"Sources and Sinks of Ocean Mesoscale Eddy Energy" workshop

Regimes of inverse energy cascade in the ocean mesoscale inertial range.

Julien Le Sommer (IGE/CNRS),

with Adekunle Ajayi, Jean Marc Molines, Aurélie Albert, Eric Chassignet, Xiabao Xu

Tallahasse, March, 12-14 2019

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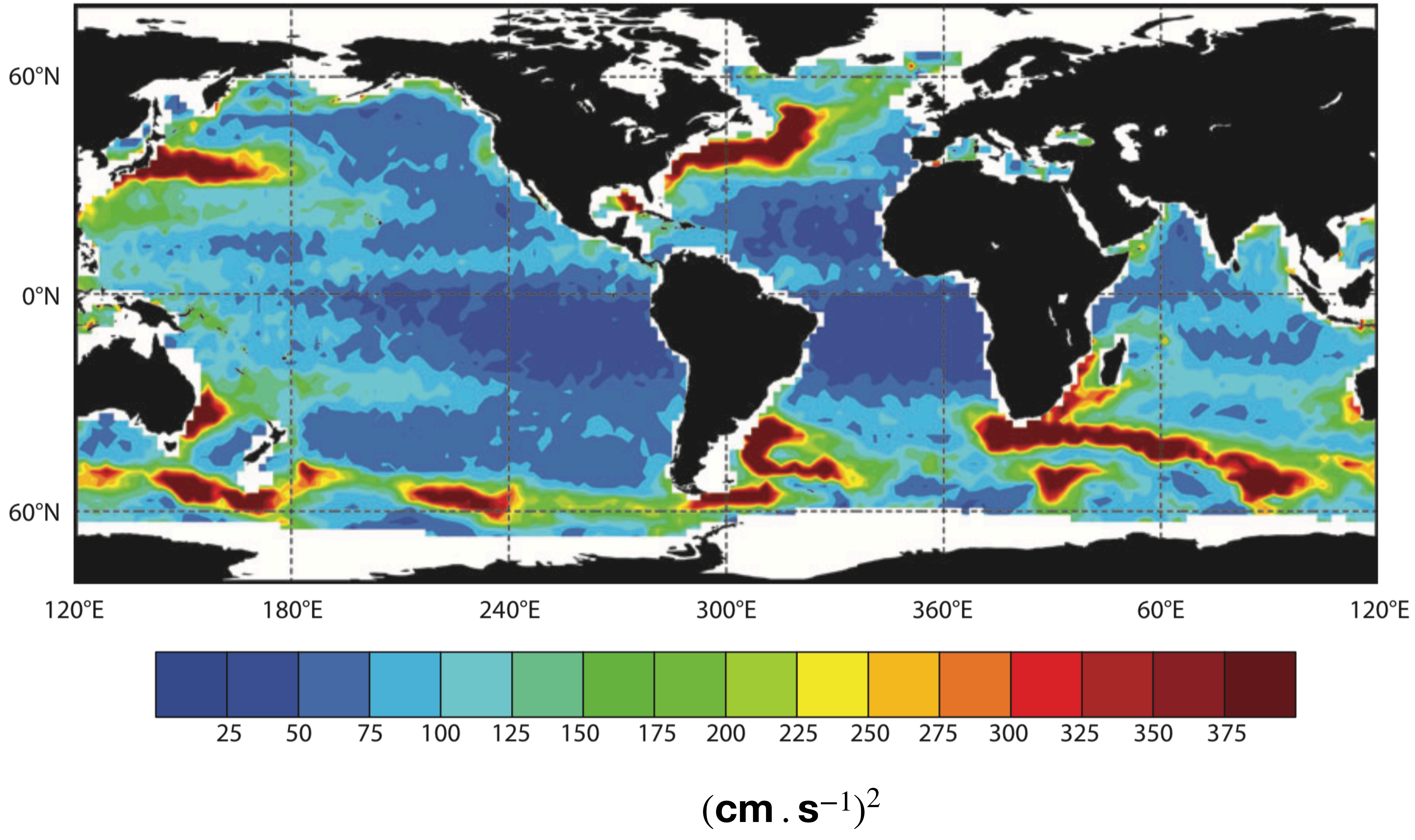
Background and motivation

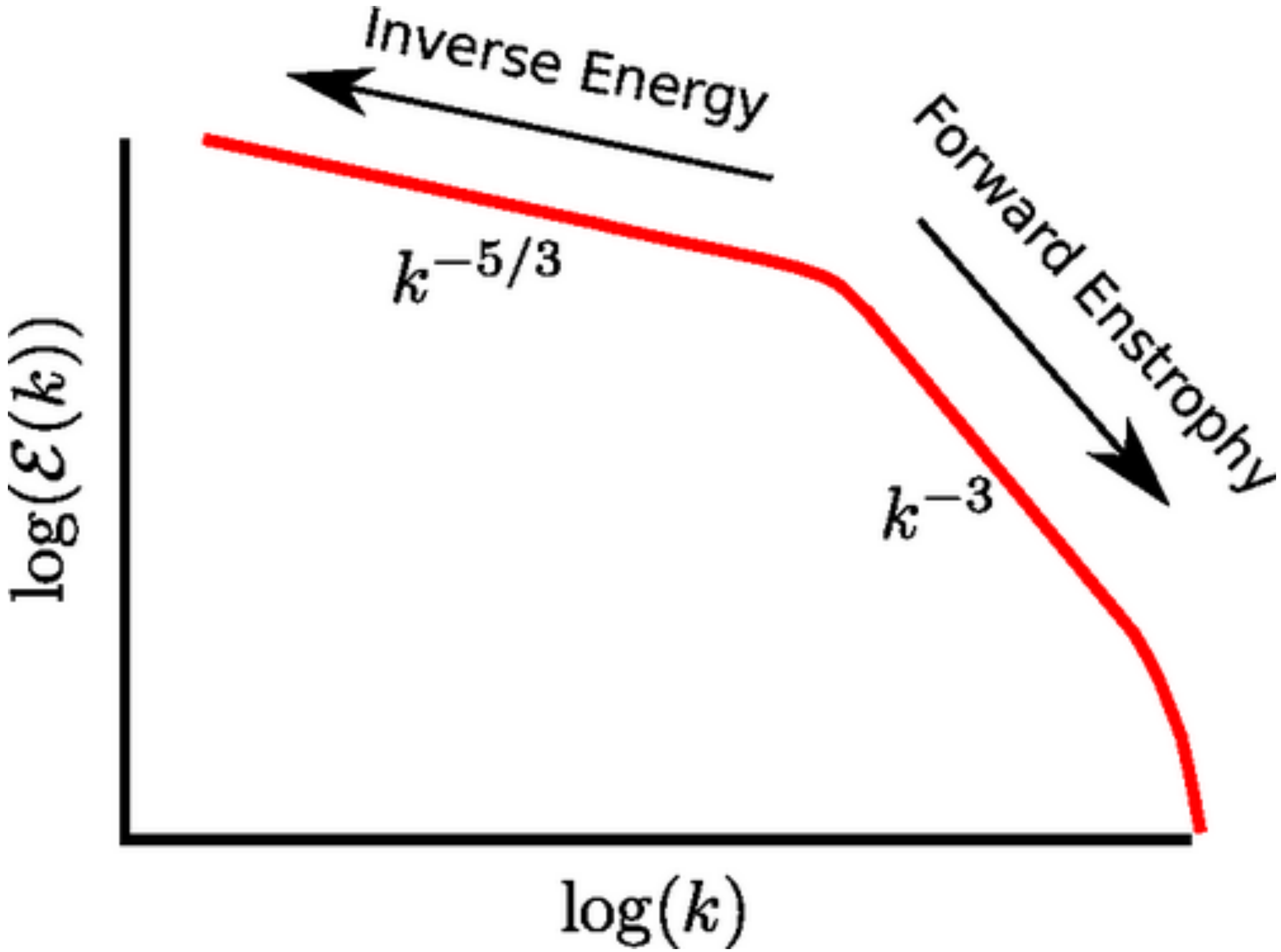
Geostrophic kinetic energy



Ferrari & Wunsch (2009), adapted from Wunsch & Stammer (1998)

- Large reservoir of mesoscale kinetic energy
- Understanding how this energy is fluxed across scales is important (!)

Cascades in 2D / QG turbulence



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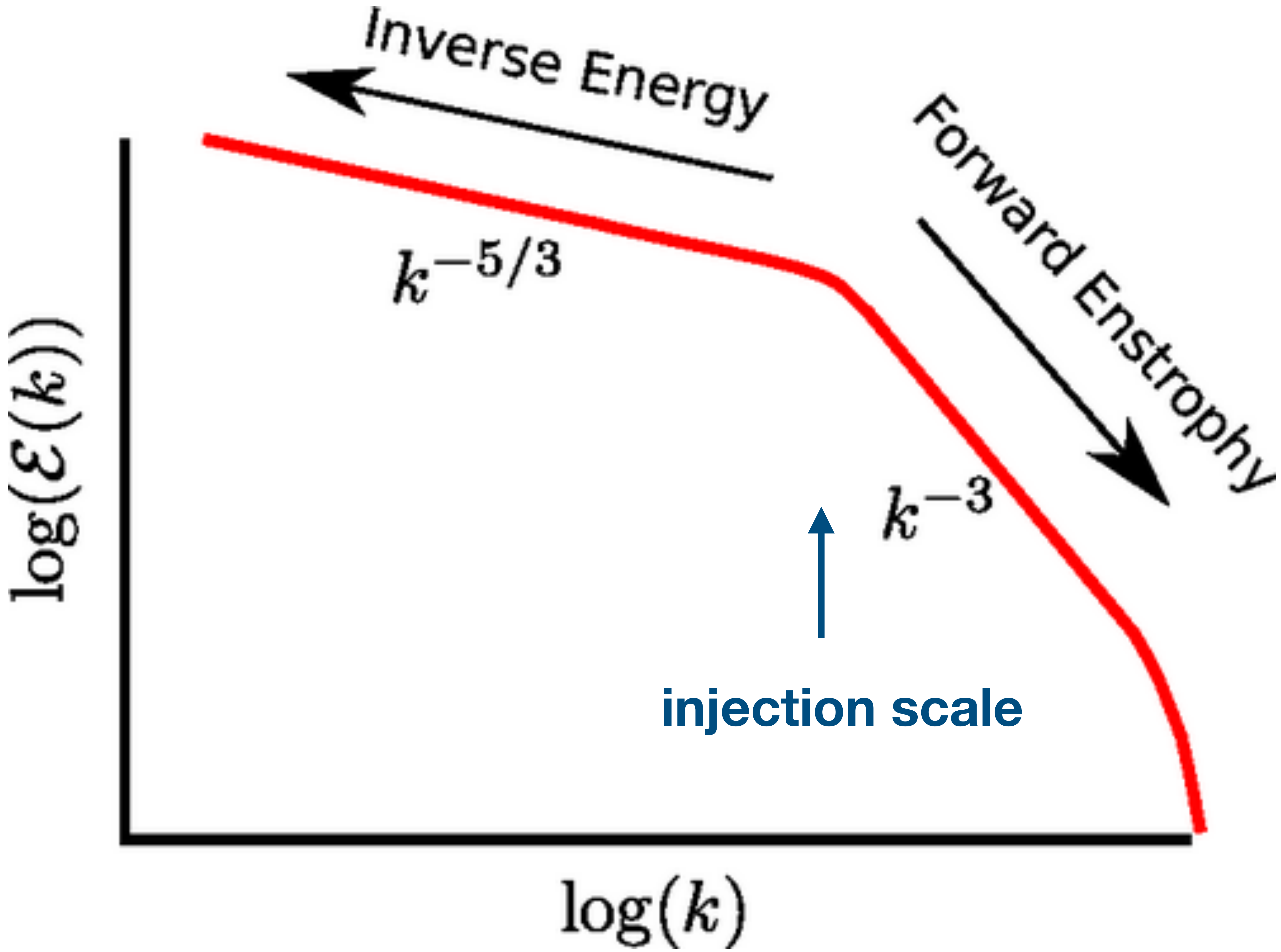

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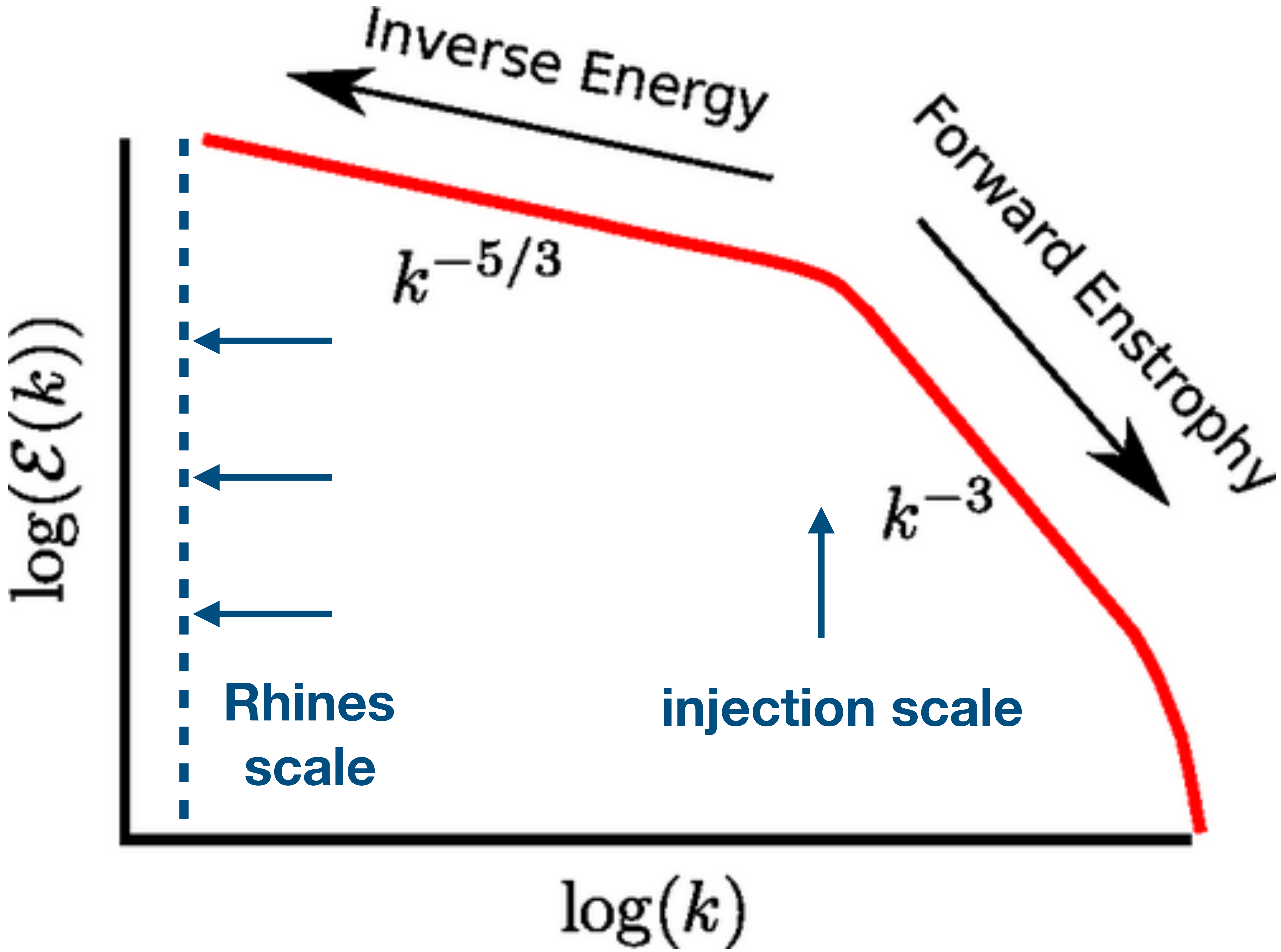

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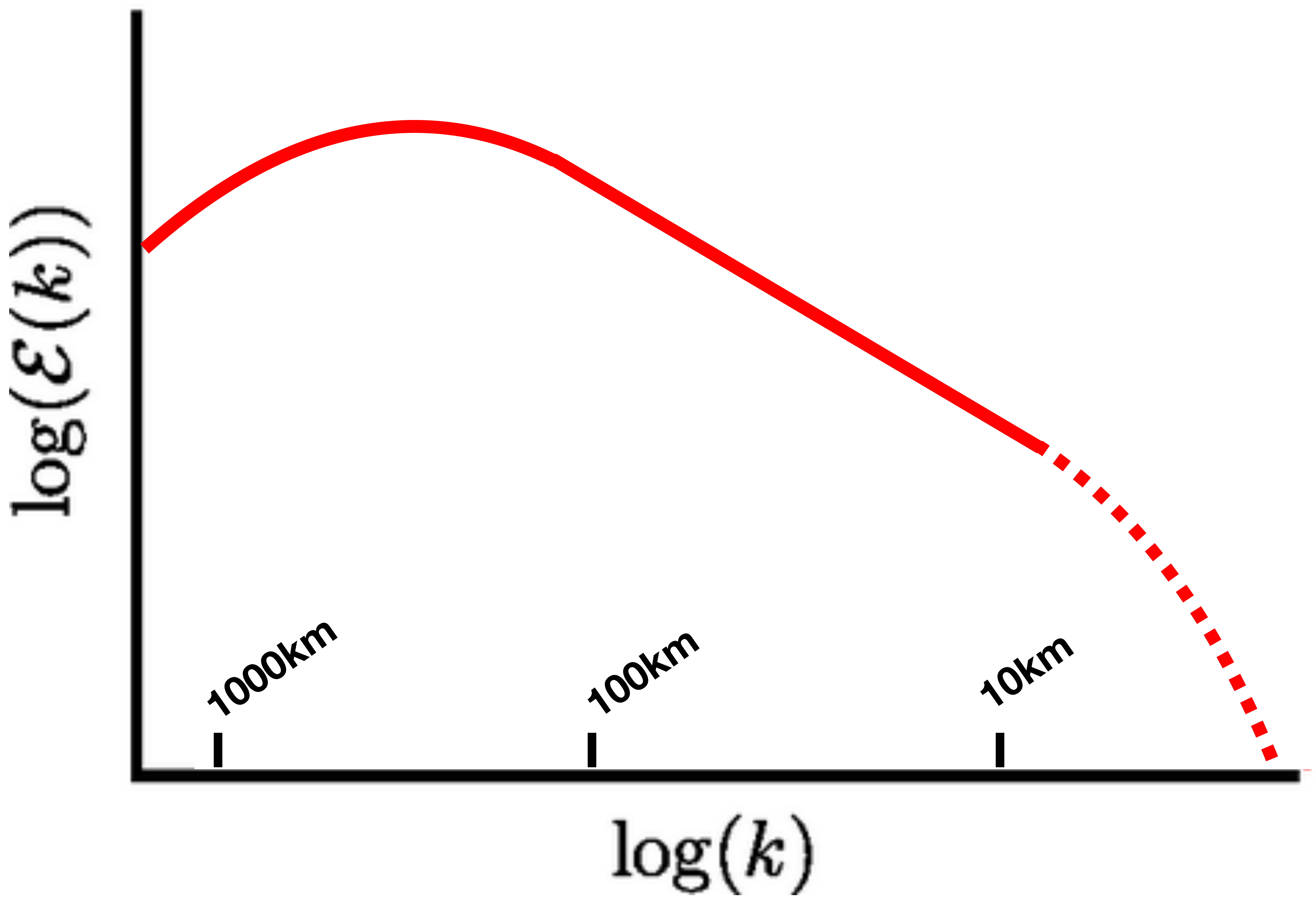
Actual kinetic energy spectra at mesoscales



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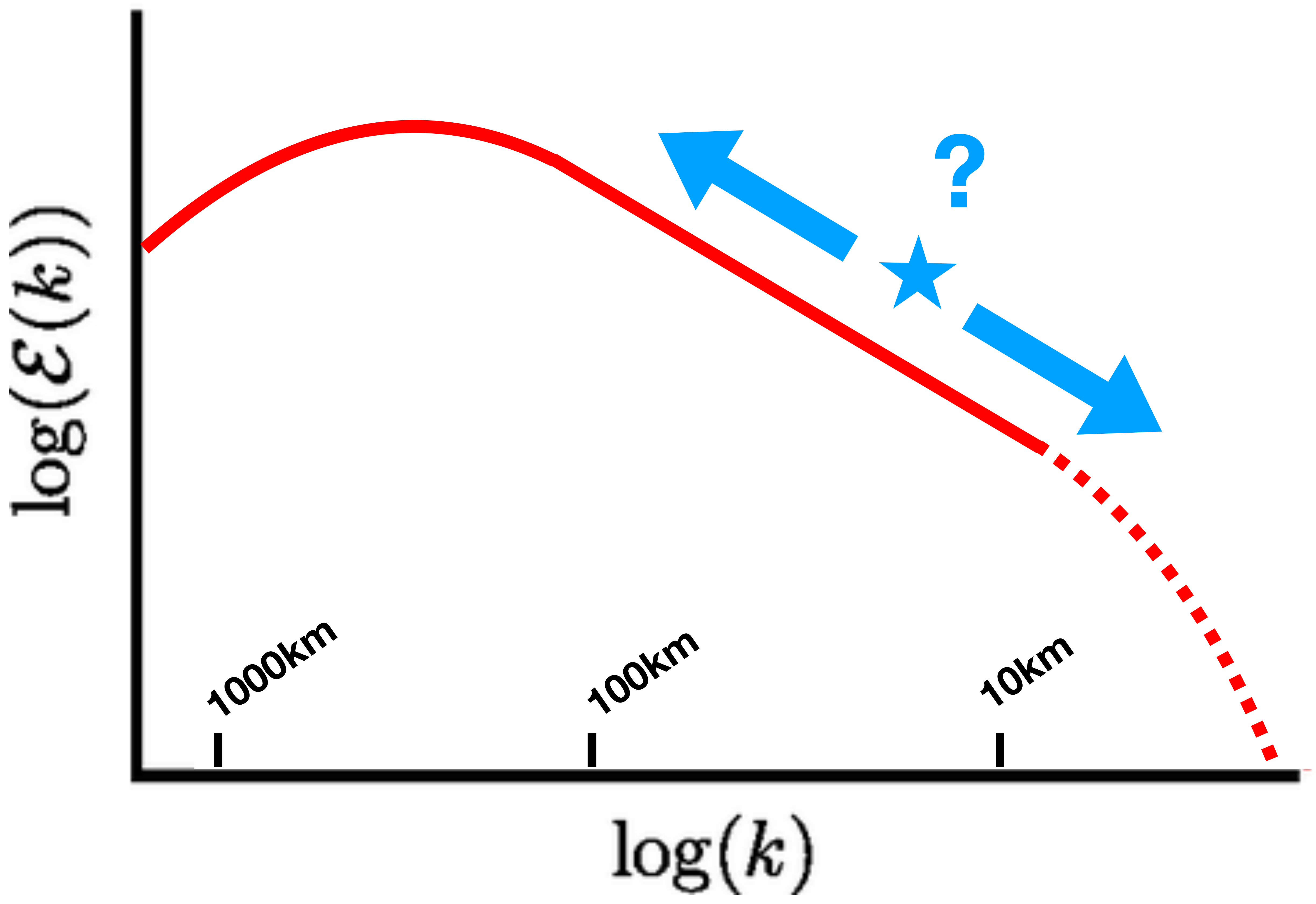

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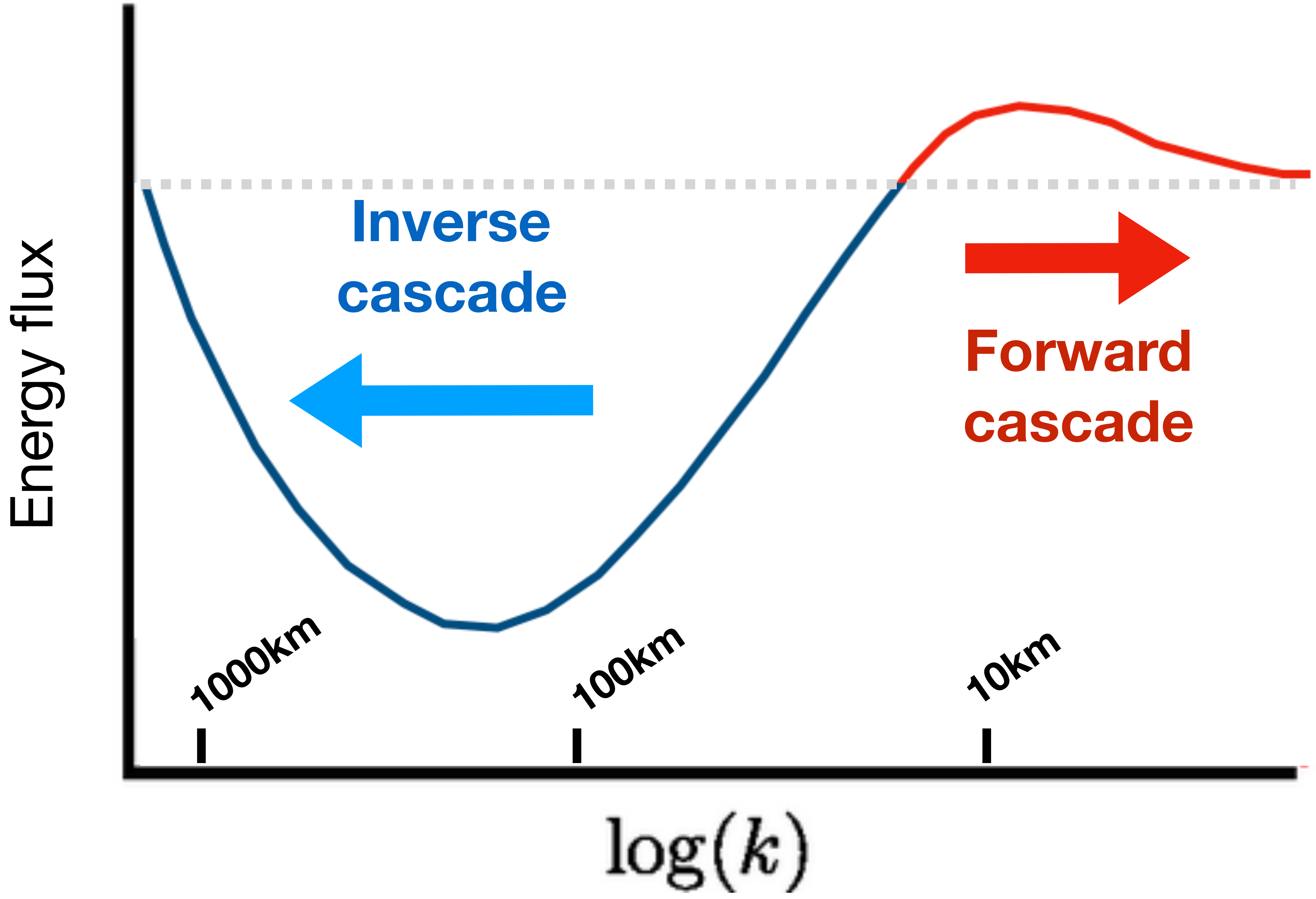
Background and motivation

