Wave-Current Interactions

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Some effects of **surface currents** on **linear deep-water** surface **waves**

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NOT going to cover:

- **Wave** effects on **currents**
- Vertical shear
- Waves in **shallow** water
- Current effects on wave-wave interactions

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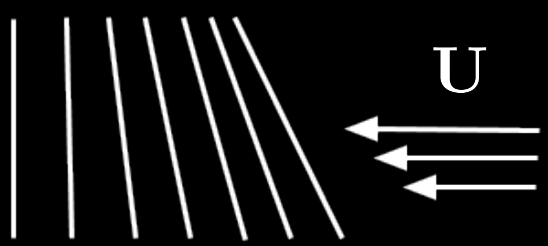
Current effects on deep-water linear waves

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

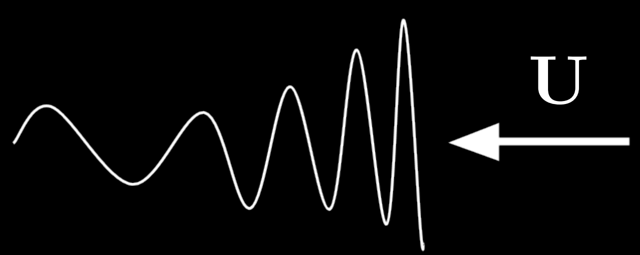
$$\dot{\omega} = \frac{d}{dt}(\boldsymbol{U} \cdot \boldsymbol{k})$$ (conservation of abs. freq.)

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

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

Some reasons to care

Climate modeling

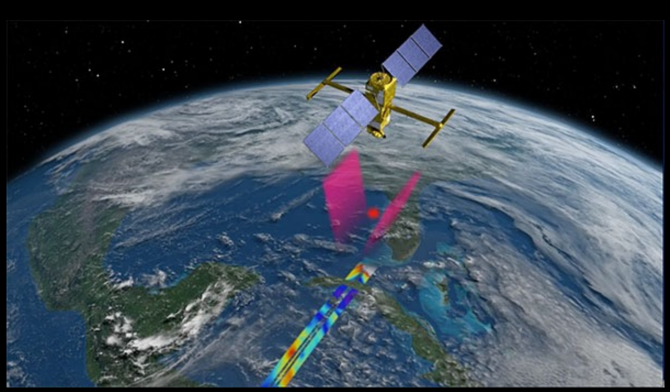
- Despite waves being strongly coupled to the upper ocean circulation and the overlying atmosphere, efforts to improve climate and wave models have evolved somewhat independently. However, surface wave physics may be key to improving climate models and better representing the coupling between the ocean and the atmosphere

Wave modeling

- Having current forcing in numerical wave models could help reduce directional and arrival time biases, for example, 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?



- 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
  - Could the signature of currents on waves be used to inferrer properties of the flow? (e.g. transition from balanced unbalanced).

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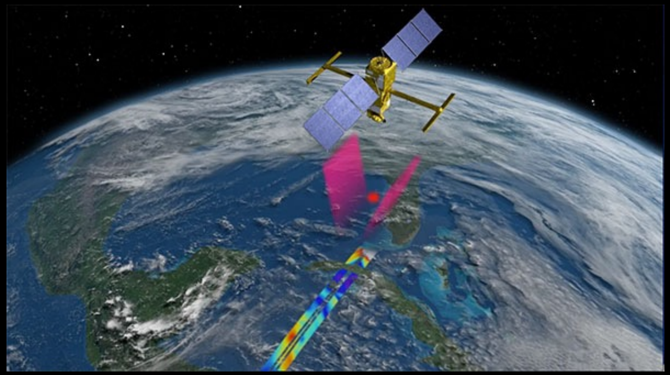

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Diffusion of surface gravity wave action by mesoscale turbulence at the sea surface

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:

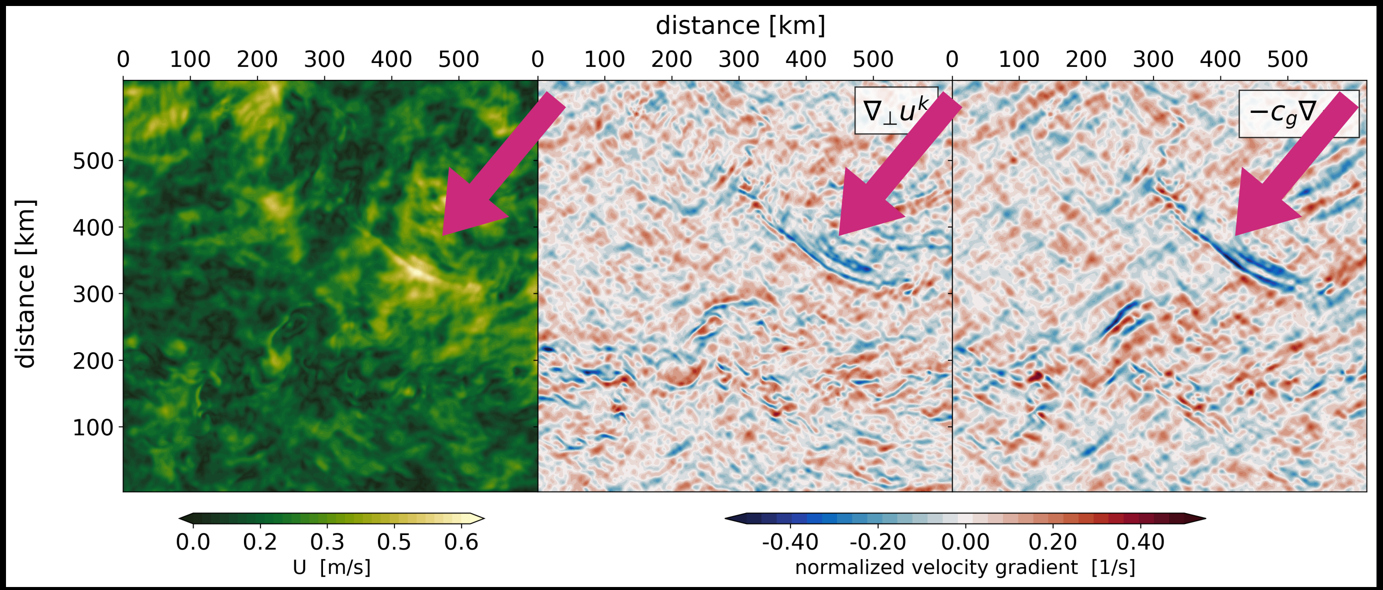
$$\alpha(k) = \frac{2}{c}\int_0^\infty q\tilde{E}^\psi(q) \;\; q$$

Surface wave response to vorticity and divergence: Insights from idealized numerical simulations

