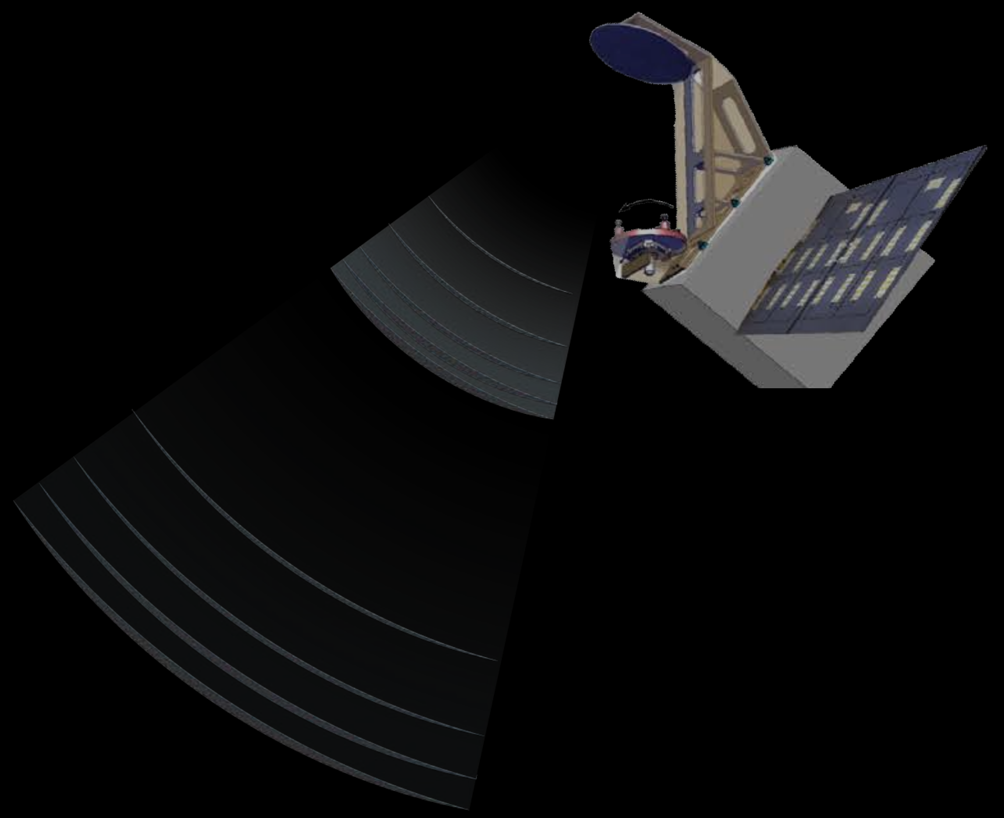
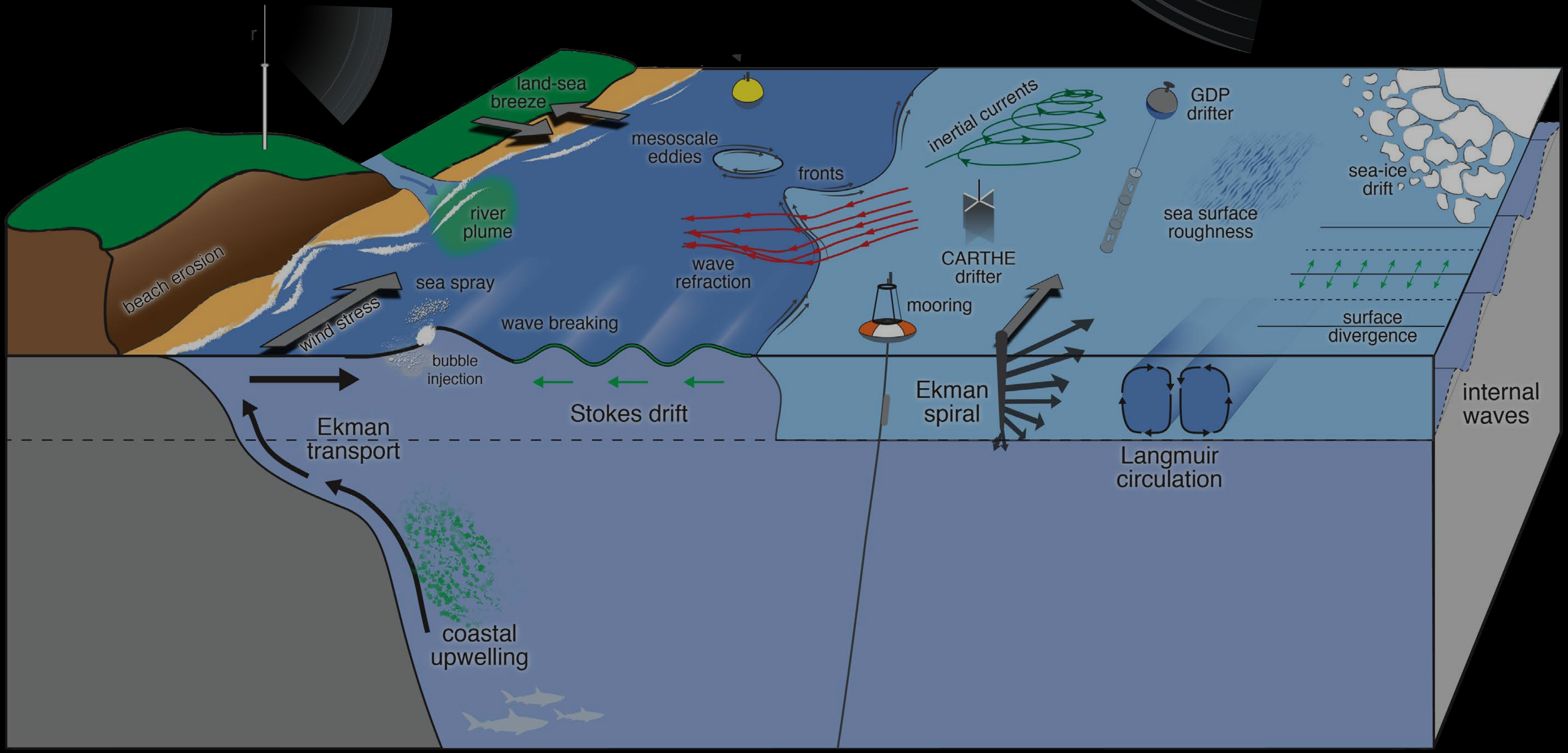
Wind, wave, and current interactions

Bia Villas Bôas

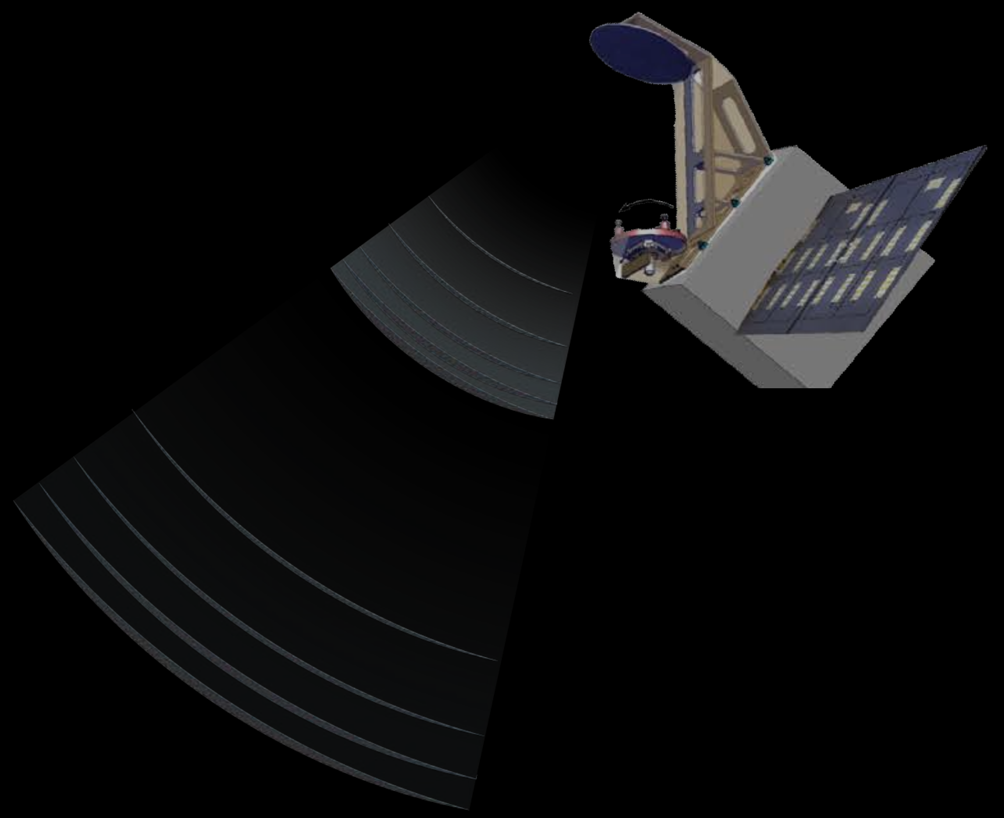
Fabrice Ardhuin, Bruce Cornuelle, Sarah Gille, Matt Mazloff, Bill Young,
Gwendal Maréchal, and many others.

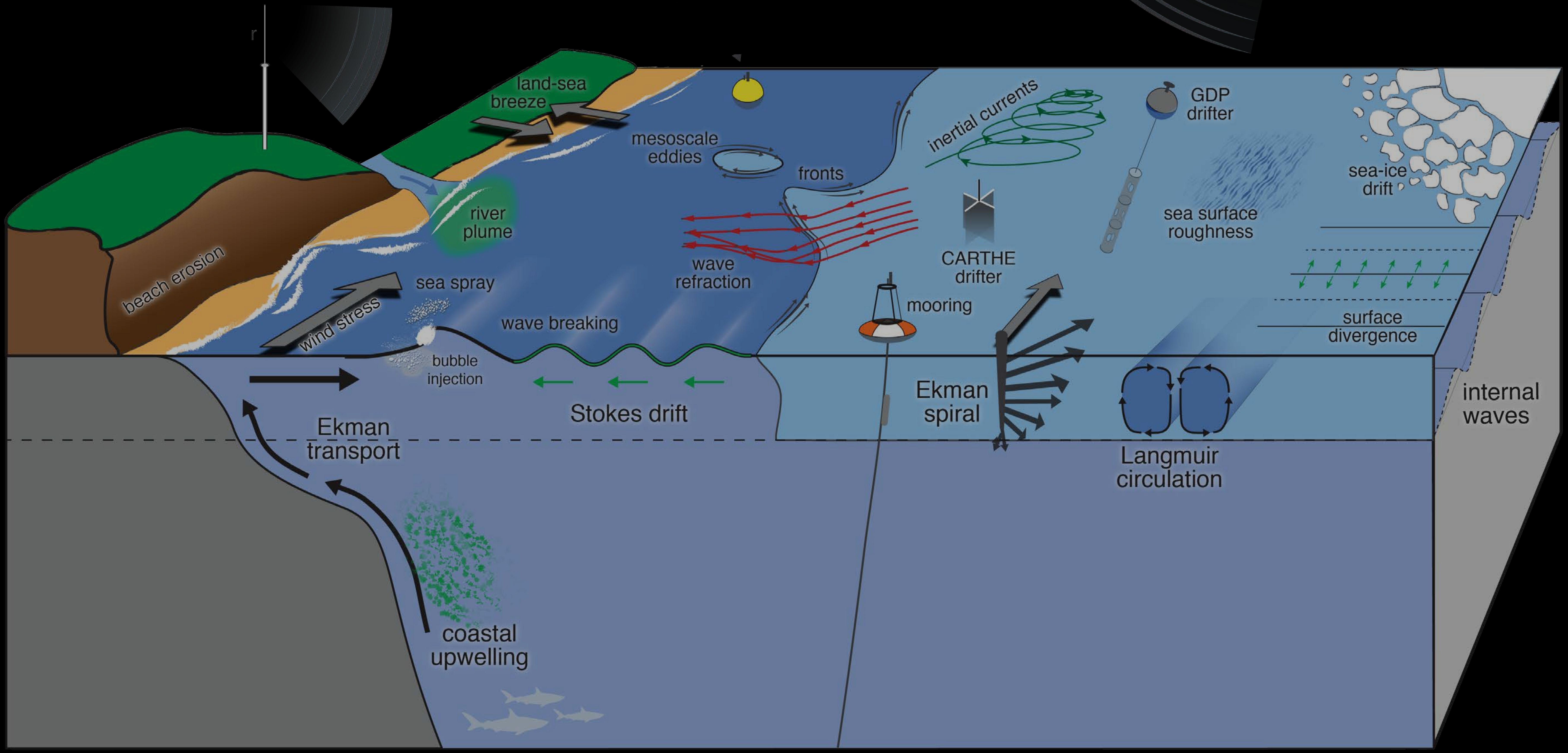




From Villas Bôas et al. (2019) by Momme Hell.

Improved understanding and representation of air-sea interactions **demand** a **combined** cross-boundary approach that can only be achieved through **integrated observations** and **modeling** of ocean **winds**, surface **currents**, and ocean surface **waves.**

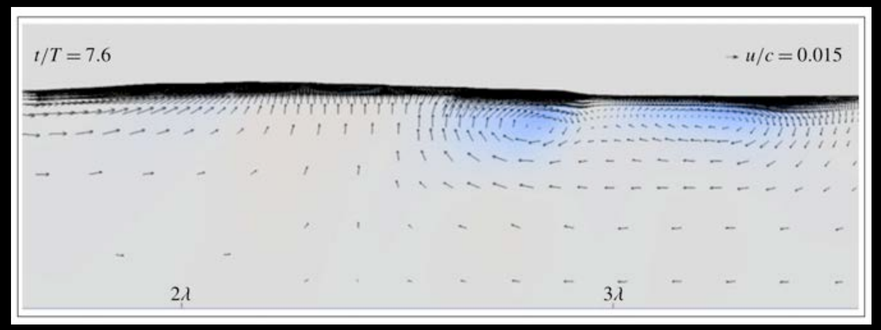




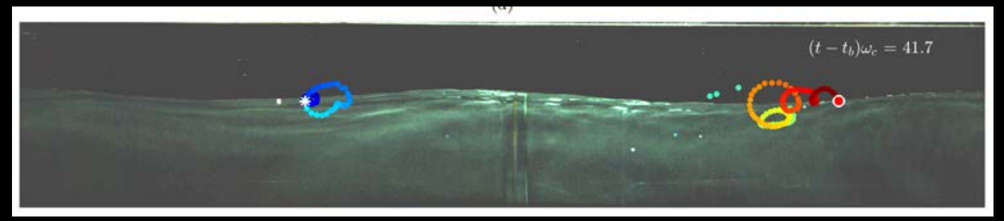
From Villas Bôas et al. (2019) by Momme Hell.

wavy processes

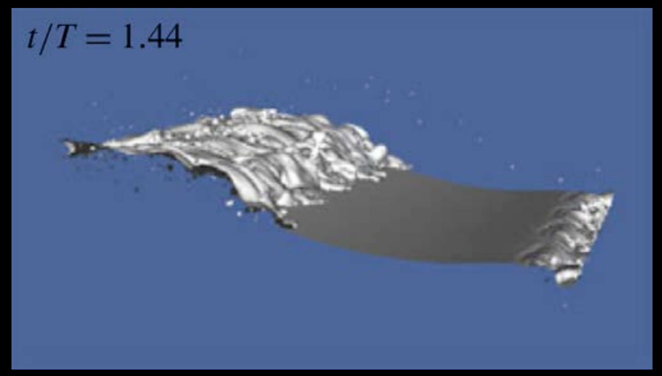
Pizzo et al., (2016)

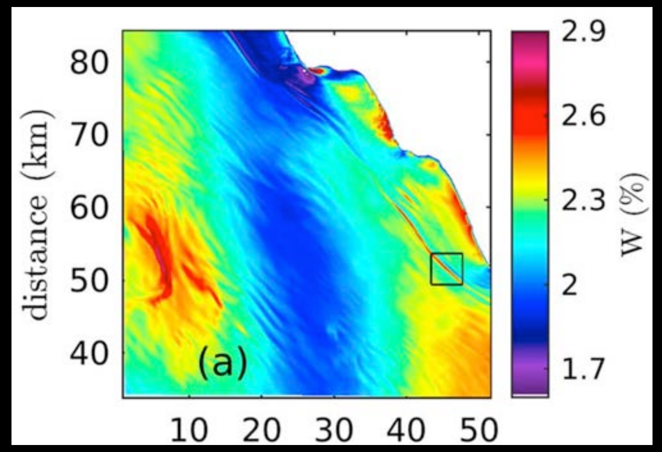


Lenain et al., (2019)



Deike et al., (2016)

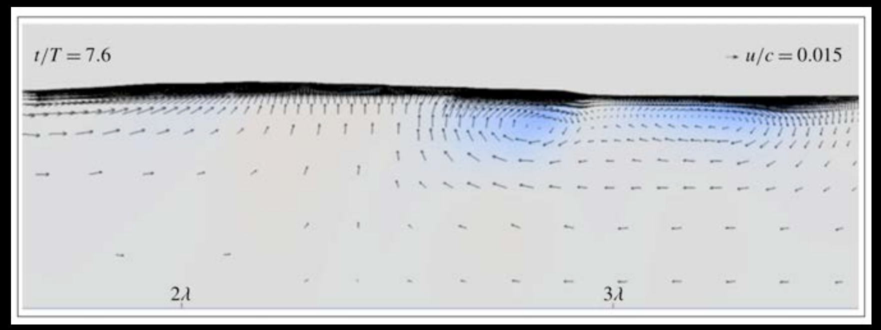




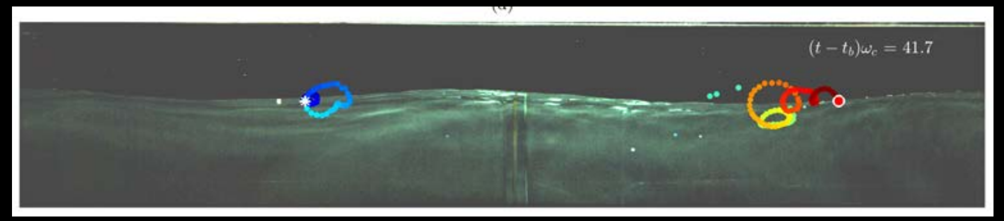
Romero (2019)

wavy processes

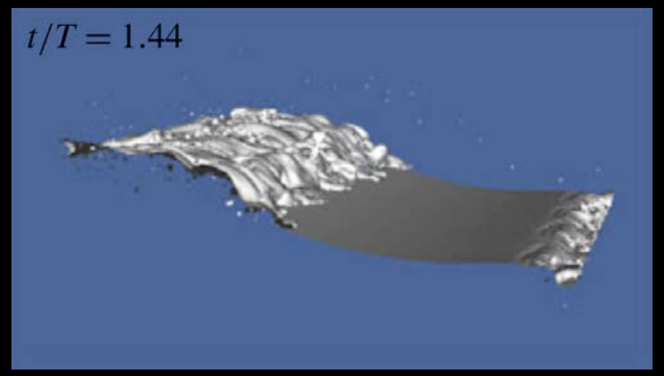
Pizzo et al., (2016)

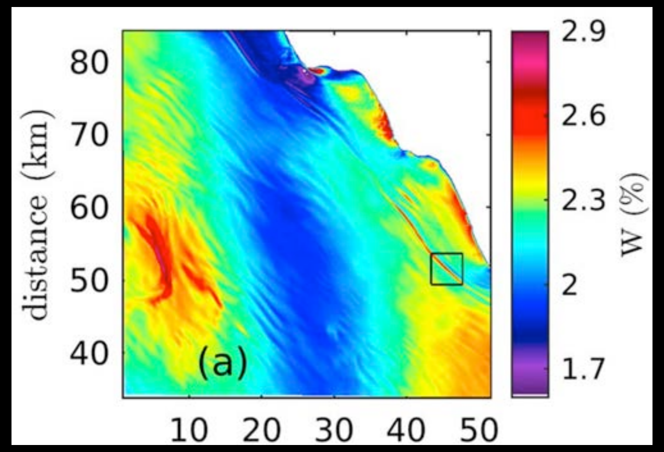


Lenain et al., (2019)



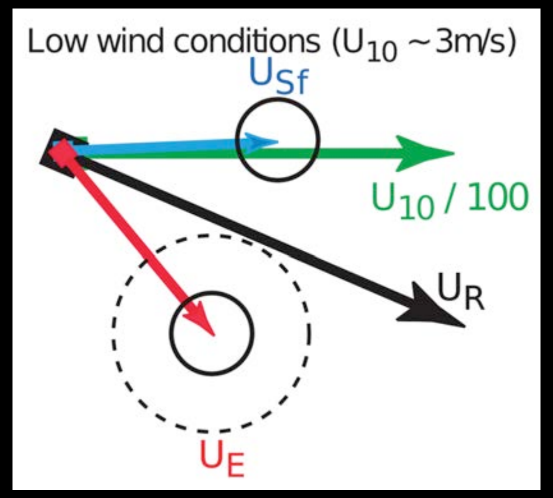
Deike et al., (2016)

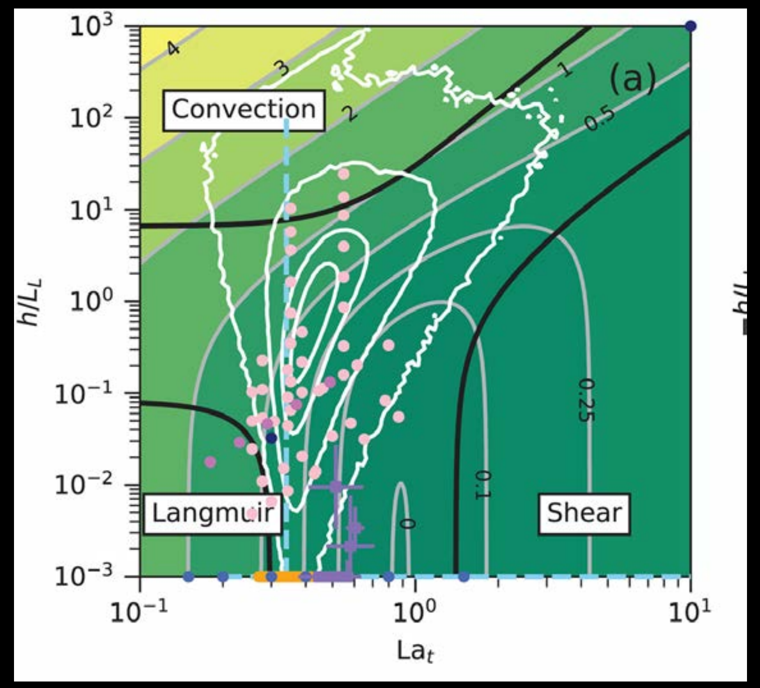




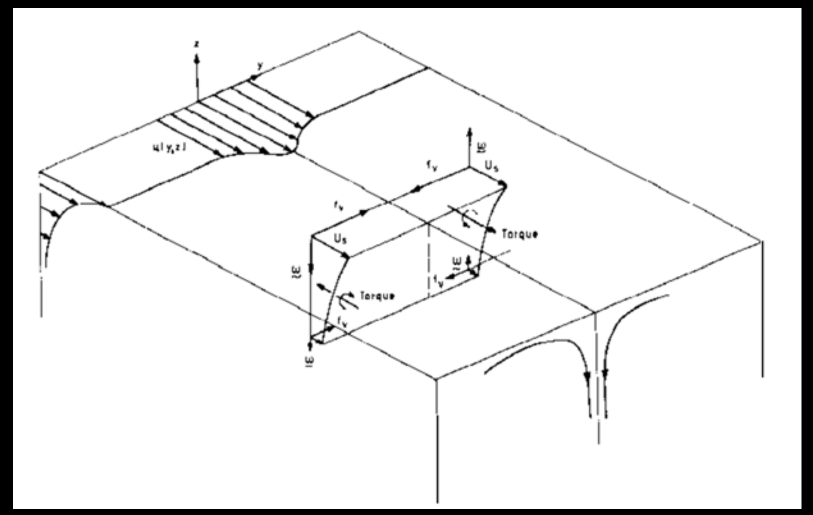
Romero (2019)

Ardhuin et al., (2009)





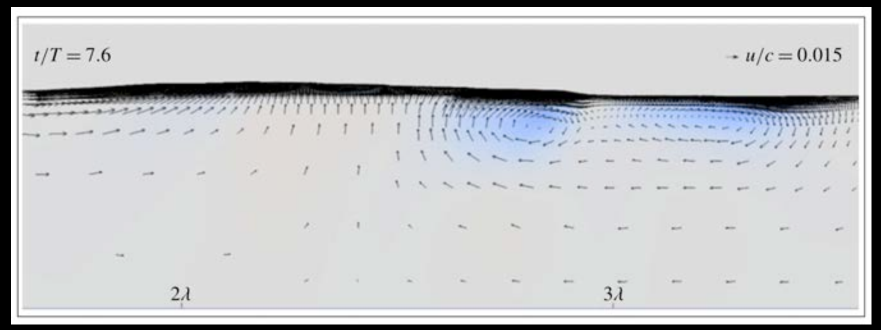
Belcher et al. (2012)
Li et al., (2016)



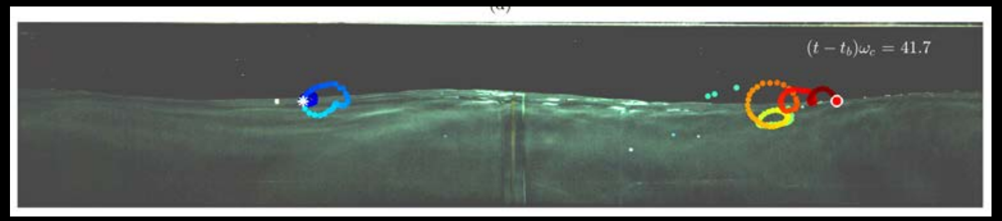
Leibovich (1983)

wavy processes

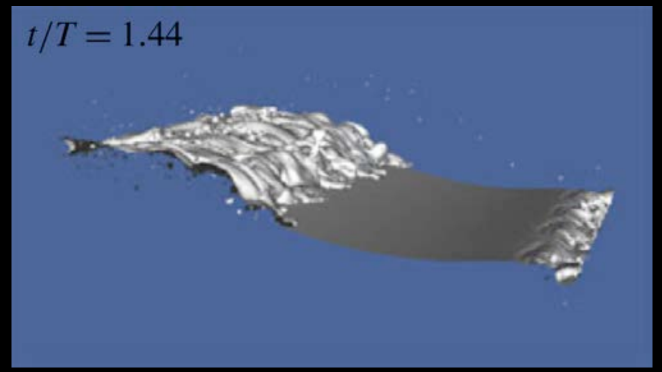
Pizzo et al., (2016)

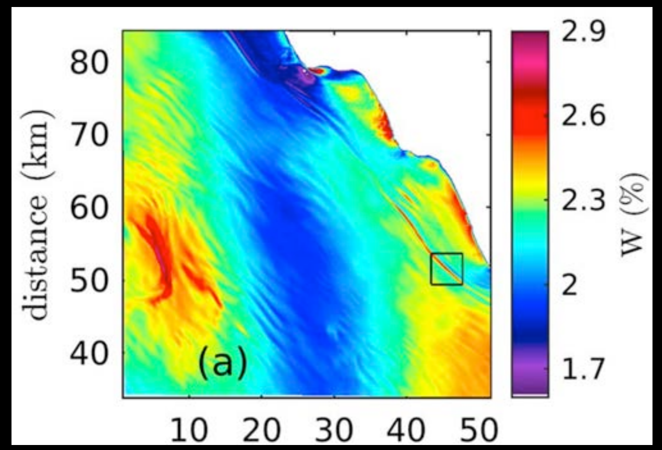


Lenain et al., (2019)



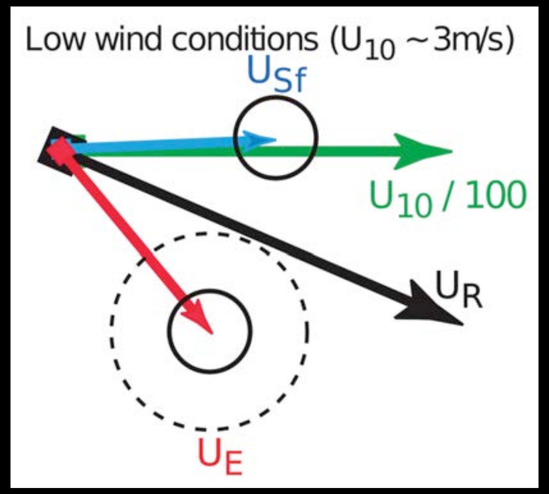
Deike et al., (2016)

