Revealing the submesoscale structure of subthermocline eddies in the North East Pacific

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Introduction

Cuddies are intrathermocline anticyclonic eddies associated with the California Undercurrent in the Northeast Pacific. Centred at ~200–250 m depth, they trap warm, salty Pacific Equatorial Waters (Pelland et al., 2013) and act as efficient agents of offshore transport of heat, salt, oxygen, nutrients, and biologically productive waters. Through this role, Cuddies strongly influence cross-shelf exchange and regional biogeochemistry, making them a key feature for understanding the Northeast Pacific dynamics. Because of their subsurface core and mesoscale-to-submesoscale dimensions, Cuddies are difficult to observe with traditional satellite altimetry (Ren and Rudnick, 2022). Autonomous underwater gliders, however, provide high-resolution vertical profiles that capture their thermohaline structure and temporal evolution. Recently, the Surface Water and Ocean Topography (SWOT) mission has offered an unprecedented opportunity to resolve their surface signature at submesoscale resolution. In this study, we combine glider observations, altimetry (SWOT and DUACS), and satellite chlorophyll-a to characterize the structure and surface signal of a Cuddy observed off Vancouver Island in summer 2023. Combining different data sources allows us to examine its thermohaline properties, velocities and to assess the consistency of SWOT-velocities with independent velocity estimates.

