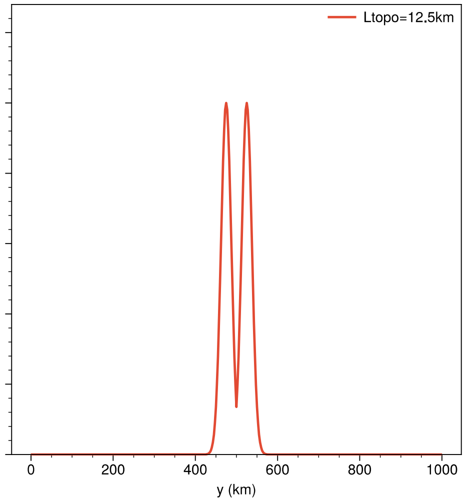




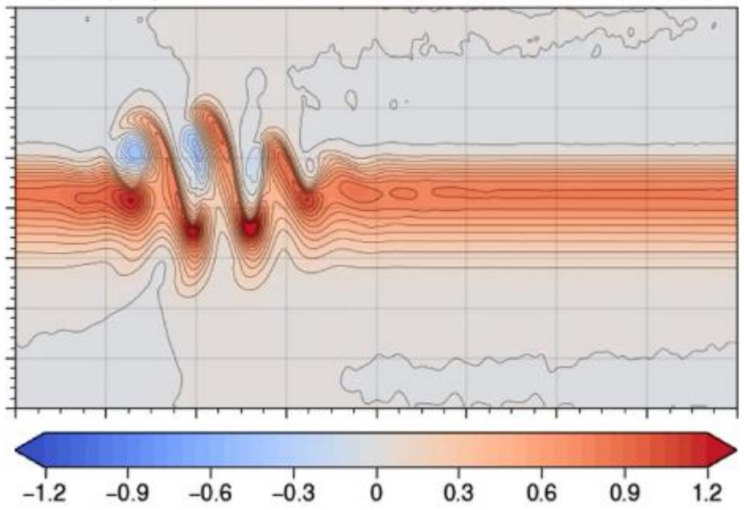


Hypothesis: Narrow seamounts => less impact on the upper layer jet => increased stability

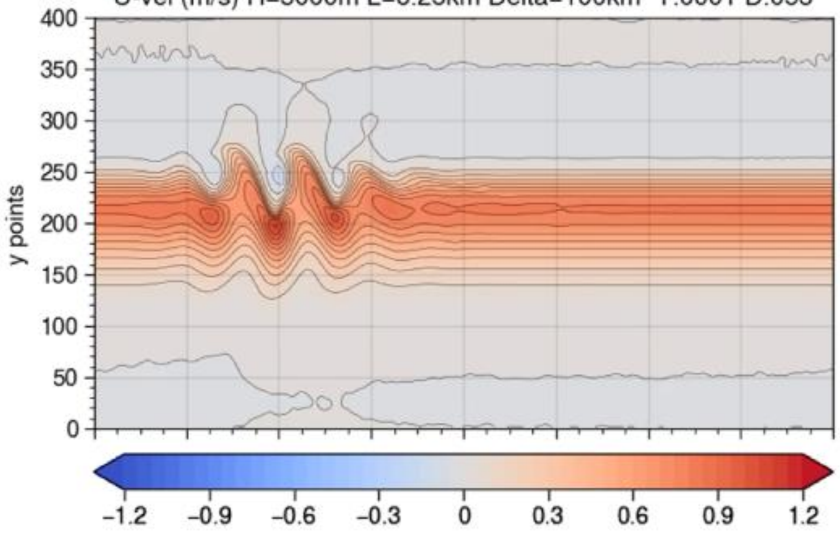
Faster instability growth with thicker seamounts

