Observations of submesoscale eddies using high-frequency radar-derived kinematic and dynamic quantities

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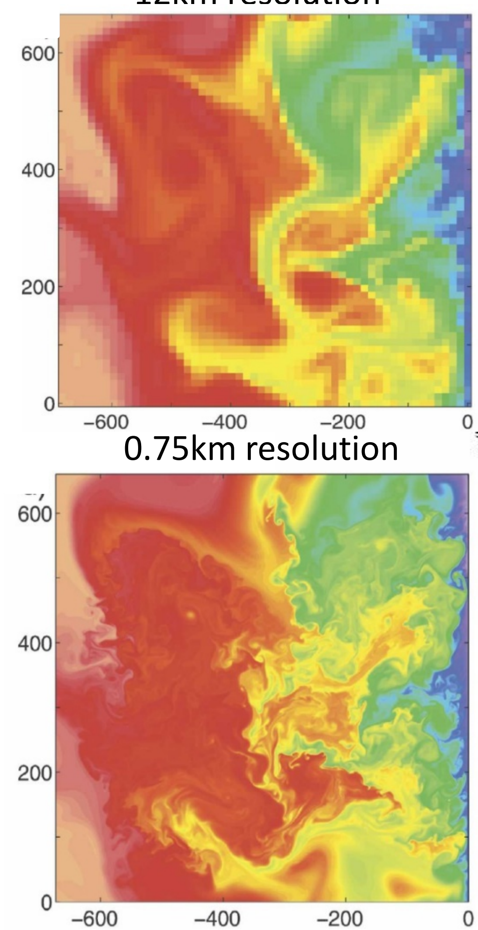
(Kim, S. Y. 2010, *Cont. Shelf Res.* 30, 1639 -1655)

Acknowledgement: Eric Terrill and Bruce Cornuelle (SIO)

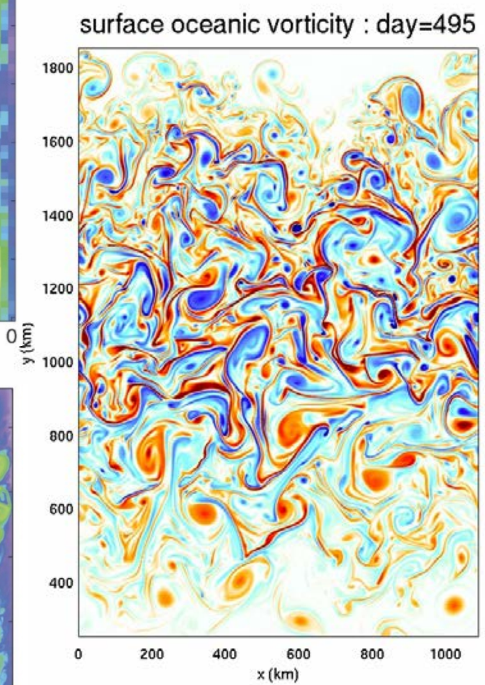
Observations of submesoscale eddies using high-frequency radar-derived kinematic and dynamic quantities

- Submesoscale processes
  - O(1) Rossby number [$Ro = U/(fL) = \zeta/f$]
  - A horizontal scale smaller than the first baroclinic Rossby deformation radius; O(1-10) km
  - Frequently observed as fronts, eddies, and filaments

Simulations on mesoscale and submesoscale grids (SST)



(Capet *et al*, JPO, 2009a)



From Klein et al

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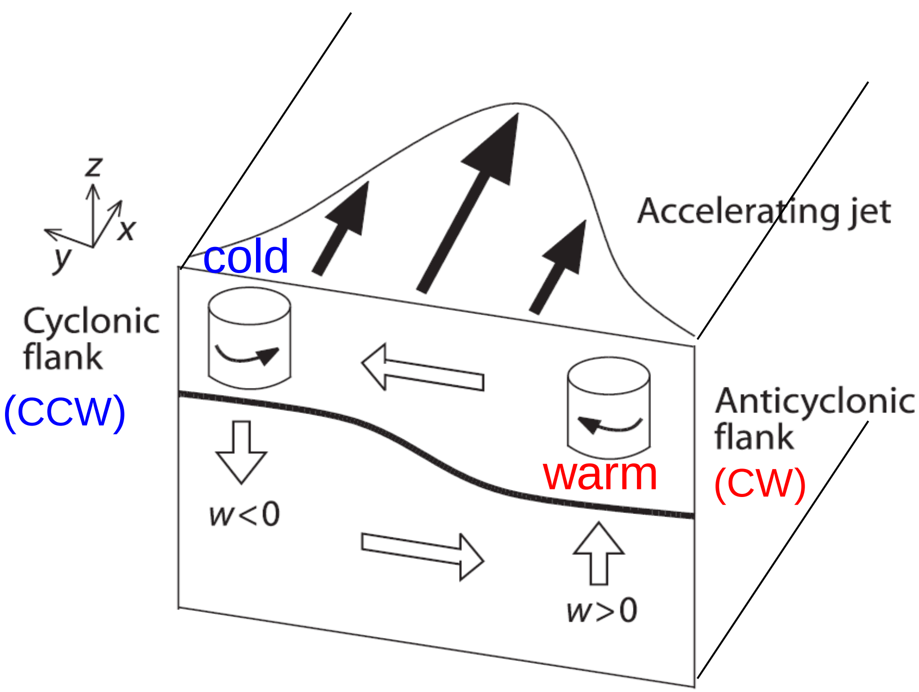
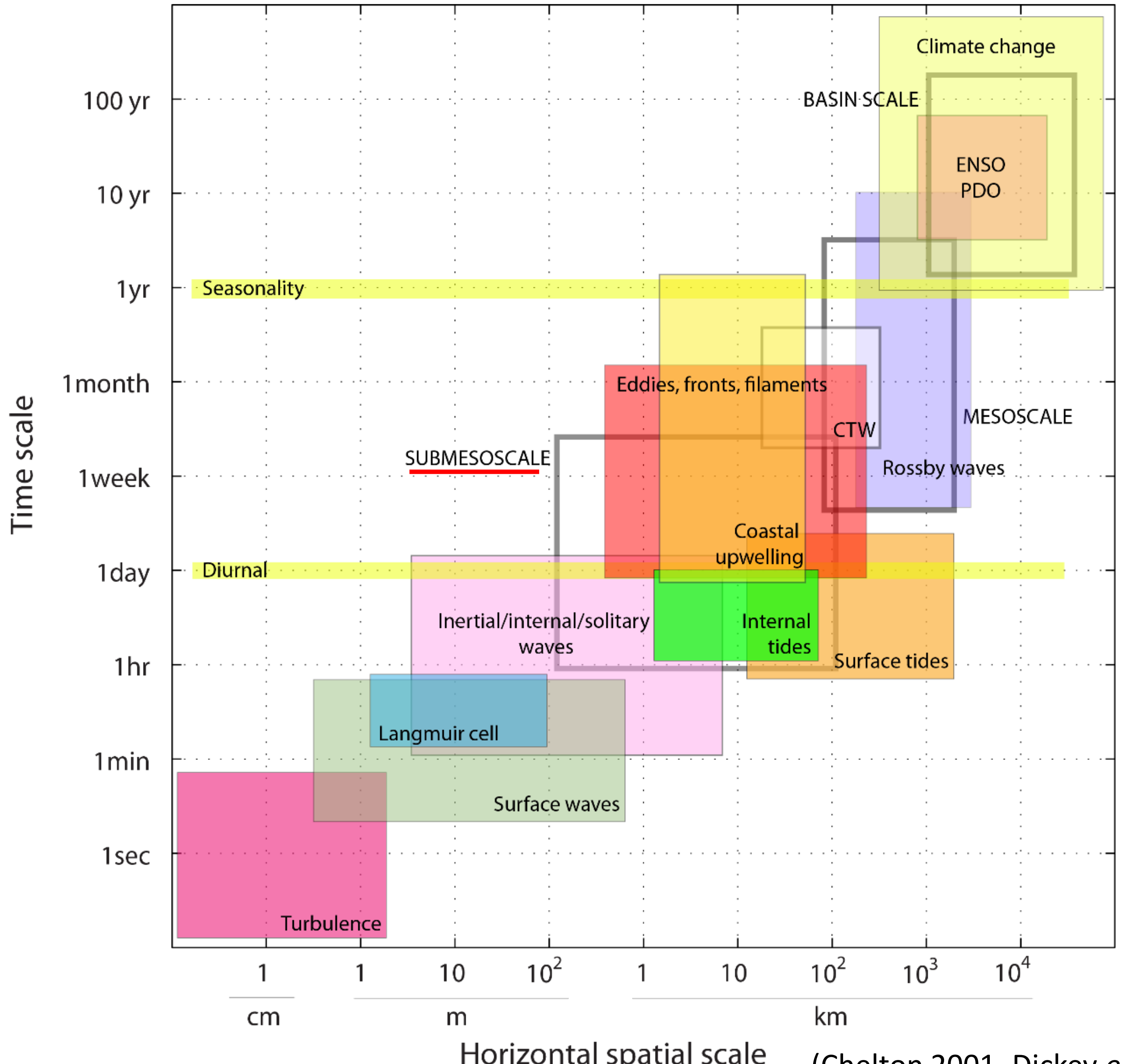
- Submesoscale processes
  - O(1) Rossby number [$Ro = U/(fL) = \zeta/f$]
  - A horizontal scale smaller than the first baroclinic Rossby deformation radius; O(1-10) km
  - Frequently observed as fronts, eddies, and filaments
  - Contribute to the vertical transport of oceanic tracers, mass, and buoyancy and rectify the mixed-layer structure and upper-ocean stratification



(Williams and Follows, 2003)

e.g., vertical frontal scale secondary circulation

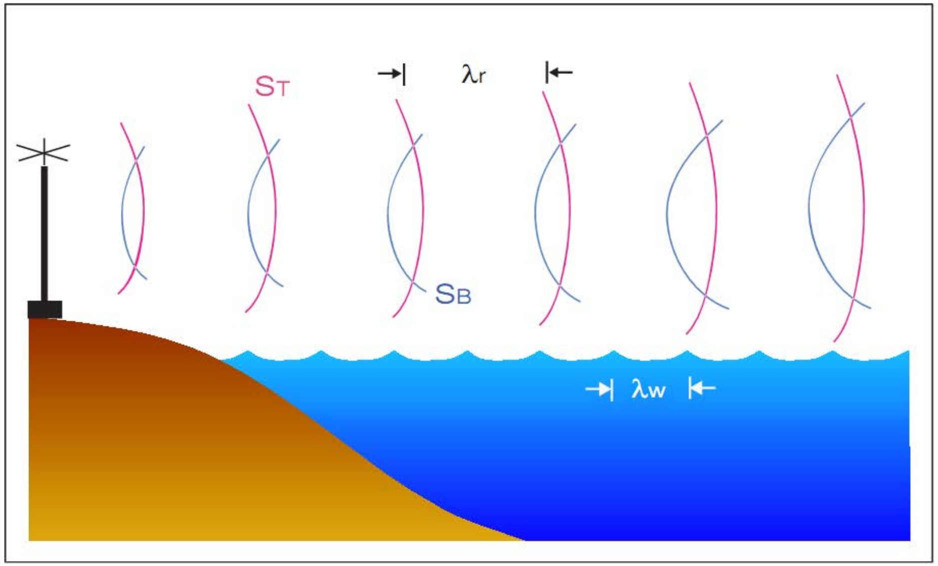
Oceanic processes in time and spatial scales



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

Observations of submesoscale eddies using high-frequency radar-derived kinematic and dynamic quantities

- An observational sensor using electromagnetic waves
  - 3-30 MHz frequency (HFR)
  - Using Doppler shift of backscattered signals of surface gravity waves to estimate the background currents
  - Upper 1 m depth-averaged currents



