Characterization of oceanic mesoscale and sub-mesoscale energy spectra

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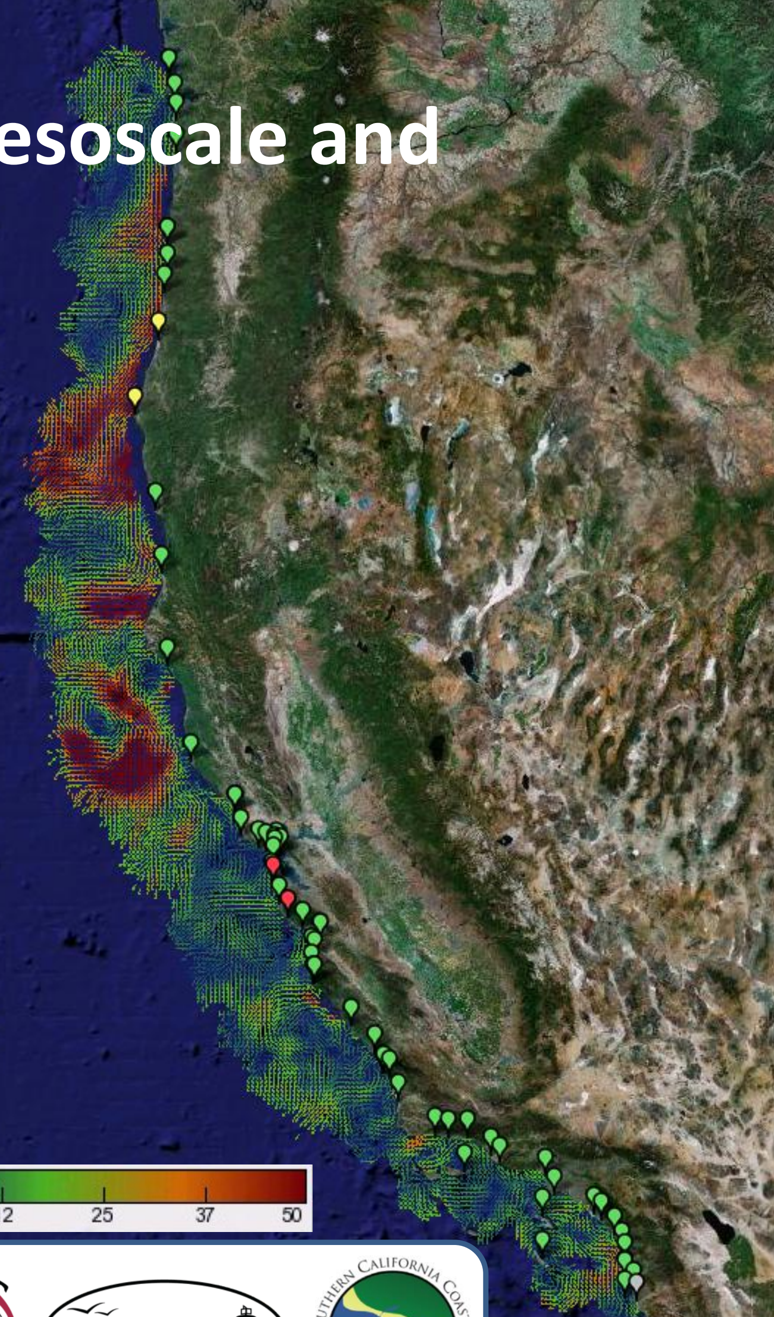

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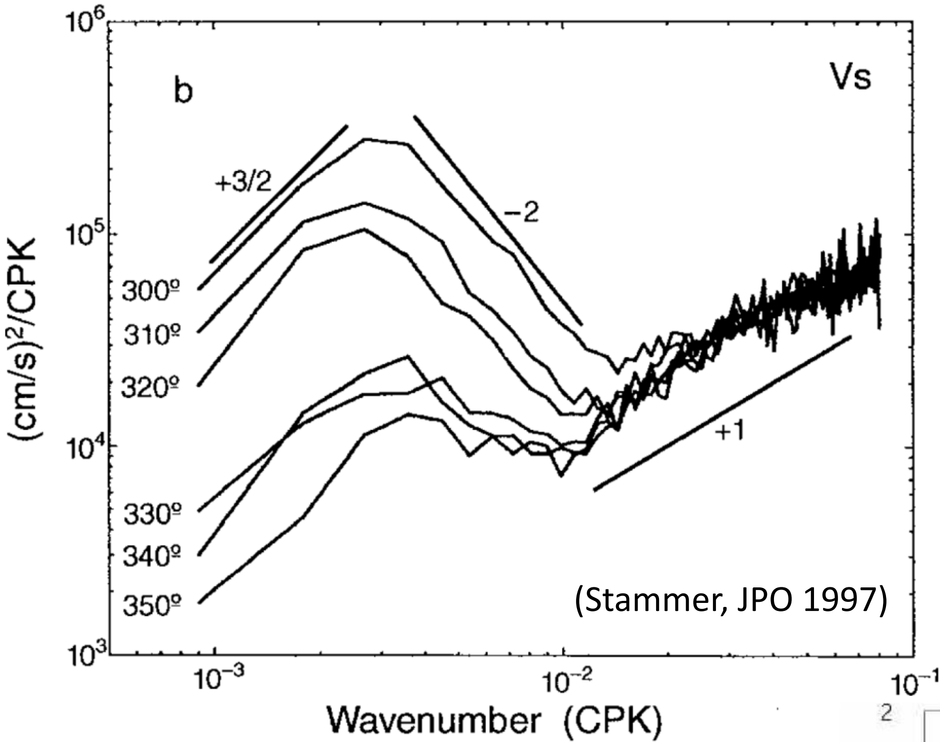
Outline

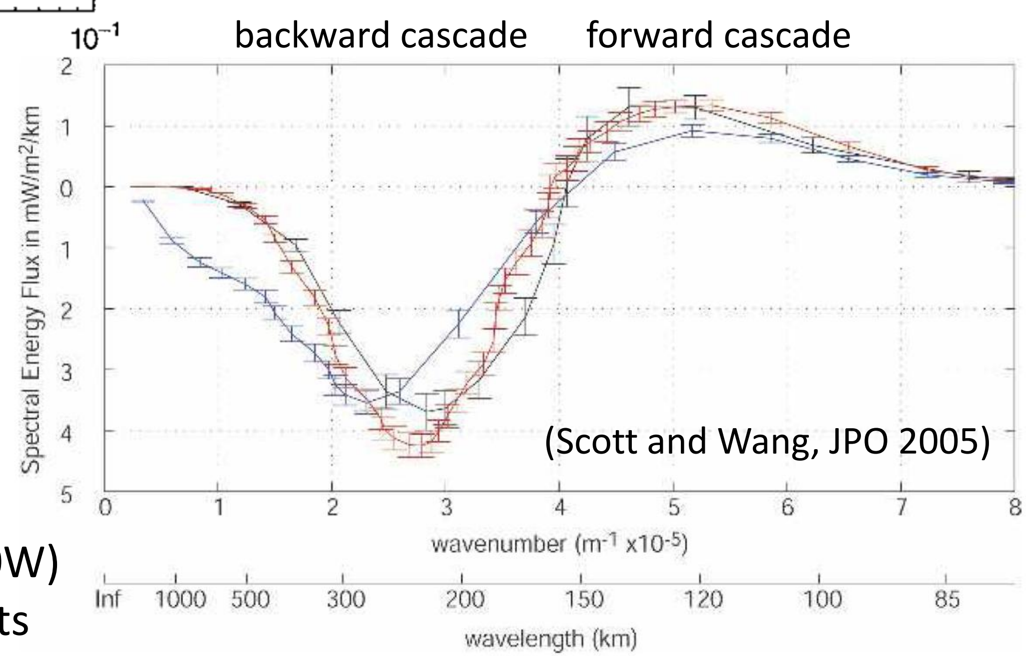
- Motivation
  - Oceanic processes in time and spatial scales
  - Wavenumber energy spectra derived from satellite altimeters
- Overview
  - Coastal surface current measurements using high-frequency radar (HFR)
  - Spectral contents in coastal surface currents off the U.S. West Coast
- Comparison of energy spectra
  - Energy spectra in wavenumber (1D) and frequency domain
  - Energy flux estimates from O(1) km HFR surface currents and sub-mesosale model results
- Summary