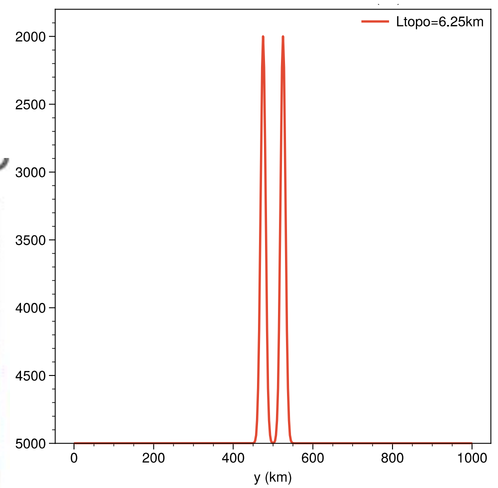


U-vel (m/s) H=2500m L=12.5km Delta=100km Y:0001 D:053

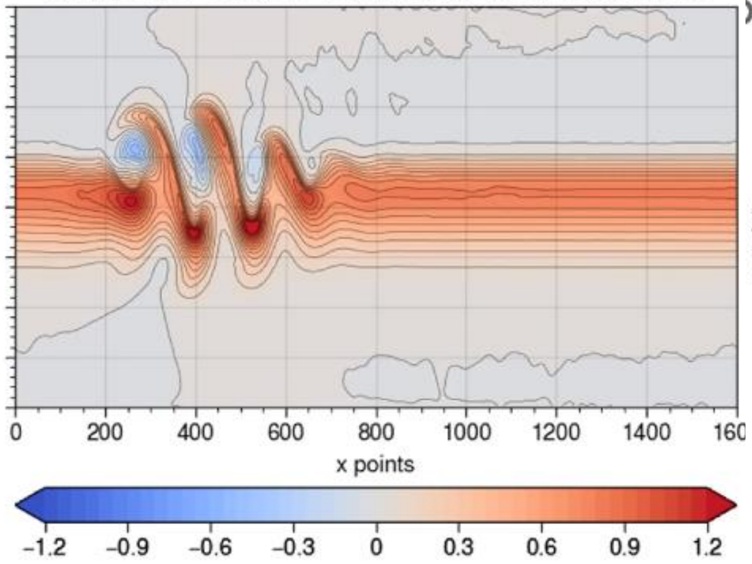


U-vel (m/s) H=3000m L=6.25km Delta=100km Y:0001 D:053

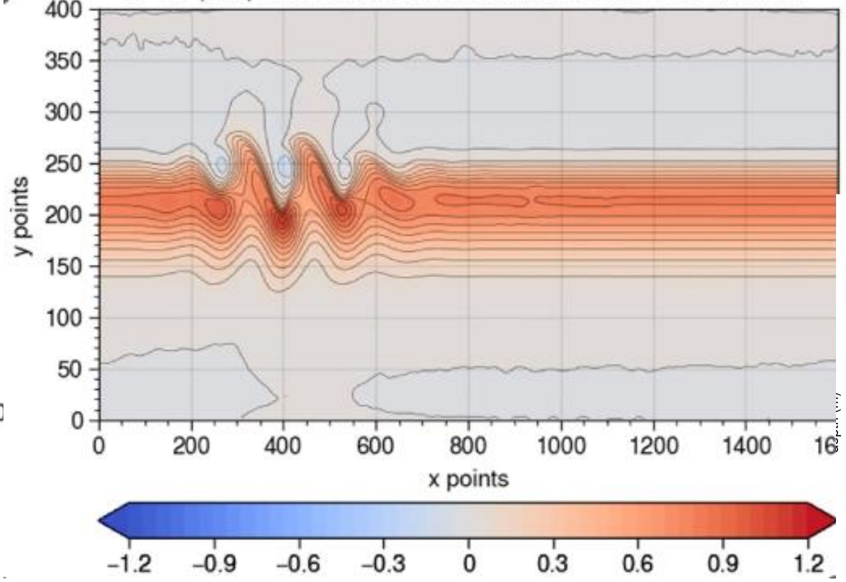


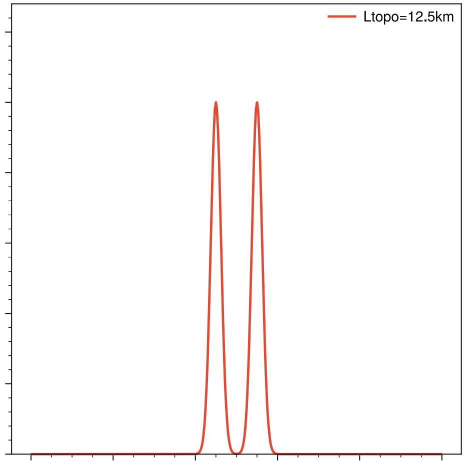


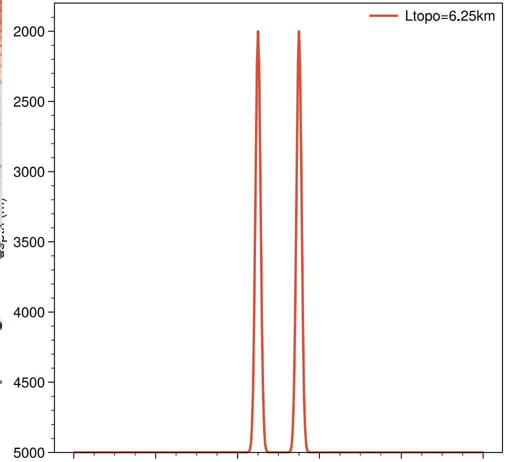
U-vel (m/s) H=2500m L=12.5km Delta=50km Y:0001 D:053



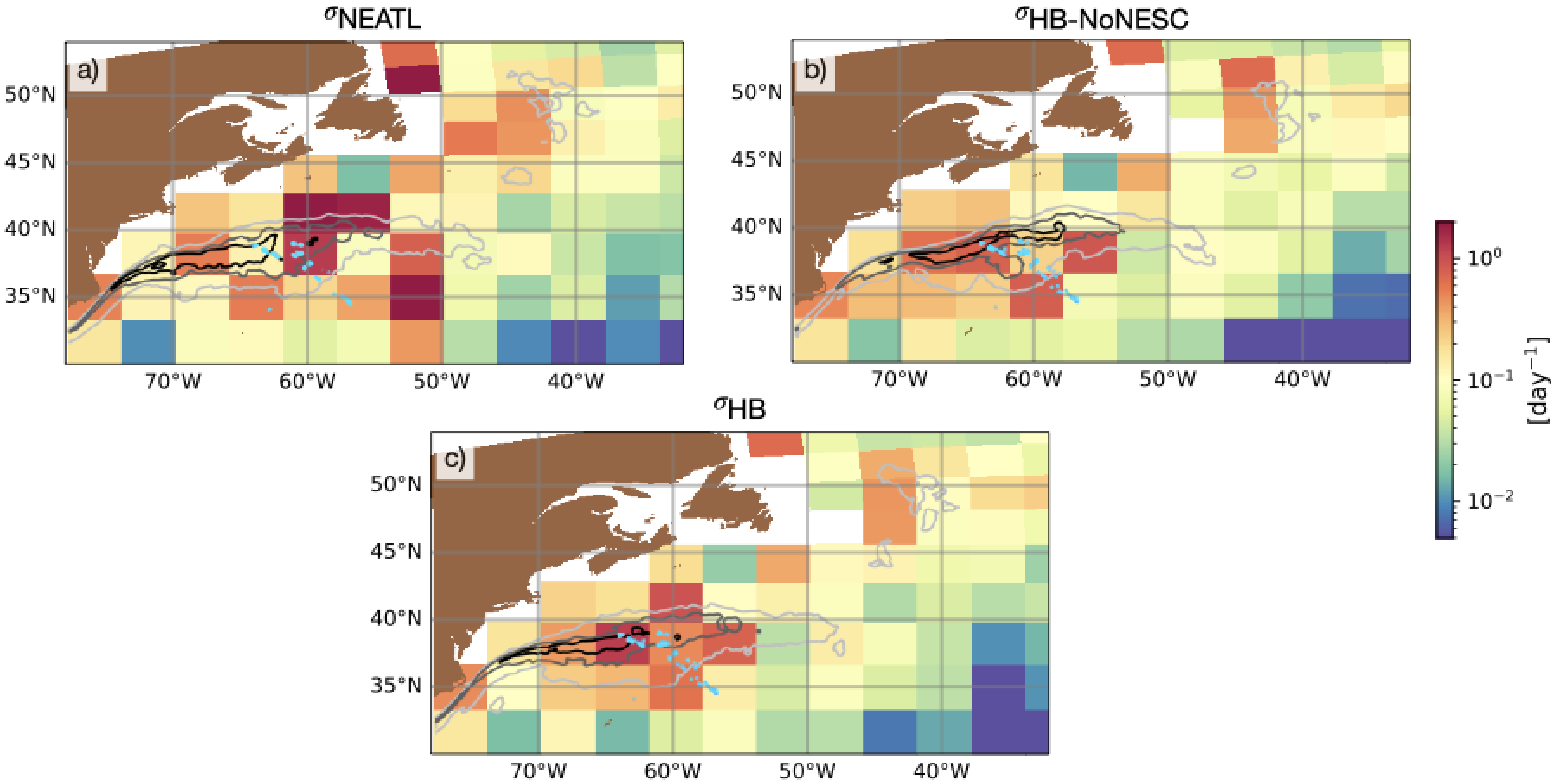
U-vel (m/s) H=3000m L=6.25km Delta=50km Y:0001 D:053







