Poleward propagating features as observed in the U.S. West Coast network of high-frequency radar

Sung Yong Kim
Marine Physical Laboratory
Scripps Institution of Oceanography

Co-advisor: Eric Terrill and Bruce Cornuelle

syongkim@mpl.ucsd.edu
 Outline

• Background of HF radar
• Poleward propagating features in the surface current observations
  – California Current System (surface circulation)
  – Historical NDBC wind data
  – Review of the coastal trapped wave observations
  – Equatorward feature removal by filtering of wind-driven surface currents
• Applications using observed surface currents
  – Lagrangian trajectory
  – Submeso-scale rotational flows
Background of HF radar
3-30 MHz (between AM radio and TV)
Wavelength ($\lambda_r$) : 10 ~ 100 (m)

Bragg Backscattering
When the radar signal backscatters in phase,

$$\lambda_w = \frac{\lambda_r}{2}$$

Klaus-Werner Gurgel, University of Hamburg, Germany
Surface radial current map

- Range ($r$)
  - Operating freq. and sweep freq.
- Radial velocity ($v_r$)
  - Doppler shift
- Angle ($\theta$)
  - Direction finding or MUSIC

- true vector
  - R1
  - R2
  - R3
Surface radial current map

- Range ($r$)
  - Operating freq. and sweep freq.
- Radial velocity ($v_r$)
  - Doppler shift
- Angle ($\theta$)
  - Direction finding or MUSIC

![Diagram showing surface radial current map with points R1, R2, and R3, and a true vector.]
Surface vector current map

- Radial combining
  - Un-weighted least-squares fit vs. optimal interpolation

- Baseline inconsistency
Surface vector current map

- Radial combining
  - Un-weighted least-squares fit vs. optimal interpolation

- Baseline inconsistency
Improved vector current map

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

(Kim et al. JGR 2008)
Uncertainty of vector current map

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

(Kim et al. JGR 2008)
Dynamic quantities

BLUE (CW/DOWN)

RED (CCW/UP)

Divergence

Normalized vorticity

Scientific notation in the figure includes:

- **Divergence**: $(m^2 s^{-1})$
- **Velocity potential**: $(m^2 s^{-1})$
- **Stream function**: $(m^2 s^{-1})$
Poleward propagating features in the surface currents along the USWC

Sung Yong Kim¹, Eric Terrill¹, Bruce Cornuelle¹, Burt Jones², Libe Washburn³, Mark Moline⁴, Jeffrey Paduan⁵, Toby Garfield⁶, John Largier⁷, and P. Michael Kosro⁸

¹Scripps Institution of Oceanography
²University of Southern California
³University of California, Santa Barbara
⁴California Polytechnic State University
⁵Naval Postgraduate School
⁶San Francisco State University
⁷University of California, Davis
⁸Oregon State University
Coastal observations along the USWC

• Observations
  – Surface currents (61 HF radars under regional COOS. e.g. SCCOOS, CeNCOOS, and NANOOS).
  – Tides (NOAA), Wind (NDBC).

• Coastline axis
  – 15-25 km offshore.
  – Passing SBC.
  – Evenly spaced axis.

• OI-mapped UV
  – 25 hrs avg. (sub-inertial)
  – Alongshore currents (v*) projected parallel to coastline axis.
Coastal observations along the USWC

- **Observations**
  - Surface currents (61 HF radars under regional COOS. e.g. SCCOOS, CeNCOOS, and NANOOS).
  - Tides (NOAA), Wind (NDBC).

- **Coastline axis**
  - 15-25 km offshore.
  - Passing SBC.
  - Evenly spaced axis.

- **OI-mapped UV**
  - 25 hrs avg. (sub-inertial)
  - Alongshore currents (v*) projected parallel to coastline axis.
California Current System

CC: California Current
DC: Davison Current
CUC: California Under Current
SCC: SoCal. Counter Current
SCE: SoCal. Eddies

(Agostini et al, CJFAS 2003)  (Batteen et al, JO 1999)
Bathymetry along the USWC

NGDC ETOPO2v2 (2’ resolution)

Coronado Is.
San Catalina Is.
San Clemente Is.
San Nicolas Is.
Anacapa Is.
Santa Cruz/Santa Rosa/San Miguel Is.

