Various aspects of coastal dynamics embedded in high-frequency radar-derived surface currents

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About KAIST

- Located in the Daejeon Science Town and established in 1971
- 4,400 (under), 6,800 (grad.), and 627 (faculty) [as of 2016 Jan.]
Observations and analysis of geophysical fluids

- Boundary layer flows at scales of $O(1)$ km and hour(s) in a rotating frame (Coriolis frequency) in coastal regions where air, sea, and land are interfaced.

(images from an aerial image of red tide and A. Mahadevan, Nature 2014)
HFR surface current observations off the USWC

- 60+ compact array HFR (CODAR) system
- Hourly surface current maps (0.5, 1, 2, and 6 km resolution)
- Upper 1 m depth averaged currents
- From nearshore to 50 - 150 km offshore
- Near-near time reports via the web (network architecture: portals, nodes, and sites)

The diagram illustrates the relationship between time scale and horizontal spatial scale in the ocean. The time scales range from seconds to centuries, while the horizontal spatial scales range from centimeters to thousands of kilometers. Key phenomena are categorized according to their timescales and spatial scales:

- **Seasonality** (1 year)
- **Diurnal** (1 day)
- **Turbulence** (1 second)
- **Inertial/ internal/ solitary waves** (1 to 10 minutes)
- **Langmuir cell** (1 minute)
- **Surface waves** (1 to 10 meters)
- **Eddies, fronts, filaments** (1 to 100 meters)
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- **Internal tides** (1 to 10 meters)
- **Coastal upwelling** (1 to 100 meters)
- **CTW** (1 to 100 meters)
- **Surface tides** (1 to 100 meters)
- **Submesoscale** (1 to 1000 meters)
- **Rossby waves** (1 to 1000 meters)
- **MESOSCALE** (1 to 1000 meters)
- **Climate change** (100 years to centuries)
- **SAT** (10 years to decades)
- **ENSO** (1 to 10 years)
- **PDO** (10 to 100 years)

The diagram uses colors to distinguish different scales and phenomena, providing a visual representation of the complexity of oceanic processes across different scales.
Science questions

• Which **driving forces** are visible in the high-frequency radar-derived surface currents?

• How does variability of their **along-shore component**, **tide-**, and **wind-coherent components** look like?

• What scales does oceanic energy reside at? What are the pathways of oceanic energy?
Science questions w/ outline

• Intro. – Surface current measurements using HFR

• Which **driving forces** are visible in the high-frequency radar-derived surface currents?

• How does variability of their **along-shore component**, **tide-**, and **wind-coherent components** look like?

• **What scales** does oceanic energy reside at? **What are the pathways of oceanic energy?**

• **Summary**
Radio signals used in high-frequency radar

3-30 MHz (between AM radio and TV)
Wavelength ($\lambda_r$) : 10 ~ 100 (m)

Bragg backscattering
When the radar signals are backscattered in phase,
$$\lambda_w = \frac{\lambda_r}{2}$$

(Paduan and Graber, Oceanography 1997)
Phased array vs. Compact array

- **Phased array**
  - Parallel radar array
  - WERA, OSCR
  - Europe, US (FL, GA), Japan

- **Compact array**
  - Monopole + 2 dipoles
  - CODAR
  - USA (West/East), Korea, Japan

*University of Hamburg, Germany*
*Point Loma, CA USA*
Surface radial current map

- Range
  - Operating and sweeping frequency
- Angle
  - Direction finding v.s. MUSIC
- Radial velocity
  - Doppler shift
  - Projected current component

- 30 cm/s
- \( \Delta r = 1.5 \text{ km}, \Delta \theta = 5 \text{ degrees} \)
Surface radial current map

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- 30 cm/s  \( \Delta r = 1.5 \text{ km}, \Delta \theta = 5 \text{ degrees} \)
Multiple surface radial current maps

- Vector current map estimates
  - Un-weighted least squares fit (UWLS)
  - Optimal interpolation (OI)

(Kim et al, JGR 2008; Kim, CSR 2010)
Vector current estimates

- Vector current map estimates
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- Baseline inconsistency

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- Baseline inconsistency

(Dx = Dy = 1 km)

(Kim et al, JGR 2008; Kim, CSR 2010)
Improved vector current map

- Optimal interpolation
  - Minimize baseline inconsistency
  - A unified uncertainty definition
  - Divergence and vorticity
  - Velocity potential and stream function

- Exponential correlation function (based on observed surface currents, estimated from non-biased estimator [e.g., non-OI]) with shorter length scales (e.g., 2 km) leads to minimum level of spatial smoothing.