Baroclinic instability growth rates

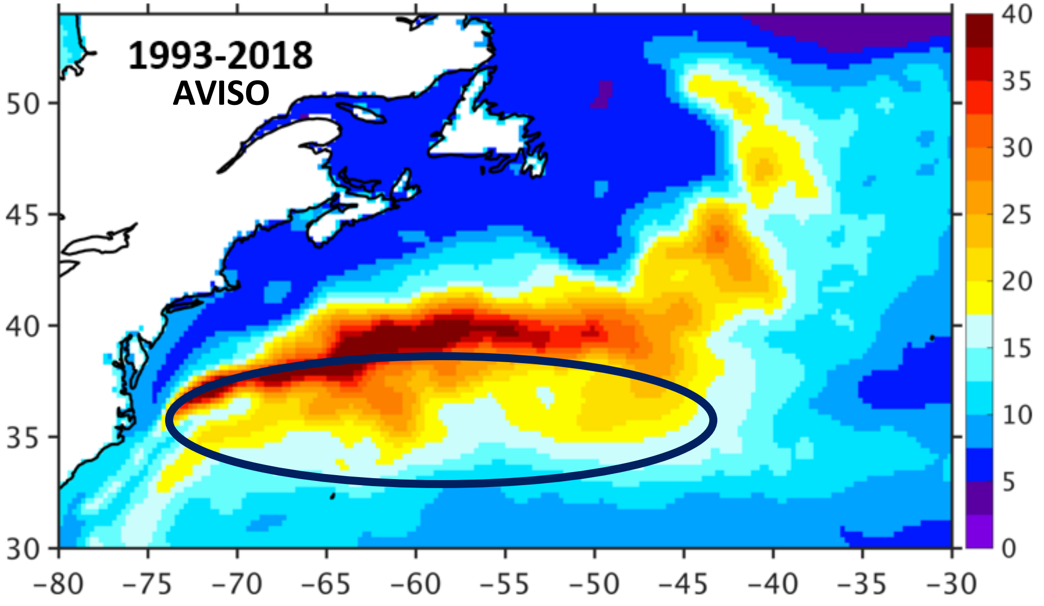


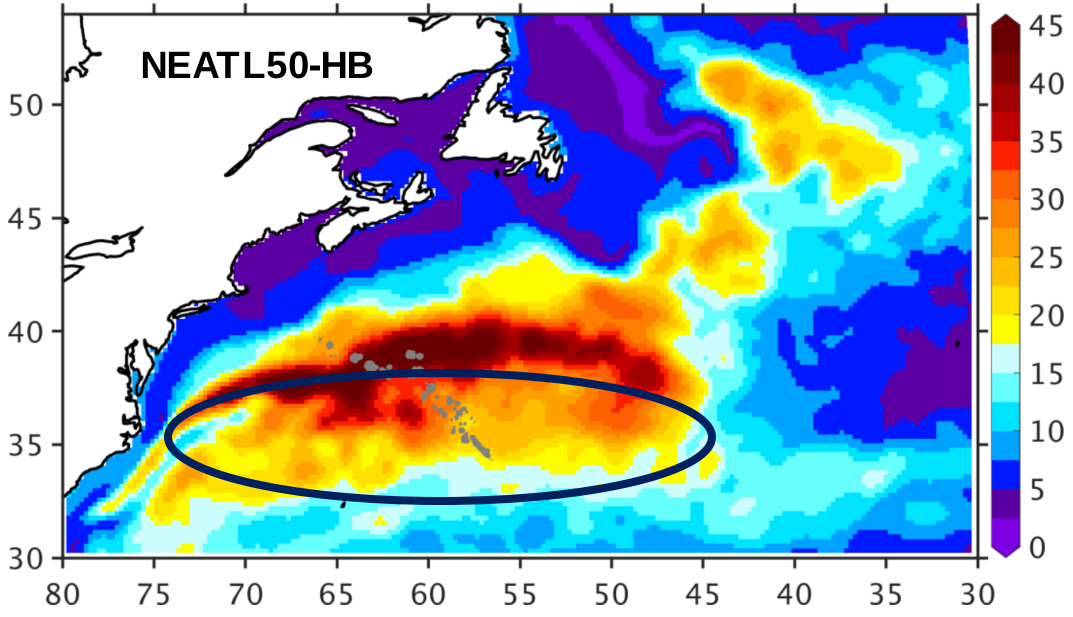
Linear quasi-geostrophic eigenvalue problem on a β-plane (background flow: 5-year temporal mean, 4°x4°)

Conclusion #2: Bathymetry

A proper representation of the fine scale structure of the New England Seamount Chain has a much more profound impact on the Gulf Stream pathway and variability than one would have a priori anticipated (Chassignet et al., 2023, JPO).