Distance (km)
0 30 60 90 120

Coastline axis
Orthogonal axis

200 m
NDBC wind (1995-2007)

- Rotated with the principal axis
- Southern Cal. < Northern Cal. & Oregon.
- Strong variance at Pt. Conception.
- Seasonal alongshore wind @ Oregon:
  - equatorward (summer)
  - poleward (winter)
Alongshore currents ($v^*$) and sea elevation anomaly ($\delta \eta$)
Alongshore currents ($v^*$) and sea elevation anomaly ($\delta \eta$)

25 hrs avg. alongshore currents

Sea elevation Anomaly (daily avg.)

O(100 km/day)
Alongshore currents ($v^*$) and sea elevation anomaly ($\delta \eta$)

Sea elevation anomaly (daily avg.)

25 hrs avg. alongshore currents

O(10 km/day)
Coastal trapped waves (CTWs)

- A hybrid of barotropic Rossby (shelf) waves (no stratification, sloping bottom, $S \to 0$) and baroclinic Kelvin waves (stratification, flat bottom, $S \to \infty$).
- Propagation along the coastline (continental shelves and slopes) on the right in the N.H. (left in the S.H.)
- Sub-inertial time scale (days~weeks)
- Potential causes:
  - Wind relaxation and reversal effects
  - Kelvin waves’ reflection on the eastern boundary
  - Wind or storm-forced CTWs
  - Enhanced poleward currents during ENSO

Burger number

$$S = \left( \frac{N_0 H}{fL} \right)^2$$
Review of CTWs along the USWC

| Studies               | $|u|$   | $C_h$  | $T$  | Seasons | Methods | Study area       |
|-----------------------|-------|--------|------|---------|---------|------------------|
| Chapman (1987)         | 294–320 (1st) | 143–160 (2nd) | CODE-1, 2 | LCTWM   |         | CODE region (38.5°N) |
| Chelton et al. (1988)  | 10–20 | 151–177| 03/84–08/84 | MR   | C. CA (34.5–37.5°N) |
| Davis and Bogden (1989) | 173   | CODE-1, 2 | EOF  | CODE region (38.5°N) |
| Collins et al. (1996)  |       | 302 (1st) | LCTWM | USWC (38–43°N) |
| Ramp et al. (1997)     | 20–40 | 140 (2nd) | 05/89–04/91 | LCTWM | C. CA (34.6–38°N) |
| Auad and Henderson (1997) | 70    | 13.6   | 01/84–06/84 | EOF/TSA | S. CA (33.5–34.7°N) |
| Pierce et al. (2000)   | 10–20 | 07/95–08/95 | TSA | N. Pacific (33–51°N)/NMFS |
| Noble et al. (2002)    | 20–30 | 5–20   | 05/92–04/93 | EOF/TSA | S. CA (33.75°N) |
| Hickey et al. (2003)   | 121–225| 02/98–09/98 | TSA | S. CA (33.5–34.3°N) |
| Agostini et al. (2006) | 10–20 | 07/95–08/95 | 07/98–08/98 | TSA | N. Pacific (33–51°N)/NMFS |
| Lavin et al. (2006)    | 15–30 | 06/03, 06/05 | SW. Mexico (17–23°N) |

Table 2. Chronological review of the observational poleward flow study in the USWC: The magnitude of the observed poleward flow ($|u|$, cm s$^{-1}$) and its propagating speed ($C_h$, km day$^{-1}$) and period ($T$, days). The observation data are analyzed with the linear CTW model (LCTWM, Brink (1982); Brink et al. (1987); Brink and Chapman (1987); Brink (1990)), and the empirical orthogonal function (EOF), and the multivariate regression (MR), and the time series analysis (TSA, Emery and Thomson (1997)) in the time and frequency domain. CODE-1 and CODE-2 data cover the upwelling season (April – July) of 1981 and 1982. National Marine Fisheries Services (NMFS)
Review of CTWs along the USWC