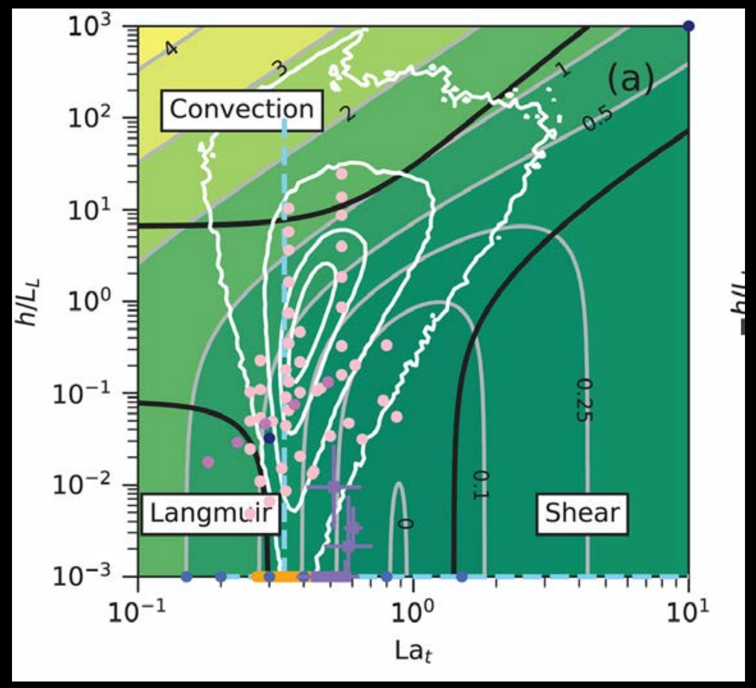




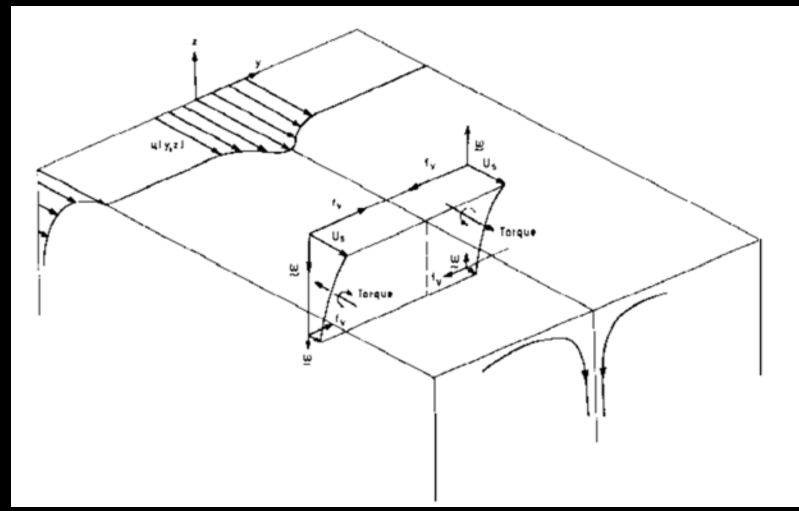
Romero (2019)

Ardhuin et al., (2009)





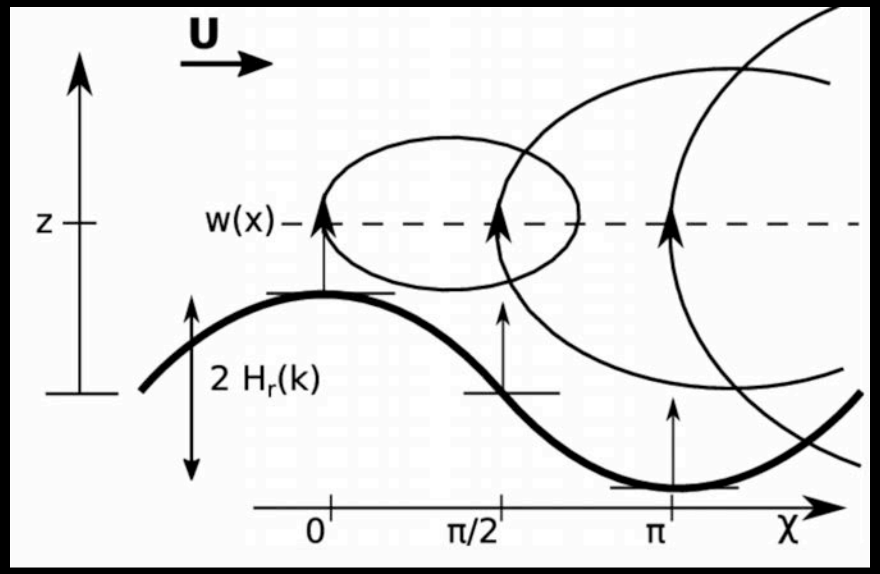
Belcher et al. (2012)
Li et al., (2016)

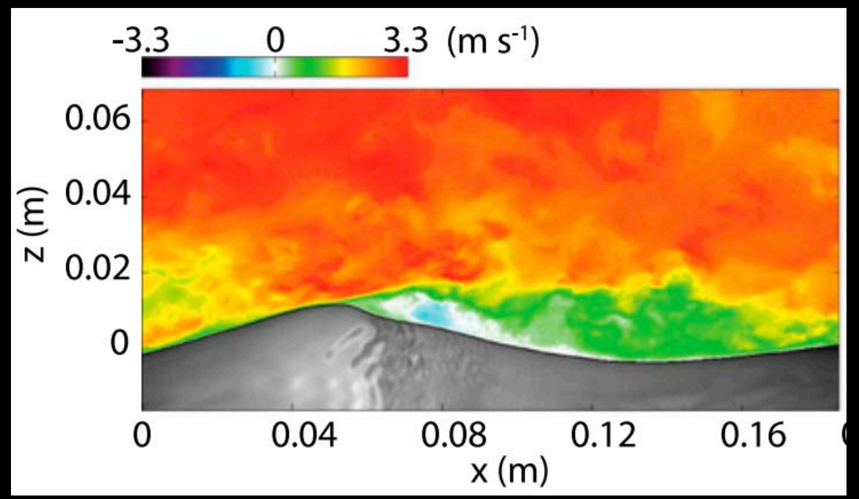


Leibovich (1983)

wavy processes

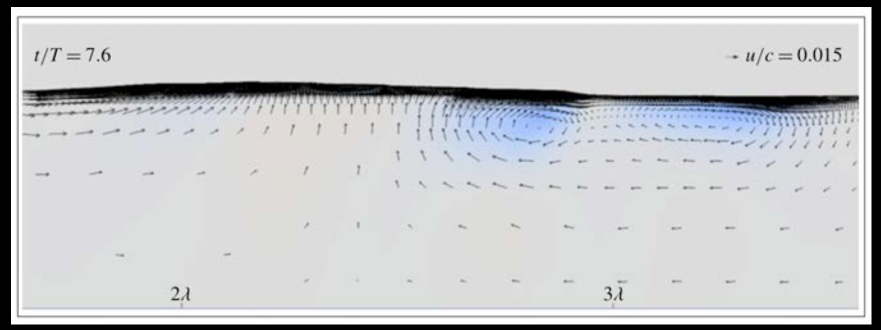
Gare et al. (2013), Buckley & Veron (2016), Ayet et al. (2019)



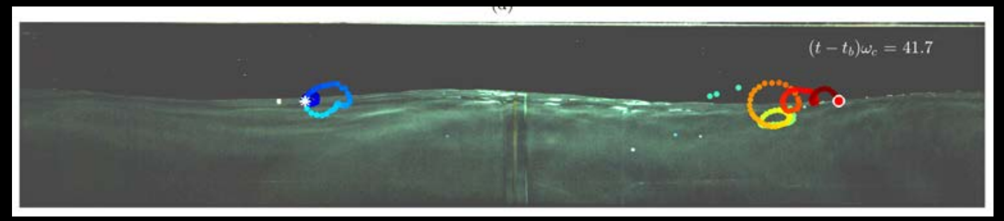


wavy processes

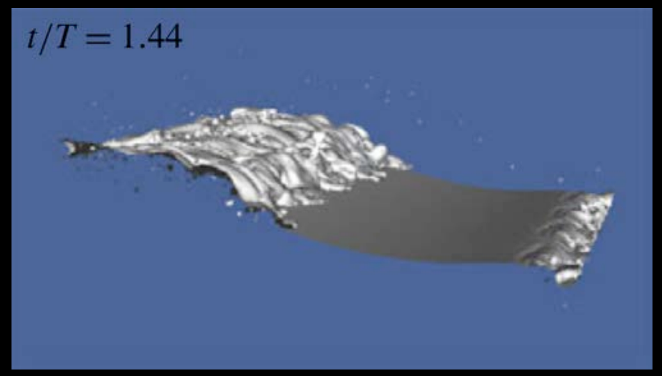
Pizzo et al., (2016)

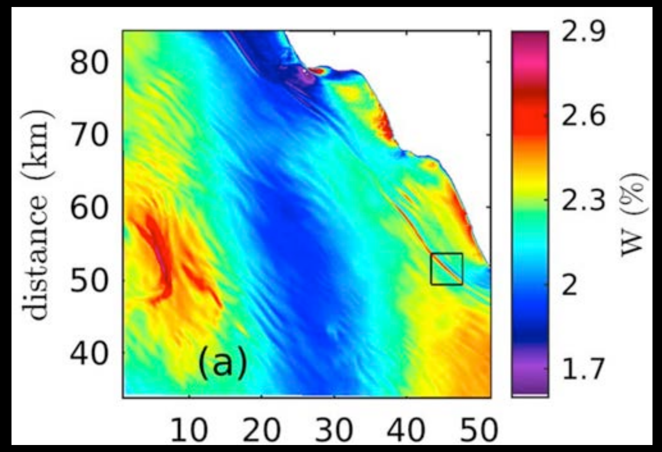


Lenain et al., (2019)



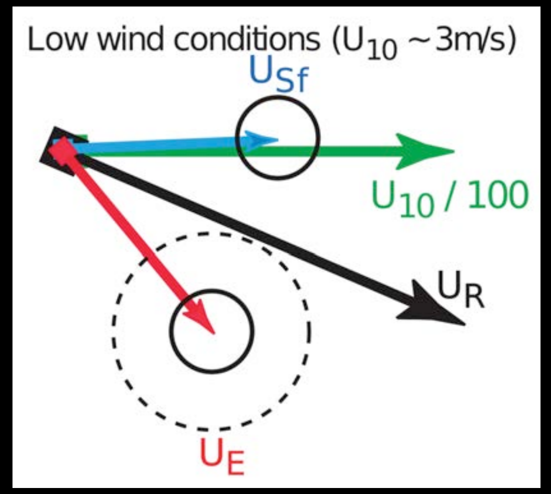
Deike et al., (2016)

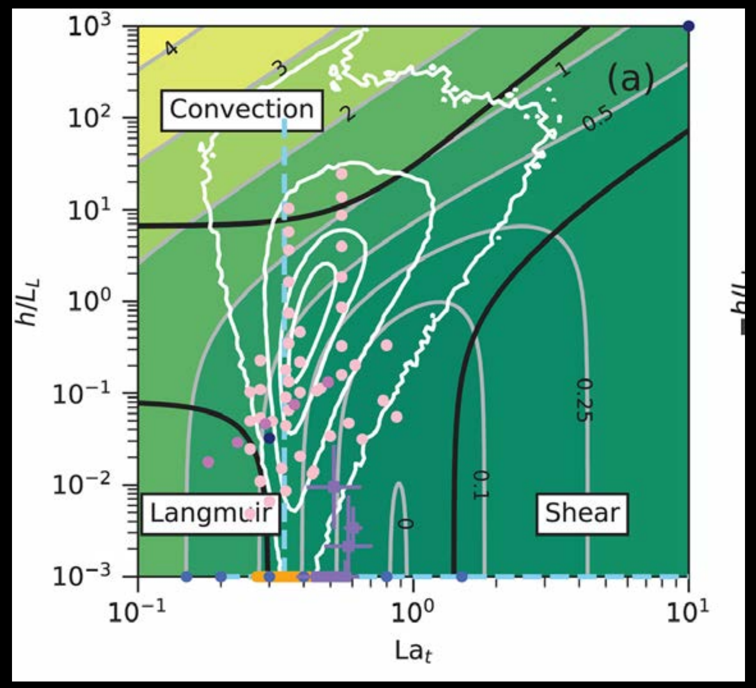




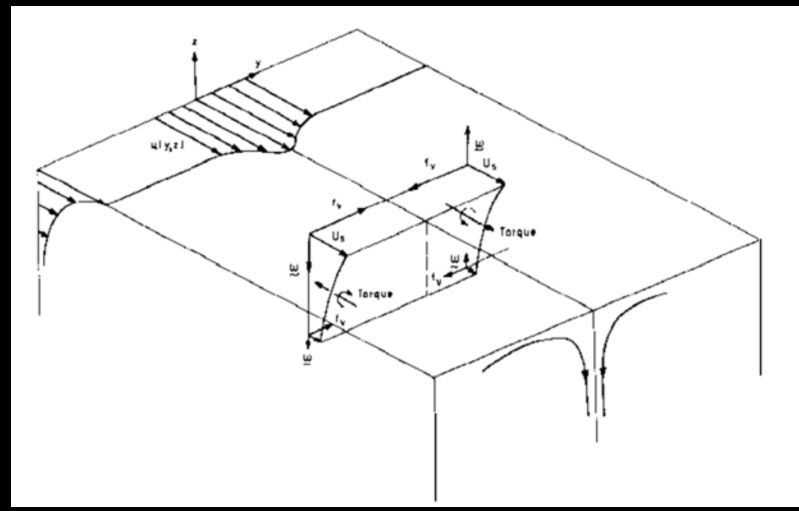
Romero (2019)

Ardhuin et al., (2009)





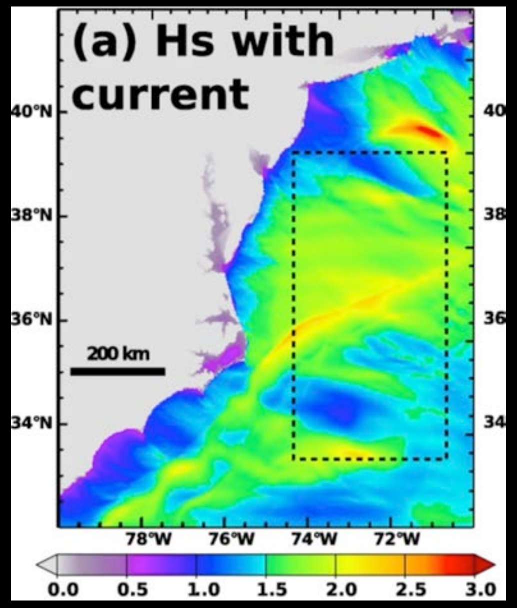
Belcher et al. (2012)
Li et al., (2016)

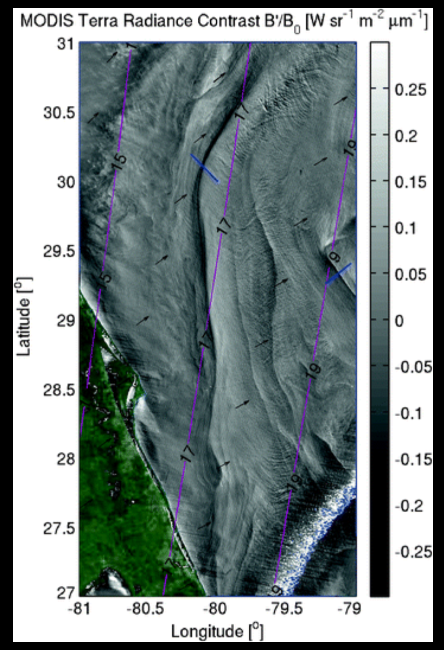


Leibovich (1983)

Romero et al (2017)

Ardhuin et al., (2017)

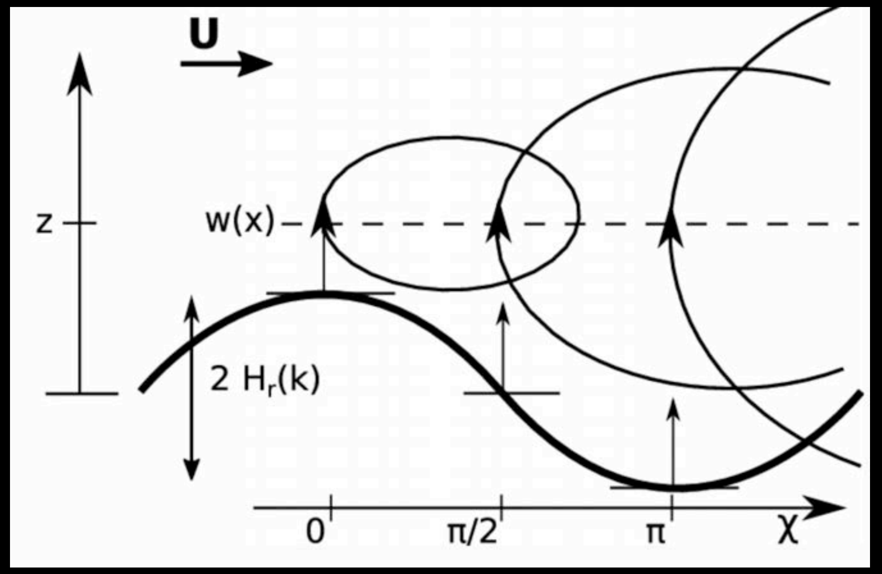


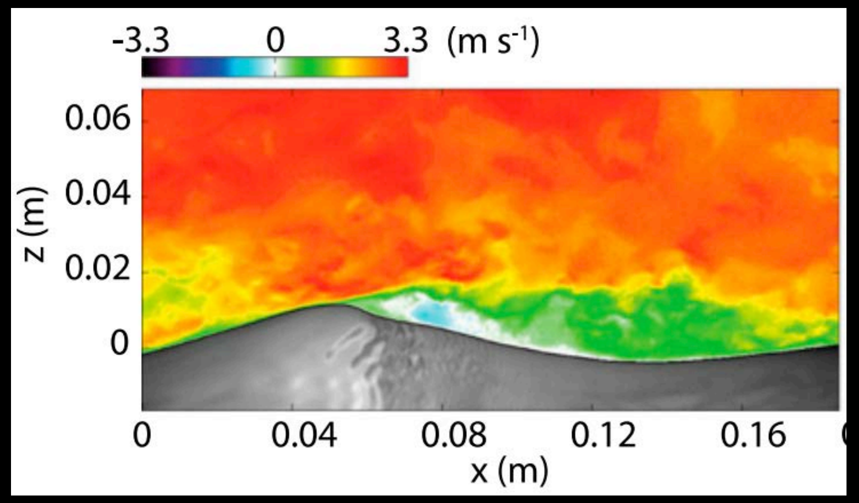


Rascle et al. (2016)

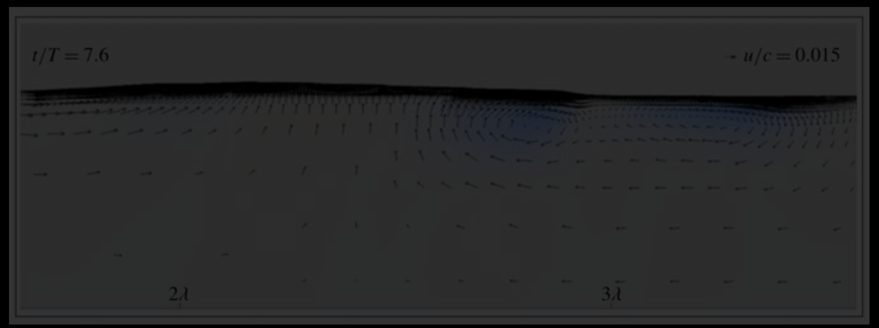
Zippel & Thomson (2016)

Gare et al. (2013), Buckley & Veron (2016), Ayet et al. (2019)

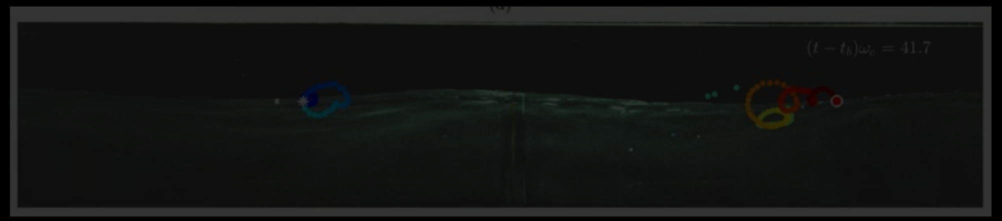




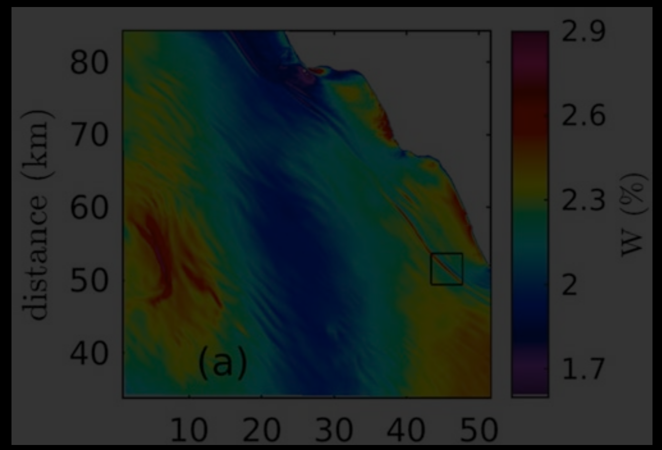
Pizzo et al., (2016)



Lenain et al., (2019)

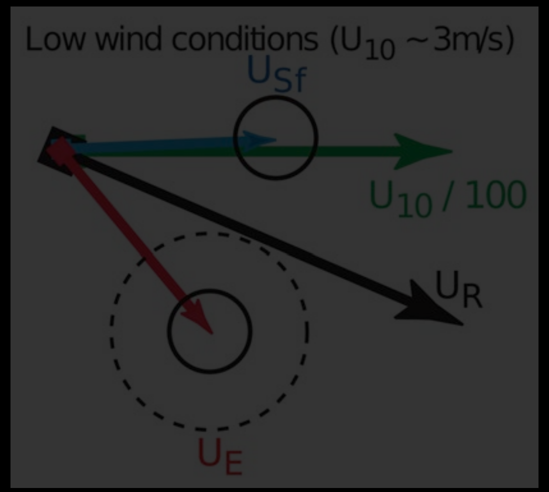


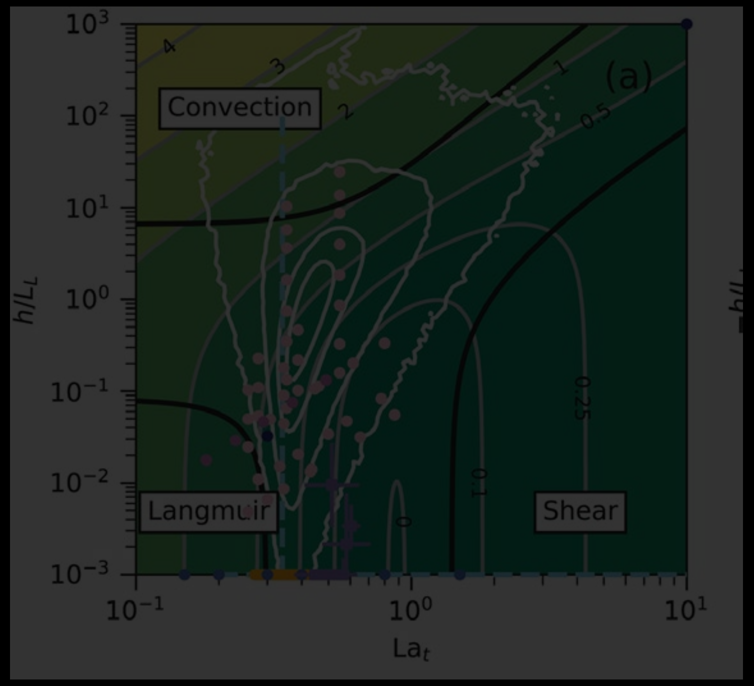
Deike et al., (2016)



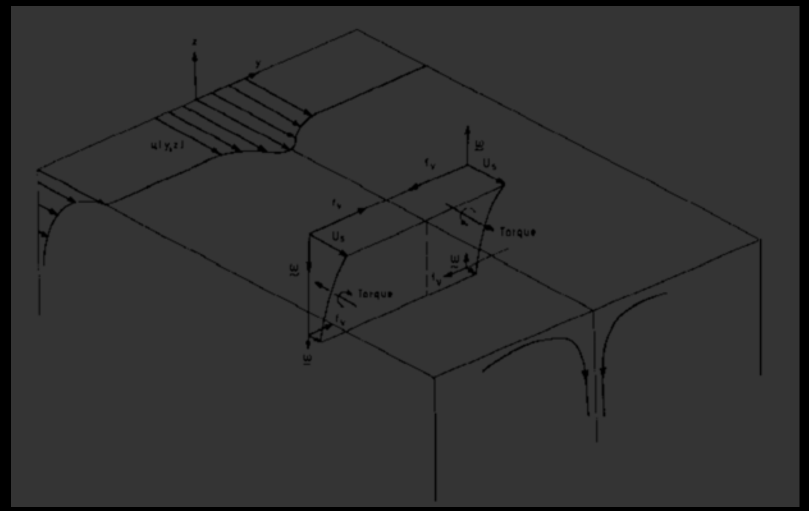
Romero (2019)

Ardhuin et al., (2009)

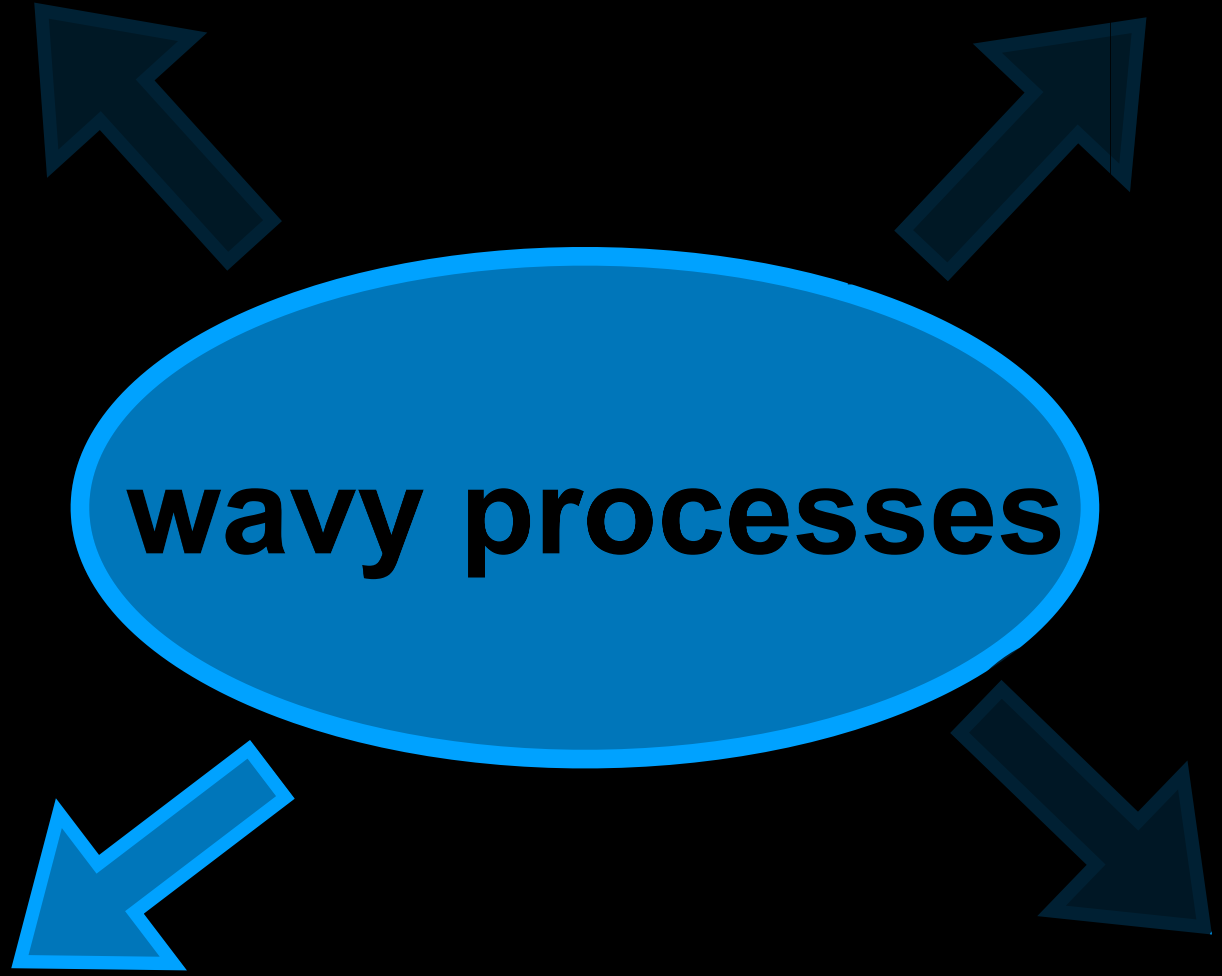




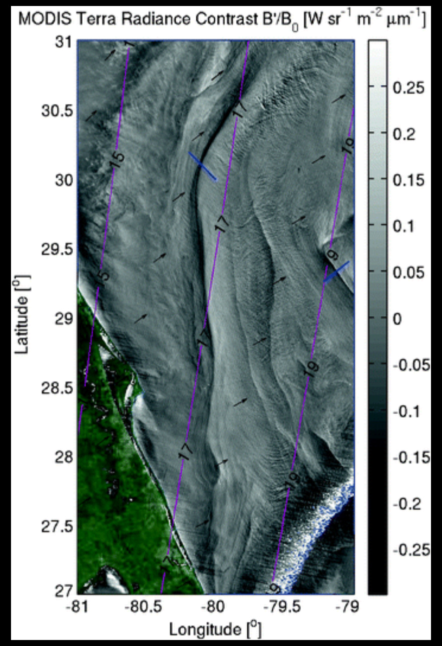
Belcher et al. (2012)
Li et al., (2016)