Discrepancy # 3: Higher EKE upstream of the NESC and south of Gulf Stream





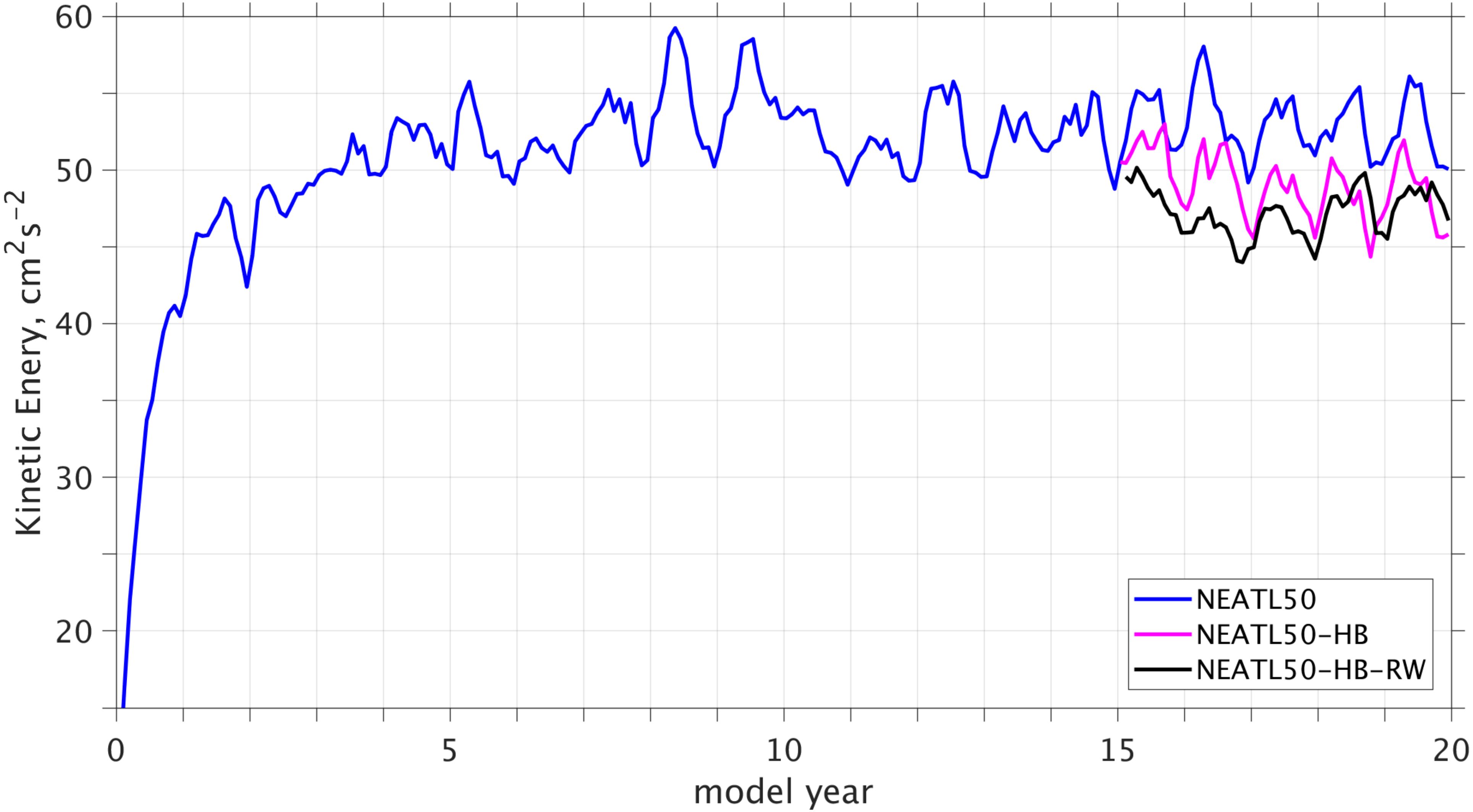
- Viscosity as a function of grid spacing (1/12° and 1/25°)
- Same viscosity for 1/25° and 1/50°

Absolute versus relative wind forcing

- All the simulations described so far use absolute wind forcing (no shear between wind and ocean currents) in the wind stress formulation.
- Relative wind induces a severe “eddy killing effect” (30% reduction in KE).
- Renault et al. (2019) proposed a 70% relative wind stress formulation to take into account ocean-atmospheric feedback.
- Less eddies also allows for a reduction of the viscosity as a function of the grid spacing.

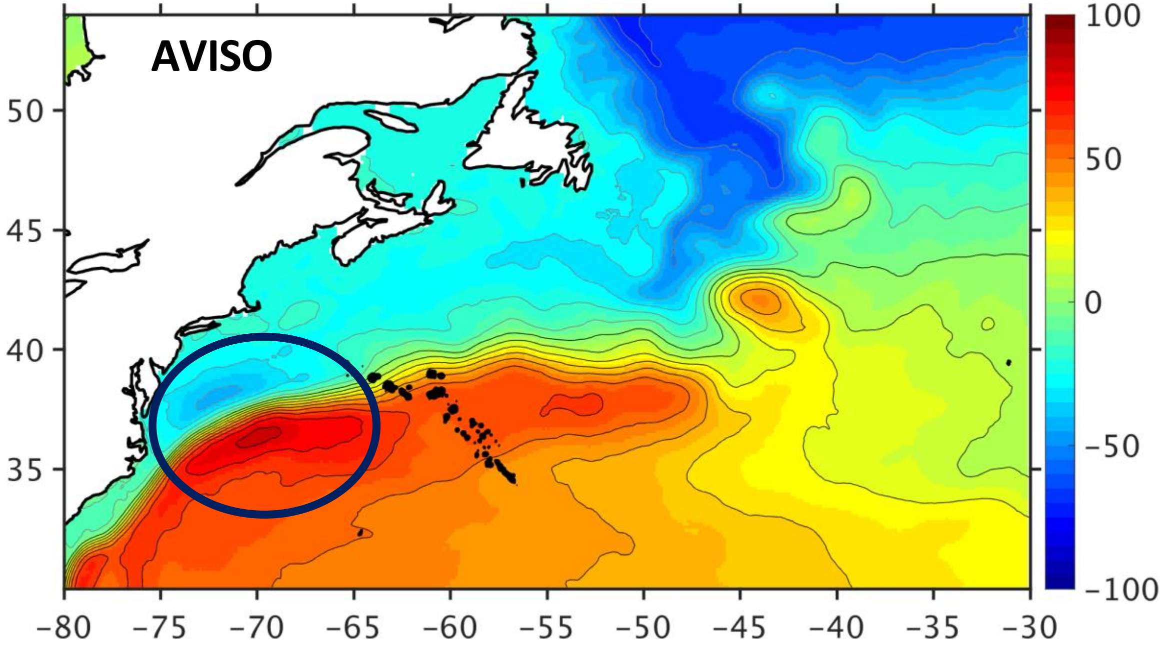
Viscosity Parameter	Absolution Wind (E026)	Relative Wind (E037)
Laplacian coefficient A	10 m2/s	5
Biharmonic diff vel. for momentum	4 cm/s	1cm/s <40N
Biharmonic diff vel. for layer thickness	4 cm/s	1cm/s <40N
Laplacian diff vel. for tracer	1 cm/s	0.5 cm/s

