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Key Points:

- Satellite observations reveal a clearer later-period surface expression of the Northern Recirculation Gyre-related westward flow
- Mooring, float, and historical current records show the surface signal is consistent with subsurface westward flow
- Energy and momentum diagnostics show concurrent adjustment in the shear zone north of the Kuroshio Extension jet

Supporting Information:

Supporting Information may be found in the online version of this article.

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Surface Expression of the Kuroshio Extension Northern Recirculation Gyre

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Abstract The Northern Recirculation Gyre (NRG) of the Kuroshio Extension (KE) has traditionally been viewed as subsurface-intensified and difficult to identify at the sea surface. We combine a 2016–2025 subsurface mooring record, satellite altimetry, Argo trajectory-based velocities, and historical near-bottom velocities to reassess the sea-surface expression of the NRG-related westward flow and its relation to subsurface variability. At and near the mooring site, velocities show low-frequency covariability across sampled depths and a westward time-mean structure. In the altimetry-defined surface-expression region, westward surface flow becomes clearer and more frequent in the later record, while retaining strong interannual modulation. The clearer sea-surface expression is accompanied by local eddy–mean adjustment in the adjacent KE–NRG shear band, as indicated by barotropic-conversion and Reynolds-stress diagnostics.

Plain Language Summary The Kuroshio Extension is a major eastward current in the North Pacific and an important part of regional climate variability. North of this current lies the Northern Recirculation Gyre (NRG), which has traditionally been considered strongest below the surface and difficult to identify from surface observations. Using satellite-derived surface currents together with mooring and Argo observations, we show that the NRG-related westward flow is more readily detected near the sea surface, despite strong year-to-year variability. At a mooring site on the northern side of this region, recent velocity changes covary at low frequencies across the sampled depths, and the mean flow is westward through the observed depth range. The surface change coincides with changes in eddy–mean interaction in the adjacent shear zone.

1. Introduction

The Kuroshio Extension (KE) is an eastward jet flanked by the Southern and Northern Recirculation Gyres (SRG and NRG) (Hall, 1989; Mizuno & White, 1983; Qiu, 2002; Schmitz et al., 1987). These recirculation gyres are generally understood to be maintained by the convergence of eddy momentum fluxes associated with KE instability and meandering, and they influence the upper-ocean thermal structure, including Subtropical Mode Water formation (Greatbatch et al., 2010; Jayne et al., 1996; Qiu & Chen, 2005; Taguchi et al., 2007; Waterman & Hoskins, 2013). On decadal timescales, the KE alternates between stable and unstable states (Qiu & Chen, 2005, 2010; Taguchi et al., 2007). Recent analyses further indicate that the KE jet has become more stable and has shifted northward during the recent record (Kawakami et al., 2023; Qiu & Chen, 2026). During the stable phase, the KE jet strengthens and shifts northward, accompanied by an intensification of the SRG (Qiu & Chen, 2010).

Although the SRG and NRG are both linked to eddy momentum-flux convergence from the KE jet, they exhibit distinct vertical characteristics. The SRG is characterized by a robust westward return flow at the surface (Qiu, 1995), whereas the NRG has traditionally been identified as a subsurface-intensified recirculation with only weak surface expression. As a result, the westward flow on the northern side of the NRG is much less evident in surface observations than the SRG return flow, and subsurface measurements are often needed to resolve the closed NRG circulation structure (Qiu et al., 2008).

Despite its weak surface signature, the NRG is dynamically important for KE transport and water-mass exchange. It helps shape the Mixed Water Region by influencing the KE separation latitude and facilitating the confluence of subtropical and subarctic waters (Qiu et al., 2008). Based on an Ocean General Circulation Model for the Earth Simulator (OFES) hindcast that reproduced the float-inferred middepth NRG, Qiu et al. (2008) estimated that the NRG volume transport varies zonally from about 9.2 Sv across 145°E to a maximum of 26.4 Sv near 150°E, decreases to 20.9 Sv across 155°E, and becomes less than 5 Sv downstream of 160°E. By contrast, the larger 2.7–

