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Xiang Wan

wan759189627@163.com

Dalian Naval Academy

Lei Zhang

Dalian Naval Academy

Maolin Li

Dalian Naval Academy

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Multiscale Spatiotemporal Variability Characteristics and Dynamical Control Mechanisms of the Kuroshio Front in the Northwest Pacific

Xiang Wan ^{1,*}, Lei Zhang ² and Maolin Li ³

¹ Dalian Naval Academy, 667 Jiefang Road, Zhongshan District, Dalian City, Liaoning Province, China; wan759189627@163.com

² Dalian Naval Academy, 667 Jiefang Road, Zhongshan District, Dalian City, Liaoning Province, China; 333_stone@sina.com

³ Dalian Naval Academy, 667 Jiefang Road, Zhongshan District, Dalian City, Liaoning Province, China; 13374013@qq.com

* Correspondence: wan759189627@163.com;

Abstract: As the western boundary current of the North Pacific Subtropical Gyre, the Kuroshio front exhibits pronounced multiscale variability that influences regional circulation and marginal-sea ecology. Using eddy-resolving reanalysis and satellite data (2002–2024), we quantified its spatiotemporal characteristics and dynamical mechanisms from the Luzon Strait to the East China Sea slope. Variance decomposition reveals marked spatial heterogeneity: mesoscale eddies dominate Kuroshio-core flow variations (>70%), seasonal cycles prevail on shallow shelves (>60%), and interannual–decadal signals govern large-scale path adjustments. The leading low-frequency mode shows a meridional dipole (50.4% variance) correlated with ENSO and PDO. Nonuniform sea-level rise appears to have strengthened the cross-stream geostrophic gradient, intensifying the Kuroshio east of Taiwan while reducing Luzon Strait intrusion, though this interpretation remains correlative. Potential vorticity analysis suggests upper-ocean thickness adjustments as a plausible constraint on Loop–Leap path transitions ($R = -0.64$, $p < 0.01$). Barotropic and baroclinic instabilities appear to drive a forward energy cascade to eddy kinetic energy, while frontal–Ekman dynamics jointly modulate seasonal frontal reversals. These findings provide a framework for understanding multiscale variability in northwestern Pacific western boundary currents.

Keywords: Kuroshio front zone; multiscale variability; dynamical mechanisms; ENSO modulation; eddy–current interaction

1. Introduction

As the main western boundary current of the North Pacific subtropical circulation system, the Kuroshio is a key marine conduit for the transport of heat, water vapor, and nutrients from low to mid-to-high latitudes. Its multiscale spatiotemporal variability directly influences ocean circulation, air–sea interaction processes, and regional climate modes in the northwestern Pacific, and it affects water mass structure, biogeochemical cycles, and ecosystem evolution in marginal seas such as the East China Sea and the South China Sea [1]. Moreover, the segment from the Luzon Strait (hereinafter “the Strait”) to the East China Sea continental slope is the most active, critical segment of the Kuroshio system’s dynamic processes. It acts as a hub for the exchange of water masses and energy between the western Pacific and marginal seas [2], and it is a region where mesoscale vortices and frontal instability processes frequently occur. Furthermore, patterns of multiscale dynamic variability and their regulatory mechanisms have long been salient scientific topics in the physical oceanography and marine climatology fields [3, 4].

