Mapping the U.S. West Coast surface circulation

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Abstract

The nearly completed U.S. West Coast (USWC) high-frequency radar (HFR) network provides an unprecedented capability to monitor and understand coastal ocean dynamics and phenomenology through hourly surface current measurements at up to 1 km resolution. The dynamics of the surface currents off the USWC are governed by tides, winds, Coriolis force, low-frequency pressure gradients (less than 0.4 cycles per day (cpd)), and nonlinear interactions of those forces. Alongshore surface currents show poleward propagating signals with phase speeds of O(10) and O(100 to 300) km/day and time scales of 2 to 3 weeks. The signals with slow phase speed are only observed in southern California. It is hypothesized that hey are scattered and reflected by shoreline curvature and bathymetry change and do not penetrate north of Point Conception. The seasonal transition of alongshore surface circulation forced by upwelling-favorable winds and their relaxation is captured in fine detail. Sub-mesoscale eddies, identified using flow geometry, have Rossby numbers of 0.1 to 3, diameters in the range of 10 to 60 km, and persistence for 2 to 12 days. The HFR surface currents resolve coastal surface ocean variability continuously across scales from sub-mesoscale to mesoscale (O(1) km to O(1000) km). Their spectra decay with k-2 at high wave number (less than 100 km) in agreement with theoretical sub-mesoscale spectra below the observational limits of present-day satellite altimeters.

Observations

Alongshore surface currents

A time-alongcoast diagram of subinertial alongshore surface currents shows two types of poleward propagating signals with phase speeds of $O(10)$ and $O(100-300)$ $\mathrm{km\,day^{-1}}$ corresponding to typical shelf mode speeds [1]. The spring and fall transitions relating to the onset and demise of seasonal upwelling-favorable winds are also visible, most prominently of central and northern California [2] (Figs. B and C).