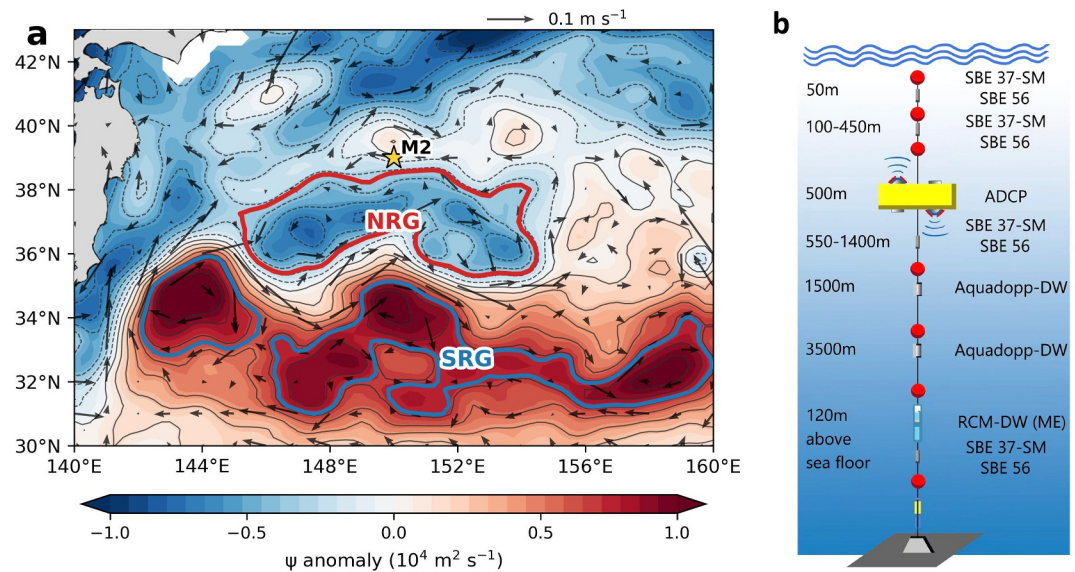


Figure 1. (a) Long-term mean near-1,000-dbar streamfunction anomaly derived from Gaussian-weighted objectively mapped Argo velocities for 2005–2022. Color shading and thin contours show the streamfunction anomaly, and black arrows show the corresponding near-1,000-dbar velocity vectors. The thick red contour denotes a representative subsurface NRG gyre boundary, defined by the selected closed negative streamfunction-anomaly contour enclosing the main northern recirculation cell ($\psi' = -0.315 \times 10^4 \text{ m}^2 \text{ s}^{-1}$). Thick blue contours denote selected closed positive streamfunction-anomaly contours ($\psi' = 0.625 \times 10^4$ – $0.725 \times 10^4 \text{ m}^2 \text{ s}^{-1}$) marking SRG-related subsurface recirculation features; these blue contours are shown for context and are not interpreted as a unique SRG boundary. The yellow star marks the M2 mooring site at 39°N, 150°E. (b) Schematic of the M2 subsurface mooring and instruments.

fold enhancement of local KE transport reported by Jayne et al. (2009) reflects the combined effect of the flanking NRG and SRG, increasing the local KE transport from about 42 Sv near Cape Ashizuri to about 114 Sv at the Kuroshio Extension System Study (KESS) array.

These earlier studies establish the dynamical importance of the NRG, but the continuous satellite altimetry record and recent subsurface observations now allow us to reassess how the NRG-related westward flow is expressed in sea-surface geostrophic velocities under the recent KE state. Relative to the weak surface signature emphasized in earlier analyses (Qiu et al., 2008), we examine whether recent observations reveal a clearer sea-surface expression of this westward flow. We also use the recent M2 mooring record to examine whether this surface expression is accompanied by low-frequency covariability across sampled depths and a time-mean westward velocity structure at and near the mooring site.

Previous work links the NRG to eddy momentum-flux convergence and basin-scale wind-forced KE variability (Qiu et al., 2008; Taguchi et al., 2010). We therefore examine whether the clearer sea-surface signal is accompanied by local eddy–mean adjustment under the recent KE state. We combine satellite altimetry with M2, Argo, and historical KESS observations to assess the surface expression and vertical consistency of the NRG-related westward flow, and apply local energy and momentum diagnostics in the adjacent shear band.

2. Data and Methods

2.1. Subsurface Mooring

We use data from the M2 subsurface mooring, deployed north of the Kuroshio Extension at 39°N, 150°E from April 2016 to April 2025 (Figure 1a), to characterize the local vertical structure of the westward flow near the northern side of the NRG-related westward-flow region. The mooring configuration consists of a main buoyancy package positioned at a depth of approximately 400–500 m (Figure 1b). Two 75-kHz Acoustic Doppler Current Profilers (ADCPs), one upward-looking and one downward-looking, are mounted on the main buoyancy package and together sample a vertical range of approximately 1,000 m. Below the main buoyancy package, three single-point current meters (Nortek Aquadopp DW or Aanderaa Seaguard RCM) are installed at nominal depths of

1,500, 3,500, and 5,500 m. The ADCPs are configured with a sampling interval of 1 hr and a vertical bin size of 16 m. The hourly velocity records are first averaged to daily means to reduce tidal and other high-frequency variability. For the low-frequency comparisons, the daily records are subsequently averaged to monthly means and smoothed with a 6-month Hann-window low-pass filter.

