Implementation of the Optical Flow to Estimate the Propagation of Eddies in the South Atlantic Ocean

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1. Overview

The ocean is filled with mesoscale eddies that account for most of the oceanic kinetic energy. The importance of eddies in transporting properties and energy across the ocean basins has led to numerous efforts to track their motion. Here, we implement a *computer vision technique*—**the optical flow**—to map the pathways of mesoscale eddies in the South Atlantic Ocean (Fig. 1). The optical flow is applied to the pairs of consecutive sea surface height maps produced from a nearly 30-year-long satellite altimetry record. In contrast to other methods to estimate the eddy propagation velocity, the optical flow can reveal the temporal evolution of eddy motion, which is particularly useful in the regions of strong currents. We present the time-dependent estimates of the speed and direction of eddy propagation in the Eulerian frame of reference. In an excellent agreement with earlier studies, the obtained average pattern of eddy propagation reveals the interaction of eddies with the background flow and the bottom topography. We show that in the Antarctic Circumpolar Current (ACC), the variability of the eddy propagation velocity is correlated with the variability of the surface geostrophic velocity, demonstrating the robustness of the optical flow to detect the time-variable part of eddy motion.

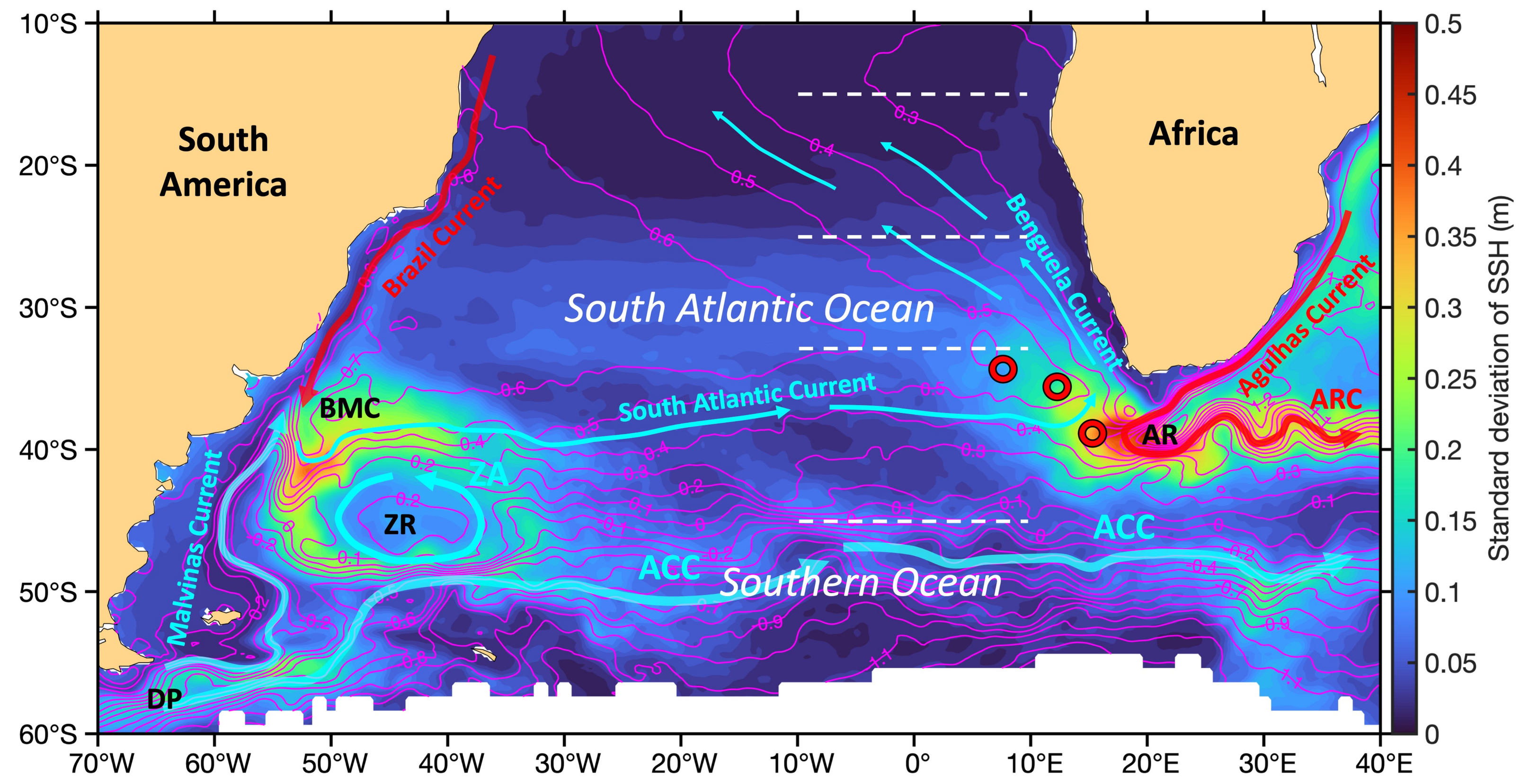


Figure 1. The map of the study region with the color shading showing the standard deviation of the mesoscale sea surface height variability and the contours representing the mean dynamic topography every 0.1 m. Abbreviations: ACC—the Antarctic Circumpolar Current, BMC—Brazil–Malvinas Confluence, ZR—Zapiola Rise, ZA—Zapiola Anticyclone, AR—Agulhas Retroflection, ARC—Agulhas Return Current, DP—Drake Passage.

2. The Optical Flow Method

Optical flow (OF) is a technique used to describe apparent motion of image objects between two consecutive frames caused by the movement of object or camera (e.g., Szeliski, 2022). Here, the OF is applied to the pairs of consecutive Sea Surface Height (SSH) anomaly maps (images), $\eta(x,y,t)$. It is assumed that the SSH change between consecutive maps (over Δt) is small: $\eta_2(x+\Delta x, y+\Delta y, t+\Delta t) \approx \eta_1(x,y,t)$ (Fig. 2a). Approximating η_2 with a Taylor series expansion up to the first-order terms and dividing by Δt yields the OF constraint equation: $\eta_x u + \eta_y v + \eta_t = 0$, where (η_x, η_y, η_t) is a vector of the zonal, meridional, and temporal derivatives of η, and u and v are the zonal and meridional propagation velocities (optical flow) of the SSH signal, respectively. The OF equation contains two unknowns (u and v) and, therefore, represents an under-constrained problem. To add additional constrains to solve for u and v, we apply the Lucas & Kanade, 1981 (LK) method, assuming that the OF within a small patch W ($n \times m$) around (x, y) is the same for all points in the neighborhood. This results in a linear system of equations:

$$\begin{bmatrix} \eta_x(1) & \eta_y(1) \\ \eta_x(2) & \eta_y(2) \\ \vdots & \vdots \\ \eta_x(nm) & \eta_y(nm) \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} -\eta_t(1) \\ -\eta_t(2) \\ \vdots \\ -\eta_t(nm) \end{bmatrix}.$$

The least-squares optimization applied to the over-constrained linear system of the form $A_{(nm\times2)}\mathbf{u} = B_{nm}$, where $\mathbf{u}(u,\ v)$ is the optical flow vector, yields the following solution: $\mathbf{u} = (A^T A)^{-1} A^T B$.

Because displacements Δx and Δy in dynamically active regions can be large (greater than a pixel), the LK method is applied recursively to multi-resolution Gaussian pyramidal representation of SSH maps: the OF is computed starting from the lowest-resolution level of the pyramid, and propagating the resultant flow to and updating it at the next higher-resolution level until the original map is reached (Fig. 2b). The number of levels in the pyramid is set to achieve a motion of roughly one-pixel at the lowest resolution (3 levels in this work).