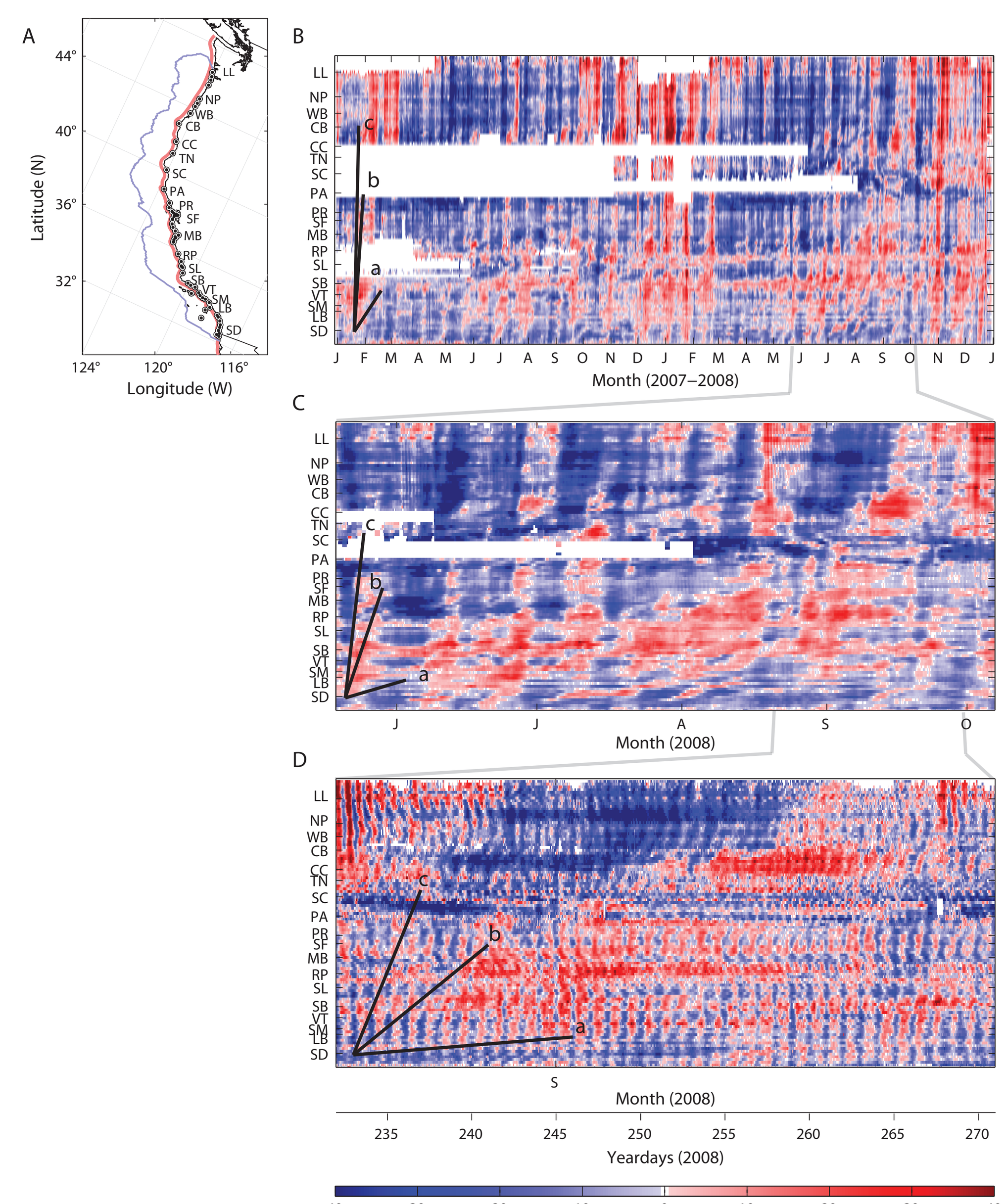
Variance of surface currents

The spectra of surface vector currents off the USWC are characterized by variance peaks in the low frequency band [$|\sigma| \leq 0.4$ cycles per day (cpd)], in two bands centered at diurnal and semi-diurnal frequencies [tides (K_1, M_2, and S_2), diurnal wind (S_1) and its harmonics], and at inertial frequency (f_c = 1.06 to 1.49 cpd for 32°N to 48°N) (Fig. A) [3]. The inertial variance of surface currents increases to the north, due in part to the response to increasingly persistent and strong winds and to energetic nonlinear interactions due to decreasing baroclinic Rossby deformation radius and increasing intermittency [4]. The variance in the counter-clockwise inertial band implies elliptical motion of near-inertial surface currents rather than pure circular motions. This succinct view of surface current energy enables us to identify possible driving forces for the surface circulation such as local and remote winds, tides, pressure gradients, and baroclinic motions due to coastal boundaries (e.g., capes, headlands, and bays) and changing bottom topography [5].

Scale continuity

The continuity of the power spectra of ocean surface currents from sub-mesoscale to mesoscale is investigated by comparing their energy in the wave-number ($k = 1/L$) and frequency ($\sigma = 1/T$) domains.

