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.]
- ASPIRE member (exchange programs..)
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)
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

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Latitudinal (N) axis: 32°40' to 32°20'
Longitudinal (W) axis: 117°30' to 117°10'

- 30 cm/s
- Δr = 1.5 km, Δθ = 5 degrees

true current

R1
R2
R3
Surface radial current map

- Range
  - Operating and sweeping frequency

- Angle
  - Direction finding v.s. MUSIC

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  - Projected current component

\[ \Delta r = 1.5 \text{ km, } \Delta \theta = 5 \text{ degrees} \]
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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$\Delta x = \Delta y = 1 \text{ km}$

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

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- Baseline inconsistency

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(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

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

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

If the covariance matrix is stationary,

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

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

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

Spatial covariance is equivalent to the Fourier transformed wavenumber spectra

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

\[ S_{\phi\phi}(k) \leftrightarrow \text{cov}_{\phi\phi}(\Delta \mathbf{x}). \]
60+ compact array HFR (CODAR) system
• Hourly surface current maps (0.5, 1, 2, and 6 km resolution)
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(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 coherent with tides, wind, low frequency signals, and Coriolis force.
• Regional noise levels
Wind skill explains how much variance of surface currents can be explained by wind (20 – 40%).
Skill is aligned with the local wind variance.
Variance of surface currents (alongshore view)

- NDBC wind
- Wind skill

Latitude (N): 44°, 40°, 36°, 32°
Longitude (W): 124°, 120°, 116°

RMS (m s⁻¹)

- $\langle u^2 \rangle^{1/2}$
- $\langle v^2 \rangle^{1/2}$

$k^2$, $\beta$
Variance of surface currents (cross-shore view)

- 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)

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

- Rotated currents following the shoreline
- 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)
Sub-inertial alongshore surface currents (zoom-in)

- 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.

\[
\begin{align*}
\hat{\tau}(\omega) & \rightarrow H(\omega) \rightarrow \hat{u}(\omega) \\
\tau(t) & \rightarrow G(t-t') \rightarrow u(t)
\end{align*}
\]

Transfer function

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

Response function

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

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

\[
R_a : \text{Regularization matrix}
\]

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

\[
\tau_N : N\text{-hour advanced time lagged wind stress}
\]

\[
R_b : \text{Regularization matrix}
\]

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

\[
\begin{align*}
\frac{\partial u}{\partial t} - f_c v &= \frac{1}{\rho} \frac{\partial}{\partial z} \left( \mu \frac{\partial u}{\partial z} \right) \\
\frac{\partial v}{\partial t} + f_c u &= \frac{1}{\rho} \frac{\partial}{\partial z} \left( \mu \frac{\partial v}{\partial z} \right)
\end{align*}
\]

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

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)

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

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

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

\[
\begin{align*}
\frac{\partial u}{\partial t} - f_c v &= \frac{1}{\rho} \frac{\partial}{\partial z} \left( \mu \frac{\partial u}{\partial z} \right) \\
\frac{\partial v}{\partial t} + f_c u &= \frac{1}{\rho} \frac{\partial}{\partial z} \left( \mu \frac{\partial v}{\partial z} \right)
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where \( f_c \) = Depth independent eddy viscosity

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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.

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

\(R_\alpha\) : Regularization matrix
Data-derived isotropic transfer function (San Diego)
Transfer functions as PDFs

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...
Anisotropic transfer functions
Momentum balance (MITgcm diagnostics)

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

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

Inertial frequency

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

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

Simpson et al, JPO 2002 (Slab layer model)

Shaffer, 1972
Ekman model

\[ Z = 0 \]
\[ Z = 0.35 \delta_E \]
Figure showing the relationship between time scale and horizontal spatial scale across various oceanographic processes. The time scale ranges from 1 sec to 100 yr, and the horizontal spatial scale ranges from cm to km. Various processes are represented within different regions, including Seasonality, ENSO, PDO, HFR, SAT, BASIN SCALE, SUBMESOSCALE, CTW, Rossby waves, and coastal upwelling. Processes such as Langmuir cell, turbulence, surface waves, internal tides, surface tides, and inertial/inertial solitary waves are also depicted within their respective scales. (Kim, JGRC 2015 submitted)
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.
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
Summary

- 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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