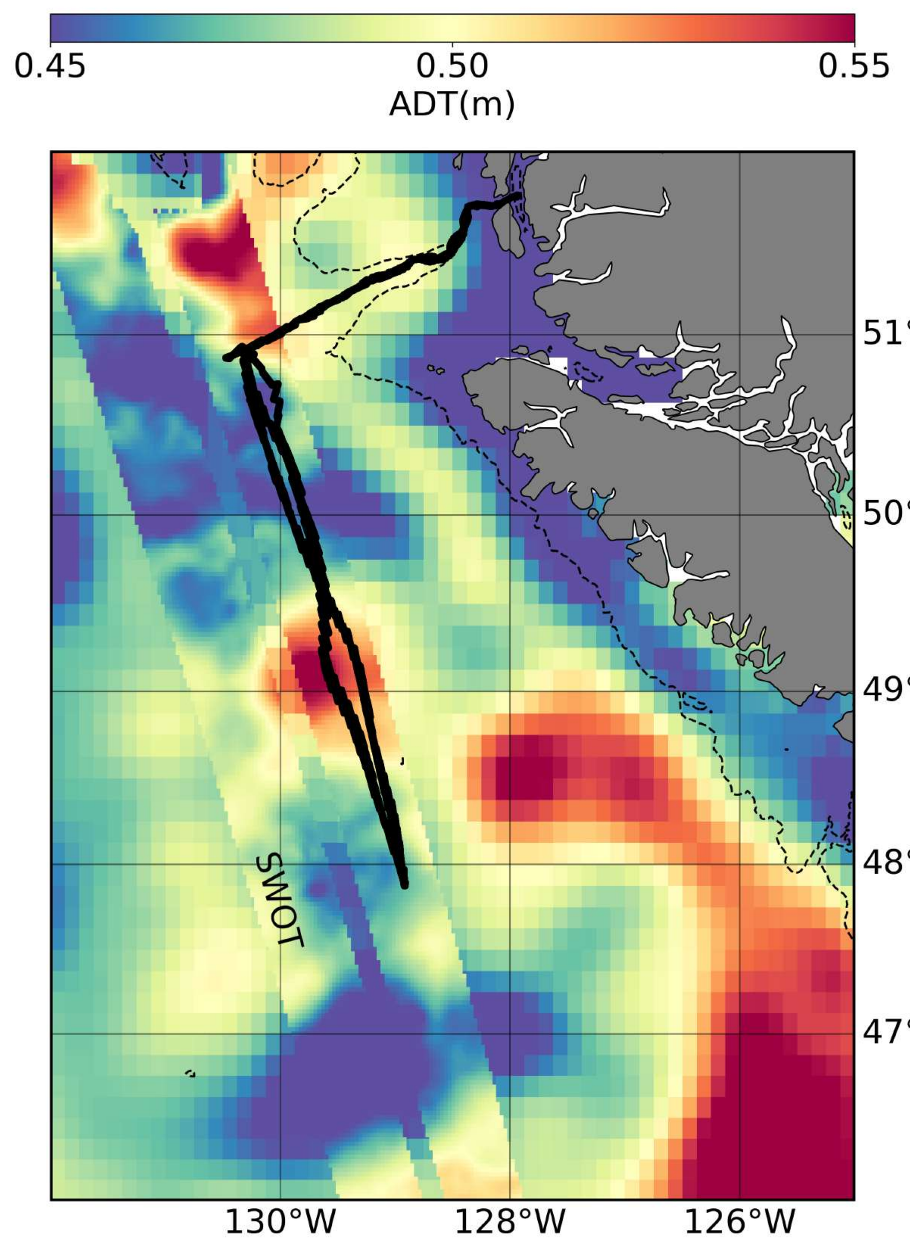

Figure 1. ADT from DUACS (background) and SWOT measurements over the pass 26 CalVal period on June 6, 2023. The glider track is indicated by the black line. The 200 m isobath is indicated by a dashed line.

Data and Methodology

- Glider observations: A Slocum G3 Deep glider (C-PROOF program, Klymak and Ross, 2025) was deployed off Vancouver Island (May–July 2023). It collected high-resolution profiles of temperature, salinity, and density to ~1000 m, completing four transects across the Cuddy (Fig. 1).
- Satellite altimetry: We used SWOT KaRIn Level-3 sea surface height and geostrophic velocity fields (2 km resolution, Pass 026), and compared them with conventional multi-mission DUACS products (0.25° resolution).
- Satellite Chlorophyll: MODIS-Aqua daily chlorophyll a (4 km resolution) were used to assess the surface signal of the eddy.
- Eddy tracking: Eddy characteristics were obtained from the AVISO+ META3.2 product, which provides daily eddy properties based on absolute dynamic topography.

Results

Vertical structure:

Glider transects revealed a subsurface-intensified eddy lens between 100–500 m depth, with a warm and salty core of Pacific Equatorial Waters at ~150 m (Fig. 2). Geostrophic velocities reached 0.22 $m\,s^{-1}$ at 100–200 m depth, consistent with previous studies of subthermocline eddies.