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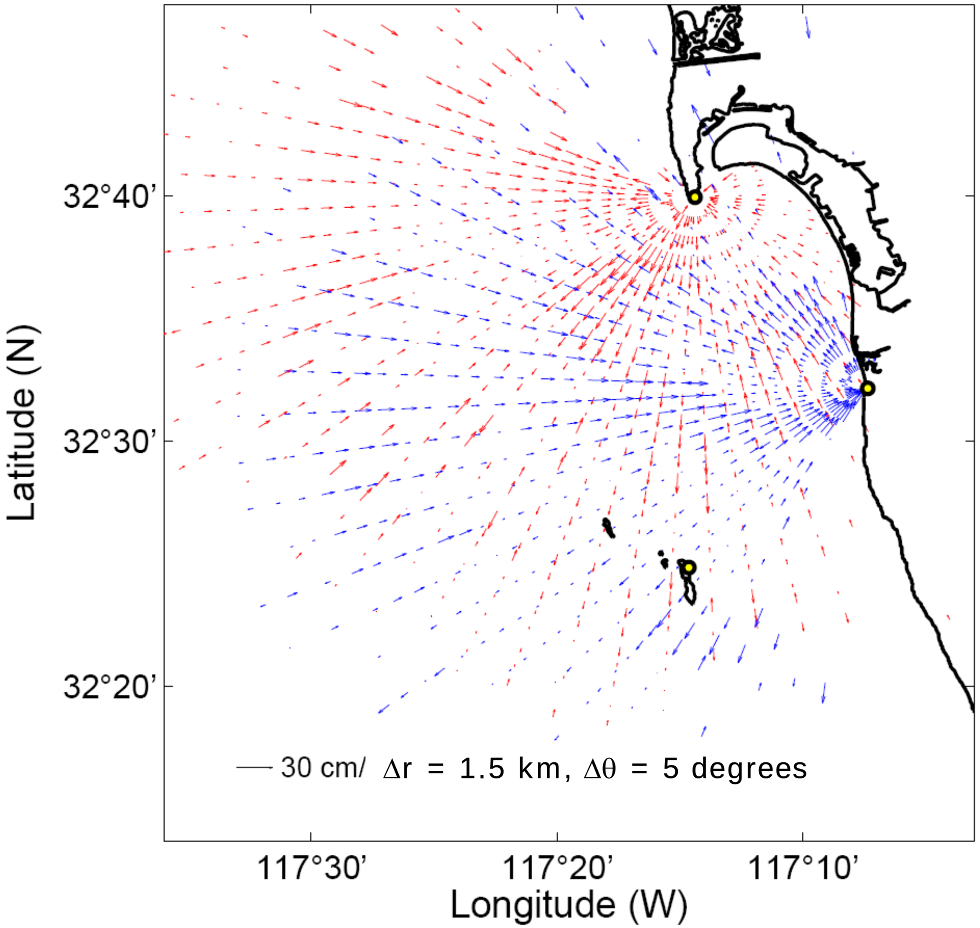
  - Surface radial velocity maps on a polar coordinate



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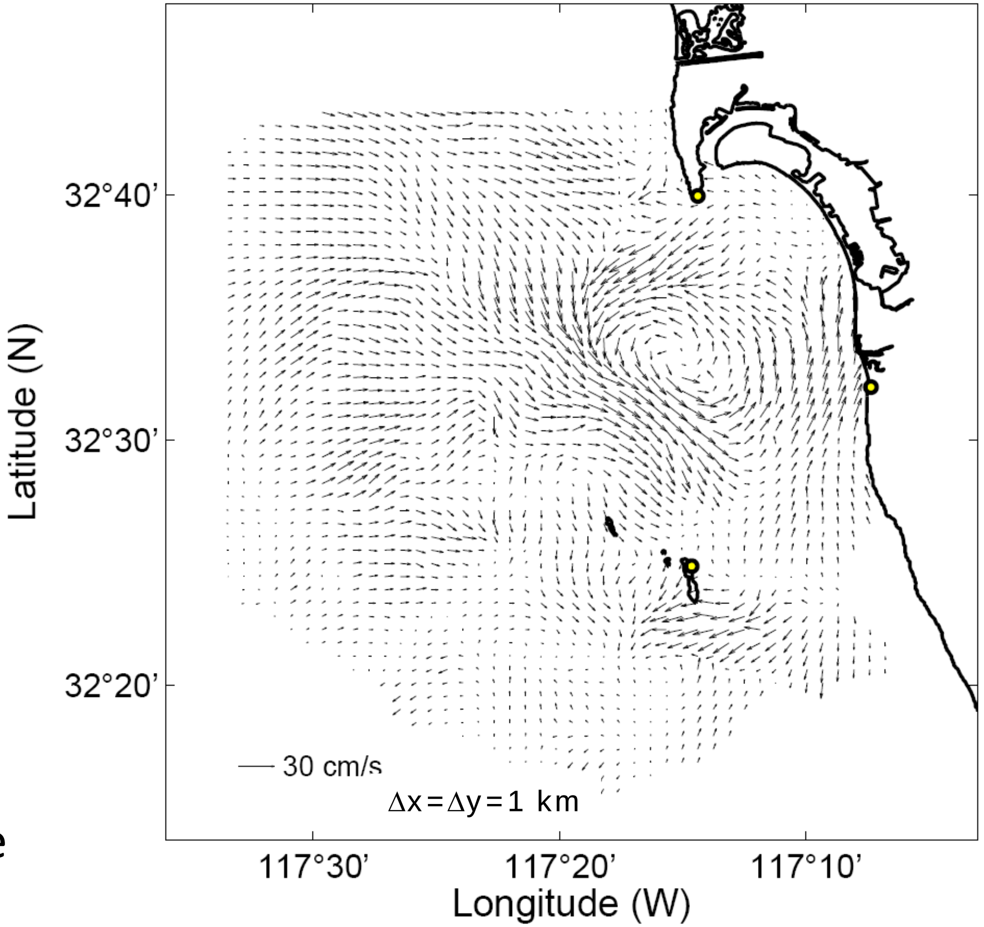
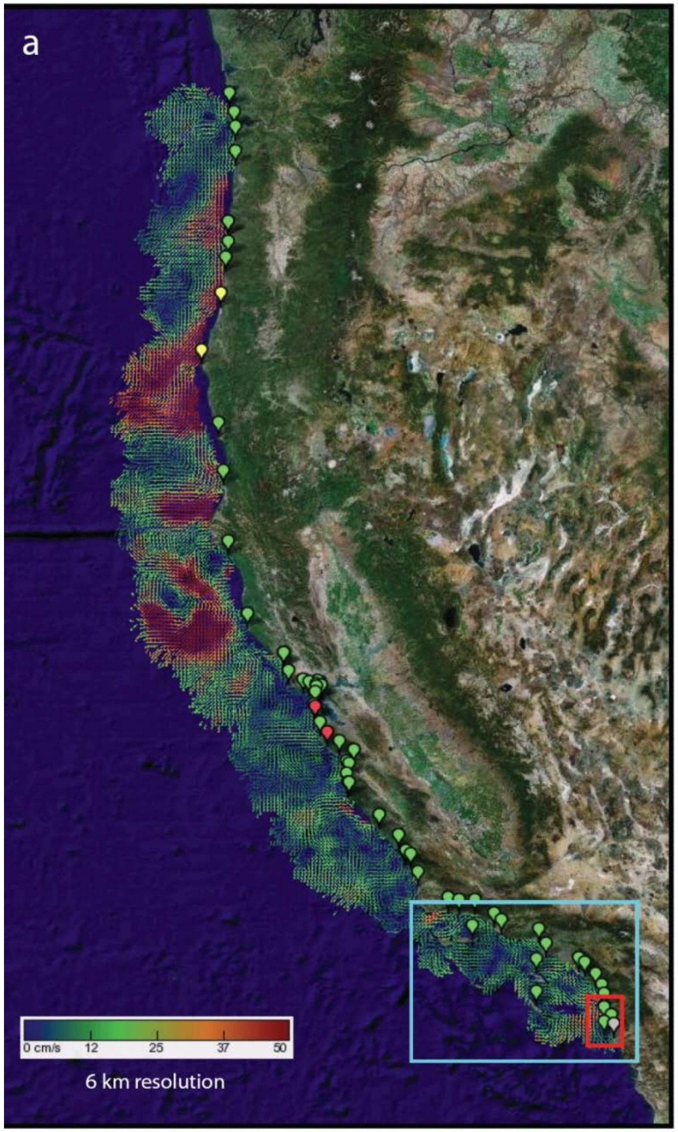
  - Upper 1 m depth-averaged currents
  - Surface radial velocity maps on a polar coordinate
  - Hourly and O(1) km scale surface current maps



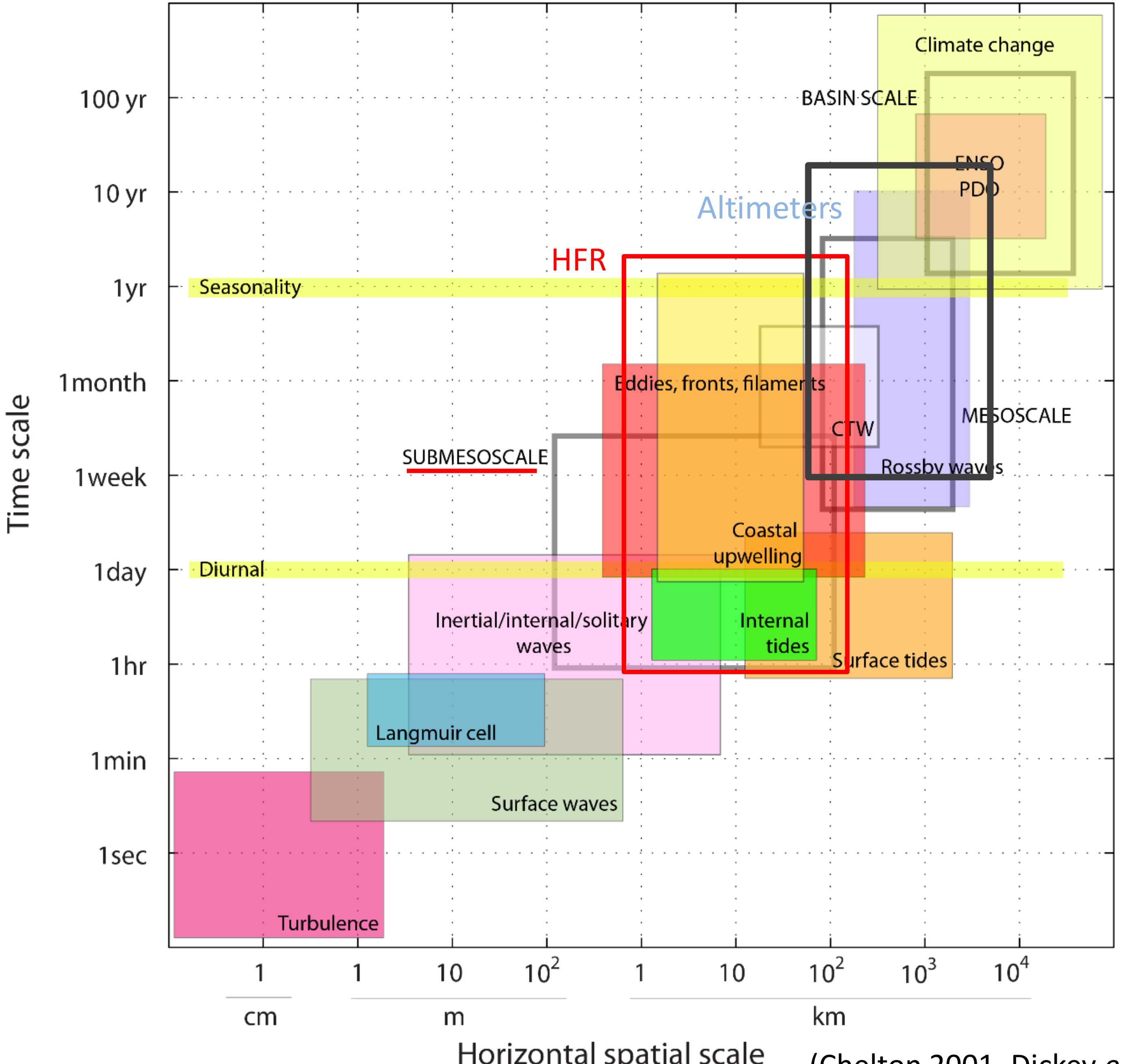
High-frequency coastal radar-derived surface currents off the U.S. West Coast



- 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.
- Due to low signal-to-noise ratio of satellite remote sensing near coastal regions, coastal surface current maps provided by a large HFR system can provide a useful resource to investigate the submesoscale eddies in a view of statistics and dynamics.