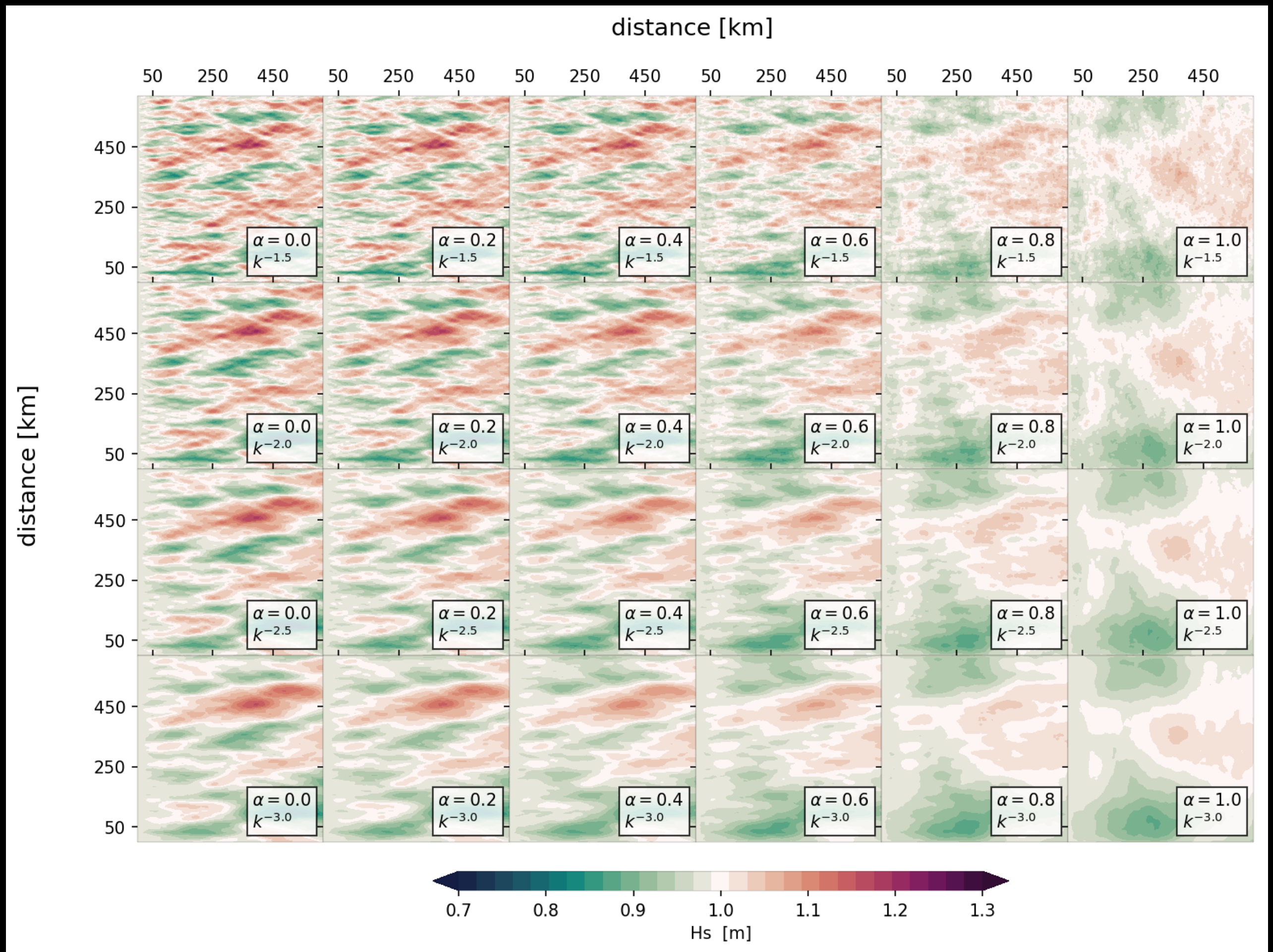
Villas Bôas, Ardhuin, Cornuelle, Gille and Mazloff

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

current **speed** current **gradient** gradient from waves



More vorticity → More divergence



How well do we understand sea state gradients?

Numerical Wave Modeling in Conditions with Strong Currents: Dissipation, Refraction, and Relative Wind

FABRICE ARDHUIN,[*] ARON ROLAND,[+] FRANCK DUMAS,[#] ANNE-CLAIRE BENNIS,[#] ALEXEI SENTCHEV,[@] PHILIPPE FORGET,[&] JUDITH WOLF,[**] FRANÇOISE GIRARD,[++] PEDRO OSUNA,[##] AND MICHEL BENOIT[@@]

- Reviews the performance of numerical models under strong current conditions.
- Do wave models represent well the most important physical processes in the presence of strong currents?

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

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change in wavenumber (magnitude)

change in the wind forcing

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

speed at which action is advected

change in wave direction

change in dissipation through breaking

1- Wave blocking and induced breaking

- If the current is equal and opposite to the local group velocity the wave energy can no longer be propagated upstream (kinematical limit).
- In reality waves get too steep and break way before this —> $\sigma << g/4U$ (see Phillips sec. 3.7).

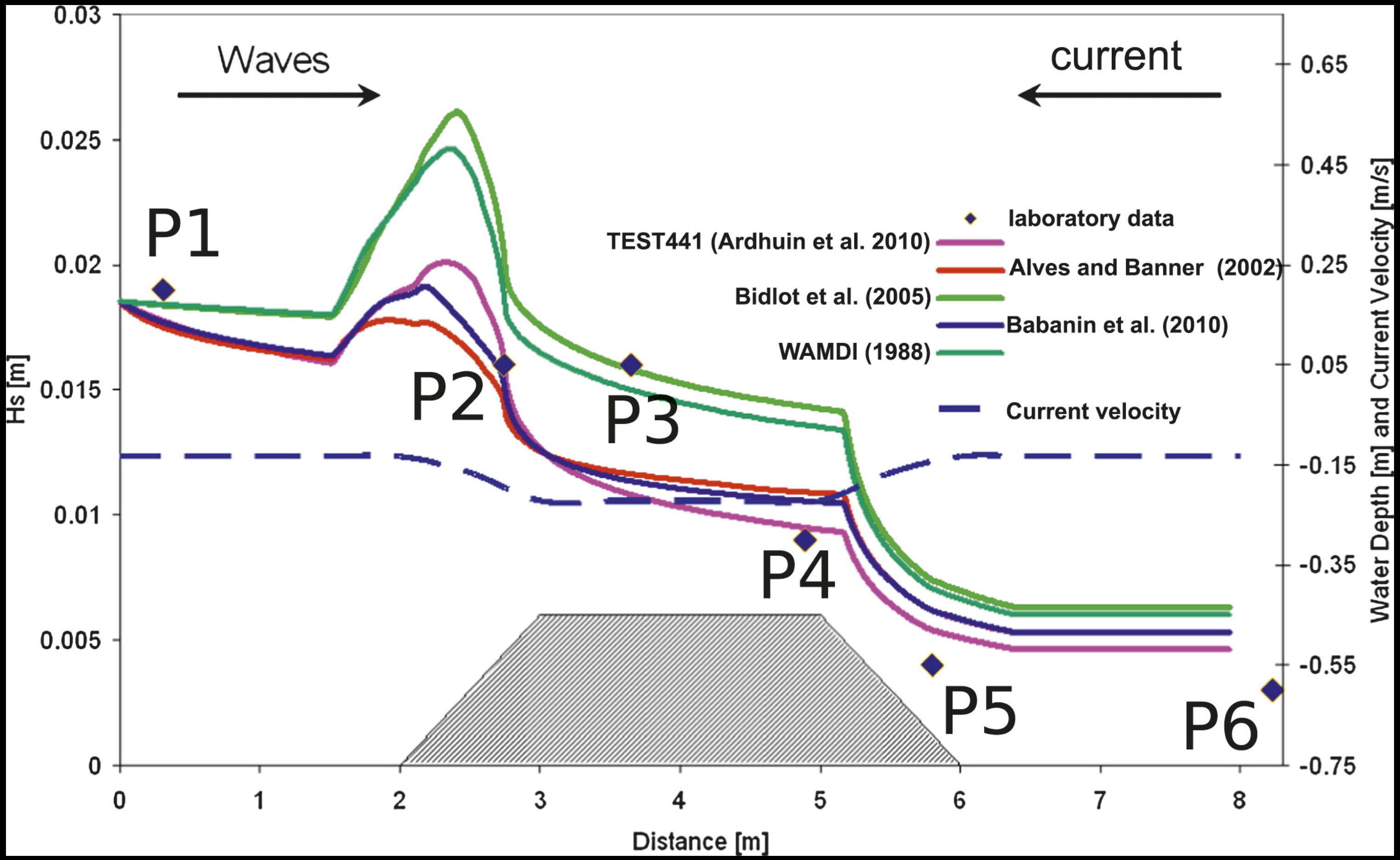
- Two groups of parametrizations:

- Global steepness (e.g., BJA)

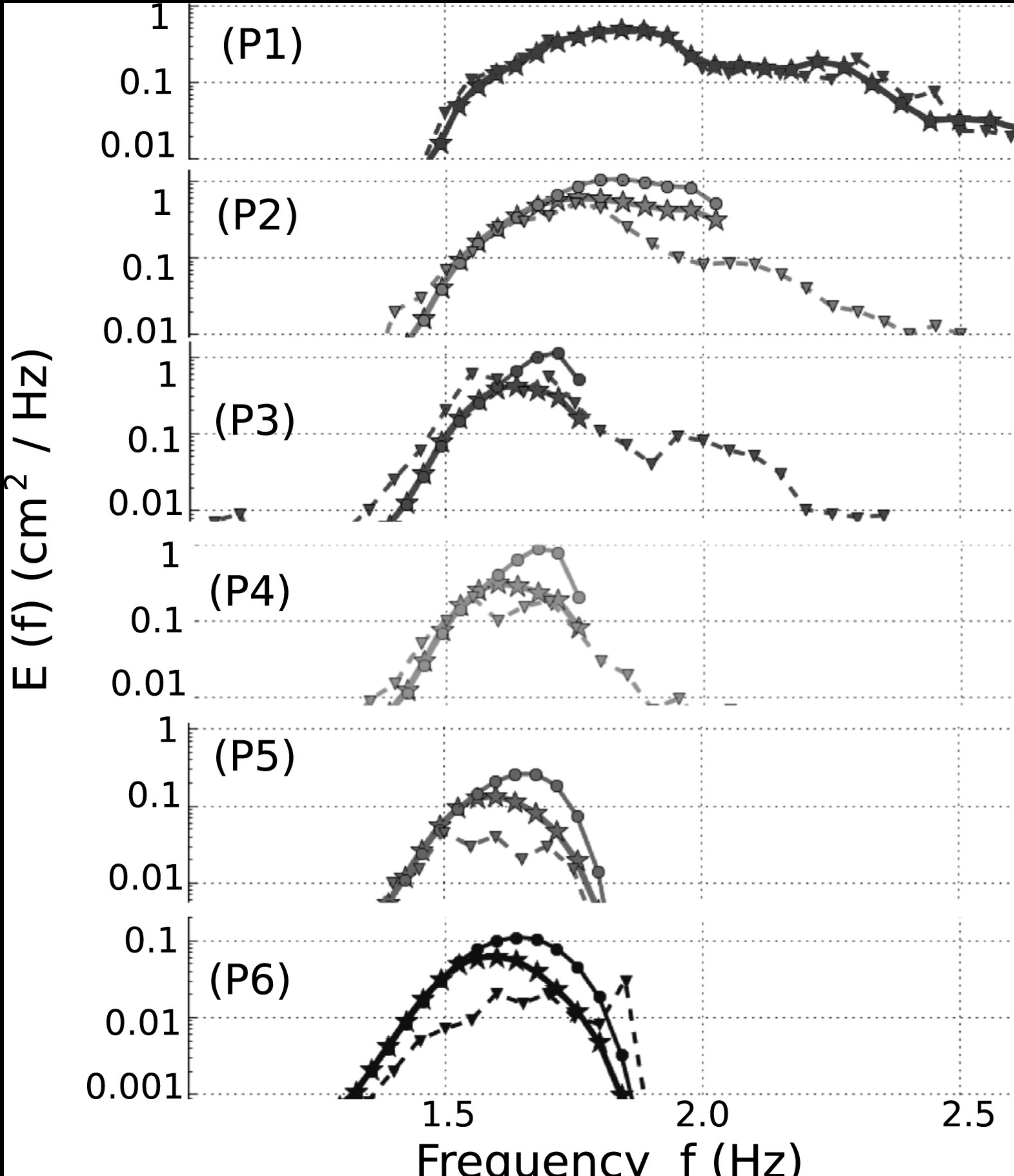
$$S_{\mathrm{oc}}^{\mathrm{KHH}}(f,\theta) = C_{\mathrm{ds}} \sqrt{g k_r} (k_r H_s)^4 \left[(1-a)\frac{k}{k_r} + a \frac{k^2}{k_r^2} \right] F(f,\theta),$$

- Saturation-based (e.g., Ardhuin et al., 2010)

$$S_{\mathrm{oc}}(f,\theta) = \sigma \frac{C_{\mathrm{ds}}^{\mathrm{sat}}}{B_r^2} [\max\{B(f) - B_r\}^2] F(f,\theta),$$