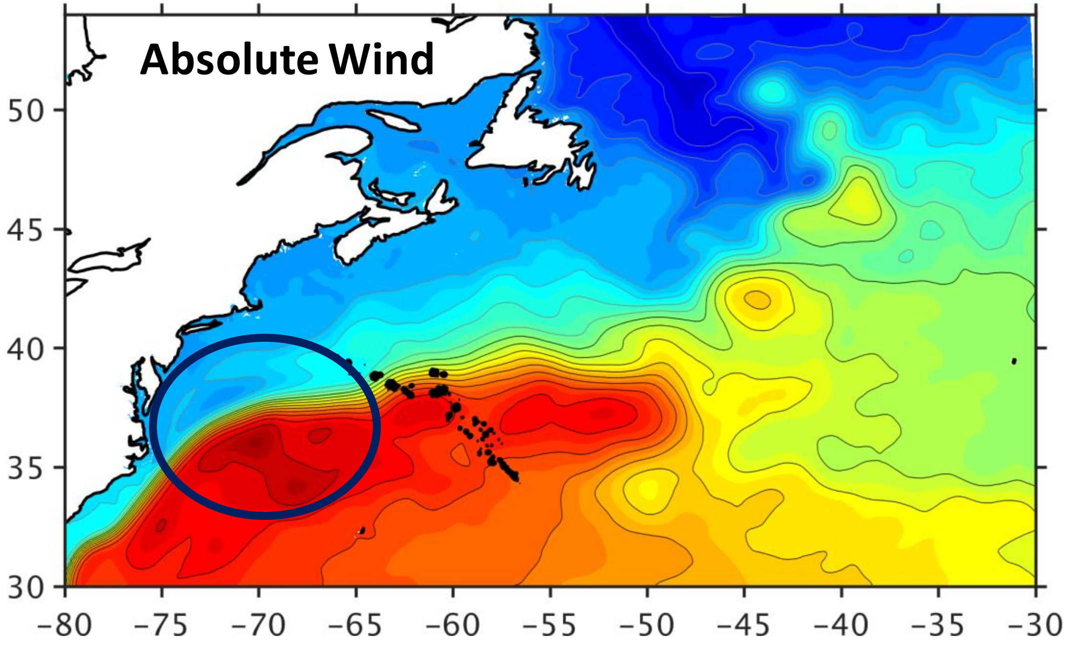
Basin-averaged KE

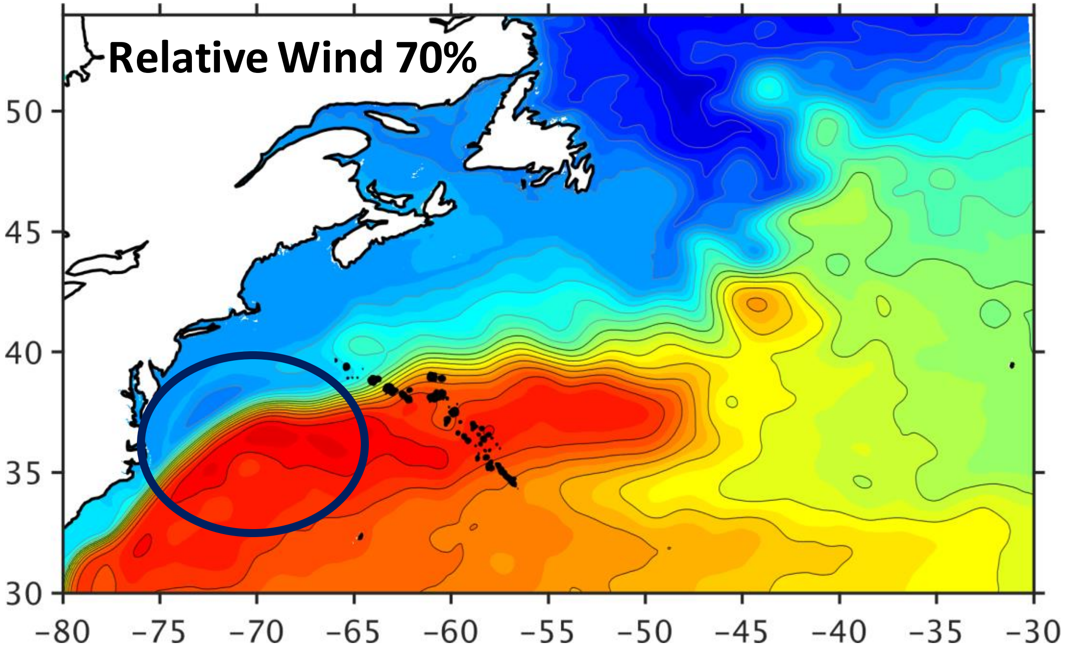


The basin averaged KE of the relative wind experiment is slightly lower than that of the absolute wind, but more comparable in the later part of the integration.

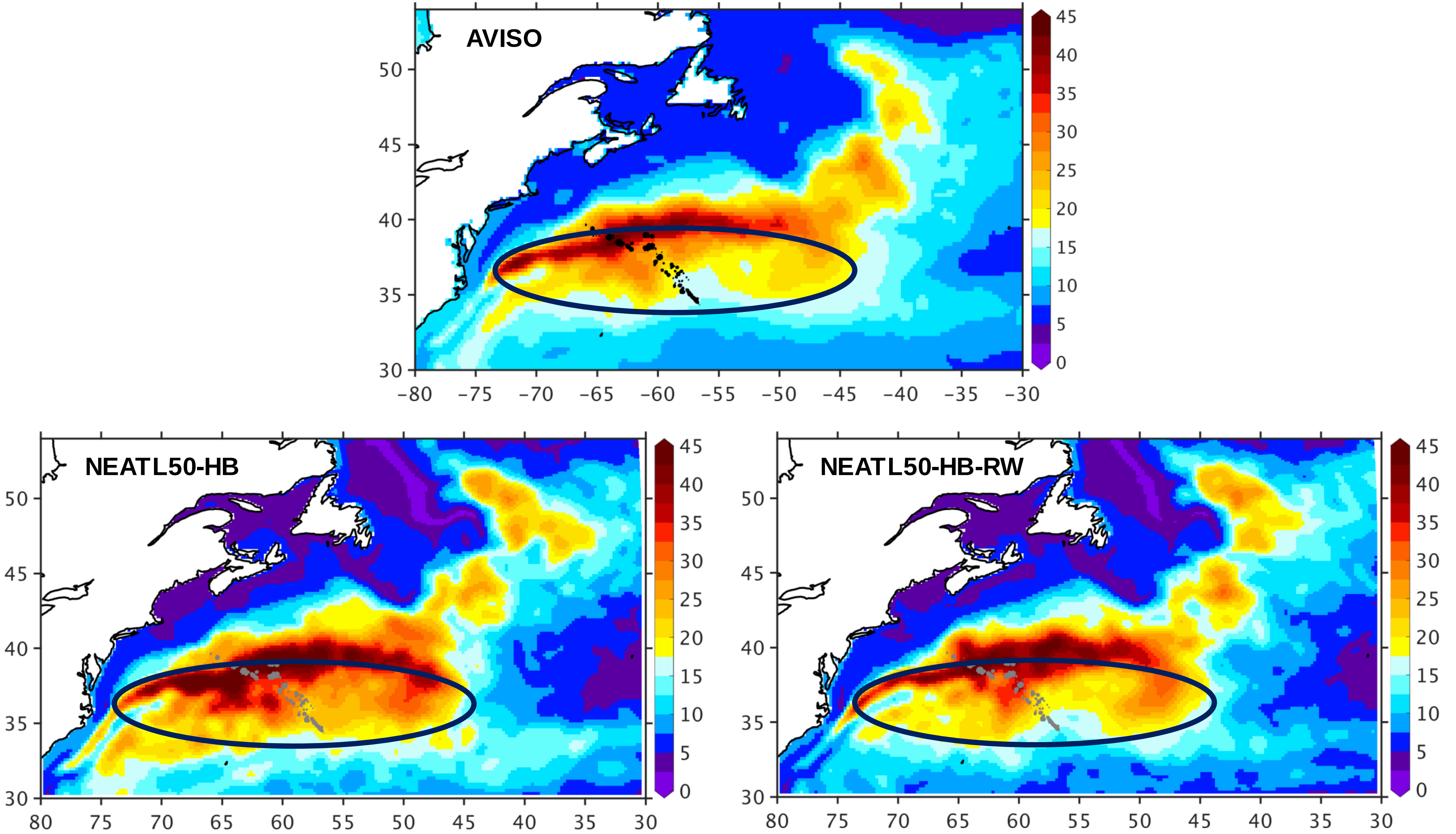
Relative wind impact on mean sea surface height