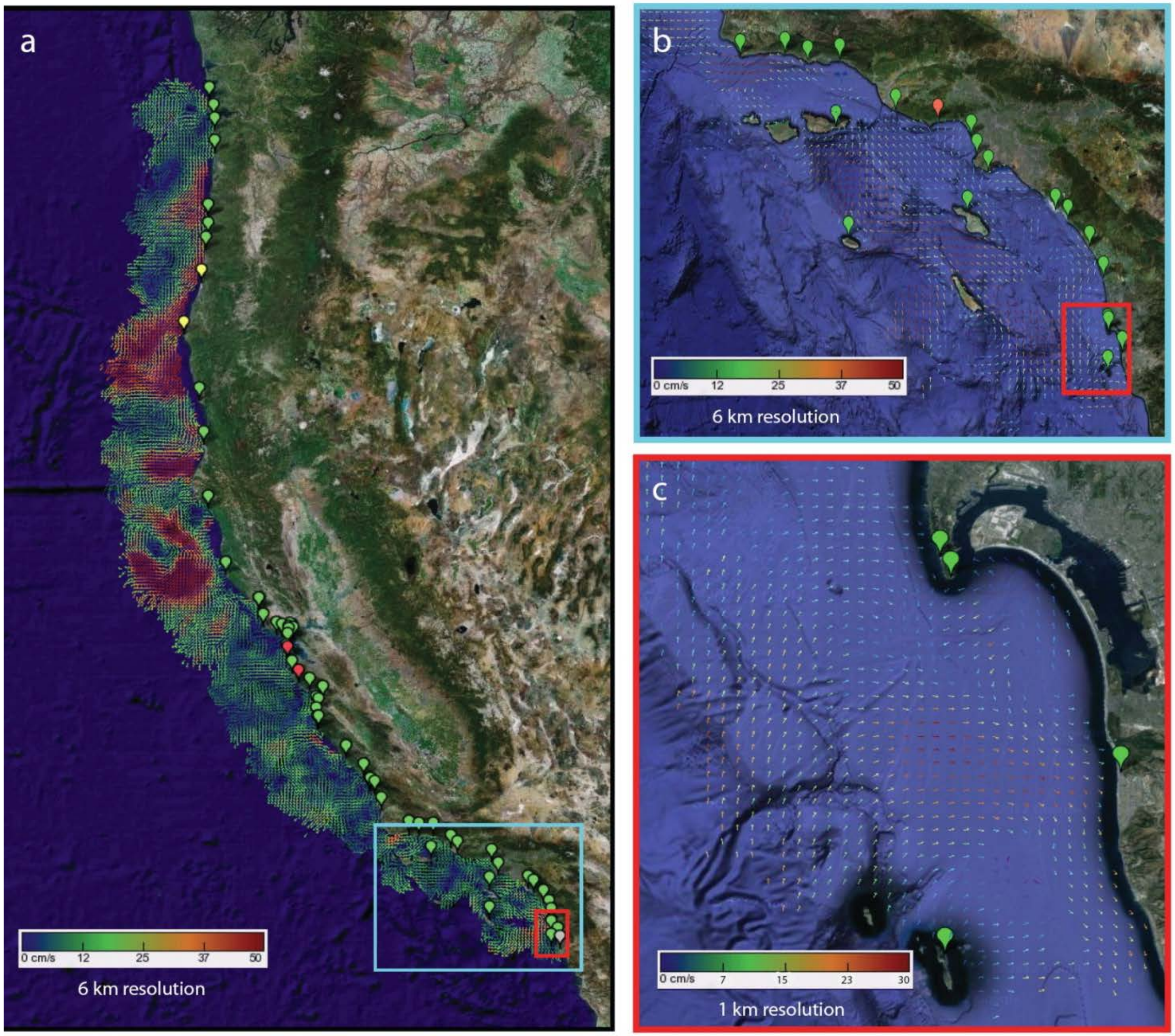
(Kim et al, JGR 2011, Kim and Crawford, GRL 2014)

Oceanic processes in time and spatial scales



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

High-frequency coastal radar-derived surface currents off the U.S. West Coast (cascade maps)



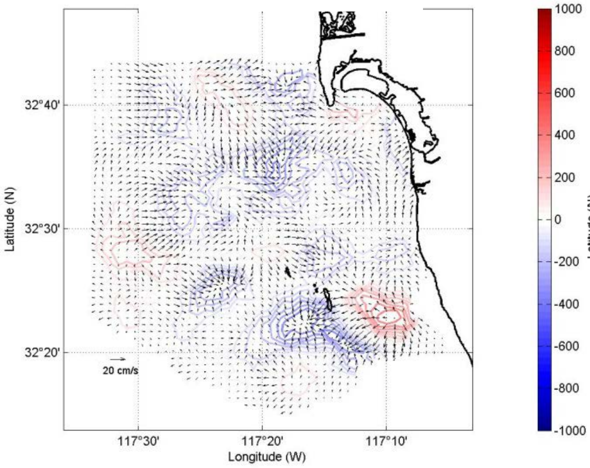
- In this talk, the surface current maps from southern San Diego are mainly used.

(Kim et al, JGR 2011, Kim and Crawford, GRL 2014)

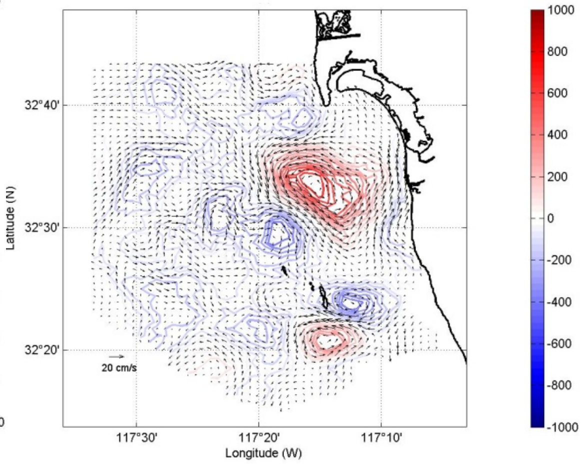
Observations of submesoscale eddies using high-frequency radar-derived kinematic and dynamic quantities

- Velocity potential and stream function

Velocity potential

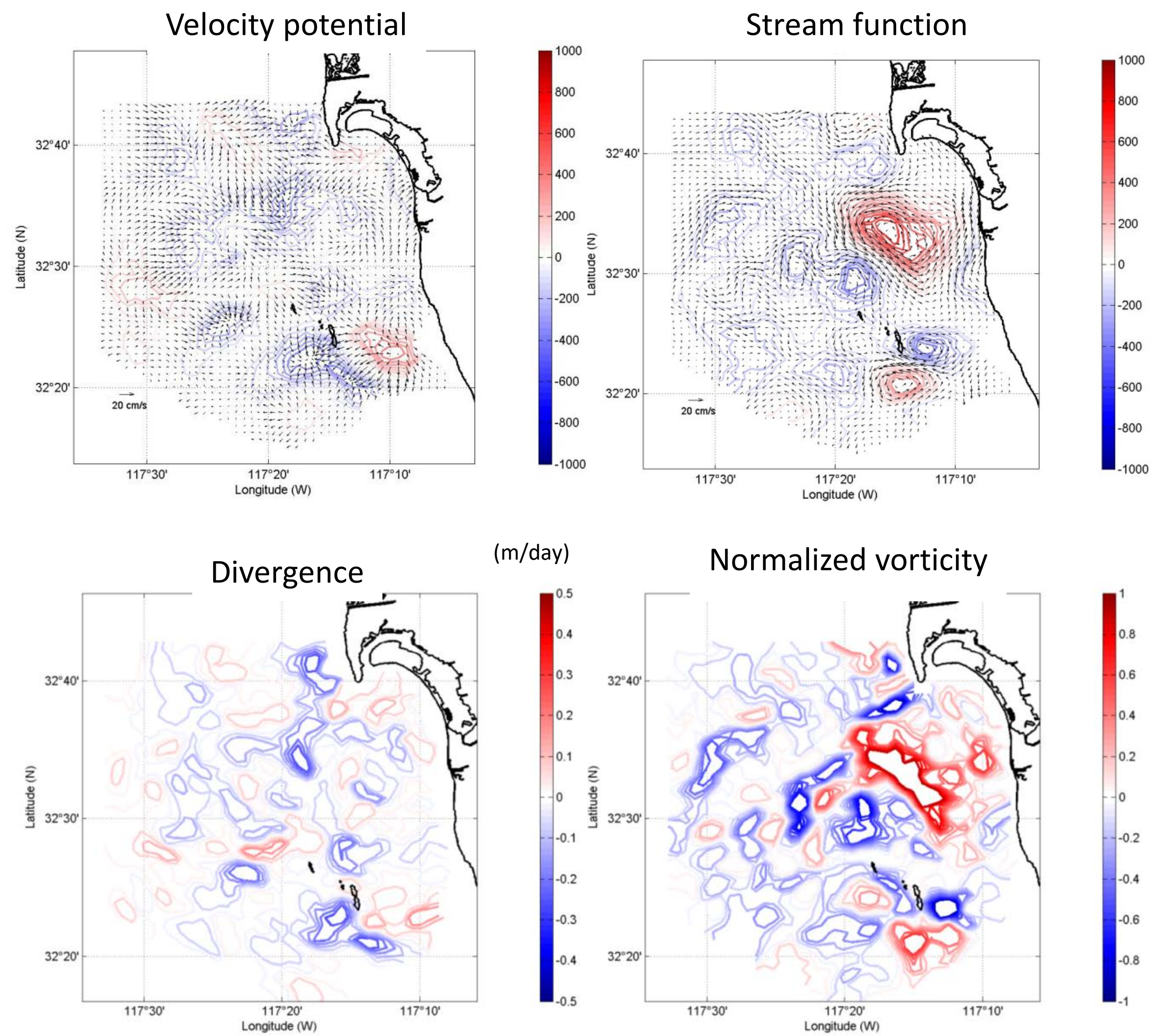


Stream function



Observations of submesoscale eddies using high-frequency radar-derived kinematic and dynamic quantities

- Velocity potential and stream function
- Divergence and normalized vorticity



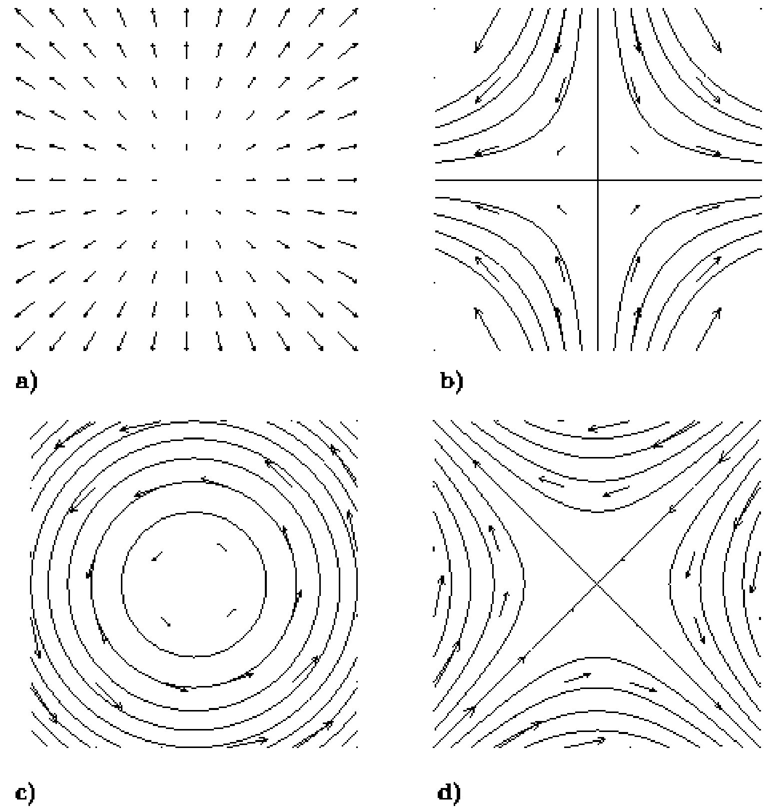
Observations of submesoscale eddies using high-frequency radar-derived kinematic and dynamic quantities