Kinetic energy fluxes across mesoscales



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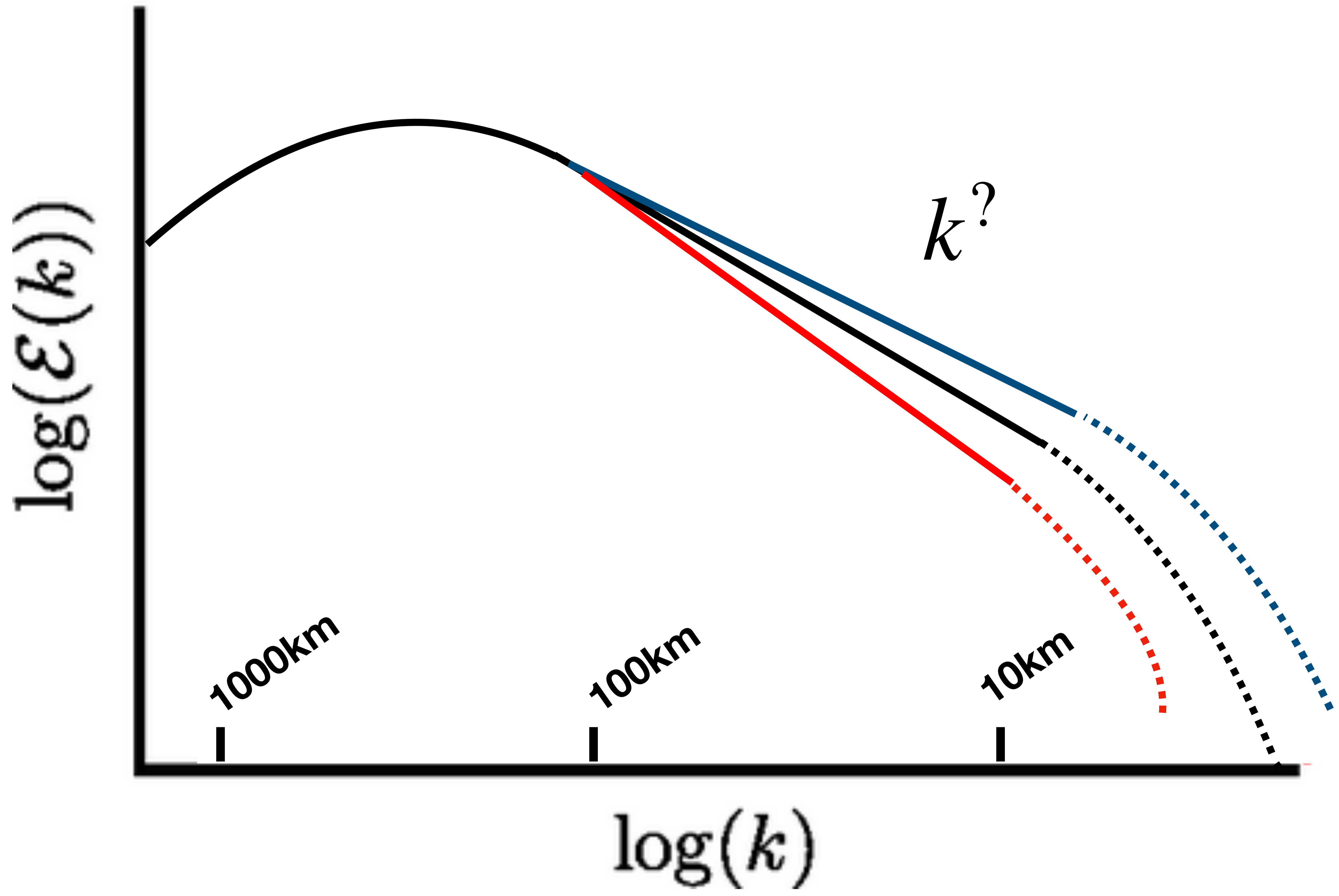
Background and motivation

Slopes of KE spectra in mesoscale inertial range



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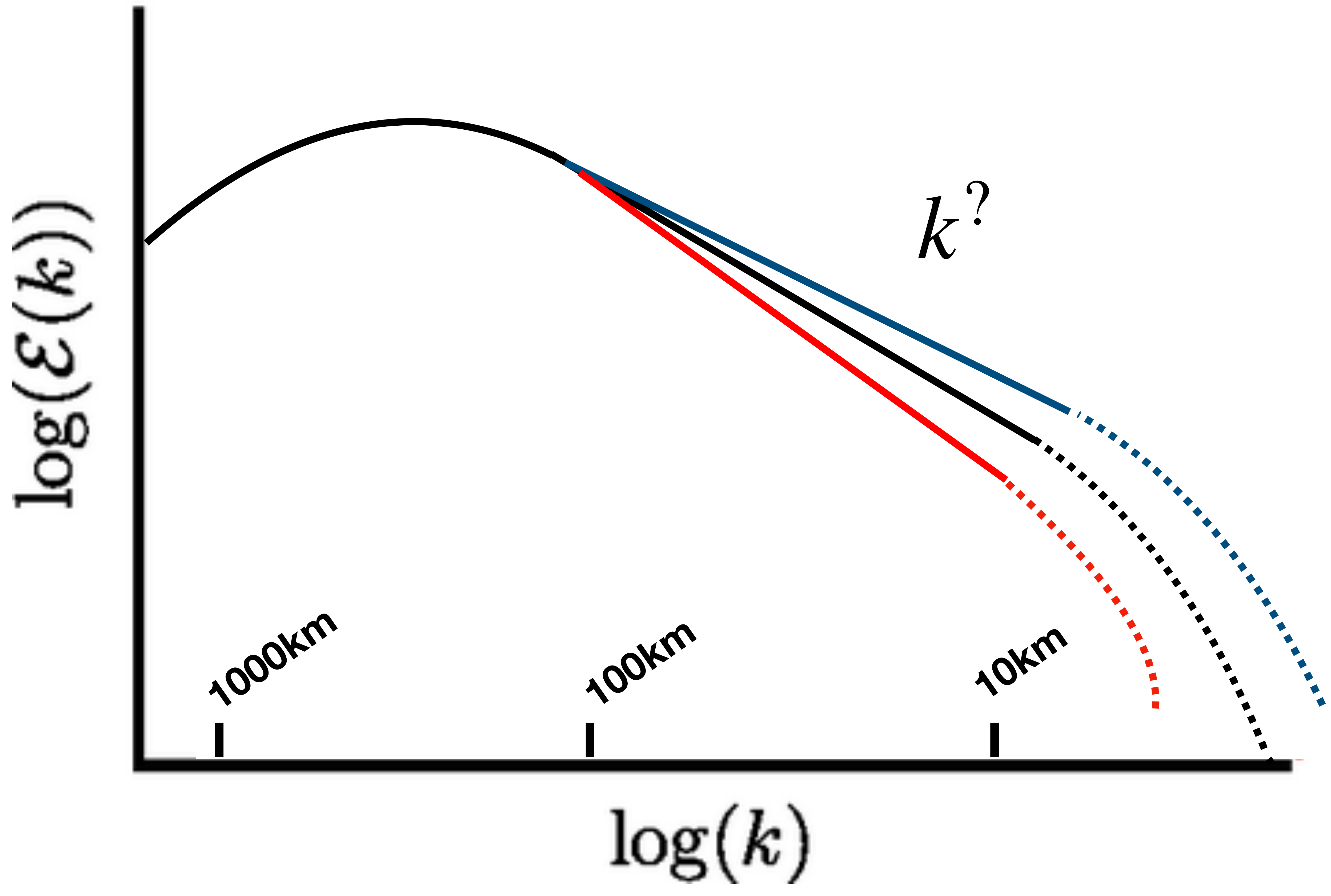

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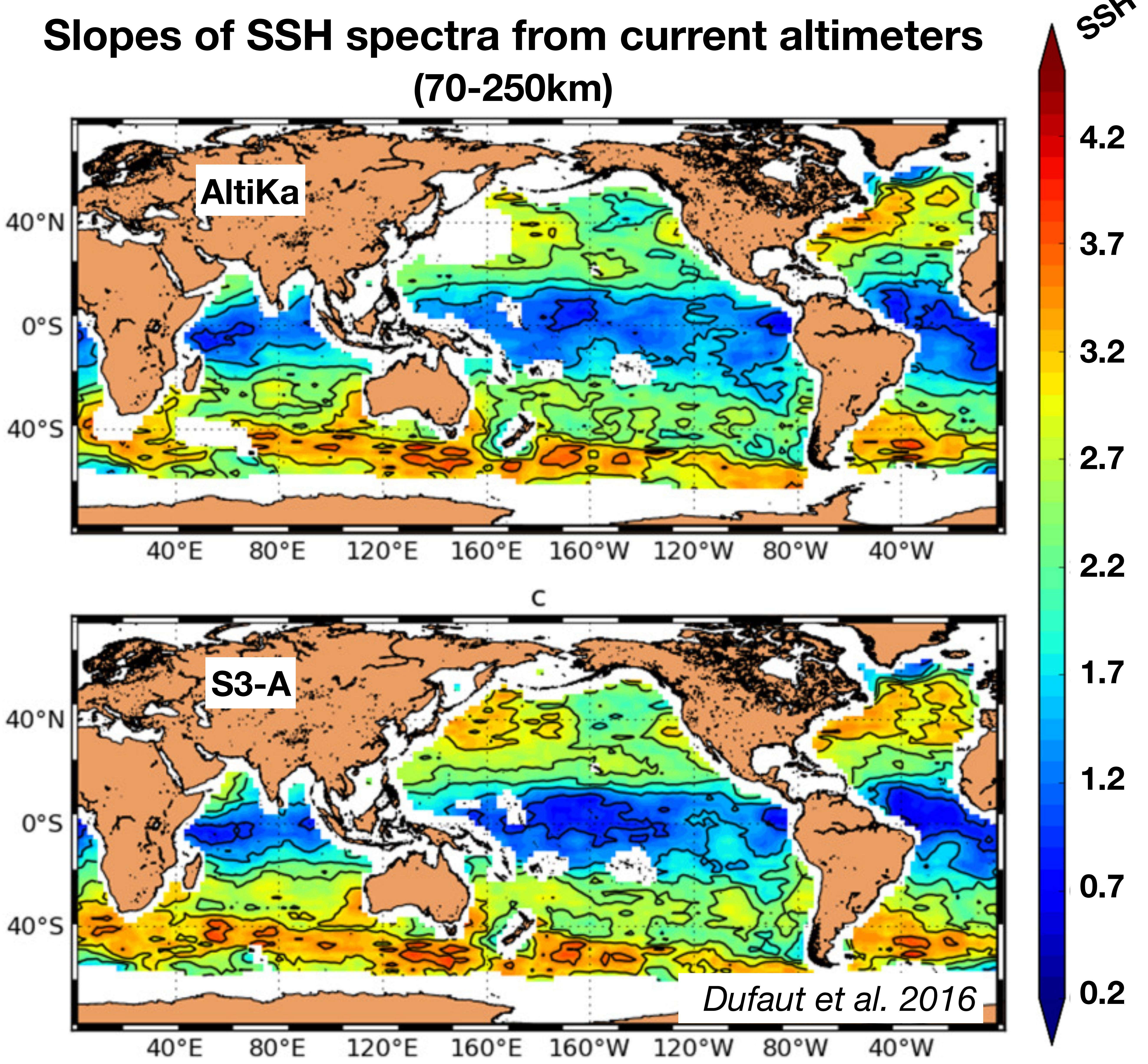
Philips-like regimes (QG)	$PSD_{\|\|u\|\|} \propto k^{-3}$
Charney-like regimes (SQG)	$PSD_{\|\|u\|\|} \propto k^{-2}$



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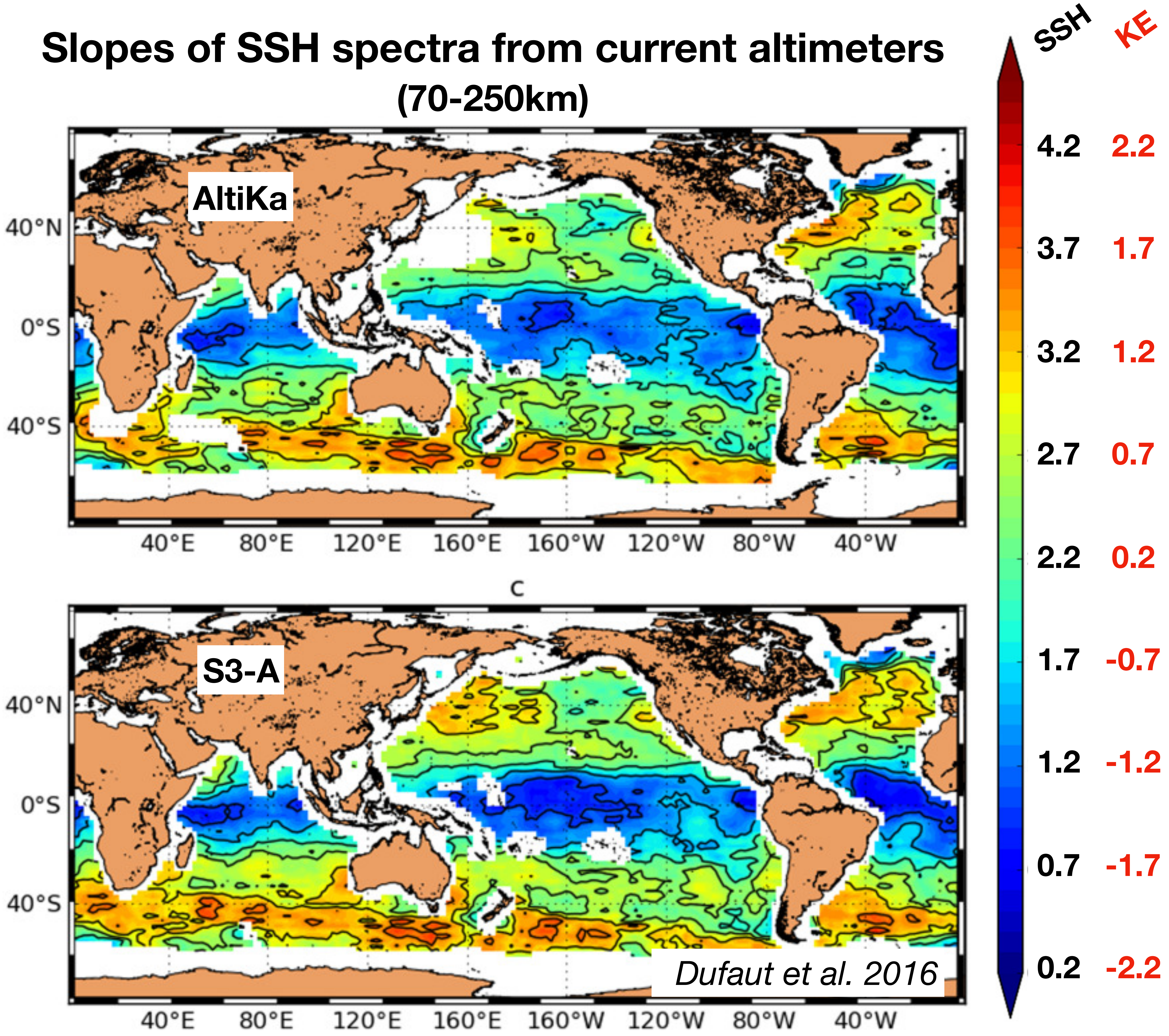
- Differences between low / high KE regions (SQG versus QG)

Slopes of SSH spectra from current altimeters (70-250km)



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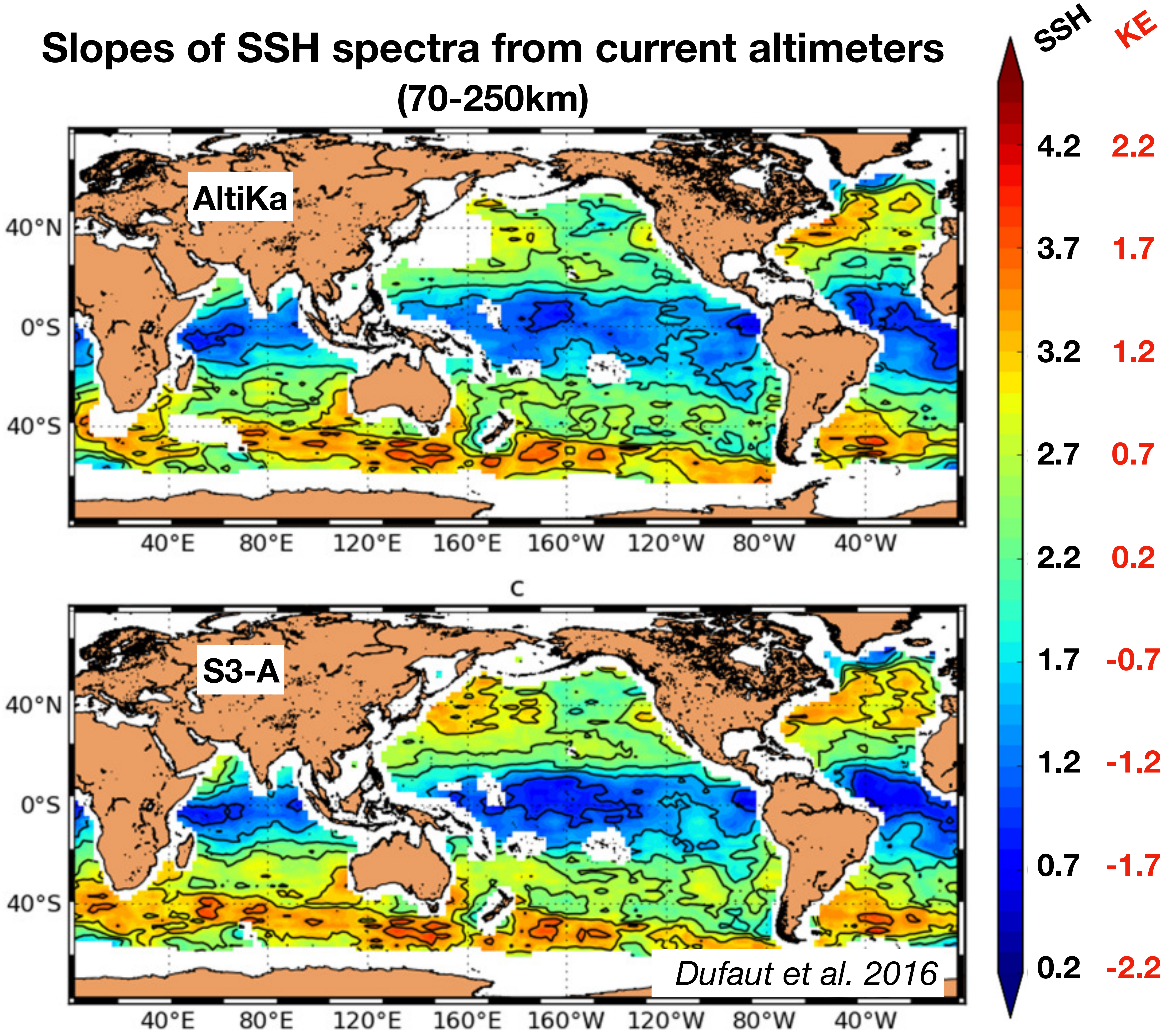

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Still unclear how energy is being fluxed across mesoscales

1. Background and motivation
2. **Model datasets : NATL60 and HYCOM50**
3. Slope of kinetic energy wavenumber spectra
4. Kinetic energy spectral flux though nonlinear advection
5. Wrap-up and conclusions

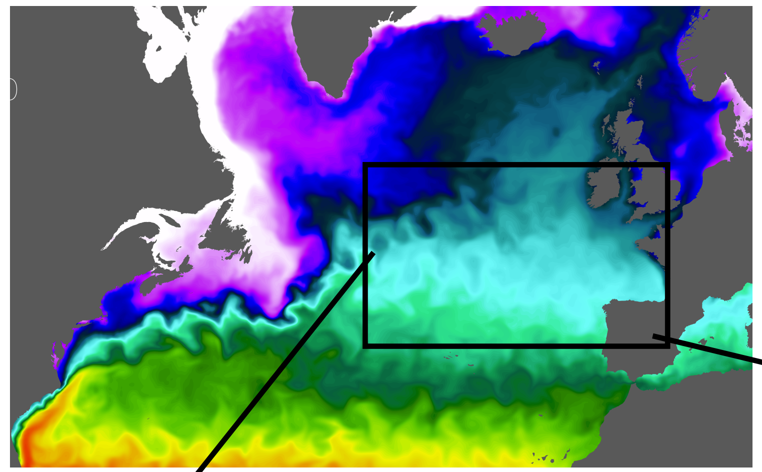
Model datasets : NATL60 and HYCOM50 (1/6)

NEMO NATL60 experiment

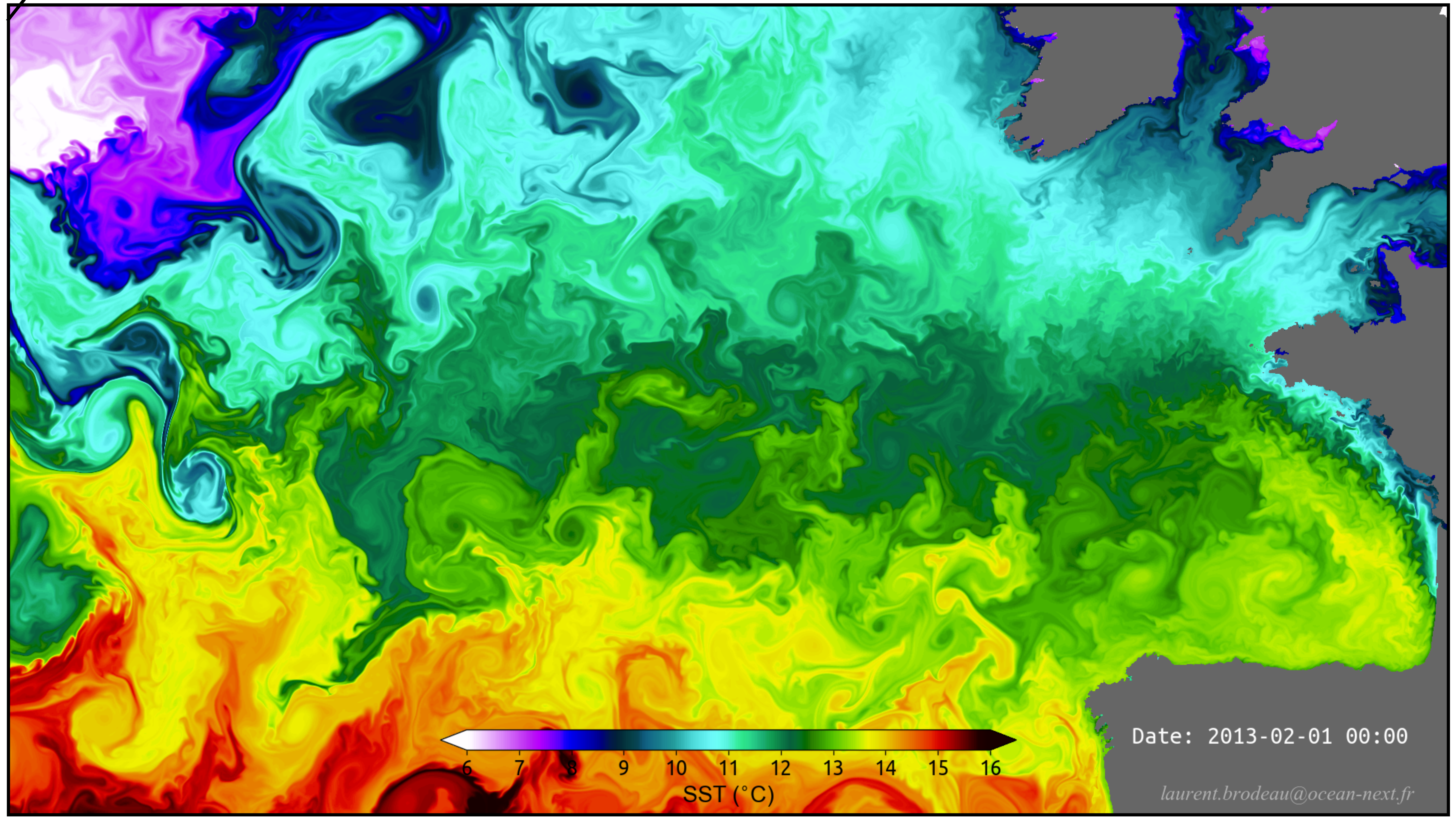
domain	25°N-66°N
Horizontal resolution	1/60° (0.9km-1.6km)
Vertical grid	300 levels (z)
Vertical coordinate	z-star
Time-step	30s
Integration period	Jan 2012-Oct.2013
Atmos forcing	DFS5.2 (ERA-i)
Boundary conditions	GLORYS 2v3
Sea ice	LIM2
SSS restoring	300 days / 50m
Equation of state	EOS-80

Momentum advection	UBS (3rd order upwind)
Tracer advection	UBS (3rd order upwind)
Vertical physics	TKE
Lateral BC	free-slip
Lateral closures	isoneutral diff. + Fox-Kemper

Effective resolution : ~10km



Ducousso et al. 2018; Fresnay et al. 2018
Gomez Navarro et al. 2018; Amores et. 2018
Le Sommer et al. in prep; Buckingham et al sub;
Ajayi et al. sub.