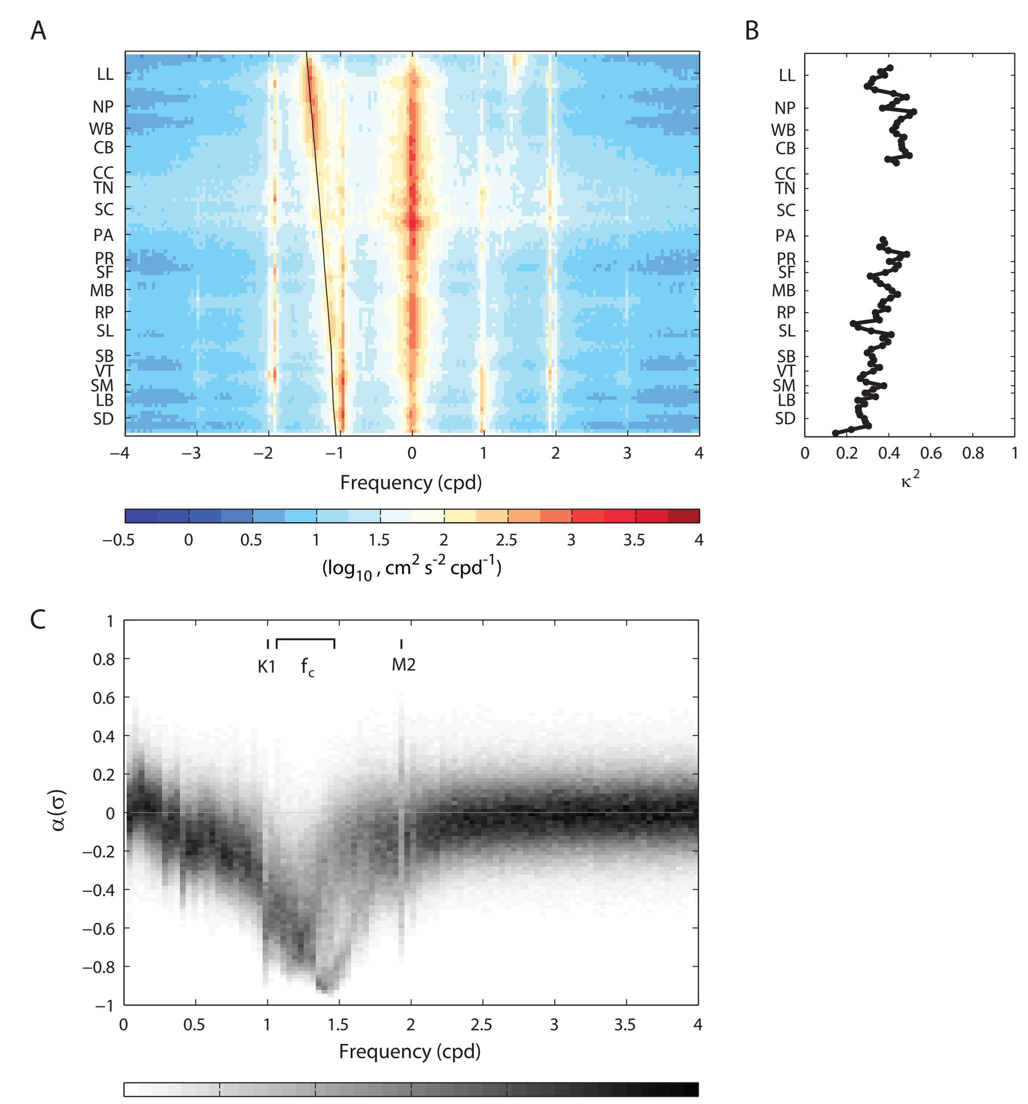
The wave-number spectra of HFR surface currents show a consistent and continuous variance distribution across three different resolutions (1, 6, and 20 km) (Fig. A). Resolved scales range from $O(1000)$ km to $O(1)$ km, and the spectra decay with k^{-2} at high wave-number in agreement with sub-mesoscale spectra [6]. Although their spectra can vary with location because of regional variations in driving forces and geostrophic contents, they have a robust k^{-2} decay.