- Velocity potential and stream function
- Divergence and normalized vorticity
- Stretching and shearing deformation rates, and strain rate

$$\varrho = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y},$$

$$\varsigma = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y},$$

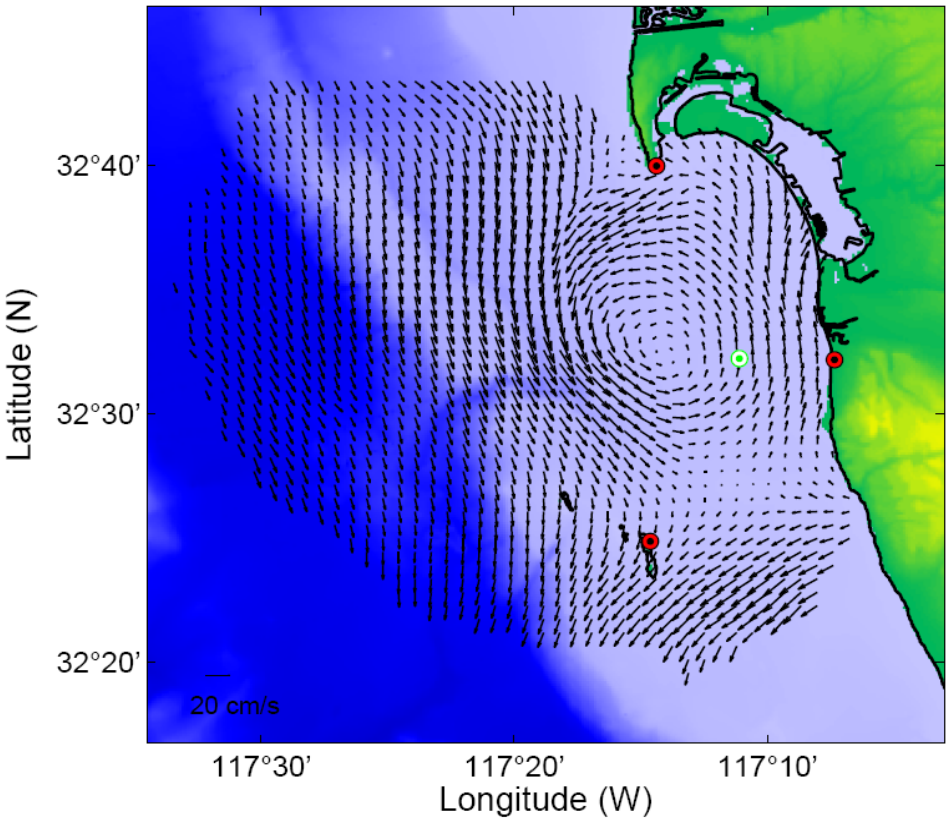
$$\kappa = \sqrt{\varrho^2 + \varsigma^2}.$$



(a) divergence; (*b*) stretching deformation; (*c*) vorticity; (*d*) shearing deformation.

Observations of submesoscale eddies using high-frequency radar-derived kinematic and dynamic quantities

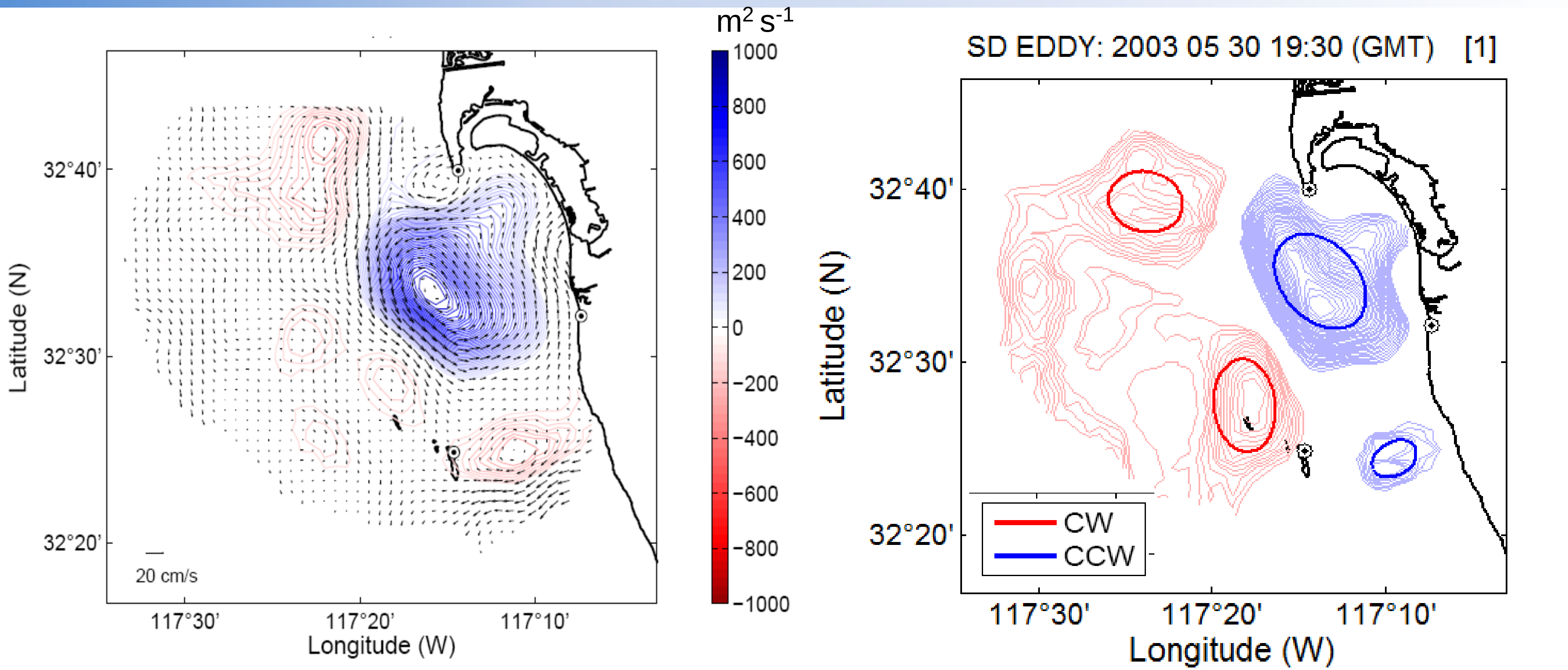
- Surface
  - Hourly and O(1) km resolution surface current maps
  - Their kinematic and dynamic quantities
- Subsurface
  - ADCP – current profiles
  - Temperature profiles – thermocline movements



Outline for rest of the talk…

- Eddy detection using surface current maps
  - Geometry-based technique
- Interpretation of submeososcale eddies
  - Statistics of diameters and Rossby numbers
  - Verification with circulation
  - Horizontal structure of identified eddies
  - Secondary circulation due to drifting submesoscale eddies
- Summary

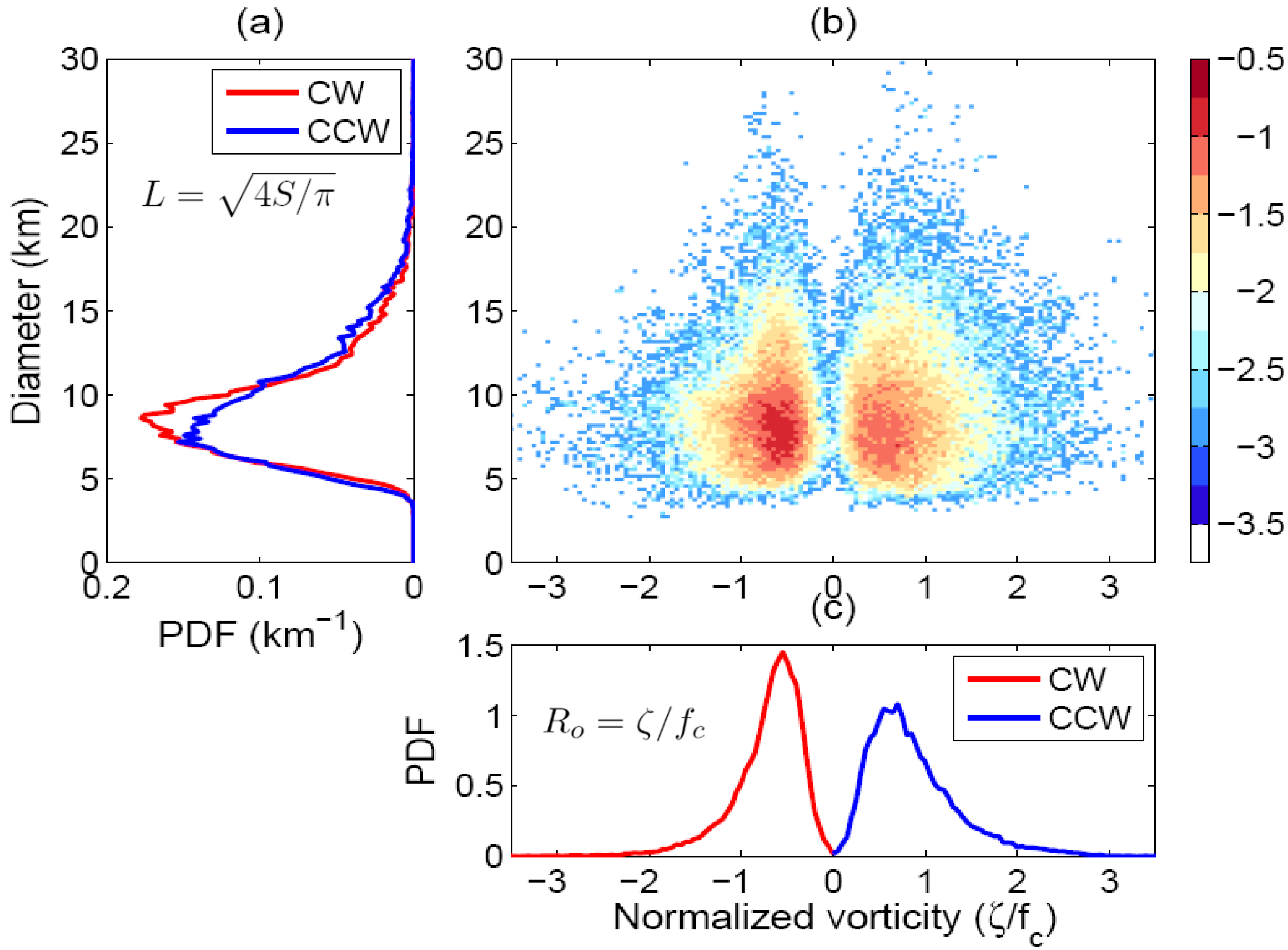
Eddy detection on HFR surface currents



- 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)