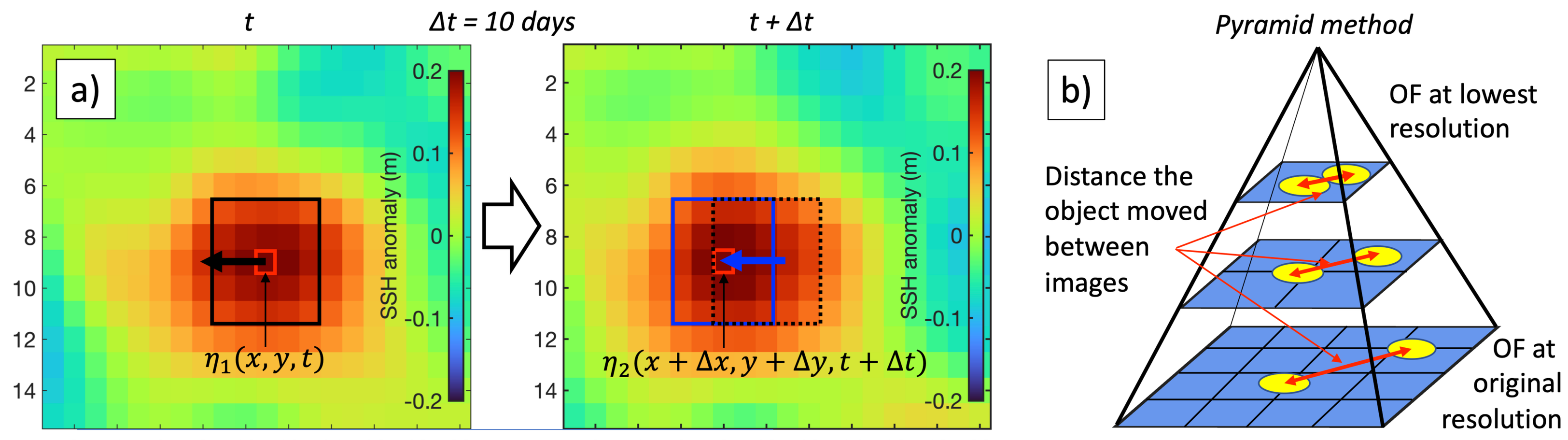


Figure 2. (a) An anticyclonic eddy propagating westward over the 10-day time interval (Δt). The black and blue rectangles show 5 × 5 pixel patches, over which the OF is assumed to be constant. During Δt, the patch shown by the black rectangle has moved in the direction shown by the black and blue arrows to the position outlined by the blue rectangle. The red rectangles outline individual pixels η_1 and η_2. (b) An illustration of the pyramid method with three layers. The optical flow (OF) is computed at each pyramid layer starting from the top layer at the lowest resolution down to the original image.