Observations and simulation studies over the past few decades have shown that large-scale Kuroshio system variations are closely tied to the North Pacific Climate Oscillation, while the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) drive Sverdrup transport anomalies in the subtropical circulation by modulating the spatial structure of the wind stress vorticity field in the North Pacific. Through baroclinic Rossby waves, these climate signals are carried across the ocean basin to the western boundary, thus triggering interannual to decadal adjustments in the Kuroshio’s transport intensity and path morphology [5, 6]. Although this macroscopic phenomenon has been validated, existing studies have largely focused on the long-term variability characteristics of the Kuroshio across its entire basin. There remains a lack of systematic quantitative analysis on the low-frequency co-evolution patterns of the Kuroshio front in the Strait–East China Sea slope section, especially concerning the long-term changes in the cross-current geostrophic gradient of the Kuroshio main axis and its modulating effects on the intrusion process in the Strait against the background of rapid global sea-level rise in the 21st century. As the sole deep-water passage connecting the Western Pacific and the South China Sea, the Kuroshio intrusion into the Strait represents a core process for the exchange of matter and energy between the two major ocean basins. Previous studies have identified two typical modes of Kuroshio intrusion, the “Loop Path” type of strong intrusion and the “Leap Path” type of weak intrusion, and have presented extensive analyses on influencing factors such as topographic limitations, monsoon forcing, and mesoscale vortex modulation [7–10]. However, there remains no systematic, closed-loop theoretical explanation for the main dynamical limitations governing abrupt changes in Kuroshio intrusion paths, especially those regarding the coupling mechanism between oceanic remote forcing and local fluid dynamics—namely, the complete dynamical process by which large-scale baroclinic signals spur the reorganization of flow field vorticity and path transitions through modifications in upper thermocline thickness, aided by the conservation of potential vorticity (PV). Moreover, the Kuroshio front, which hosts these multiscale dynamic processes, acts as a zone of strong temperature and density gradients created by the

interaction between the strong westerly boundary current and surrounding waters. The front is an energy hotspot for mesoscale and sub-mesoscale ocean processes. Although energy analyses based on a Reynolds-averaged framework have shown that the mean flow–vortex interaction driven by barotropic and baroclinic instability processes [11–13] is the main source of vortex energy in the Kuroshio front zone and the driving mechanism for high-frequency variations in the local flow field [14], most existing studies have analyzed the individual effects of barotropic or baroclinic instability in isolation. However, there remains a lack of systematic quantitative assessments across the entire region on the synergistic effects of these two processes in different segments of the Kuroshio front zone, as well as the spatial heterogeneity of the contributions of components at various time scales to the total variance. Furthermore, in-depth mechanistic analyses have yet to be conducted on the regulatory mechanisms of multiscale dynamic processes in the Kuroshio front zone on ecological habitats [15], particularly the superposition and antagonistic effects of frontal secondary circulation and wind-driven Ekman suction processes on the seasonal timescale.

To address these issues, this study systematically analyzed the climatologically averaged structure and multiscale spatiotemporal variability of the Kuroshio front zone in the northwestern Pacific, from the Strait to the East China Sea continental slope, based on a vortex-resolution global ocean reanalysis dataset (2002–2024) and high-resolution satellite sea surface temperature (SST) observations. Moreover, using Reynolds-like decomposition filtering techniques, we separated multiscale signals in the flow field variations and quantitatively determined the contributions of seasonal cycles, interannual–decadal low-frequency variations, and high-frequency vortical processes to the total variance, as well as their spatial distribution patterns. Furthermore, combining area-weighted empirical orthogonal function (EOF) analysis, Sverdrup balance theory, energetics diagnostics, and the principle of PV conservation, we identified the dynamical regulatory mechanisms, ranging from climate-scale remote forcing at the ocean basin level to local nonlinear processes at the frontal scale. We also clarified the primary dynamical limitations governing the “Loop-Leap” path transition of the Kuroshio in the Strait. Finally, we explored the seasonal regulatory mechanisms of frontal dynamics and Ekman suction processes on the Kuroshio front zone under the influence of the East Asian monsoon. The results of this study attempt to refine the dynamical theoretical framework for multiscale variability in the western boundary current of the northwestern Pacific, lending scientific support to regional eddy-resolving ocean numerical forecast model optimization, marine ecological environment assessment, and dynamical response prediction in the western Pacific marginal seas in the climate change context.

Section 2 of this paper gives a detailed introduction to the datasets and analytical methods employed in the study. Section 3 systematically analyzes the mean-state structure, multiscale spatiotemporal variability characteristics, and path-switching patterns of the Kuroshio front zone. Section 4 offers an in-depth analysis of the dynamical regulatory mechanisms of variability at different scales. Finally, Section 5 highlights the study’s main conclusions and future research directions.