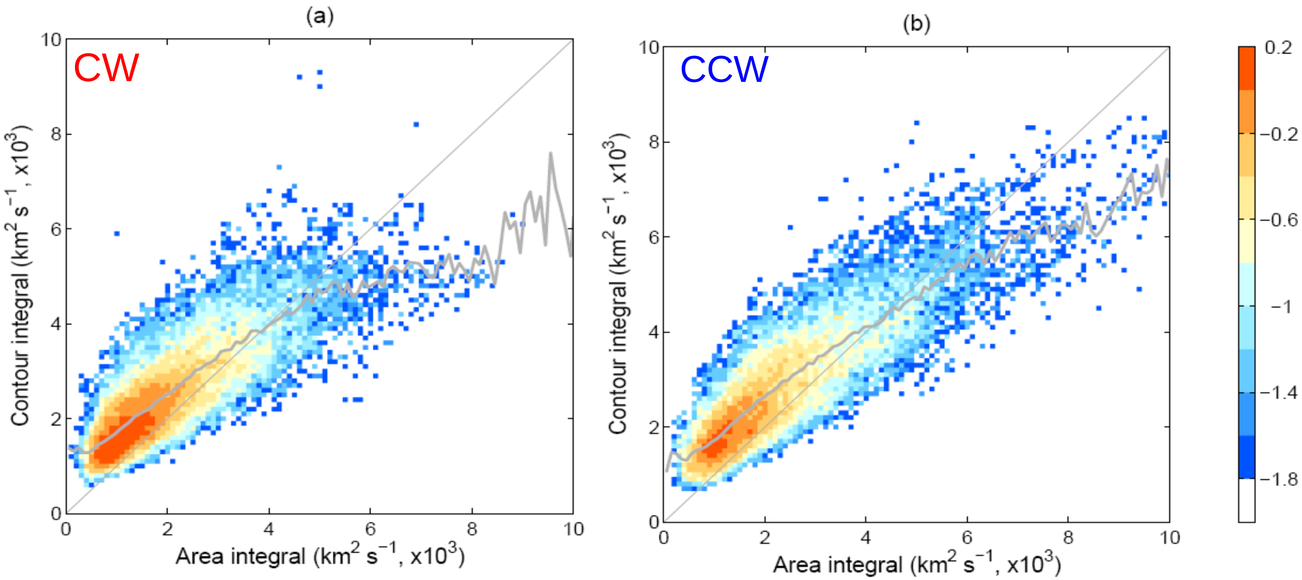
Rossby number and size



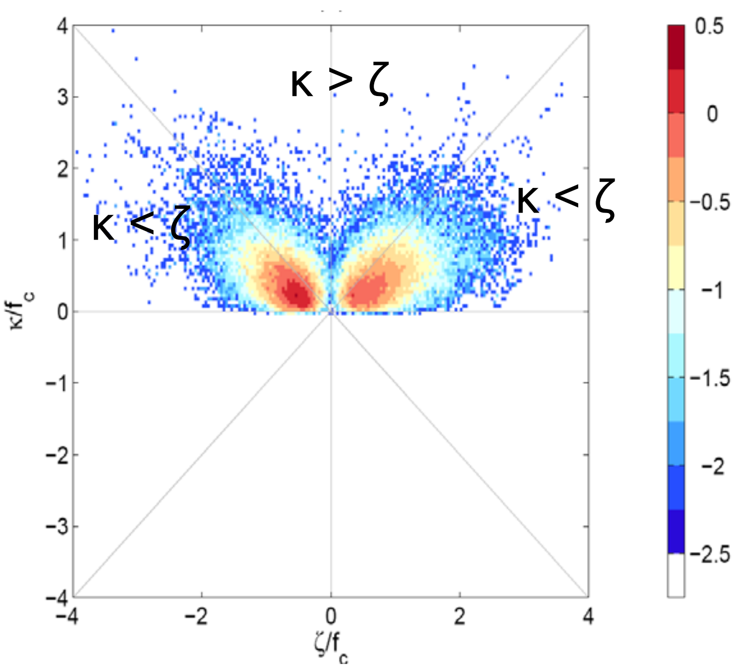
- Based on 2-year hourly observations.
- About 700 eddies are identified for each rotation
- O(0.5-1) Rossby number at the center of eddies
- 5 – 20 km size diameter (L) eddies

(Kim, CSR 2010)

Circulation & WO parameter



$$\Gamma \equiv \oint_C \mathbf{u}\cdot d\mathbf{l} = \oint_C \mathbf{u}_\psi\, dl \approx \sum \mathbf{u}_\psi \Delta l,$$
$$\equiv \iint_S (\nabla \times \mathbf{u})\cdot d\mathbf{S} = \iint_S \bar{\zeta}\cdot d\mathbf{S}$$
$$\approx \bar{\zeta} S,$$



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

$$\kappa = \sqrt{\varrho^2 + \varsigma^2}$$ strain rate

$$\varrho = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}$$ shear deformation rate

$$\varsigma = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}$$ stretching deformation rate

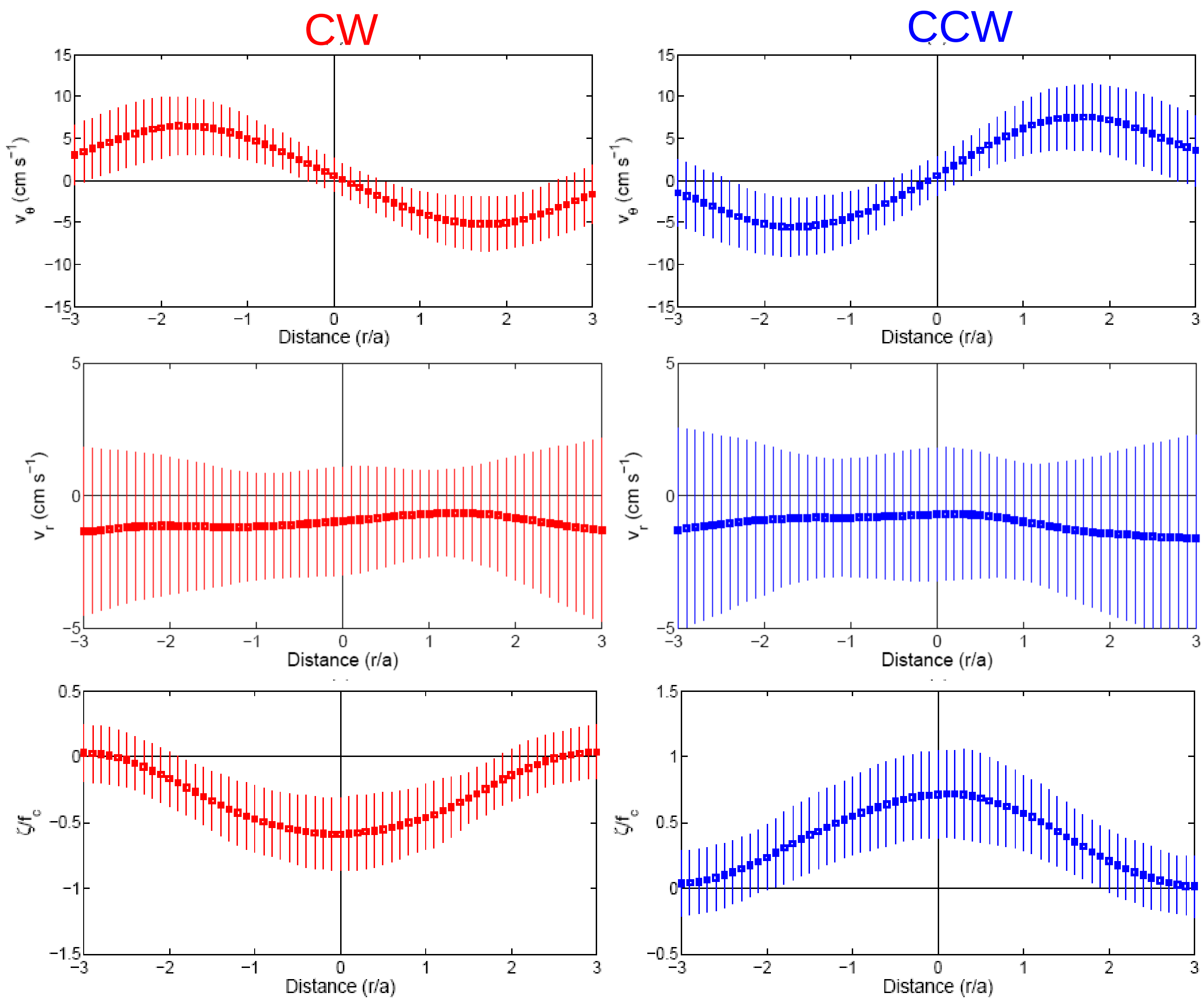
(Kim, CSR 2010)

Horizontal structure

V_Θ Tangential velocity

V_r Radial velocity

ζ/f_c Rossby number

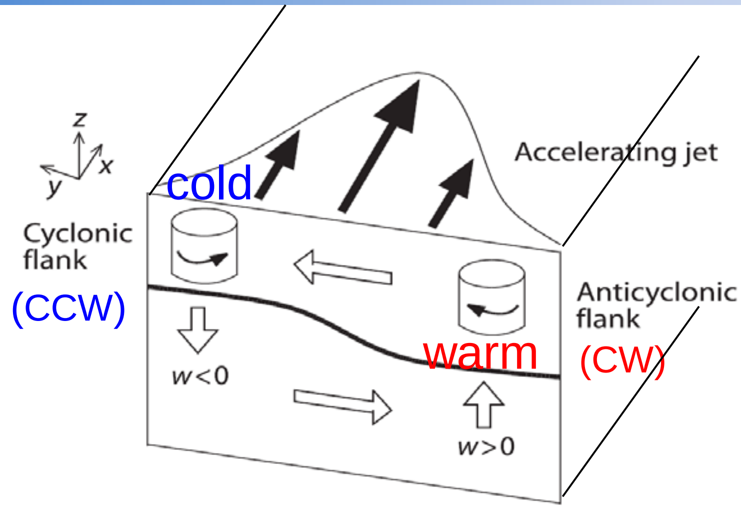


r/a: Relative distance on the major axis

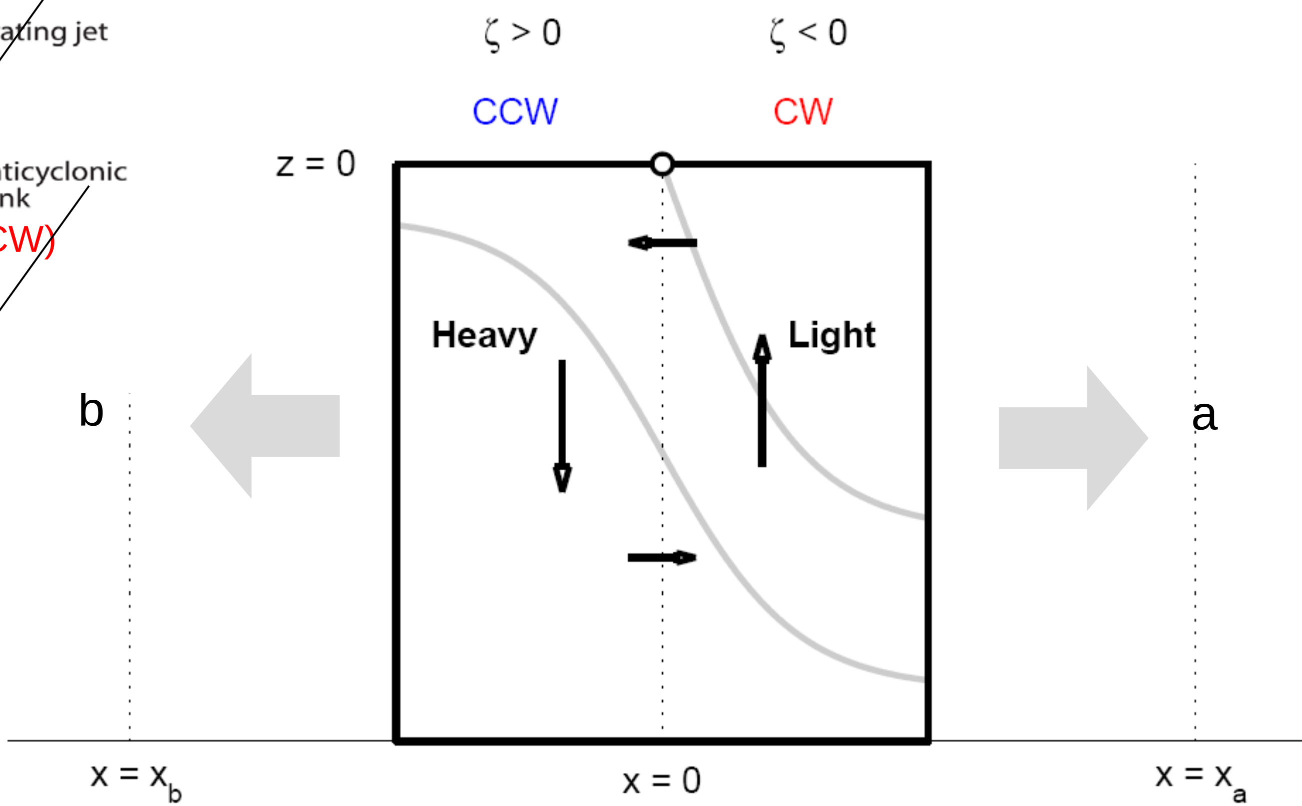
- V_Θ and ζ/f_c have similar shapes to the Taylor eddy.