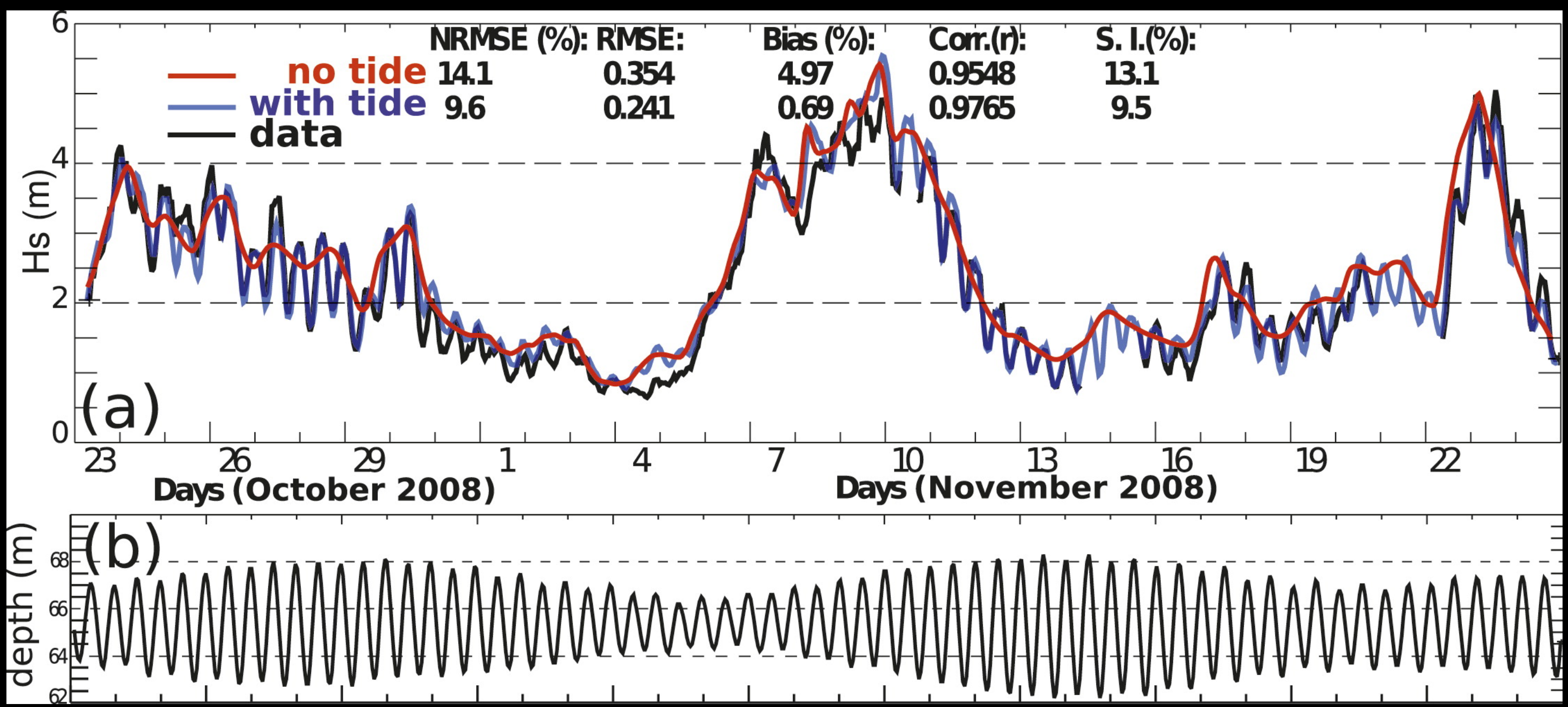


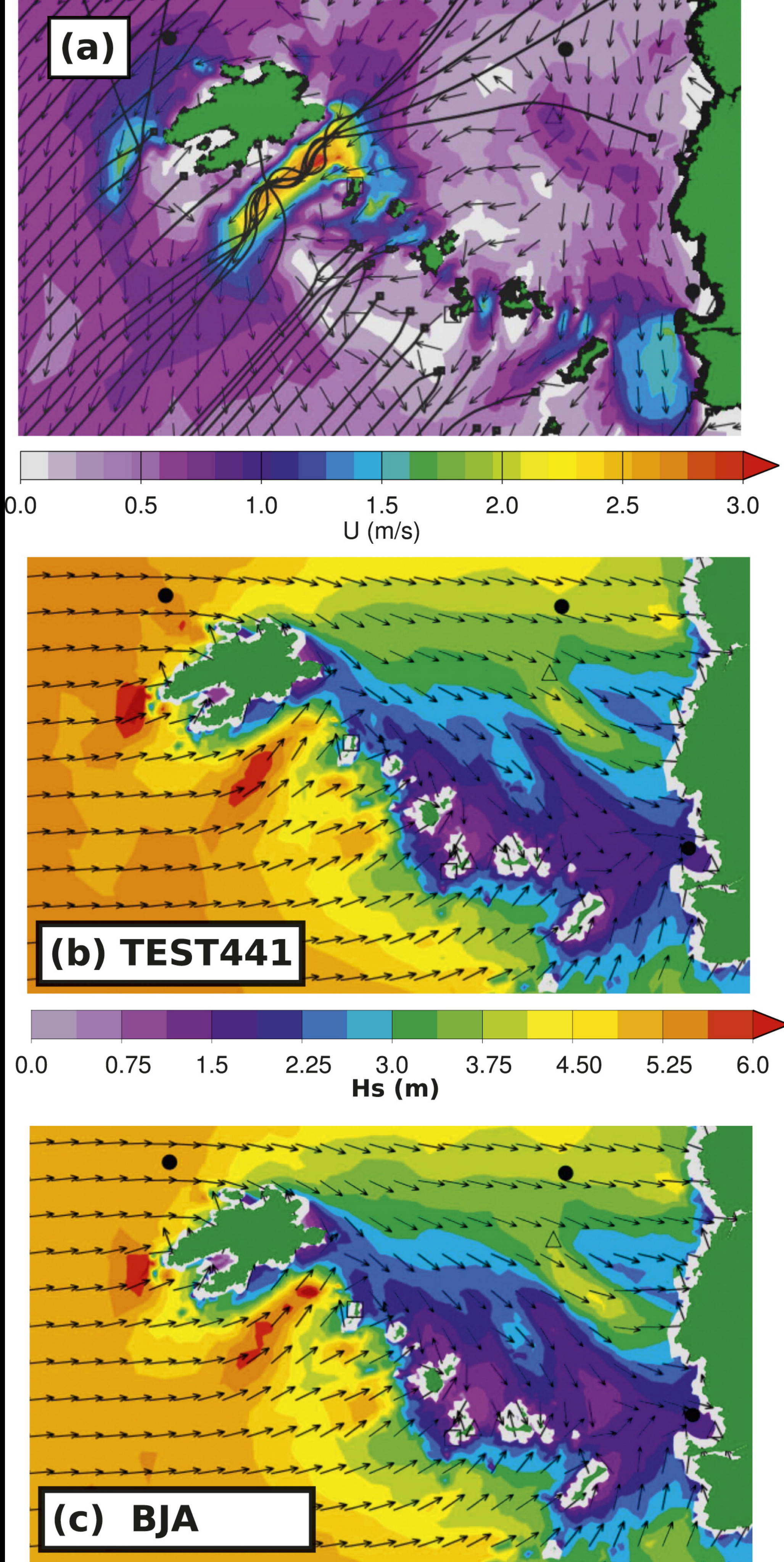
Question: Should the saturation depend on the directional distribution? What does it mean to have minimum dissipation at the mean direction? What defines a good parametrization? (spectrum vs bulk)