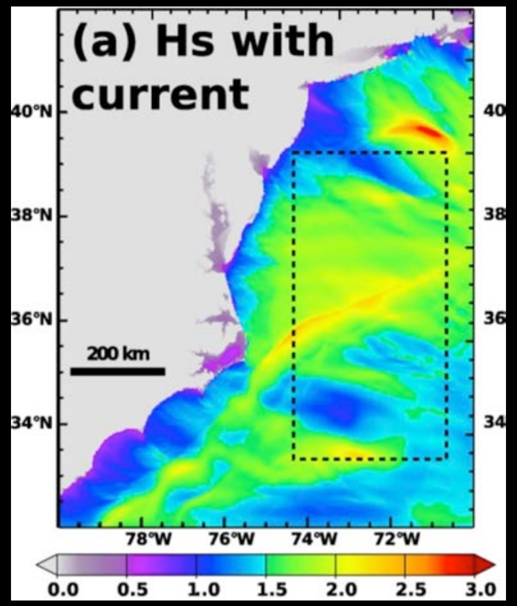
Leibovich (1983)



Romero et al (2017)

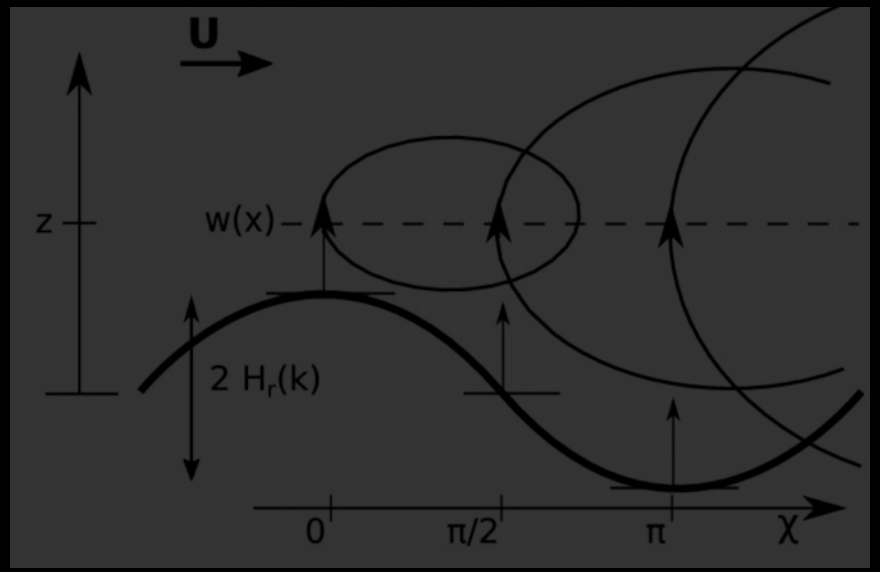


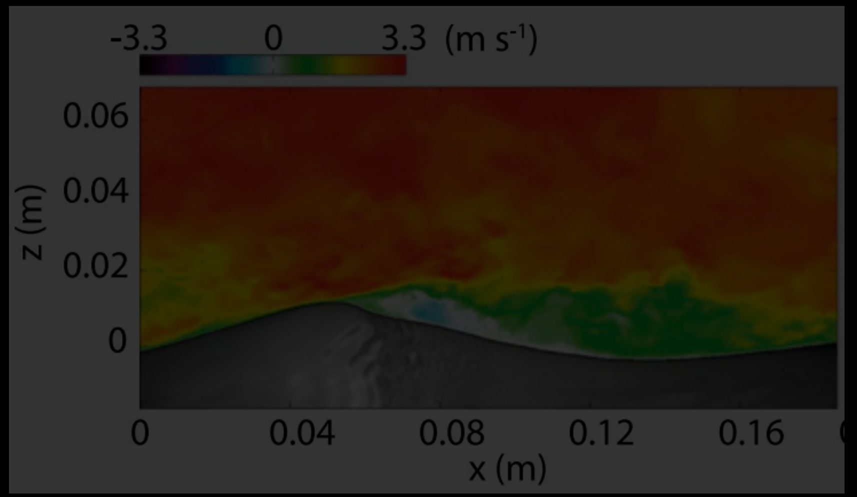
Ardhuin et al., (2017)



Zippel & Thomson (2016)

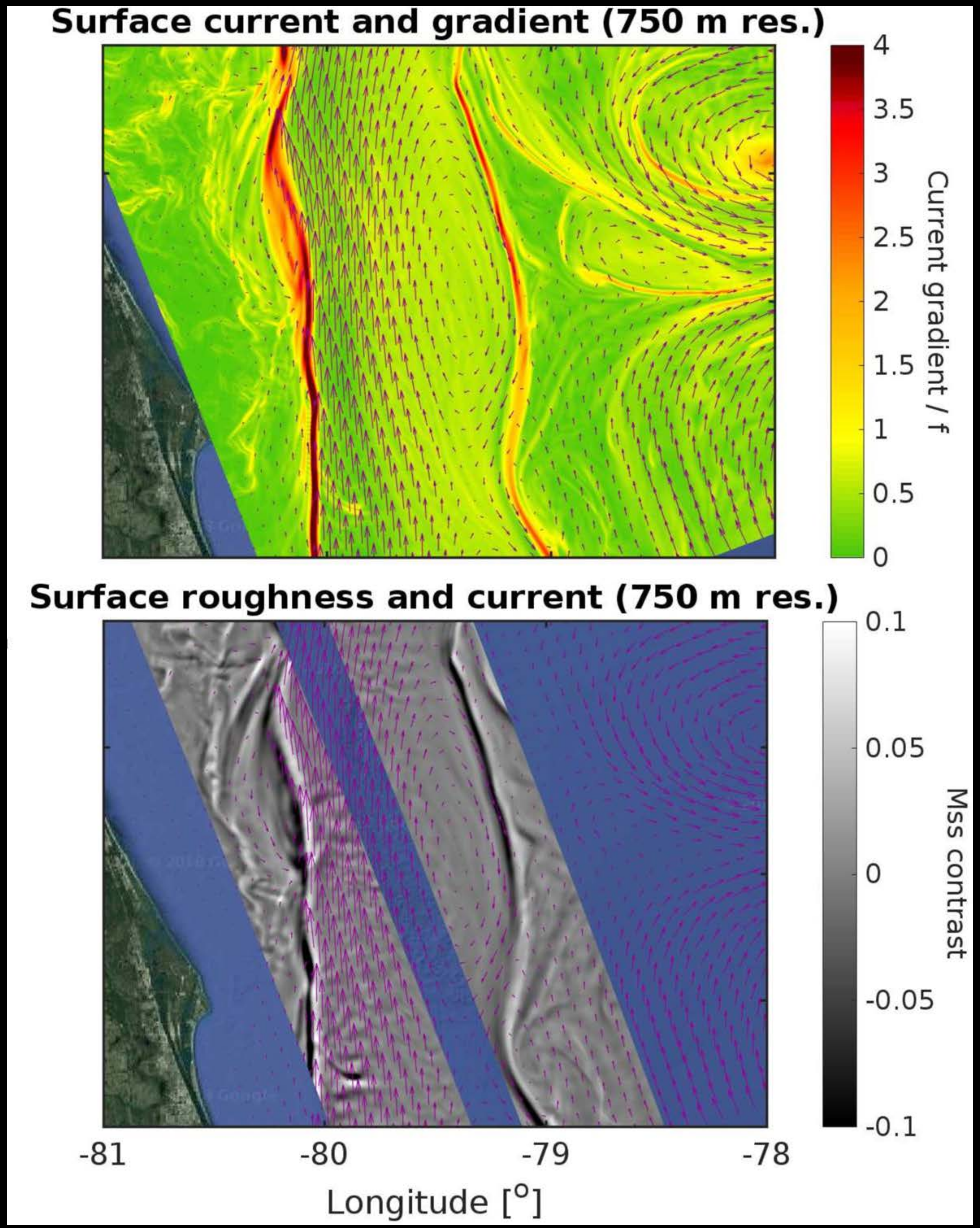
Gare et al. (2013), Buckley & Veron (2016),
Ayet et al. (2019)

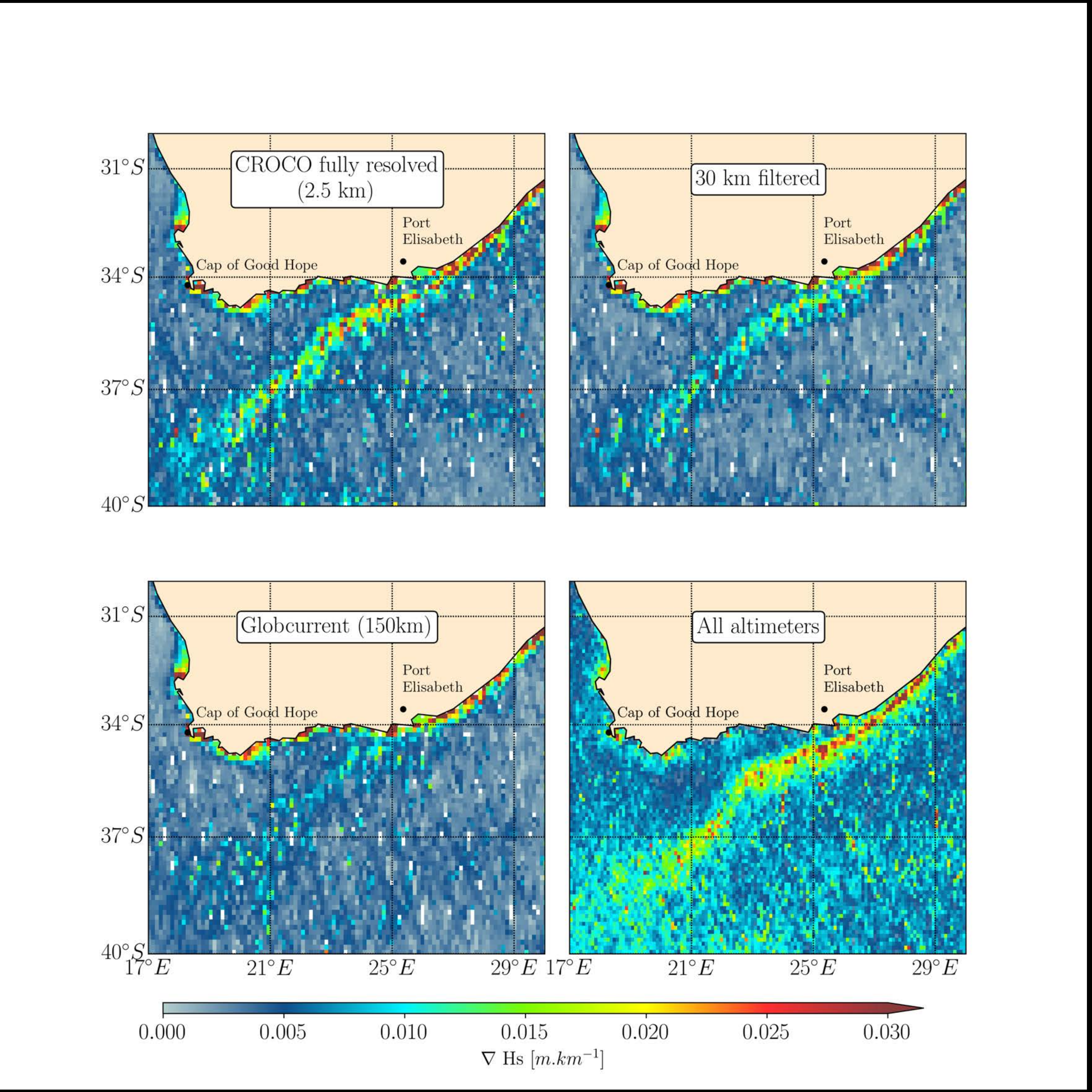




What do we know? Wave properties vary on small scales!

Morrow et al., 2019 and Rascle et al., 2016

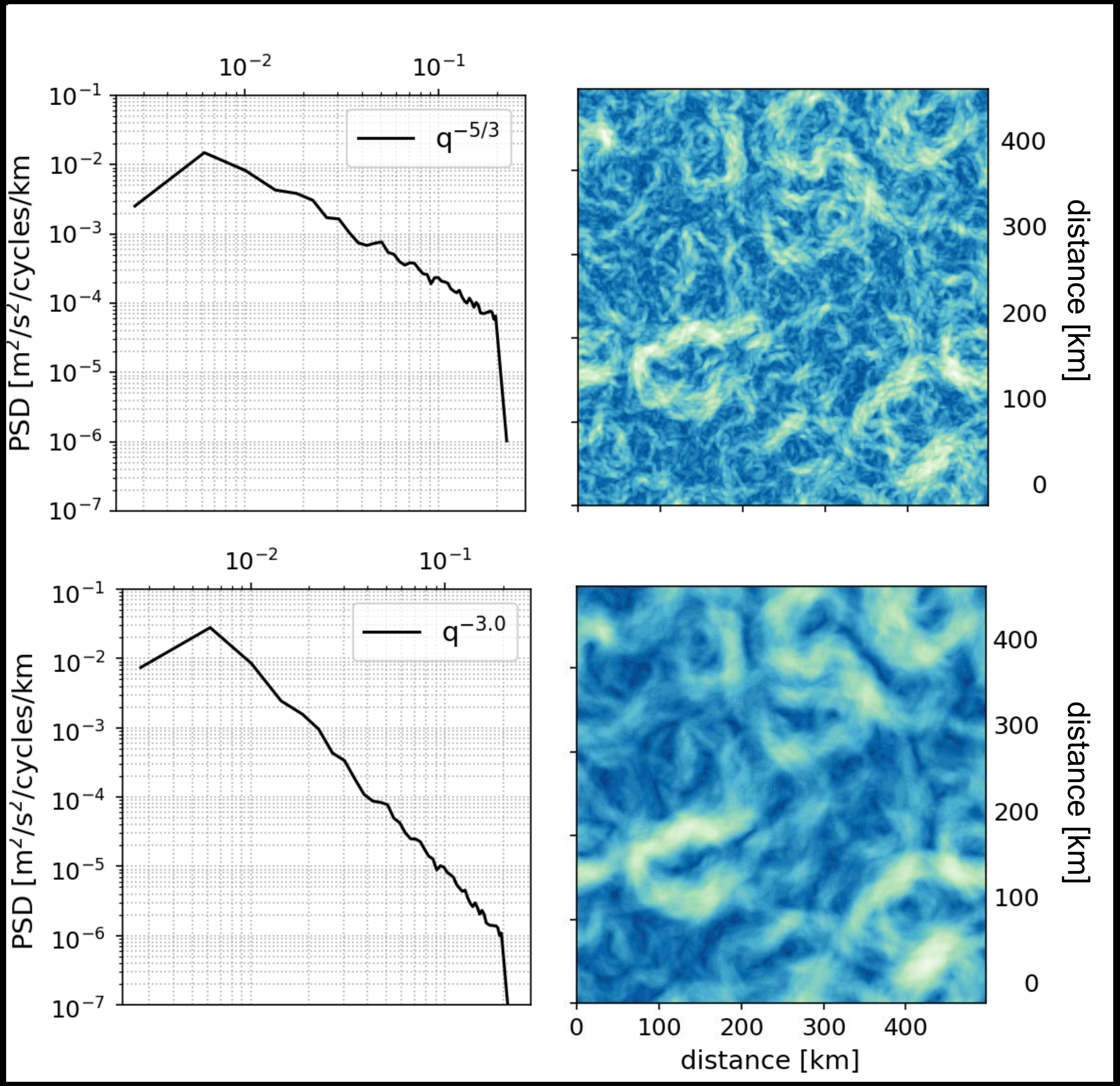




Work from Gwendal Marechal and Fabrice Ardhuin

How well do we understand these sea state gradients? surface wave response to vorticity and divergence.

Synthetic surface currents

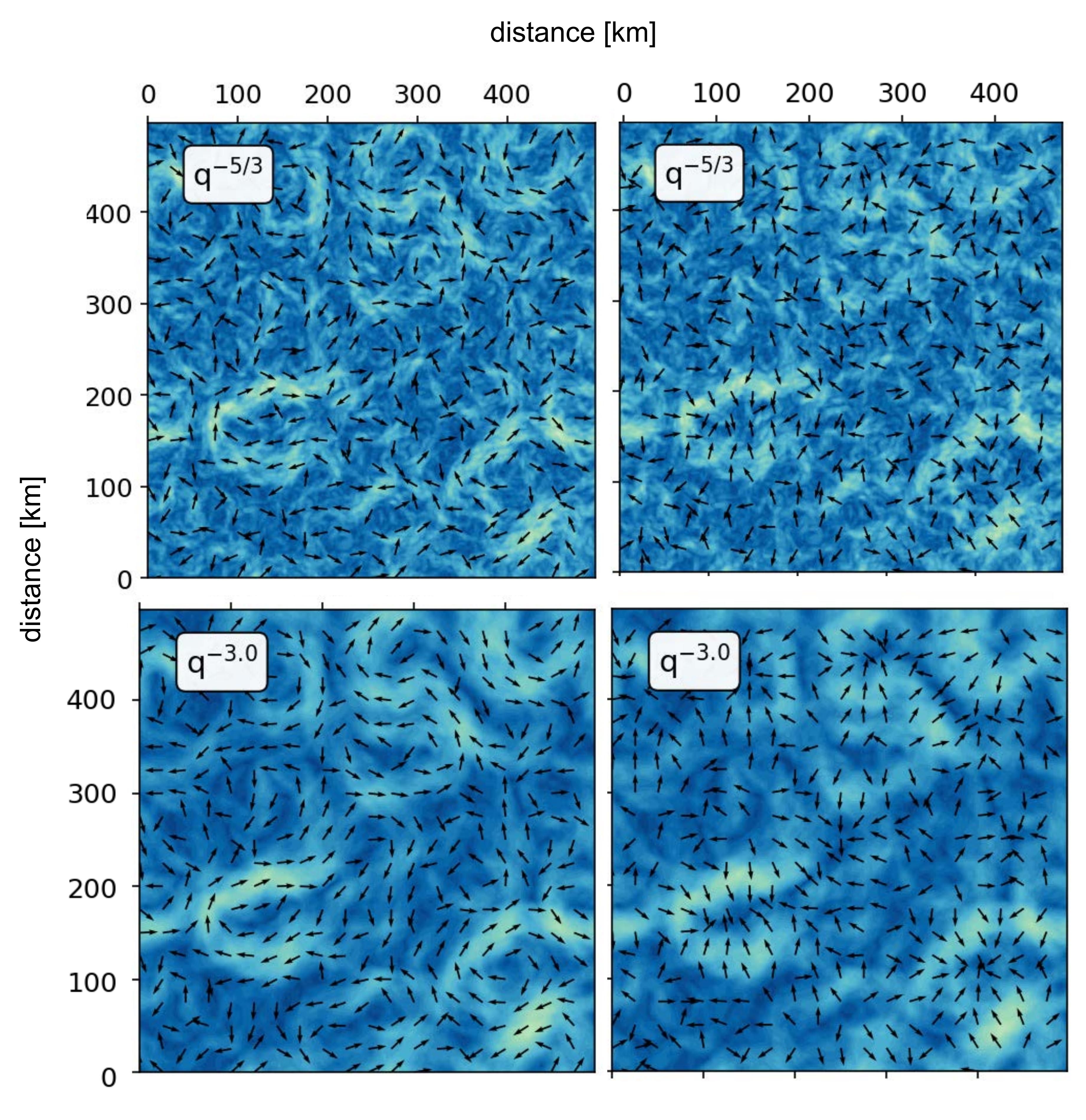


The variance of the flow is all contained in wavelengths between 5km and 300km.

Helmholtz

decomposition

rotational (solenoidal) **divergent** (potential)

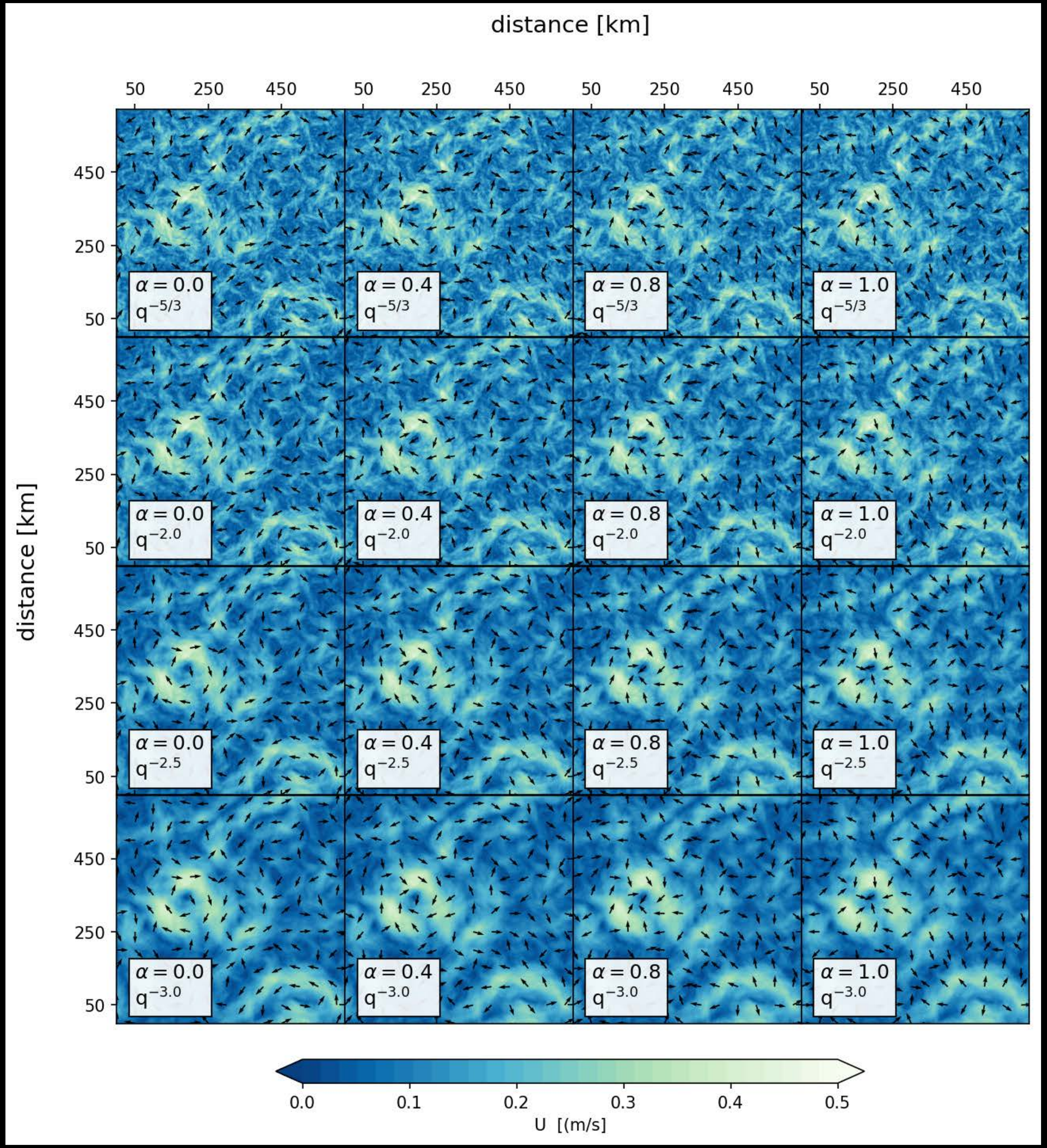


The final velocity is produced by a combination of the rotational and the divergent parts normalized to a prescribed variance:

More vorticity → More divergence

Shallower spectral slope

Steeper spectral slope



Same variance spectra, different vort/div ratio

All panels have the same variance (mean kinetic energy) and same phase.

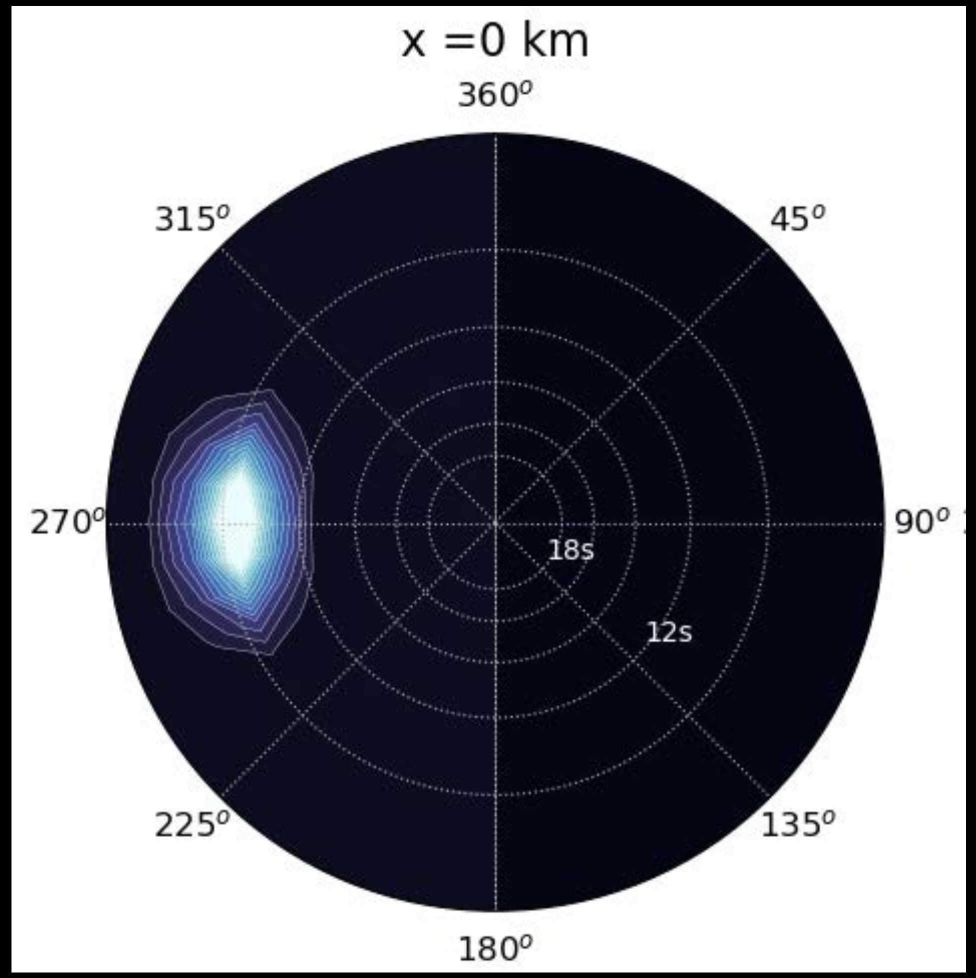
Wave Model:

We use the wave model WaveWatch III (WW3) to integrate the action balance equation (with no source terms):

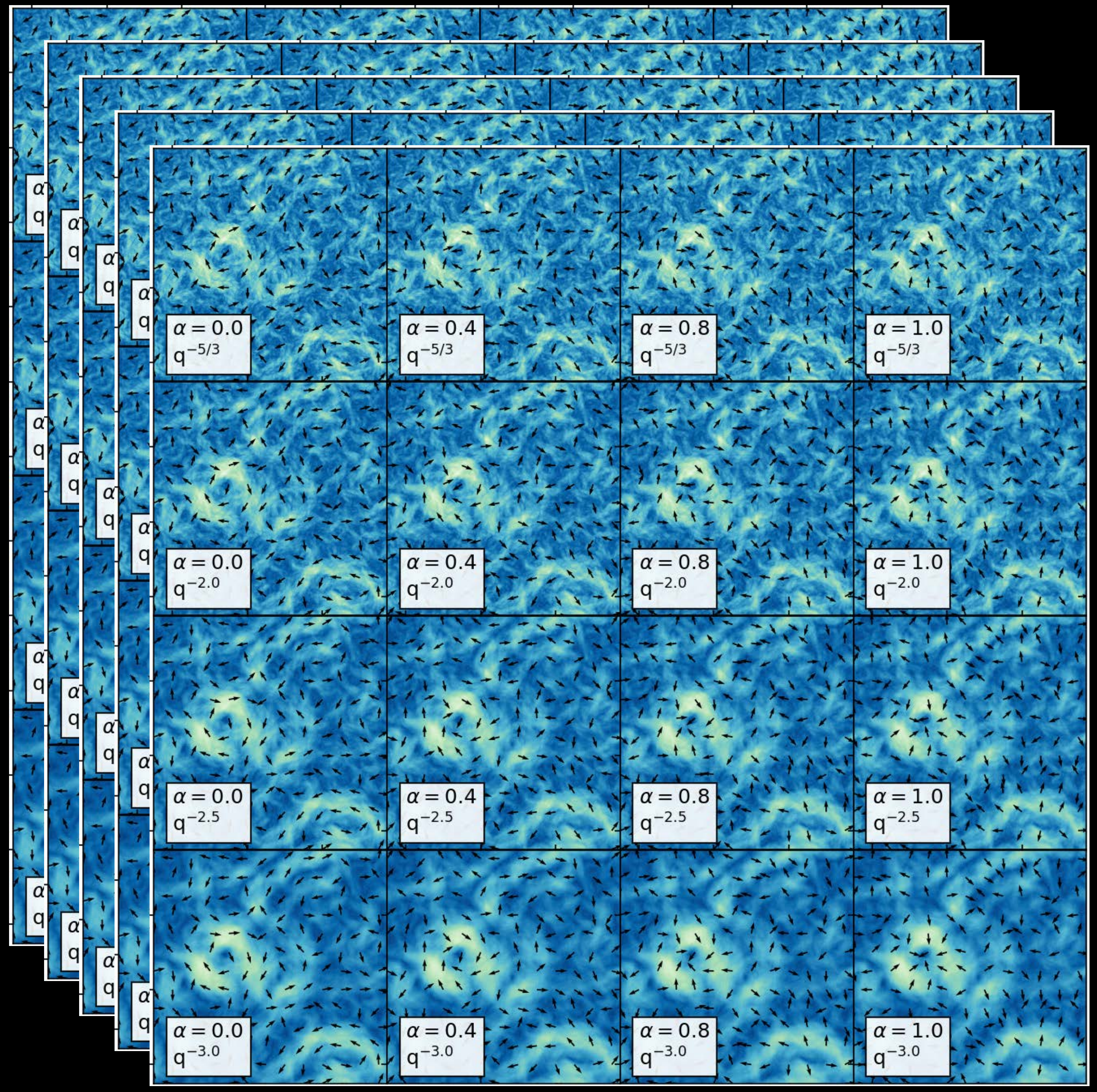
$$\frac{\partial N}{\partial t} + \nabla \cdot (\dot{\boldsymbol{x}} N) + \frac{\partial}{\partial k}(\dot{k} N) + \frac{\partial}{\partial \theta}(\dot{\theta} N) = 0$$

for an initially narrow-banded wave spectrum with waves propagating from the left side of the domain.

