Wave-Current Interactions in the California Current Region: Insights from Idealized Numerical Simulations

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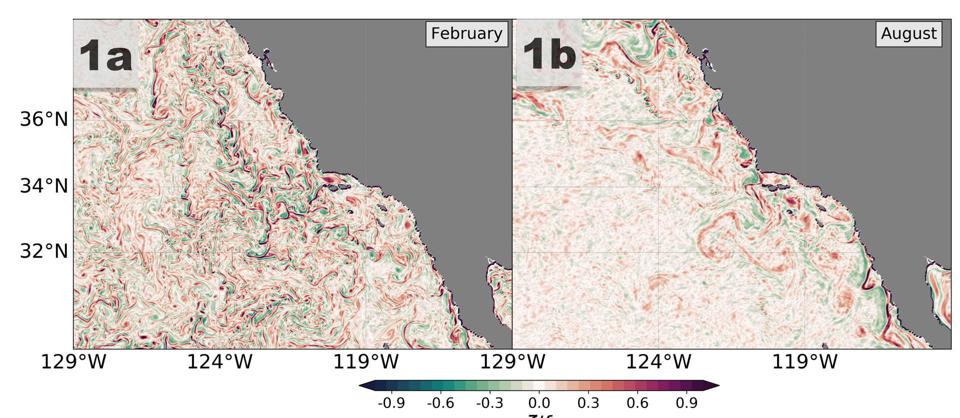
1. Motivation

Surface gravity waves play a major role in the exchange of momentum, heat, energy, and gases between the ocean and the atmosphere. **Waves** are modulated by **ocean currents** via **wave-current interactions**, which lead to **variations** in their **direction**, **frequency**, and **amplitude**. Recent studies of wave-current interactions[1] suggest that the variability of the significant wave height at submesoscales (10-100 km) is dominated by the variability of the current field. At these scales, **divergent** motions associated with tides and inertia-gravity waves may **contribute** to a large portion of the **surface kinetic energy** (EKE)[2].

In the California Current region, for example, the EKE is mostly dominated by balanced (rotational) motions in late winter/spring, while divergence is stronger in late summer/fall[3]. If surface waves respond differently to divergence and vorticity flows, seasonal changes in the dominant regime of surface currents may lead to significant changes in the surface wave field. In the present work we use the wave model WaveWatch III to assess:

Snapshots of normalized vorticity from the MITgcm llc4320



- How does the wave field respond to rotational and divergent flows?
- Could the signature of currents on waves be used to inferrer properties of the flow?

2. Background and methods

Wave Model:

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

$$\dot{\theta} = -\frac{1}{k}\hat{\mathbf{n}} \cdot \nabla(\mathbf{k} \cdot \mathbf{U}) \quad \text{(refraction)}$$

$$\dot{k} = -\nabla(\mathbf{k} \cdot \mathbf{U}) \quad \text{(change in wavenumber)}$$

$$\dot{\mathbf{x}} = \mathbf{c_g'} + \mathbf{U} \quad \text{(advection)}$$

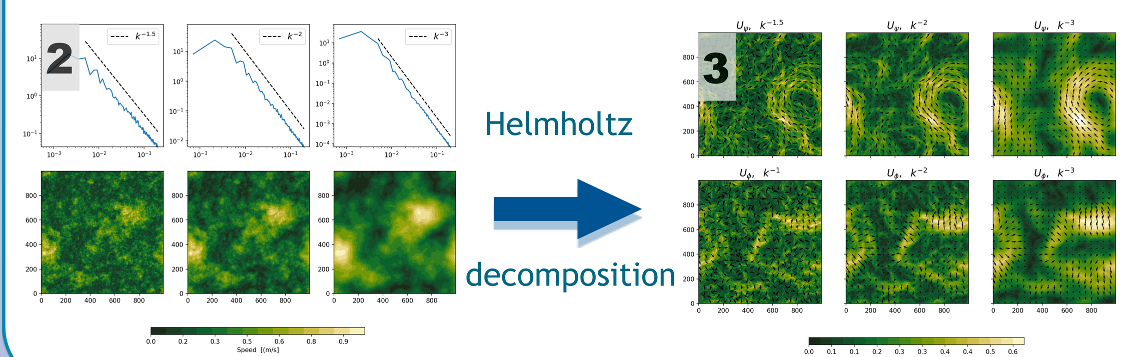
We use the wave model WaveWatch III (WW3) to integrate the action balance equation:

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

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

Synthetic Flow

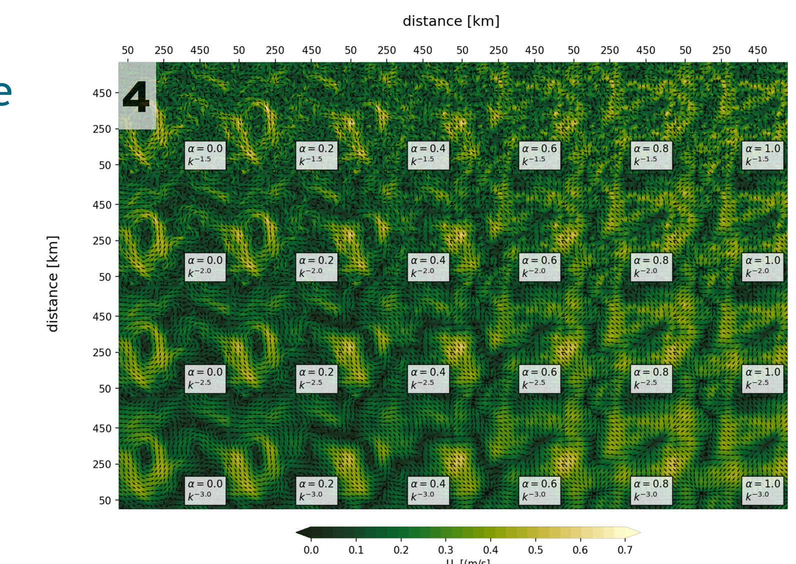
We start by creating synthetic flow fields with prescribed spectral slope and random phase.



Parameter Space						
Divergence Fraction (α)	0.0	0.2	0.4	0.6	0.8	1.0
Spectral Slope	-1.5	-2.0	-2.5	-3.0		
Wave Period	7.0 s	10.3 s	13.7 s	16.6 s		

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

$$u = (1-\alpha)u_\psi + \alpha u_\phi; \; v = (1-\alpha)v_\psi + \alpha v_\phi$$



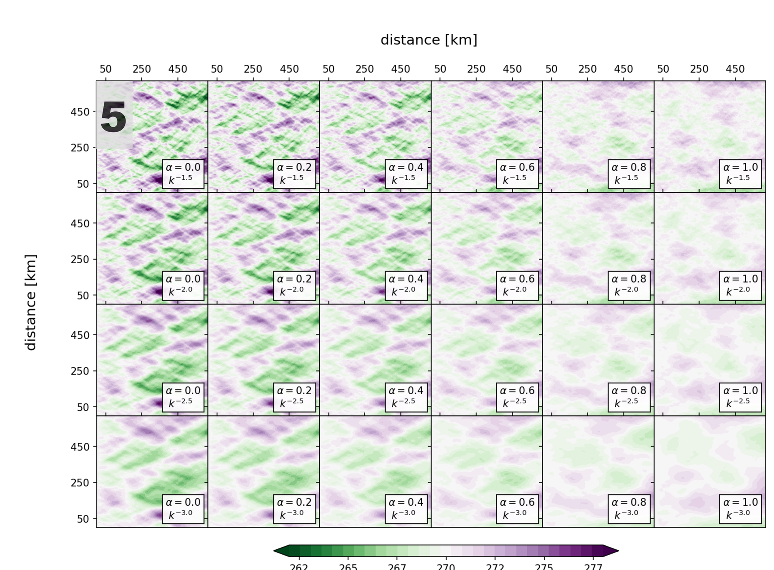
The flow can be decomposed into a part that is purely divergent (described by a velocity potential φ) and a part that is purely rotational (described by a stream function Ψ) such that the sum of both reconstruct the original velocities completely.