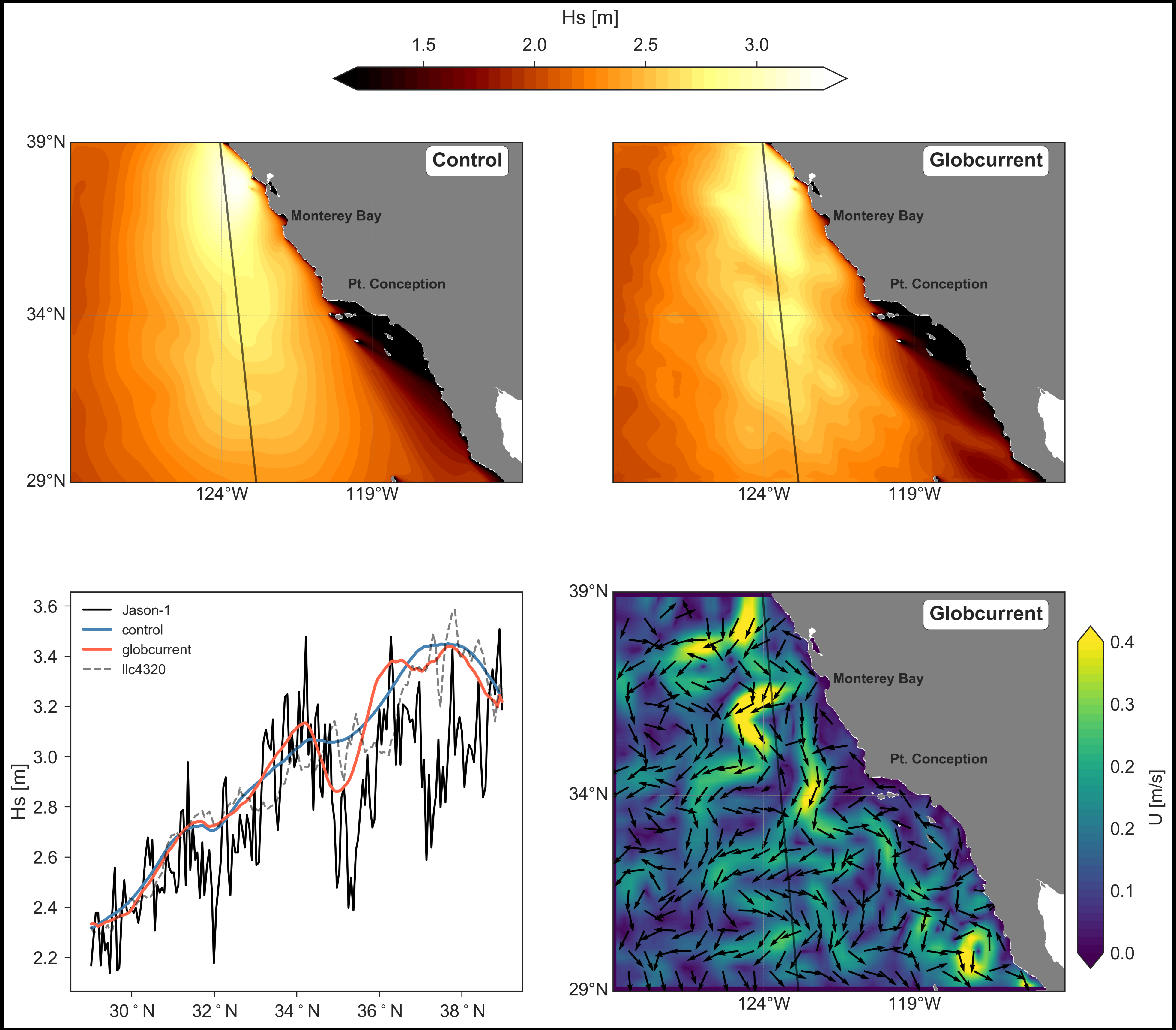
- High frequencies are “filtered out” as you move along the channel.
- Not sure why the range of frequencies for model/obs are so different at P2 and P3