3. Results

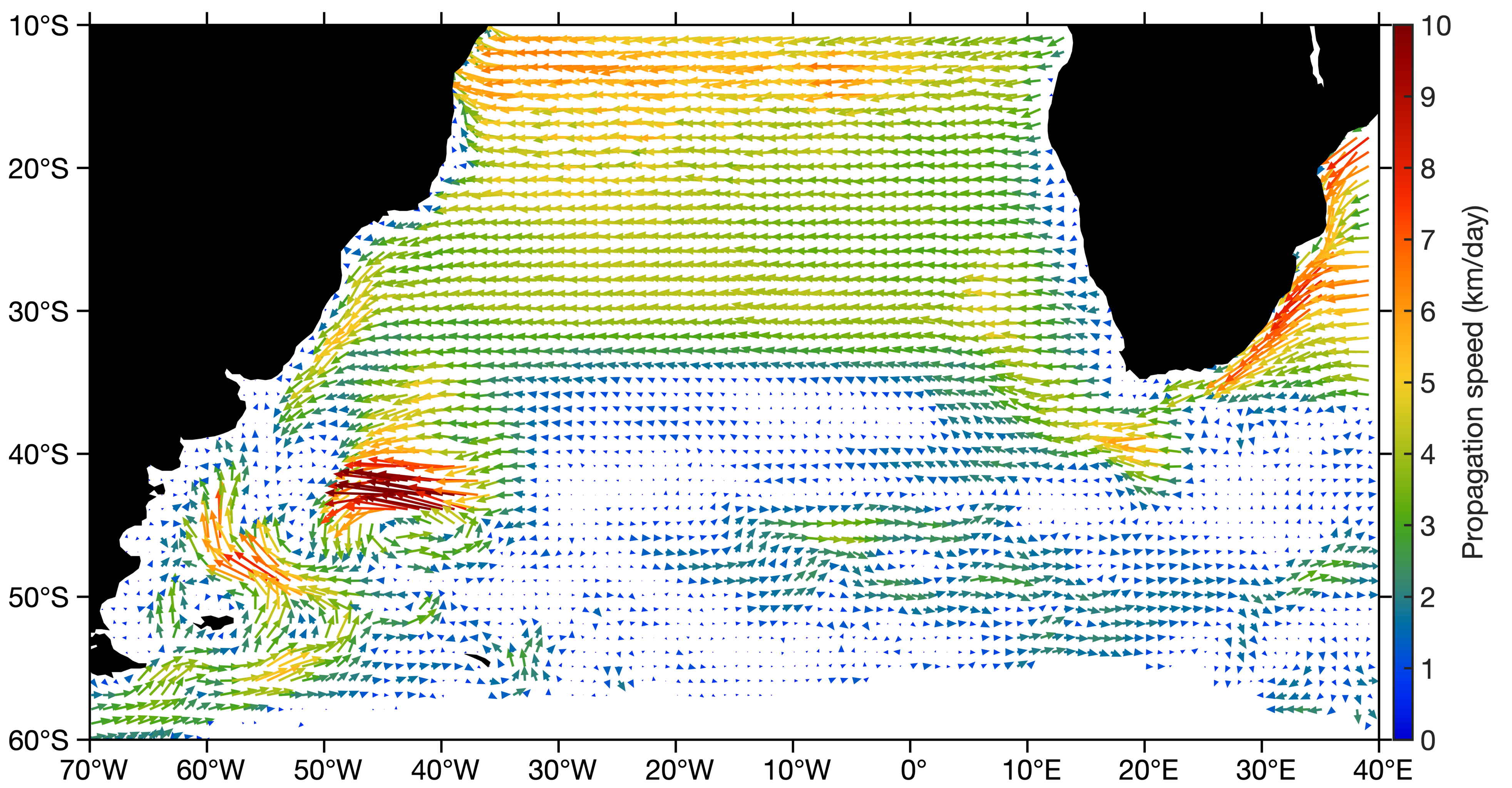


Figure 3. The time–mean vectors of the horizontal movement of SSH patterns associated with transient eddy variability in the Eulerian frame of reference. The color shading indicates the absolute speed in km per day. The strongest eddy propagation velocities are observed in Zapiola Anticyclone and along boundary currents.

- **In some periods the intensity of fronts is correlated with the eastward eddy propagation velocity (Fig. 6).**