(Kim, CSR 2010)

Frontal-scale secondary circulation: Expectation



(Williams and Follows, 2003)



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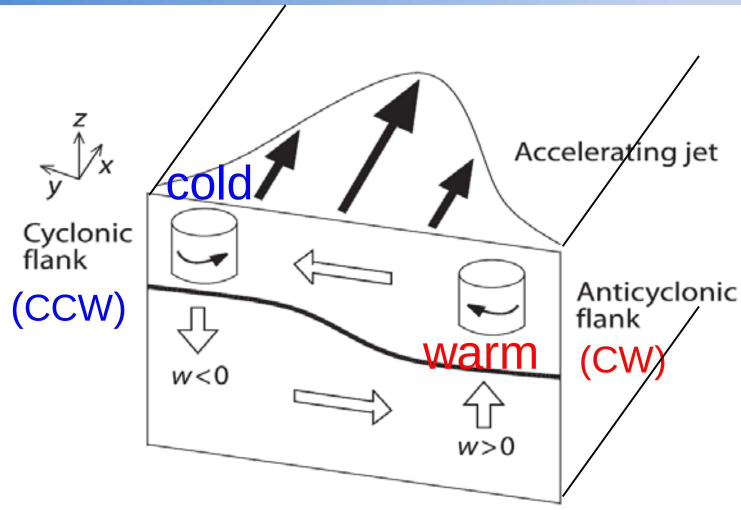

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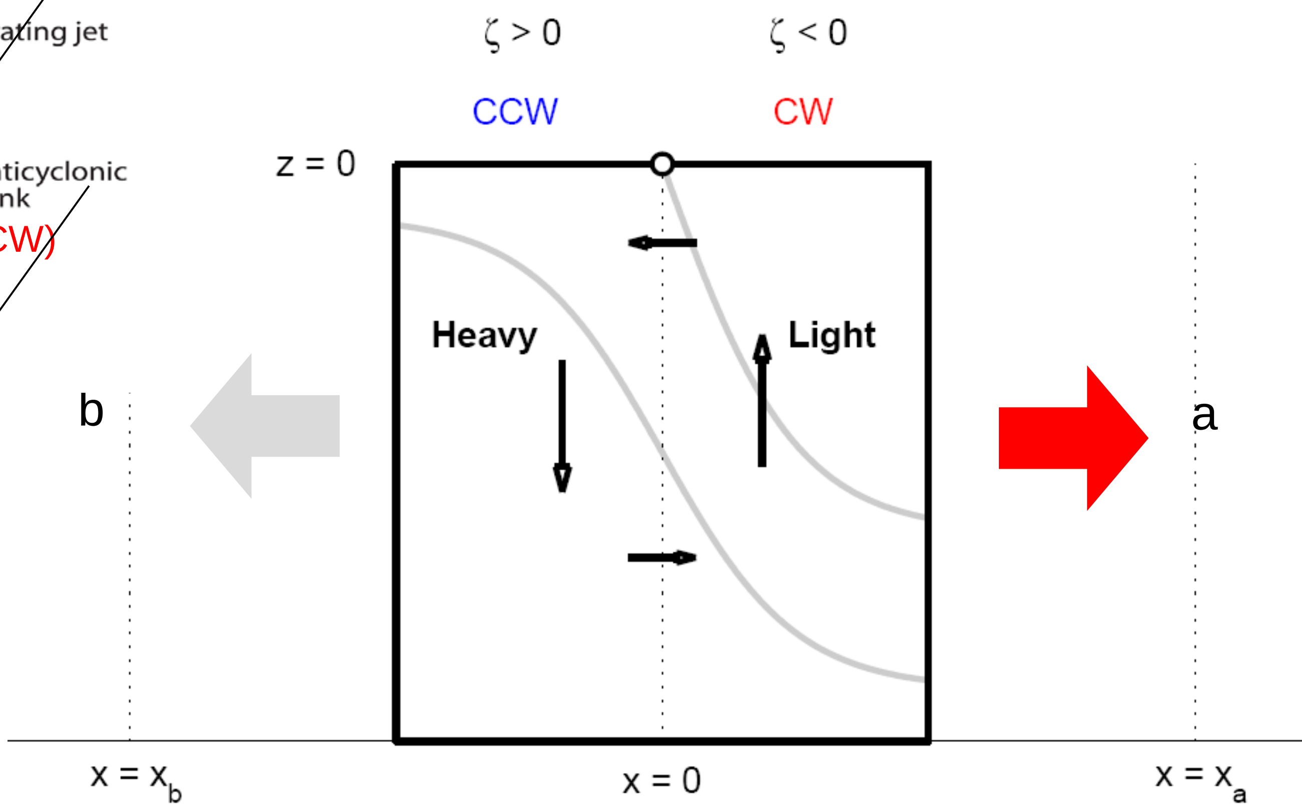
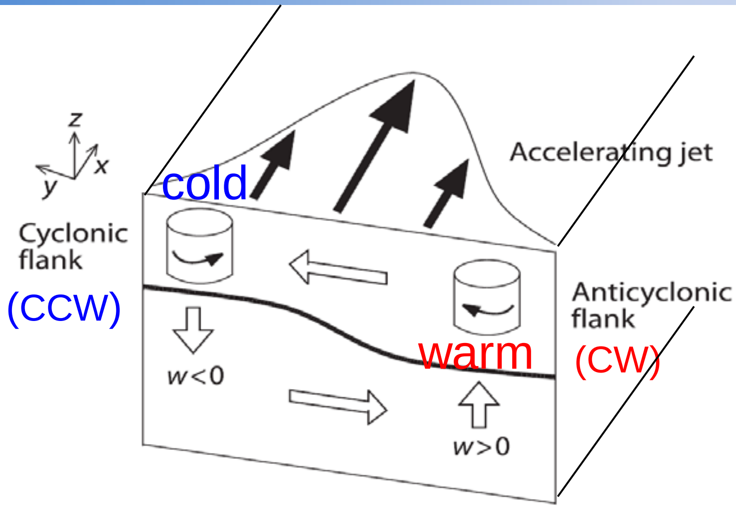


- Paired eddies (a front) move to ‘a’, thermoclines fluctuate up- and down-ward.

Frontal-scale secondary circulation: Expectation



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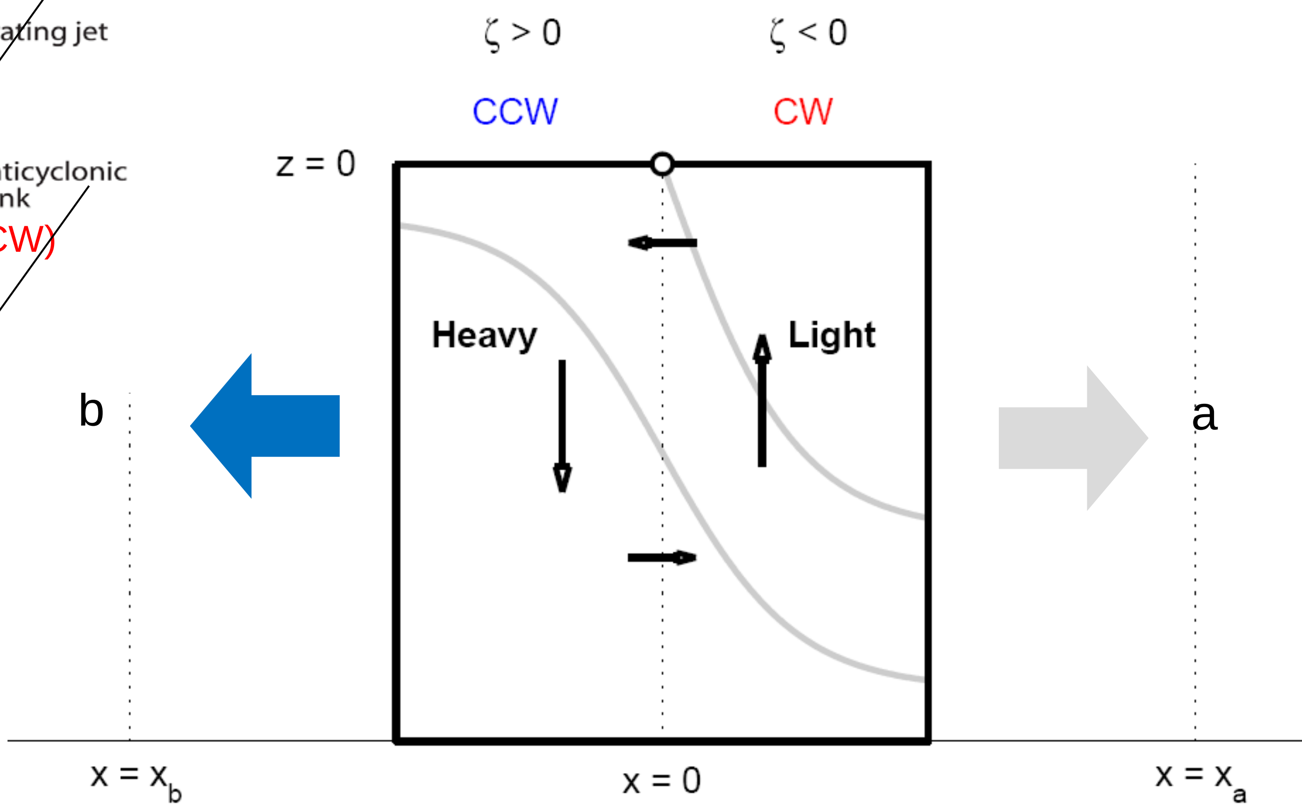


- Paired eddies (a front) move to ‘a’, thermoclines fluctuate up- and down-ward.
- On other hand, due to moving paired eddies (front) to ‘b’, the thermoclines fluctuate down- and up-ward.