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

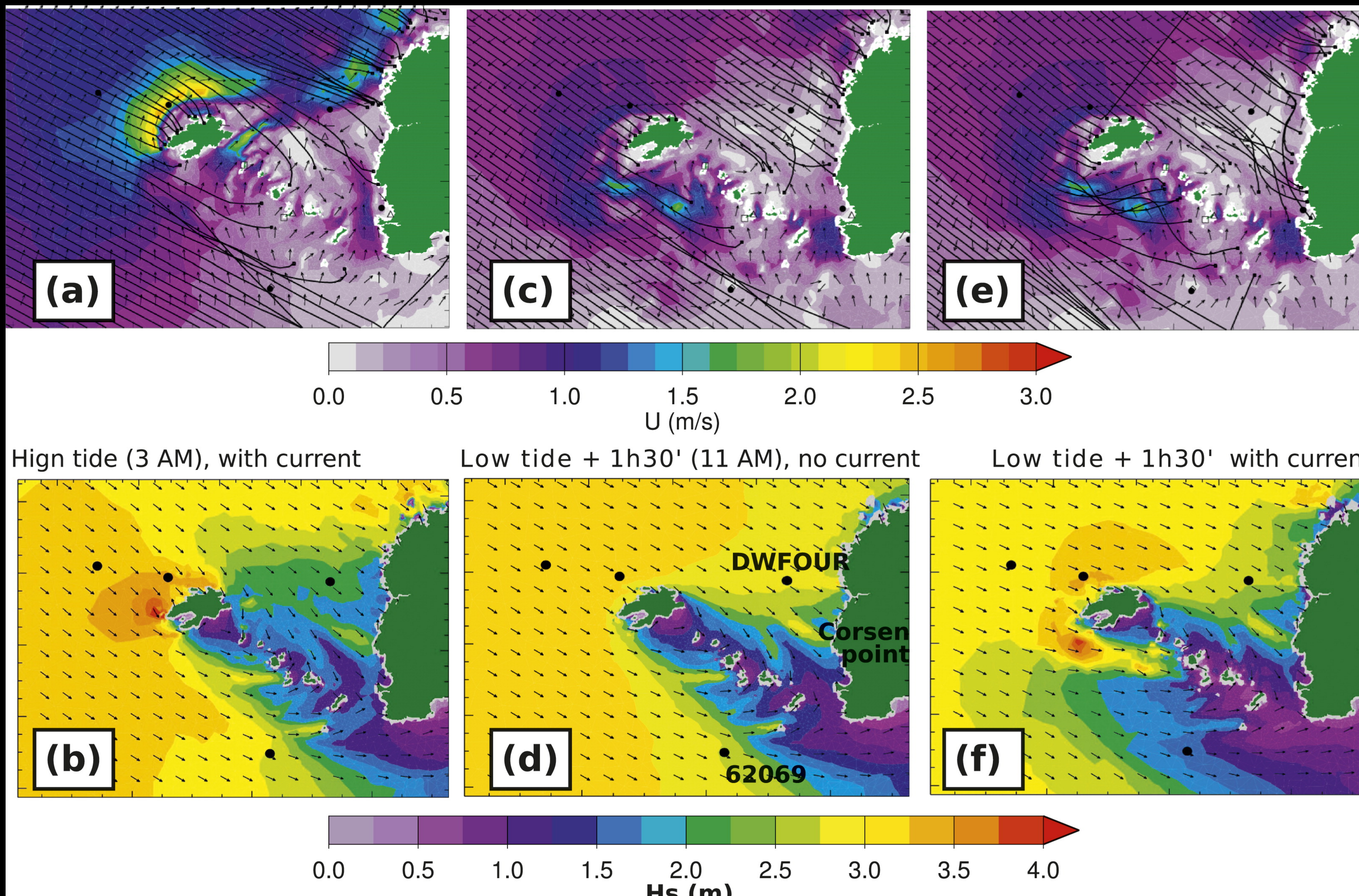


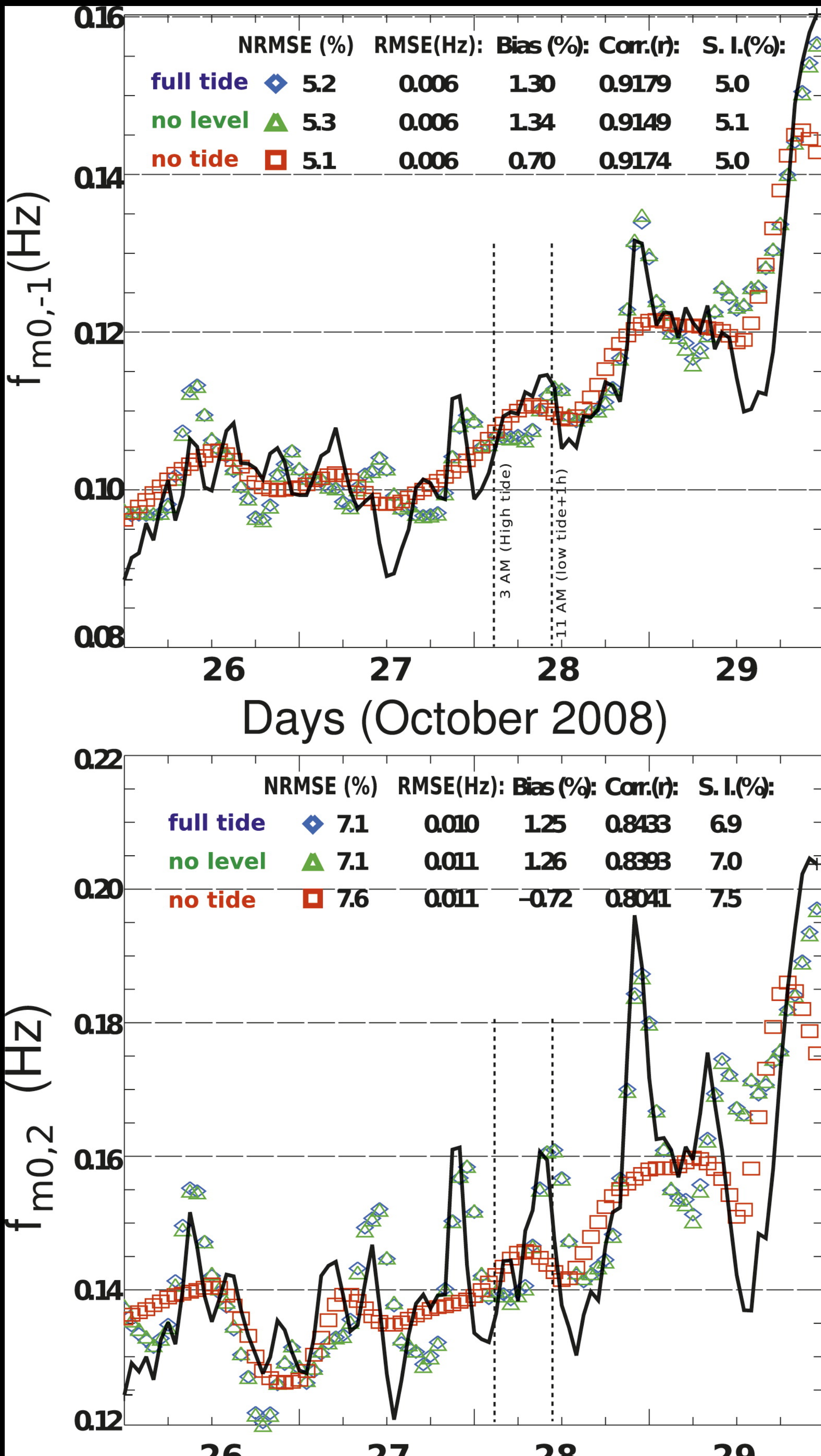


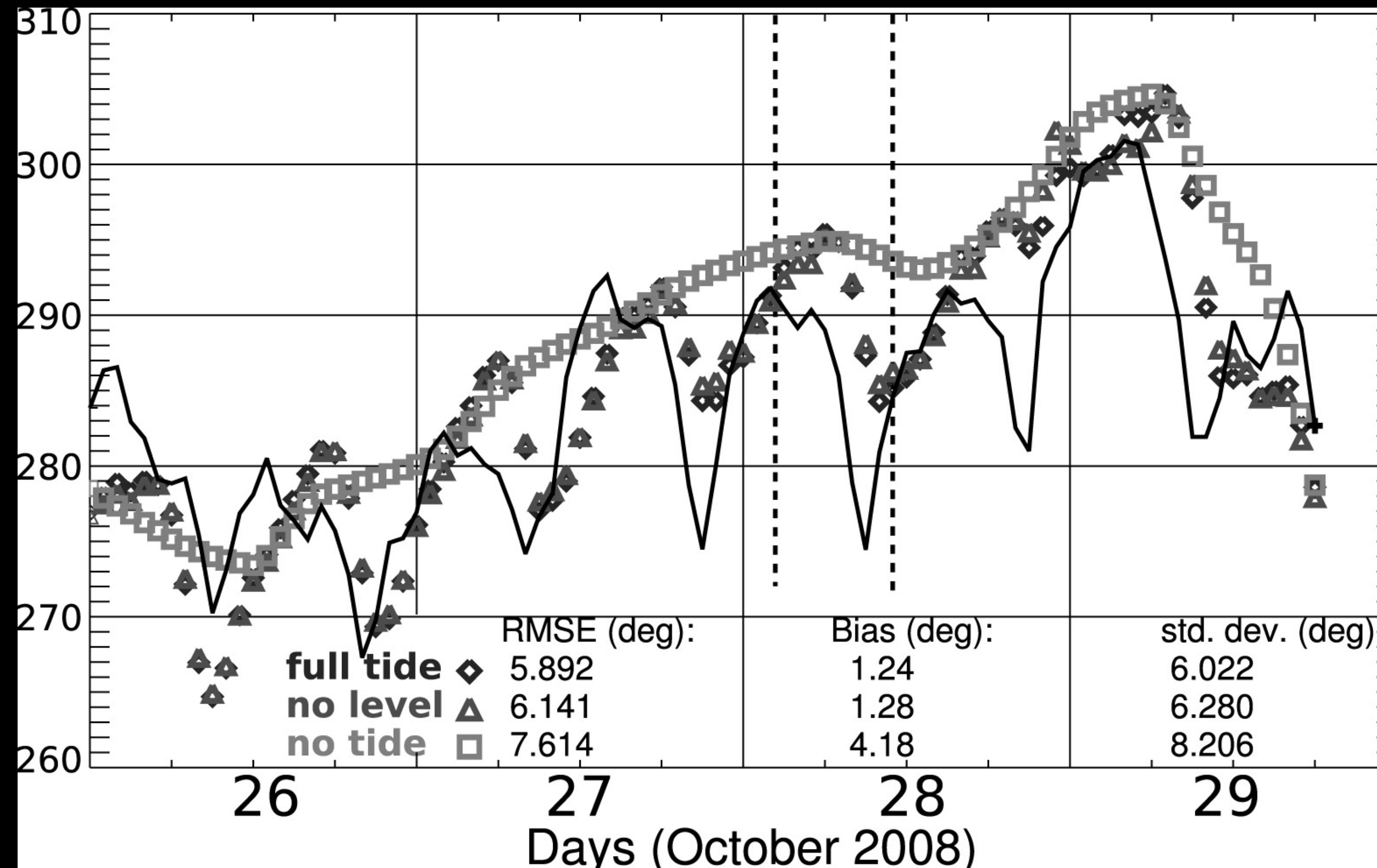
Aside: backyard example



2- Refraction





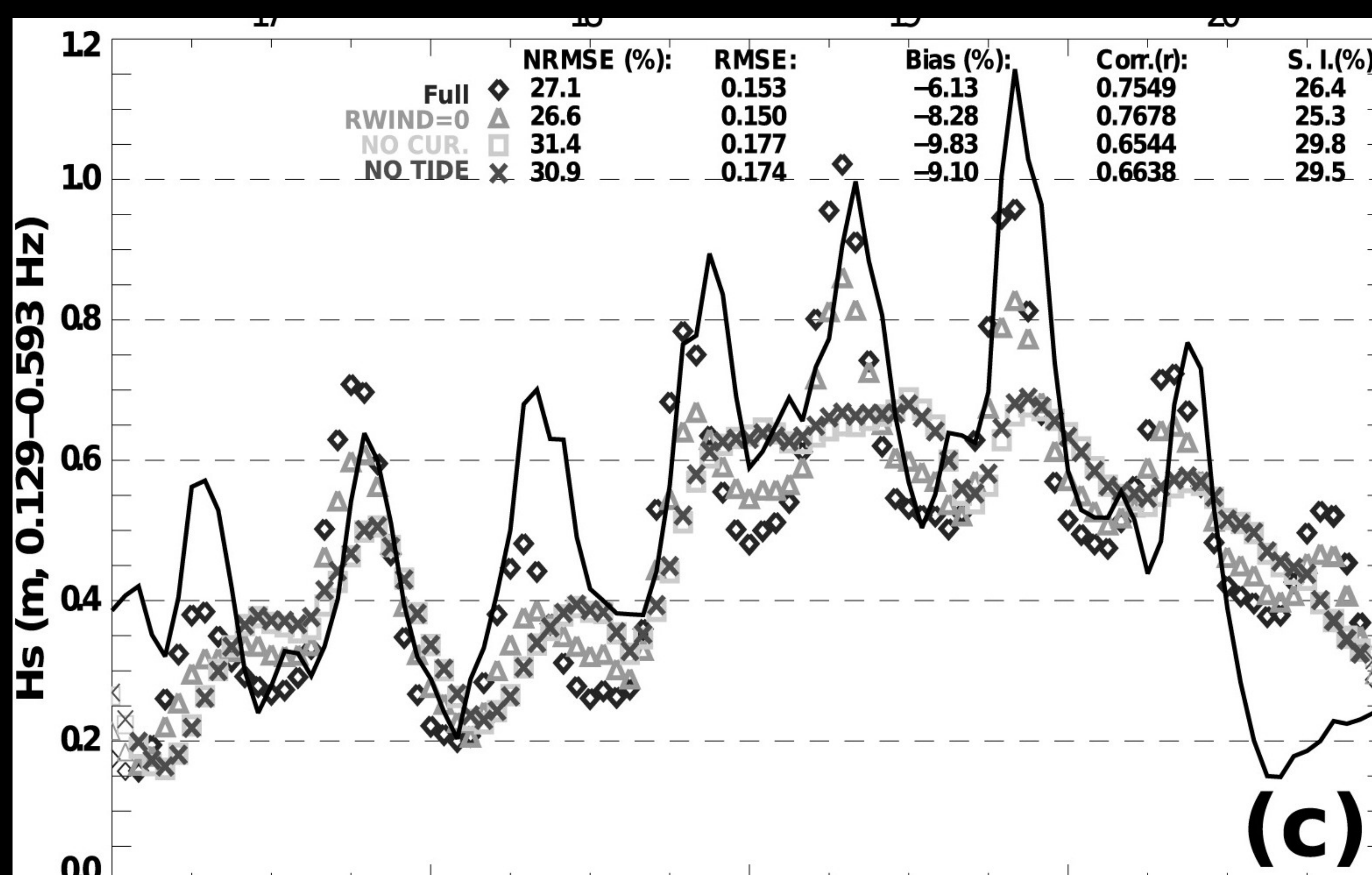