(Kim et al, JGR 2008; Kim, CSR 2010)
Uncertainty of vector current map

- Optimal interpolation
  - Minimize baseline inconsistency
  - A unified uncertainty definition
  - Divergence and vorticity
  - Velocity potential and stream function

(Kim et al, JGR 2008; Kim, CSR 2010)
Kinematic and dynamic quantities

\[ \mathbf{u} = \mathbf{u}_\phi + \mathbf{u}_\psi = \nabla_H \phi + \mathbf{k} \times \nabla_H \psi, \]

\[ \mathbf{d}(\mathbf{x}) = \sum_k \mathbf{m}(k) \exp(i \mathbf{k} \cdot \mathbf{x}) = \mathbf{Gm}. \]

If the covariance matrix is stationary,

\[ \langle \mathbf{d}(\mathbf{x}_1)\mathbf{d}(\mathbf{x}_2)^\dagger \rangle = \text{cov}(\mathbf{x}_1 - \mathbf{x}_2), \]

\[ \langle \mathbf{m}(\mathbf{k}_1)\mathbf{m}(\mathbf{k}_2)^\dagger \rangle = \sigma^2(\mathbf{k}_1) \delta(\mathbf{k}_1 - \mathbf{k}_2), \]

\[ \text{cov}(\Delta \mathbf{x}) = \sum_k \sigma^2(\mathbf{k}) \exp(i \mathbf{k} \cdot \Delta \mathbf{x}) = \mathbf{G} \langle \mathbf{mm}^\dagger \rangle, \]

Spatial covariance is equivalent to the Fourier transformed wavenumber spectra

\[ \text{cov}_{\mathbf{u}\mathbf{u}}(\Delta \mathbf{x}) \leftrightarrow k^2 S_{\phi\phi}(k) \]

\[ S_{\phi\phi}(k) \leftrightarrow \text{cov}_{\phi\phi}(\Delta \mathbf{x}) \]
Variance of surface currents (alongshore view)

- 60+ compact array HFR (CODAR) system
- Hourly surface current maps (0.5, 1, 2, and 6 km resolution)
- Upper 1 m depth averaged currents
- From nearshore to 50 - 150 km offshore

(Kim et al, JGR 2011)
Variance of surface currents (alongshore view)

- 61 HFRs, 14 NDBC wind buoys hourly observations (2007 to 2008)
- Effective spatial coverage (blue; 6 km) and coastline axis (red; 25 km apart from shoreline)
Variance of surface currents (alongshore view)

- Variance coherent with tides, wind, low frequency signals, and Coriolis force.
- Regional noise levels

Rotary power spectrum

Frequency (cpd)
• Cross-shore variation of tide-, wind-, low frequency-forced energy
• Low frequency pressure setup against the coast
• Inertial variance gets narrow offshore
• Variance of tide-coherent currents decrease with offshore distance

(Kim et al, JGR 2011)
Variance of surface currents (cross-shore view)

- Cross-shore variation of tide-, wind-, low frequency-forced energy
- Low frequency pressure setup against the coast
- Variance of tide-coherent currents decrease with offshore distance.
- Inertial variance gets narrow offshore

(Kim et al, JGR 2011)
Subinertial alongshore surface currents

- Rotated currents following the coastline axis
- Daily averaged alongshore surface currents.
- Seasonal California Currents.
- Phase speeds of 10 and 100 – 300 km/day
- Slower mode feature is found in southern CA and (intermittently) north.

(Kim et al., JGR 2011)
• Hourly alongshore surface currents.
• High-frequency structure coherent with diurnal wind and tides.
• Poleward progression of convergence front.

(Kim et al., JGR 2011)
Wind transfer/response functions

- A statistical linear framework to represent the link between wind and currents in the frequency and time domains.
- Isotropic and anisotropic analyses/models.

\[ \hat{\tau}(\omega) \rightarrow H(\omega) \rightarrow \hat{u}(\omega) \]

**Transfer function**

\[ \hat{u}(z, \omega) = H(z, \omega) \hat{\tau}(\omega) \]

\[ H(z, \omega) = \left( \langle \hat{u}(z, \omega) \hat{\tau}^\dagger(\omega) \rangle \right) \left( \langle \hat{\tau}(\omega) \hat{\tau}^\dagger(\omega) \rangle + R_a \right)^{-1} \]

- \( R_a \): Regularization matrix

\[ G(t - t') \rightarrow u(t) \]

**Response function**

\[ u(z, t) = \int_{t'}^{t} G(z, t - t') \tau(t') \, dt' \]

\[ G(z, t) = \left( \langle u(z, t) \tau_N^\dagger(t) \rangle \right) \left( \langle \tau_N(t) \tau_N^\dagger(t) \rangle + R_b \right)^{-1} \]

- \( \tau_N \): \( N \)-hour advanced time lagged wind stress
- \( R_b \): Regularization matrix

(Kim et al, JPO 2009, Kim et al, JGR 2010a, 2010b)
Isotropic model

\[
\frac{\partial u}{\partial t} - f_c v = \frac{1}{\rho} \frac{1}{\partial z} \left( \mu \frac{\partial u}{\partial z} \right)
\]

\[
\frac{\partial v}{\partial t} + f_c u = \frac{1}{\rho} \frac{1}{\partial z} \left( \mu \frac{\partial v}{\partial z} \right)
\]

\[\mathbf{u} = u + iv \quad \boldsymbol{\tau} = \tau_x + i\tau_y \quad : \text{isotropic assumption}\]

Then, Fourier transform

\[\lambda^2 \hat{u}(z, \omega) = \frac{\partial^2 \hat{u}(z, \omega)}{\partial z^2},\]

where \(\lambda = \sqrt{i(\omega + f_c) / \nu}\).