3. Synthetic currents

More vorticity → More divergence

Changes in the peak wave **direction** (**refraction**) are **larger** for **rotational** flows (figure 5, left panels) than divergent (figure 5, 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[5]:

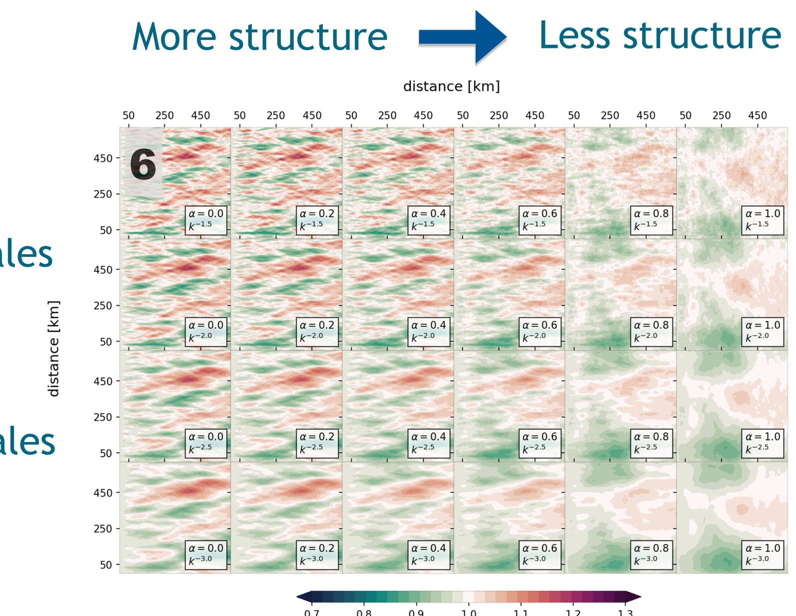
$$\chi = \frac{\zeta}{c_g}$$



More structure → Less structure

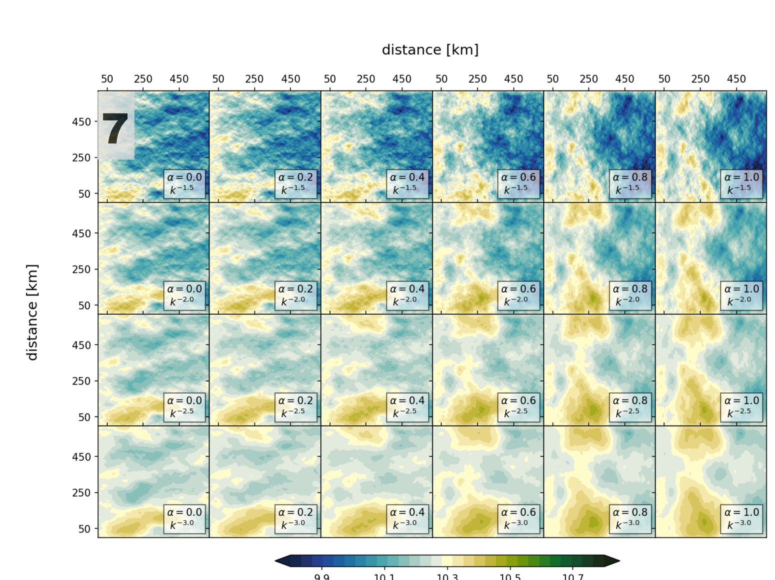
Finer scales

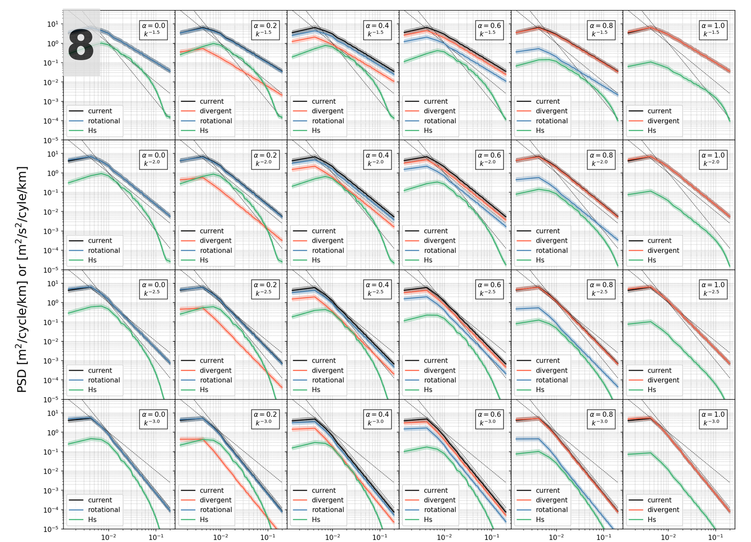
Larger scales



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** (α = 0). In addition, current fields with shallower spectral slope, are associated with finer structures in the Hs maps.

Stronger **divergence** leads to **higher** variations in the wave **period** (right panels), which changes Hs via conservation of wave action. Note that the spatial pattern of Hs in the purely divergent case (figure 6, last column) nearly matches the spatial pattern of the peak period (figure 7, last column).