Motivation



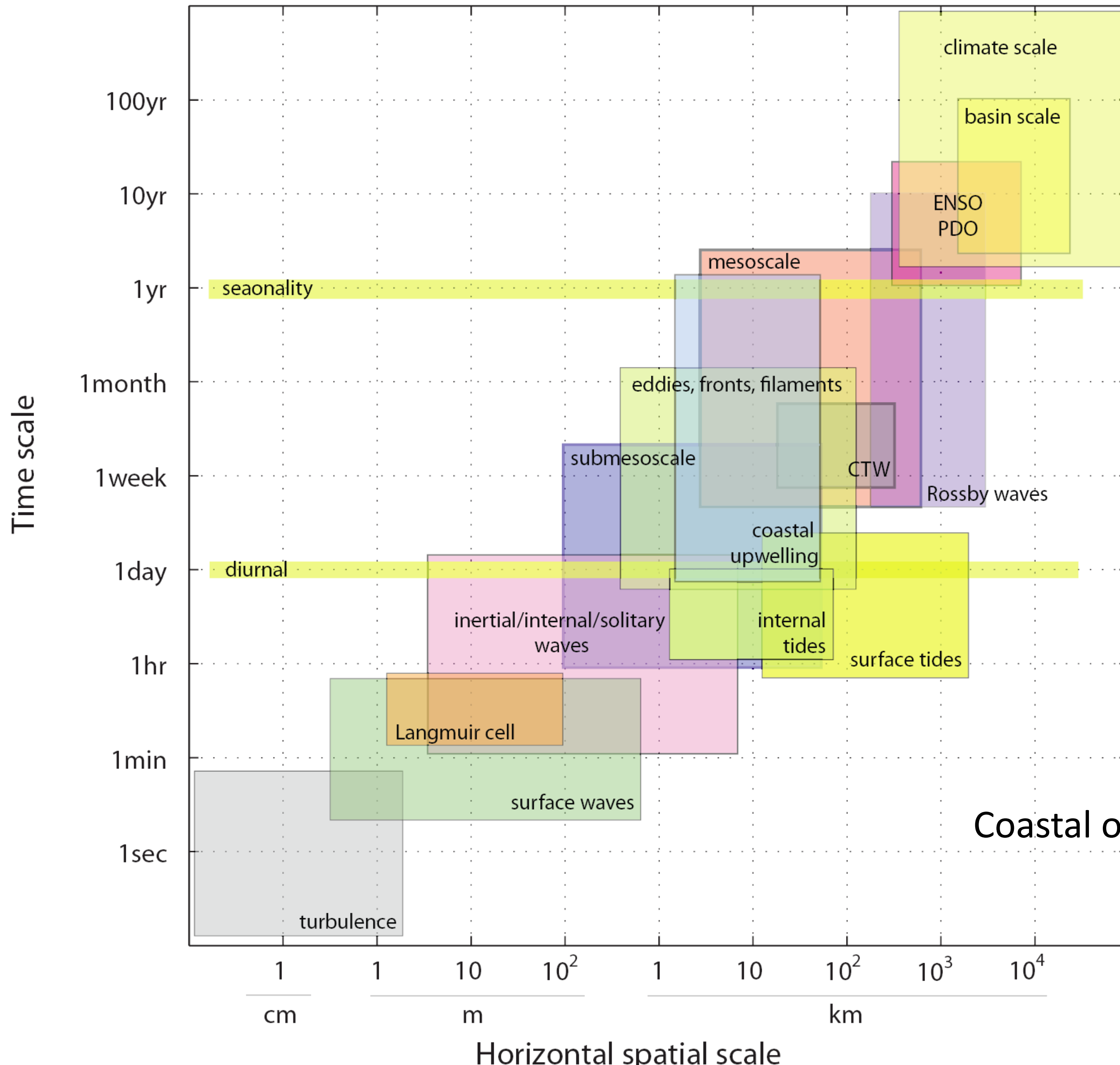
- What can be the slope of energy spectra and kinetic energy flux below 100 km scale?

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



Kinetic energy flux in ACC region (57S, 120W)
Optimally interpolated 1/3° AVISO products

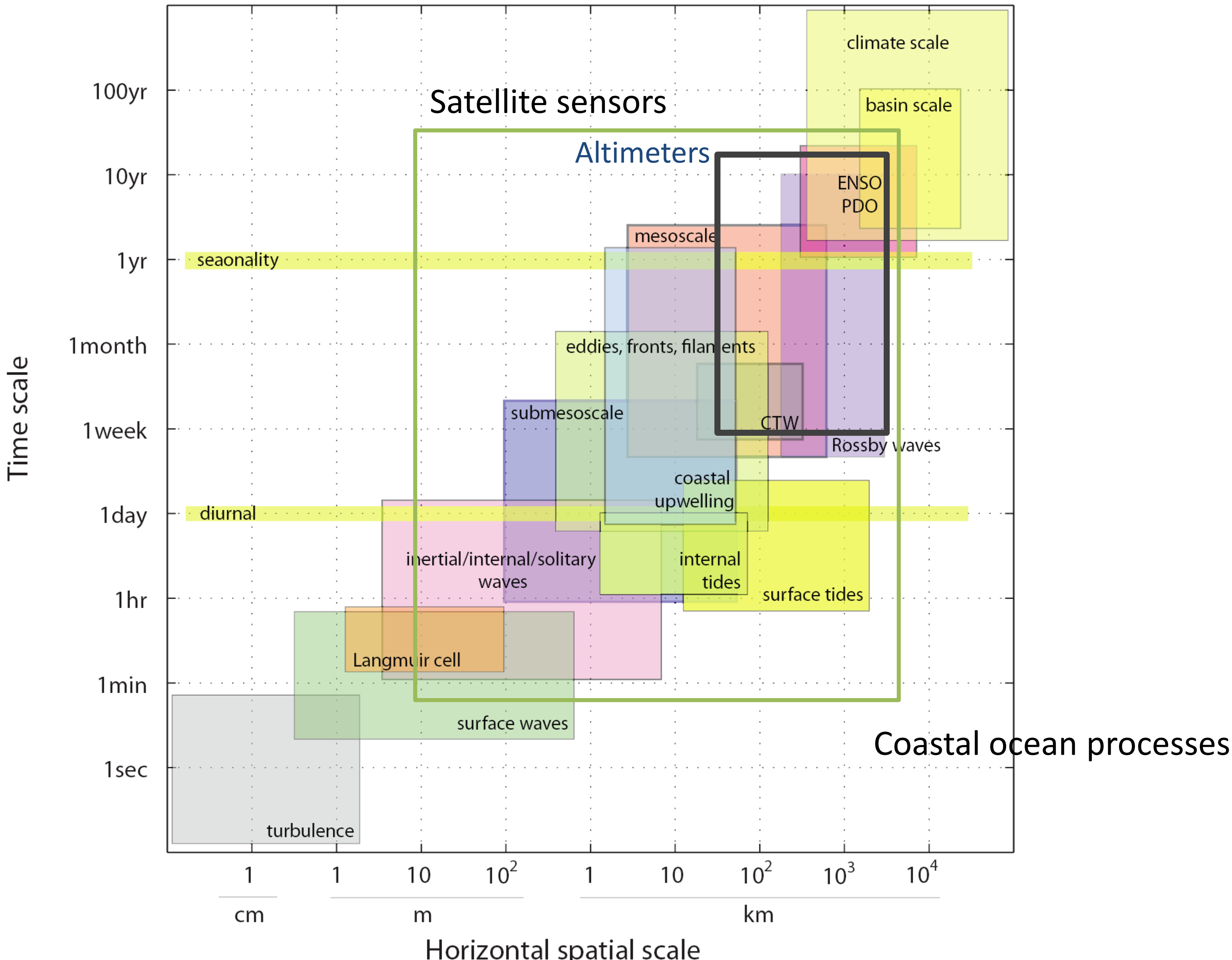
Oceanic processes in time and spatial scales



Coastal ocean processes

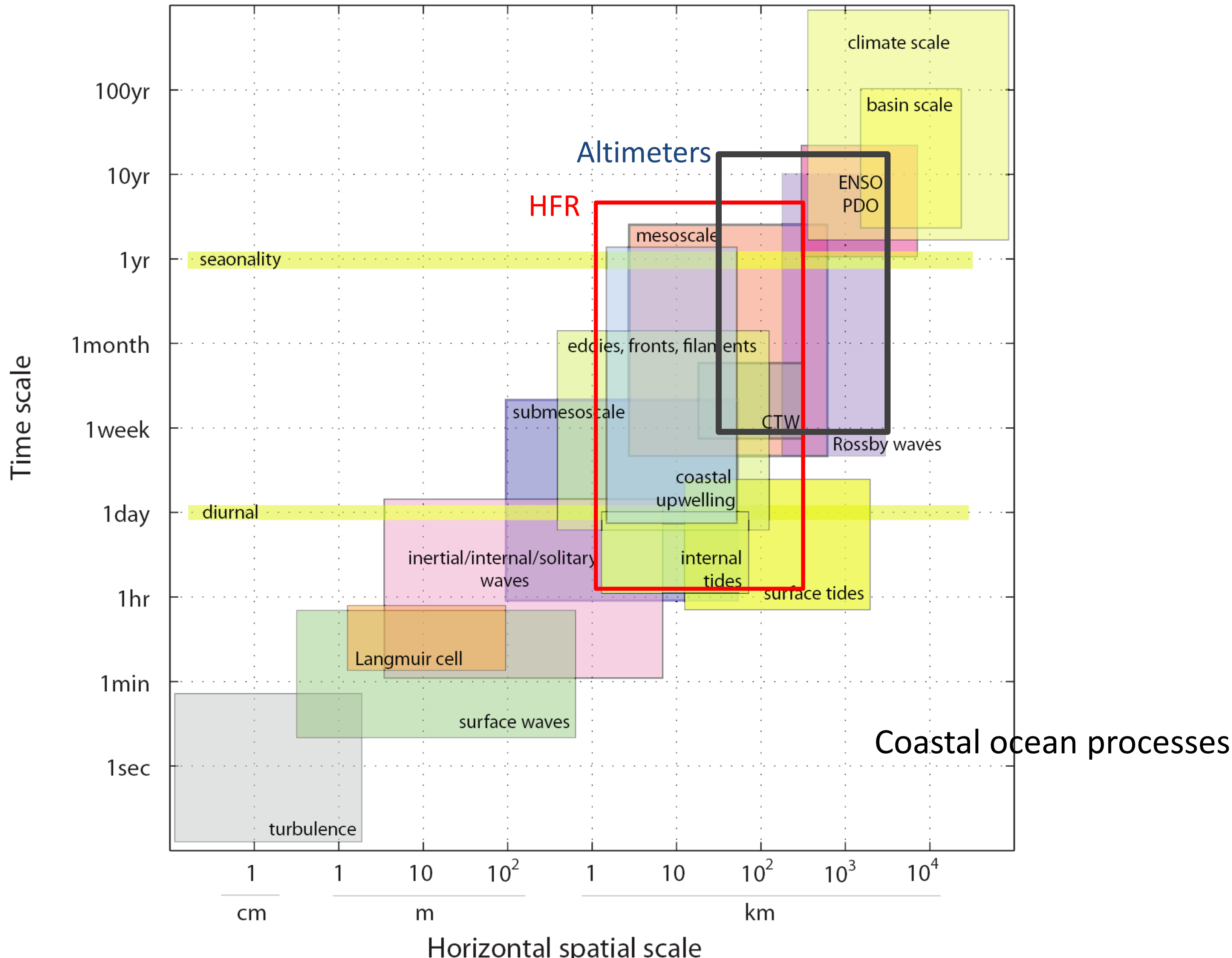
(Chelton 2001, Dickey *et al*, RG 2006)