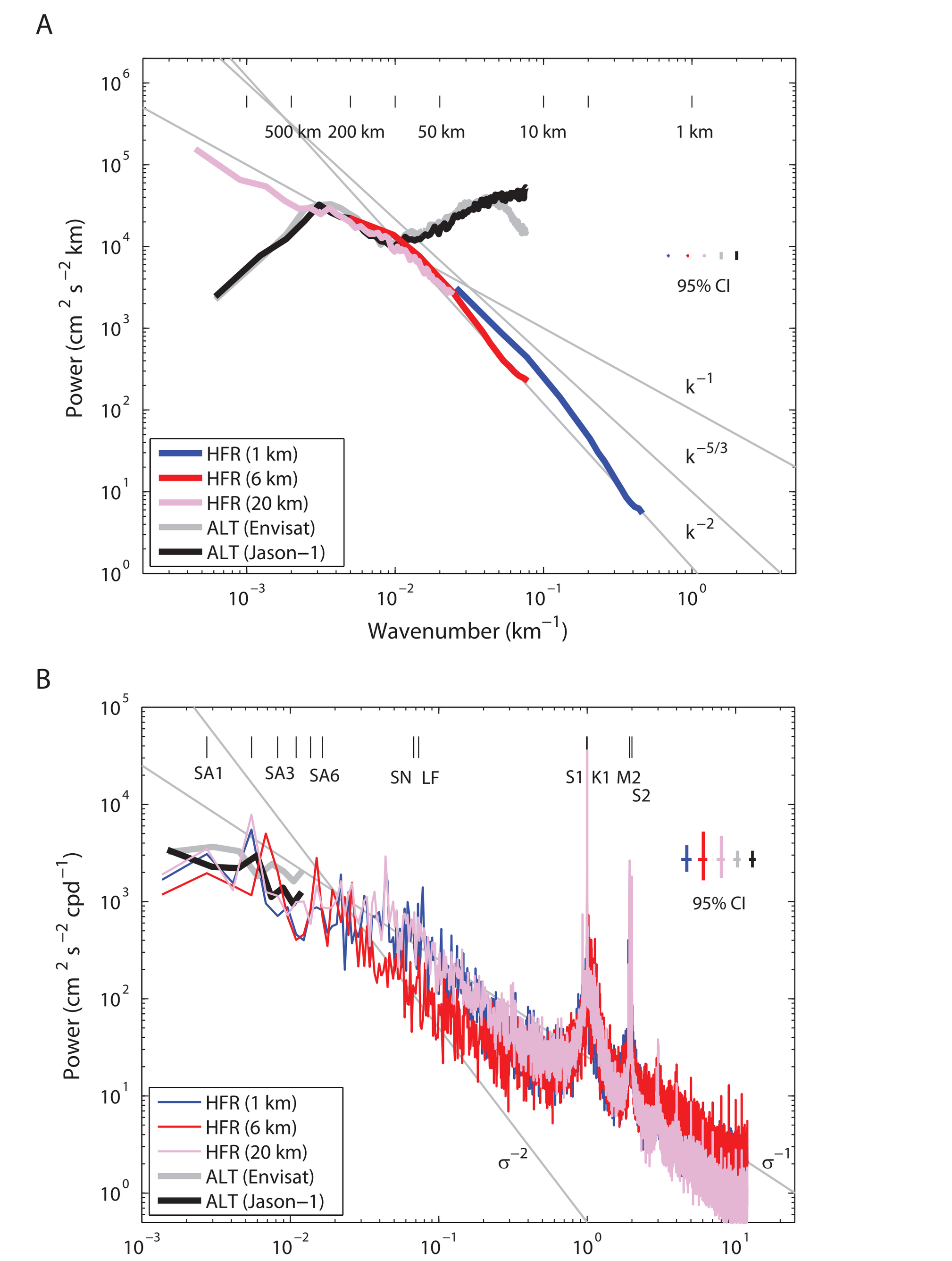
A. High-frequency radar (HFR) network on the USWC for the surface current observation (61 HFRs are marked as black dots as of January of 2009). The blue curve indicates the effective spatial coverage of surface current map over two years (2007 – 2008) and a red curve denotes the coastline axis. For reference, major coastal regions are denoted by abbreviated two letter names from south to north: San Diego (SD), Long Beach (LB), Santa Monica (SM), San BuenaVentura (VT), Santa Barbara Channel (SB), Port San Luis (SL), Ragged Point (RP), Monterey Bay (MB), San Francisco (SF), Point Reyes (PR), Point Arena (PA), Shelter Cove (SC), Trinidad (TN), Crescent City (CC), Cape Blanco (CB), Winchester Bay (WB), Newport (NP), and Loomis Lake (LL). B and C. Time-alongcoast diagram of subinertial alongshore surface currents ($\mathrm{cm\,s^{-1}}$) for two years (2007 – 2008) and about five months of 2008 (May 20 – October 10), respectively. Red and blue colors indicate the poleward (upcoast) and equatorward (downcoast) currents. The missing observations are presented with white space. Three black lines indicate the reference phase speeds of 10 (a), 100 (b), and 300 (c) $\mathrm{km\,day^{-1}}$. D. Time-alongcoast diagram of hourly alongshore surface currents ($\mathrm{cm\,s^{-1}}$) on yeardays 232 – 271 of 2008 (August 20 – September 28). The first day of each month and the midnight of each day are labeled in B – D and D, respectively.

Moreover, HFR observations resolve variability at scales smaller than $L \approx 100$ km, where the noise in satellite altimeter-derived (ALT) currents becomes dominant over oceanic signals [4]. For example, the wave-number spectra of HFR surface currents in a region (e.g., southern California) with minimum wind-driven components (Fig. B) are comparable to the spectra of along-track ALT geostrophic currents (Envisat and Jason-1) in the northeastern Pacific (30°N – 50°N, 114°W – 133°W). The mismatch at low wave-number ($L > 500$ km) is because of coverage area of each instrument (e.g., coastal regions and open ocean): HFR surface currents contain alongshore coastal signals with large wavelength (Figs. B – D).

