Observing meso/submesoscale turbulence using coastal radar observations

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Outline

• Introduction to surface current measurements using high-frequency radars (HFRs)

• Examples of submesoscale studies using HFR surface currents
  • Detection and analysis of submesoscale eddies
  • Energy spectra and fluxes at submesoscale

• Summary
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)

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)
Surface radial current map

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

△r = 1.5 km, △θ = 5 degrees

30 cm/s

true current

R1
R2
R3
Surface radial current map

- **Range**
  - Operating and sweeping frequency

- **Angle**
  - Direction finding v.s. MUSIC

- **Radial velocity**
  - Doppler shift
  - Projected current component

- **Projected current component**

- 30 cm/s
- $\Delta r = 1.5$ km, $\Delta \theta = 5$ degrees

- True current

- R1, R2, R3

- Longitude (W) and Latitude (N)
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
- Un-weighted least squares fit (UWLS)
- Optimal interpolation (OI)

Δx = Δy = 1 km  

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

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- Baseline inconsistency

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(R1) (R2)

(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

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

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

If the covariance matrix is stationary,

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

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

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

Spatial covariance is equivalent to the Fourier transformed wavenumber spectra

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

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

Power $(\text{cm/s}^2)/\text{cpd}$

Frequency (cpd)

Frequency bands: K1, N2, M2, S2, MK3, S3, M4
Eddy detection on HFR surface currents

- Streamlines (nearly closed polygons) are identified with winding angle method.
- Co-centered streamlines are fitted into an ellipse.
- If the center of ellipses in consecutive time steps is within a drifting range (e.g., 1.5 km) with the same rotation, ellipses are considered as a part of an eddy time series. The length of time series is called as persistency.

(Kim, CSR 2011)
Rossby number and size

- About 700 eddies are identified for each rotation.
- $O(0.5-1)$ Rossby number at the center of eddies
- 5-20km diameter ($L$)

\[ L = \sqrt{\frac{4S}{\pi}} \]
Circulation & WO parameter

Weiss-Okubo (WO) criterion \( g = \kappa^2 - \zeta^2 \)
- \( g > 0 \), strain-dominated region
- \( g < 0 \), vorticity-dominated region

\[
\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}
\]
- vorticity

\[
\kappa = \sqrt{\zeta^2 + \phi^2}
\]
- strain rate

\[
\phi = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}
\]
- shear deformation rate

\[
\zeta = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}
\]
- stretching deformation rate
Frontal-scale secondary circulation

\[ \zeta > 0 \quad \zeta < 0 \]

CCW

CW

Heavy

Light

\[ x = x_b \quad x = 0 \quad x = x_a \]

\[ \psi, \phi \text{ (m}^2\text{s}^{-1}) \]

Yeardays (2003)

\[ \zeta/f_c, \phi/f_c \]

\[ \zeta/f_c, \phi/f_c \]

\[ \rho/f_c, \phi/f_c \]

Yeardays (2003)

Latitude (N)

Longitude (W)

Depth (m)

Yeardays (2003)
Frontal-scale secondary circulation

\[ \alpha(t) = \frac{-\sum_{m<0} S(m, t) + \sum_{m>0} S(m, t)}{\sum_{m<0} S(m, t) + \sum_{m>0} S(m, t)} \]

\[ \pm 10 \text{ cm/s} \]

\[ \pm 25 \text{ cm/s} \]
Demography of sub-mesoscale eddies

Using flow geometry of the stream functions.

A cluster of streamlines is fitted with an ellipse. (Kim CSR, 2010)

Vorticity at the center of eddies.

About 2200 eddies for each rotation are identified (at least two days persistence).

(Kim et al, JGR 2011)
Kinetic energy (KE) spectra and fluxes (1/2)

- Kinetic energy (KE) spectra of currents \([E(k)]\) and spectra of passive tracers \([P(k); \text{CHL}]\)
- Transition (injection) scale and dissipation scale

\[
\frac{\partial}{\partial t} E(k^*) + \Pi(k^*) = -2\nu\Omega(k^*) + F(k^*),
\]

(Frisch 1995)

(Soh and Kim 2017; submitted)
Kinetic energy (KE) spectra and fluxes (2/2)

- What can be the decay slope of KE spectra and the injection scales to have zero crossing in the KE flux below 100 km scale?