$\sigma_\theta = 12^\circ; \sigma_f = 0.01\mathrm{Hz}$



$\theta_0 = 270^\circ$



Divergence Fraction	0.0	0.2	0.4	0.6	0.8	1.0
Spectral Slope	-5/3	-2.0	-2.5	-3.0		
Wave Period	7.0s	10.3s	16.6s			

For each member of the ensemble, there are 72 possible combinations of wave period, flow spectral slope and divergence fraction giving a total of 3600 simulations.

Peak direction (refraction)

Changes in the peak wave **direction** are **larger** for **rotational** flows (left panels) than divergent (right panels).

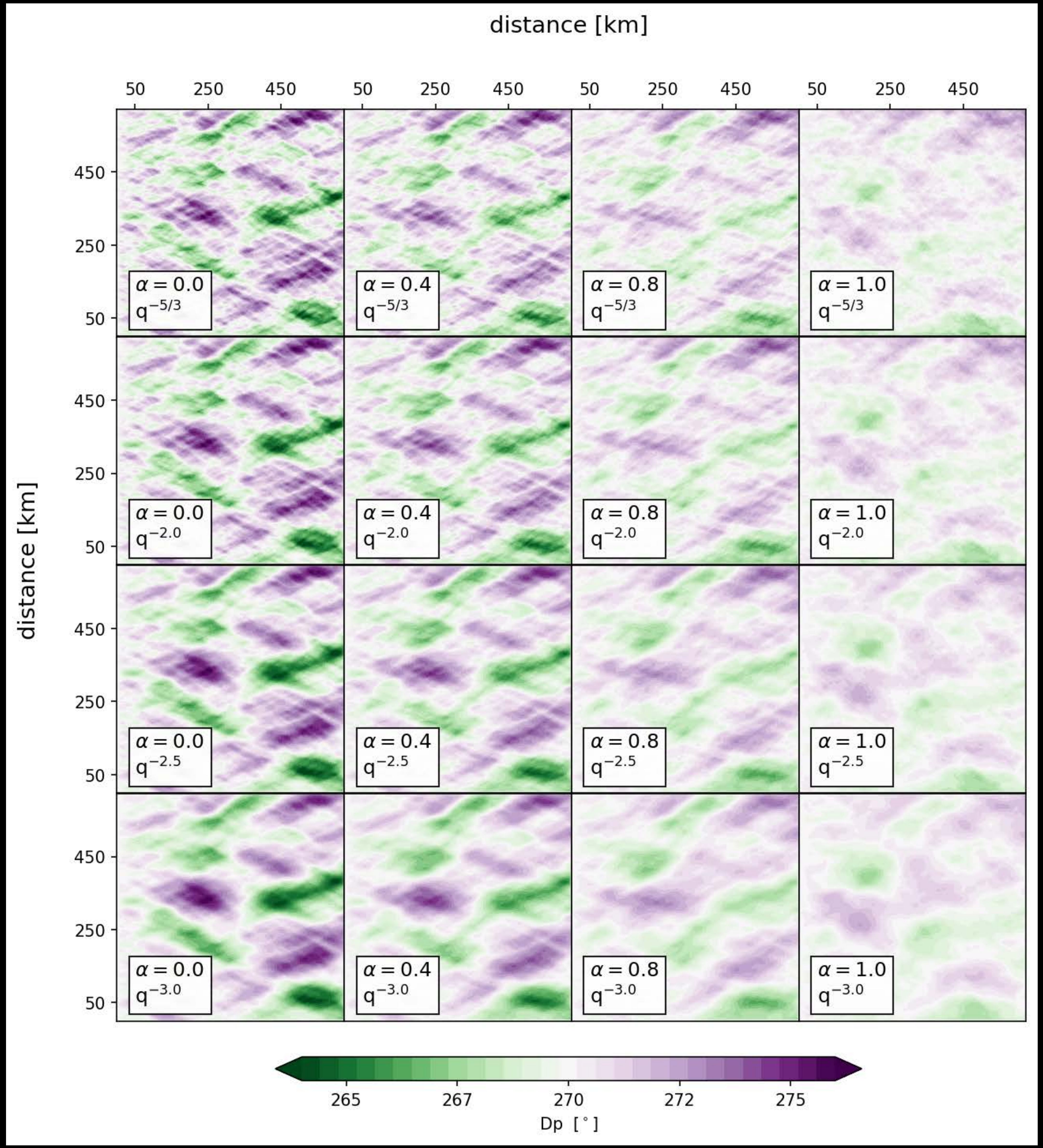
This result is consistent with the predictions from **ray theory:** in the limit of weak current gradients one can approximate the curvature of individual rays by the ratio between the **vorticity** of the flow and the **group velocity** of the waves:

$$\chi = \frac{\zeta}{c_g}$$

More vorticity → More divergence

Shallower spectral slope

Steeper spectral slope



Landau and Lifshitz (1959), Kenyon (1971), Dysthe (2001)

Significant wave height (Hs)

The spatial variability of significant wave height is highly dependent on the nature of the flow

Strong **refraction** leads to strong convergence and divergence of **wave action.**

As a consequence, there is more **structure** in the significant wave height (Hs) for the flow with more **vorticity**

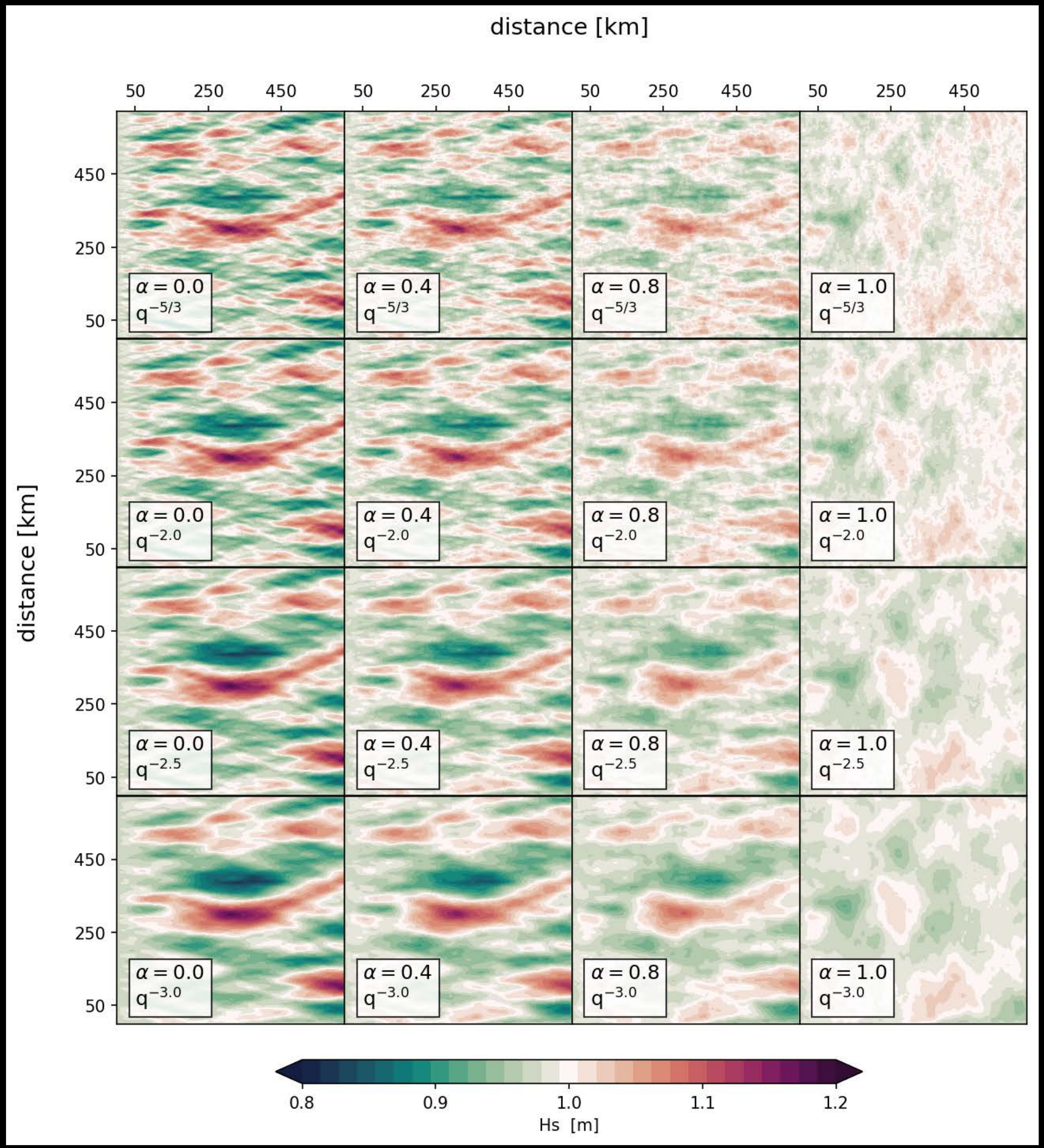
Changes of up to **30%** in **Hs** over scales of **tens** of **kilometers.**

Shallower KE spectral slope, are associated with finer structures in the Hs maps,

More vorticity → More divergence

Shallower spectral slope

Steeper spectral slope



More structure → Less structure

Directional spreading

Directional spreading **increases** as the waves propagate through the domain.

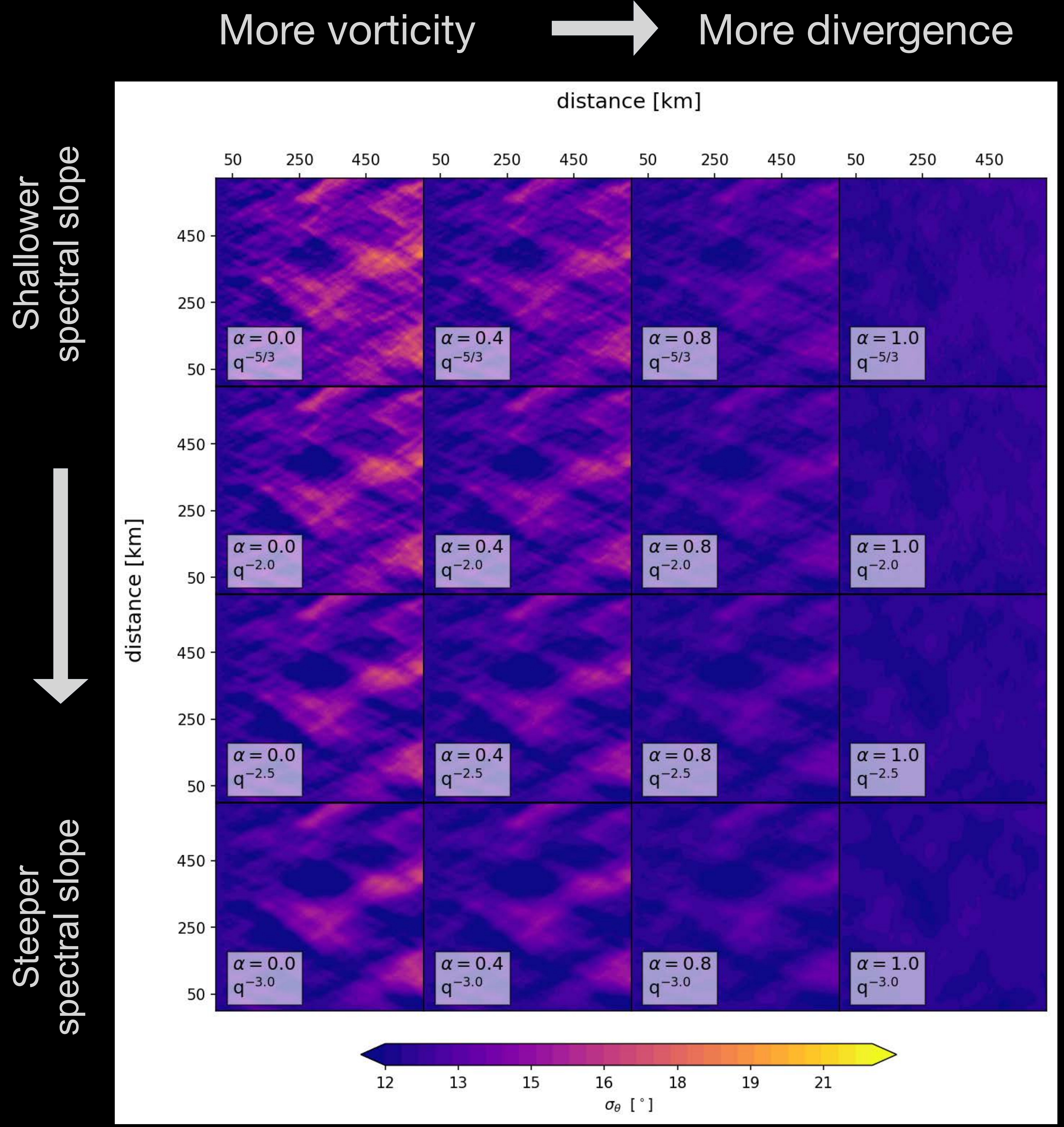
More vorticity leads to more spreading

Shallower spectral slope leads to higher spreading

Virtually no spreading for purely divergent flows.

The potential component of the flow has NO contribution to the directional diffusion of wave action.

See the theoretical explanation in Villas Bôas and Young, *in press* in JFM (email me for a copy).



Directional spreading

Directional spreading **increases** as the waves propagate through the domain.

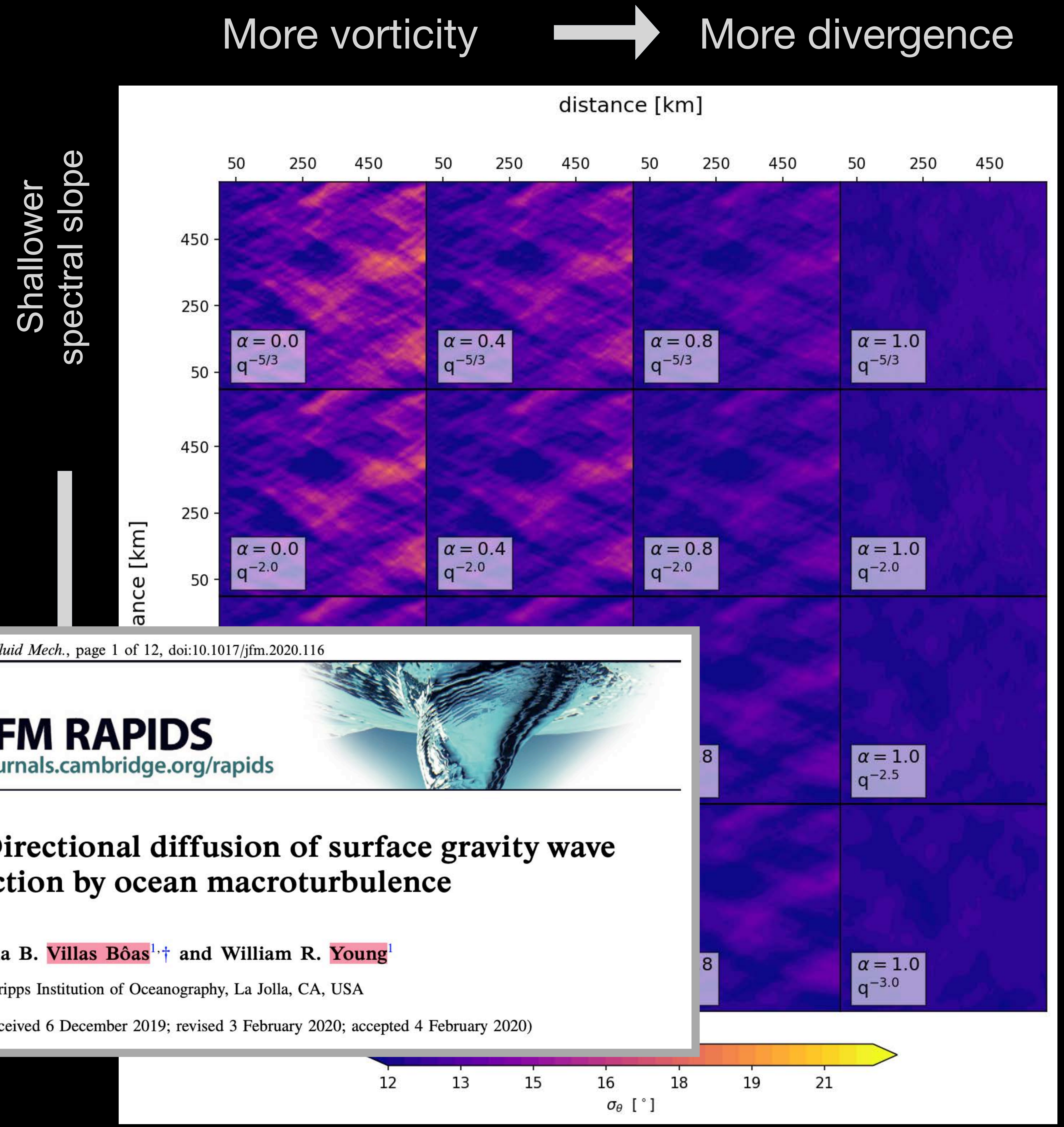
More vorticity leads to more spreading

Shallower spectral slope leads to higher spreading

Virtually no spreading for purely divergent flows.

The potential component of the flow has NO contribution to the directional diffusion of wave action.

See the theoretical explanation in Villas Bôas and Young, *in press* in JFM (email me for a copy).



J. Fluid Mech., page 1 of 12, doi:10.1017/jfm.2020.116

JFM RAPIDS
journals.cambridge.org/rapids

Directional diffusion of surface gravity wave action by ocean macroturbulence

Q1 Q2 Ana B. Villas Bôas[1,†] and William R. Young[1]

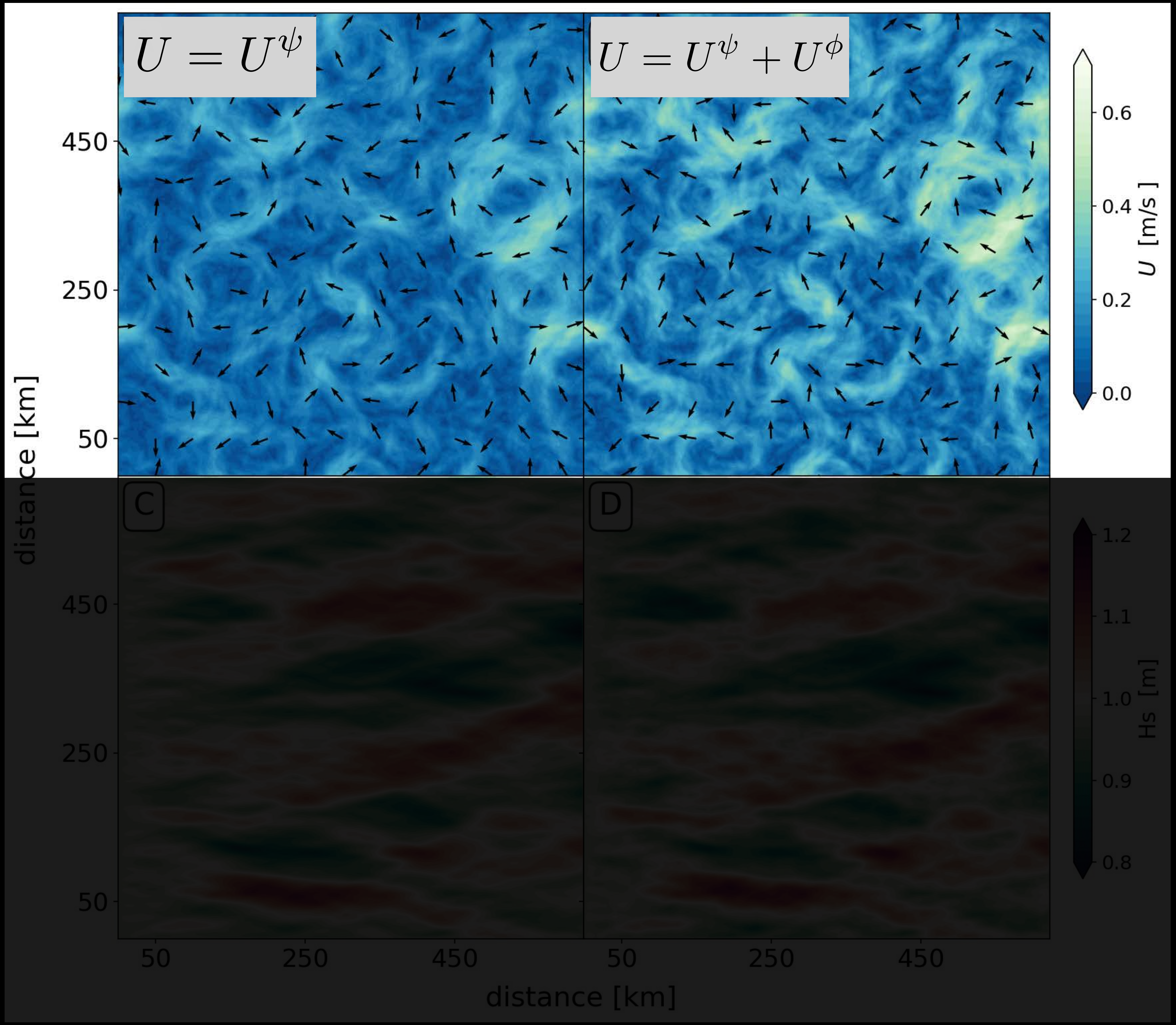
Q3 [1]Scripps Institution of Oceanography, La Jolla, CA, USA

(Received 6 December 2019; revised 3 February 2020; accepted 4 February 2020)

Hypothesis: The spatial variability of Hs is dominated by the spatial variability of the **rotational** component of the flow

Hypothesis: The spatial variability of Hs is dominated by the spatial variability of the **rotational** component of the flow

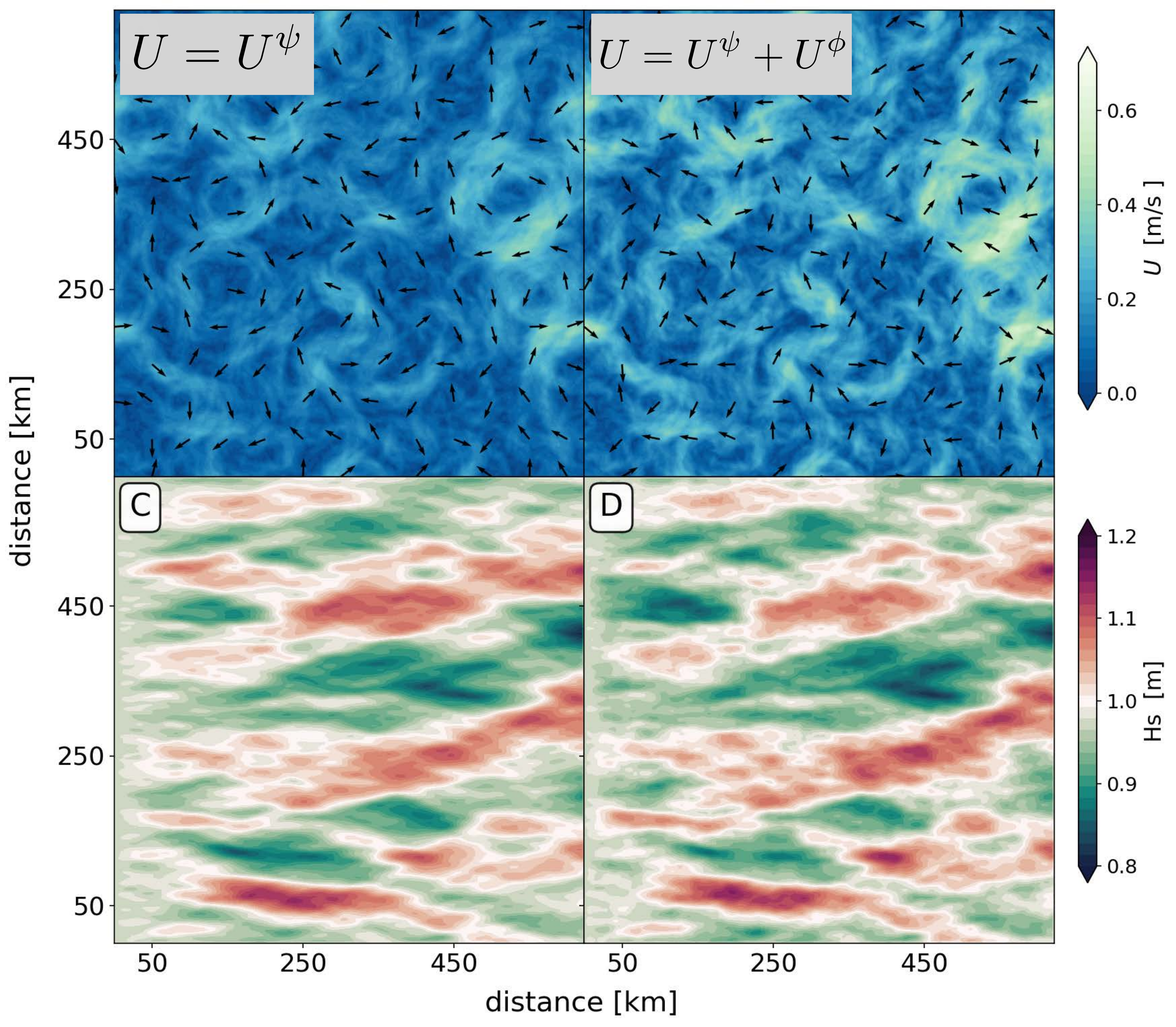
We **double** the kinetic **energy** of the purely rotational flow by adding a potential component.



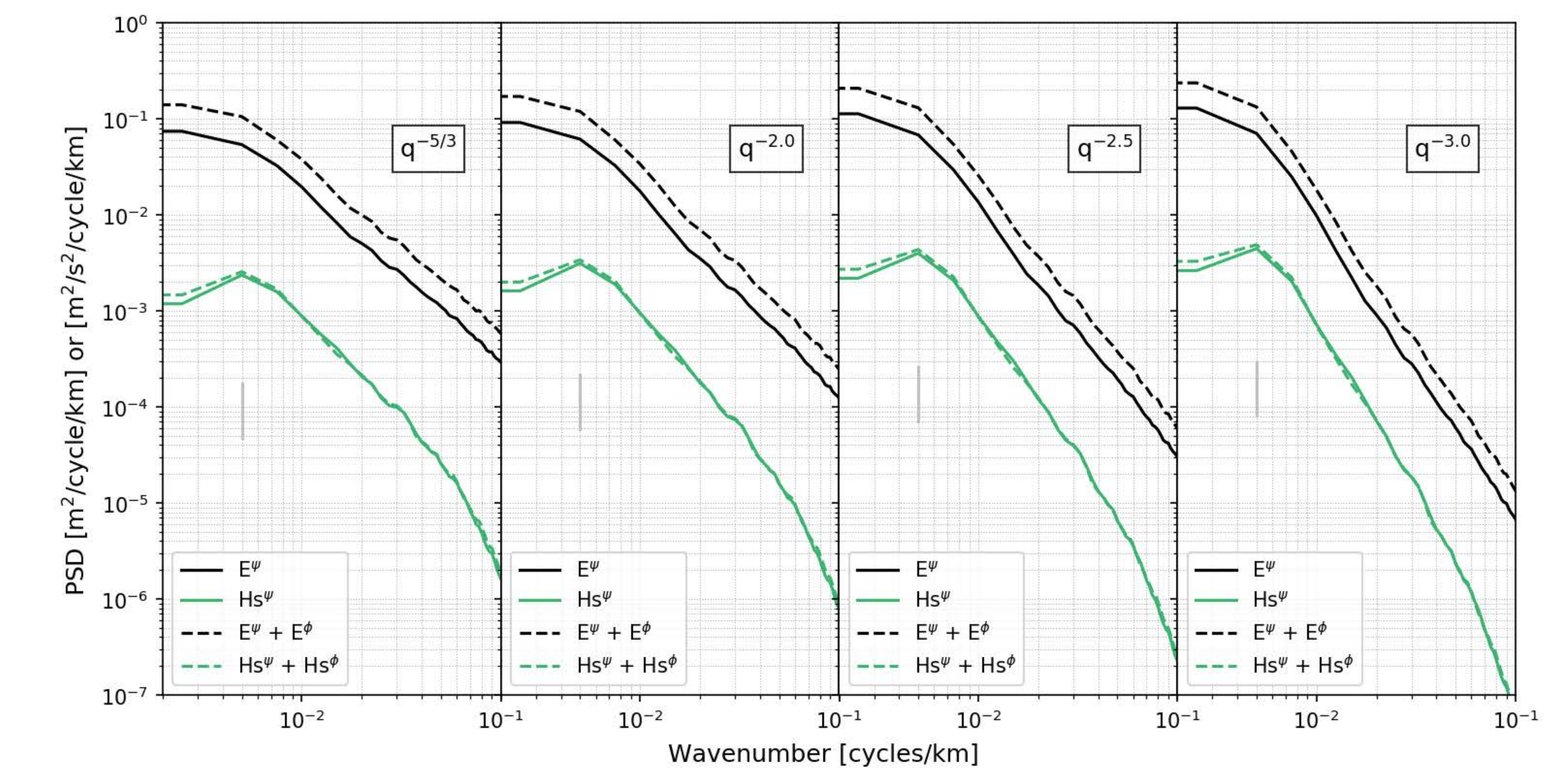
Hypothesis: The spatial variability of Hs is dominated by the spatial variability of the **rotational** component of the flow

We **double** the kinetic **energy** of the purely rotational flow by adding a potential component.