| Studies                      | \( |u| \) cm s\(^{-1}\) | \( C_h \) km day\(^{-1}\) | \( T \) days | Seasons | Methods   | Study area               |
|------------------------------|----------------------|-------------------|-------------|---------|-----------|-------------------------|
| Chapman (1987)               | 294–320 (1st)        | 143–160 (2nd)     | 83–90 (3rd) |         | CODE-1,-2 | LCTWM CODE region (38.5° N) |
| Chelton et al. (1988)        | 10–20                | 151–177           |             | 03/84–08/84 | MR        | C. CA (34.5–37.5° N) |
| Davis and Bogden (1989)      | 173                  |                   |             | CODE-1,-2 | EOF       | USWC CODE region (38.5° N) |
| Collins et al. (1996)        |                      |                   |             |         |           | USWC (38–43° N)         |
| Ramp et al. (1997)           | 20–40                | 302 (1st)         | 140 (2nd)   | 05/89–04/91 | LCTWM     | C. CA (34.6–38° N) |
| Auad and Hendershott (1997)  | 70                   | 13.6              |             |         | EOF/TSA   | S. CA (33.5–34.7° N) |
| Pierce et al. (2000)         | 10–20                |                   |             | 07/95–08/95 | TSA       | N. Pacific (33–51° N)/NMFS |
| Noble et al. (2002)          | 20–30                | 5–20              |             | 05/92–04/93 | EOF/TSA   | S. CA (33.75° N) |
| Hickey et al. (2003)         | 121–225              |                   |             | 02/98–09/98 | TSA       | S. CA (33.5–34.3° N) |
| Agostini et al. (2006)       | 10–20                |                   |             | 07/95–08/95 | TSA       | N. Pacific (33–51° N)/NMFS |
| Lavin et al. (2006)          | 15–30                |                   |             | 06/03, 06/05 | SW Mexico | Sw. Mexico (17–23° N) |

Table 2. Chronological review of the observational poleward flow study in the USWC: The magnitude of the observed poleward flow \( |u| \) cm s\(^{-1}\) and its propagating speed \( C_h \) km day\(^{-1}\) and period \( T \) days. The observation data are analyzed with the linear CTW model (LCTWM, Brink (1982); Brink et al. (1987); Brink and Chapman (1987); Brink (1990)), and the empirical orthogonal function (EOF), and the multivariate regression (MR), and the time series analysis (TSA, Emery and Thomson (1997)) in the time and frequency domain. CODE-1 and CODE-2 data cover the upwelling season (April – July) of 1981 and 1982. National Marine Fisheries Services (NMFS)
Power spectrum of alongshore surface currents

2D power spectra of 25h avg. alongshore current (v*)

\[ S = \left( \frac{N_0 H}{fL} \right)^2 \]

(Brink, ARFM 1991)
Power spectrum of alongshore surface currents

2D power spectra of 25h avg. alongshore current ($v^*$)

Kelvin wave

200 km/day

10 km/day

$S = \left( \frac{N_0 H}{fL} \right)^2$

(Brink, ARFM 1991)
Power spectrum of alongshore surface currents

2D power spectra of 25h avg. alongshore current ($v^*$)

- Kelvin wave
- 200 km/day
- 10 km/day

$$S = \left( \frac{N_0 H}{fL} \right)^2$$

(Brink, ARFM 1991)
Summary

• Surface current measurements using HF radar
  - Hourly, 1-150 km spatial coverage
  - Surface current map and dynamic quantities

• Poleward propagating features
  - O(10-100) km/day phase speed, 10-30 days period
  - Locally wind-driven currents were filtered out to magnify the poleward propagating features.
  - Numerical models
Wind-driven current estimate

- Wind impulse response function (WIRF) estimate using hourly NDBC buoy winds and hourly de-tided surface currents.
- Time/frequency domain iso-/anisotropic WIRF.
- 6 days time lag wind stress as the impulse.