\(\nu = \text{Depth independent eddy viscosity}\)

With BCs (finite or infinite depth)

\[
\frac{\partial \hat{u}(z, \omega)}{\partial z} \bigg|_{z=0} = \frac{\hat{\tau}(\omega)}{\rho \nu}, \quad \hat{u}(z, \omega)|_{z=-\infty} = 0,
\]

\[
H(z, \omega) = \frac{\hat{u}(z, \omega)}{\hat{\tau}(\omega)} = \frac{e^{-\lambda z}}{\lambda \rho \nu}.
\]

(Gonella, DSR 1972; Ekman 1905)
Isotropic transfer function

\[
\frac{\partial u}{\partial t} - f_c v = \frac{1}{\rho} \frac{\partial}{\partial z} \left( \frac{\mu}{\partial z} \right),
\]

\[
\frac{\partial v}{\partial t} + f_c u = \frac{1}{\rho} \frac{\partial}{\partial z} \left( \frac{\mu}{\partial z} \right),
\]

\[u = u + iv \quad \tau = \tau_x + i\tau_y \quad \text{: isotropic assumption}\]

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\]

(Gonella, DSR 1972; Ekman 1905)
Data-derived isotropic transfer function (San Diego)

- The transfer function is inversely Fourier transformed into the impulse response function (temporal weighting), which decays with the inertial period.

\[
H(z, \omega) = \left( \langle \hat{u}(z, \omega) \hat{\tau}^\dagger(\omega) \rangle \langle \hat{\tau}(\omega) \hat{\tau}^\dagger(\omega) \rangle + R_\alpha \right)^{-1}
\]

\(R_\alpha\) : Regularization matrix
Data-derived isotropic transfer function (San Diego)
Transfer functions at all grid points are presented as PDFs at individual frequency bins.
Transfer functions as maps (steady state)

Enhanced nearshore
Geostrophic balance

Less veering angles nearshore due to deeper Ekman depth? (Kirincich et al 2005; Lentz 2001)

MITgcm results more to come...
Relevance of transfer functions and momentum balance

- 1km and hourly resolution, real bathymetry
- Idealized (spatially uniform) wind stress in individual directions
- 30 days run for each; wind stress at low, diurnal, and inertial frequency and the current responses

(Kim et al, Ocean Dynamics 2015)
Anisotropic transfer functions
Momentum balance (MITgcm diagnostics)

\[
\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + f_c \times \mathbf{u} = -\frac{1}{\rho} \nabla p + \nabla_h (A_h \nabla_h \mathbf{u}) + \frac{\partial}{\partial z} \left( A_z \frac{\partial \mathbf{u}}{\partial z} \right),
\]

(g) $\mathbf{C}_R$  
(h) $\mathbf{P}_G$  
(i) $\mathbf{V}_D$

![Images of wind patterns](image1.png)

Latitude (N)

Depth (m)
USWC-wide wind transfer functions

\[ f_c = -1.07 \text{ cpd} \]

Inertial frequency

(Kim et al, JGR 2011)
Resonant responses at the critical latitude

Resonant latitude due to land/sea breeze: ±30° N

Z = 0
Z = 0.35δ_E

Shaffer, 1972
Ekman model

Simpson et al, JPO 2002 (Slab layer model)

(Kim et al, GRL 2014)
Remote sensing – Geostationary Ocean Color Imagery

(0.5 km and hourly; GOCI @ KOSC)
Submesoscale process studies

- have benefited from primarily idealized numerical models and theoretical frameworks because they require the use of high-resolution observations of less than one hour in time and $O(1-10)$ km in space.

(Yoo et al, in prep)
On-going research topics

- Tracking of water-borne materials at submesoscale
  - Pollutants; red tides; oil spills; larvae transports
  - Particle trajectory model
  - Estimates of diffusion coefficients using 1D/2D advection-diffusion equations

- Bio-physical interactions at submesoscale
  - Finite-size/Finite-time Lyapunov Exponents (FSLE/FTLE) using current field (AVIOS; HFR; model)
  - Comparison with concentration maps (e.g., CHL/CDOM)

- Fontal instability s at submesoscale
  - Upwelling fronts; Submesoscale eddies and fronts
  - Reynolds flux estimates
  - Instability due to horizontal density gradients; feature extractions and energy spectra
• The operational HFR network provides the detailed aspects of coastal surface circulation and ocean dynamics at a resolution (km in space and hourly in time) containing responses to the low frequency, tides, wind forcing, and Earth rotation.
• Poleward propagating alongshore surface currents have a similar feature and phase speed of coastally trapped waves.
• Wind transfer function analysis can be interpreted with the analytic models.
• Scale continuity between sub-mesoscale and mesoscale. Due to the noise at 100 km scale in altimeter observations, studies on energy spectra and flux below that scale can be explored with sub-mesoscale observations.
• Sub-mesoscale eddies off the USWC: Rossby number of O(0.1-2) and 5-80 km diameter
Thank you!
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