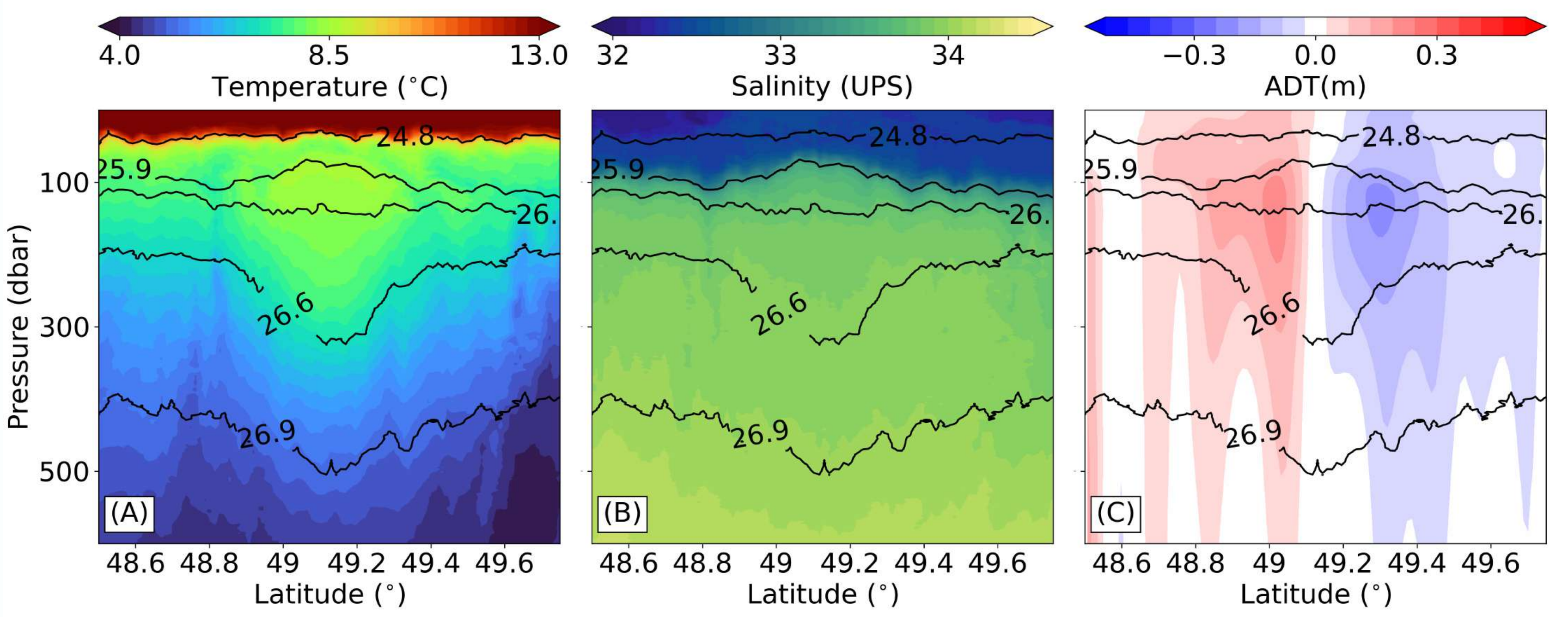

Figure 2. Vertical sections of (A) temperature, (B) salinity based on glider observations and (C) geostrophic velocity derived from glider hydrography combined with SWOT surface velocities.

Surface signal:

SWOT-derived surface velocities displayed sharper gradients and more submesoscale detail than conventional altimetry, including internal jets and spiral arms within the eddy core (Fig. 3). SWOT captures significantly more spectral energy than DUACS at submesoscale ranges (< 70 km). Chlorophyll-a data confirmed the surface signal of subsurface structure, with filaments and spiral arms rotating at contrasting rates between the eddy's interior (4 days per revolution) and its periphery (~36 days) (Fig. 4). The surface features detected by satellites were vertically coherent, consistent with the subsurface structure revealed by glider observations.