Code + namelists : `https://doi.org/10.5281/zenodo.1210116`

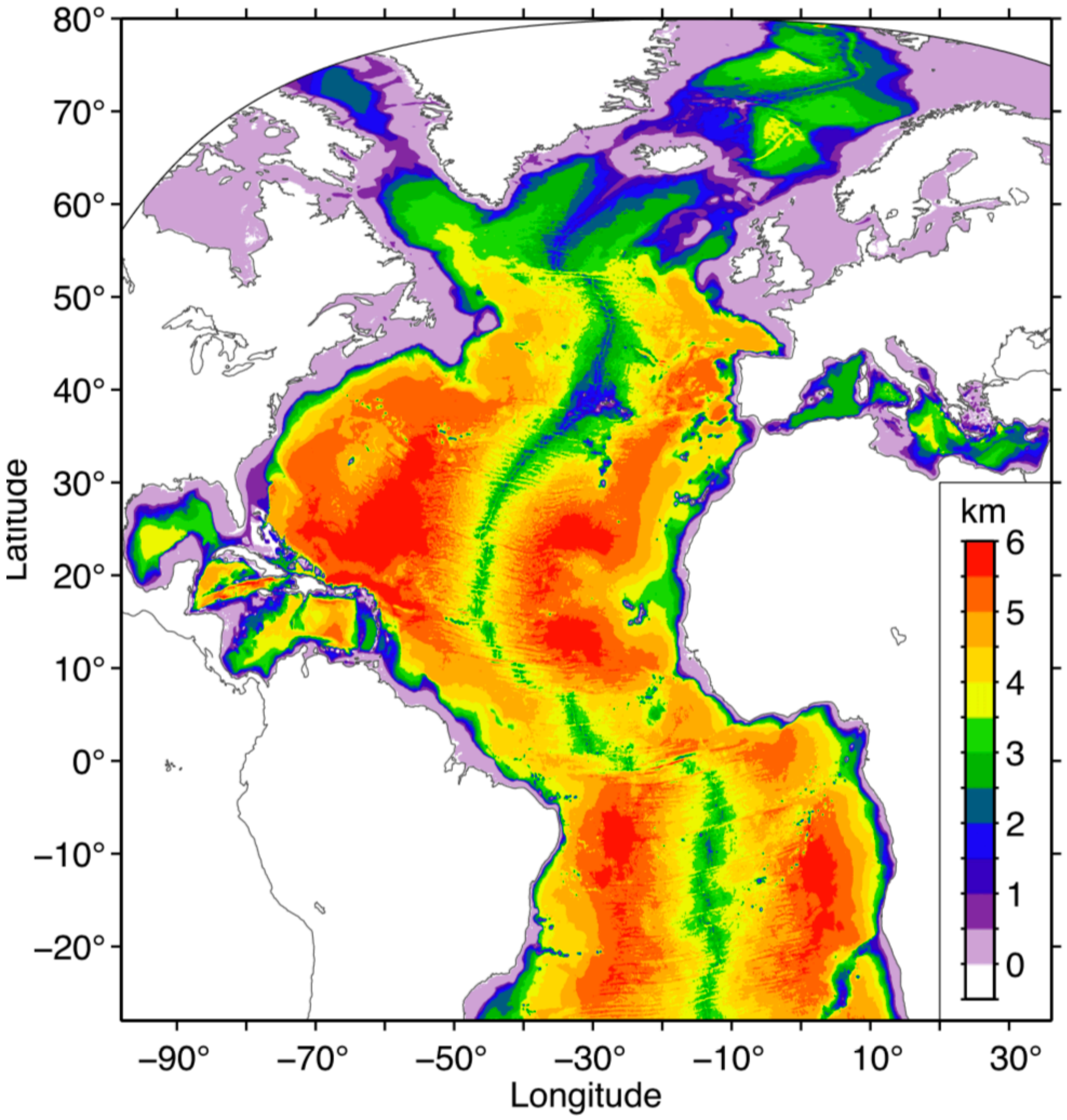
HYCOM50 experiment

domain	28°S-80°N
Horizontal resolution	1/50°(1.1km-2.2km)
Vertical grid	32 levels (iso)
Vertical coordinate	hybrid/iso
Integration period	20 years
Atmos forcing	ERA-40
SSS restoring	15m / 30 days
Boundary conditions	GDEM

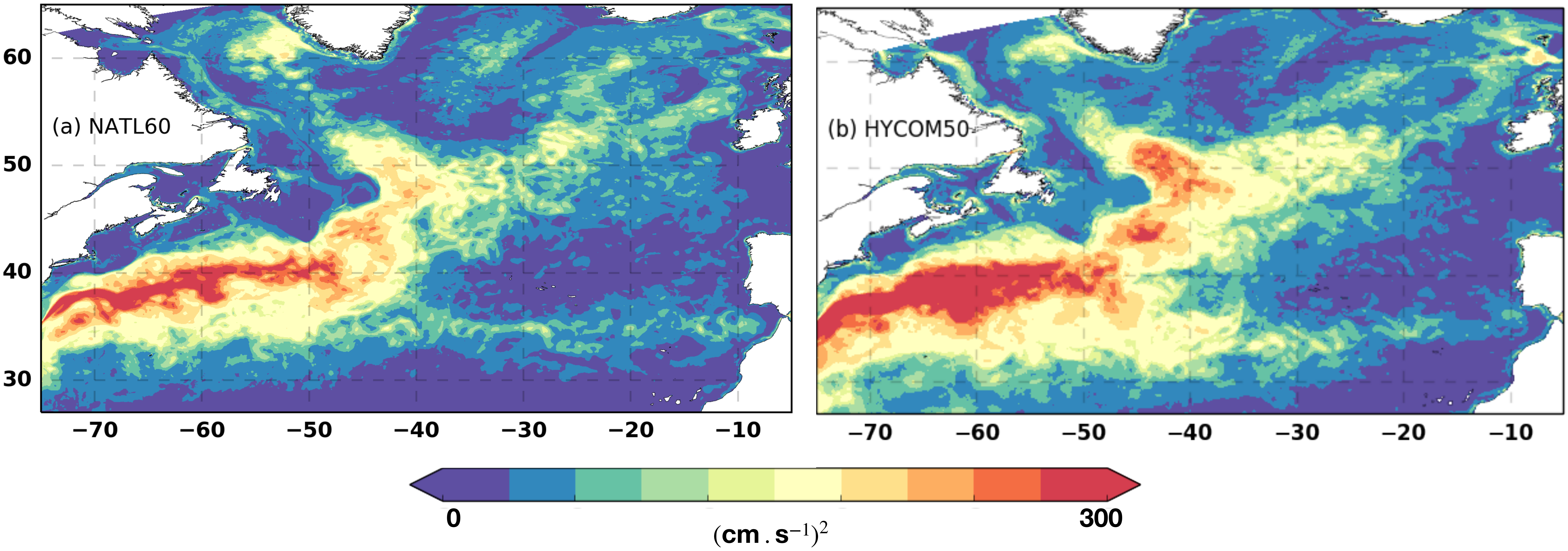
Vertical physics	KPP
Lateral BC	no-slip
Lateral closures	Biharmonic + Laplacian

Effective resolution : ~10-15km

Described and assessed in detail in Chassignet and Xu 2017



Comparison of surface eddy kinetic energy



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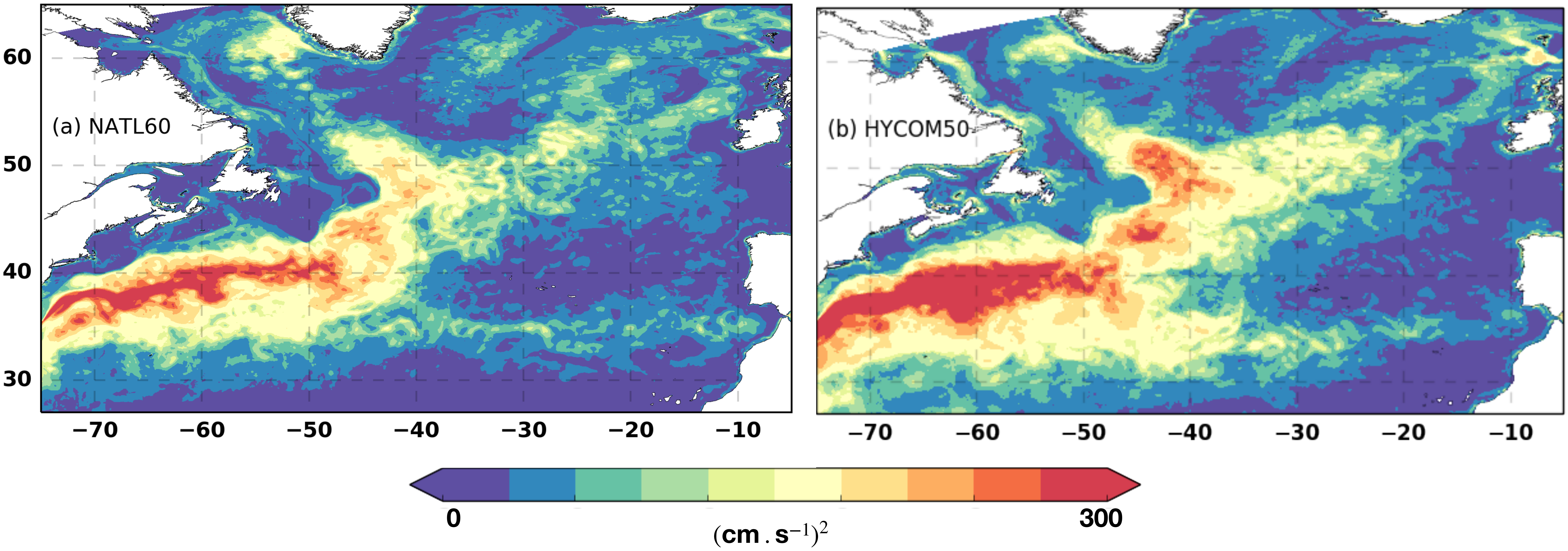

The two models show "realistic" levels of eddy variability (HYCOM50 more energetic)

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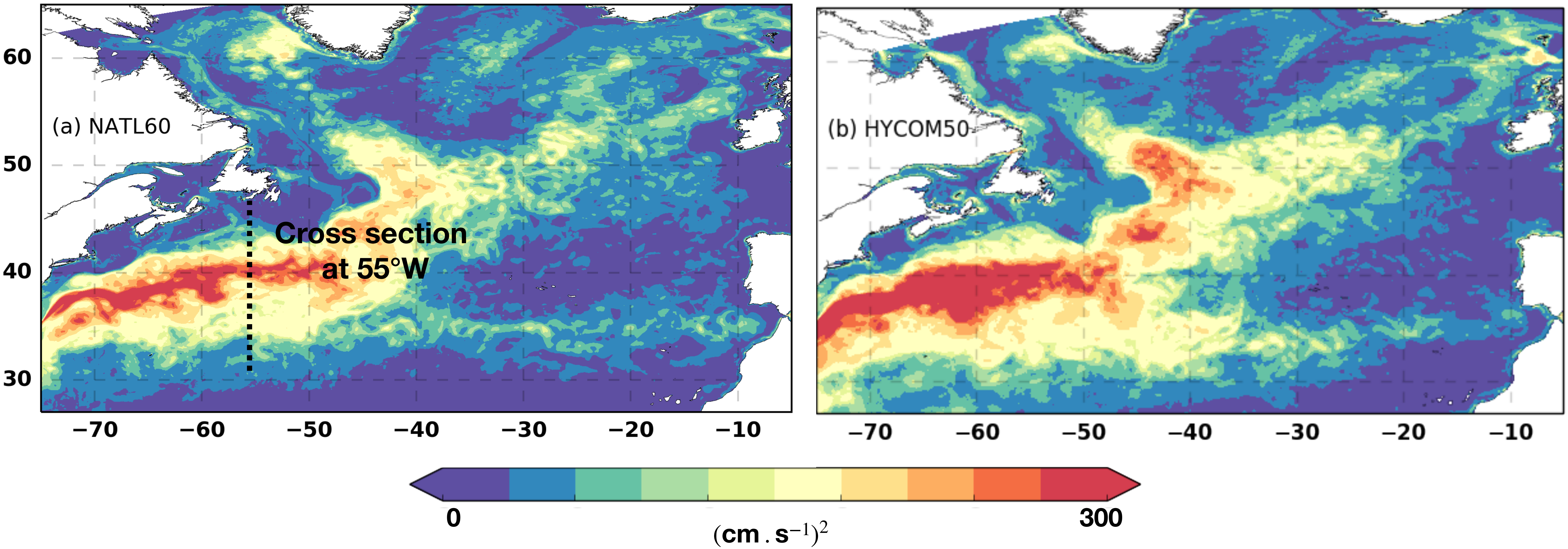

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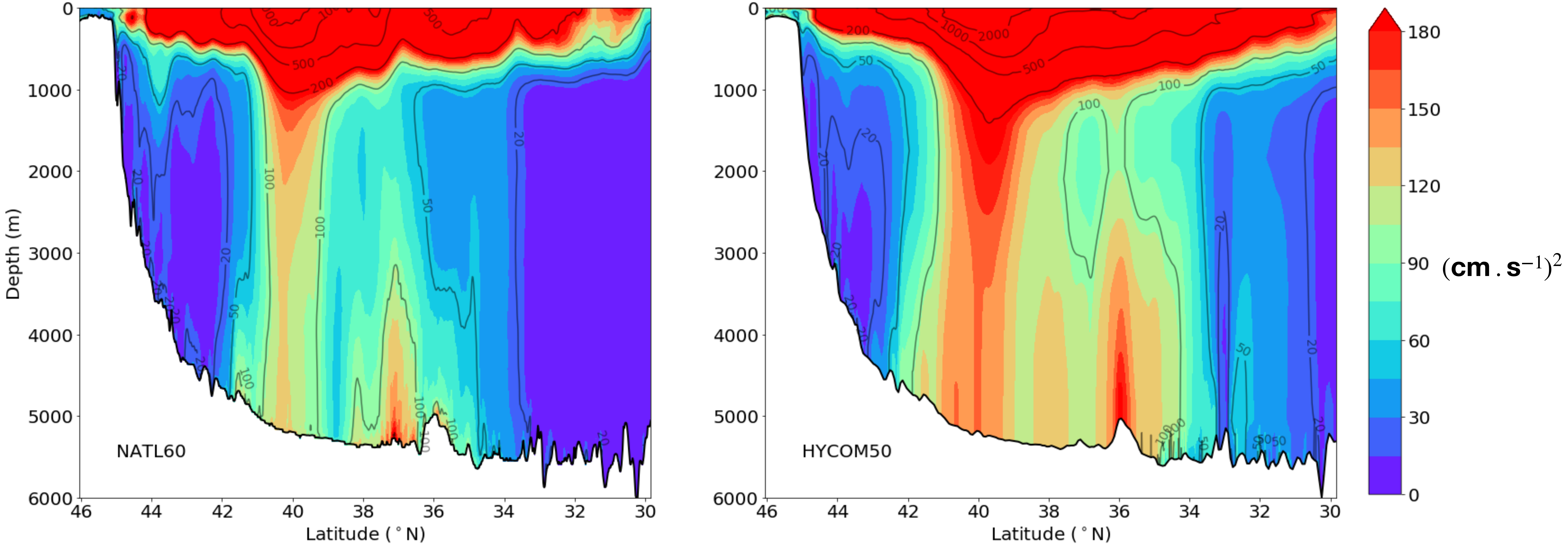
Model datasets : NATL60 and HYCOM50 (4/6)

Eddy kinetic energy cross section at 55°W



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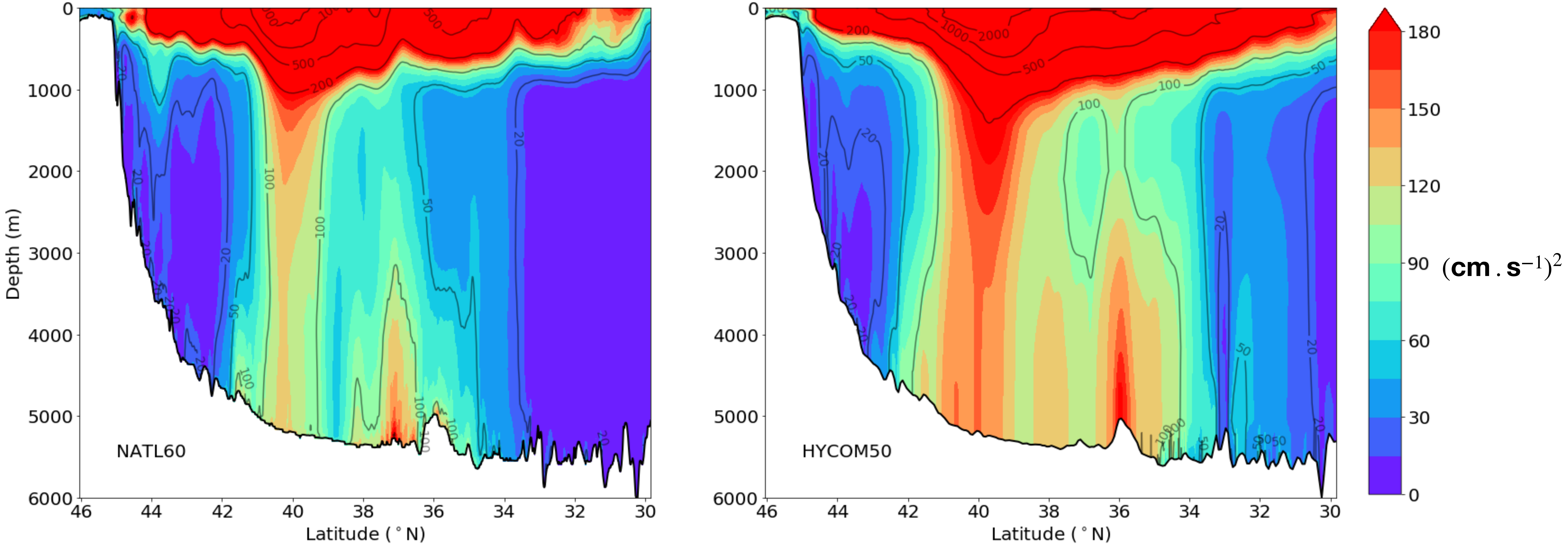
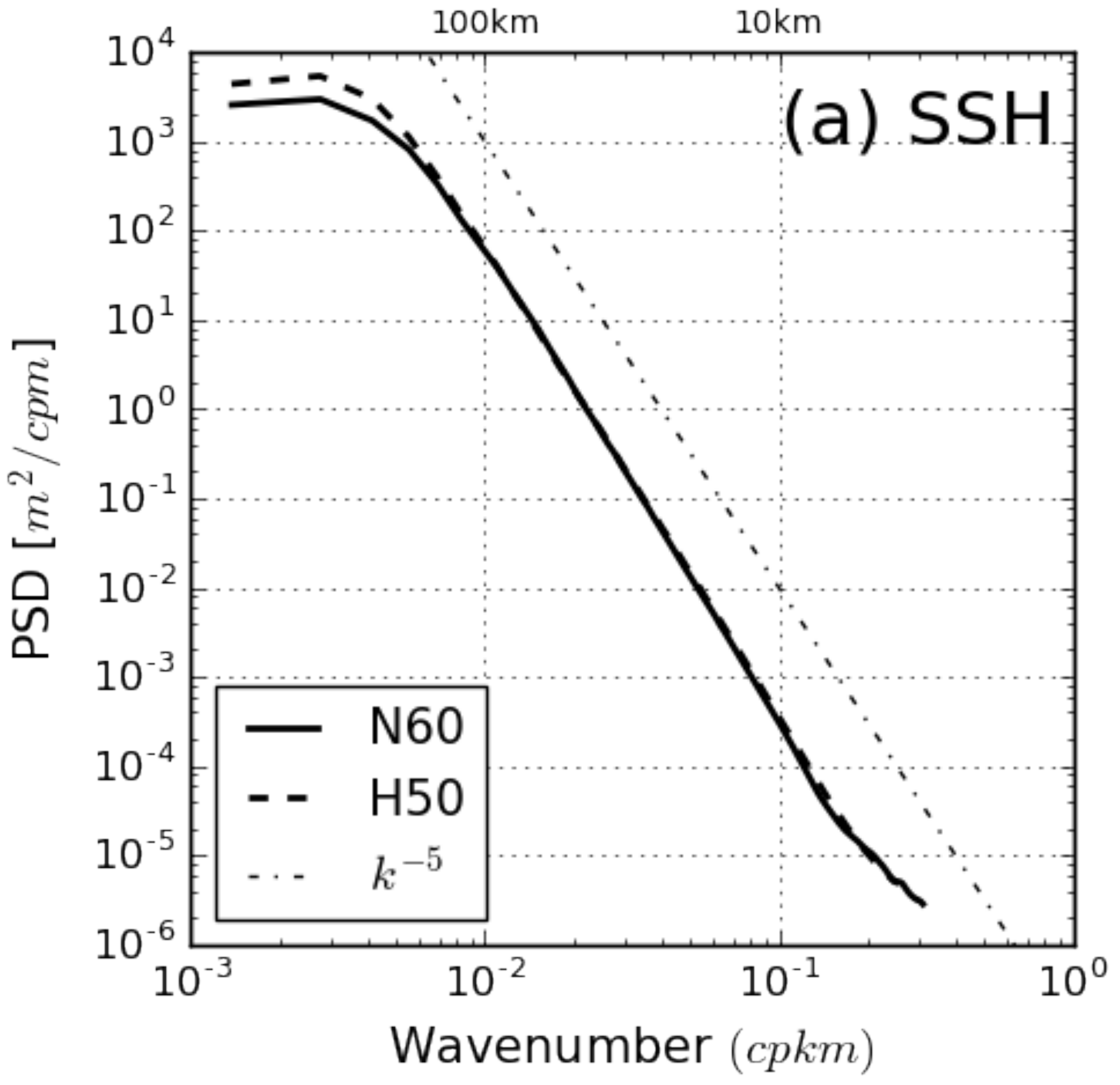
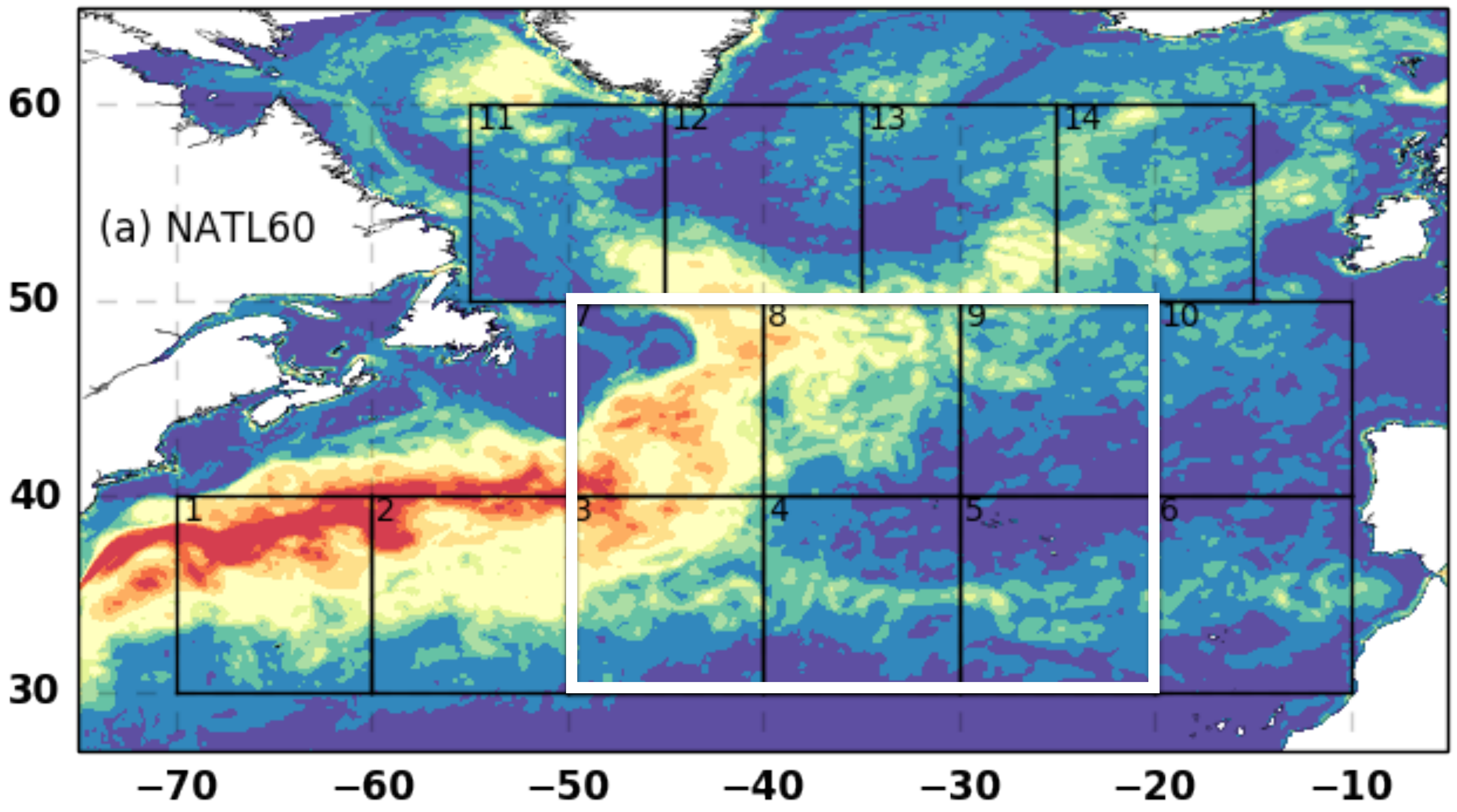