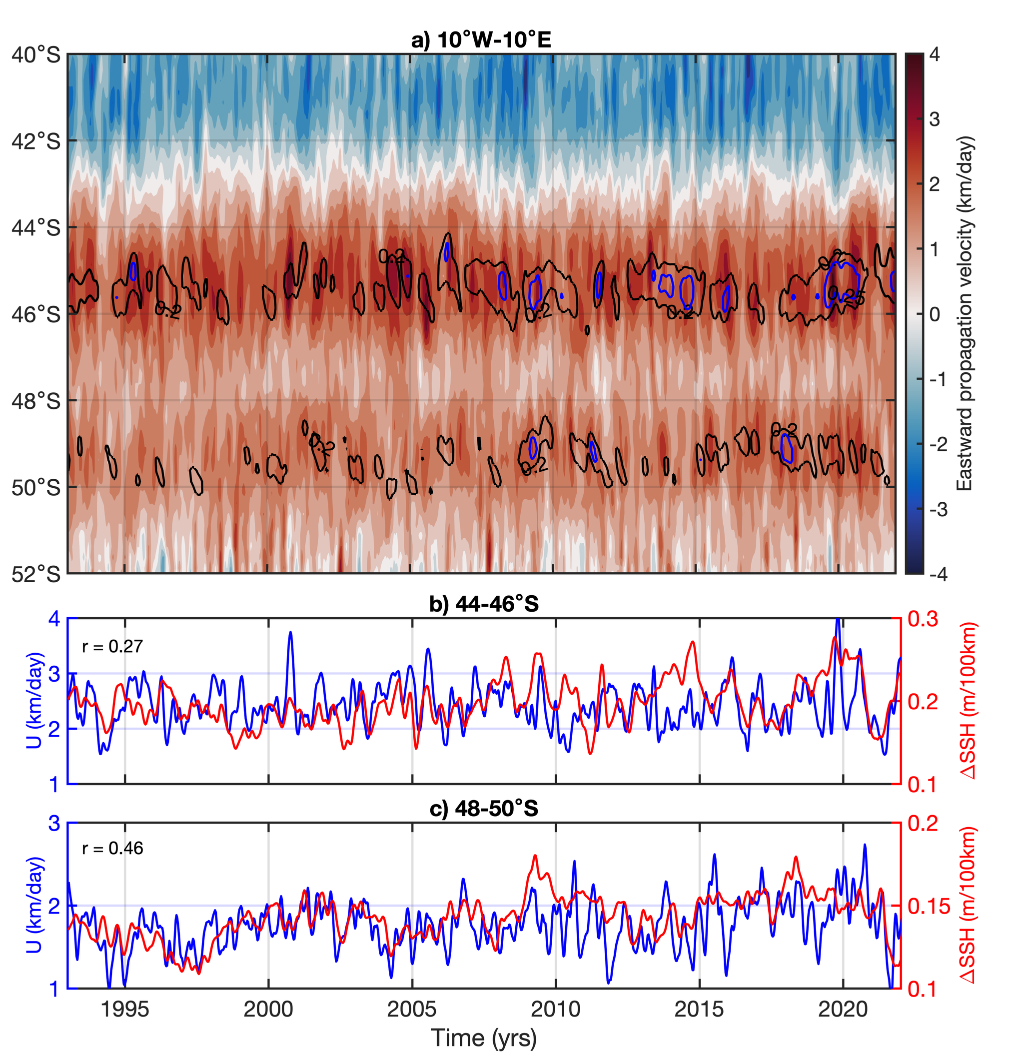


Figure 6. (a) The time–latitude diagram of (color shading) the zonal eddy propagation velocity (positive eastward) and (contours) the meridional SSH gradient averaged between 10°W–10°E. The black and blue contours show the meridional SSH gradients of 0.2 m per 100 km and 0.25 m per 100 km, respectively. (b,c) The time series of (blue) the zonal eddy