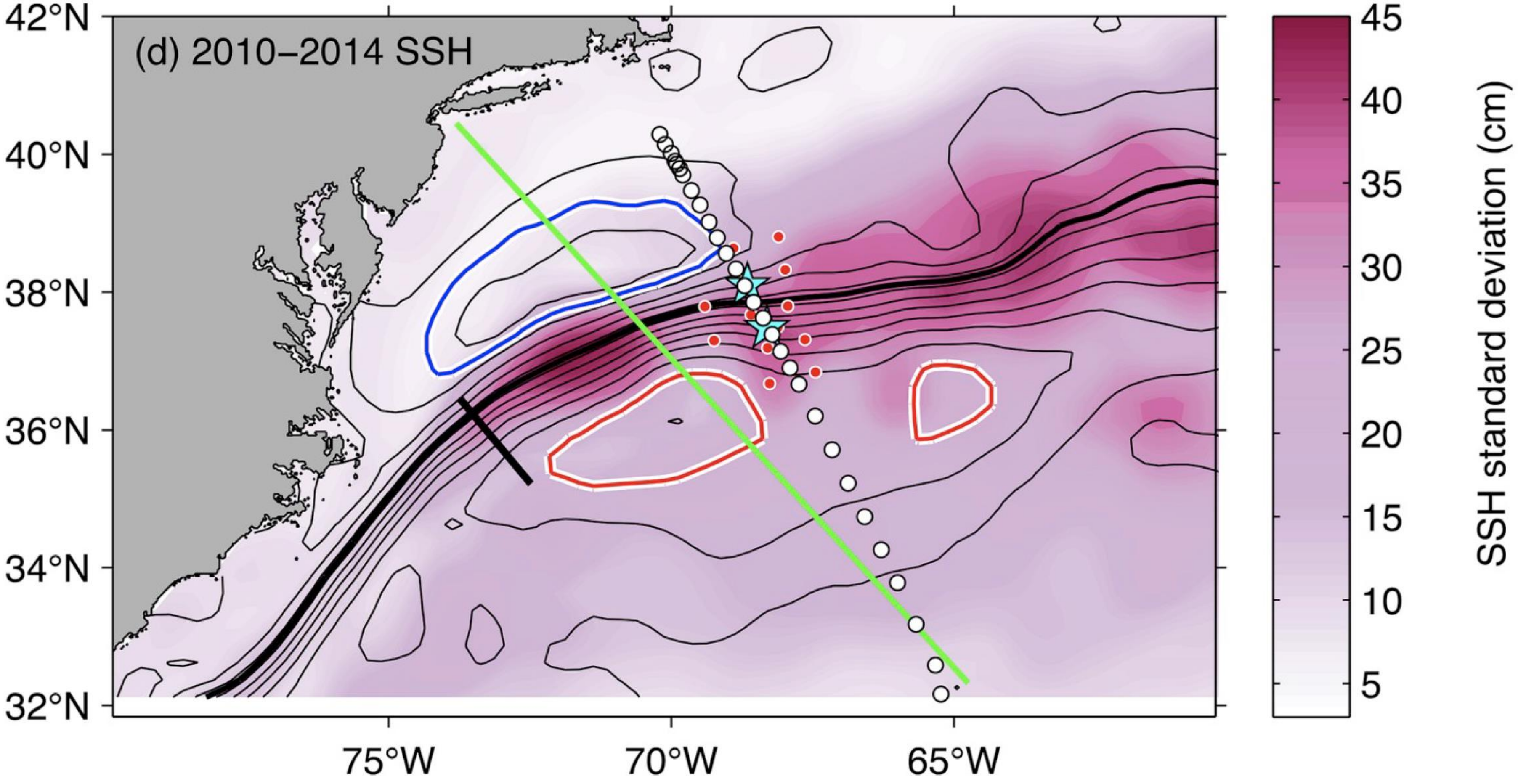




Relative wind impact on surface EKE

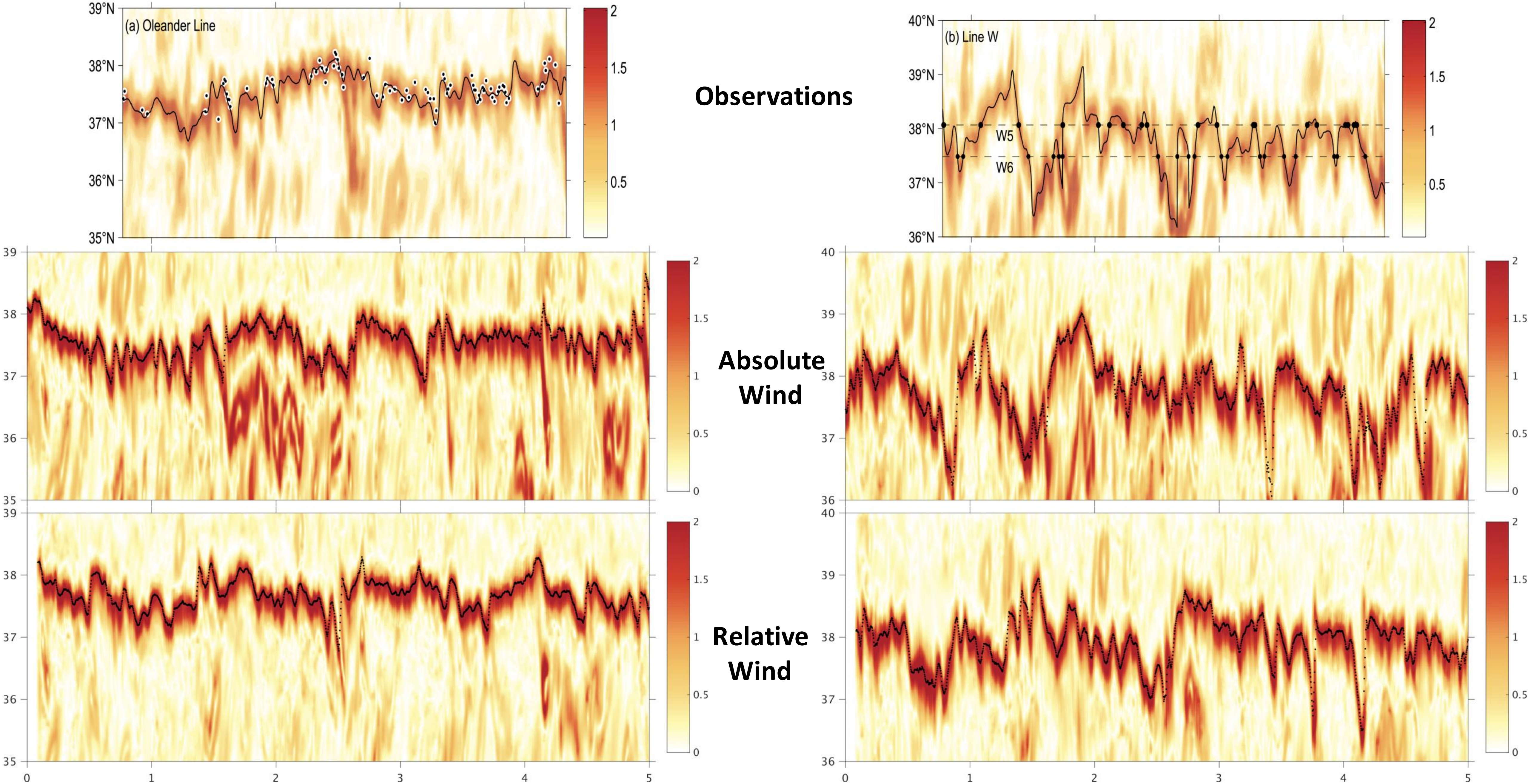


Comparison with Oleander & W line results (Andres et al., 2020)



Oleander-Line

W-Line



Observations

Absolute Wind

Relative Wind

Conclusion #3: Relative wind

Reducing the viscosity together with implementing the 70% relative wind as in Renault et al. (2019) not only maintains the overall kinetic energy, but it also reduce the excessive EKE south of the Gulf Stream (Chassignet and Xu, GRL, in prep).

Summary

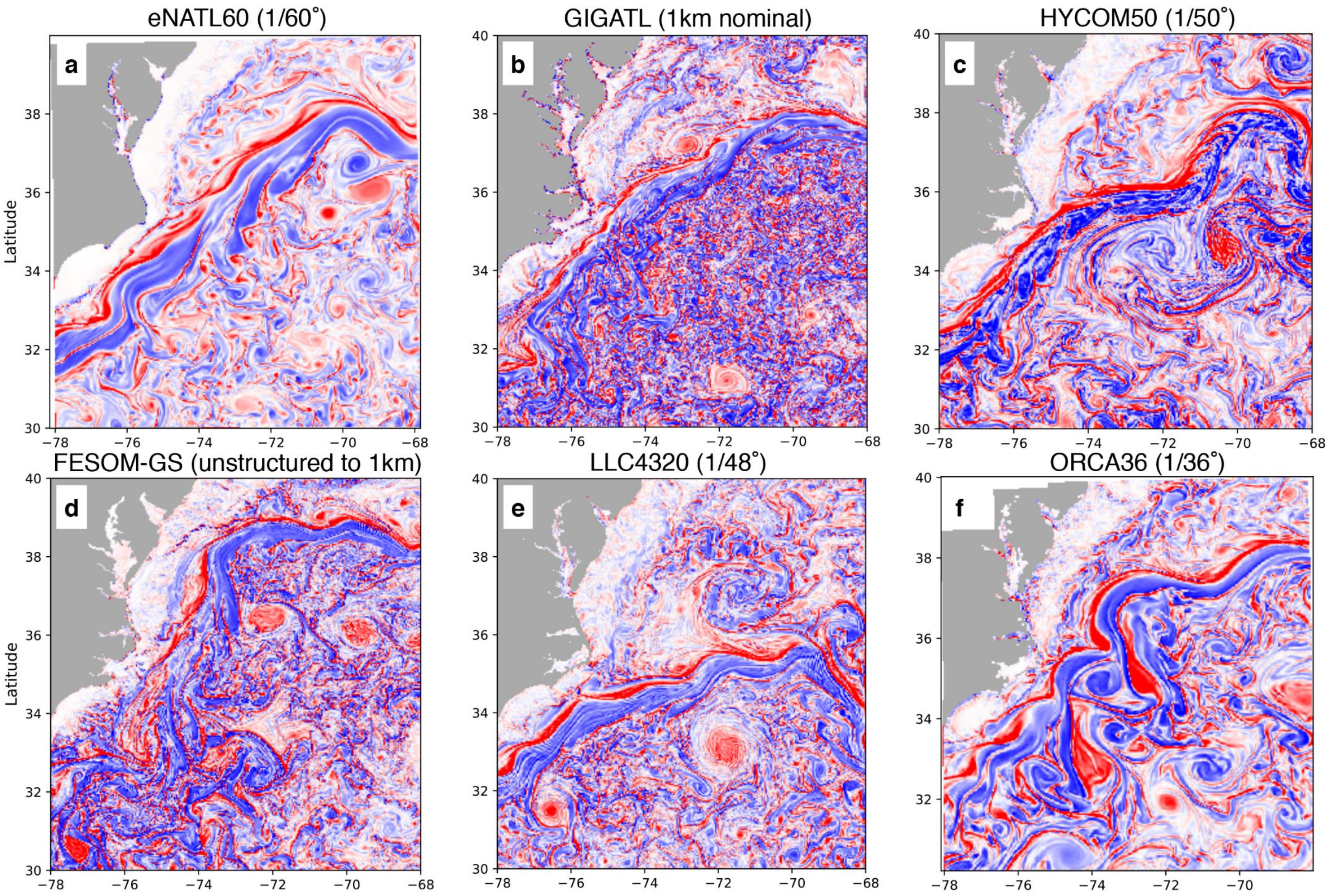
- ✓ Internal tides flattens the slope within the mesoscale range and explains the difference between non-tidal ocean models and observations (Xu et al., 2022, JGR).
- ✓ A proper representation of the fine scale structure of the New England Seamount Chain has a much more profound impact on the Gulf Stream pathway and variability than one would have a priori anticipated (Chassignet et al., 2023, JPO).
- ✓ Reducing the viscosity together with implementing the 70% relative wind as in Renault et al. (2019) not only maintains the overall kinetic energy, but it also reduce the excessive EKE south of the Gulf Stream (Chassignet and Xu, GRL, in prep).