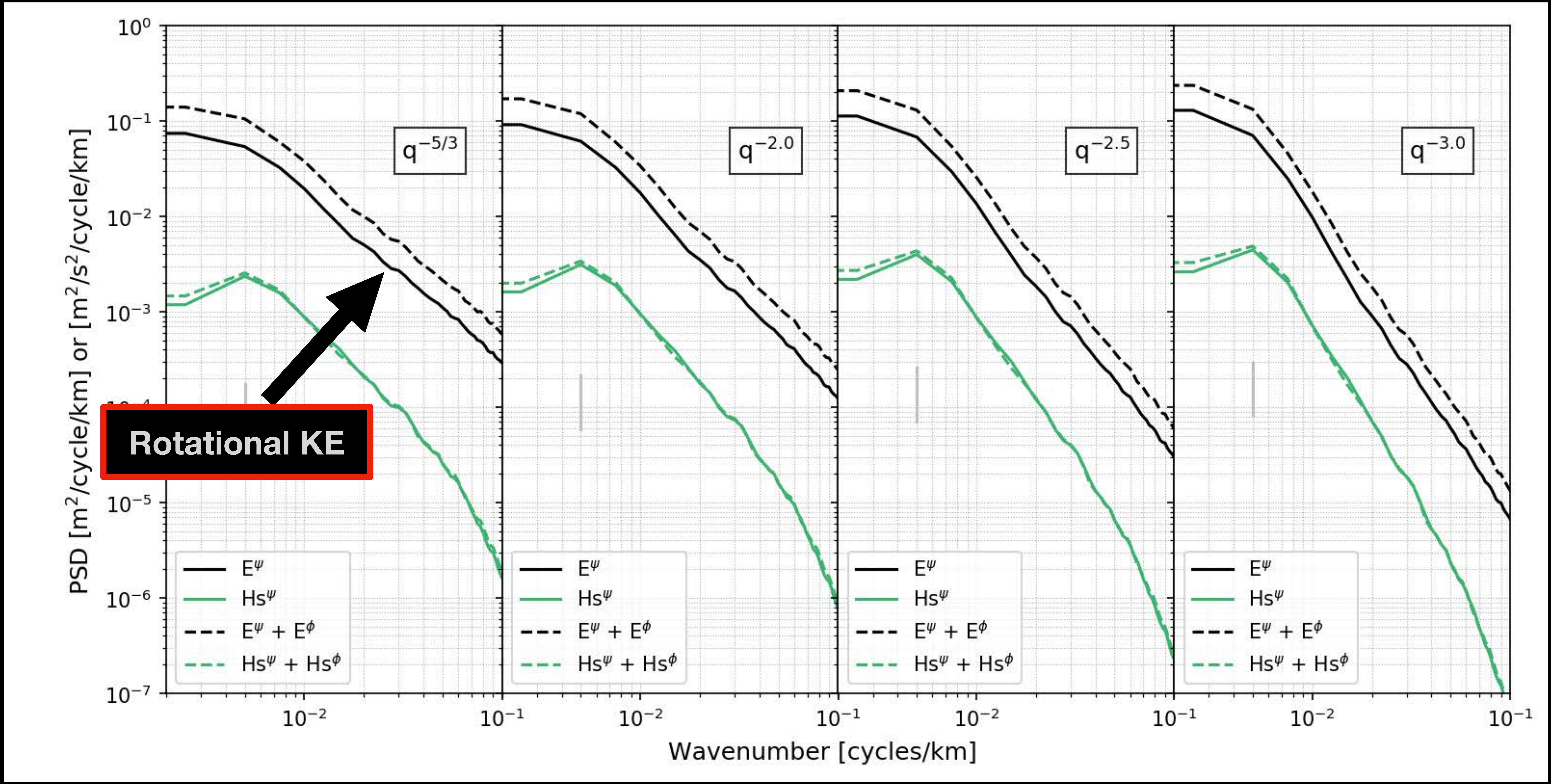
The Hs response is virtually the same: The spatial variability of Hs at these scales is not affected by the potential component of the flow.



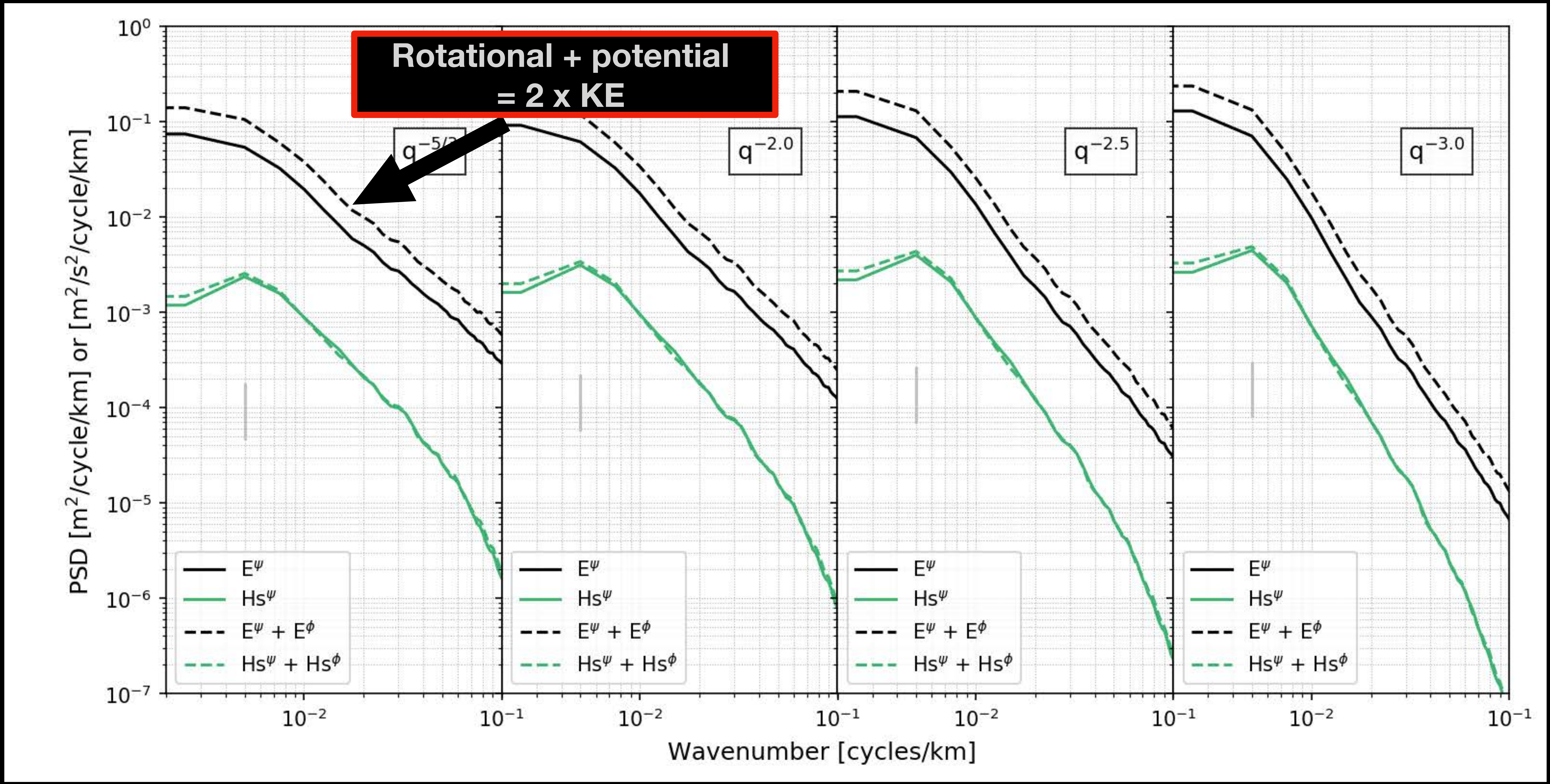
- The wavenumber spectra of Hs (averaged across the ensemble) is **not** affected by the **potential** flow



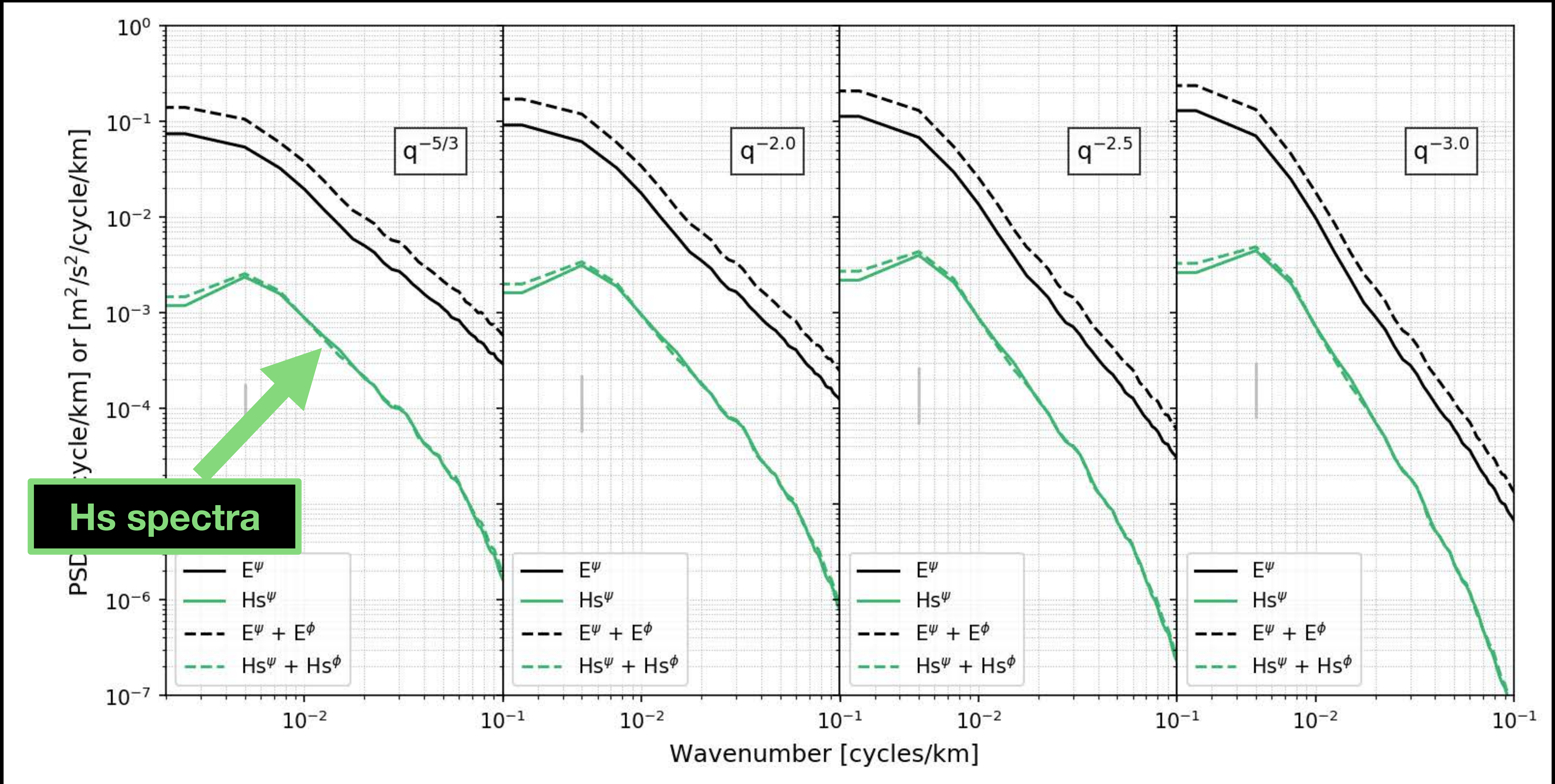
- The wavenumber spectra of Hs (averaged across the ensemble) is **not** affected by the **potential** flow



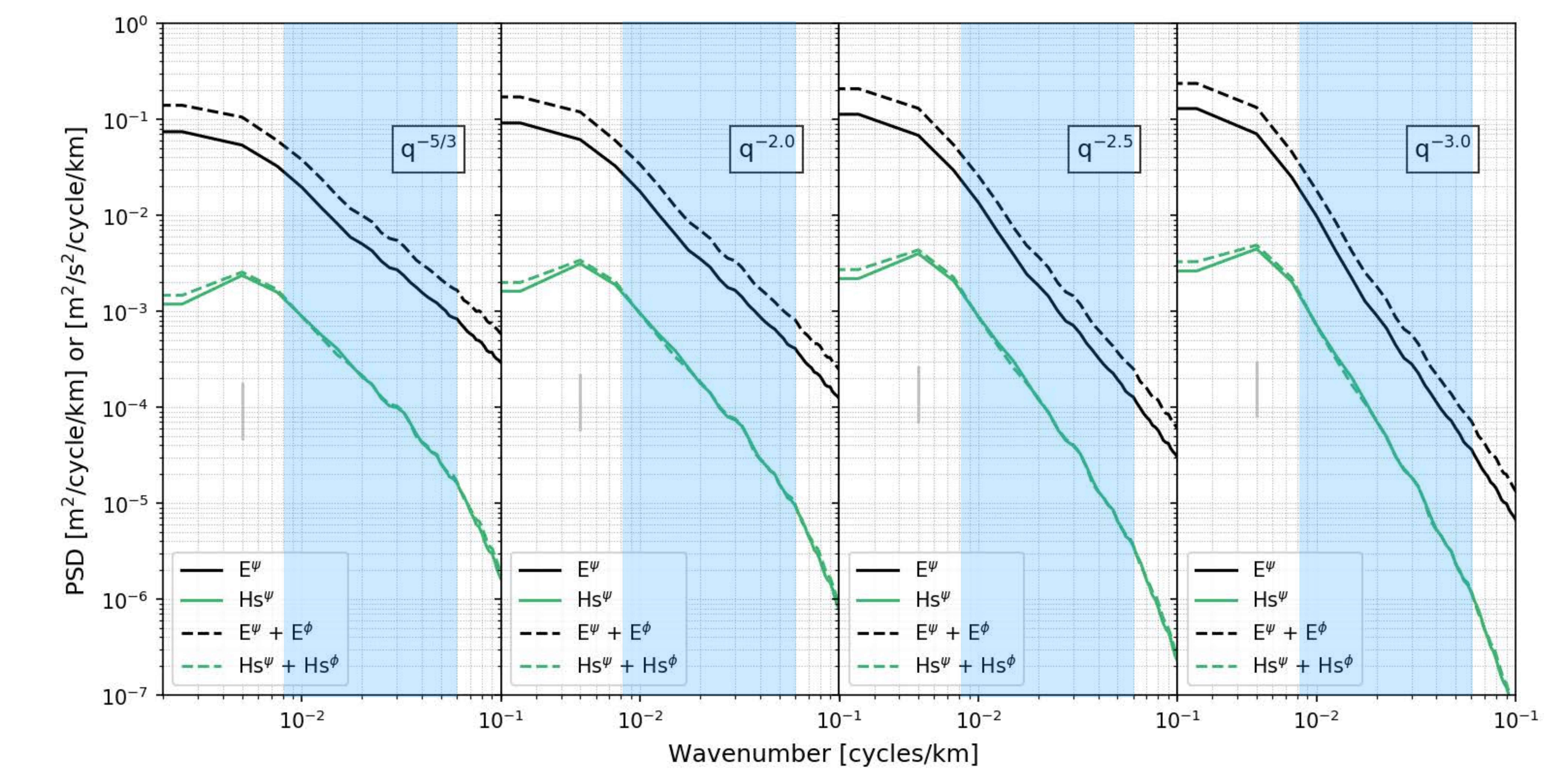
The wavenumber spectra of Hs (averaged across the ensemble) is **not** affected by the **potential** flow



- The wavenumber spectra of Hs (averaged across the ensemble) is **not** affected by the **potential** flow



- The wavenumber spectra of Hs (averaged across the ensemble) is **not** affected by the **potential** flow



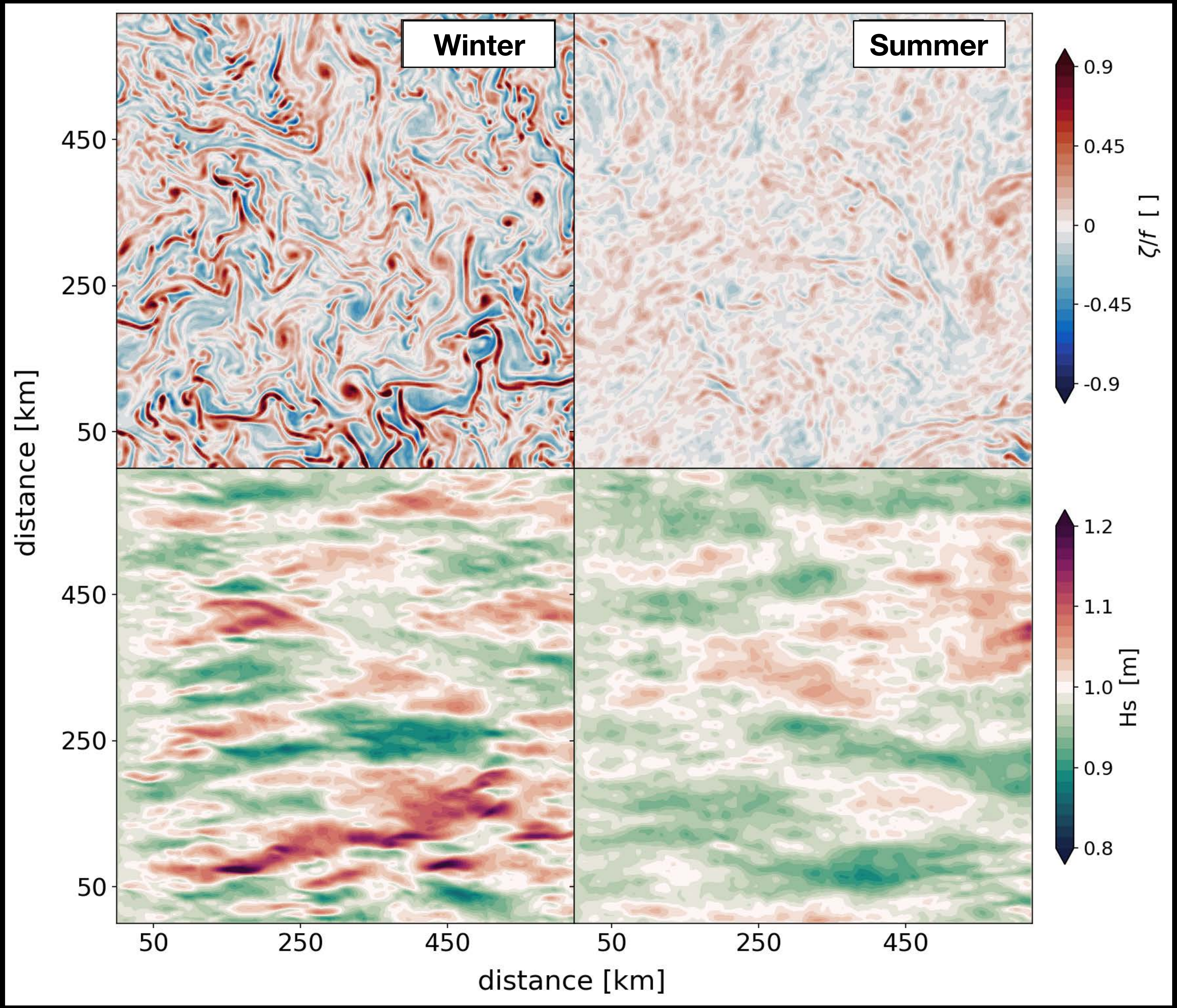
- Steeper KE spectral slopes lead to steeper Hs spectral slopes

Do these results hold for realistic currents?

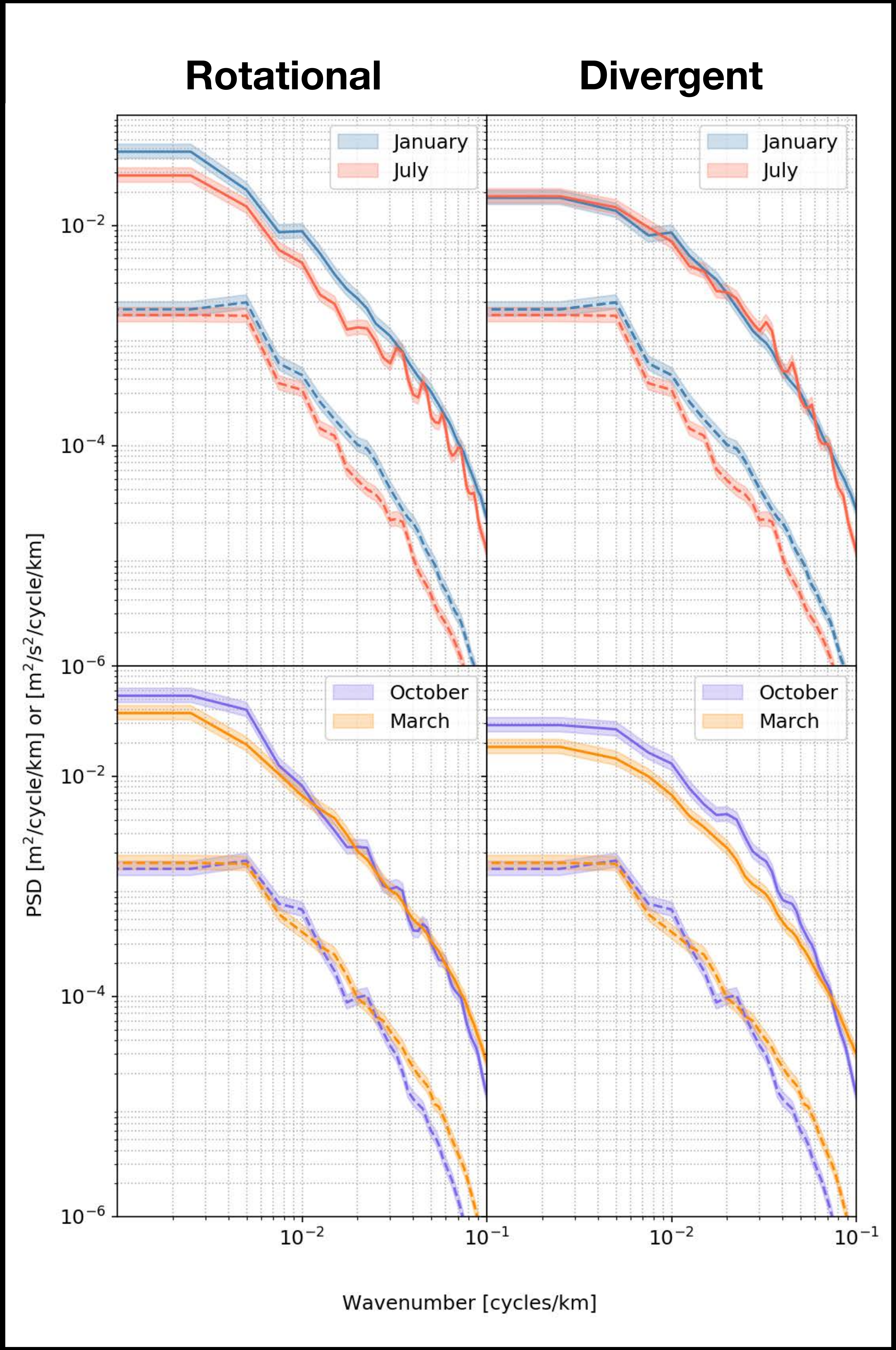
We used an equivalent setup to run WaveWatch III forced with realistic currents from the MITgcm LLC4320 in the CCS region.

This example illustrates how the **seasonality** of the **submesoscale** in the CCS affects the wave field leading to stronger/weaker gradients in Hs.