propagation velocity and (red) the meridional SSH gradient averaged between 10°W–10°E in (b) 44–46°S (Sub-Antarctic Front) and (c) 48–50°S (Polar Front).

- **The ACC determines the eastward eddy propagation, which intensifies in the locations where the ACC is stronger (steeper cross-stream SSH gradients; Fig. 4).**

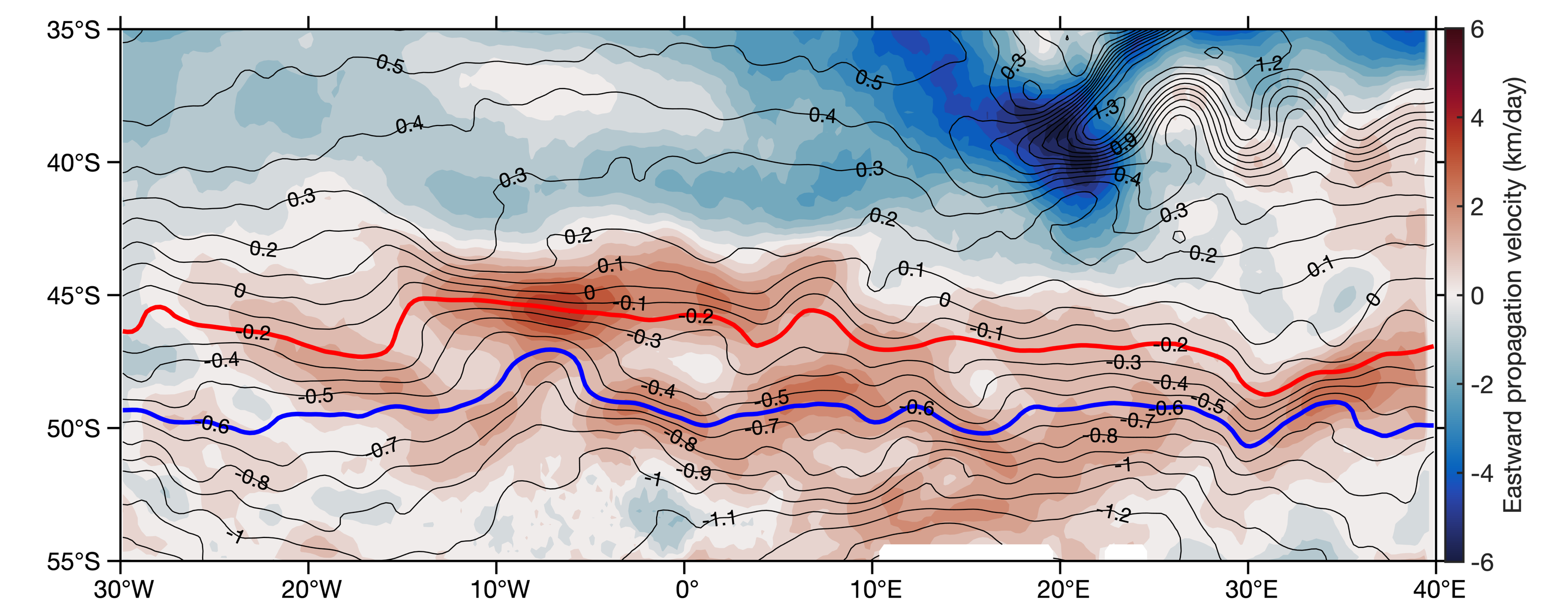
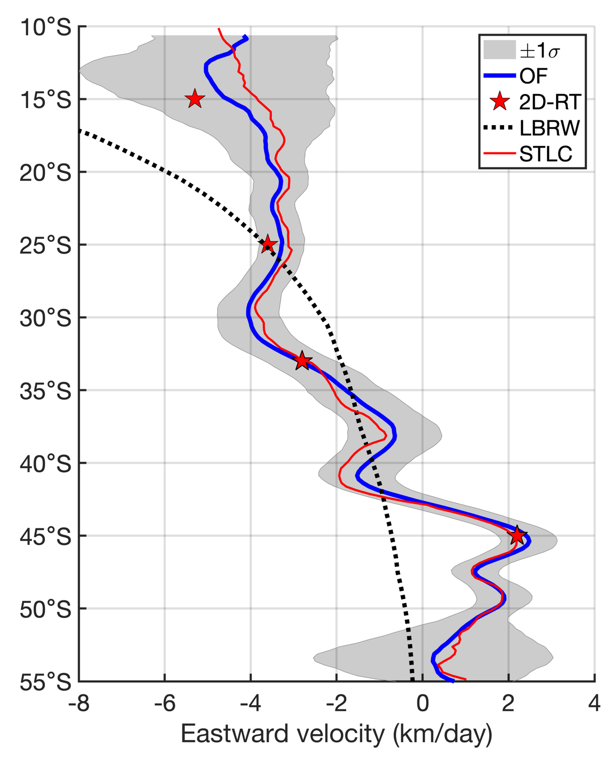