Oceanic processes in time and spatial scales



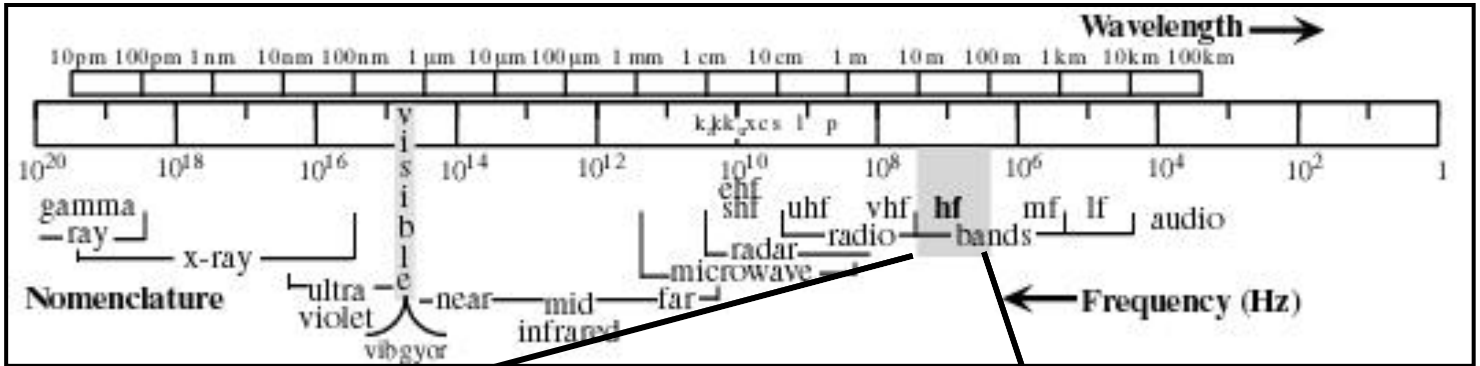
(Chelton 2001, Dickey *et al*, RG 2006)

Oceanic processes in time and spatial scales



(Chelton 2001, Dickey *et al*, RG 2006)

Radio signals used in high-frequency radar



(Paduan and Graber, Oceanography 1997)

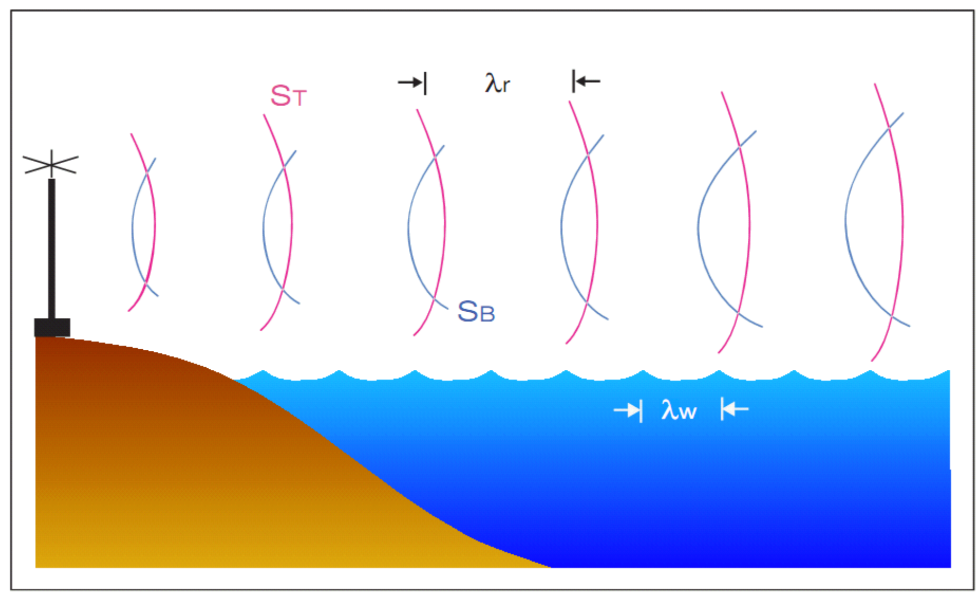
3-30 MHz (between AM radio and TV)

Wavelength (λ_r) : 10 ~ 100 (m)