2.2. Satellite Data

To characterize the surface geostrophic circulation and compare it with the subsurface estimates, we use surface absolute geostrophic velocities derived from multi-satellite altimetry products produced by the Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO) (Ducet et al., 2000). The product is provided on a regular $0.25^\circ \times 0.25^\circ$ grid at daily temporal resolution. The record analyzed here spans January 1993 to April 2025. For the surface streamfunction maps, AVISO absolute dynamic topography, η , is converted to an approximate geostrophic streamfunction, $\psi_s = g\eta/f$, where g is gravitational acceleration and f is the Coriolis parameter. The spatial mean over the mapping domain is then removed to obtain the streamfunction anomaly used for visualization.

2.3. Argo-Based Velocity

Subsurface velocities at the parking depth are obtained from the Scripps Argo Trajectory-Based Velocity Product (Zilberman et al., 2023). The product provides absolute velocities derived from Argo float displacements at the nominal parking depth of 1,000 dbar. For the large-scale mapping, we use all available data within 140°E – 160°E and 30°N – 43°N during 2005–2022. The mapping procedure uses a distance-weighted Gaussian function,

$$C_r = \exp\left[-\frac{x^2 + y^2}{R^2}\right], \quad (1)$$

where x and y are the zonal and meridional distances between each Argo observation and the target grid point, respectively, and $R = 100$ km is the spatial decorrelation scale for this region (Qiu et al., 2008).

For Figure 1a, the streamfunction is obtained from the long-term mean mapped velocity field by solving a least squares problem for ψ on the valid mapped grid points, using finite-difference constraints from $u = -\partial\psi/\partial y$ and $v = \partial\psi/\partial x$. The arbitrary additive constant is removed by subtracting the domain mean, yielding the streamfunction anomaly, ψ' , which is used to depict the regional subsurface recirculation structure.

For the near-M2 vertical-structure comparison, near-1,000-dbar Argo trajectory velocities from 148°E – 152°E and 37°N – 41°N are mapped to a 0.25° grid over 149.50°E – 150.50°E and 38.50°N – 39.50°N , centered on M2. The mapped zonal velocities are averaged over this near-M2 target box for 3-month windows when samples are available. This procedure yields 17 finite estimates during the mooring period and is used only as an auxiliary, irregularly sampled near-1,000-dbar comparison.

For the Argo–AVISO collocation analysis, near-1,000-dbar Argo trajectory-based velocities are selected within the surface-expression box (146.50°E – 148.50°E , 37.25°N – 38.00°N ; Figure S1 in Supporting Information S1). Daily AVISO surface geostrophic velocities are interpolated to the corresponding Argo observation times and locations, and the collocated velocities are then averaged by month when Argo samples are available. This procedure yields 44 Argo velocity estimates across 28 sampled months. Because sampling in this small box is sparse and irregular, the collocation is used as a descriptive subsurface comparison rather than as a primary low-pass-filtered time-series significance test.

2.4. Historical KESS Near-Bottom Velocity

As an independent historical deep-current comparison, we use near-bottom zonal velocities from the KESS Current- and Pressure-recording Inverted Echo Sounder (CPIES) observations during 2004–2006 at the deep NRG core identified by Jayne et al. (2009) (147.87°E , 37.81°N). Daily AVISO surface geostrophic zonal velocities are collocated to the CPIES site and compared with the near-bottom velocities after applying a 30-day low-pass filter to both records.

2.5. Barotropic Energy Conversion and Momentum Diagnostic

To diagnose the local kinetic-energy exchange term between the mean flow and the eddy field, we calculate the surface barotropic conversion rate, denoted by C_{BT} , from AVISO-derived geostrophic velocities. The daily velocity field is decomposed into a low-frequency mean component ($\bar{u}$, $\bar{v}$) and a transient eddy component (u' , v'), such that $u = \bar{u} + u'$ and $v = \bar{v} + v'$. The low-frequency mean is obtained using a 300-day low-pass filter, and the transient eddies are defined as deviations from this mean state. After forming the eddy products, the same 300-day low-pass filter is applied to obtain the Reynolds stresses $\overline{u'u'}$, $\overline{u'v'}$, and $\overline{v'v'}$. The barotropic conversion rate is defined as

$$C_{BT} = - \left[\overline{u'u'} \frac{\partial \bar{u}}{\partial x} + \overline{u'v'} \left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right) + \overline{v'v'} \frac{\partial \bar{v}}{\partial y} \right]. \quad (2)$$