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

\[
\mathbf{G}(z,t) = \left( \langle \mathbf{u}(z,t) \mathbf{\tau}_{\mathbf{N}}(t) \rangle \right) \left( \langle \mathbf{\tau}_{\mathbf{N}}(t) \mathbf{\tau}_{\mathbf{N}}(t) \rangle + \mathbf{R}_b \right)^{-1}
\]

where

\[
\langle \mathbf{\tau}_{\mathbf{N}}(t) : N \text{ hour advanced time lag wind stress} \rangle
\]

(Kim et al., JPO 2008 in review)
Wind impulse response function

Gonella (DSR 1972)
Wind impulse response function

Gonella (DSR 1972)
Unconditioned vs. wind-free surface currents

- Most of wind-driven currents are downcoast, so upcoast currents are discovered and the noises are added.
Additional topics

- Environmental research using Lagrangian particle trajectory for
  - Water quality monitoring
  - Oil spill (experiments)
  - Biological larvae spreading
  - Rescue

- Submesoscale rotational flows
San Diego shoreline water quality sampling

Water quality

Rainfall

River flux
Lagrangian particle track model

- Objectively mapped surface currents
- Forward time integration
- Particle concentrations vs. water quality samplings
- ROC (Receiver Operating Characteristics) analysis

AOC = 0.72
Hyperion outfall

Hyperion sewage was diverted from 5-mile to 1-mile outfall on Nov. 28-30, 2006
Oil spill (experiment)

Office of Spill Prevention and Response (OSPR): dye, GPS-tracked drifters, surface currents

San Francisco Bay Oil Spill (Nov. 3, 2007 0830 (PST))
Sub-mesoscale rotational flows detected by HF radar-derived surface currents
Classifications of the rotational flow

- Stream function from the radial current map (daily mean)
- Ellipse fit

<table>
<thead>
<tr>
<th>Variables</th>
<th>Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center (Longitude, Latitude)</td>
<td>$x, y$</td>
</tr>
<tr>
<td>Time stamp</td>
<td>$t$</td>
</tr>
<tr>
<td>Comparable size (Diameter)</td>
<td>$L$</td>
</tr>
<tr>
<td>Major, minor axes, and angle</td>
<td>$\alpha, \beta, \theta$</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>$\epsilon$</td>
</tr>
<tr>
<td>Strength</td>
<td>$n$</td>
</tr>
<tr>
<td>Representative current speed</td>
<td>$V$</td>
</tr>
<tr>
<td>Normalized vorticity</td>
<td>$\zeta/f_c$</td>
</tr>
<tr>
<td>Eddy ID</td>
<td>$\kappa$</td>
</tr>
</tbody>
</table>
Basic statistics

Persistency

Normalized vorticity

Size of eddies

\[ S = \pi \alpha \beta \approx \pi \frac{L^2}{4} , \]
2D PDF of EKE* vs. wavenumber

**CW**

**CCW**

Energy density (m$^2$ s$^{-3}$)

Wavenumber ($1/(2\pi D)$, rad m$^{-1}$)

12 km  6 km  3 km
2D PDF of EKE* vs. wavenumber

(Capet et al. JPO 2008)
EKE in surface currents @ SD & SBC

Acknowledgement:
Coastal Ocean Current Monitoring Program (COCMP)
Office of Naval Research (ONR)
NOAA IOOS
SCCOOS, CeNCOOS, OSU, and SFSU
State of California
City of San Diego, San Diego County
CORDC at Scripps Institution of Oceanography
Extra slides
K. Brink’s CTW 1D model

1 dyne/cm² = 10⁻³ cm

If \( v = 30 \text{ cm/s}, \)
\[ P = 10^4 \text{ dyne/cm}^2 \]
\[ = 10 \text{ cm elevation} \]
Low freq. forcing

ADCP

Comparison of the alongshore currents
Spaghetti plots of identified eddies

CW CCW
NDBC wind steadiness

Directional steadiness

\[ \gamma = \frac{\sqrt{\langle u \rangle^2 + \langle v \rangle^2}}{\langle u^2 + v^2 \rangle} \]

\( \gamma \rightarrow 1 : \text{steady wind} \)
Continuity of Altimetry- and HF radar-derived surface currents

- **Resolution**
  - Altimetry (30 km)
  - HF radar (1-6 km)

- **Coverage limit**
  - Altimetry (~50 km)
  - HF radar (0.5 km)

Coastline axis (15-20 km offshore)
Continuity of Altimetry- and HF radar-derived surface currents

Resolution: Altimeter (~30 km) / HF radar (1-6 km)

Coverage limit from coastline:
Altimeter (~50 km) / HF radar (~0.5 km)

Coastline axis (15-20 km offshore)
Wind-driven surface currents

25 hrs avg. cross shore wind-driven currents

25 hrs avg. alongshore wind-driven currents