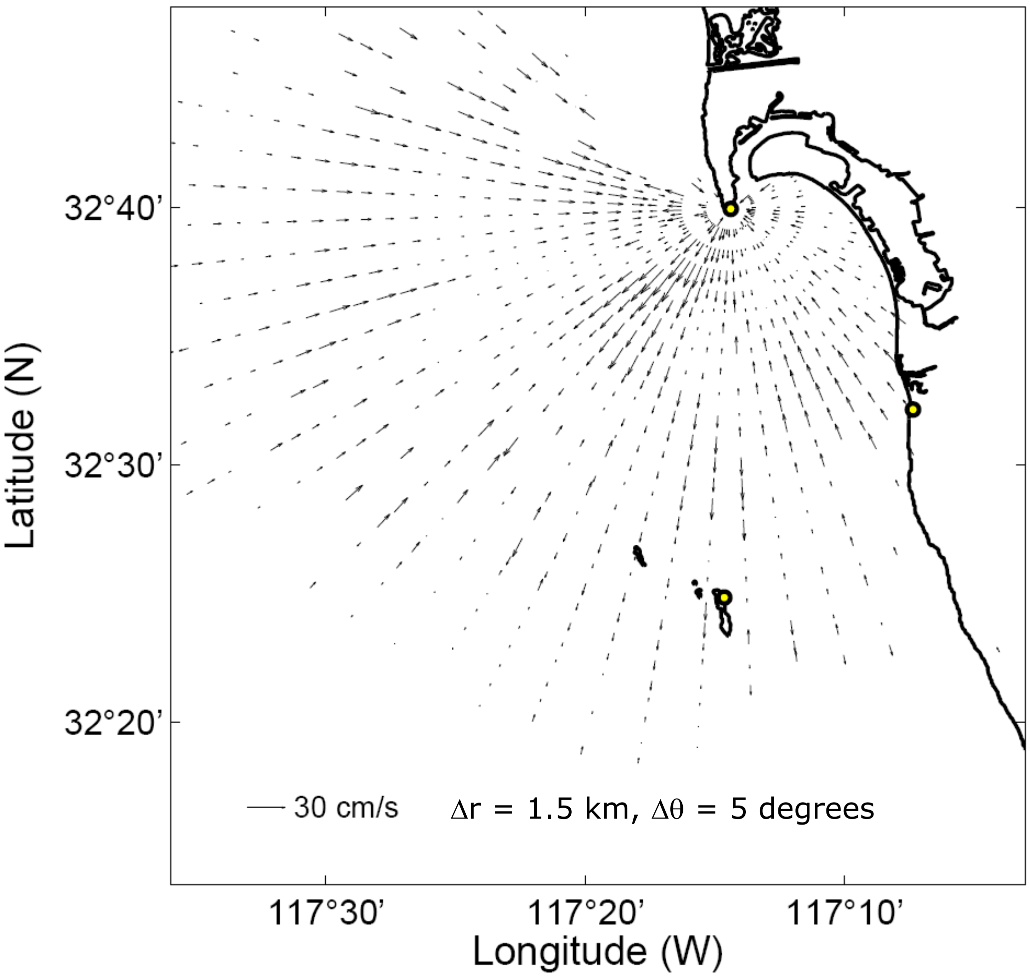
Bragg backscattering

When the radar signals are backscattered in phase,

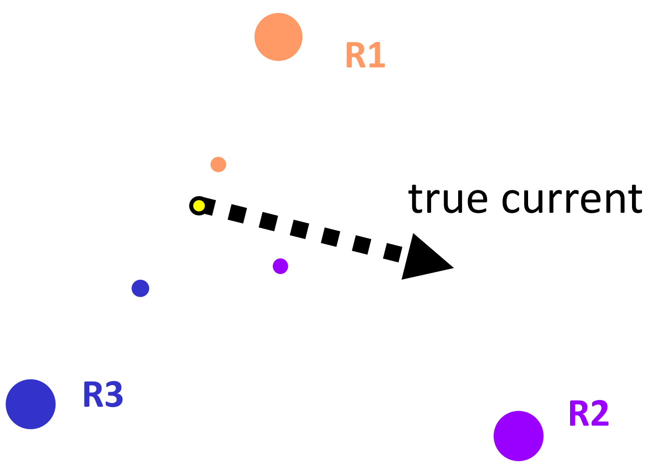
$$\lambda_w = \lambda_r / 2$$



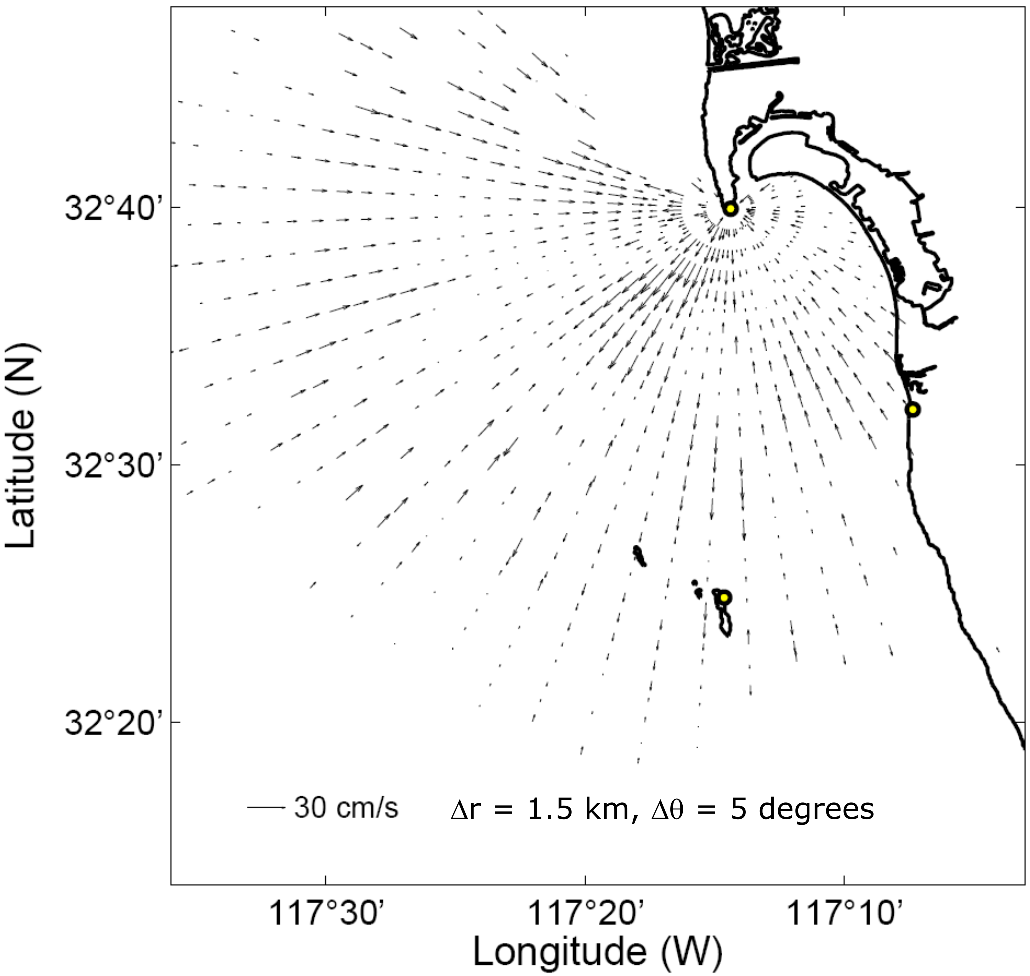
Surface radial current map



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



Surface radial current map



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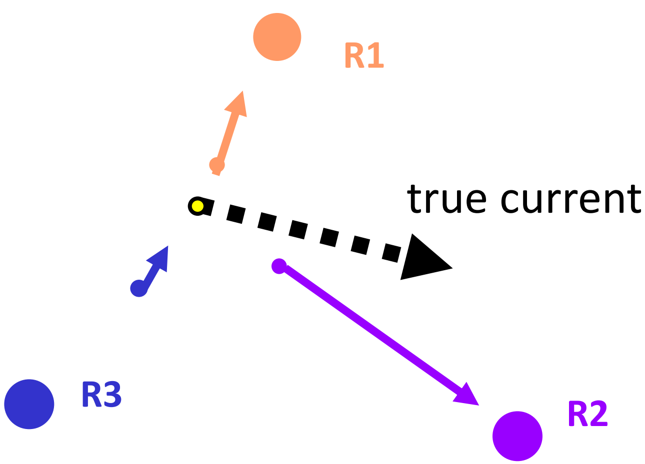
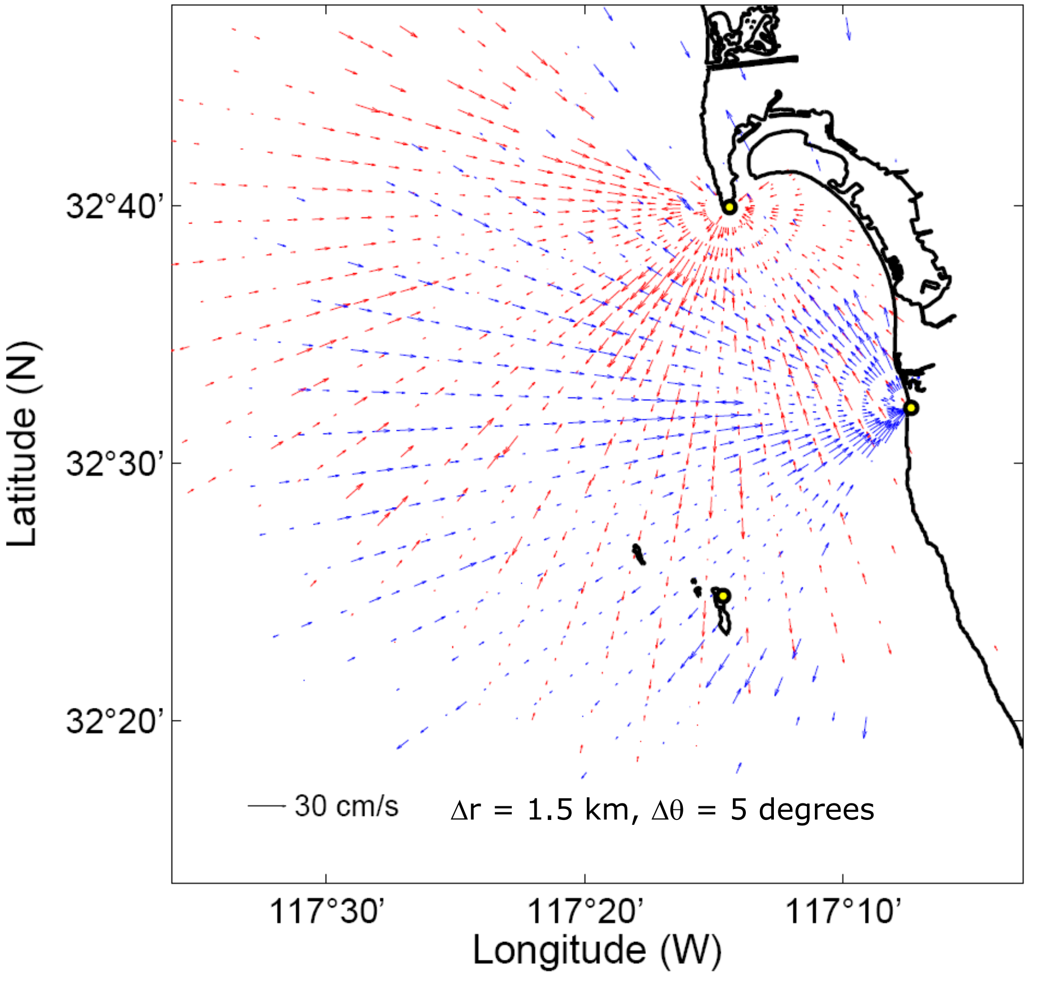


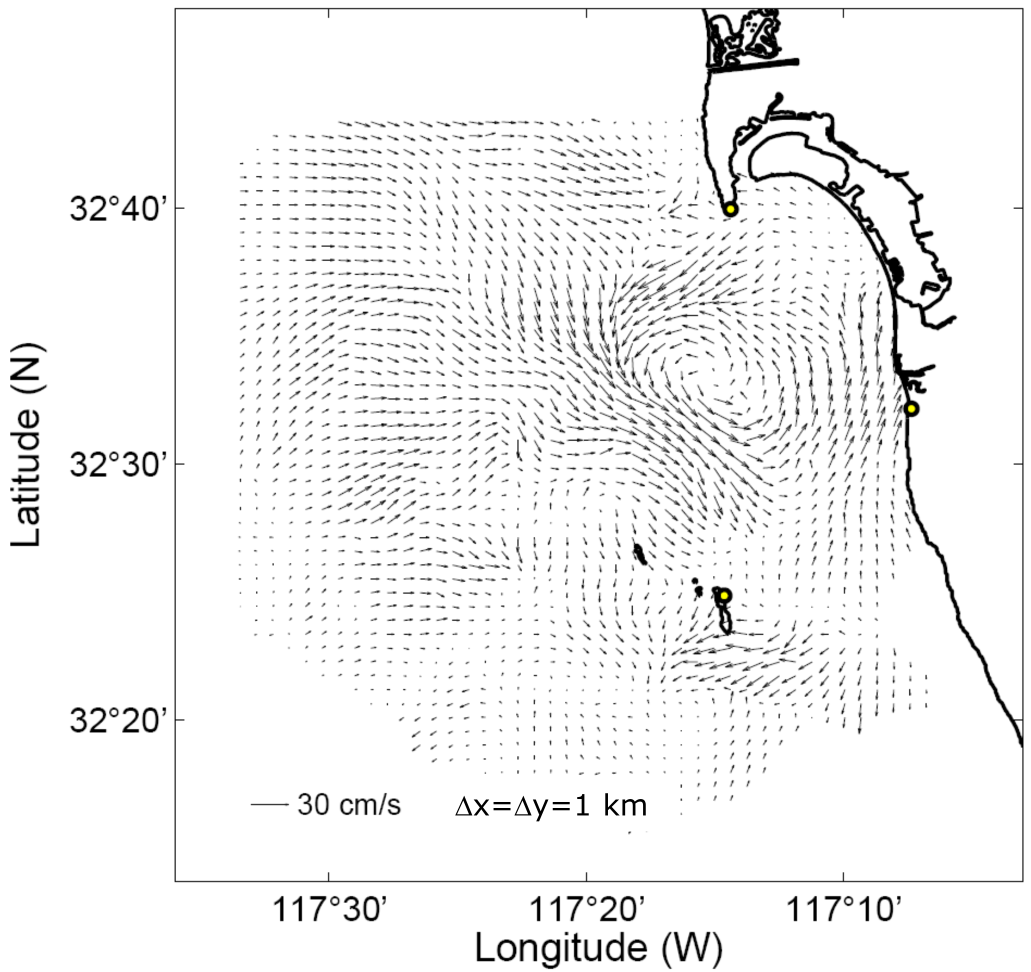
Multiple surface radial current maps



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

(Kim *et al*, JGR 2008; Kim, CSR 2010)