Frontal-scale secondary circulation: Data-derived indicator

- Surface
  - Stream function, velocity potential
  - Divergence and vorticity,
  - Shearing and stretching deformation rates, and strain rate

$$\delta = \nabla_H \cdot \mathbf{u} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y},$$

$$\zeta = \nabla_H \times \mathbf{u} = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y},$$

$$\varrho = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y},$$

$$\varsigma = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y},$$

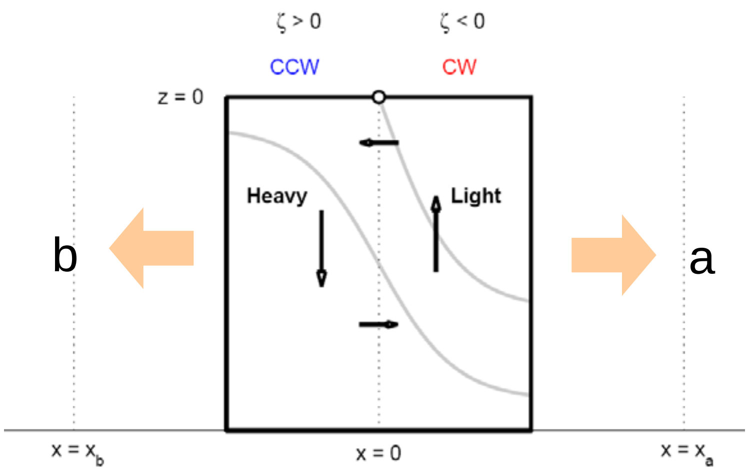
$$\kappa = \sqrt{\varrho^2 + \varsigma^2}.$$

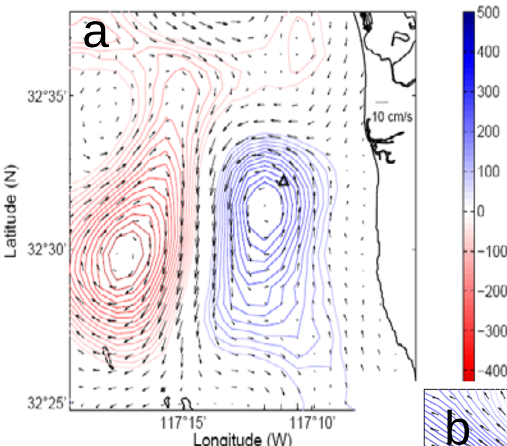
- Subsurface
  - ADCP Current profiles [**u** = **u**(z, t)]
  - Rotational tendency of whole water column: Vertical rotary coefficients

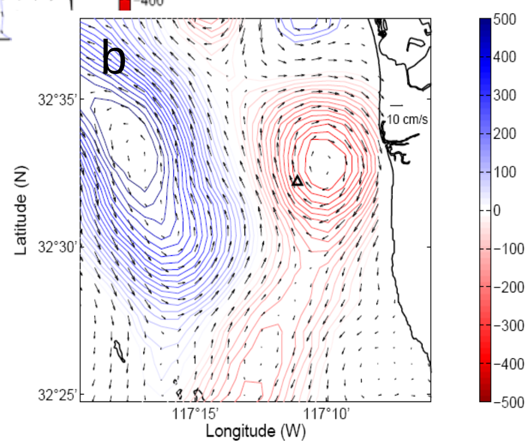
$$\alpha(t) = \frac{-\sum_{m<0} S(m,t) + \sum_{m>0} S(m,t)}{\sum_{m<0} S(m,t) + \sum_{m>0} S(m,t)},$$

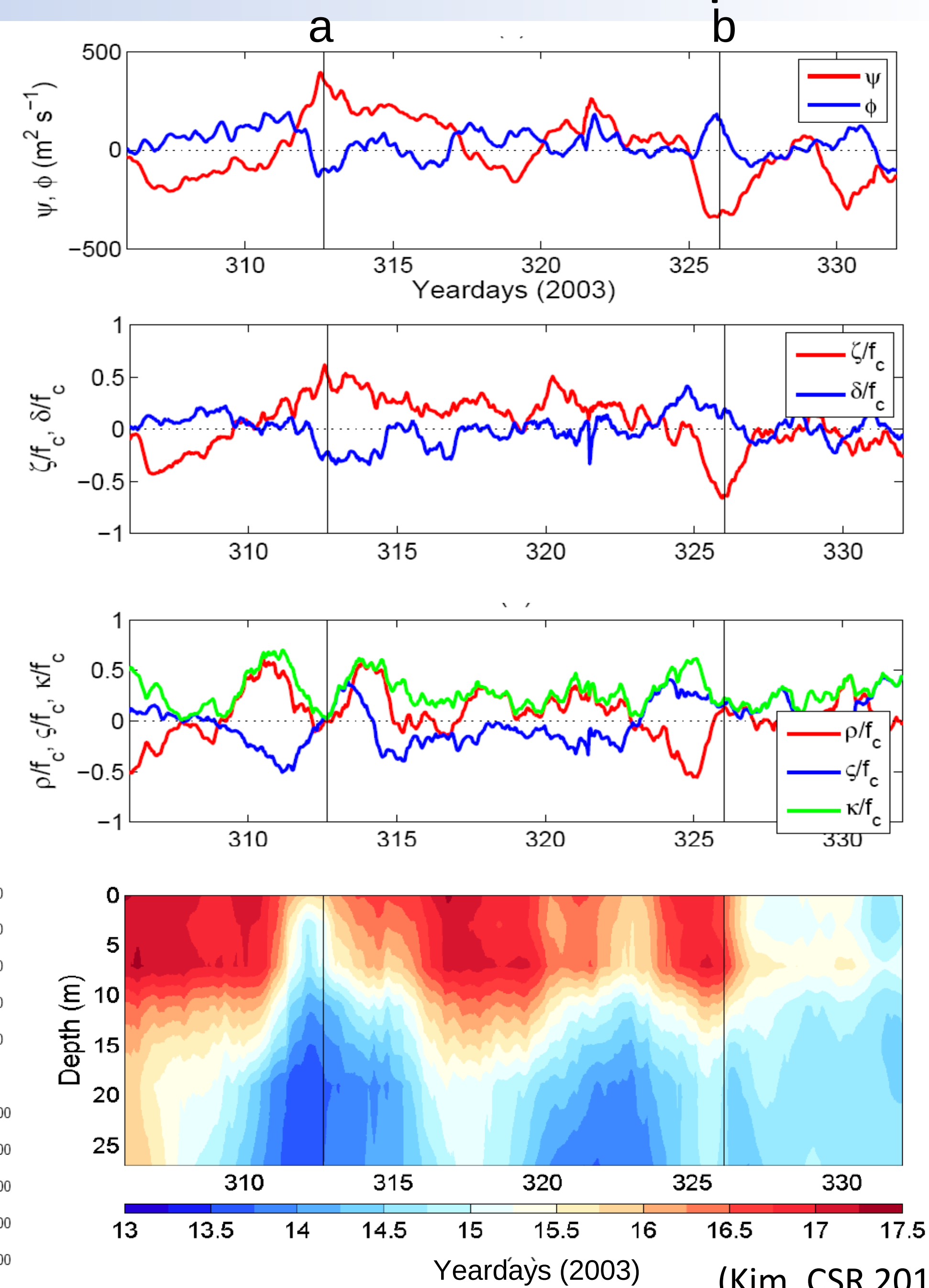
  - Vertical movements of thermoclines [T-string data]

Frontal-scale secondary circulation: Surface & Temp.



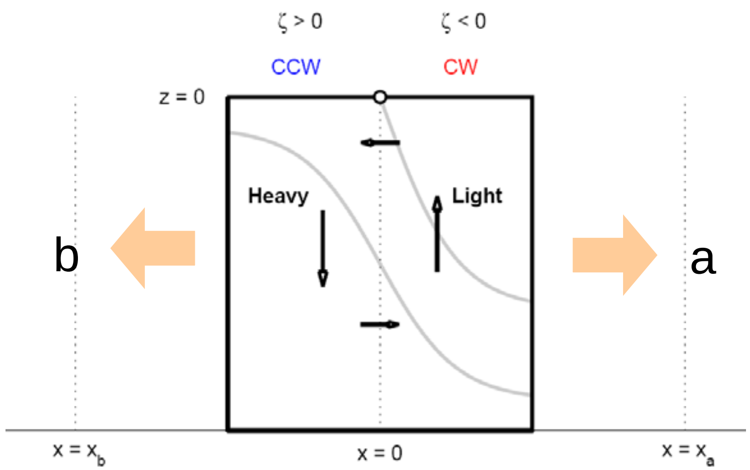


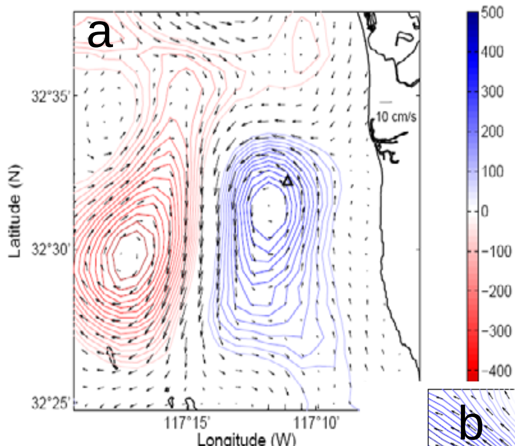




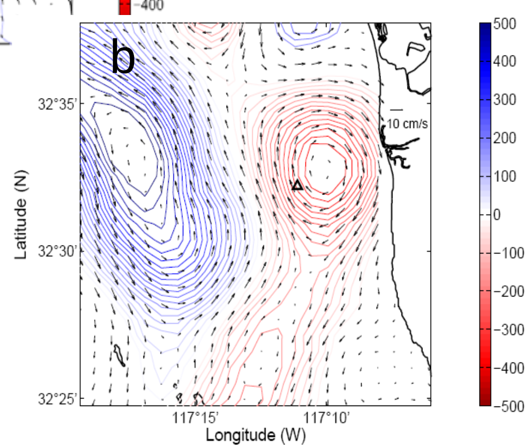
(Kim, CSR 2010)

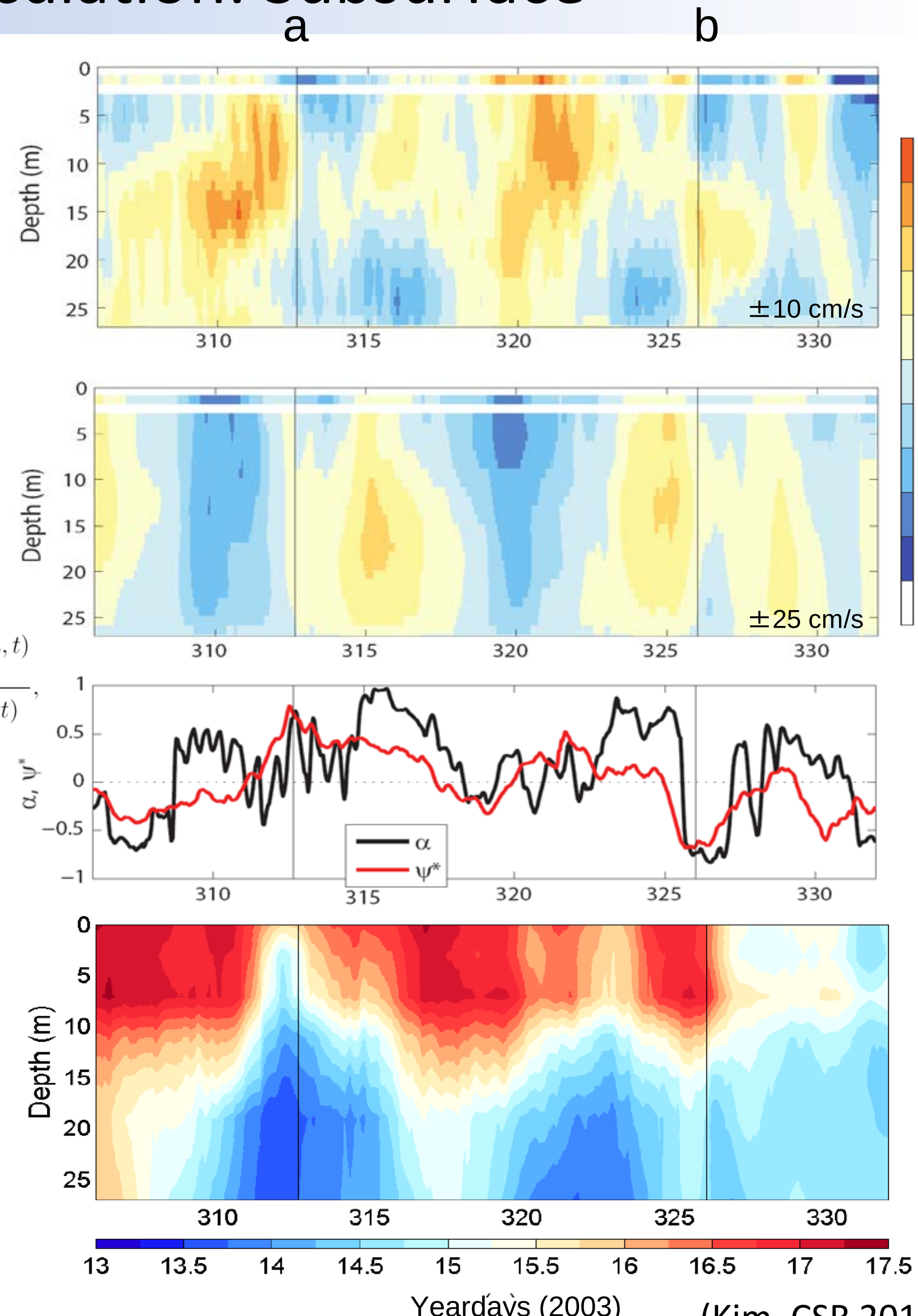
Frontal-scale secondary circulation: Subsurface