LLC4320 vorticity

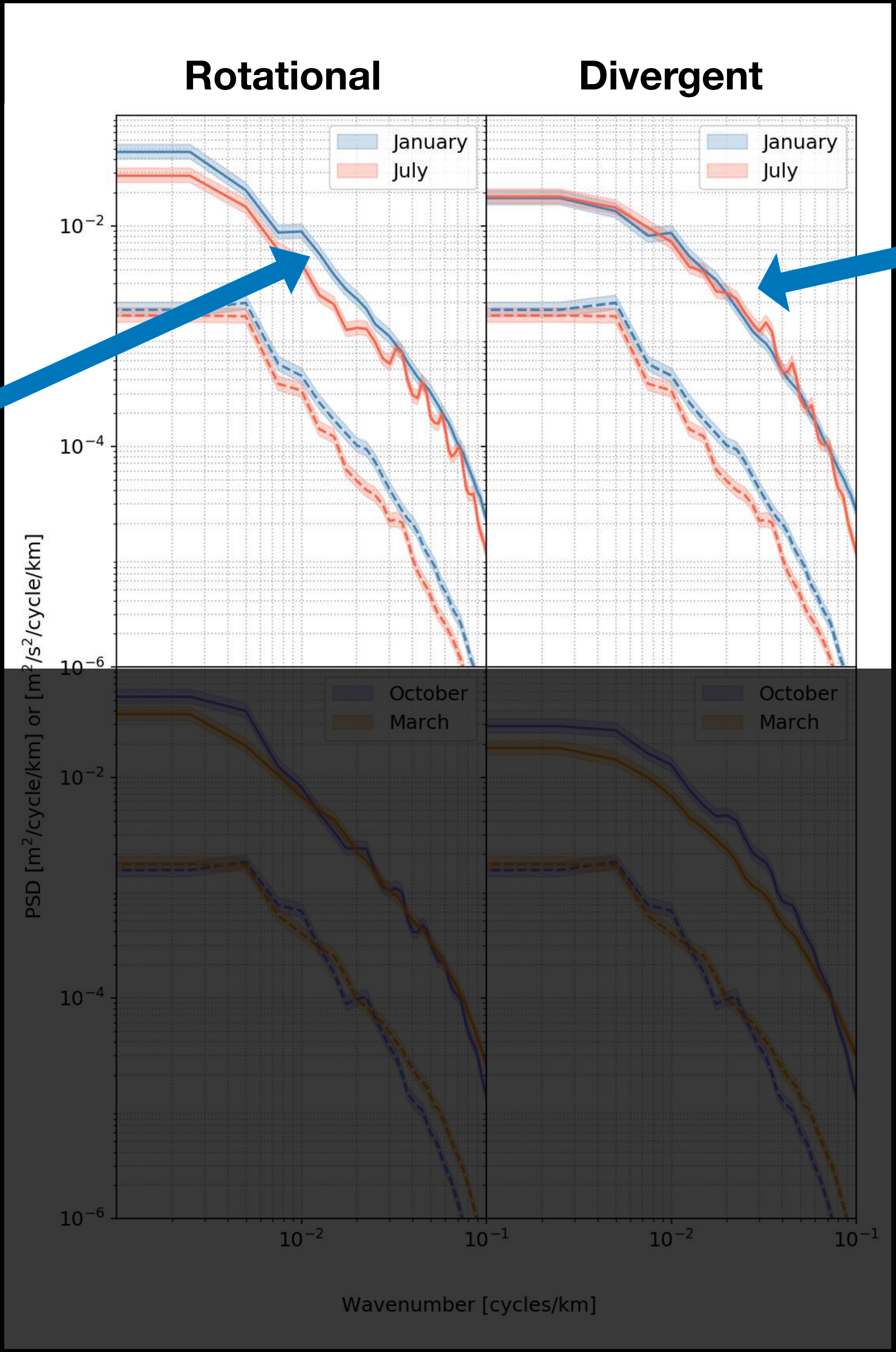


Seasonality of the surface kinetic energy in the CCS



Seasonality of the surface kinetic energy in the CCS

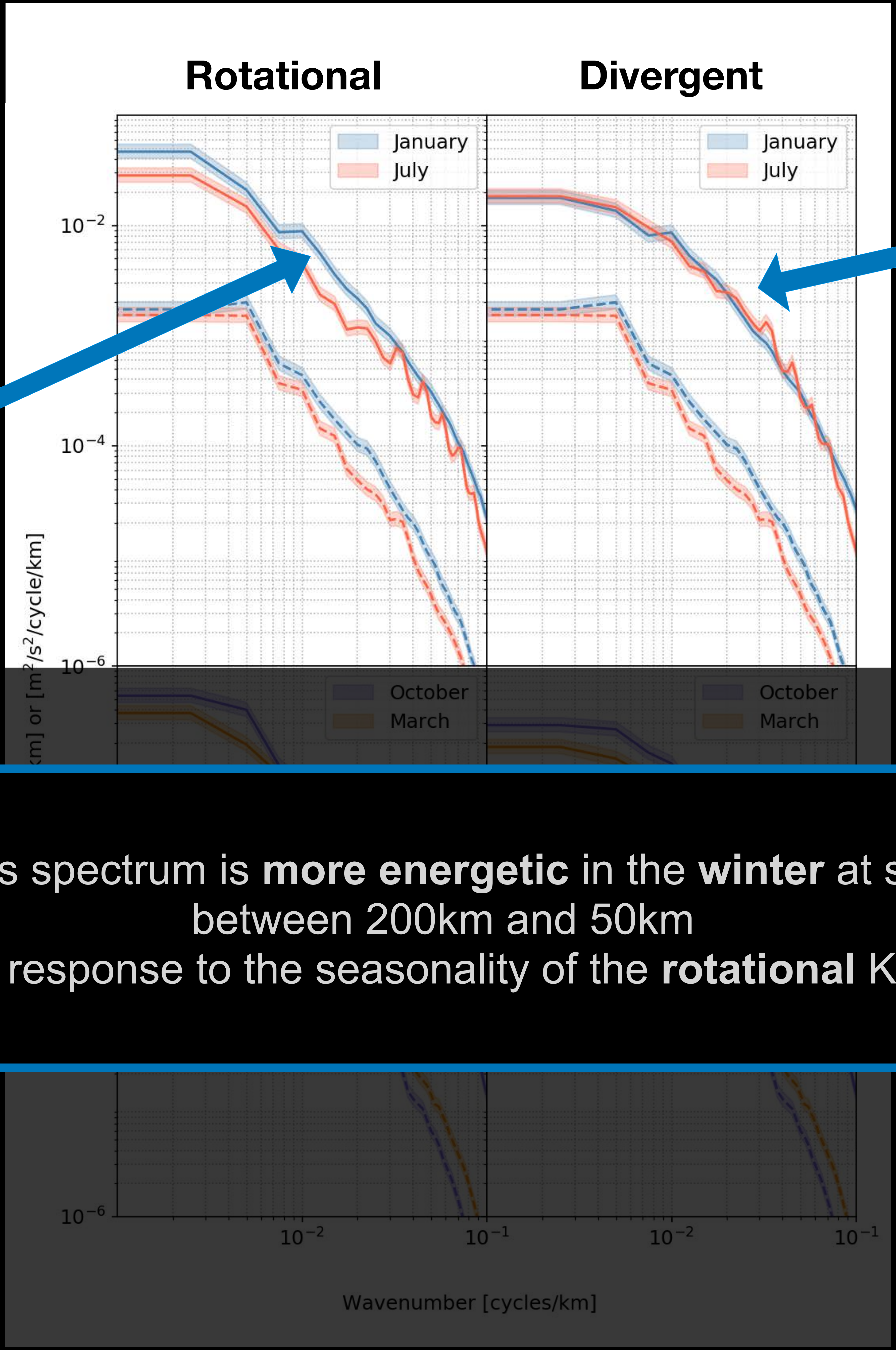
The surface kinetic energy at submesoscales in the CCS is dominated by balanced motions (rotational) in late winter/spring.



Between January and July the KE spectra of the **divergent** component **do not** change much.

Seasonality of the surface kinetic energy in the CCS

The surface kinetic energy at submesoscales in the CCS is dominated by balanced motions (rotational) in late winter/spring.

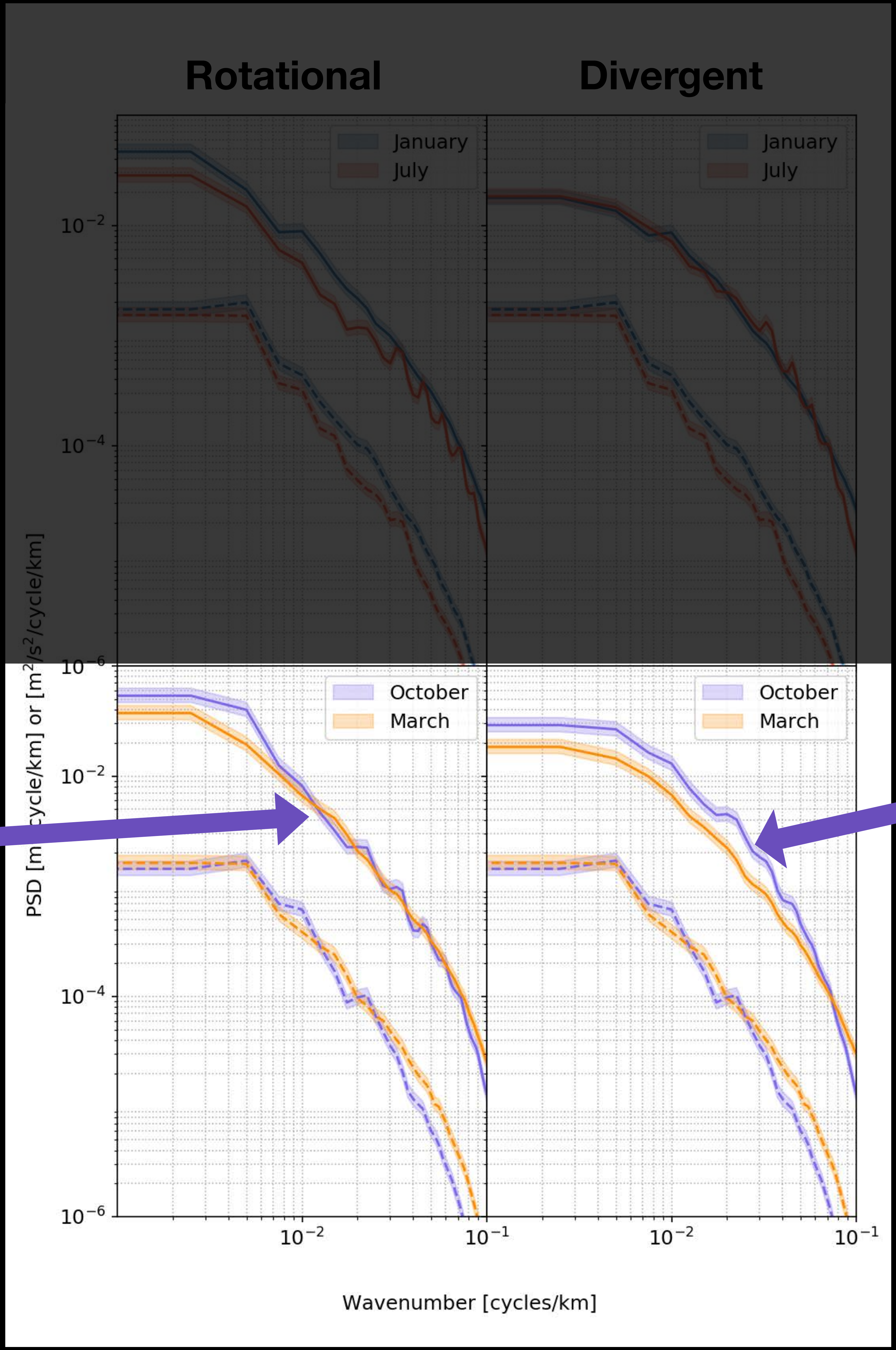


Between January and July the KE spectra of the **divergent** component **do not** change much.

The Hs spectrum is **more energetic** in the **winter** at scales between 200km and 50km in response to the seasonality of the **rotational** KE

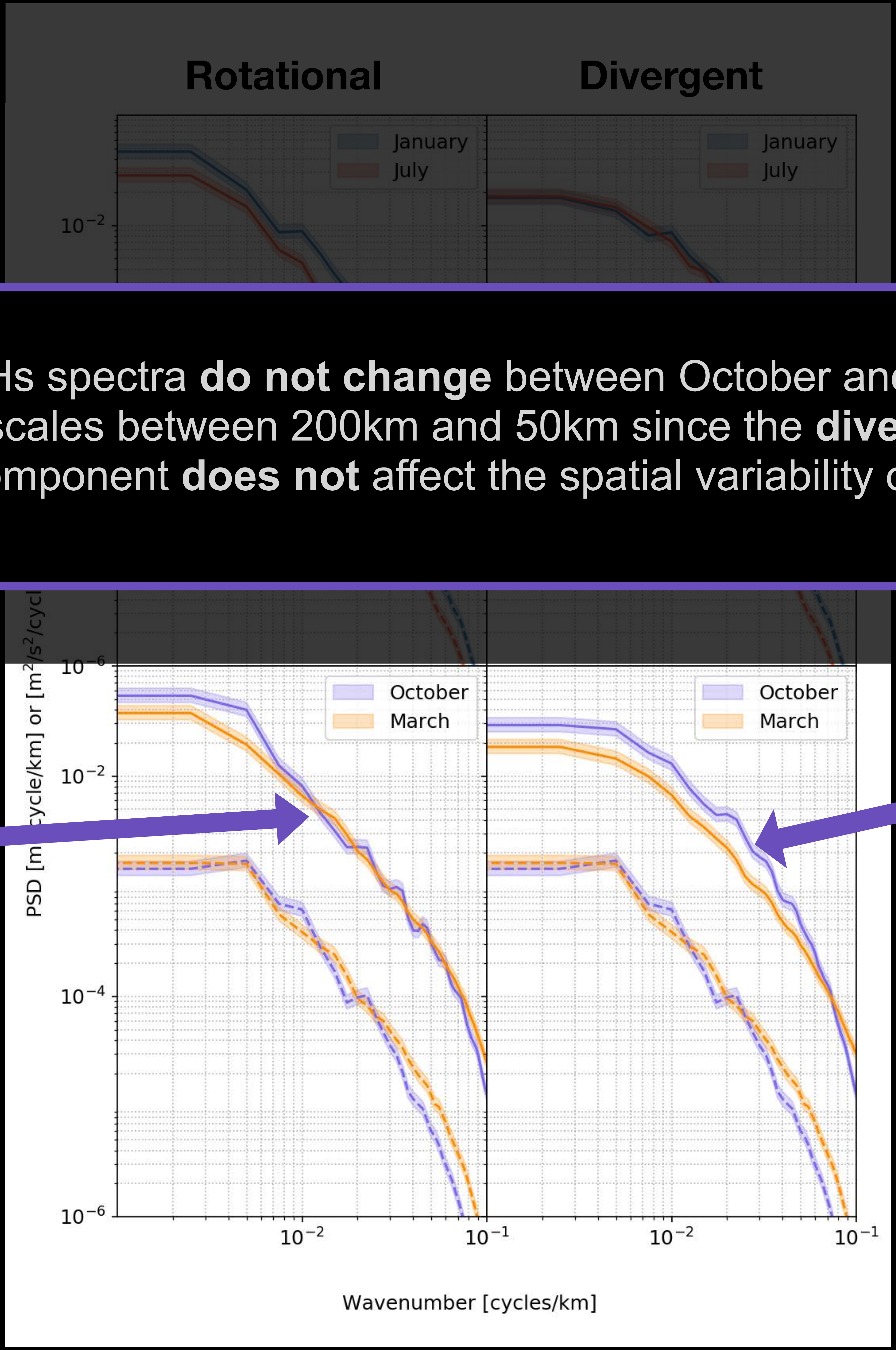
Seasonality of the surface kinetic energy in the CCS

Between October and March the KE spectra of the **solenoidal** component **do not** change much at scales smaller than 200km.



Between January and July the KE spectra of the **divergent** component **do not** change much.

Seasonality of the surface kinetic energy in the CCS



The Hs spectra **do not change** between October and March at scales between 200km and 50km since the **divergent** component **does not** affect the spatial variability of Hs

Between October and March the KE spectra of the **solenoidal** component **do not** change much at scales smaller than 200km.

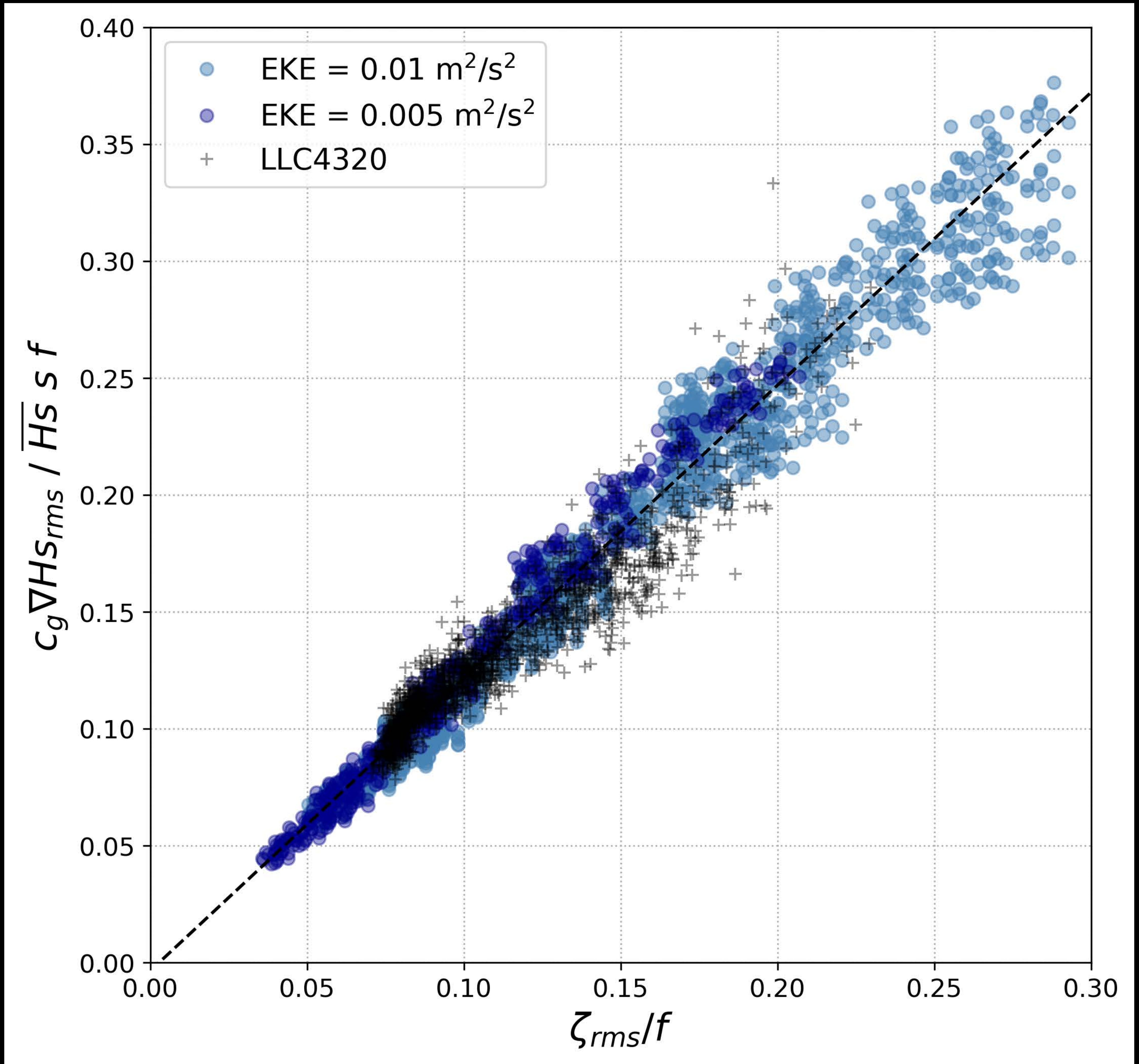
Between January and July the KE spectra of the **divergent** component **do not** change much.

Spatial gradients of Hs are correlated with vorticity

- Direct relationship between spatial gradients of significant wave height and the vertical vorticity of the flow ($r^2 > 0.9$):

$$c_g \frac{(\nabla Hs)_{rms}}{\overline{Hs}s} = \zeta_{rms}$$

- Good agreement between the idealized currents and the LLC4320 in the CCS region.



Could the signature of currents on waves be used to infer properties of the flow?

Current **speed** from the **LLC4320**

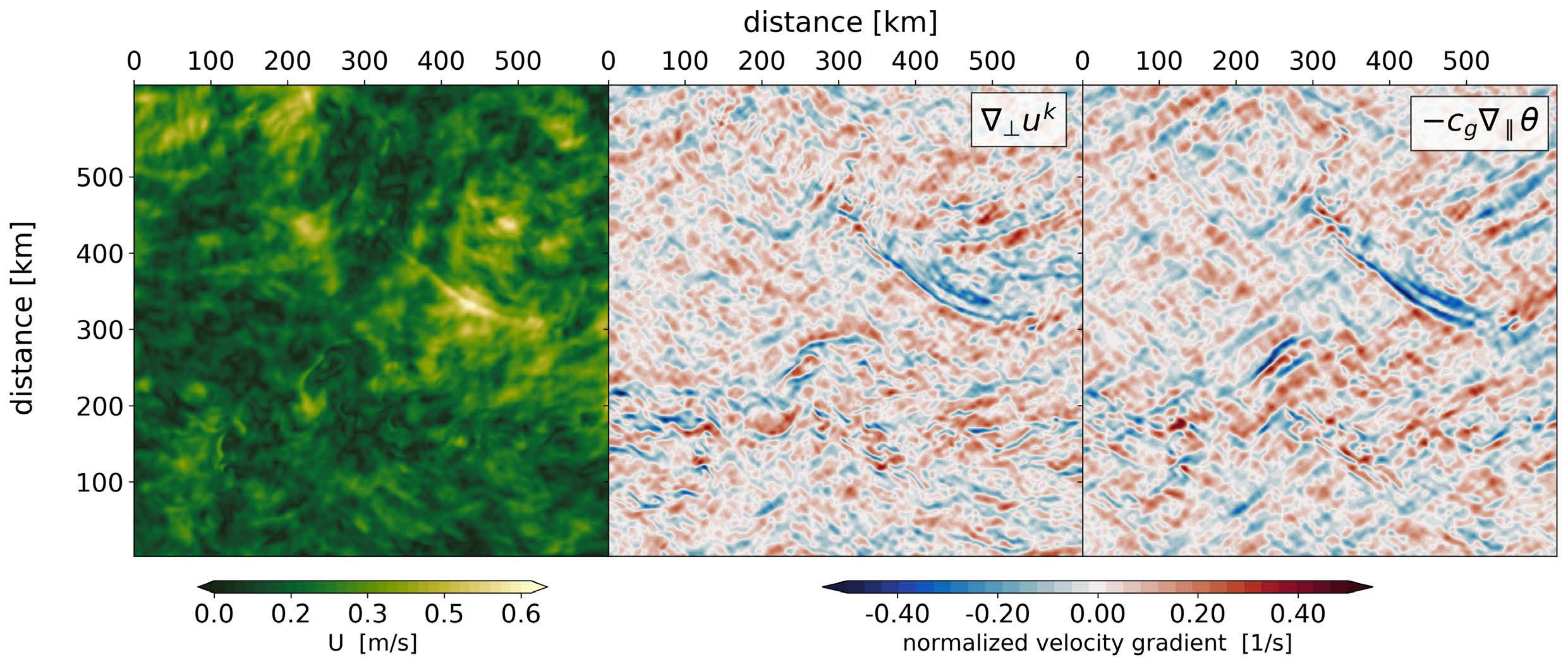
Current **gradient** from the **LLC4320**

Current gradient estimated from the **gradient** of the wave **direction**

Assuming that the current speed is small in comparison to the group velocity of the waves, the ray equation for changes in wave direction can be approximated by:

$$\hat{n} \cdot \boldsymbol{\nabla}(\hat{k} \cdot \boldsymbol{U}) \approx -c_g(\hat{k} \cdot \boldsymbol{\nabla})\theta$$

such that the gradient of the current can be obtained from the gradient in the wave direction.



Could the signature of currents on waves be used to infer properties of the flow?

Assuming that the current speed is small in comparison to the group velocity of the waves, the ray equation for changes in wave direction can be approximated by:

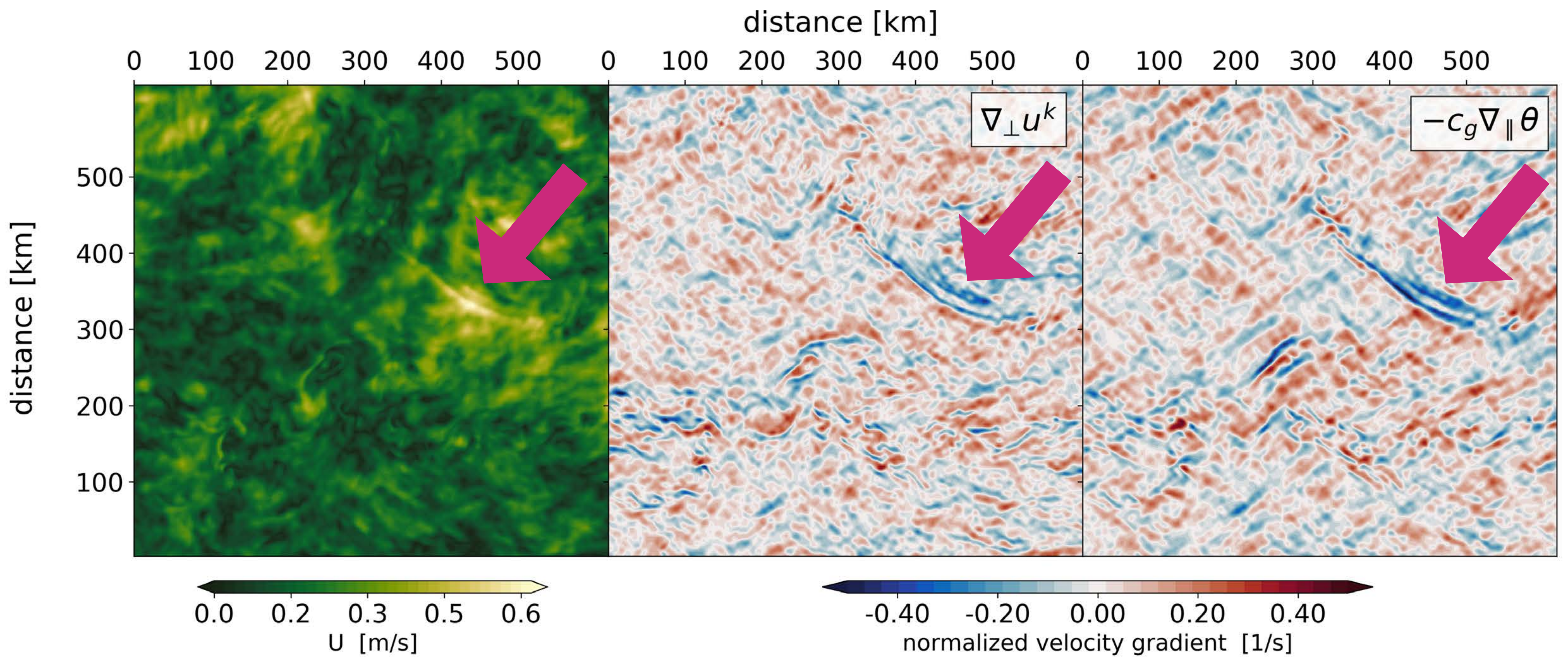
$$\hat{n} \cdot \boldsymbol{\nabla}(\hat{k} \cdot \boldsymbol{U}) \approx -c_g(\hat{k} \cdot \boldsymbol{\nabla})\theta$$

such that the gradient of the current can be obtained from the gradient in the wave direction.

Current **speed** from the **LLC4320**

Current **gradient** from the **LLC4320**

Current gradient estimated from the **gradient** of the wave **direction**



Climate modeling

- Surface wave physics is key to improving climate models and better representing the coupling between the ocean and the atmosphere

Climate modeling

- Surface wave physics is key to improving climate models and better representing the coupling between the ocean and the atmosphere

Wave modeling

- Wave models without currents do not capture the small-scale and high-frequency variability of wave heights (and other wave properties).

- Having current forcing in numerical wave models could help reduce directional and arrival time biases, but doing that globally is somewhat impractical: it is computationally costly and surface current observations at scales shorter than 100 km are rare.

Climate modeling

- Surface wave physics is key to improving climate models and better representing the coupling between the ocean and the atmosphere

Wave modeling

- Wave models without currents do not capture the small-scale and high-frequency variability of wave heights (and other wave properties).
- Having current forcing in numerical wave models could help reduce directional and arrival time biases, but doing that globally is somewhat impractical: it is computationally costly and surface current observations at scales shorter than 100 km are rare.

Remote sensing

- Surface waves and their spatial gradients are often a source of error for remote sensing measurements (e.g., sea state bias, layover, wave-induced Doppler…).
  - How well do we understand sea state gradients? Waves respond very differently to vorticity and divergence.
- With **present altimetry** it's straight forward to get **geostrophic** currents from **SSH** measurements. **SWOT** we will be measuring at **scales** where the **SSH** signal might **not** be associated motions that are in **geostrophic** balance
- The signature of currents on waves could potentially be used to inferrer properties of the flow (e.g. transition from balanced unbalanced).

Extra

Peak period (Doppler)

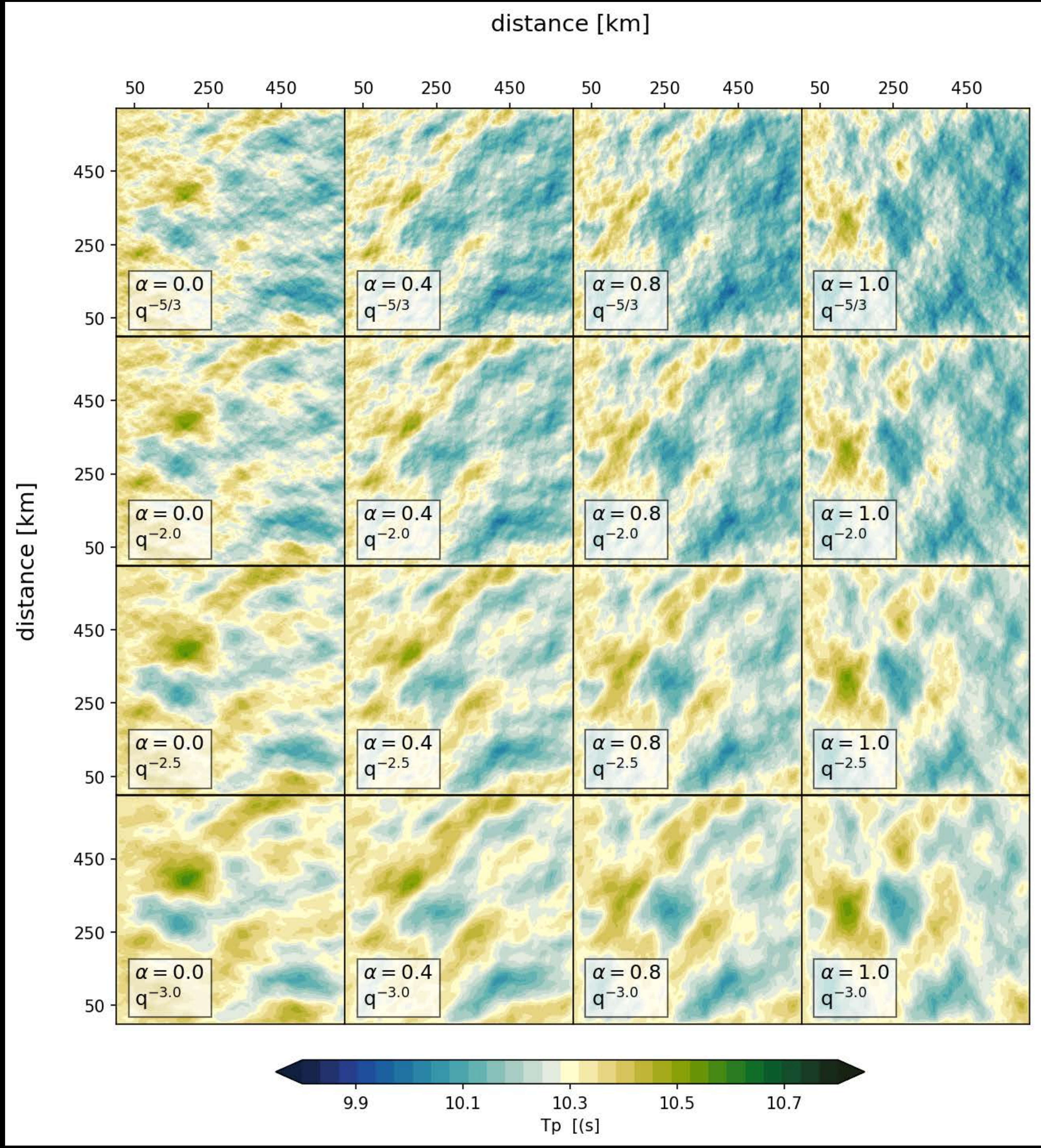
The effect of random surface currents on the peak period is relatively small (< 3%).