The two models show deep penetration of eddy kinetic energy (with differences)

Comparaison of surface wavenumber spectra





Model datasets : NATL60 and HYCOM50 (5/6)

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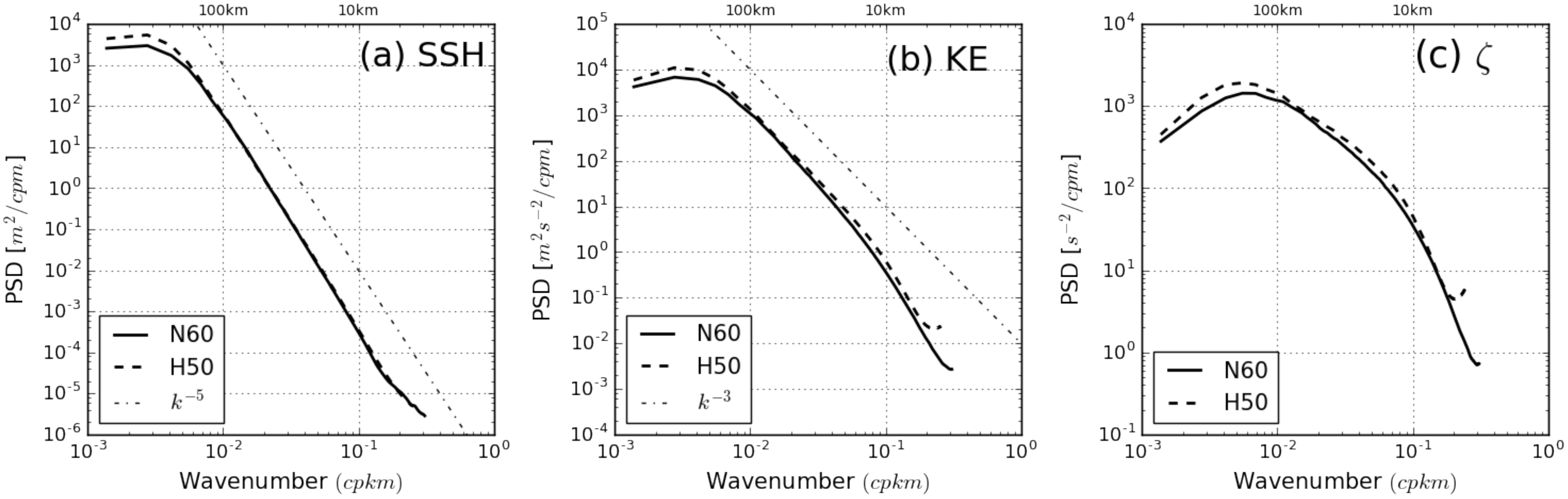

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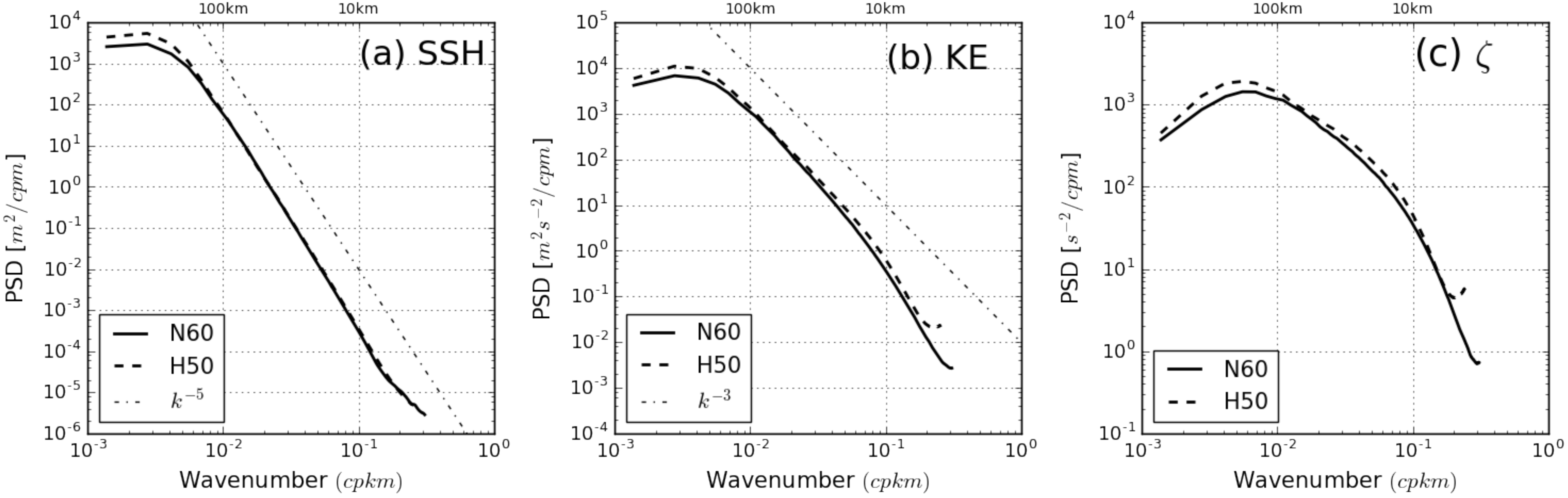
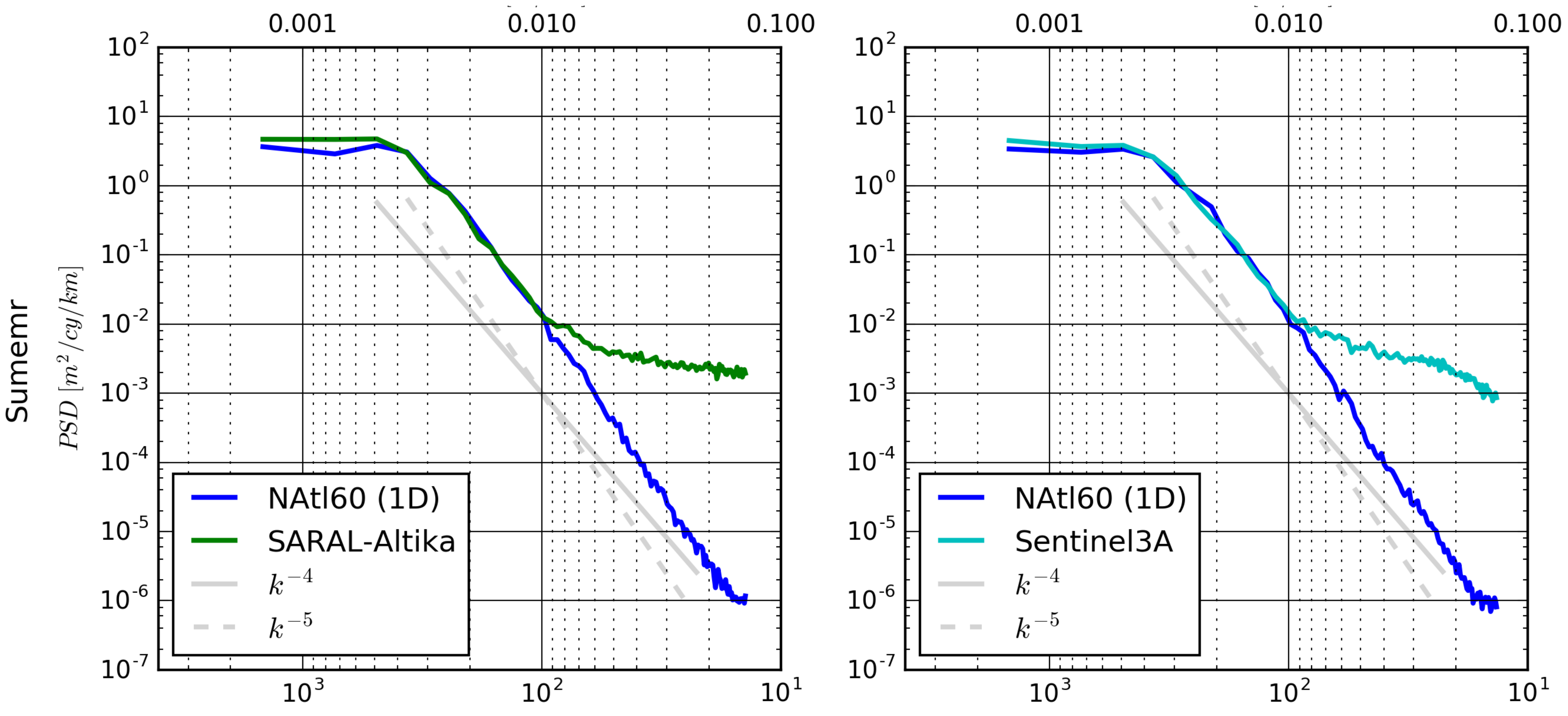


Good agreement of the two models in terms of surface wavenumber spectra

Assessment of surface wavenumber spectra



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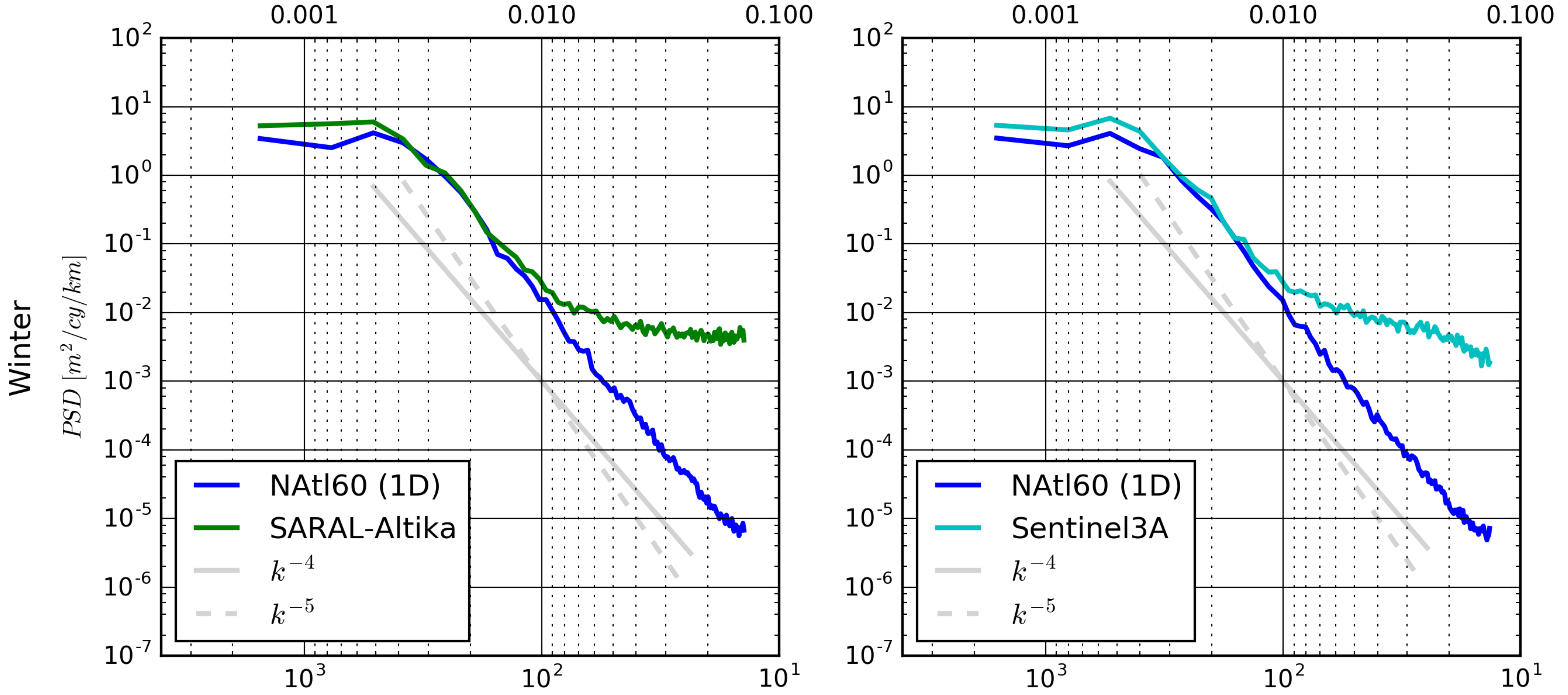

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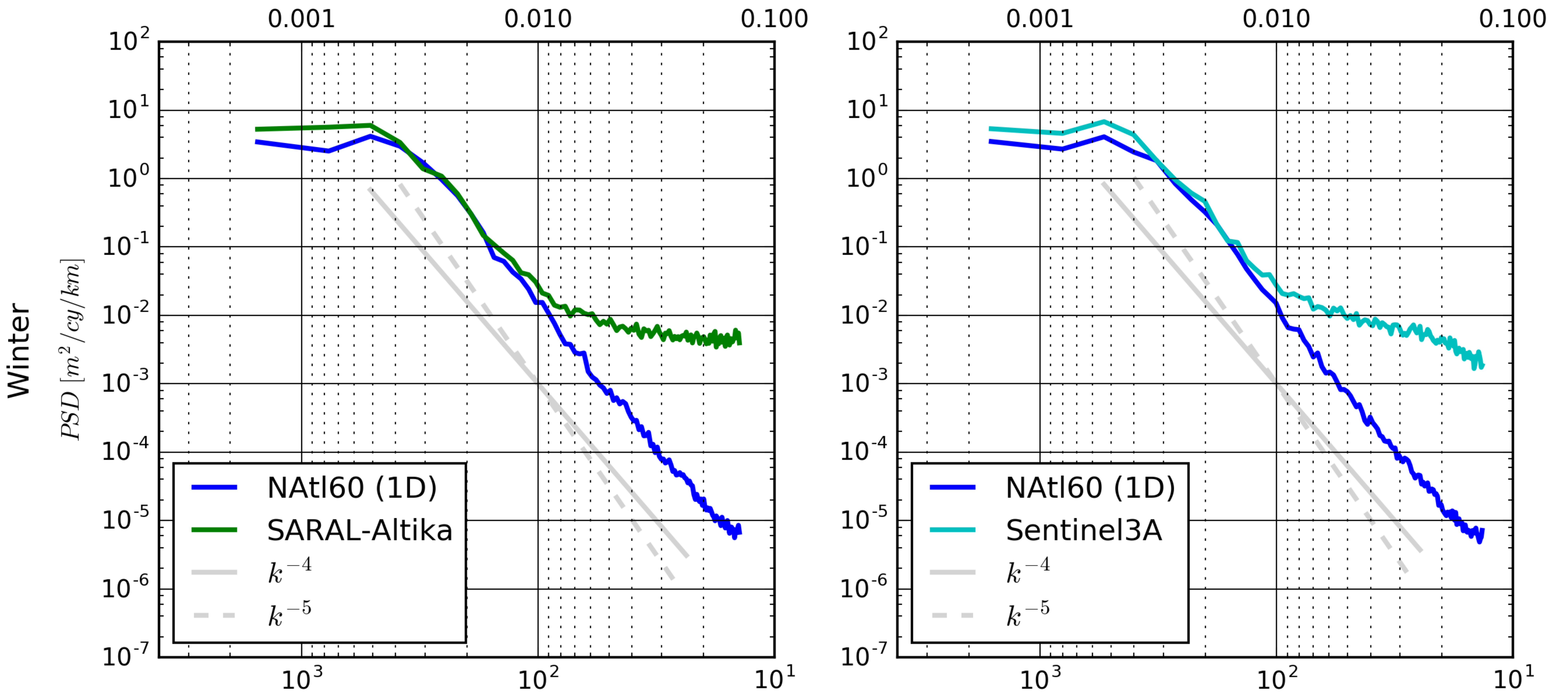

Good agreement of NATL60 with current altimeters in both winter and summer

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4. Kinetic energy spectral flux though nonlinear advection
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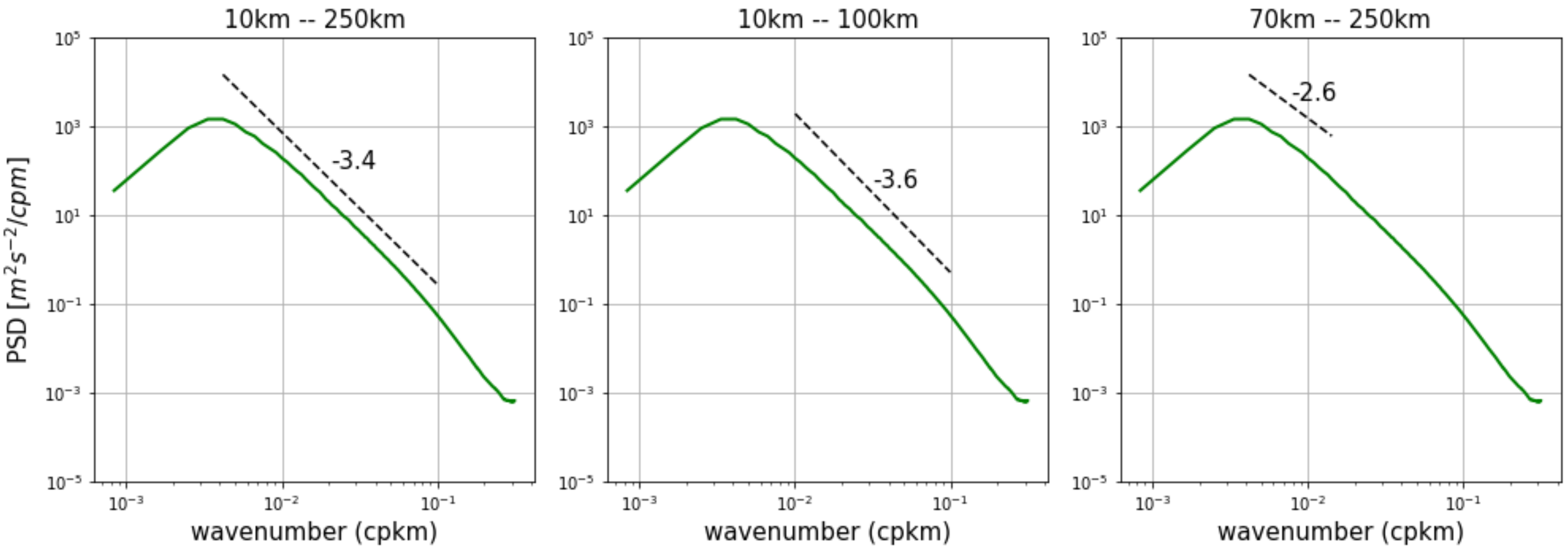
Slopes of kinetic energy wavenumber spectra (1/4)



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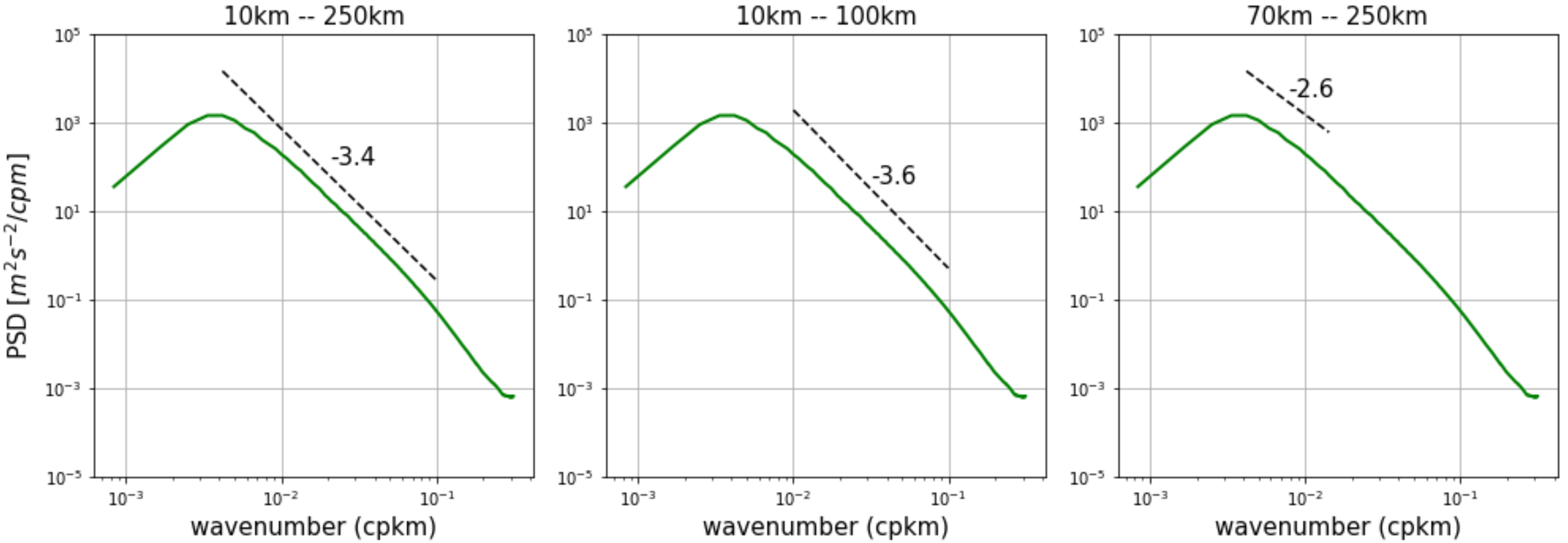
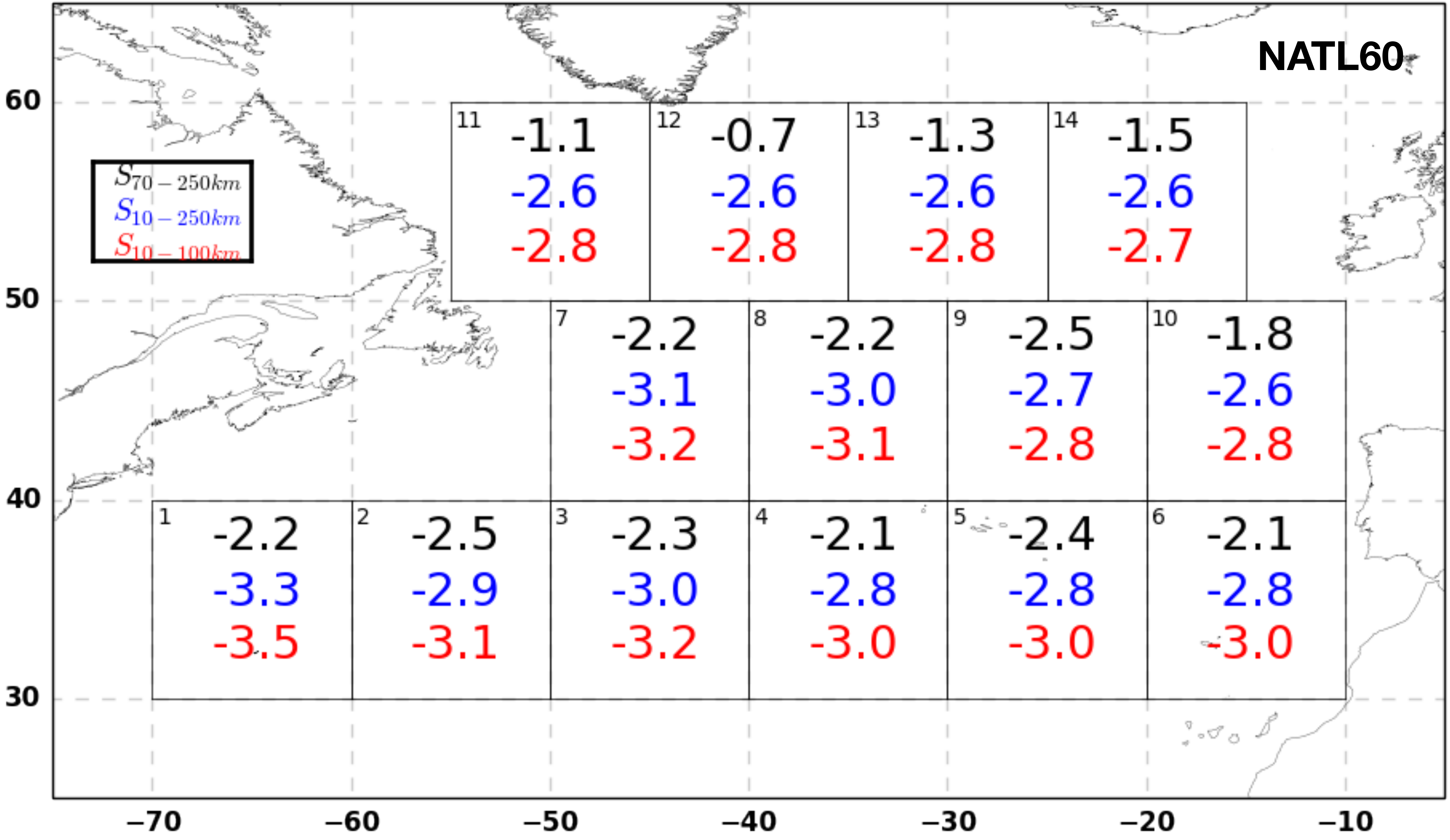
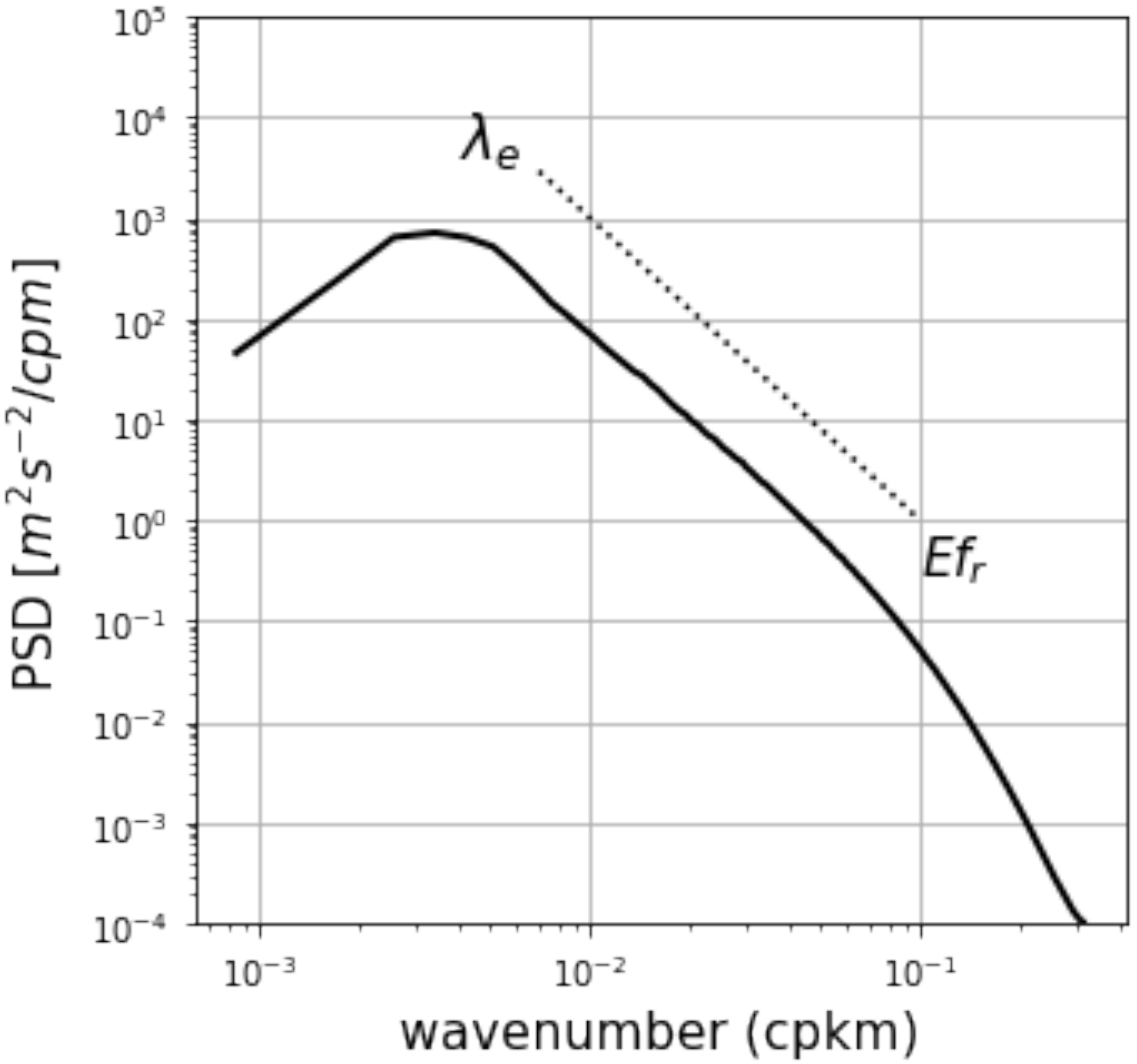