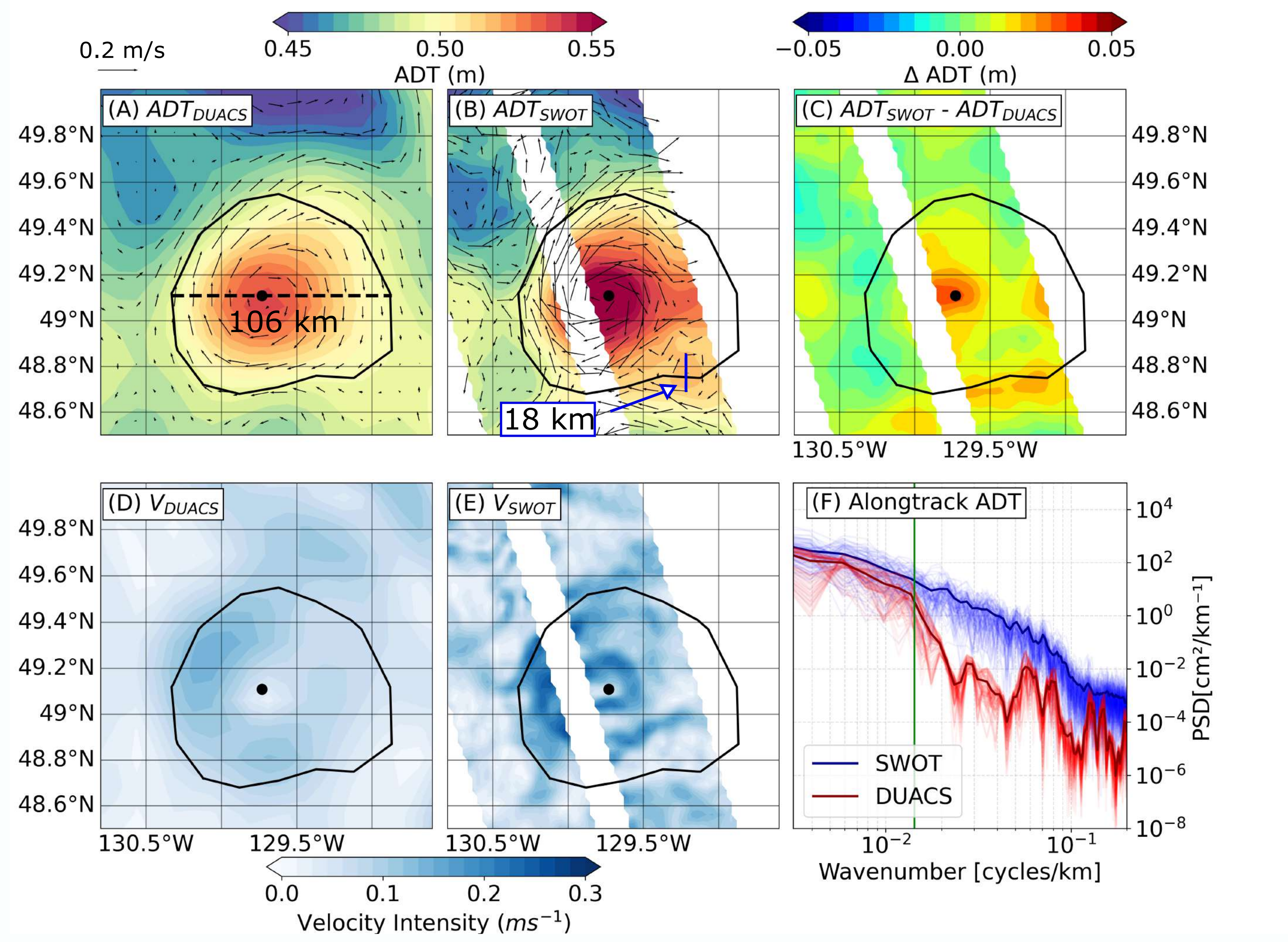

Figure 3. Fields on June 6, 2023. (A, B) DUACS and SWOT ADT, (C) ADT differences: SWOT - DUACS, (D, E) Velocity intensity DUACS and SWOT. The black dot indicates the center of the eddy, and the black line the effective contour based on the Eddy Tracker tool from AVISO. (F) Power spectral density of ADT along SWOT swath (pixel 50) for SWOT in red and DUACS in blue during the Cal/Val period, the time mean spectrum is indicated in dark blue and dark red, respectively. Vertical green line indicates wavenumber of 1/70km.

Validation SWOT velocities

Satellite-derived chlorophyll filaments reveal submesoscale velocities that strongly agree with SWOT observations. Chlorophyll filaments tracked over two days allowed us to estimate six velocity vectors, which were compared with SWOT and DUACS geostrophic velocities (Fig. 4 and 5). Velocities from filaments strongly correlated with both DUACS (R^2 = 0.75) and SWOT (R^2 = 0.78). It is important to mention that zonal components display notably higher agreement (R^2 = 0.84 for both DUACS and SWOT) compared to meridional components (R^2 = 0.18 and 0.41, respectively). The strong agreement between both velocities indicates SWOT's ability to resolve surface circulation in the eddy.