- Mean direction is better represented when currents are taken into account
- Mean frequency is also better represented (specially higher frequencies)

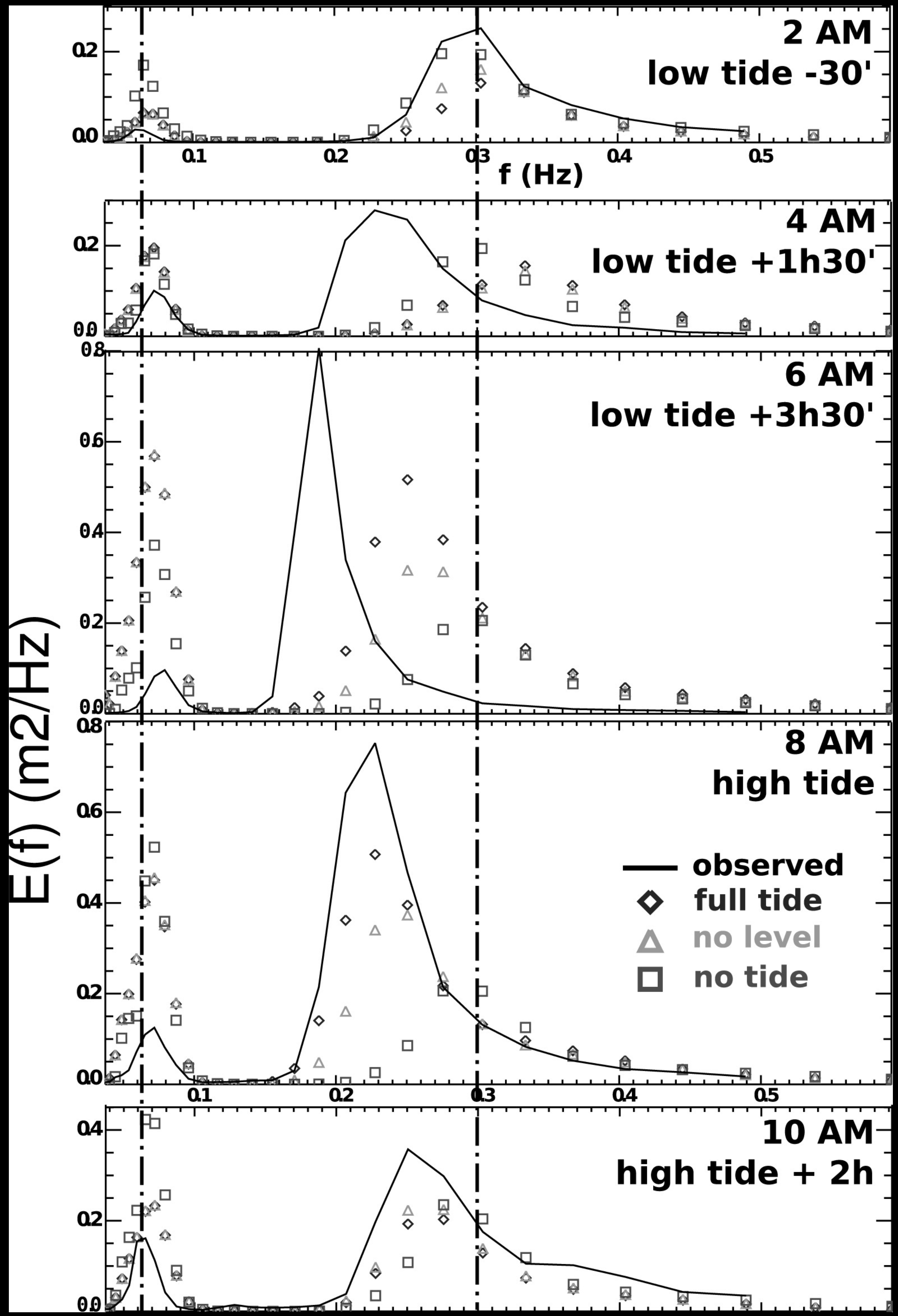
Question: what do wave buoys measure?