Large sensitivity of diagnosed slopes to the range of scales considered

Slopes of kinetic energy wavenumber spectra (2/4)



Slopes of kinetic energy wavenumber spectra (3/4)

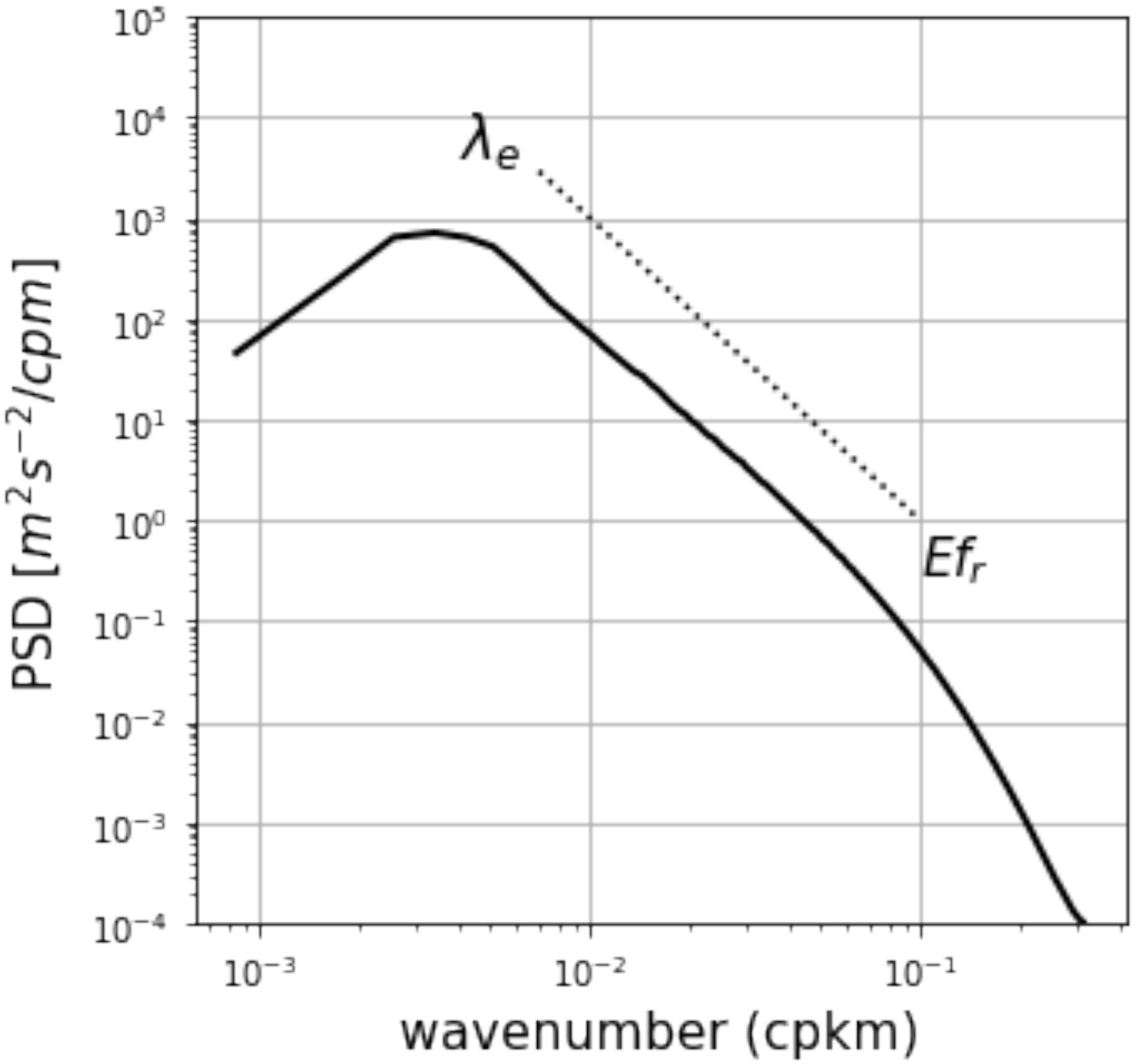


Kinetic energy integral scale

$$\lambda_e = \frac{\int\int E(k,l)dkdl}{\int\int \sqrt{k^2+l^2}E(k,l)dkdl}$$

Model effective resolution

based on Soufflet et al. 2016, 5-10 times dx



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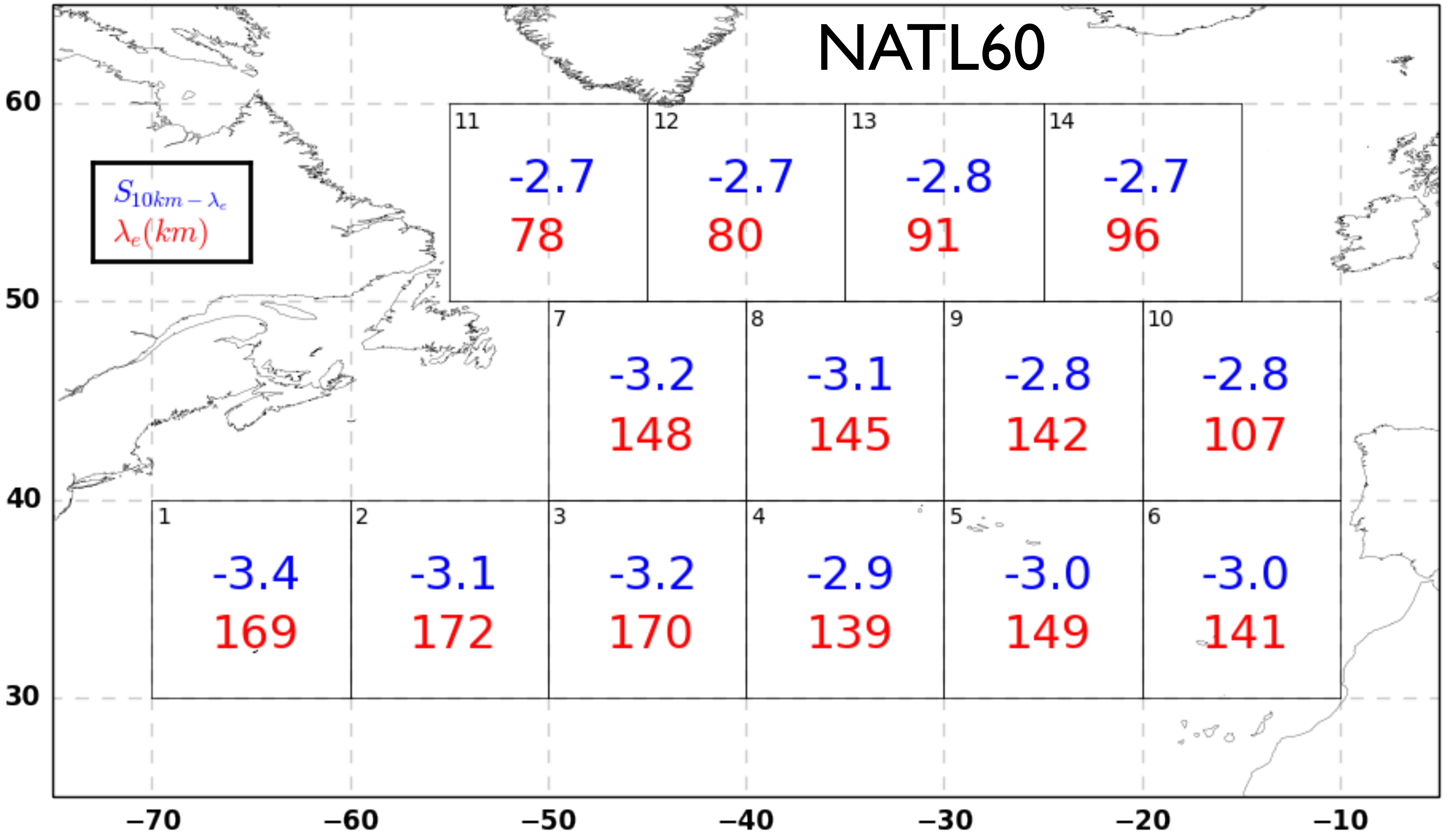
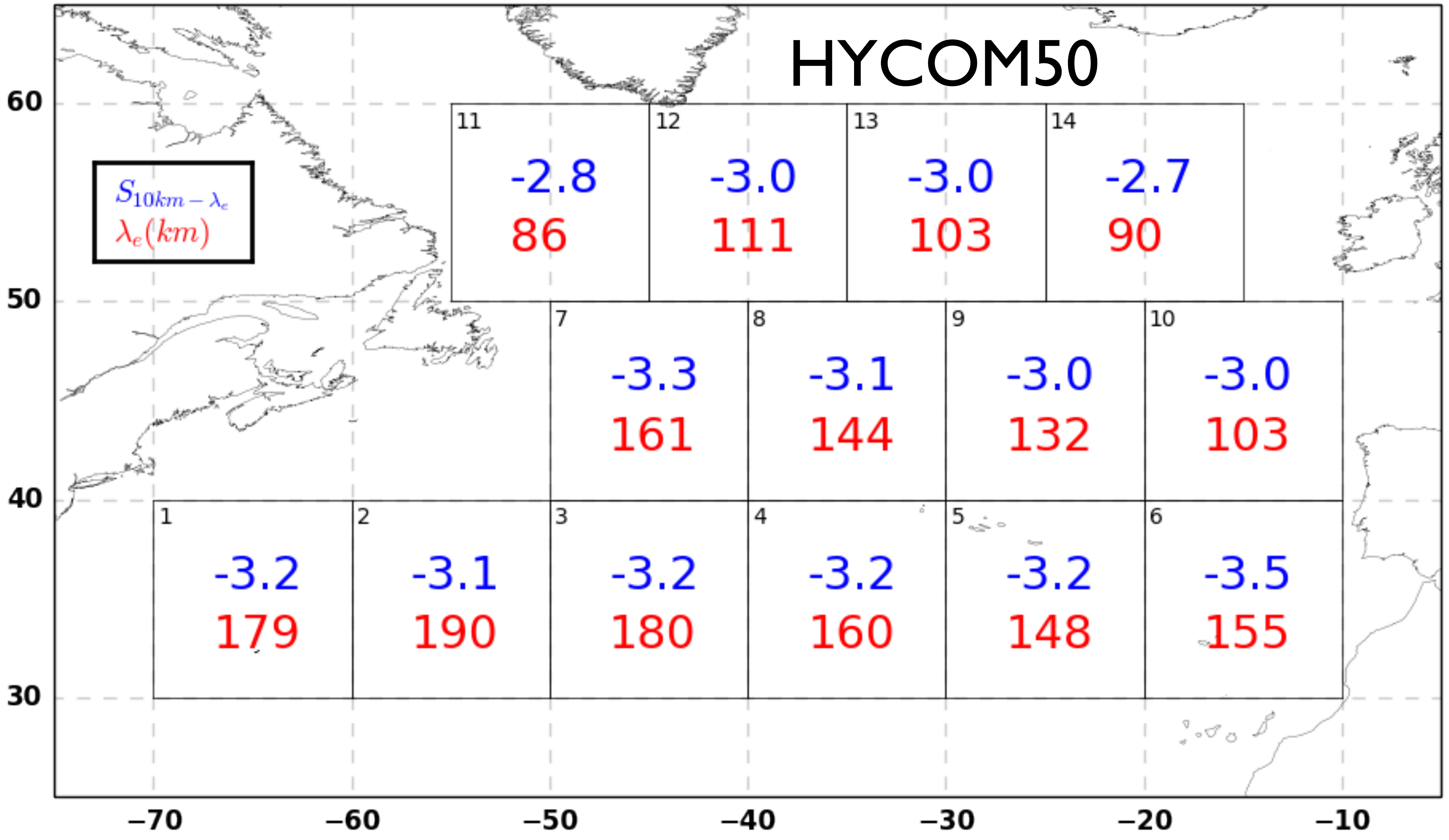
Dynamically based definition of the mesoscale inertial range
(see also Vergara et al. 2019)

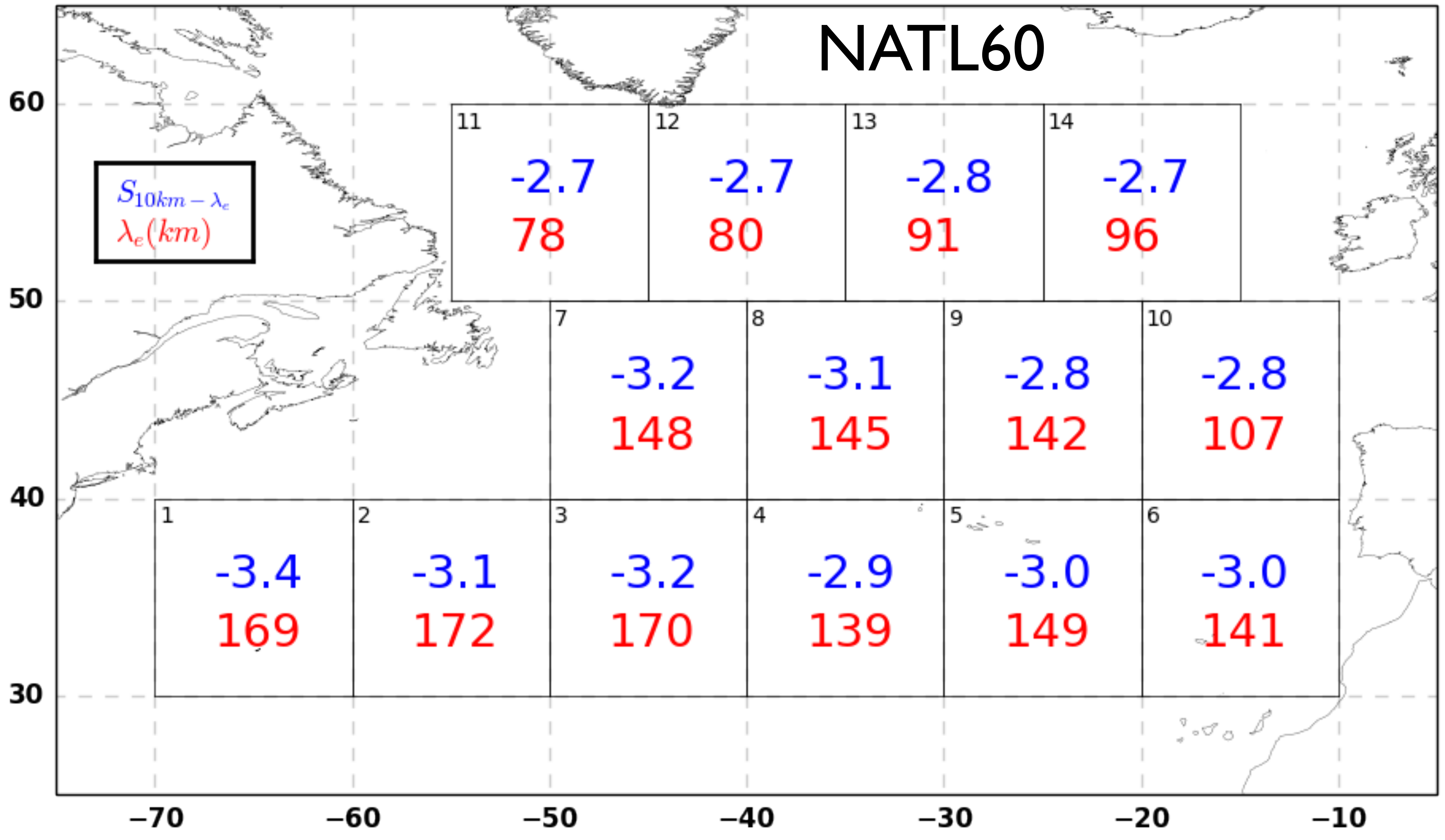
Slope of kinetic energy spectra in the mesoscale inertial range

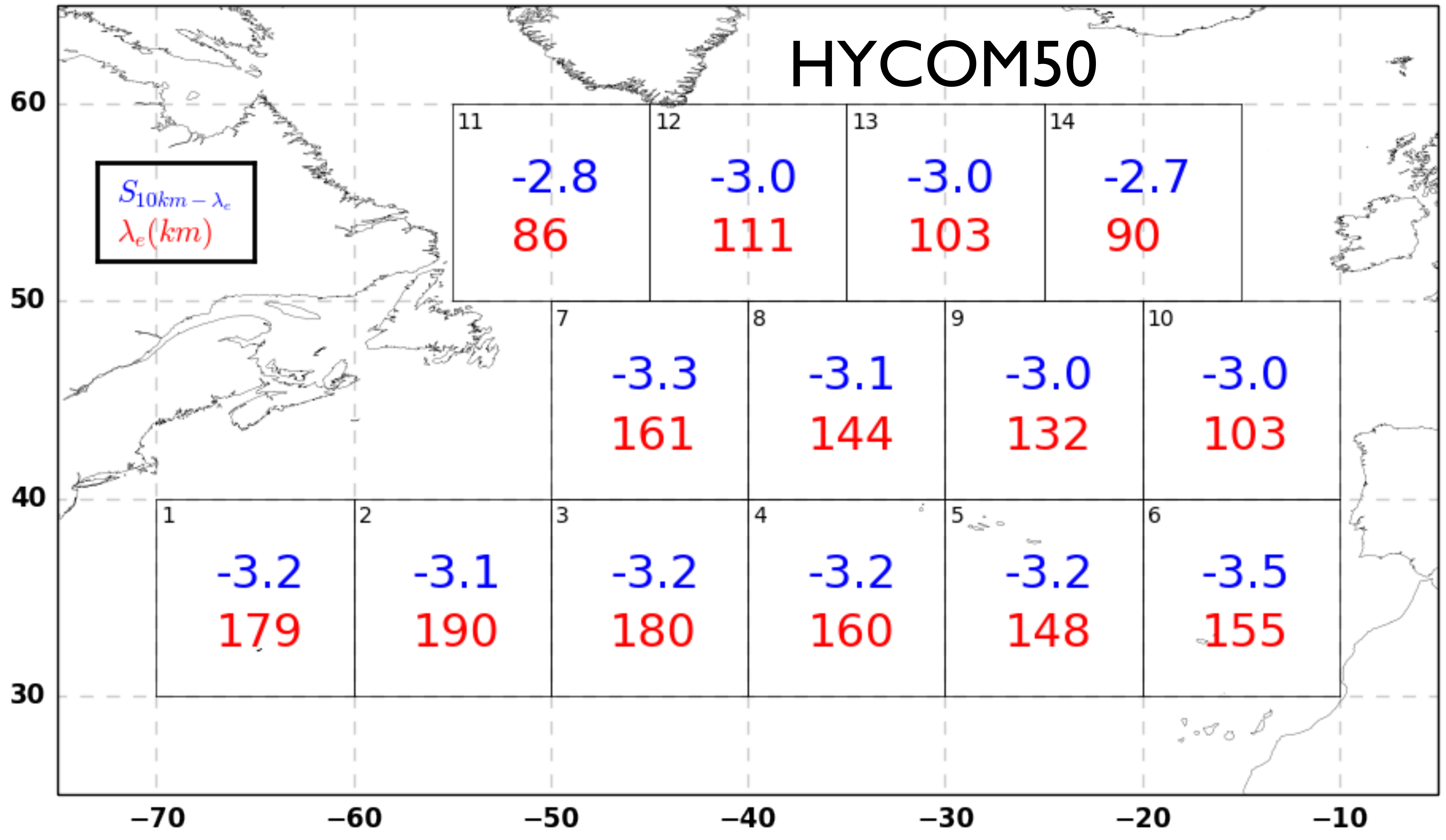




Slopes of kinetic energy wavenumber spectra (4/4)

Slope of kinetic energy spectra in the mesoscale inertial range





As expected the integral scale varies with latitude (following the Rossby radius)

More surprisingly, KE spectral <u>slopes follow QG predictions</u> in both models