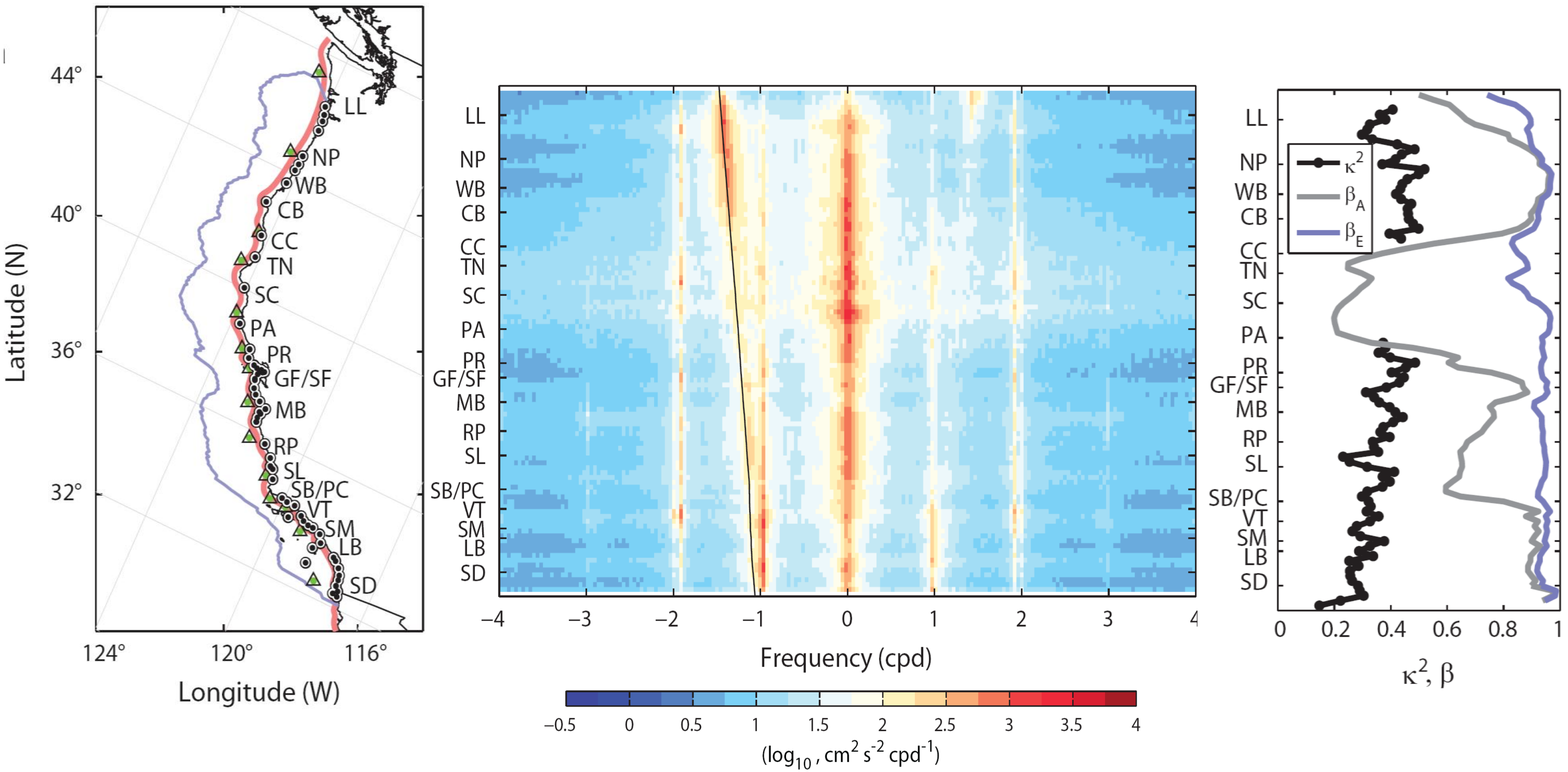
Improved vector current map



- Optimal interpolation
  - Minimize baseline inconsistency
  - A unified uncertainty definition
  - Divergence and vorticity
  - Velocity potential and stream function
  - Exponential correlation function (based on data covariance matrix) leads to minimum level of spatial smoothing.

(Kim *et al*, JGR 2008; Kim, CSR 2010)

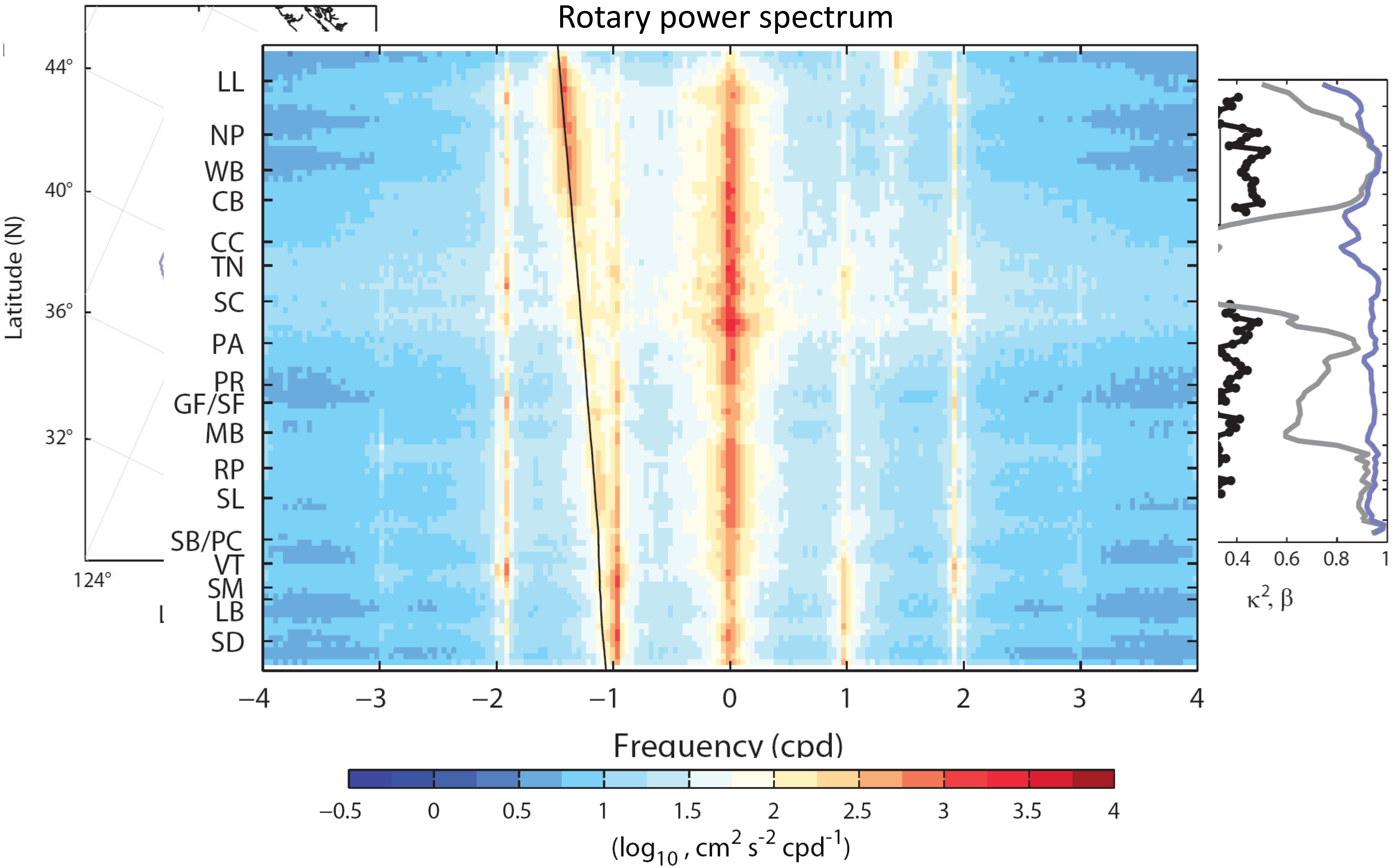
Variance of surface currents (alongshore view)