Wavenumber KE spectra of altimeter-derived cross-track geostrophic currents (30N to 40 N)

\[ S_{u_\perp}(k_\parallel) = \left( \frac{g}{f_c} \right)^2 \left( 2\pi k_\parallel \right)^2 S_{\eta_\parallel}(k_\parallel), \]

Kinetic energy flux in ACC region (57S, 120W)
Optimally interpolated 1/3° AVISO products
A network of high-frequency radars (HFRs) along the coast over 2500 km of US West Coast provides km resolution and hourly surface current maps which cover about 150 km offshore from shoreline as the upper 1 m depth averaged currents.

Due to low signal-to-noise ratio of satellite remote sensing near coastal regions, coastal surface current maps provide a useful resource to investigate the submesoscale processes in a view of statistics and dynamics.

(Kim et al, JGR 2011, Kim and Crawford, GRL 2014)
KE spectra (USWC HFR; Altimeters; Shipboard ADCPs)

\[ S_{\mathbf{u}_\perp}(k_\parallel) = \left( \frac{g}{f_c} \right)^2 \left( 2\pi k_\parallel \right)^2 S_{\eta_\parallel}(k_\parallel), \]

Power spectrum of cross-track geostrophic currents from along-track SSAs

$K^{-2}$ power law related to sub-mesoscale.

Robust estimate on $k^{-2}$ spectra with data in other regions.

Two kinds of ALT data: Envisat and Jason-1

HFR data with three resolutions:
1 km and 6 km data are sampled from SoCAL, because minimum ageostropic components are expected.
20 km data are from the coastline axis. (Kim et al, JGR 2011)
 KE spectra (USWC HFR; Altimeters; Shipboard ADCPs; Glider)

\[ S_{u_{\perp}}(k_{\parallel}) = \left( \frac{g}{f_c} \right)^2 \left( 2\pi k_{\parallel} \right)^2 S_{\eta_{\parallel}}(k_{\parallel}), \]

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HFR data with three resolutions:
1 km and 6 km data are sampled from SoCAL, because minimum ageostrophic components are expected.
20 km data are from the coastline axis. (Kim et al, JGR 2011)
- Decay slopes of KE spectra range between $k^{-2}$ and $k^{-3}$
- Zero-crossings of KE fluxes appear $O(10)$ km

(Soh and Kim 2017; submitted)
• Surface currents are observed at the verge of the confluence of two regional boundary currents.
• **Hourly and 1-km resolution HFR-derived surface currents** for one year (2013)

• Geostationary Ocean Color Imagery (GOCI)-derived chlorophyll data at resolutions of an hour (during a day; approx. 8 samples a day) and **0.5 km** for 5 years (2011 to 2015)

• **Bi-monthly CTD** (temperature, salinity, and nutrients) sampling at the C0 to C11 stations (1960 to currents) are used to derive the **climatology of stratification**.
KE spectra of submesoscale surface currents

(Yoo et al, 2017 submitted)
Spectra of submesoscale surface CHLs (1/2)

(Lee and Kim, 2017 submitted)

(Lee and Kim, 2017 submitted)
Spectra of submesoscale surface CHLs (2/2)

(Lee and Kim, 2017 submitted)
• Transition and dissipation scales appear near 10 km and 2 km, respectively
Summary

• Kinetic energy (KE) spectra and fluxes of submesoscale surface currents show the decay slopes of $k^{-2}$ and $k^{-3}$ and the injection scale as $O(10)$ km.

• Consistently, the spectra of passive tracers (CHL) exhibit the injection scale of $\sim 10$ km and dissipation scale of $\sim 2$ km under a cautionary consideration of the use of bloomed CHLs as a passive tracer.

• Both results are more consistent with quasi-geostrophic (QG) turbulent theory than others (sQG, semi-QG, fsQG, etc).

• The baroclinic instability in the mixed layer plays a dominant role in the regional submesoscale driver rather than the mesoscale eddy-derived surface frontogenesis at a scale of $O(100)$ km.