The spatial pattern of Hs in the purely divergent case (last column) nearly matches the spatial pattern of the peak period ->

Changes in Hs for the purely divergent cases are direct response to changes in period (frequency)

$$N = \frac{E}{\sigma} = const$$

More vorticity → More divergence



Peak period (Doppler)

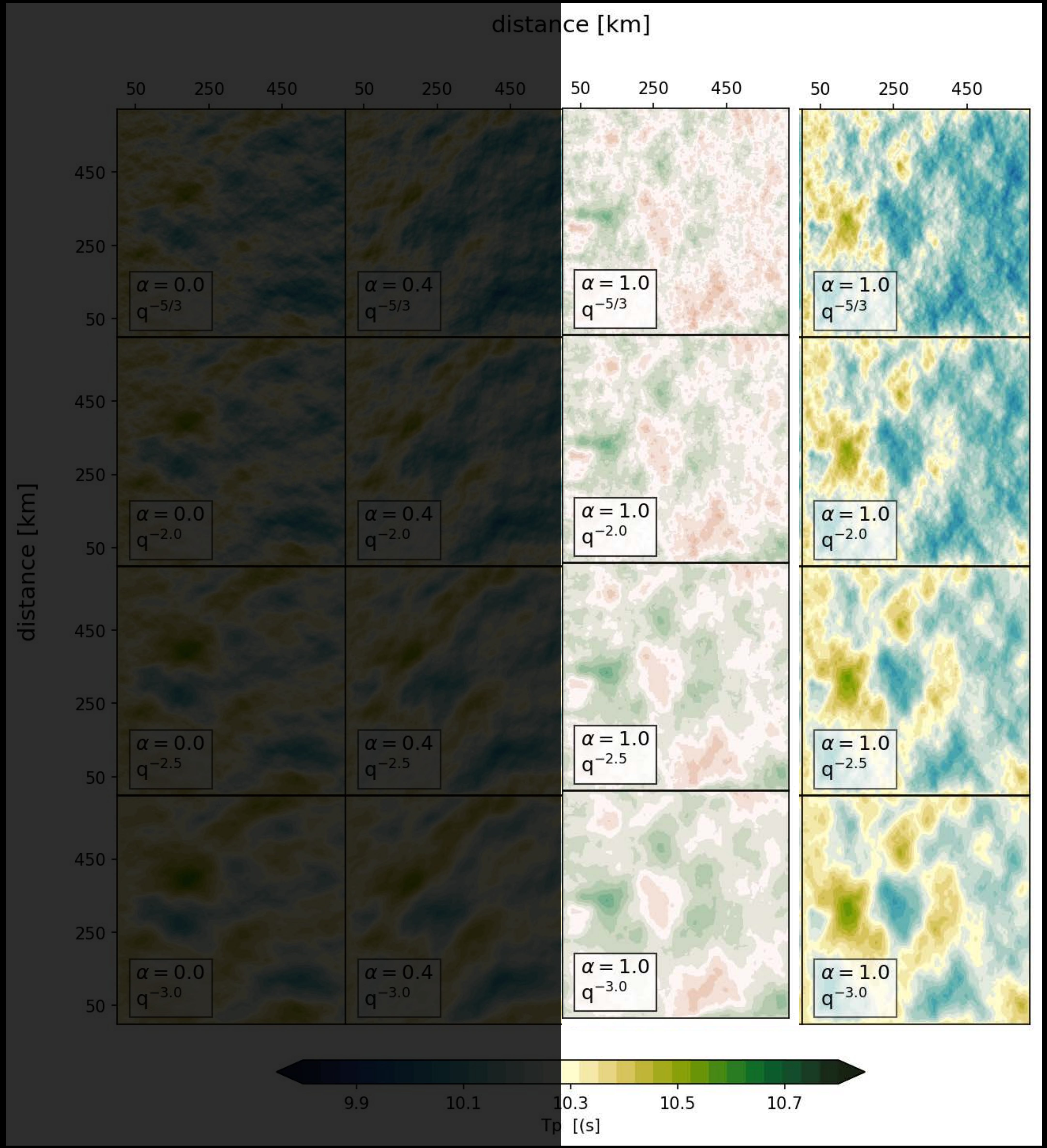
The effect of random surface currents on the peak period is relatively small (< 3%).

The spatial pattern of Hs in the purely divergent case (last column) nearly matches the spatial pattern of the peak period ->

Changes in Hs for the purely divergent cases are direct response to changes in period (frequency)

$$N = \frac{E}{\sigma} = const$$

More vorticity → More divergence



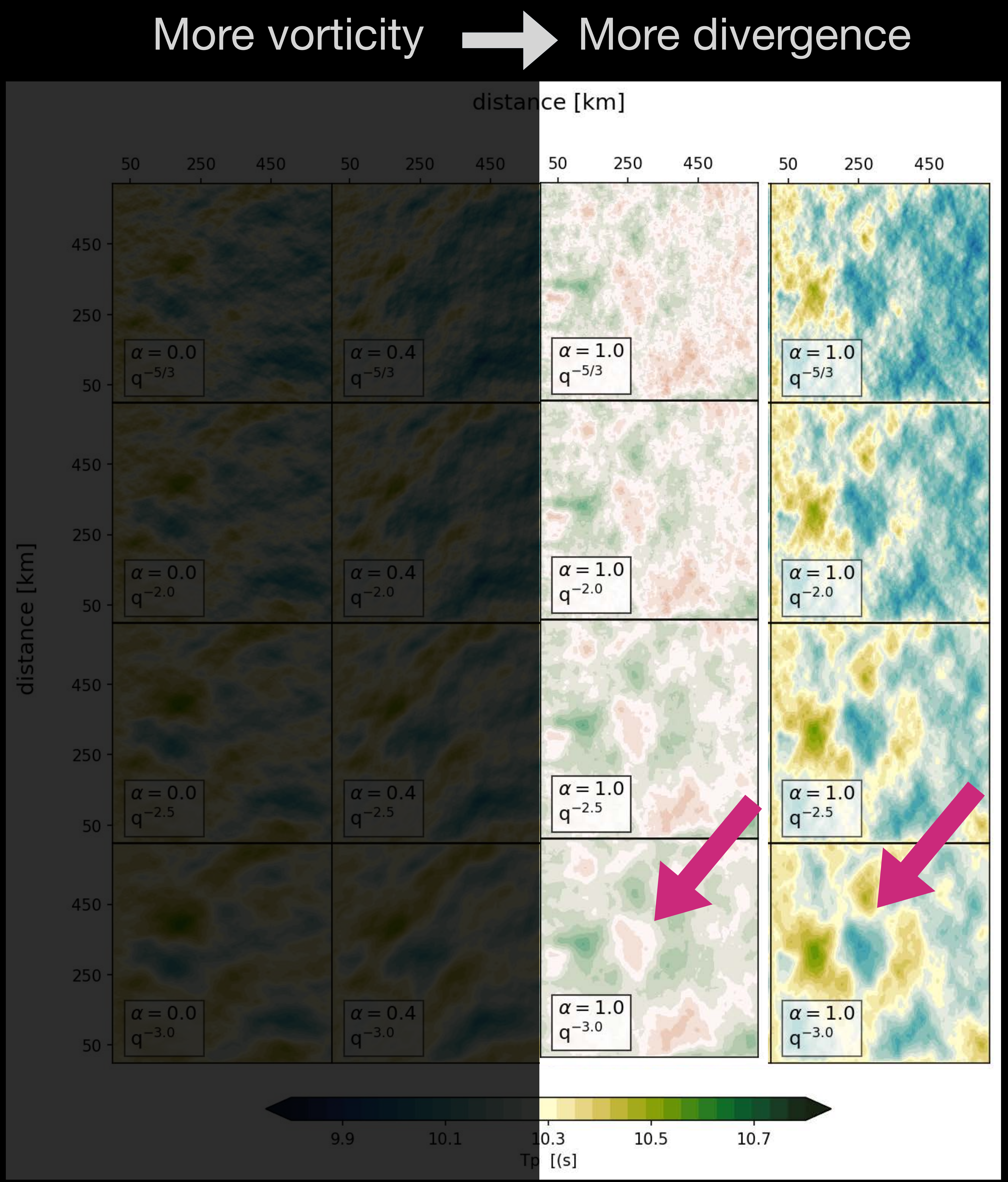
Peak period (Doppler)

The effect of random surface currents on the peak period is relatively small (< 3%).

The spatial pattern of Hs in the purely divergent case (last column) nearly matches the spatial pattern of the peak period ->

Changes in Hs for the purely divergent cases are direct response to changes in period (frequency)

$$N = \frac{E}{\sigma} = const$$

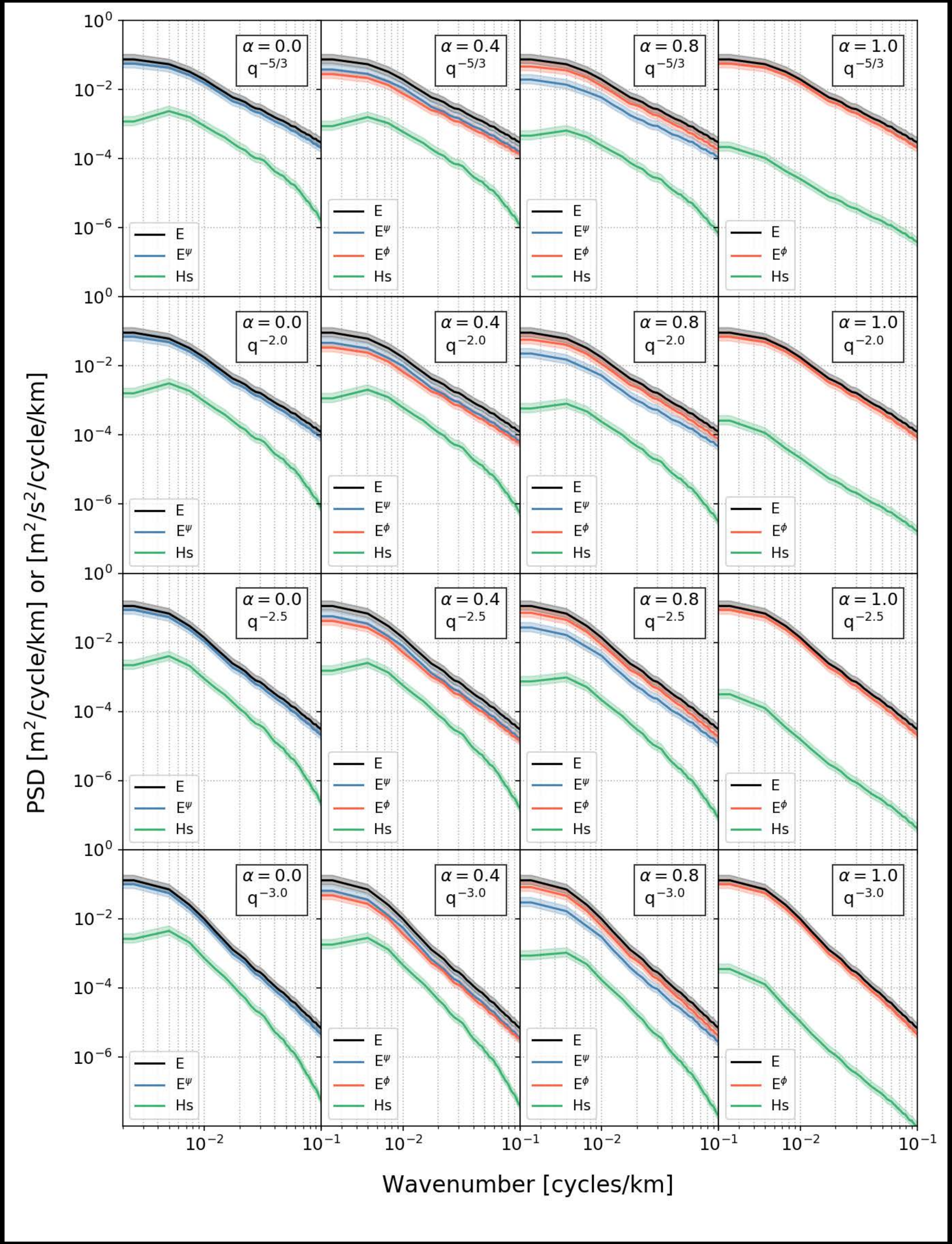


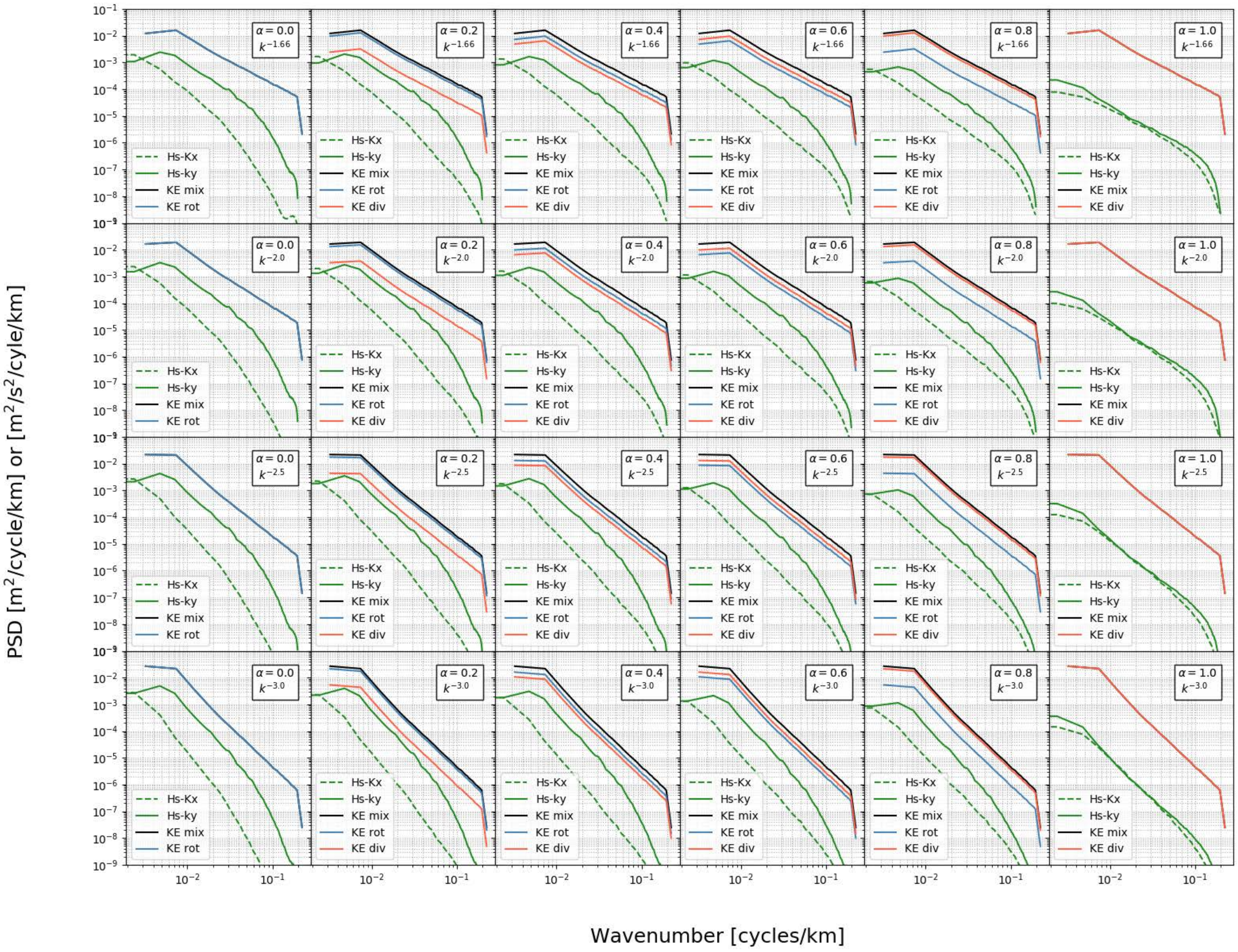
Wavenumber spectra of Hs

Varying the ratio of rotational to divergent flow while keeping the same EKE wavenumber spectrum (fixed spectral slope and variance) leads to strikingly different responses in the **Hs wavenumber spectra**.

In agreement with the cases illustrated in the snapshots, the **variance of Hs** is **larger** for purely **rotational** flows, in particular at lower wavenumbers.

For cases where the flow is predominantly **divergent**, the Hs wavenumber spectra have a more uniform slope that nearly **follows** the **spectral slope** of the **current** spectrum.





PSD [m^2/cycle/km] or [m^2/s^2/cyle/km]
Wavenumber [cycles/km]
$\alpha = 0.0$
$\alpha = 0.2$
$\alpha = 0.4$
$\alpha = 0.6$
$\alpha = 0.8$
$\alpha = 1.0$
$k^{-1.66}$
$k^{-2.0}$
$k^{-2.5}$
$k^{-3.0}$
Hs-Kx
Hs-ky
KE mix
KE rot
KE div

As long as there is some vorticity…

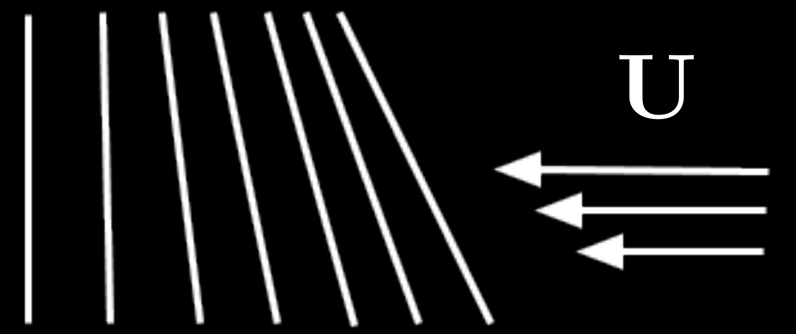
- The spatial correlation drops from 0.6 for 95% of divergence to nearly 0 for 100% of divergence.
- This holds for all spectral slopes.

Current effects on deep-water linear waves

From a geometrical optics approximation framework, the effects of currents on the kinematics of the waves can be described by the ray equations:

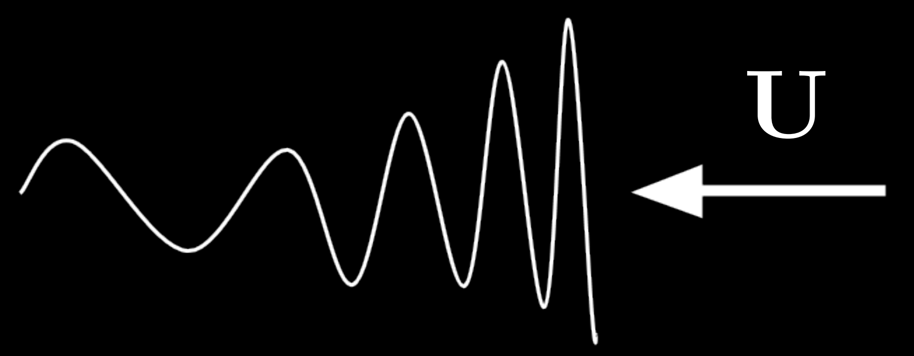
$$\dot{\omega} = \frac{d}{dt}(\boldsymbol{U} \cdot \boldsymbol{k})$$ (conservation of abs. freq.)

$$\dot{\theta} = -\frac{1}{k}\hat{\boldsymbol{n}} \cdot \boldsymbol{\nabla}(\boldsymbol{k} \cdot \boldsymbol{U})$$ (Refraction)



$$\dot{k} = -\hat{\boldsymbol{k}} \cdot \boldsymbol{\nabla}(\boldsymbol{k} \cdot \boldsymbol{U})$$ (Change in wavenumber)

$$\dot{\boldsymbol{x}} = -\boldsymbol{c}_{\boldsymbol{g}}' + \boldsymbol{U}$$ (Advection)



While, wave dynamics is governed by the conservation of wave action density:

$$\frac{\partial N}{\partial t} + \boldsymbol{\nabla} \cdot (\dot{\boldsymbol{x}} N) + \frac{\partial}{\partial k}(\dot{k} N) + \frac{\partial}{\partial \theta}(\dot{\theta} N) = S_{in} + S_{ds} + S_{nl}$$

Current effects on deep-water linear waves

change in wavenumber (magnitude)

change in the wind forcing

$$\frac{\partial N}{\partial t} + \boldsymbol{\nabla} \cdot (\dot{\boldsymbol{x}} N) + \frac{\partial}{\partial k}(\dot{k} N) + \frac{\partial}{\partial \theta}(\dot{\theta} N) = S_{in} + S_{ds} + S_{nl}$$

speed at which action is advected

change in wave direction

change in dissipation through breaking

Current effects on deep-water linear waves

The right-hand side relies on parametrizations:

lack of observations ⟶ not so good parametrizations ⟶ not so good modeling

Left-hand side:

- Ok without currents for bulk quantities, BUT adding currents could improve
  - Delayed arrival times
  - Directional biases
  - Spatial gradients of significant wave height

change in wavenumber

change in the wind forcing

$$\frac{\partial N}{\partial t} + \boldsymbol{\nabla} \cdot (\dot{\boldsymbol{x}} N) + \frac{\partial}{\partial k}(\dot{k} N) + \frac{\partial}{\partial \theta}(\dot{\theta} N) = S_{in} + S_{ds} + S_{nl}$$

speed at which action is advected

change in wave direction

change in dissipation through breaking

Diffusion of surface gravity wave action by mesoscale turbulence at the sea surface

Villas Bôas and Young

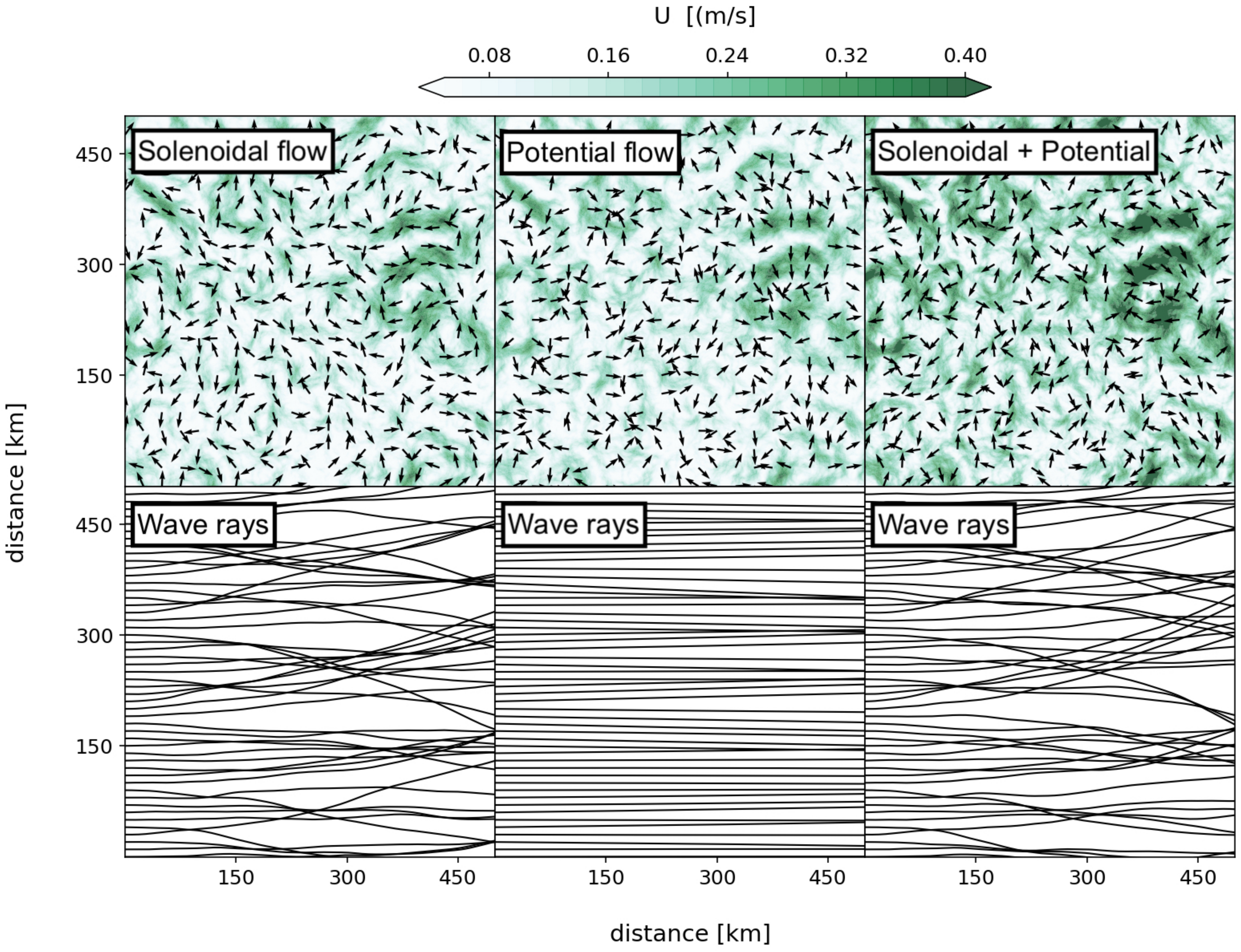
$$\partial_t A + \dot{x}_n \partial_{x_n} A + \dot{k}_n \partial_{k_n} A = 0$$

We apply a multiple-scale expansion approach to average the wave action balance equation over an ensemble of sea-surface velocity fields.