- 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

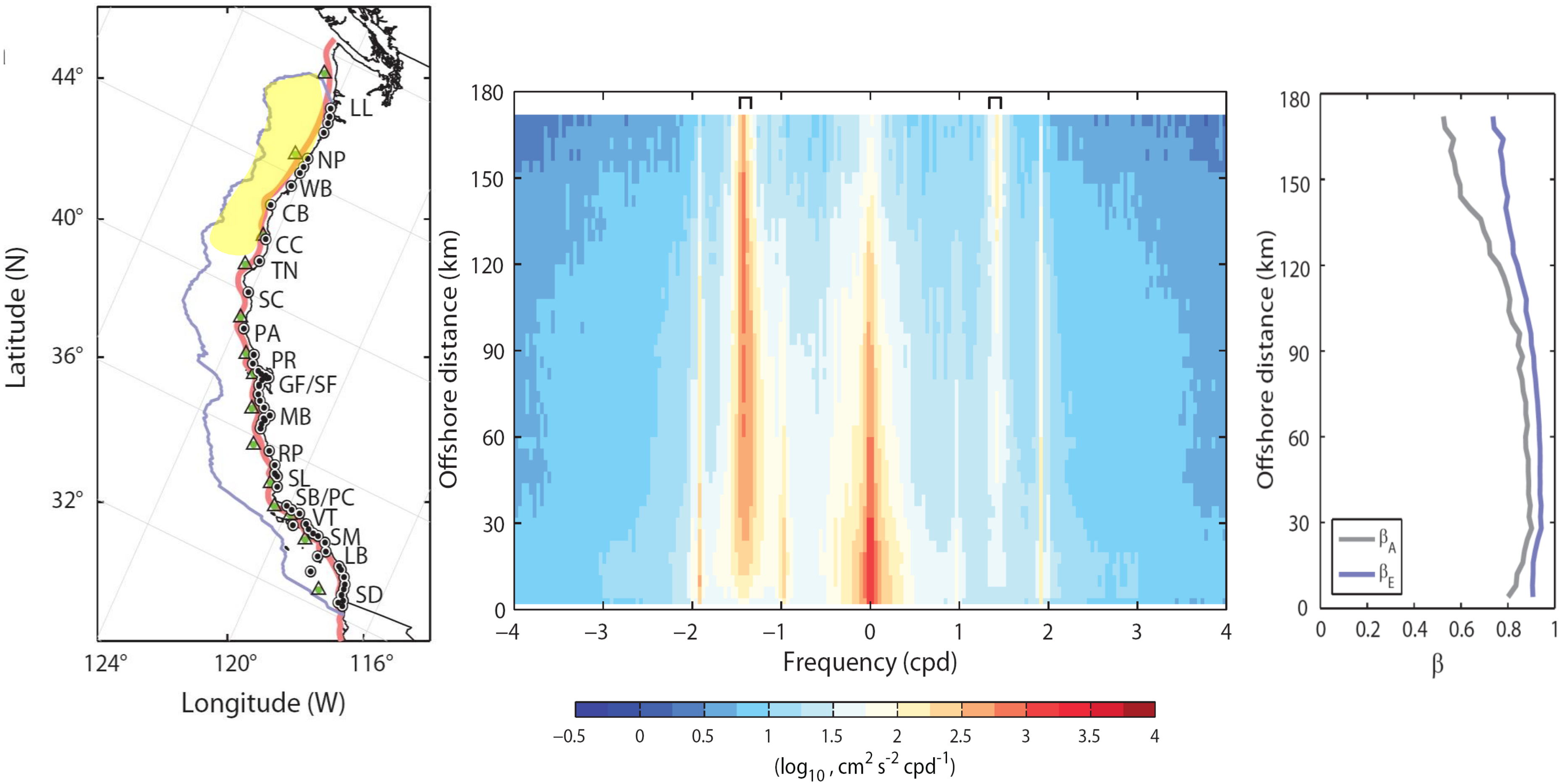
(Kim *et al*, JGR 2011)

Variance of surface currents (alongshore view)



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

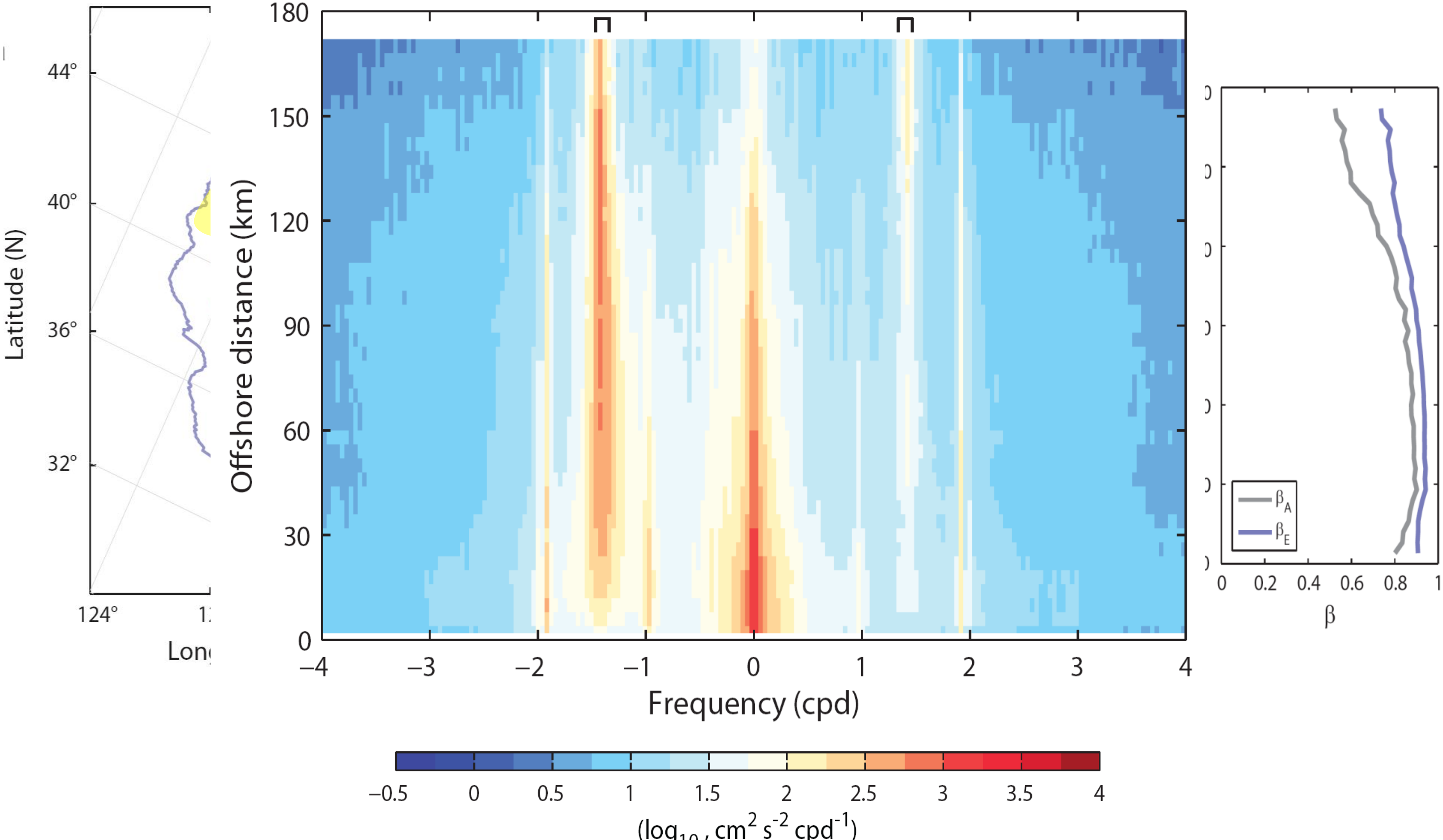
Variance of surface currents (cross-shore view)



- 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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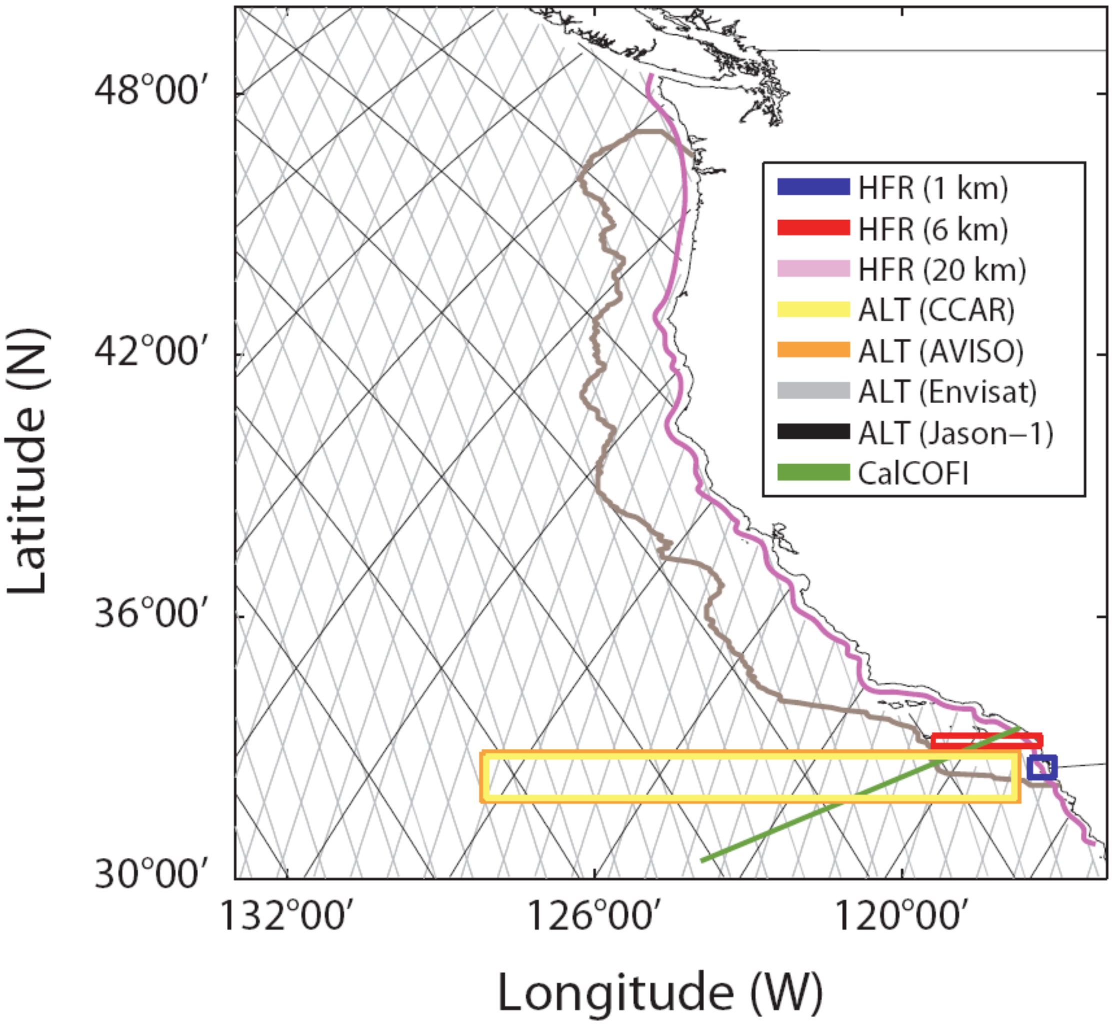
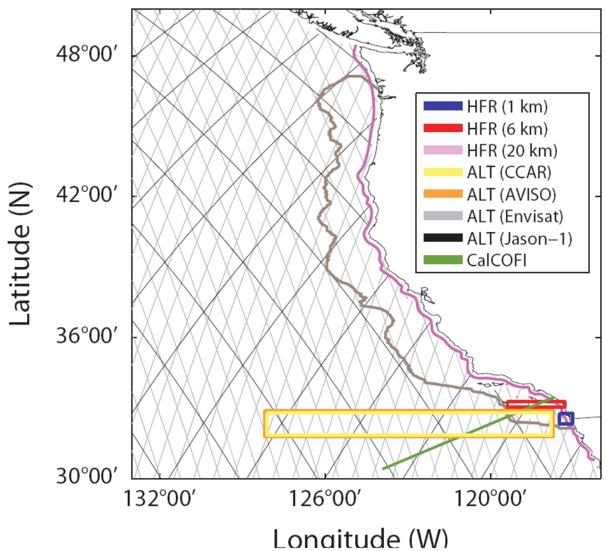
Sampling domain in computation of energy spectra