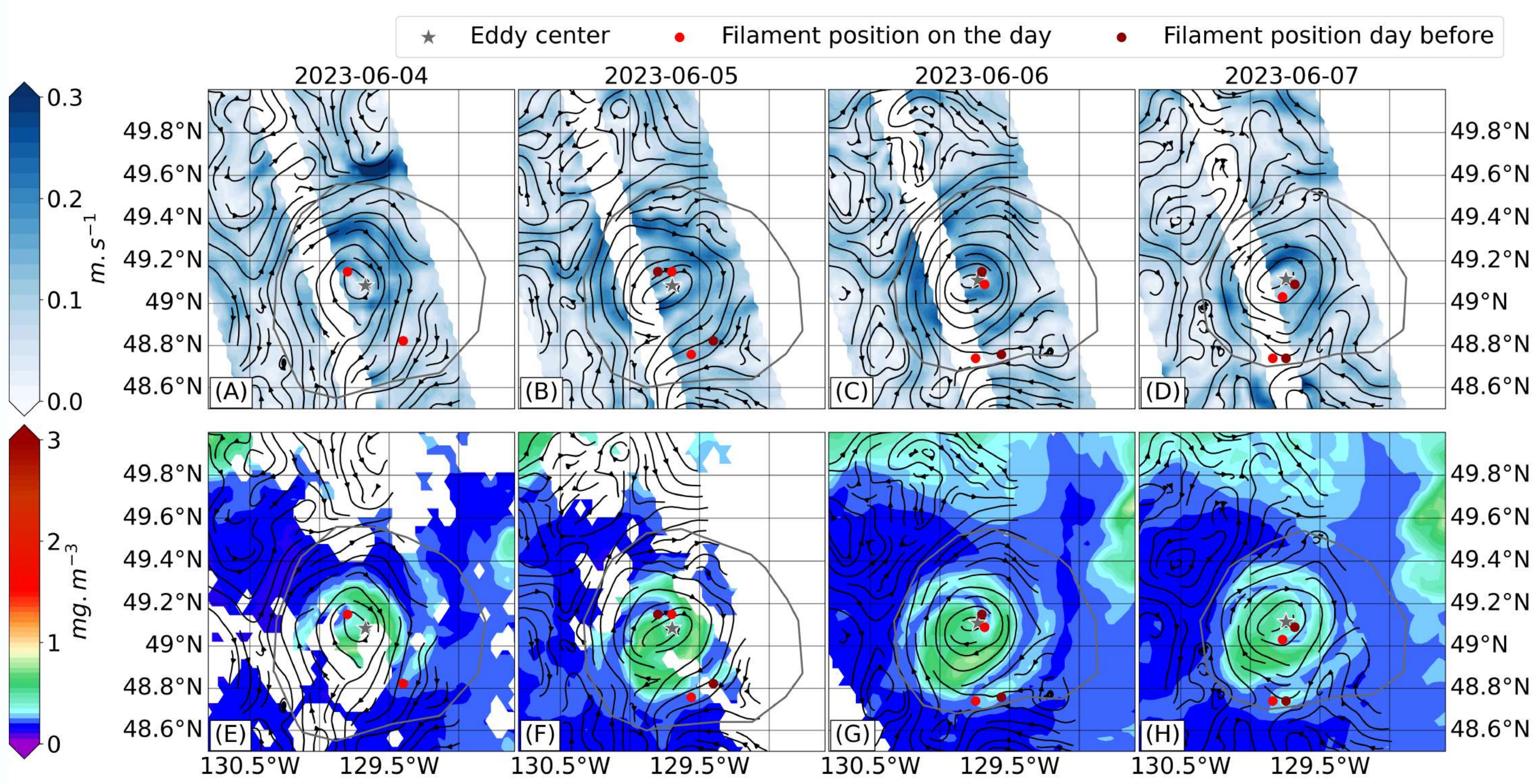

Figure 4. Velocity field from SWOT (A-D), chlorophyll-a concentration (L3) (E-H). The center and the edge of the eddy are indicated by a grey star and a grey line, respectively. The inner and outer filaments on the day are indicated by a red dot, and the positions of those filaments the day before are indicated by dark red dots.

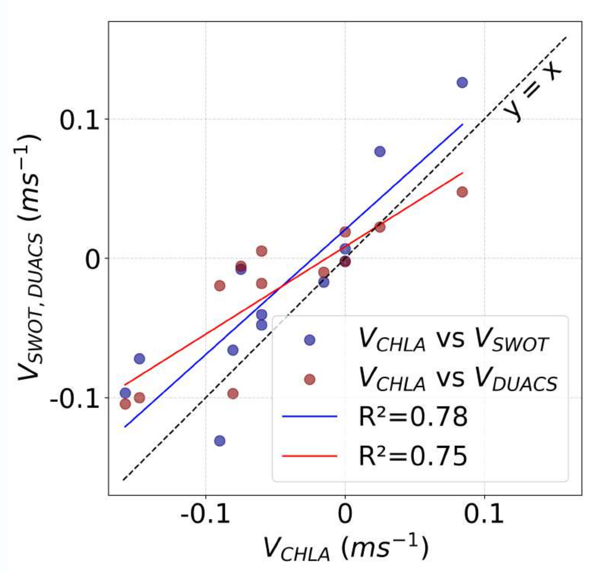

Figure 5. Scatter plot of velocity components (U,V).

Conclusions

These results highlight :

(i) The Cuddy exhibited vertical coherence between its subsurface dynamics and submesoscale surface features.

(ii) The importance of SWOT in resolving submesoscale eddy structures and their surface signatures.

(iii) The strong agreement between the velocity vectors estimated from chlorophyll-a filaments and the geostrophic velocities from SWOT supports the ability of SWOT to capture submesoscale surface circulation associated with the eddy.

References:

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Pelland, N. A., C. C. Eriksen, and C. M. Lee, 2013: Subthermocline Eddies over the Washington Continental Slope as Observed by Seagliders. J. Phys. Oceanogr.