Spatial derivatives are calculated on the AVISO grid using metric distances. We use the same compact box in the adjacent KE–NRG shear band (147.5°E–151°E, 36.5°N–37.5°N) for both diagnostics. The box was selected from the diagnosed spatial patterns and is distinct from the NRG surface-expression region; its box-mean statistics and p values are treated as nominal and descriptive. Under this sign convention, positive C_{BT} corresponds to the mean-to-eddy sign of the local barotropic-conversion term, whereas negative C_{BT} corresponds to the eddy-to-mean sign. Because finite-region kinetic-energy budgets also include nonlocal energy fluxes, pressure work, advection, and boundary terms (Chen et al., 2014, 2016; Matsuta & Masumoto, 2021; Murakami, 2011), C_{BT} is used as an indicator of local eddy–mean kinetic-energy exchange, not as a closed local mean-energy budget.

As a complementary momentum-based diagnostic, we calculate the full horizontal Reynolds-stress convergence relevant to the zonal momentum equation,

$$F_u^{\text{eddy}} = - \frac{\partial \overline{u'u'}}{\partial x} - \frac{\partial \overline{u'v'}}{\partial y}. \quad (3)$$

Negative values are consistent with a westward eddy-induced zonal momentum tendency in this surface-altimetry-based diagnostic. We show its horizontal change and an area-mean time series over the same 147.5°E–151°E, 36.5°N–37.5°N box used for C_{BT} . Because the complete zonal momentum balance also includes mean advection, pressure-gradient, Coriolis, and other terms, F_u^{eddy} represents one contribution to the balance rather than a closed momentum budget.

3. Results

At M2, near the northern side of the NRG-related westward-flow region, the 2016–2025 mooring record shows low-frequency covariability across sampled depths and a westward time-mean flow (Figure 2). The filtered AVISO surface geostrophic zonal velocity at M2 is correlated with the M2 upper-200-m velocity ($r = 0.96$, $p_{\text{eff}} < 0.001$) and with the M2 1,500-m velocity ($r = 0.79$, $p_{\text{eff}} < 0.001$; Table S1 in Supporting Information S1). Within the M2 mooring record, the correlations are $r = 0.79$ between the upper-200-m and 1,500-m velocities, $r = 0.64$ between the 1,500-m and 3,500-m velocities, and $r = 0.90$ between the 3,500-m and 5,500-m velocities; all remain significant after the effective-degrees-of-freedom (effective-DOF) correction (Table S1 in Supporting Information S1).

The separate time-mean profile (Figure 2c) shows westward zonal velocity in the AVISO surface estimate, throughout the reliable M2 ADCP range, at the deep current-meter levels, and in the auxiliary near-1,000-dbar Argo estimate. Together with the filtered correlations, it provides local evidence for westward flow across sampled depths at and near M2 during the mooring period.

The historical KESS near-bottom observations provide an additional deep-current comparison during 2004–2006. At the deep NRG core identified by Jayne et al. (2009) (147.87°E, 37.81°N), the 30-day low-pass-filtered AVISO surface geostrophic zonal velocity is significantly correlated with the near-bottom zonal velocity ($r = 0.50$, $p_{\text{eff}} < 0.01$; Figure S2 and Table S1 in Supporting Information S1). This period-specific comparison indicates that the surface and near-bottom zonal velocities covary at this site during the KESS period.