This is true in both high and low EKE regions

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2. Model datasets : NATL60 and HYCOM50
3. Slopes of kinetic energy wavenumber spectra
4. **Kinetic energy spectral flux though nonlinear advection**
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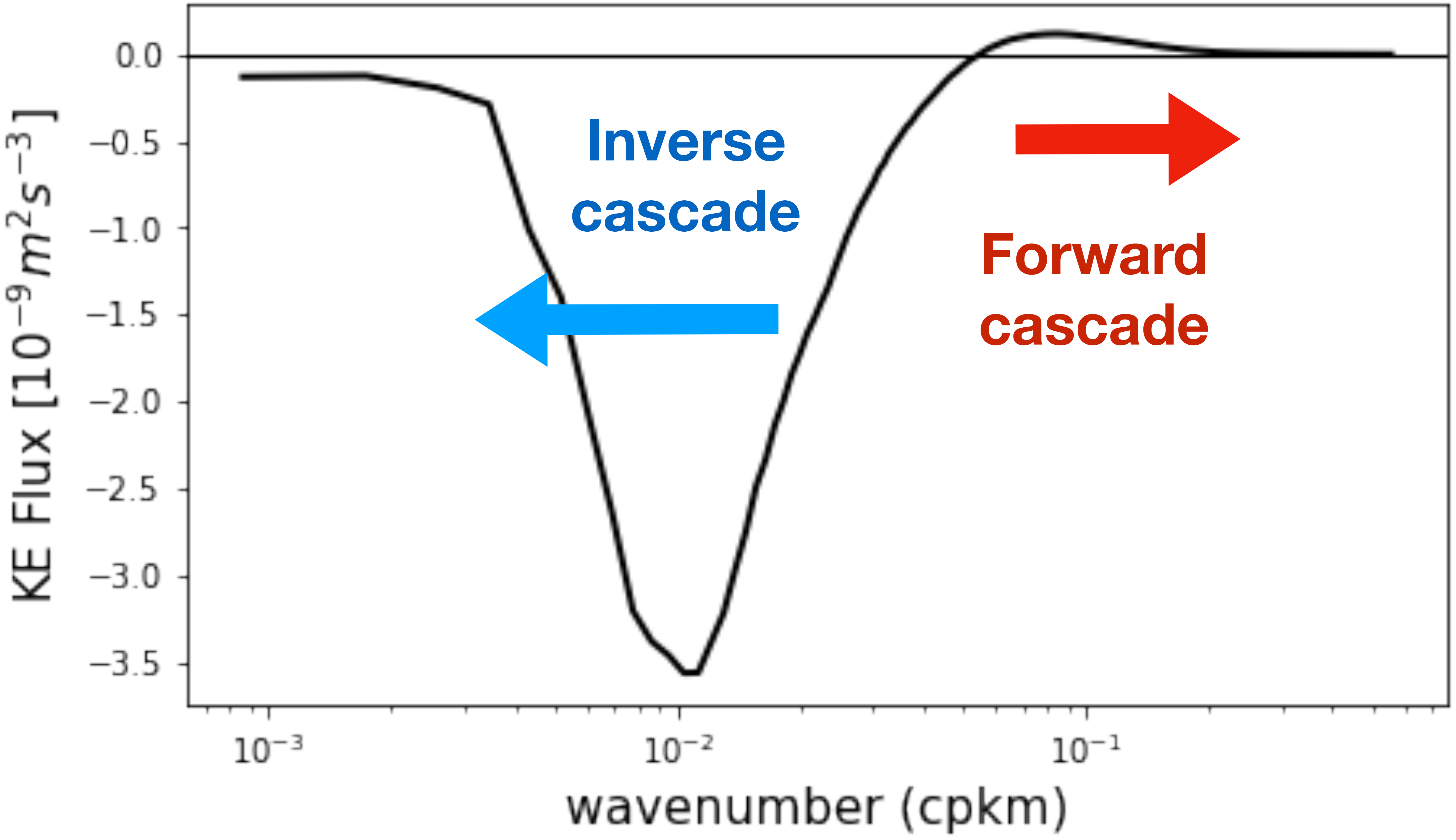
Kinetic energy spectral flux though nonlinear advection (1/4)

Diagnosing kinetic energy exchanges



$$\Pi_A(k) = \int_k^{k_s} -\mathrm{Re}\left[\widehat{\mathbf{u}}^* \cdot \left(\widehat{\mathbf{u} \cdot \nabla_H \mathbf{u}}\right)\right](k)\, dk,$$

following Capet et al. 2008, and many others

Caveats of this approach : see Aluie et al. 2018

Kinetic energy spectral flux though nonlinear advection (2/4)

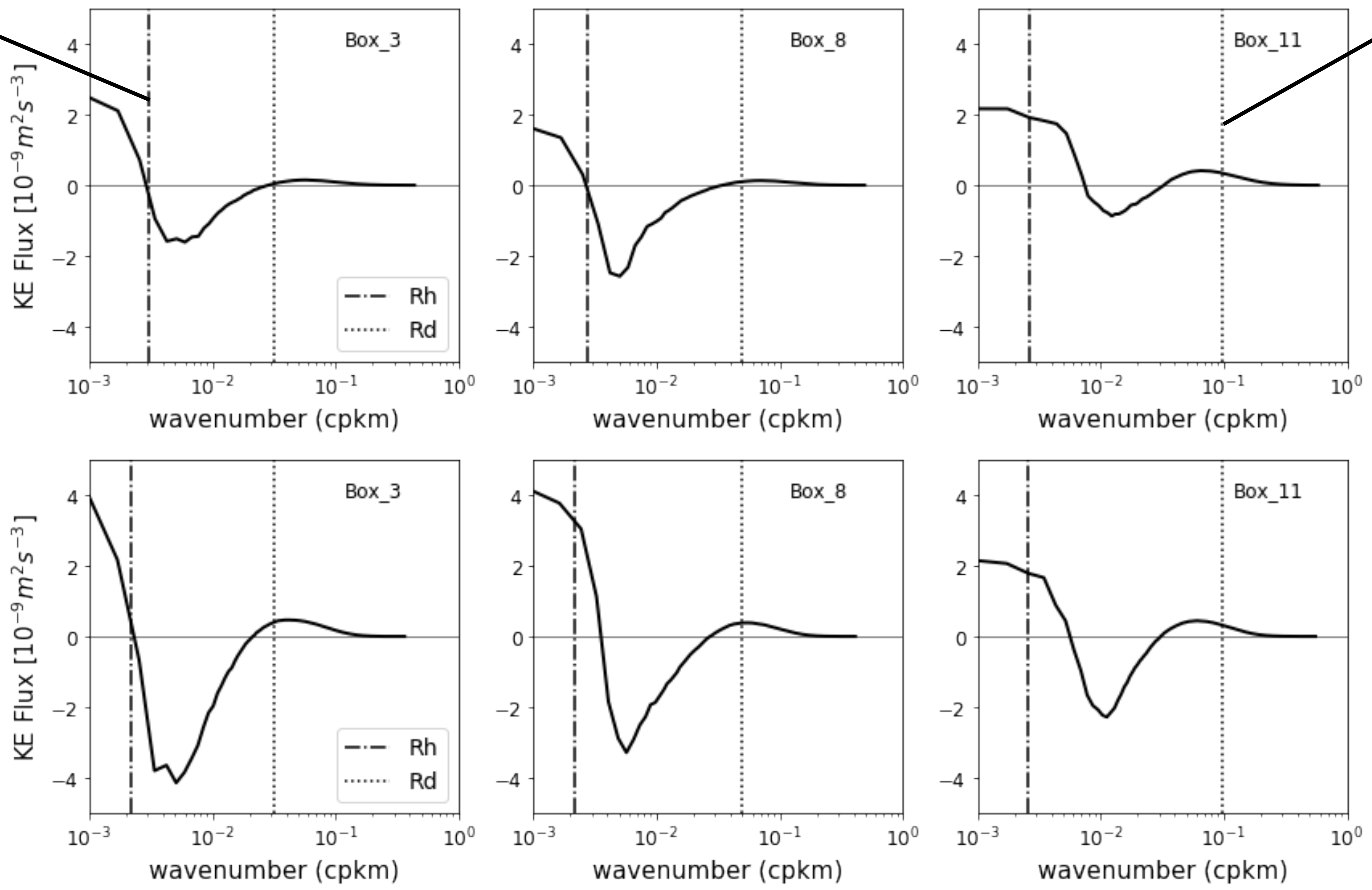
$$L_R = \sqrt{\frac{U_{rms}}{\beta}}$$ Rhines scale

Rossby Radius $$L_D = \sqrt{\frac{C_1}{f}}$$

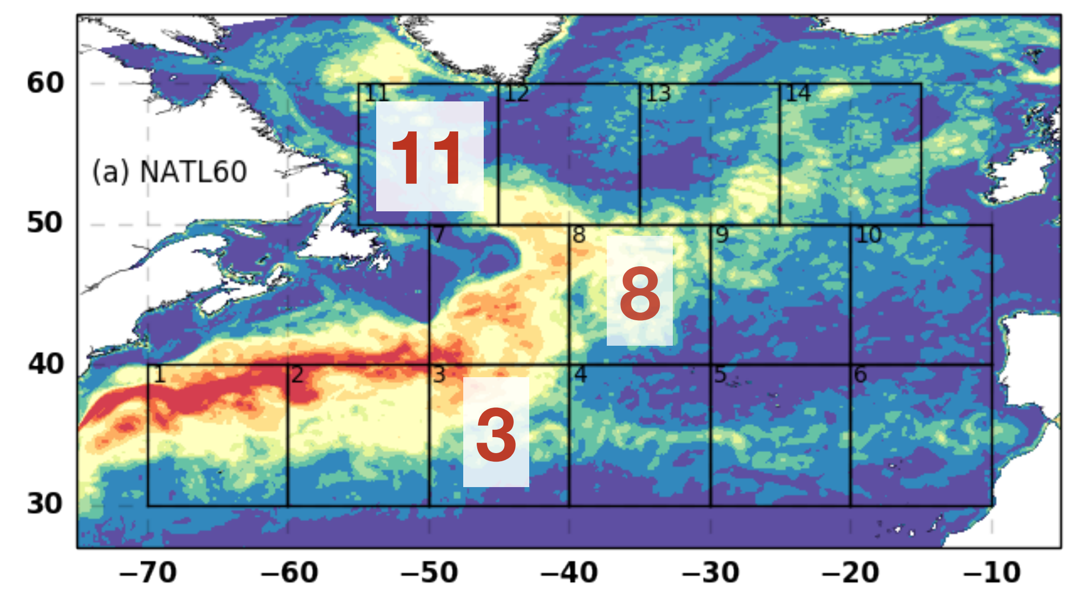
Lat = 35° | Lat = 45° | Lat = 55°

NATL60

HYCOM50



Net annual average



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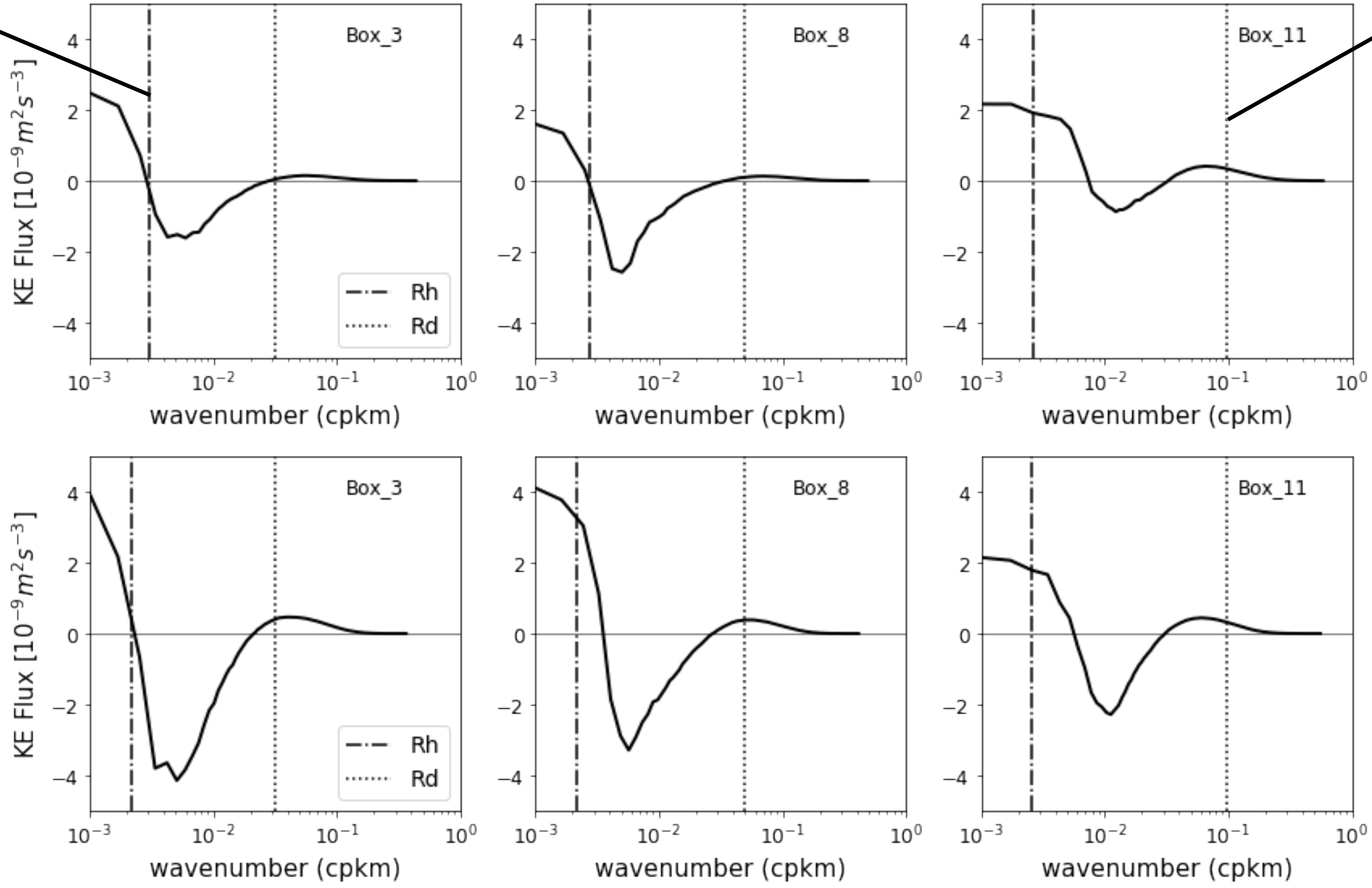

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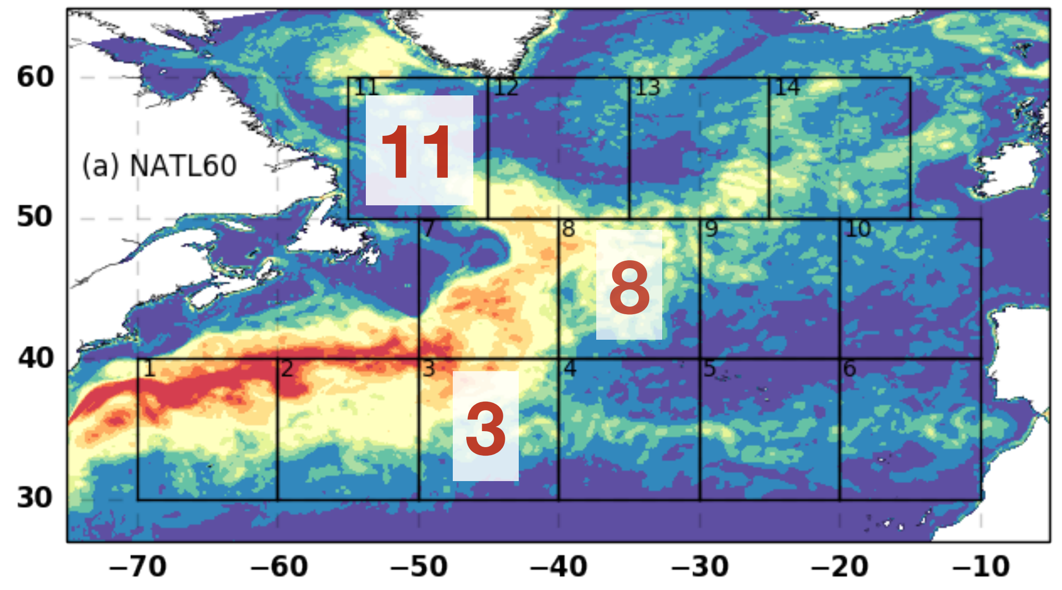

- **Energy is injected at scales close to the Rossby radius (Rd)**
- **Evidence of both inverse (at large scale) and direct energy cascade (at high wavenumber)**
- **Inverse energy cascade is arrested ~Rhine scales (Rh) except in the subpolar region.**

Kinetic energy spectral flux though nonlinear advection (3/4)

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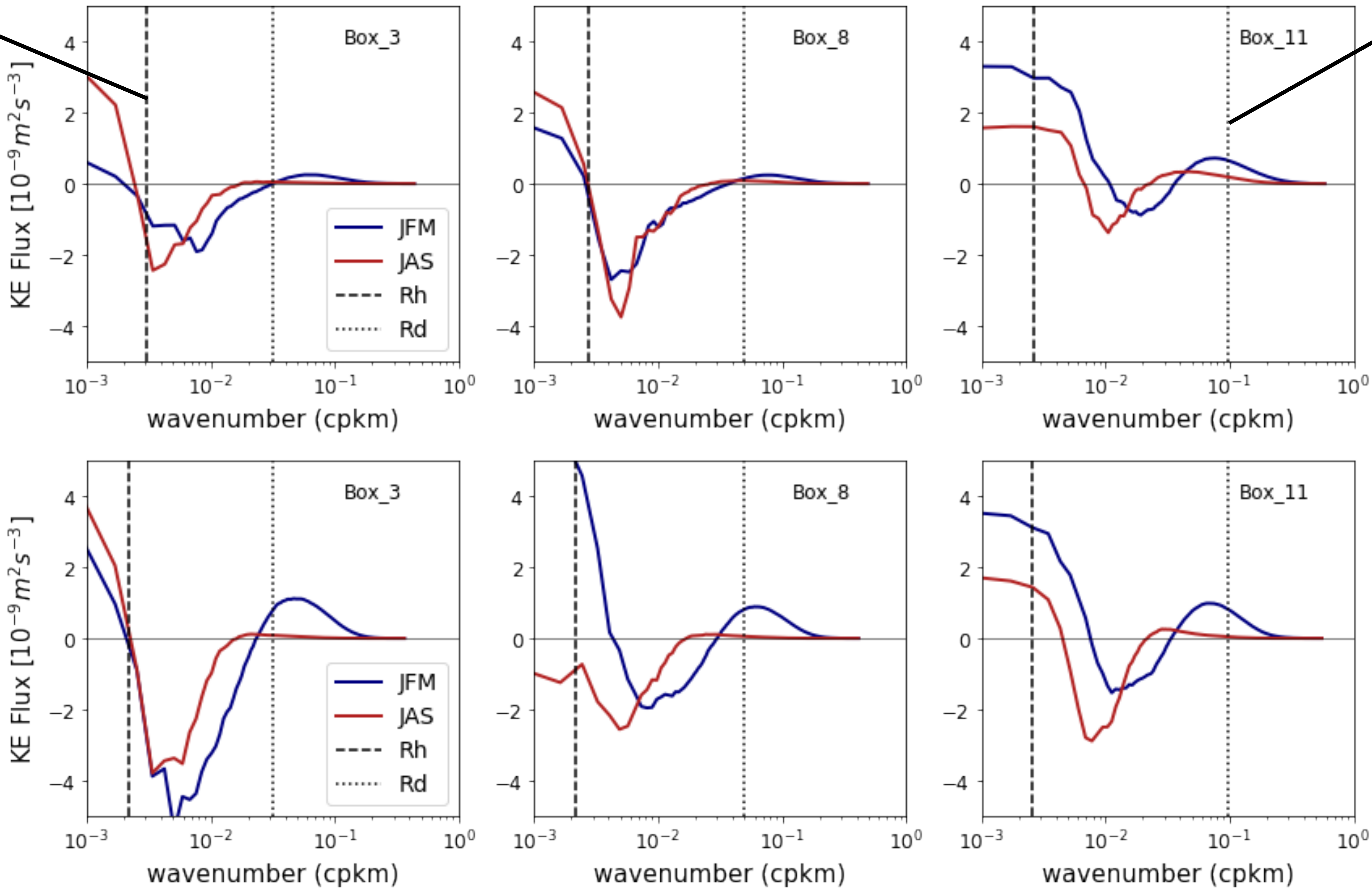
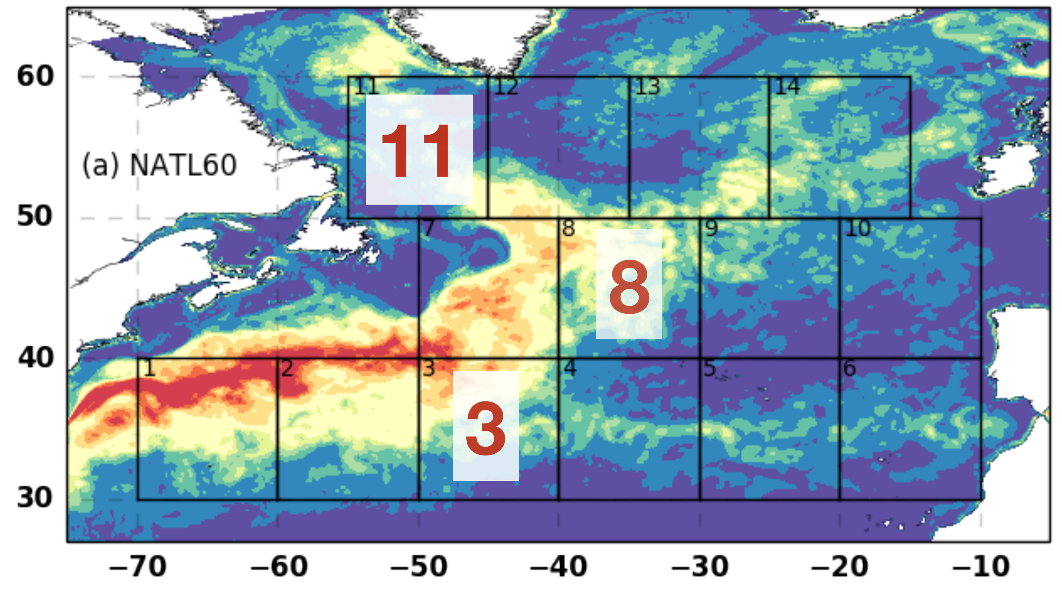


Winter versus **Summer**



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NATL60

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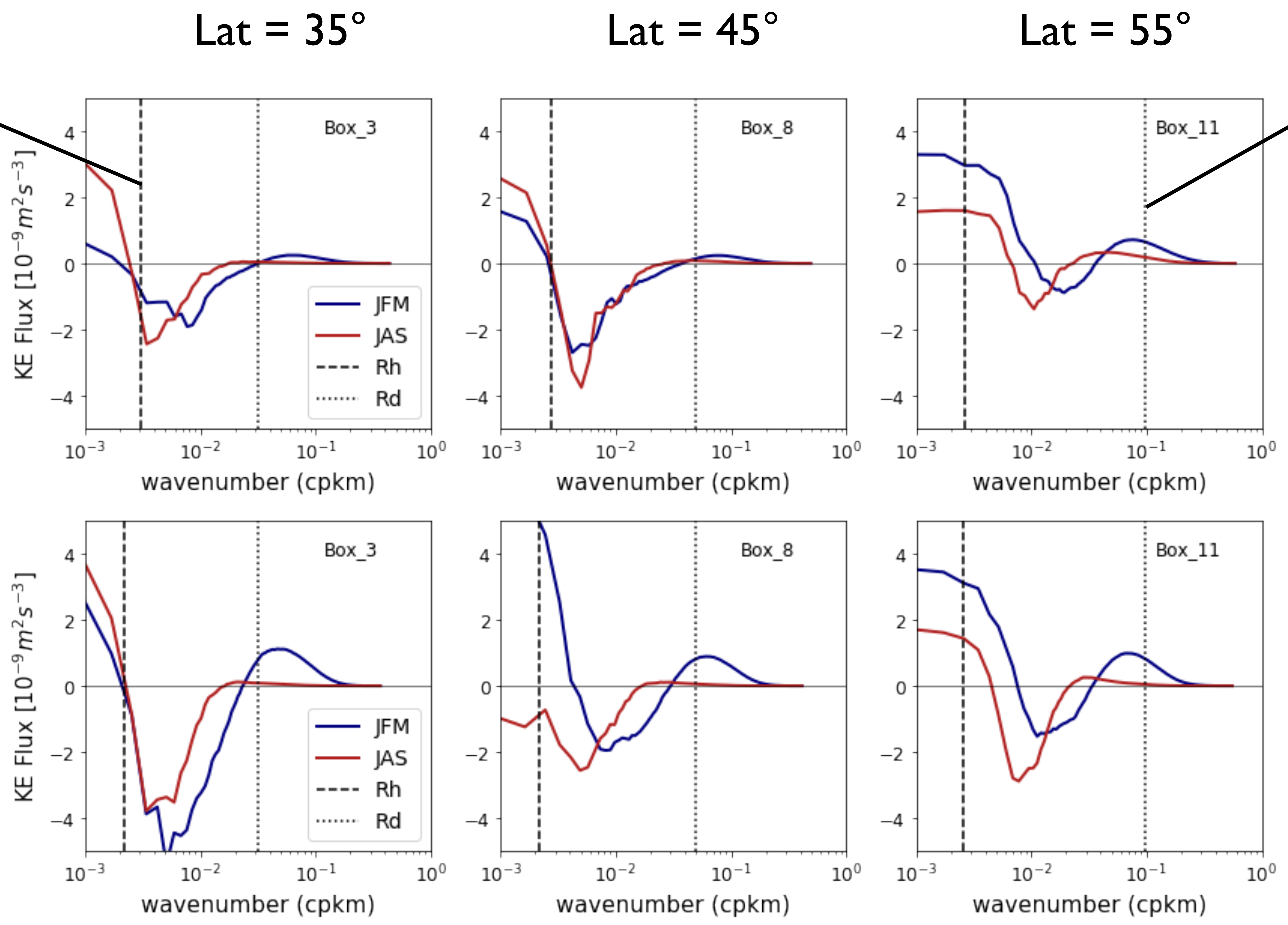