Figure 4. The Southern Ocean segment of the study domain: (color shading) zonal (eastward) eddy propagation velocity (km/day) and the time–mean SSH (contours). The ACC reverses the generally westward propagation of eddies. The intensification of the eastward eddy propagation happens in the locations where the ACC is stronger, associated with steeper SSH gradients and, consequently, stronger surface geostrophic flows. There are two bands of steep SSH gradients or fronts within this segment of the ACC: (i) the Sub-Antarctic Front (SAF) centered approximately along −0.2 m mean SSH contour (red contour) and (ii) the Polar Front (PF) centered at about −0.6 m mean SSH contour (blue contour).

- **Time-mean eddy propagation velocities obtained with the OF are in an excellent agreement with those obtained with other methods (Fig. 5).**

Figure 5. The time–mean zonal eddy propagation velocities estimated with the optical flow (OF) and averaged zonally between 10°W and 10°E (blue curve). The gray shading indicates the ±1 standard deviation. The red stars show the zonal propagation velocities of mesoscale eddies at 15°S, 25°S, 33°S, and 45°S estimated using the two-dimensional Radon transform of time–longitude (Hovmöller) diagrams at these latitudes for the zonal segments between 10°W–10°E (white dashed lines in Fig. 1). The red curve shows the zonal eddy propagation estimated with the space–time-lagged correlation analysis (STLC; Fu, 2006). The dotted black curve shows the zonally averaged (between 10°W and 10°E) propagation velocity of the first-mode long baroclinic Rossby waves (LBRW) computed using the Rossby radius of deformation from Chelton et al. (1998).



4. Conclusions

- The OF method provides a description of eddy motion in the Eulerian frame of reference, similar to the space–time-lagged correlation analysis of Fu (2006).
- The obtained pattern illustrates the latitude-dependent westward propagation of Rossby waves, as well as the interaction of eddies with ocean currents and with the bottom topography.
- An advantage of the OF over the other methods is that it allows the computation of the time-variable part of the eddy propagation velocity → the OF provides the potential to study changes in the mid-depth circulation in the regions where strong background flow significantly affects the propagation of eddies.

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