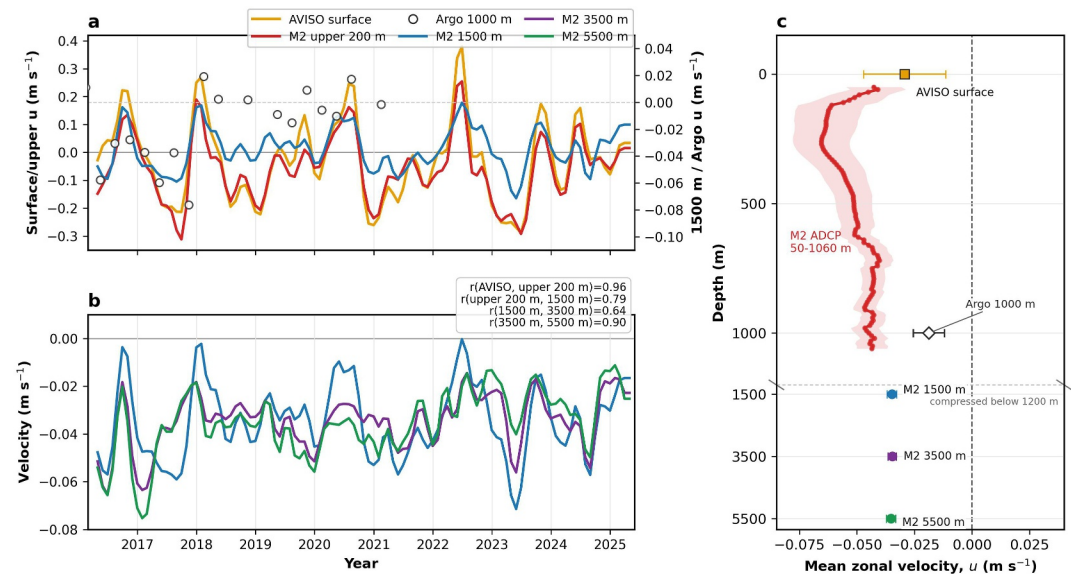


Figure 2. Vertical structure of the westward flow observed at and near M2, near the northern side of the NRG-related westward-flow region. (a) AVISO surface geostrophic zonal velocity at M2, M2 upper-200-m velocity, M2 1,500-m velocity, and auxiliary Argo trajectory-based velocity near 1,000 dbar. The M2 upper-200-m velocity is defined as the ADCP average over 50–200 m. (b) M2 zonal velocities at 1,500, 3,500, and 5,500 m. The continuous time-series curves in (a) and (b) are monthly averaged and smoothed with the same 6-month Hann low-pass filter; the reported correlations quantify low-frequency covariability across sampled depths, with effective-degrees-of-freedom (effective-DOF) tests summarized in Table S1 in Supporting Information S1. Negative velocity denotes westward flow. (c) Mean zonal velocity versus depth at and near M2, shown as the separate diagnostic for the vertical consistency of the time-mean westward flow. The red profile uses the reliable M2 ADCP range from 50 to 1,060 m, with 61–109 valid monthly means depending on depth. Its light red shading shows one standard error of the mean at each depth. Horizontal error bars show the same uncertainty measure for the discrete estimates: the AVISO surface and M2 current-meter means use 109 monthly means, whereas the Argo near-1,000-dbar mean uses 17 available 3-month-window estimates during the M2 period. The depth coordinate is compressed below 1,200 m for visual clarity; tick labels show the true depths.

We then use the longer AVISO record to extend these period-specific in situ comparisons to the broader surface expression of the NRG-related westward flow. The 1966–2025/04 mean AVISO surface geostrophic streamfunction anomaly, derived from absolute dynamic topography, shows a closed low-value streamfunction-anomaly feature north of the KE and closed high-value streamfunction-anomaly features associated with the SRG south of the KE (Figure 3a). The M2 site lies near the northern side of the broader NRG-related westward-flow region, while the strongest and most coherent AVISO surface westward-flow signal associated with this region is captured by the surface-expression box identified in Figure S1 in Supporting Information S1. We therefore define a surface-expression index as the area-averaged AVISO surface geostrophic zonal velocity over this box (146.50°E–148.50°E, 37.25°N–38.00°N), corresponding to the dashed rectangle in Figure 3a. This index is used only as a surface-expression metric, not as a full-depth or gyre-wide measure of NRG strength.

Within the surface-expression box, sparse Argo–AVISO collocations provide an additional subsurface consistency check. The near-1,000-dbar Argo trajectory velocities and the collocated AVISO surface geostrophic velocities are both westward on average during Argo-sampled months (Figure S3 in Supporting Information S1). The pointwise sign agreement is 81.8%, and the monthly collocated velocities are positively correlated ($r = 0.83$); because the samples are sparse and irregular, these values are reported as descriptive consistency measures. Together, the M2, KESS, and Argo comparisons provide period-specific upper-ocean, subsurface, and deep consistency checks for the AVISO-derived surface westward-flow signal.

The surface-expression index retains strong interannual modulation but shifts toward a more westward low-frequency mean state in the later record (Figure 3b). The mean of the monthly box-mean zonal velocity changes from 0.013 m s^{-1} during 1993–2003 to -0.045 m s^{-1} during 2004–2015 and -0.120 m s^{-1} during 2016–2025/04. Calculated from the same surface-expression box, the mean fraction of grid area with westward flow increases from 53.4% to 68.7% and 76.4%, and the fraction of months with westward box-mean flow