What about vertical resolution?

- A 1 km grid spacing will resolve the mid-latitude Rossby radius of deformation up to the 5th mode => the latter is easily modeled by the vertical grid used in most models.
- Vertical resolution is needed in order to properly represent the various water masses present in the global ocean.
- Vertical resolution needs to be three times higher in z-level models than in isopycnic/layer models to discretize the water masses.

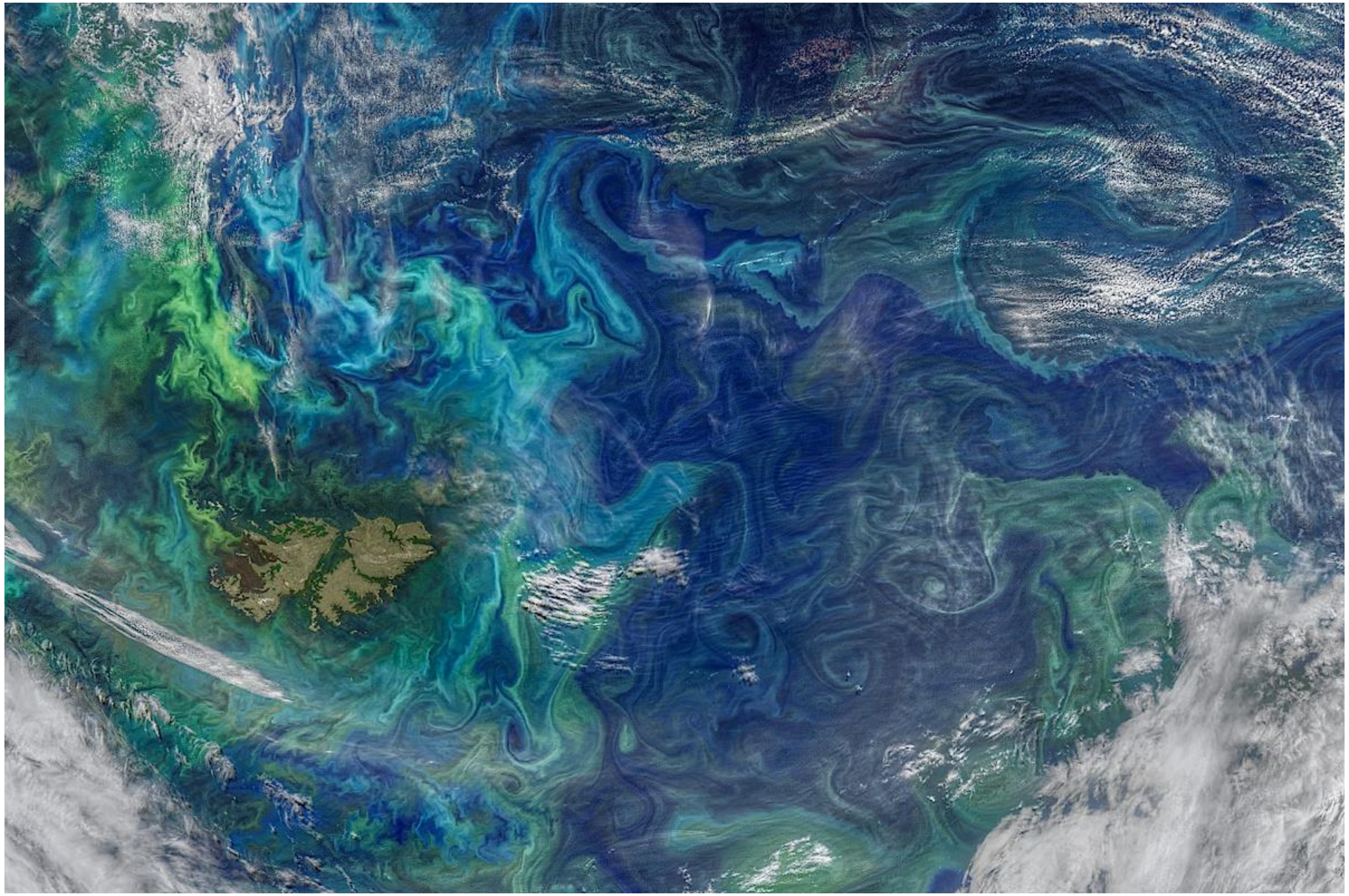
Xu, Chassignet, et al. (2023, Ocean Modelling)

Representation of submesoscale features in km-scale ocean models



Uchida et al. (2022)

Five 1-km scale models with very different behavior: Which one is closer to reality?



Phytoplankton blooms (shown in green and light blue) in the South Atlantic Ocean on Jan. 5, 2021.
<u>Credits</u>: NASA using data from the NOAA-20 satellite and the joint NASA-NOAA Suomi NPP satellite.

Few observations are available for validation, but with the advent of SWOT and other satellite measurements, there is an ongoing effort to address the above and quantify the impact of the closure used by the models for subgrid scale parameterization.

Concluding remarks

- ✓ Km-scale models are needed for a realistic nature run on global/basin scale (i.e., less systematic bias) => there is a clear impact of submesoscale features and of properly resolving the bathymetry on large-scale ocean circulation
- ✓ However, what is reality? Very different representation of vorticity among present 1-km ocean models
- ✓ Open question: When will increasing horizontal resolution stop impacting the large scale?
- ✓ Ocean is only one element of the earth system: coupling with ice, land, and atmosphere impacts its behavior

Questions?