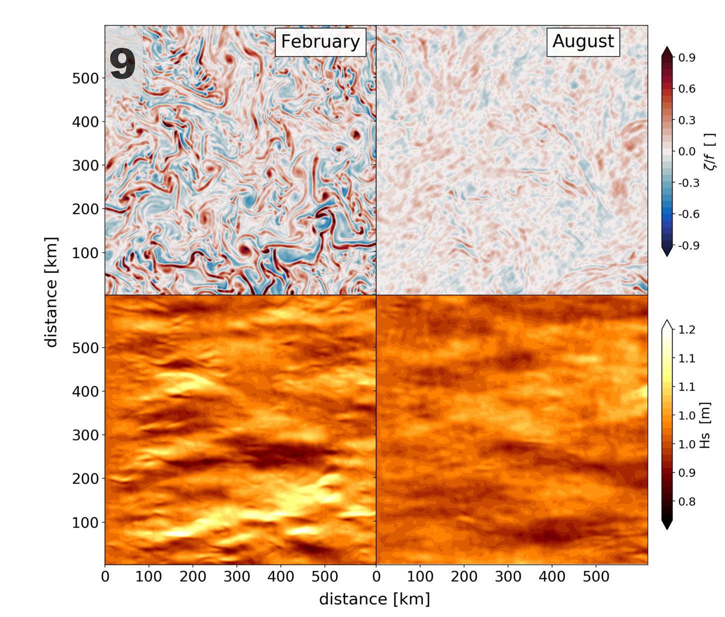




Varying the ratio of rotational to divergent flow while keeping the same EKE wavenumber spectrum (fixed spectral slope and variance) leads to strikingly different responses in the **Hs wavenumber spectra.** In agreement with the cases illustrated in the snapshots, the **variance of Hs** is **larger** 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.

4. LLC4320 in the California Current Region

An equivalent set up was used to run WaveWatch III forced with realistic currents from the MITgcm LLC4320 in the CCS region. **Figure 9** shows snapshots of surface **vorticity** from the **MITgcm** in **February** (left) and **August** (right) and and the resulting Hs from WaveWatch III. This example illustrates how the **seasonality** of the **submesoscale** in the CCS affects the wave field leading to strong gradients in Hs.



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:

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

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

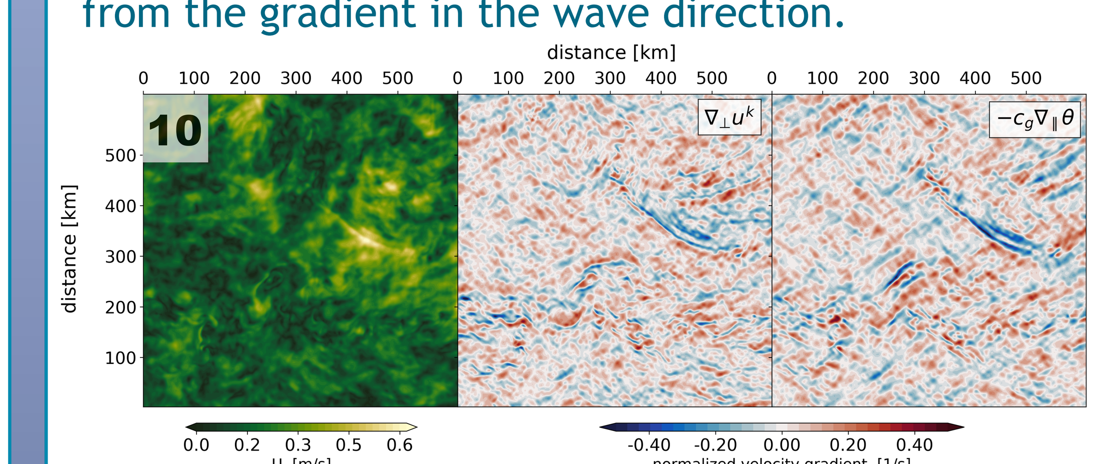
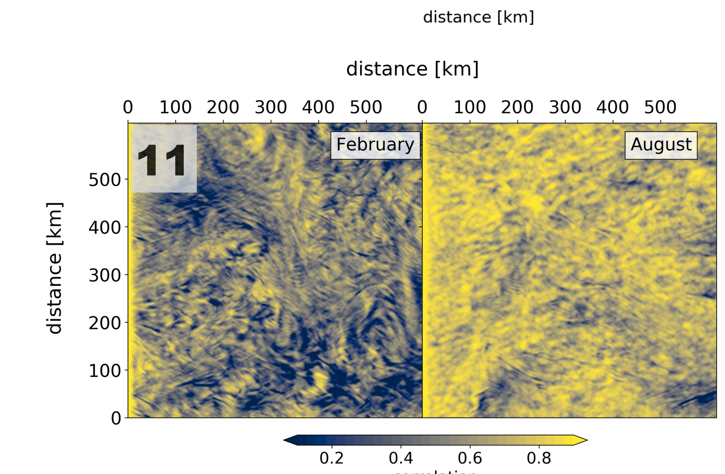


Figure 10 illustrates how this approximation captures the frontal structure that appears on the right side of this snapshot of the LLC4320 velocity field.



The correlation coefficient between the velocity gradient calculated from the LLC4320 and that derived from the wave direction gradient varies significantly seasonally, with better skill in months of weaker vorticity (figure 11).

5.Final Remarks

- An ensemble of synthetic flow fields were used to force WaveWatch III and assess the relative importance of current divergence and rotation in modifying several properties of the wave field.
- The wavenumber **spectrum** of **significant wave height** is highly sensitive to the nature of the underlying current. At wavelengths from 10-100 km the spectral slope of the **significant wave height** nearly **follows** the **spectral slope** of the **currents**.
- A set of idealized simulations with **realistic currents** from an ocean model suggests that wave parameters could be used to detect and characterize strong gradients in the velocity field.
- Understanding how surface waves respond to divergence and vorticity in a realistic scenario may shed some light on the extent to which **surface waves** could be used to **infer properties of surface currents**, which is particularly relevant for SWOT, as well as CFOSAT and other proposed satellite missions.

References

[1] Ardhuin, Fabrice, et al. "Small-scale open ocean currents have large effects on wind wave heights." *Journal of Geophysical Research: Oceans* 122.6 (2017): 4500-4517.

[2] Qiu, Bo, et al. "Seasonality in Transition Scale from Balanced to Unbalanced Motions in the World Ocean." *Journal of Physical Oceanography* 48.3 (2018): 591-605.

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[4] White, Benjamin S., and Bengt Fornberg. "On the chance of freak waves at sea." *Journal of fluid mechanics* 355 (1998): 113-138.

[5] Dysthe, Kristian B. "Refraction of gravity waves by weak current gradients." *Journal of Fluid Mechanics* 442 (2001): 157-159.

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