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

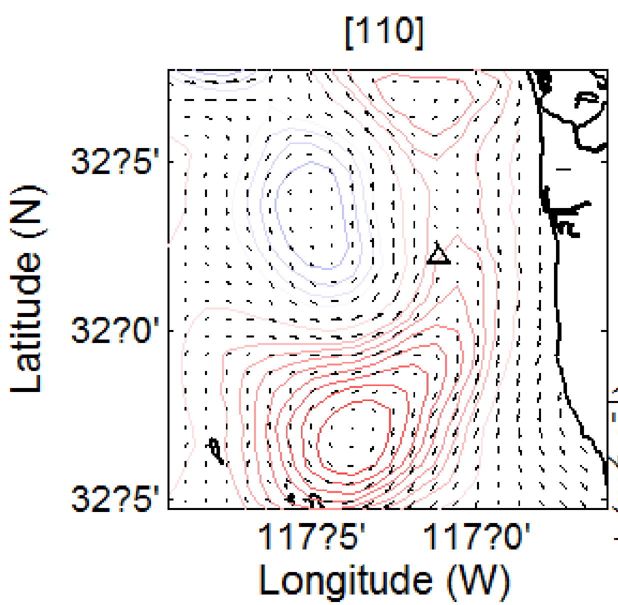


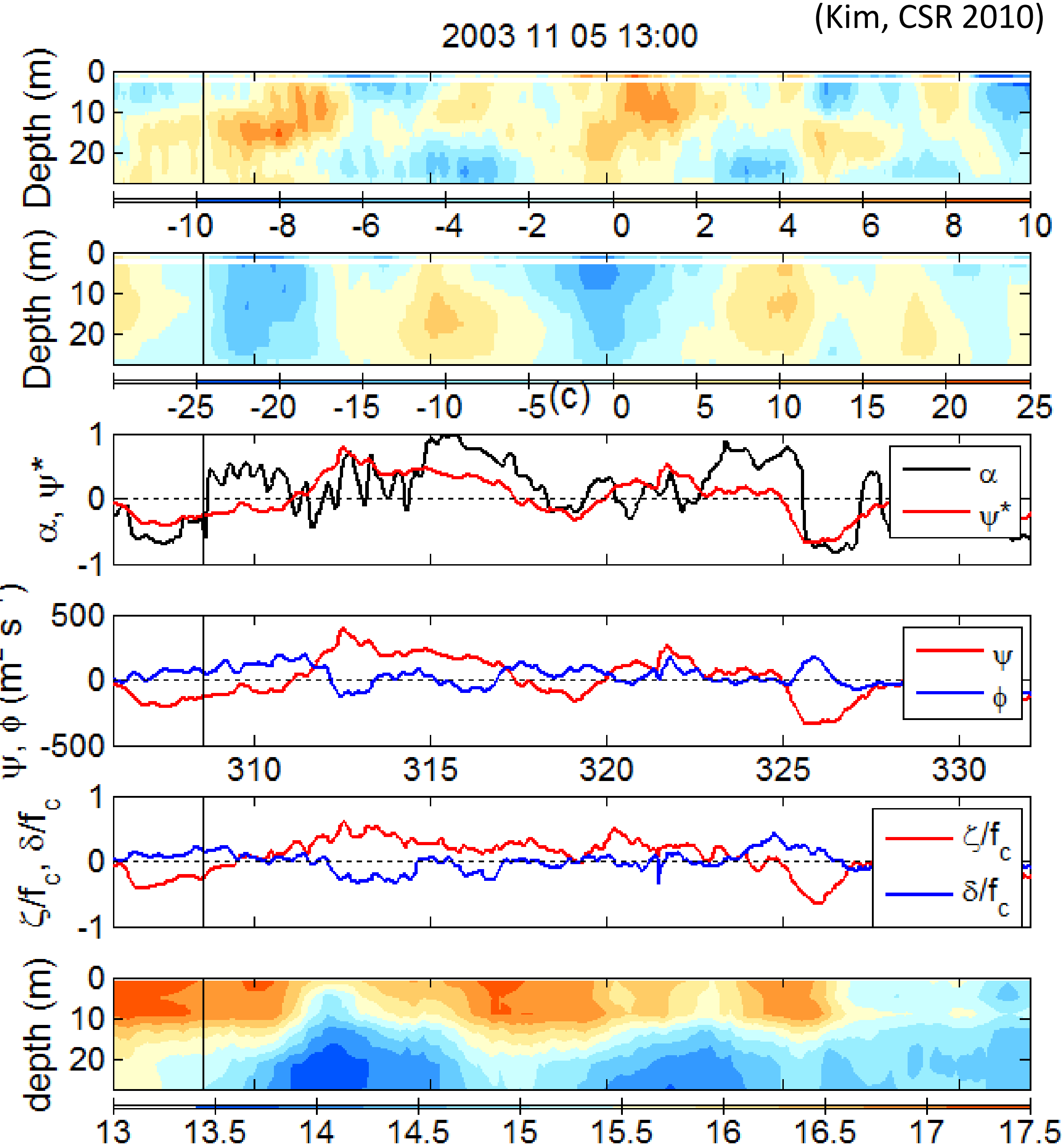


(Kim, CSR 2010)

Two events of submesoscale eddies approaching ADCP/T-string

(Kim, CSR 2010)





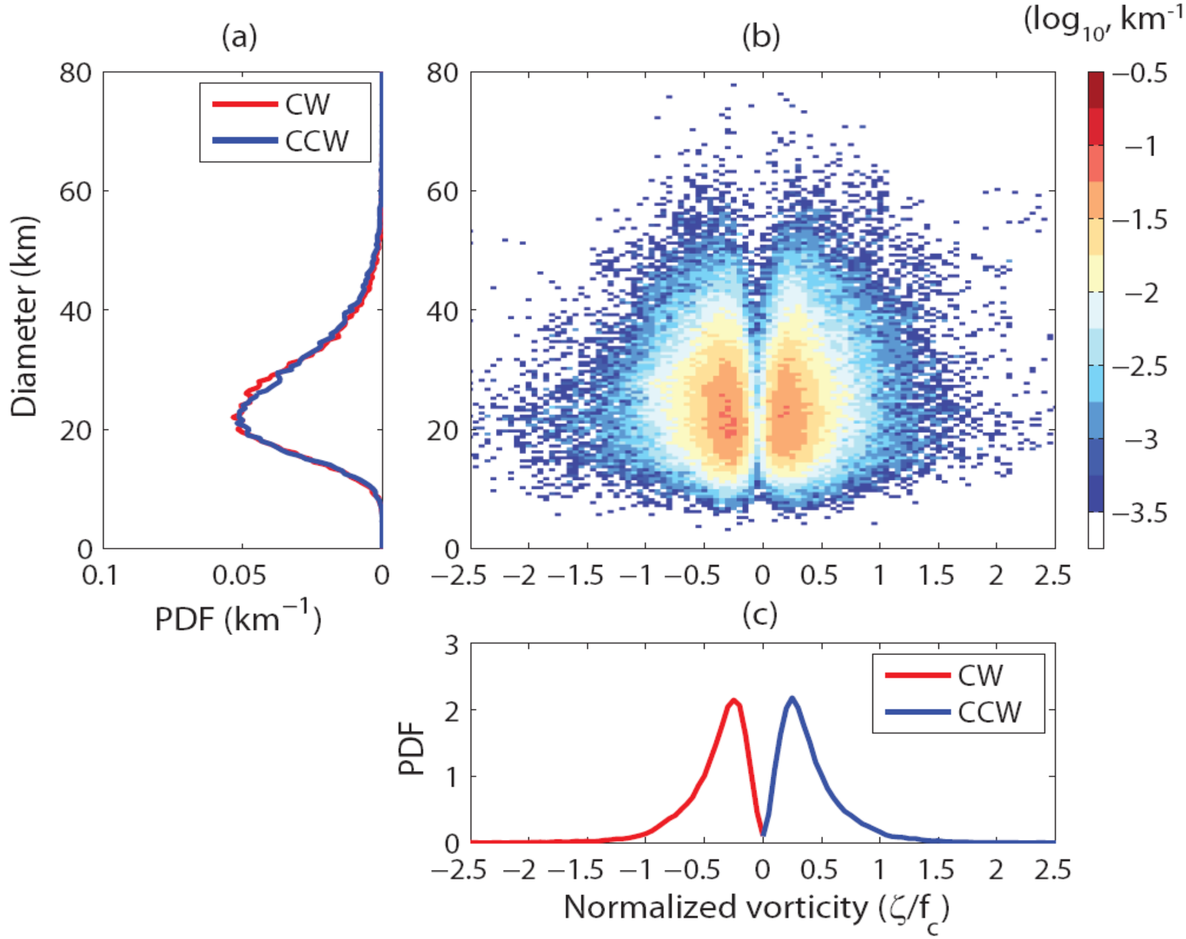
Demography of sub-mesoscale eddies off the USWC

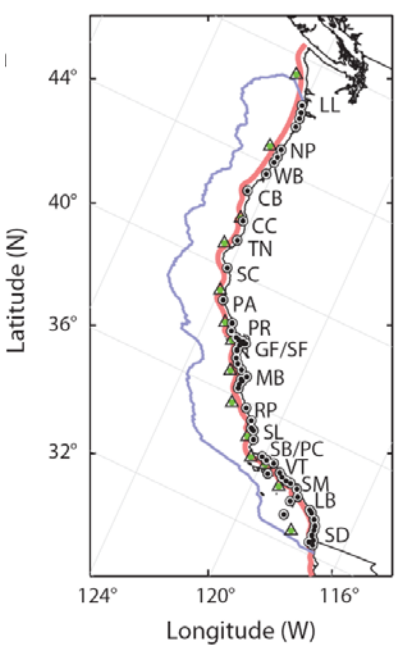
Using flow geometry of the stream functions.

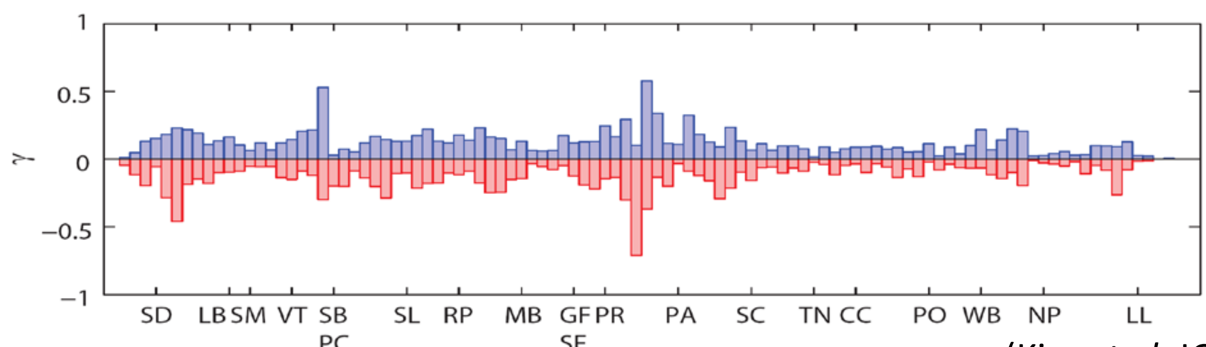
A cluster of streamlines is fitted with an ellipse. (Kim CSR, 2010)

Vorticity at the center of eddies.

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







(Kim *et al*, JGR 2011)

Summary

- Submesoscale eddies off southern San Diego detected from direct estimate of kinematic and dynamic quantities of HFR observations and ADCP: Rossby number of O(0.5-1) and 5-25 km diameter
- Frontal-scale vertical circulation due to drifting eddies undulates thermoclines.
- Available submesoscale observational resources are very sparse and few, but they may enhance our understanding on the submesoscale process studies.