- HFR surface currents (1, 6, and 20 km resolution; hourly) off southern California and on coastline axis (USWC)
- Gridded ALT products [CCAR (daily) and AVISO (weekly)] and along-track altimeter (ALT; Envisat/Jason-1; weekly) on NE Pacific
- CalCOFI shipboard ADCP (Line 90; quarterly)
- SoCAL was chosen because it contains relatively minimum ageostrophic components.

Energy spectra in the wavenumber domain (1D)

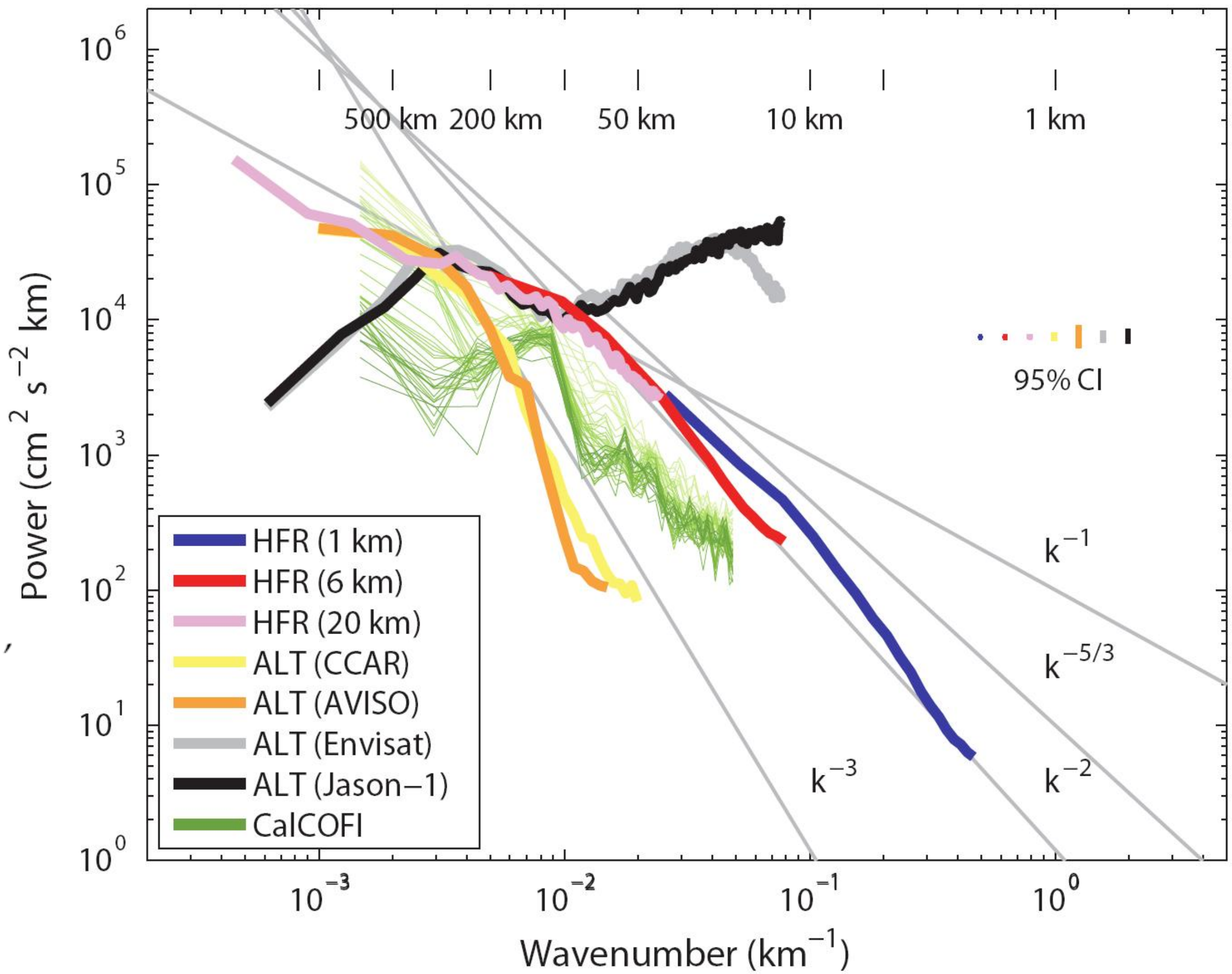


$$S_{\mathbf{u}_\perp}(k_\parallel) = \left(\frac{g}{f_c}\right)^2 \left(2\pi k_\parallel\right)^2 S_{\boldsymbol{\eta}_\parallel}(k_\parallel),$$

Power spectrum of cross-track geostropic currents from along-track SSHAs

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

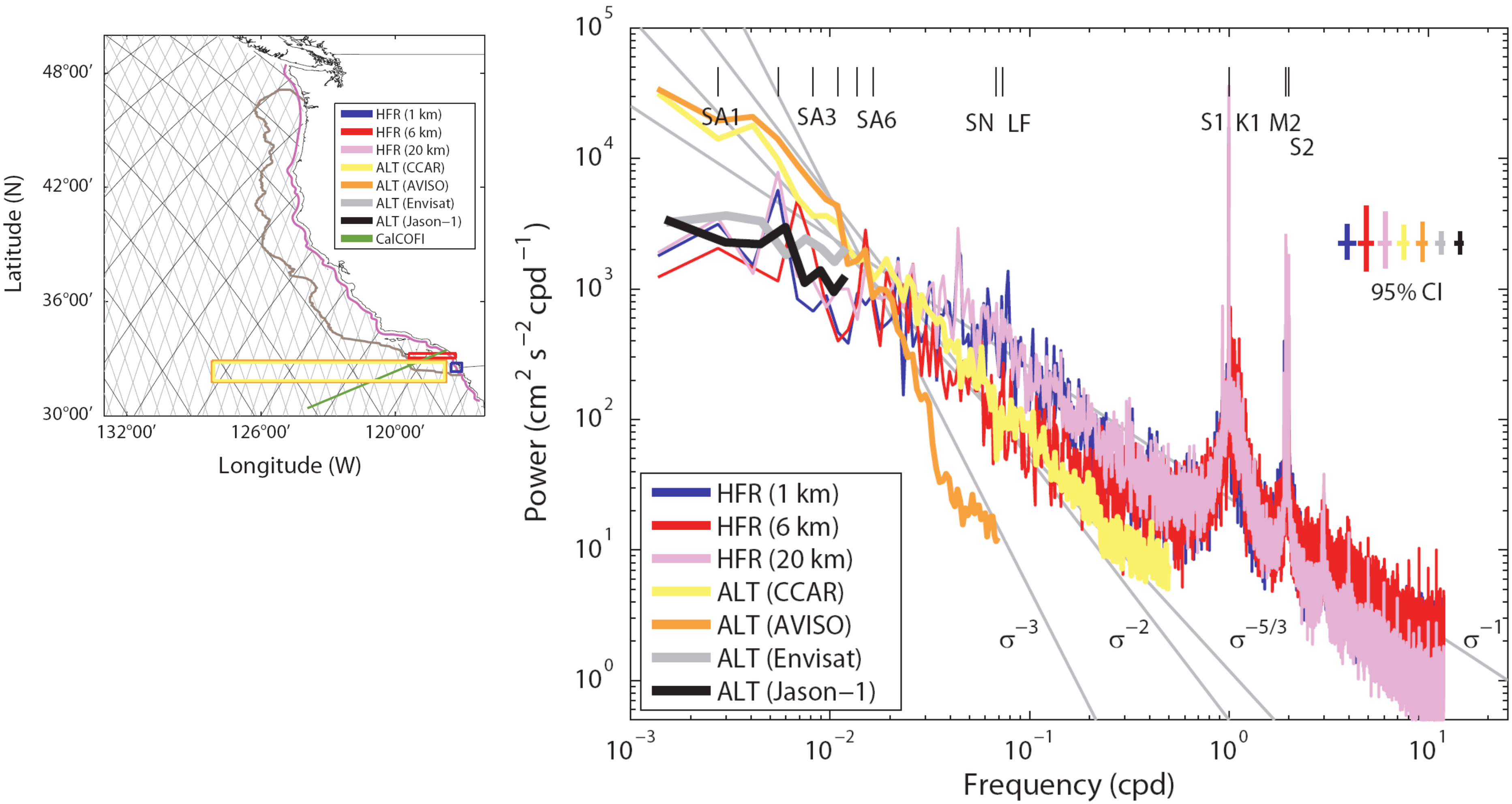
Robust estimate on k-2 spectra with data in other regions.