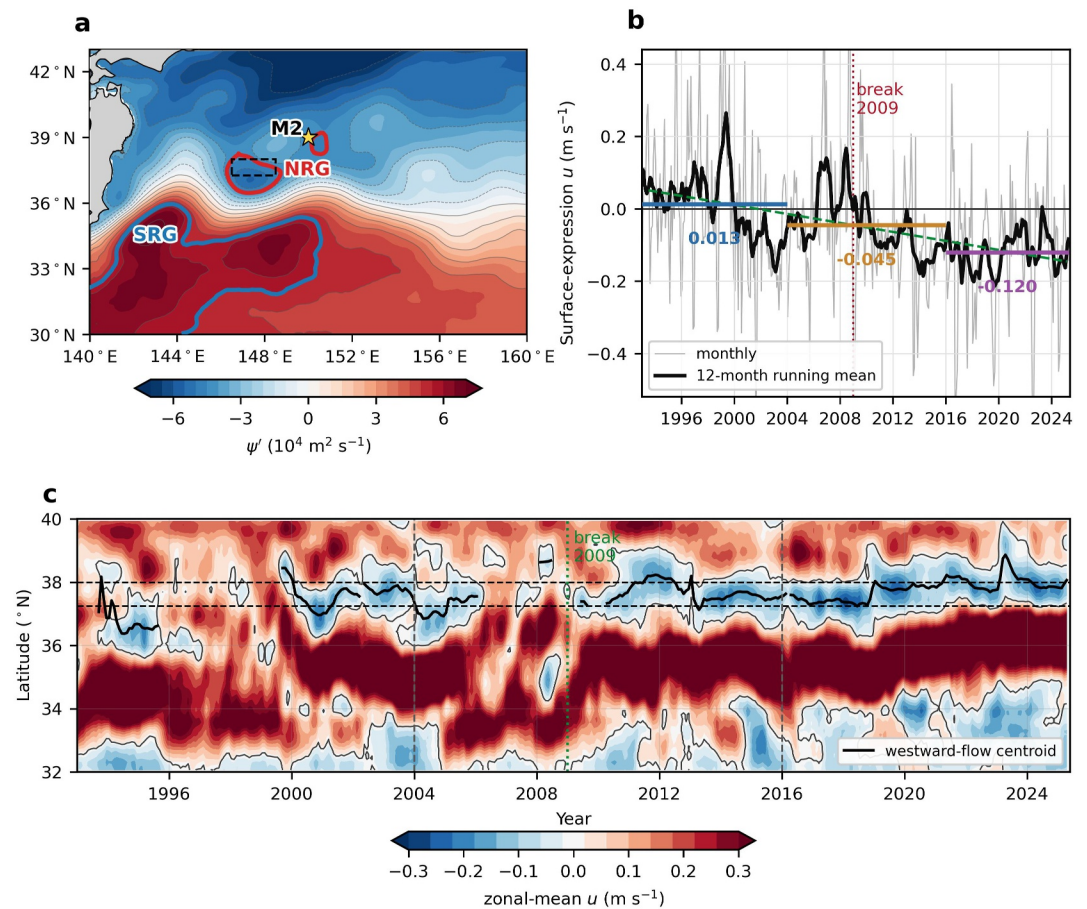


Figure 3. AVISO-derived surface expression of the NRG-related westward flow. (a) Mean surface geostrophic streamfunction anomaly during 2016–2025/04, derived from AVISO absolute dynamic topography. Thick red outlines mark the closed low-value streamfunction-anomaly feature north of the KE, thick blue outlines mark closed high-value streamfunction-anomaly features associated with the SRG south of the KE, the yellow star marks M2, and the dashed rectangle marks the surface-expression box. (b) Surface-expression index, defined as the area-averaged AVISO surface geostrophic zonal velocity over 146.50°E–148.50°E, 37.25°N–38.00°N. Gray and black curves show monthly values and the 12-month running mean, respectively; colored horizontal lines show stage means, and the green dashed line shows the least squares linear trend fitted to complete-year annual means for 1993–2024. The red dotted line marks the 2009 diagnostic breakpoint selected by minimizing the residual sum of squares in the two-regime mean model. The breakpoint year is treated as the first year of the later regime. (c) Hovmöller diagram of AVISO zonal velocity averaged over 146.50°E–148.50°E and smoothed with a 12-month running mean. Negative values denote westward flow. The black curve shows the westward-flow-weighted center latitude, computed from negative zonal velocities only using westward speed as the weight. Horizontal dashed lines mark the latitude limits of the surface-expression box, gray dashed vertical lines mark the composite-stage boundaries, and the green dotted line marks the 2009 diagnostic breakpoint.

increases from 49.2% to 72.9% and 78.6%, respectively. The three-stage composites provide the corresponding spatial view of these stage statistics (Figure S4 in Supporting Information S1), showing a progression from weak and spatially fragmented zonal flow during 1993–2003 to more frequent and stronger westward flow during 2004–2015 and 2016–2025/04.