3- Relative wind

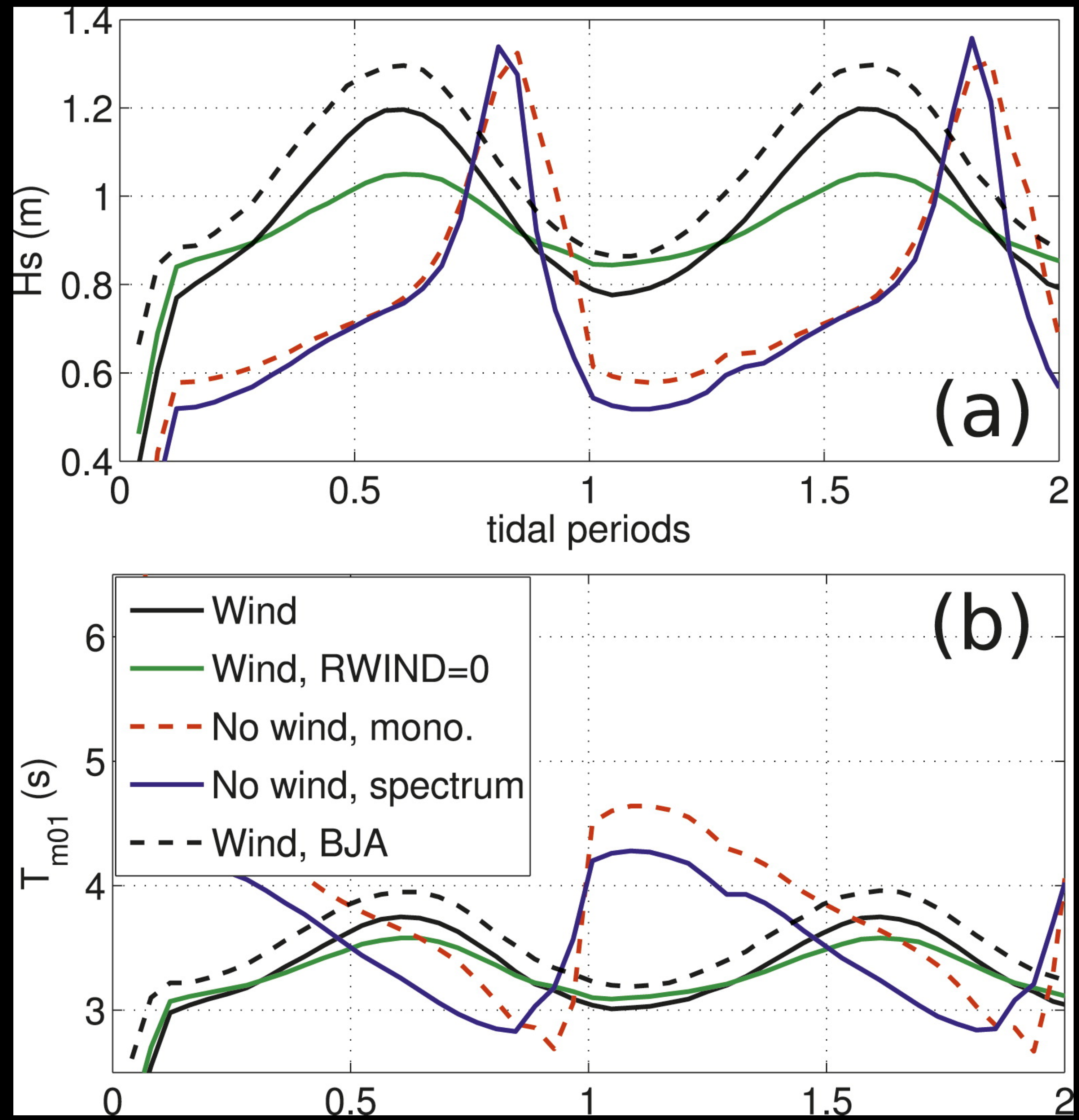
- NO CUR (squares)does a poor job
- RWIND (triangle) means that the wind forcing changes, but there are no other effects of the currents.
- Full (diamonds) means that all currents effects are ON.
- RWIND effect might be overestimated (doesn't allow for atmospheric adjustment)



- Wind-sea has more energy and at lower frequencies at high tide.
- Energy at frequencies higher than the “blocking” frequency suggests locally generated waves.
- Improvements in the wind-sea from “no tide” to “full time”. Small effect of the water level on the short waves.
- Simulations with no refraction suggests that the effects of currents on the wind-sea are dominated by things other than refraction.



Question: how do we separate between having effectively more momentum being transferred from the atmosphere to the ocean (stronger winds) from the action being advected at slower/faster speeds?



Conclusions and discussion points

At global scales the accuracy of wave models depend on:

1. Quality of the input forcing fields (winds and currents)
2. Representativeness of the parameterization schemes
3. Model numerics

Both the wave spectrum and bulk parameters are highly modulated by surface currents (even if the currents are weak).

We need to measure winds, (hires) currents, and waves at the same time!

How much of the problem is:

- We don’t understand the physics
- We can’t afford the computational cost of having the right physics
- We don’t have measurements to improve/validate present parametrization of wave-current interactions

- Nonlinear interaction in the presence of vertically sheared currents
- Validity of WKB specially when you consider wave effects on currents (likely to have no scale-separation)

Random

- Do we know much about the directionality of breaking?
- "In these cases, the choice of dissipation parameterization, either Bidlot et al. (2005) or Ardhuin et al. (2010) has no noticeable impact, as long as a single wave system is present, for example, one swell or one wind sea" ?