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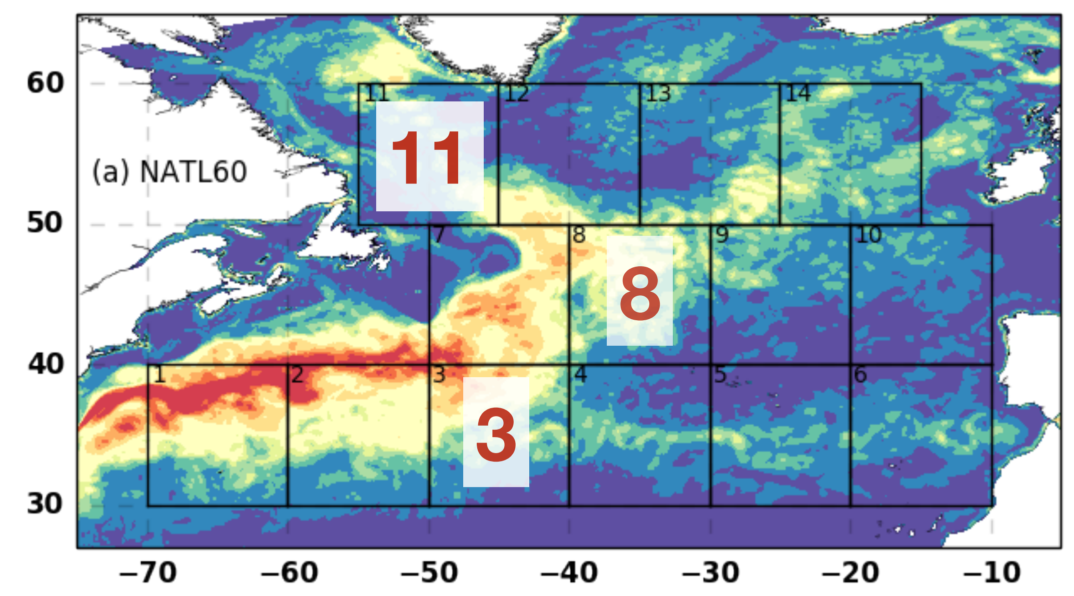

Winter dynamics favours :

- **stronger forward cascade at high wavenumber.**
- **Inverse energy cascade from 25km upward.**

Kinetic energy spectral flux though nonlinear advection (4/4)

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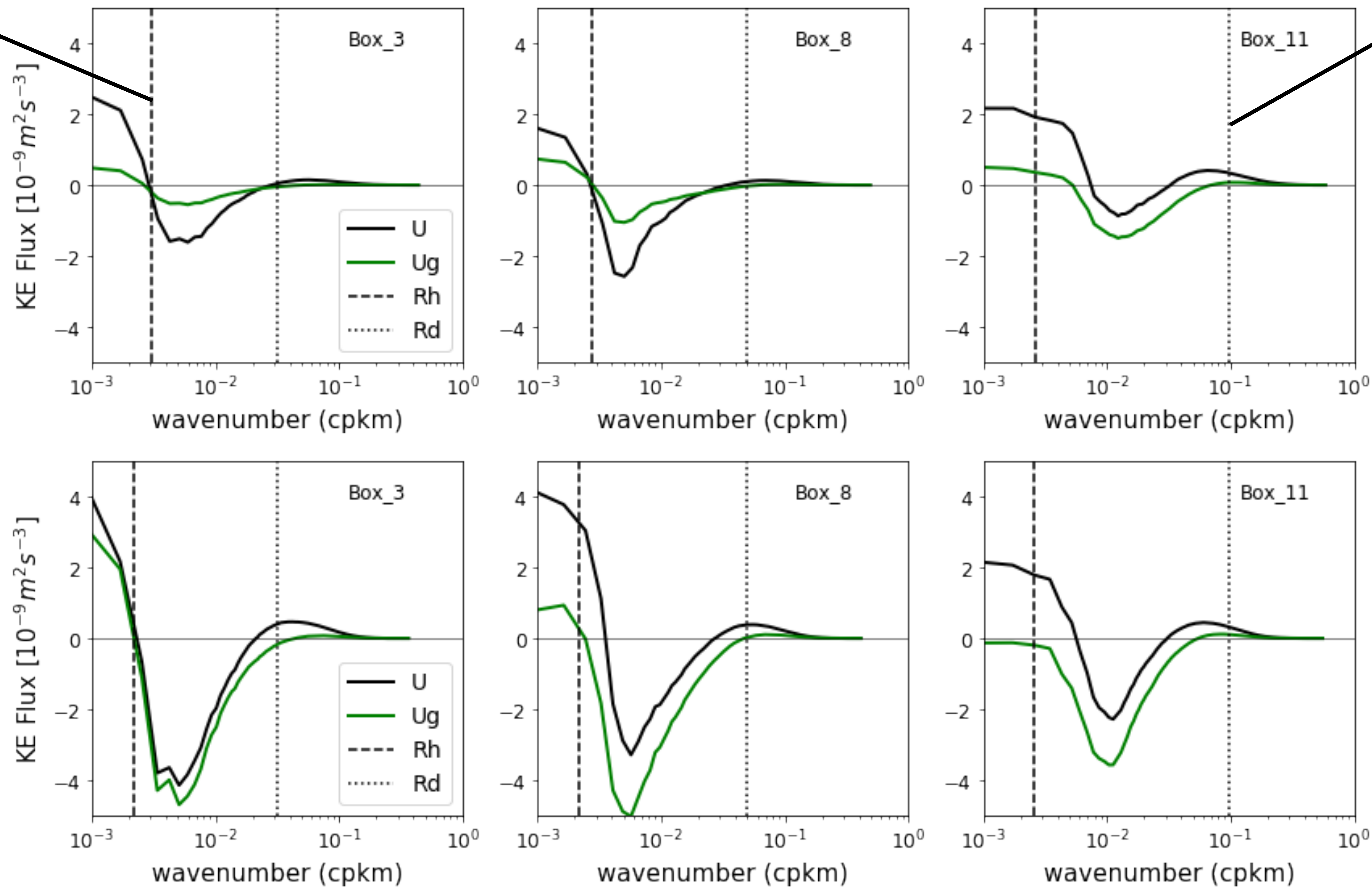
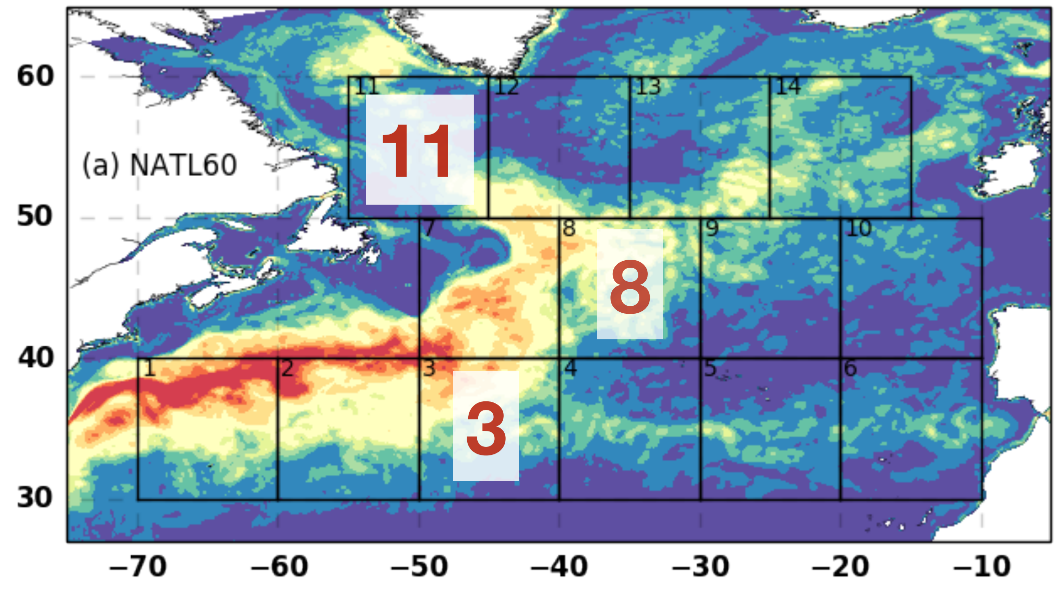
NATL60

HYCOM50



Geostrophic versus **total velocity**



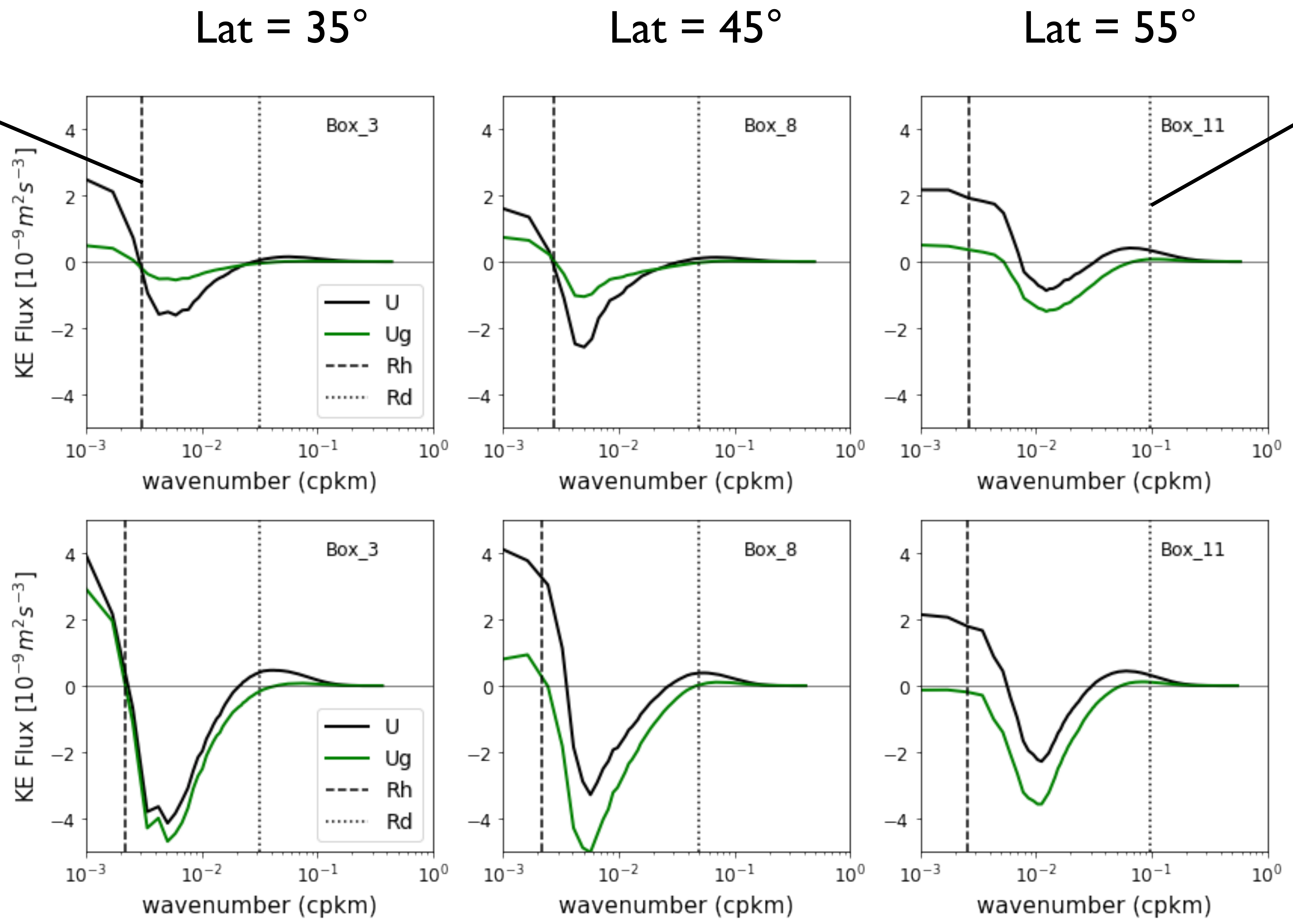
Kinetic energy spectral flux though nonlinear advection (4/4)

$L_R = \sqrt{\frac{U_{rms}}{\beta}}$ Rhines scale

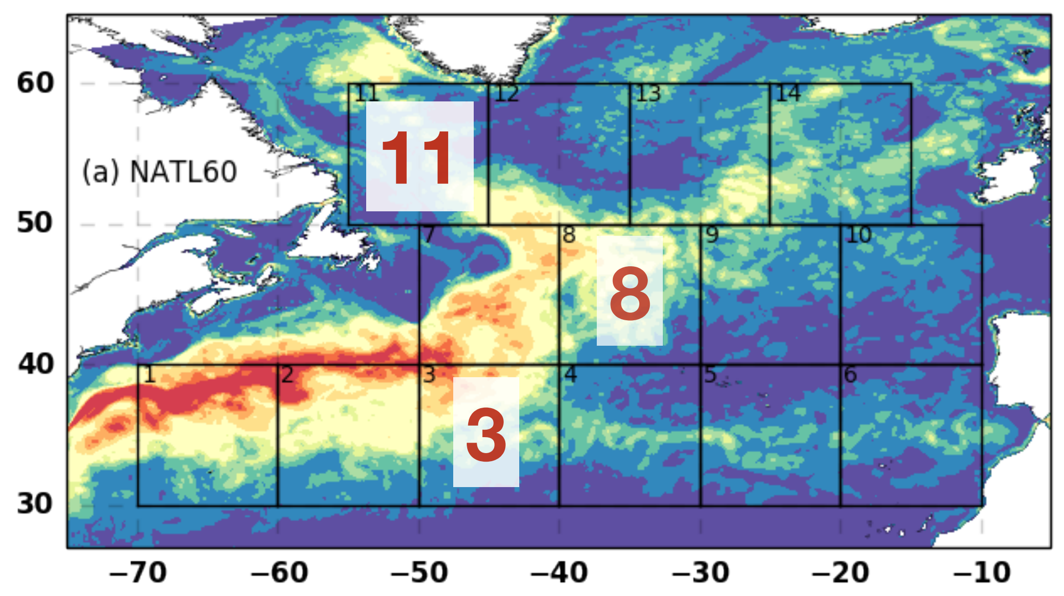
Rossby Radius $L_D = \sqrt{\frac{C_1}{f}}$

NATL60

HYCOM50



Geostrophic versus **total velocity**



- **Forward cascade at high wavenumber is strongly influenced by ageostrophic flow.**
- **KE spectral flux from geostrophic velocity differ from the flux from total velocity**

1. Background and motivation
2. Model datasets : NATL60 and HYCOM50
3. Slopes of kinetic energy wavenumber spectra
4. Kinetic energy spectral flux though nonlinear advection
5. **Wrap-up and conclusions**

Wrap up and conclusions

- Importance of better understanding how energy is fluxed across mesoscales
- Current observations do not allow yet to directly answer this question (until SWOT flies)
- although SSH spectral slopes from altimeters provide important information
- Current generation high res ocean models (developed for preparing SWOT mission) can help

Wrap up and conclusions

- Importance of better understanding how energy is fluxed across mesoscales
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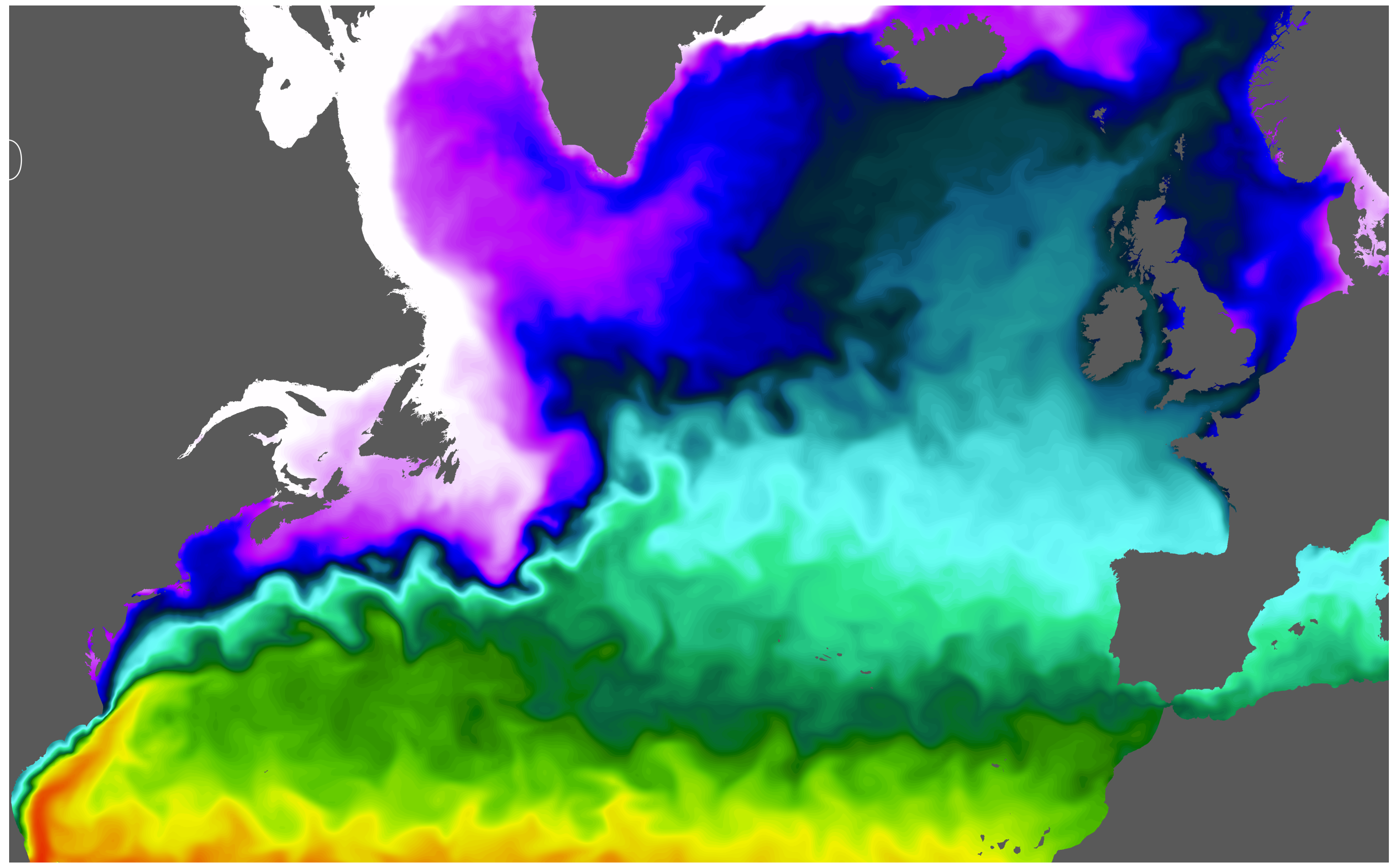
Here, results based on **two high resolution ocean models (dx ~1km)** show that :

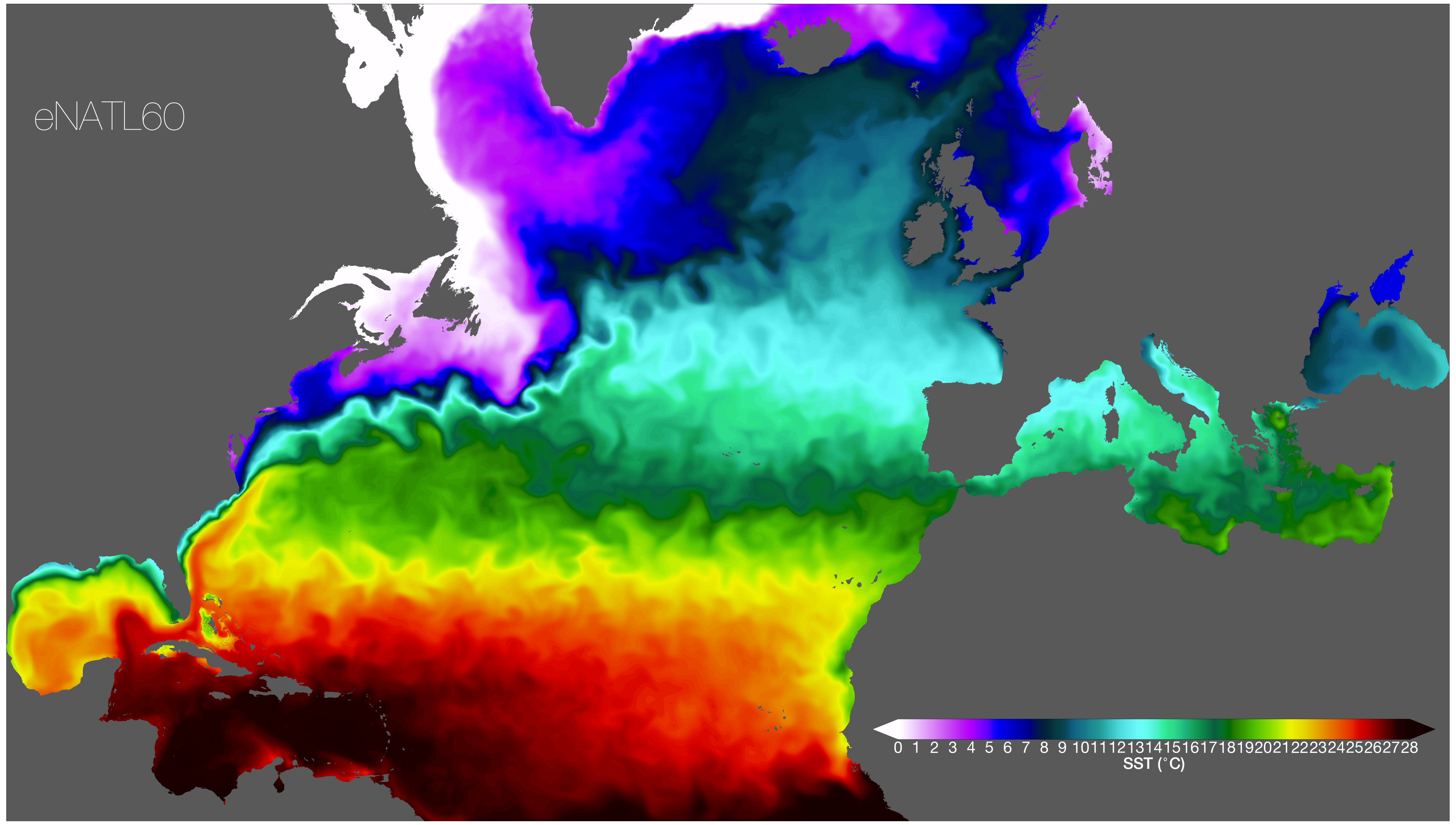
- Midlatitude dynamics **follows QG predictions** almost everywhere north of 30°N.
- An **inverse cascade of energy** is indeed occurring at scale > 25km.
- KE flux based on **geostrophic currents differ** from the flux computed from total velocity.
- This questions our ability to infer **energy cascade from the upcoming SWOT mission** alone
- How much are **ageostrophic flows** (IGW) contributing to energy exchanges across scales ?