We quantify the low-frequency shift by fitting the complete-year annual surface-expression index for 1993–2024 with a single-breakpoint, two-regime mean model. Candidate break years are required to leave at least five complete annual means on each side, and the selected break minimizes the residual sum of squares. This diagnostic selects 2009 as the first year of the later regime, with the annual mean changing from 0.0148 m s^{-1} before the break to -0.108 m s^{-1} after the break. The 2004 and 2016 boundaries are used only for descriptive composites, whereas the 2009 diagnostic breakpoint is used for the before/after comparisons below. We do not

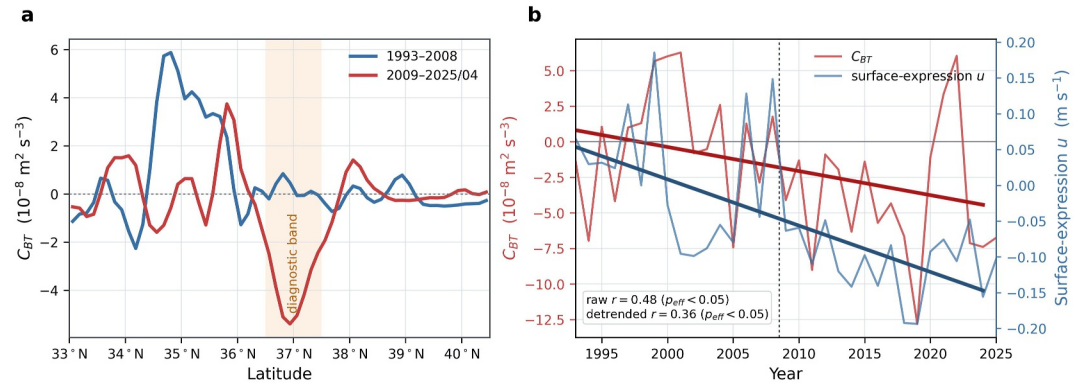


Figure 4. Local barotropic-conversion diagnostic for the common KE–NRG shear-band box (147.5°E – 151°E , 36.5°N – 37.5°N). (a) Latitude profiles of C_{BT} averaged over 147.5°E – 151°E for 1993–2008 and 2009–2025/04. The shaded band marks the latitude range used for the local C_{BT} index. (b) Area-mean annual C_{BT} in the common box and the surface-expression index; raw and detrended correlations are calculated from complete annual indices through 2024 using the effective-DOF correction. The associated p values are nominal and interpreted descriptively. The vertical dotted line marks the 2009 diagnostic breakpoint.

interpret the exact year as a sharply defined dynamical transition; the key result is the later-period shift toward more frequent westward flow.

The Hovmöller diagram shows the latitude–time structure underlying the surface-expression index (Figure 3c). Westward flow remains intermittent and meridionally variable throughout the record. However, after the 2009 diagnostic breakpoint, negative zonal velocities occupy the 37.25°N – 38.00°N surface-expression latitude band for longer intervals. Thus, the shift of the index toward more westward values reflects a more sustained occupation of the NRG-related surface westward-flow band, not merely isolated monthly anomalies within the box.

To examine whether the surface-expression change is accompanied by local eddy–mean adjustment, we next evaluate C_{BT} in the adjacent KE–NRG shear band. Figure 4a compares the early- and late-period C_{BT} latitude profiles averaged over 147.5°E – 151°E ; the shaded band marks the latitude range of the local diagnostic box. The box partly overlaps the southern edge of the surface-expression box but represents the adjacent shear band rather than the NRG surface-expression region. This fixed-band calculation does not identify the cause of the change.

The local C_{BT} diagnostic shows a shift toward the eddy-to-mean sign of the local conversion term in the KE–NRG shear band (Figure 4). The period-mean C_{BT} changes from $0.18 \times 10^{-8} \text{ m}^2 \text{ s}^{-3}$ during 1993–2008 to $-3.97 \times 10^{-8} \text{ m}^2 \text{ s}^{-3}$ during 2009–2025/04, a later-minus-earlier change of $-4.15 \times 10^{-8} \text{ m}^2 \text{ s}^{-3}$ (nominal $p = 0.010$). For complete-year annual means over 1993–2024, the C_{BT} trend is $-16.92 \times 10^{-9} \text{ m}^2 \text{ s}^{-3}$ per decade (nominal $p_{\text{eff}} = 0.118$). Over the same record, the surface-expression index trends westward at -0.065 m s^{-1} per decade ($p_{\text{eff}} < 0.001$). The local C_{BT} and surface-expression indices covary for the raw annual indices ($r = 0.48$, nominal $p_{\text{eff}} < 0.05$) and after linear detrending ($r = 0.36$, nominal $p_{\text{eff}} < 0.05$).