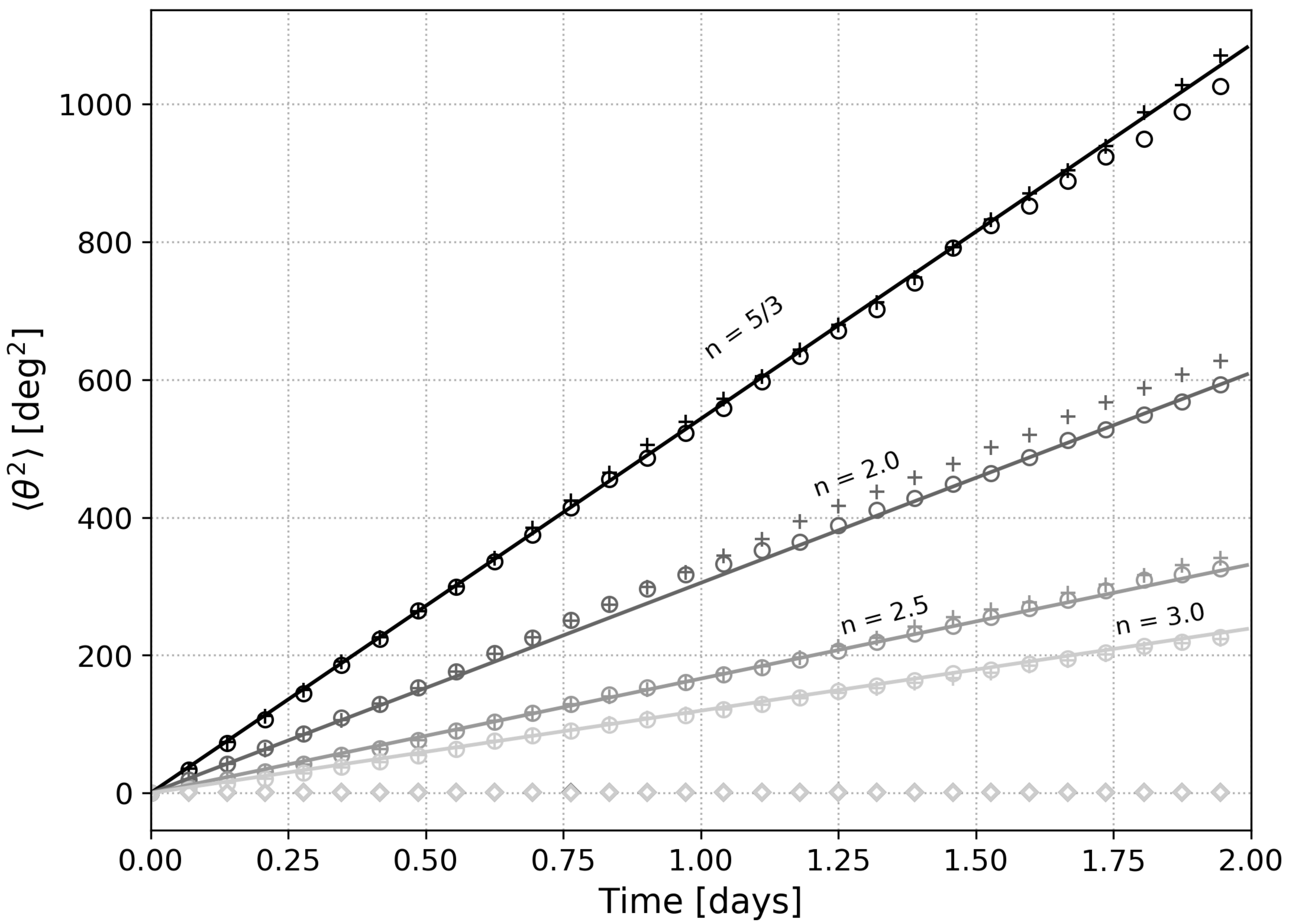
$$\bar{A}_t + c\cos\theta \bar{A}_x + c\sin\theta \bar{A}_y = \alpha \bar{A}_{\theta\theta}$$

For isotropic velocity fields, the diffusion of wave action can be written in terms of the energy spectrum of the rotational component of the flow:

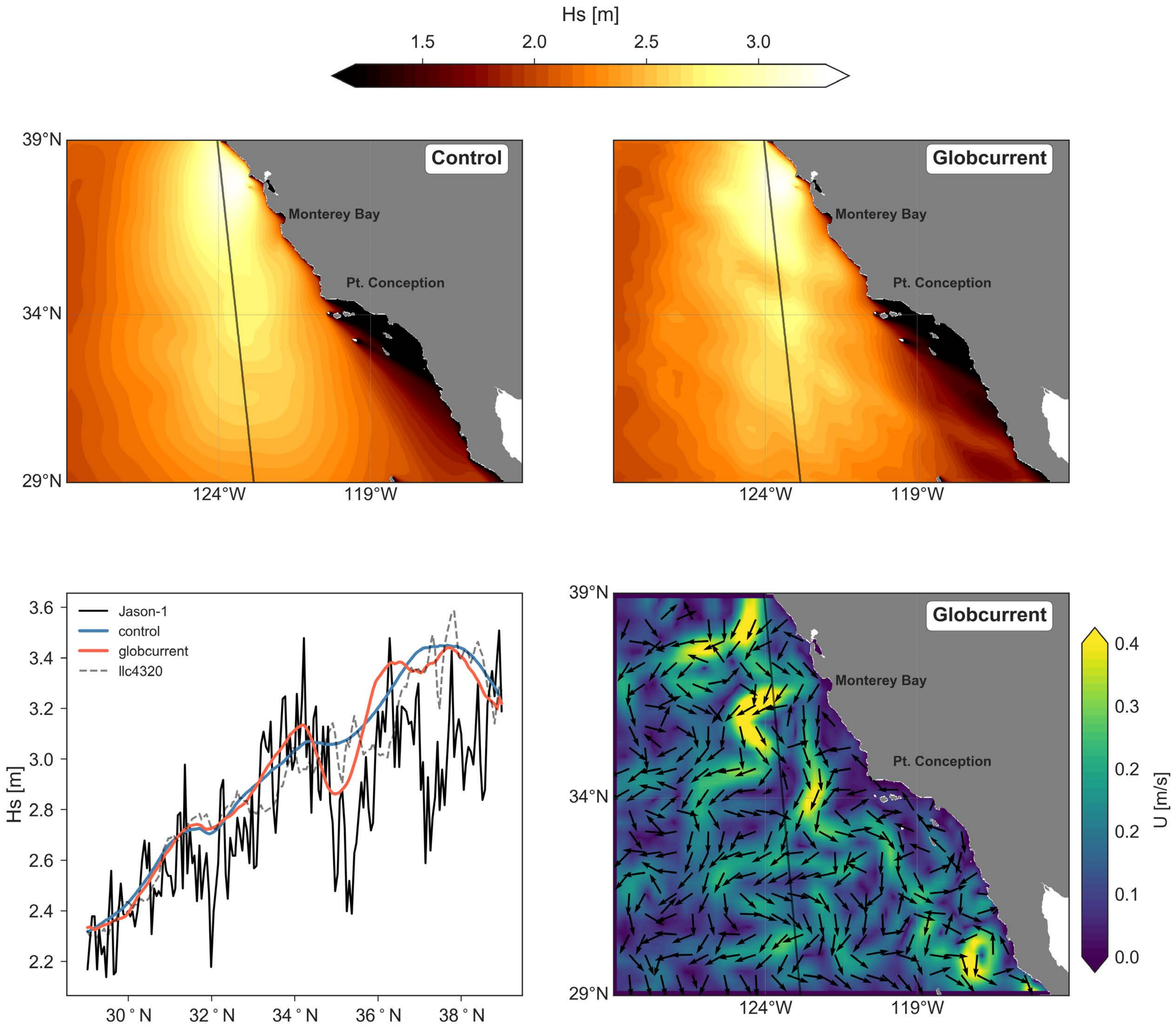
$$\alpha(k) = \frac{2}{c}\int_0^\infty q\tilde{E}^\psi(q) \; q$$



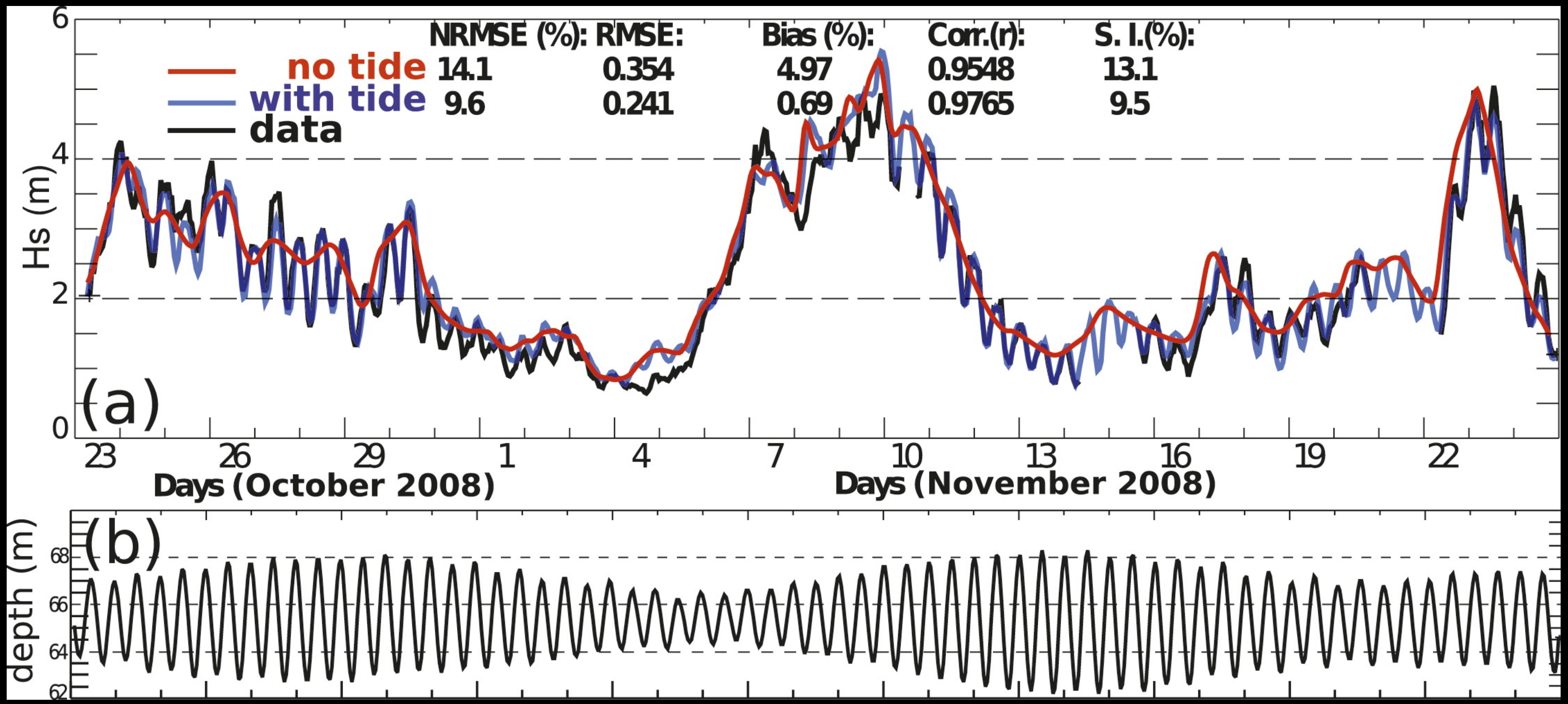
U [(m/s]
0.08
0.16
0.24
0.32
0.40
Solenoidal flow
Potential flow
Solenoidal + Potential
Wave rays
Wave rays
Wave rays
distance [km]
distance [km]
450
300
150
450
300
150
150
300
450
150
300
450
150
300
450

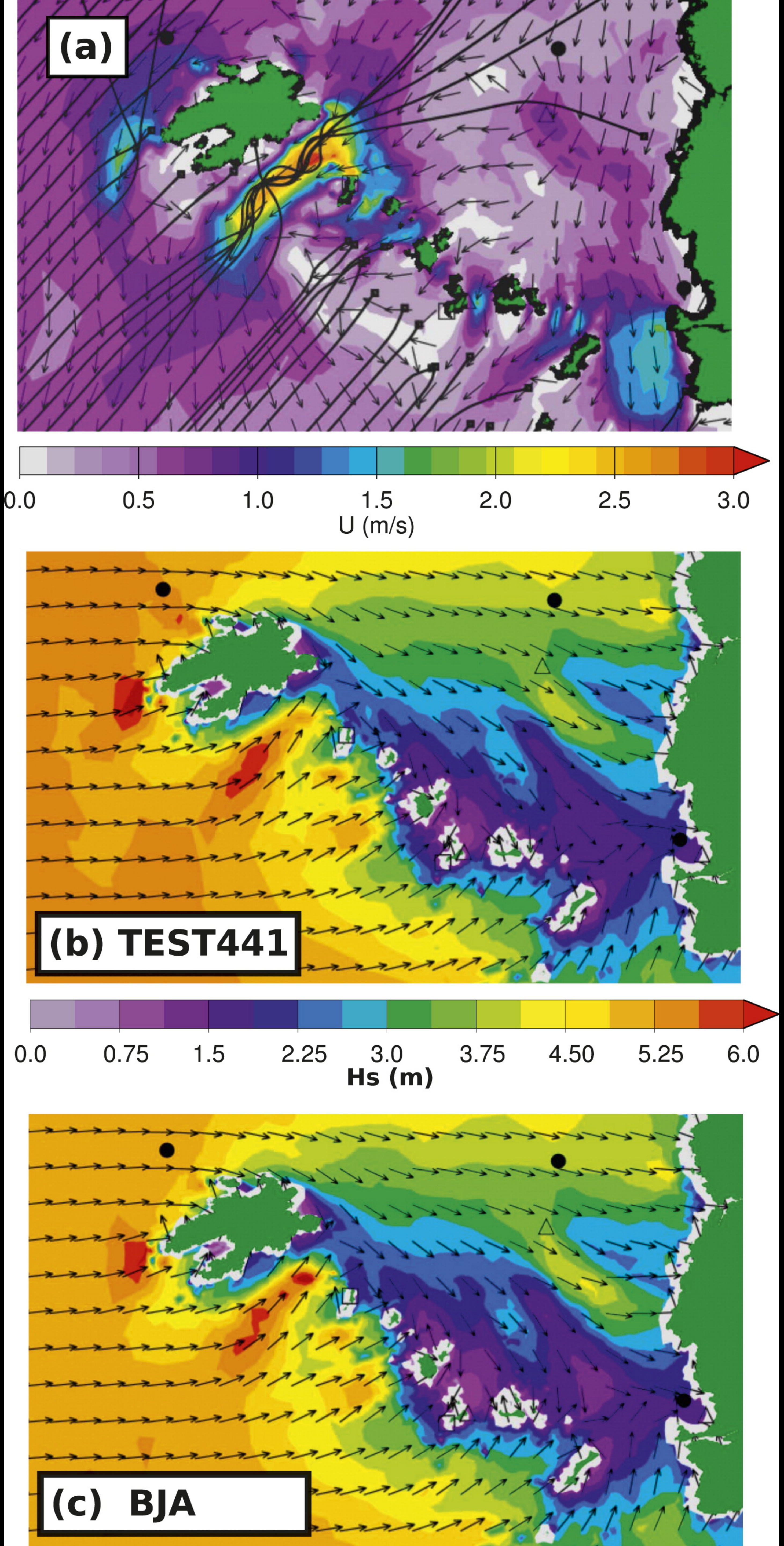


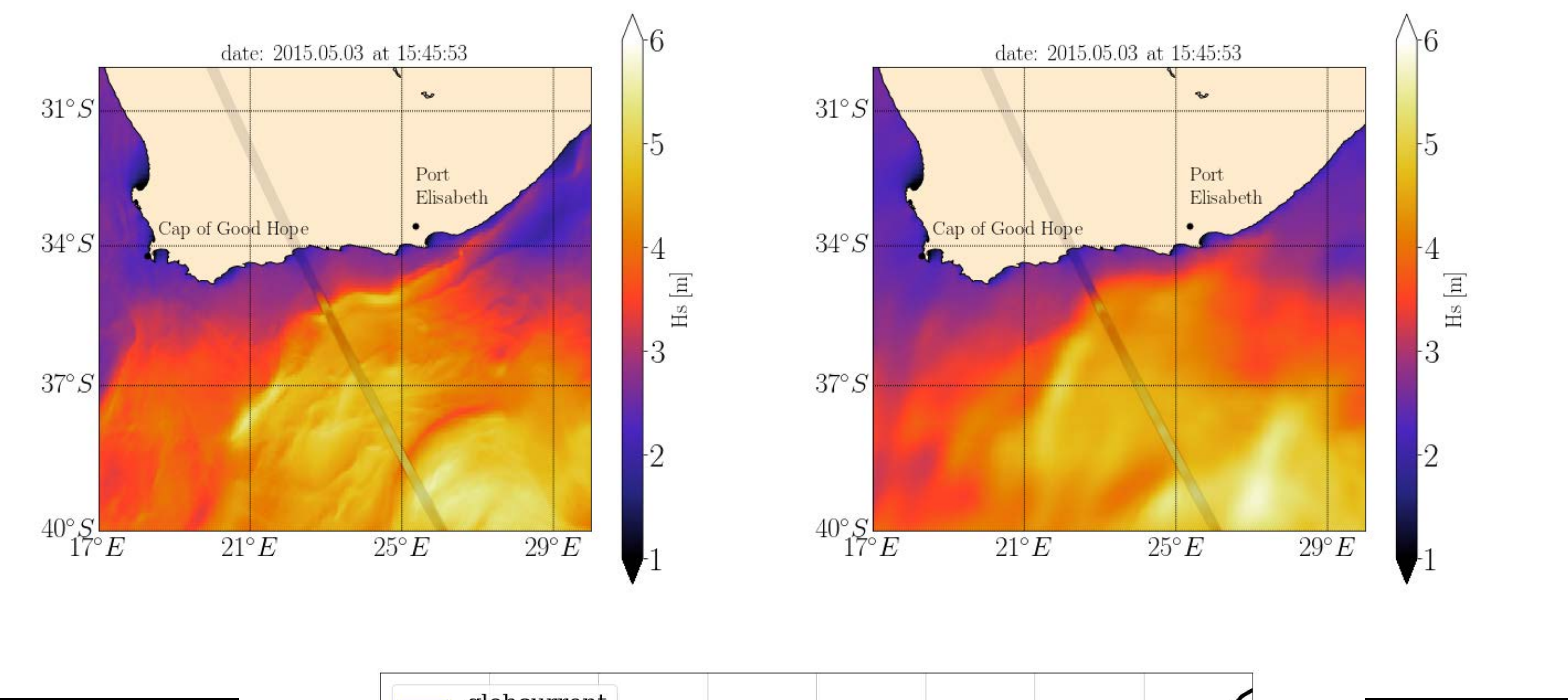
n = 5/3
n = 2.0
n = 2.5
n = 3.0
1000
800
600
400
200
0
⟨θ²⟩ [deg²]
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Time [days]

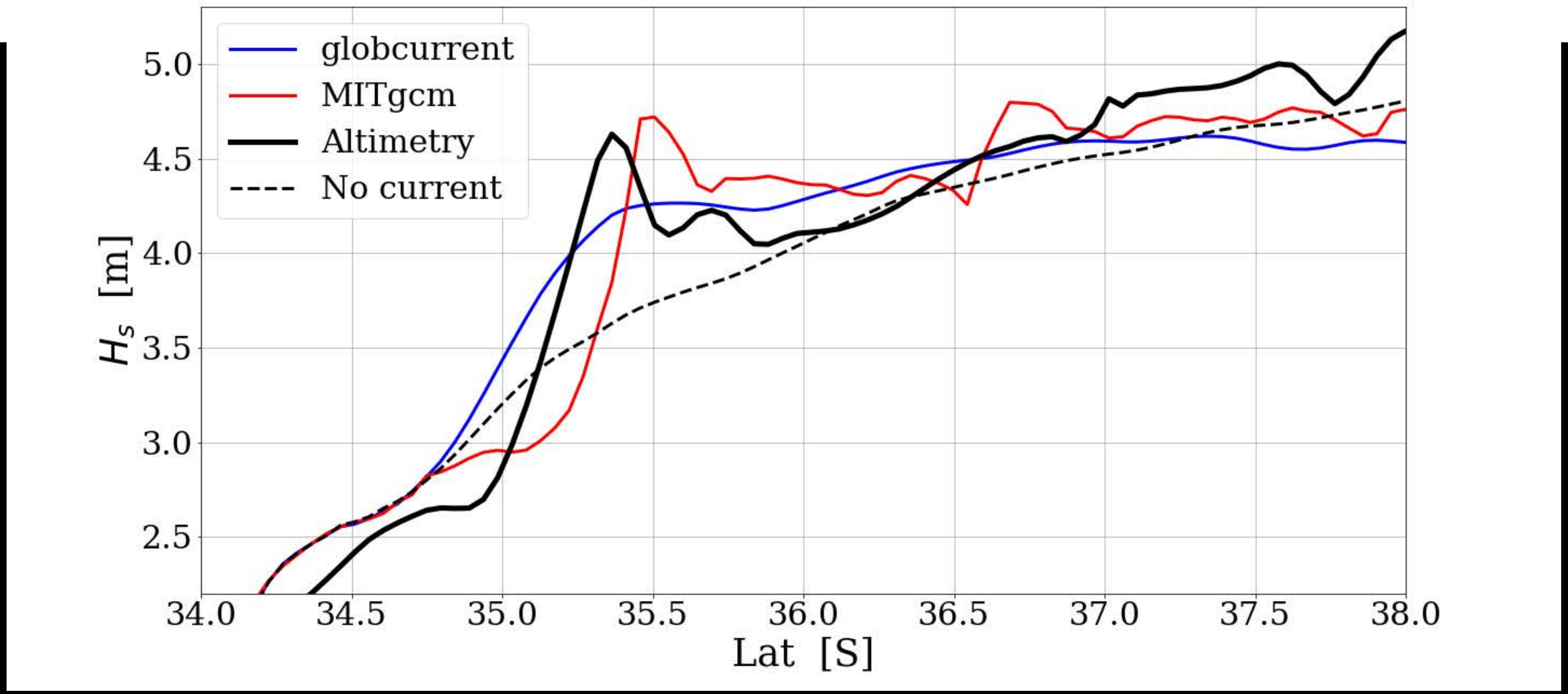

Hs [m]
1.5
2.0
2.5
3.0
Control
Globcurrent
Monterey Bay
Pt. Conception
39°N
34°N
29°N
124°W
119°W
Jason-1
control
globcurrent
llc4320
Hs [m]
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
30 ° N
32 ° N
34 ° N
36 ° N
38 ° N
U [m/s]
0.4
0.3
0.2
0.1
0.0

- The high-frequency variability of Hs is completely missed without currents






date: 2015.05.03 at 15:45:53
Port
Elisabeth
Cap of Good Hope
31°S
34°S
37°S
40°S
17°E
21°E
25°E
29°E
Hs [m]
1
2
3
4
5
6
date: 2015.05.03 at 15:45:53
Port
Elisabeth
Cap of Good Hope
31°S
34°S
37°S
40°S
17°E
21°E
25°E
29°E
Hs [m]
1
2
3
4
5
6


globcurrent
MITgcm
Altimetry
No current
H_s [m]
Lat [S]
2.5
3.0
3.5
4.0
4.5
5.0
34.0
34.5
35.0
35.5
36.0
36.5
37.0
37.5
38.0

2. Langmuir turbulence

Craik and Leibovich (1976) :

Stokes Drift Velocity

$$\bar{\mathbf{u}}^s(z)$$

↔

Wave-Averaged Currents (Eulerian)

$$\zeta^E = \nabla \times \mathbf{u}^{\mathbf{E}}$$

The Stokes drift velocity interacts with the mean Eulerian flow.

This interaction shows up in the momentum equation as a "vortex force"

Vortex Force

$$\mathbf{F}^s = \bar{\mathbf{u}}^s \times \zeta^E$$

- The relative importance between the shear instability of the wind-driven currents and the vortex force is given by the **turbulent Langmuir number**:

$$La_t = \left(\frac{u^*}{u_s}\right)^{1/2}$$

$La_t = \mathcal{O}(1)$ ⟹ Langmuir Turbulence

(After McWilliams et al. 1997)

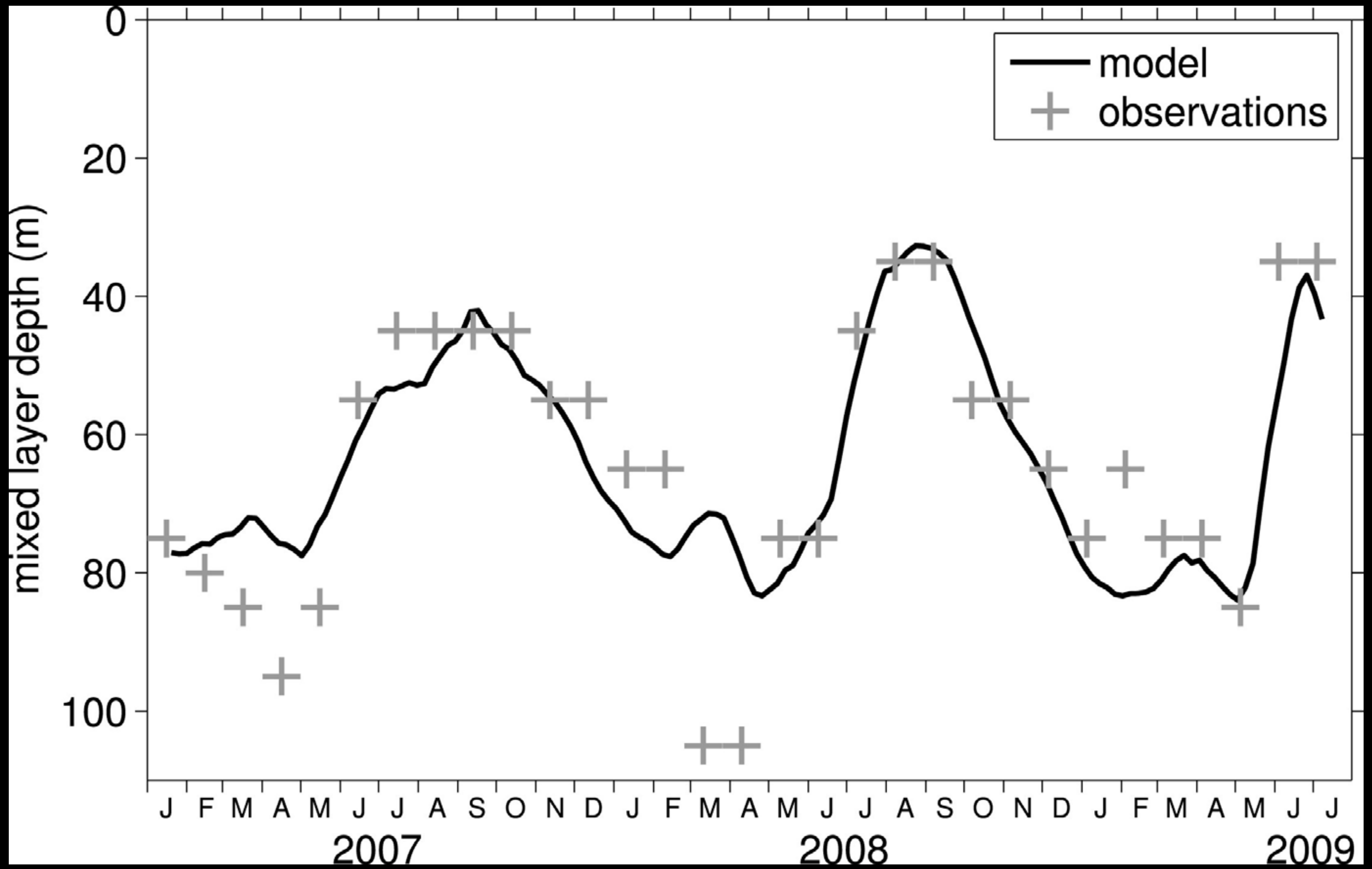
- Langmuir turbulence penetrates deeper than the layer directly affected by Stokes drift

- Large Eddy Simulations (LES) of the wave–averaged momentum equations (Moeng, 1984)

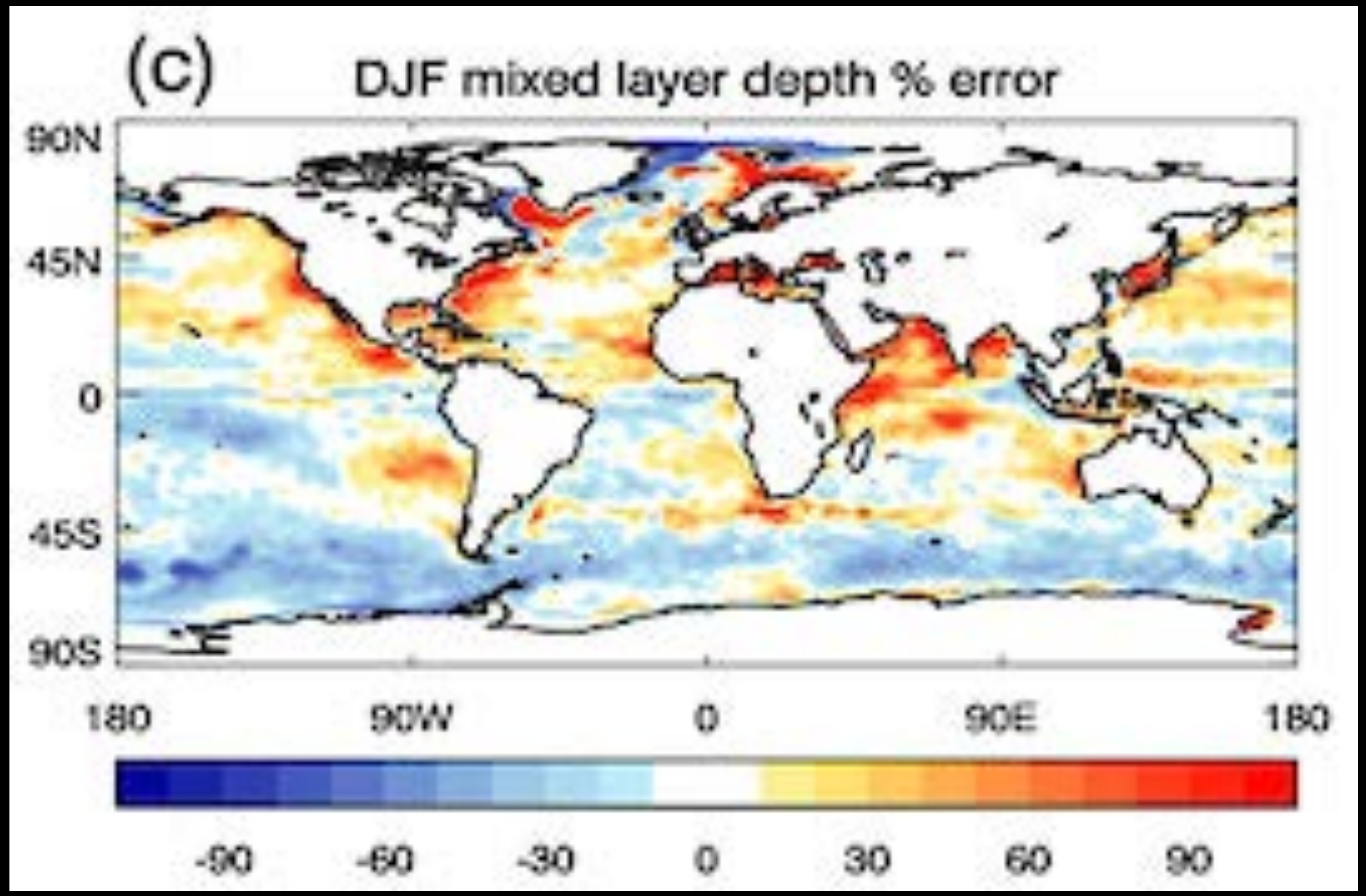
  - Have inspired multiple scalings for the vertical turbulent kinetic energy [e.g., McWilliams and Sullivan (2000), Harcourt and D'Asaro (2008), Van Roekel et al. (2012)]

- Only a few studies have tested theses scalings in climate models

- Persistent **biases** in the modeled **mixed layer** suggests the there could be processes relevant for **turbulent mixing** that have been **ignored** in most parameterizations of the mixed layer in climate models



Verdy et al. (2013)



Belcher et al. (2012)

1. Do we have good observations for wind-wave-current interactions? If not, what more/else do we need?

2. How well do models represent wind-wave-current interactions?

3. What additional observations/information do we need to improve the parameterization and data assimilation of wind-wave-current coupled interactions?