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)

Energy spectra in the frequency domain



Along-track altimeter data are binned in 2° x 2° grid boxes and averaged in time (7-daily → 30 daily time series) to increase signal to noise ratio.

(Kim *et al*, JGR 2011)

Scale-by-scale energy budget equation

$$\frac{\partial}{\partial t}E(k^*) + \Pi(k^*) = -2\nu\Omega(k^*) + F(k^*),$$ (Frisch 1995)

where

$$E(k^*) = \frac{1}{2}\sum_{|\mathbf{k}|<k^*} |\hat{\mathbf{u}}(\mathbf{k})|^2,$$ Cumulative kinetic energy

$$\Pi(k^*) = \langle \mathbf{u}_< \cdot (\mathbf{u} \cdot \nabla \mathbf{u})\rangle,$$ Cumulative advective kinetic energy flux

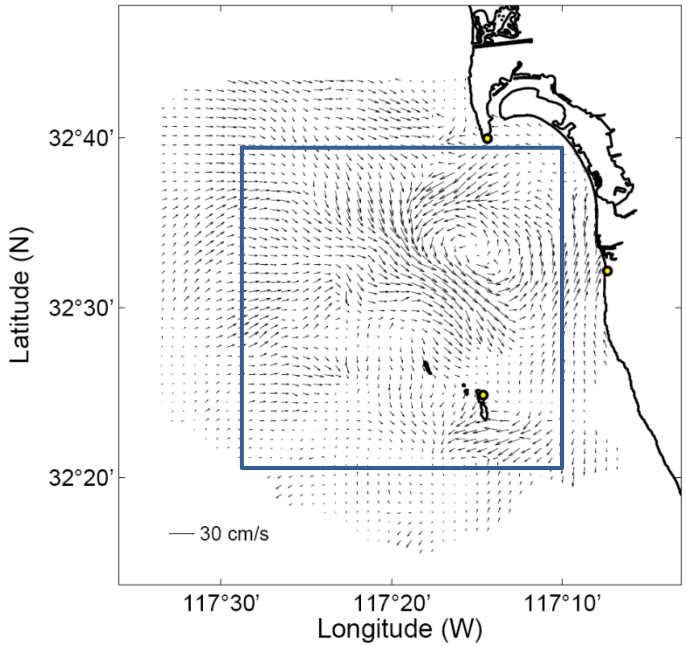
$$= \langle \mathbf{u}_< \cdot (\mathbf{u}_< \cdot \nabla \mathbf{u}_>)\rangle + \langle \mathbf{u}_< \cdot (\mathbf{u}_> \cdot \nabla \mathbf{u}_>)\rangle,$$

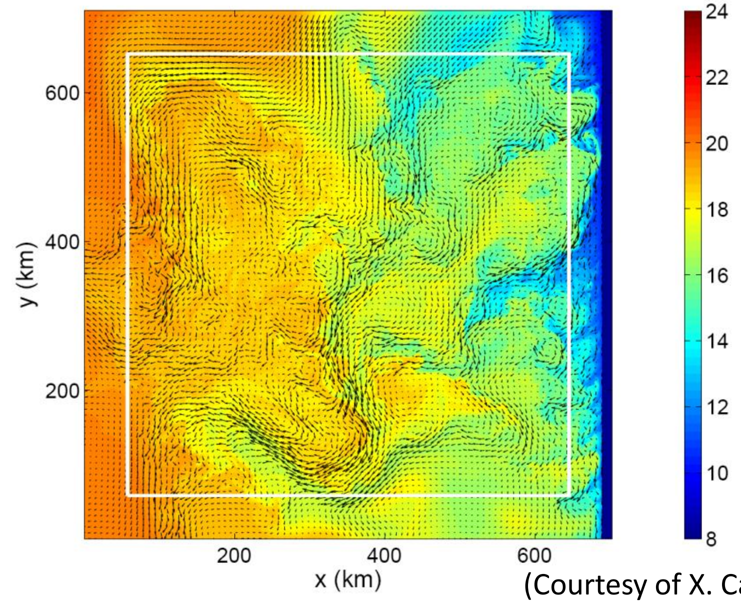
$$\Omega(k^*) = \frac{1}{2}\sum_{|\mathbf{k}|<k^*} \mathbf{k}^2|\hat{\mathbf{u}}(\mathbf{k})|^2,$$ Cumulative enstrophy

$$\mathbf{u}(\mathbf{x}) = \mathbf{u}_<(\mathbf{x}) + \mathbf{u}_>(\mathbf{x}), = \sum_{|\mathbf{k}|<k^*} \hat{\mathbf{u}}(\mathbf{k})e^{i\mathbf{kx}} + \sum_{|\mathbf{k}|>k^*} \hat{\mathbf{u}}(\mathbf{k})e^{i\mathbf{kx}},$$

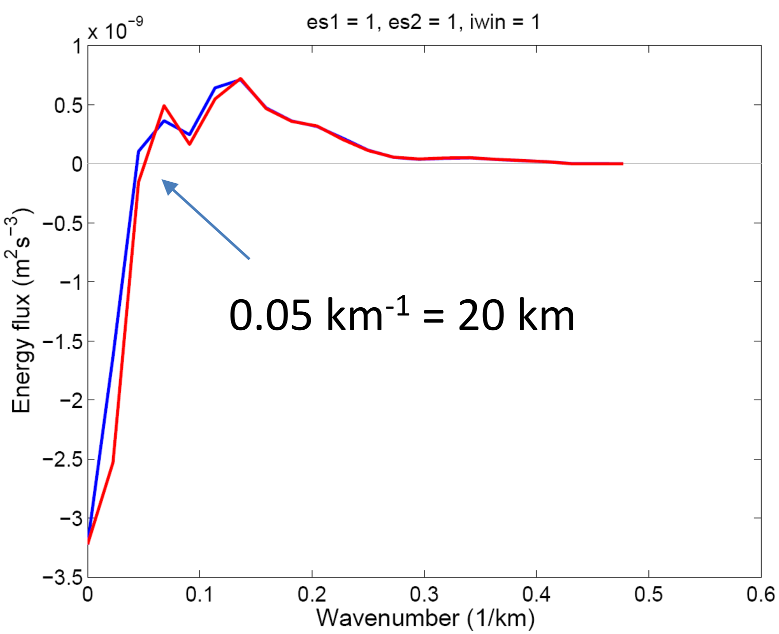
- Surface currents from HFR observations (1 km) and sub-mesoscale model (0.75 km; X. Capet *et al*, 2009) off southern California

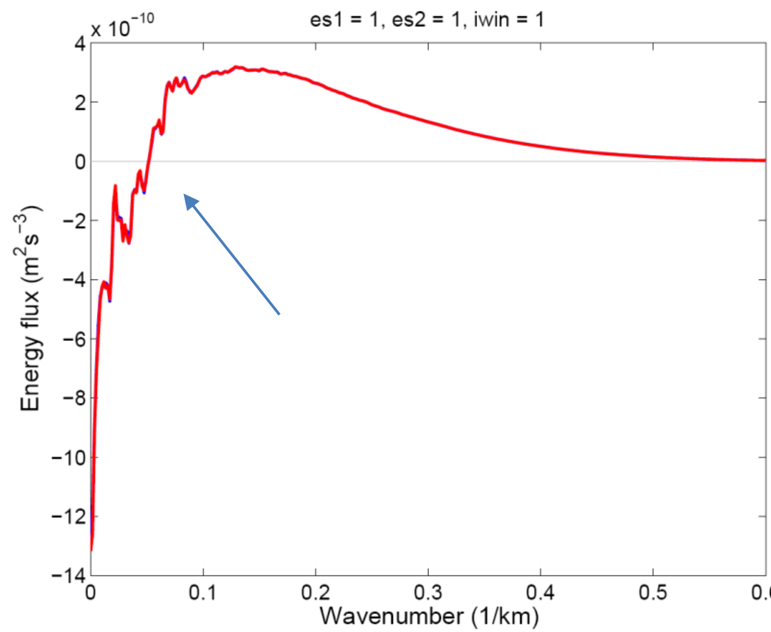
Comparison of advective kinetic energy flux [Π(k*)]





(Courtesy of X. Capet)





Summary

- Energy spectra at mesoscale and sub-mesoscale are examined with altimeter-, high-frequency radar-, shipboard ADCP-derived (coastal) currents.
- 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.
- 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.
- The spatial covariance appears as an anisotropic exponential shape with decorrelation length scales of 20 km nearshore and 100 km offshore parallel to the shoreline, consistent with approximate k-2 decay behavior.