2. Data and Research Methods

2.1 Data Used in This Study

The daily, globally covered SST data used in this study were obtained from the optimal interpolation (OI) SST product developed by Remote Sensing Systems, Inc. (REMSS). Specifically, this study used the high-resolution microwave-infrared fusion version (MW_IR OI SST, v5.1), with a spatial grid resolution of 9 km (approximately 0.09°). This dataset leverages the observational advantages of microwave sensors (e.g., TMI, AMSR-E, Wind Sat, and GMI) in penetrating cloud cover while integrating the high spatial resolution and reliability of infrared radiometers (e.g., MODIS and VIIRS) for coastal detection. To scientifically eliminate the diurnal variation effects on SST, this product integrates a physical diurnal warming model (which comprehensively considers solar radiation, sea surface wind speed, and local observation time) to uniformly correct all day and night satellite-derived data, thus obtaining a “Foundation SST” that excludes the influence of diurnal thermal stratification. Moreover, the data fusion process employs OI technology. This algorithm assigns weights to observed values based on the specific error statistics of each sensor, which ensures that low-quality inversion data contaminated by strong winds or heavy precipitation are appropriately down weighted.

The ocean current data, sea surface height (SSH) data, and thermocline thickness data used in this study were sourced from the Global Ocean Physical Reanalysis dataset (GLORYS12V1) published by the Copernicus Marine Environment Monitoring Service (CMEMS). Specifically, GLORYS12V1 is a global eddy-resolution ocean and sea ice reanalysis system designed and implemented under the CMEMS framework. It encapsulates the complete time series since the start of satellite altimetry and delivers high-quality four-dimensional ocean state estimates for research on global ocean dynamics, climate variability analysis, and operational ocean forecasting. The dataset has a horizontal resolution of 1/12° (around 8 km at the equator) and can resolve eddy-scale oceanic dynamics globally, thus meeting the standards for eddy-resolution ocean reanalysis. Vertically, it is divided into 50 standard layers, covering the entire water column from the sea surface to the seafloor. Moreover, the spatial coverage encompasses oceans globally, with a latitude range of 80°S–90°N and a longitude range of 180°W to 180°E. The temporal coverage spans from January 1, 1993, to the present, with daily and monthly averages available as output formats. Data variables include the three-dimensional SST, salinity, ocean current velocity (eastward and northward components), sea surface height, mixed layer depth, and sea ice parameters. The accuracy of the GLORYS12V1 reanalysis product in the Kuroshio region of the northwestern Pacific has been confirmed and recognized by multiple independent studies. For instance, Kim et al. [16] undertook a comparative evaluation of GLORYS12V1 against in-situ CTD observations from summer cruises in the East China Sea and the northwestern Pacific. The results show that GLORYS12V1 exhibited superior root-mean-square errors for temperature and salinity in the northwestern Pacific region compared with other reanalysis products, maintaining high data reliability even under conditions of multiple typhoon passages. Furthermore, an overall performance evaluation of GLORYS12V1 showed that this reanalysis system could accurately capture major interannual signals of marine climate variability, large-scale

circulation features, and water exchange processes across various ocean basins, and that its ability to characterize small-scale variations in surface dynamic processes aligned well with observational data.

2.2 Methodology

2.2.1 Extraction of Multiscale Spatiotemporal Variations

To divide different spatiotemporal scales within complex flow fields during signal separation and variance contribution analysis, this study employed filtering and smoothing techniques similar to Reynolds decomposition. The raw surface velocity was deconstructed into the climatological mean $\bar{V}$, seasonal cycle V_{season} , low-frequency/interannual signal V_{low} (extracted via a 13-month moving average), and high-frequency residual/vortex signal V_{res} :

$$V(t) = \bar{V} + V_{season}(t) + V_{low}(t) + V_{res}(t) \quad (1)$$

Next, the dominant dynamic processes in different sea areas (e.g., the NEC branching zone, the Strait, and the East China Sea) were quantitatively evaluated by calculating the variance contribution of each component.

In conducting a low-frequency evolution analysis of SSH, we employed area-weighted EOFs. As the Earth is spherical, the actual area of high-latitude grid cells is smaller than that at the equator. Therefore, the square root of the latitude cosine ($\sqrt{\cos \theta}$) was introduced as the weight matrix for singular value decomposition to derive the most accurate low-frequency dominant modes. Furthermore, before conducting the EOF analysis, we performed a strict detrending operation.

$$SSH(x, t) = a(x)t + b(x) + SSH_{detrended}(x, t) \quad (2)$$

This step isolated the global sea-level rise signal, ensuring that the extracted PC1 accurately reflected interdecadal climate oscillations (e.g., the alternating strength of the Kuroshio Current modulated by ENSO or PDO).