To assess the contributions to the local C_{BT} change, we evaluate its four deformation terms. The later-minus-earlier changes in $-\overline{u'u'} \partial \bar{u} / \partial x$, $-\overline{u'v'} \partial \bar{u} / \partial y$, $-\overline{u'v'} \partial \bar{v} / \partial x$, and $-\overline{v'v'} \partial \bar{v} / \partial y$ are $(-9.41, +0.83, -2.00, +6.44) \times 10^{-8} \text{ m}^2 \text{ s}^{-3}$, respectively.

The full Reynolds-stress-convergence diagnostic shows the momentum change in the same compact shear-band box (Figure S5 in Supporting Information S1). Its horizontal map contains neighboring positive and negative changes, indicating pronounced zonal nonuniformity; the box-mean series summarizes the change within the selected shear band. Within the common box, the period mean of $-\partial \overline{u'u'} / \partial x - \partial \overline{u'v'} / \partial y$ changes from $+0.86 \times 10^{-7}$ to $-1.35 \times 10^{-7} \text{ m s}^{-2}$ between 1993–2008 and 2009–2025/04, giving a later-minus-earlier change of $-2.21 \times 10^{-7} \text{ m s}^{-2}$ (nominal $p = 0.014$). The complete-year trend is $-1.28 \times 10^{-7} \text{ m s}^{-2}$ per decade (nominal $p_{\text{eff}} = 0.026$). The corresponding later-minus-earlier changes in the zonal and meridional components are $-1.64 \times 10^{-7} \text{ m s}^{-2}$ (nominal $p = 0.025$) and $-0.57 \times 10^{-7} \text{ m s}^{-2}$ (nominal $p = 0.316$), respectively.

4. Summary and Discussion

This study combines M2 mooring observations, satellite altimetry, Argo trajectory-based velocities, and historical KESS near-bottom observations to reassess how the Kuroshio Extension (KE) Northern Recirculation Gyre (NRG)-related westward flow is expressed in sea-surface geostrophic velocities and how this altimetry-derived surface signal relates to available in situ observations during sampled periods. At M2, near the northern side of the NRG-related westward-flow region, the 2016–2025 mooring record shows low-frequency covariability across sampled depths and a westward time-mean velocity structure. Historical KESS near-bottom observations and sparse Argo–AVISO collocations provide additional period-specific consistency checks. Together, these in situ comparisons support the interpretation of the AVISO-derived surface signal as a surface expression of the NRG-related westward flow, while not implying a continuous full-depth reconstruction or a gyre-wide measure of NRG strength.

The long-term AVISO record indicates that the NRG-related westward flow has become a more recognizable feature of the sea-surface geostrophic circulation in recent decades, while retaining the pronounced interannual variability characteristic of the KE system. This change is best interpreted as a low-frequency shift toward a more westward mean state and more frequent westward flow, with more sustained occupation of the NRG-related latitude band, rather than as the continuous presence of a steady surface current. The complete-year annual single-breakpoint diagnostic selects 2009 as the first year of the later surface-expression regime, but the exact year is used as a diagnostic breakpoint rather than as a sharply defined dynamical transition.

Both dynamical diagnostics show changes within the adjacent KE–NRG shear band. The local C_{BT} shifts toward the eddy-to-mean sign of the conversion term, and the full Reynolds-stress convergence becomes more negative within the same compact box, corresponding to a more westward eddy-induced zonal momentum tendency. The mapped changes are spatially heterogeneous, and neither calculation closes the full energy or momentum budget. We therefore do not infer a local causal mechanism for the NRG surface-expression change.

These changes are broadly consistent with previous studies linking the KE state to NRG-related recirculation (Kawakami et al., 2023; Qiu et al., 2008; Waterman & Jayne, 2011). The observations show a clearer recent surface expression of the NRG-related westward flow accompanied by local changes in the adjacent shear band, but do not demonstrate gyre-wide acceleration or strengthening of the NRG circulation.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The in situ mooring data from the Kuroshio Extension Mooring System (KEMS) used in this study are available at <https://cn-kems.net/Data/data.zip.001>; <https://cn-kems.net/Data/data.zip.002>. The KESS CRIES near-bottom current data used for Figure S2 in Supporting Information S1 are archived by NOAA National Centers for Environmental Information as NODC/NCEI Accession 0073269 (Tracey & University of Rhode Island, Graduate School of Oceanography, 2011). The satellite altimetry data (SEALEVEL_GLO_PHY_L4_MY_008_047; European Union-Copernicus Marine Service, 2021) are produced by AVISO/Copernicus Marine Service. The Argo trajectory-based velocity product is available through the UC San Diego Library Digital Collections at Zilberman et al. (2022). The code used in this study is preserved at Zenodo (haihuo, 2026).

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