Transitioning from NATL60 to eNATL60

NATL60



eNATL60

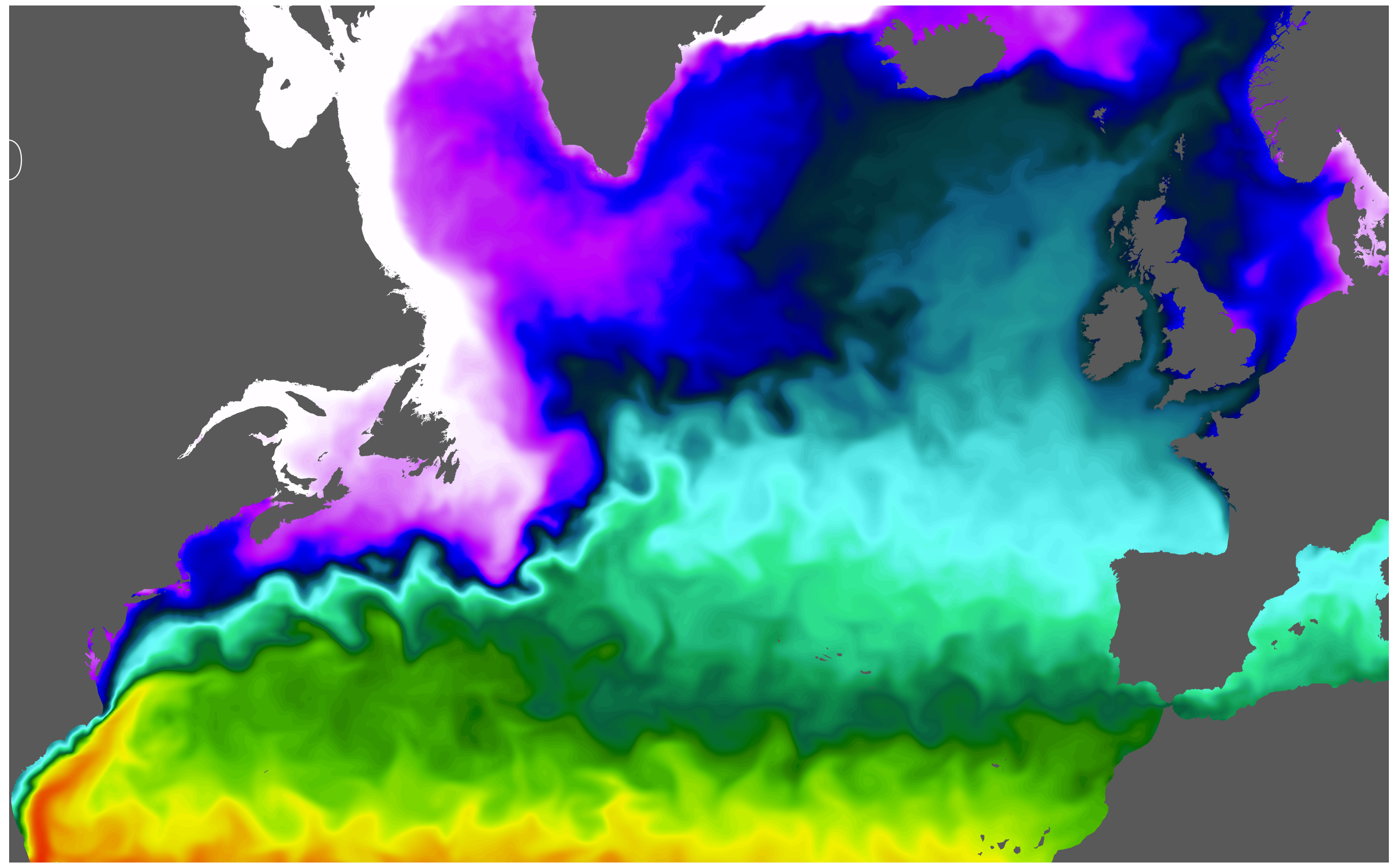


eNATL60 :

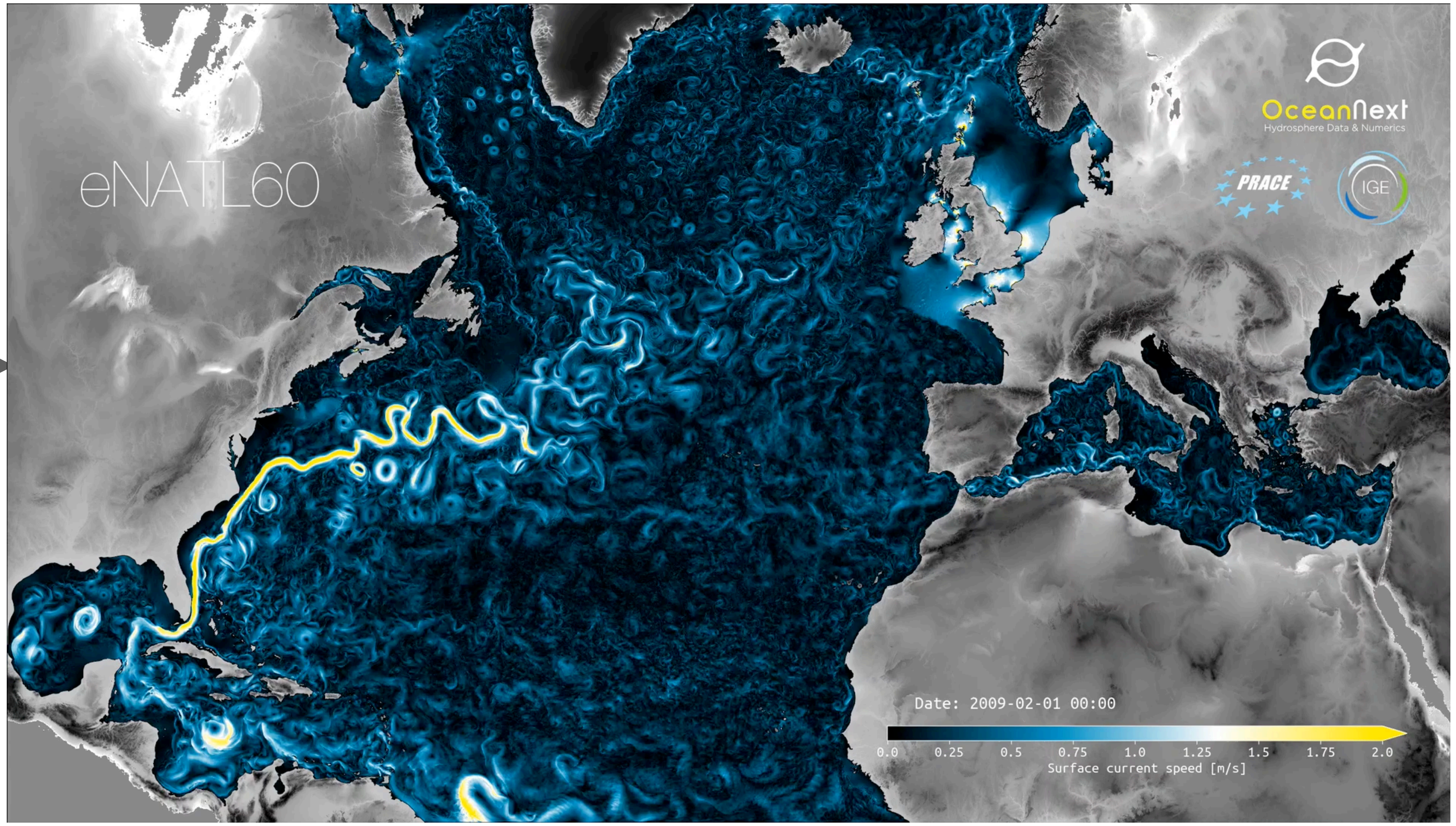
- extended domain : 6°N + enclosed seas
- tidal signals : K1, O1, S2, M2, N2
- improved numerics

Transitioning from NATL60 to eNATL60

NATL60



eNATL60



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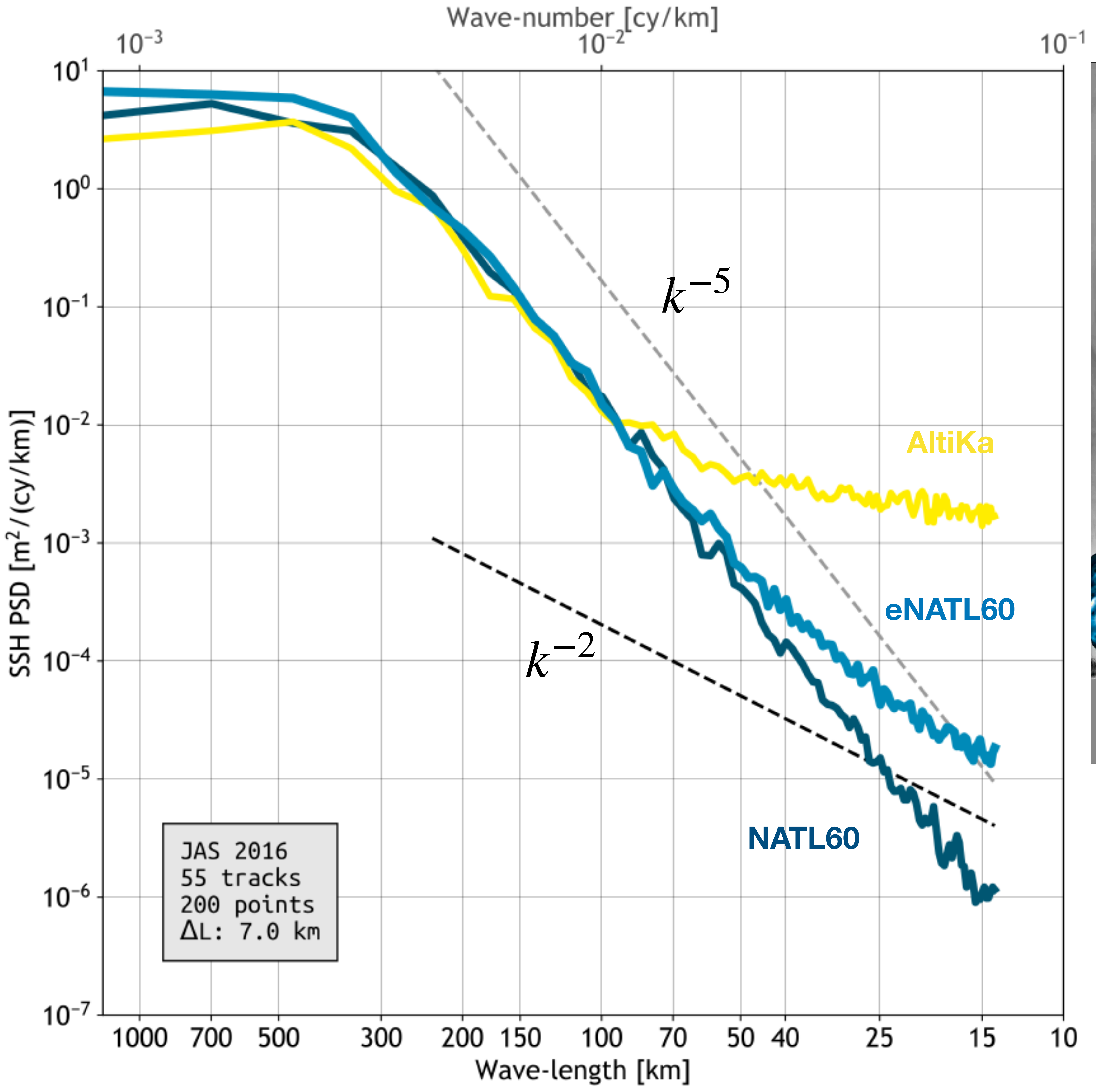
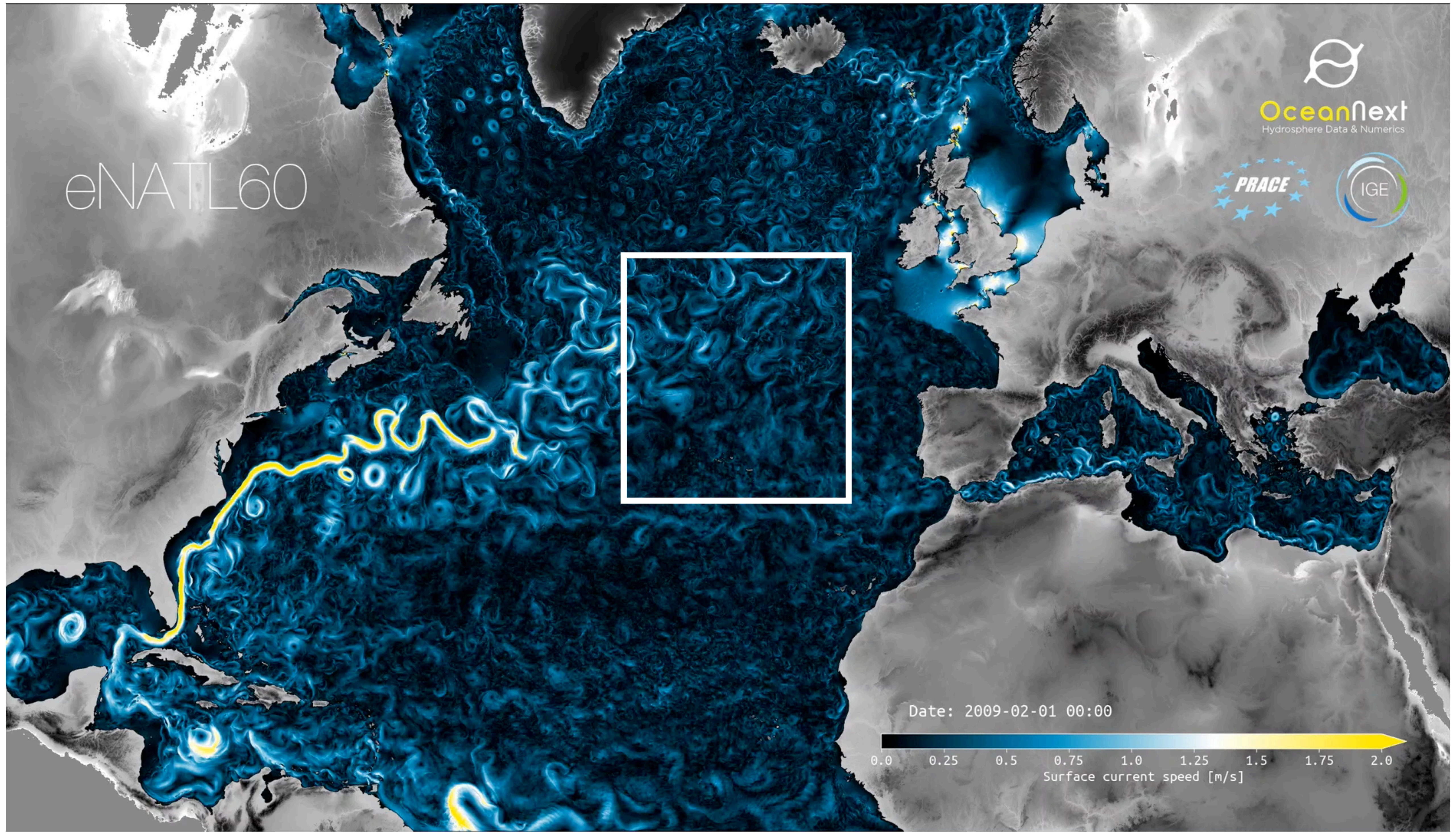
Transitioning from NATL60 to eNATL60

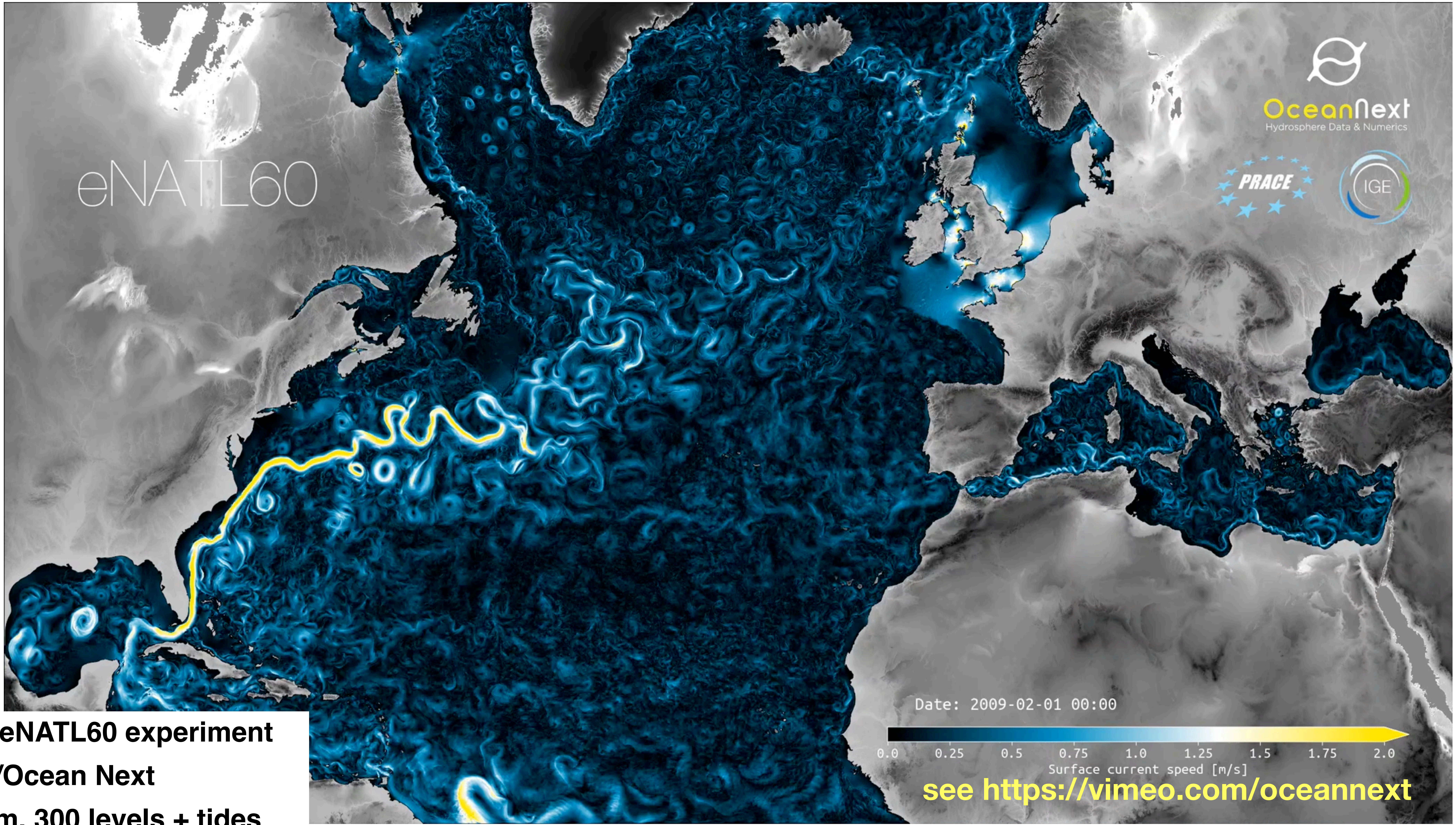


eNATL60



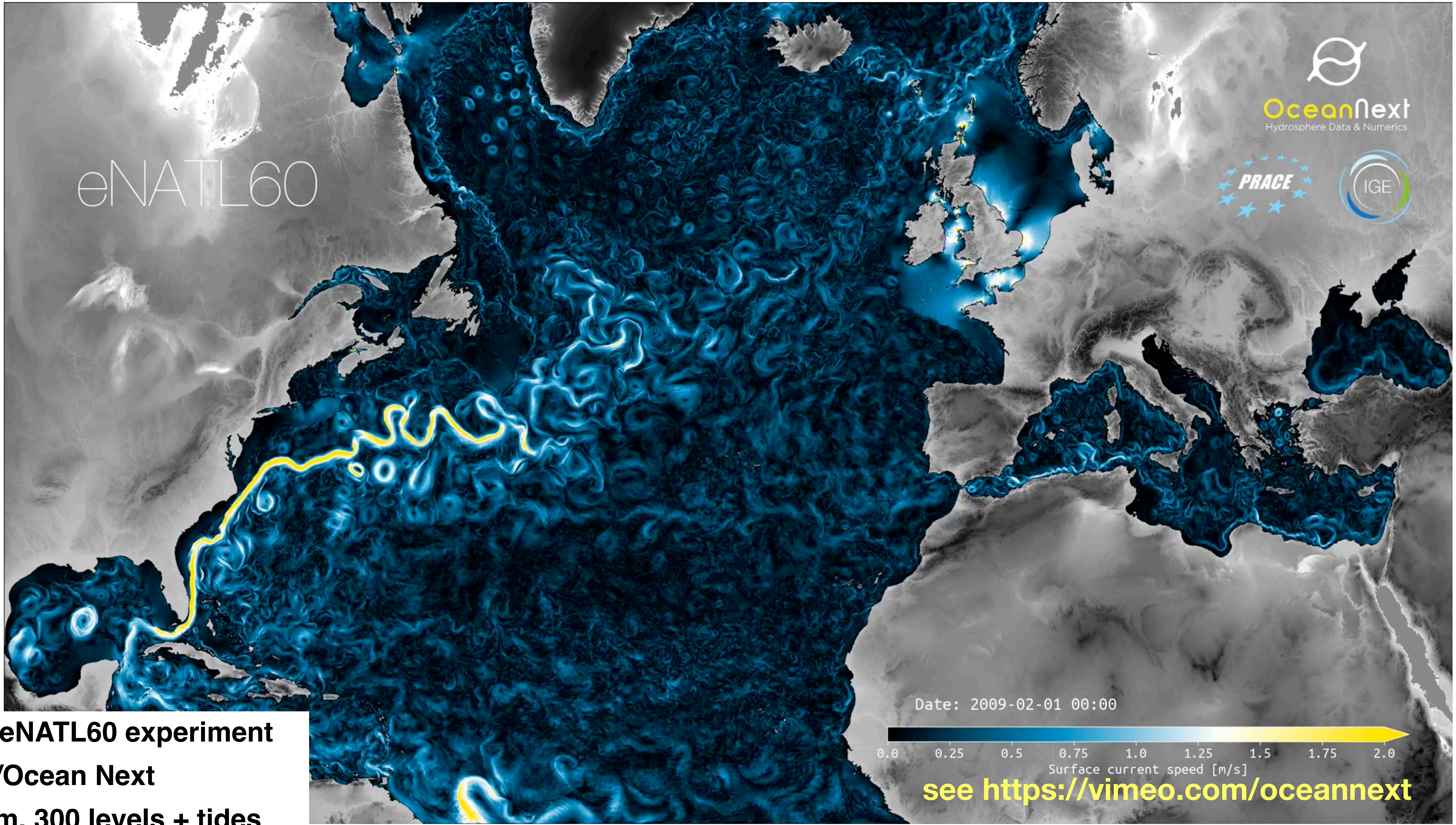
SSH powerspectra
NATL60, eNATL60, AltiKa

Transitioning from NATL60 to eNATL60



NEMO-eNATL60 experiment
by IGE/Ocean Next
dx ~1km, 300 levels + tides

Transitioning from NATL60 to eNATL60



NEMO-eNATL60 experiment
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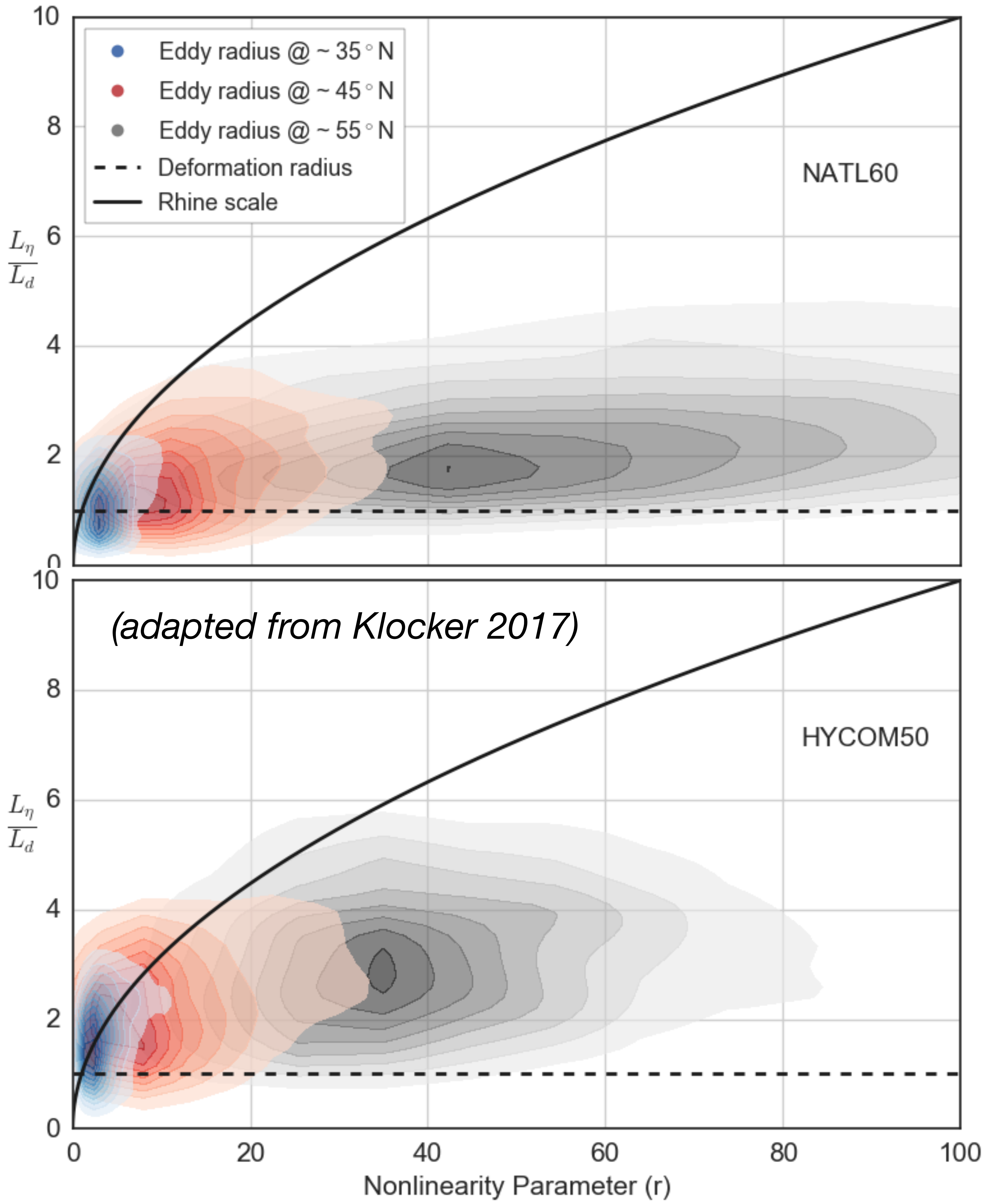
Additional material

Scale of eddy variability in HYCOM50 and NATL60



Nonlinearity parameter : $$\frac{\text{Eddy velocity}}{\text{Rossby wave speed}} = \frac{U_{eddy}}{\beta R_d^2}$$

Normalised eddy scale : $$\frac{\text{Eddy scale}}{\text{Rossby Radius}} = \frac{L}{R_d}$$

- Most of the eddy scales lie between the Rossby radius of deformation and the Rhine scale.
- Most of the eddies in the North Atlantic are nonlinear and the nonlinearity increases with latitude.
- Eddies in the 55 lat band are more linear in NATL60 compare to HYCOM50.
- Eddies in HYCOM50 tend to follow more closely the Rhine scale (stronger inverse cascade ?).