2.2.2 Integral Solution for Sverdrup Transport Anomalies

Regarding the anomalous modes of the North Pacific wind stress curl ($\nabla \times \tau$), this study went beyond the statistical level to explore large-scale dynamics by solving the Sverdrup equilibrium equation:

$$\beta V = \frac{1}{\rho_0} \nabla \times \tau \quad (3)$$

By introducing boundary conditions (zero flow function at the eastern boundary) and performing a numerical integration from the east coast westward along the latitudinal circles, we could ensure that the wind field anomalies would drive a portion of the Sverdrup transport flow function anomalies Ψ' [17]:

$$\Psi'(x, y) = -\frac{1}{\rho_0 \beta} \int_{x_E}^x (\nabla \times \tau') dx \quad (4)$$

2.2.3 Vorticity–Current Interaction and Energy Conversion

When calculating eddy kinetic energy (EKE) and instability conversion rates, we first performed a rigorous Reynolds decomposition to compute the mean flow ($\bar{u}, \bar{v}$) and the transient anomaly (u', v'), which was then utilized to solve for $EKE = \frac{1}{2} (\overline{u'^2} + \overline{v'^2})$. Furthermore, the shear and strain of the flow field were computed to find the barotropic conversion rate (BTR),

$$BTR = -\left(\overline{u'u'}\frac{\partial\bar{u}}{\partial x} + \overline{u'v'}\left(\frac{\partial\bar{v}}{\partial x} + \frac{\partial\bar{u}}{\partial y}\right) + \overline{v'v'}\frac{\partial\bar{v}}{\partial y}\right) \quad (5)$$

as well as the baroclinic conversion rate proxy (BCR) based on eddy heat flux:

$$BCR \propto -\left(\overline{u'T'}\frac{\partial\bar{T}}{\partial x} + \overline{v'T'}\frac{\partial\bar{T}}{\partial y}\right) \quad (6)$$

These two equations aim to quantify the forward cascade mechanisms from mean kinetic energy (MKE) and mean effective potential energy (MAPE) to EKE, respectively.

2.2.4 PV and Ekman Suction

To explain the variation in the Kuroshio's intrusion path through the Strait, we introduced the theory of PV conservation in ocean circulation dynamics [18]:

$$PV = \frac{\zeta + f}{H} \approx \text{const} \quad (7)$$

where $\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$ is the relative vorticity, f denotes the Coriolis parameter, and H is the water column thickness (determined by the thermocline/mixing layer thickness). When the main axis of the Kuroshio changes owing to large-scale wind forcing, resulting in H , the relative vorticity ζ must adjust accordingly to maintain PV conservation.

To investigate the influence of dynamics on ecological processes (e.g., nutrient upwelling), we calculated the SST gradient $|\nabla SST|$ to locate frontal systems and used wind stress vorticity to calculate the Ekman pumping velocity (W_e).

$$W_e = \nabla \times \tau_p / \rho_0 f \quad (8)$$

Moreover, by comparing the spatial superposition of frontal intensity and W_e between winter and summer, this study revealed the superposition or antagonistic effects of wind-driven updrafts and mesoscale frontal dynamics across different seasons.