In the frequency domain (Fig. B), the energy at the major tidal constituents, inertial frequency, and diurnal harmonic frequencies, and their enhanced variance in nearby bands are clearly identified. Their energy decays with a factor between σ^{-1} and σ^{-2} at high frequency [7]. In the very-low-frequency band ($\sigma < 2 \times 10^{-2}$ cpd, i.e., $T > 50$ days), the coastal surface current spectra include mesoscale energy.



A. The rotary power spectra ($\log_{10}$ scale, $\mathrm{cm^2\,s^{-2}\,cpd^{-1}}$) of surface vector currents in the entire domain (Fig. A) as a function of frequency (cpd) and coastal regions on the USWC, averaged in each frequency bin and alongshore bin. A black curve indicates the inertial frequency. B. Wind skill (κ^2) – the fraction of variance explained by coastal surface winds at the NDBC buoys through linear regression. The wind skill between PA and CC is excluded due to lack of concurrent observations of coastal winds and surface currents on the coastline axis in Fig. A. C. A probability density function of polarization coefficients at each frequency bin. A range of the inertial frequency (f_c) and two tidal frequencies (K_1 and M_2) are indicated. See Fig. A for the abbreviated name of coastal regions.



Power spectra of high-frequency radar-derived (HFR; 1, 6, and 20 km resolutions) surface currents and altimeter-derived geostrophic currents (ALT; along-track Envisat and Jason-1) for two years (2007 – 2008) in the wave-number domain (A) [Length scales (L) of 1, 5, 10, 50, 100, 200, 500, and 1000 km are marked] and frequency domain (B) [Six seasonal harmonics ($SA_1 - SA_6$), spring-neap (SN, 14.765-day), lunar fortnightly (LF, 13.661-day), S_1, K_1, M_2, and S_2 tidal frequencies are marked]. The auxiliary lines are denoted as k^{-1}, $k^{-5/3}$, and k^{-2} in the wave-number domain and σ^{-1} and σ^{-2} in the frequency domain. The 95% confidence interval (CI) of individual spectra is indicated.

Concluding remarks

High-resolution, large scale coastal surface current measurements enabled by the USWC HFR network provide an observational basis to examine the coastal surface circulation at scales from sub-mesoscale through mesoscale, including poleward signals near the coast, tide-coherent (barotropic and baroclinic components), and wind-coherent surface currents. Coupled with other ongoing in-situ observational programs and satellite remote sensing missions, surface current observations are crucial for monitoring continuous ocean variability by filling the gaps of in-situ instruments from offshore to nearshore and can provide timely input and fundamental scientific resource to the management of coastal waters.

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References

[1] S. R. Ramp, L. K. Rosenfeld, T. D. Tisch, and M. R. Hicks. Moored observations of the current and temperature structure over the continental shelf off central California 1. A basic description of the variability. *J. Geophys. Res.*, 102(C10):22877–22902, 1997.

[2] P. T. Strub, J. S. Allen, A. Huyer, R. L. Smith, and R. C. Beardsley. Seasonal cycles of currents, temperatures, winds, and sea level over the northeast Pacific continental shelf: 35°N to 48°N. *J. Geophys. Res.*, 92(C2):1507–1526, 1987.

[3] J. D. Paduan and L. K. Rosenfeld. Remotely sensed surface currents in Monterey Bay from shore-based HF radar (Coastal Ocean Dynamics Application Radar). *J. Geophys. Res.*, 101(C9):20669–20686, 1996.

[4] D. Stammer. Global characteristics of ocean variability estimated from regional TOPEX/POSEIDON altimeter measurements. *J. Phys. Oceanogr.*, 27(8):1743–1769, 1997.

[5] L. K. Rosenfeld and R. C. Beardsley. Barotropic semidiurnal tidal currents off Northern California during the Coastal Ocean Dynamics Experiment (CODE). *J. Geophys. Res.*, 92(C2):1721–1732, 1987.

[6] J. C. McWilliams. Submesoscale, coherent vortices in the ocean. *Rev. Geophys.*, 23(2):162–182, 1985.

[7] R. Ferrari and C. Wunsch. Ocean circulation kinetic energy: Reservoirs, sources, and sinks. *Annu. Rev. Fluid Mech.*, 41:253–282, 2009.