3. Analysis and Discussion of the Kuroshio Front in the Northwest Pacific

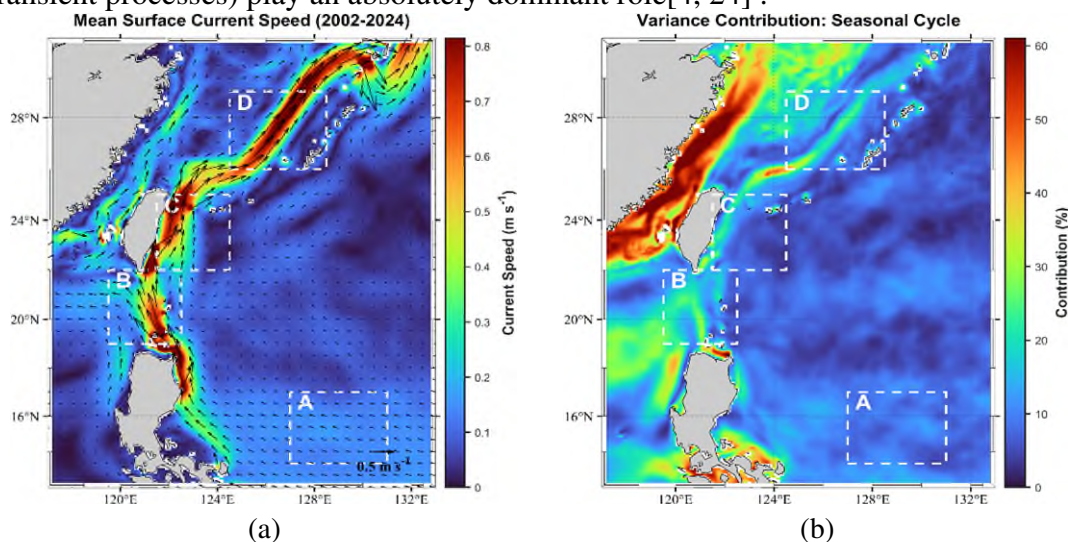
3.1 Spatial and Energy Distribution of the Kuroshio Front

Based on a long-term, high-resolution reanalysis dataset spanning 2002 – 2024, this study constructed the climatological mean structure of the surface current field in the study area (Fig. 1a). Building on this, the total variance of the surface current was decomposed into three independent temporal-scale components: seasonal circulation (Fig. 1b), low-frequency variability (Fig. 1c), and high-frequency residuals (Fig. 1d), to achieve a quantitative spatial description of the multiscale dynamic variability of the Kuroshio.

As shown in Figure 1a, the multi-year average sea surface current field exhibits the structure of the Northwest Pacific Boundary Current. The North Equatorial Current (NEC, Region A) bifurcates in the waters east of the Philippines, with its northward branch converging to form the Kuroshio source region ([19, 20]). As it flows through the Luzon Strait (Region B), part of the water mass intrudes into the South China Sea in the form of complex branches or vortices; while its main body accelerates northward along the eastern coast of Taiwan (Region C), evolving into a narrow, highly concentrated current zone with core velocities significantly exceeding 0.8 m/s. Upon entering the East China Sea (Region D), the main axis of the Kuroshio Current is constrained by potential vorticity due to the topography of the continental slope,

resulting in a stable northeastward transport along the edge of the East China Sea continental shelf.

The results of the temporal decomposition of the total variance further reveal the highly heterogeneous dynamical mechanisms in this region. High-value regions of the seasonal circulation variance [21] are confined to shallow shelf and nearshore waters (e.g., the Taiwan Strait, the coast of mainland China, and the northwest of Luzon), where their contribution to the total variance can reach 40% to 60% or more. This is primarily controlled by the periodic wind stress forcing of the East Asian monsoon system and topographic effects [22]. However, in the main Kuroshio current region and deep ocean waters, the direct contribution of seasonal forcing to surface kinetic energy variability is relatively weak (typically less than 20%). Low-frequency variability components spanning interannual and decadal scales (such as those associated with ENSO and PDO) account for a relatively small proportion of the global total surface variance (the color-coded range in Figure 1b is only 0 – 18%). Regions where low-frequency variance is relatively concentrated (contributing approximately 10% – 15%) are primarily distributed at the Kuroshio's source (east of the Philippine Islands), the meandering section of the Kuroshio Front (south of Japan), the area where the Kuroshio enters the South China Sea, and the outer slope of the East China Sea. Although the amplitude of surface velocity variations directly driven by these processes is much smaller than that of high-frequency transient processes, large-scale climatic low-frequency oscillations can still significantly modulate the overall flow and large-scale path of the Kuroshio Current [23]. In the main branch of the Kuroshio Current and the vast subtropical deep-water ocean, high-frequency residual components (primarily manifested as mesoscale vortical kinetic energy and subseasonal high-frequency transient processes) play an absolutely dominant role [4, 24].



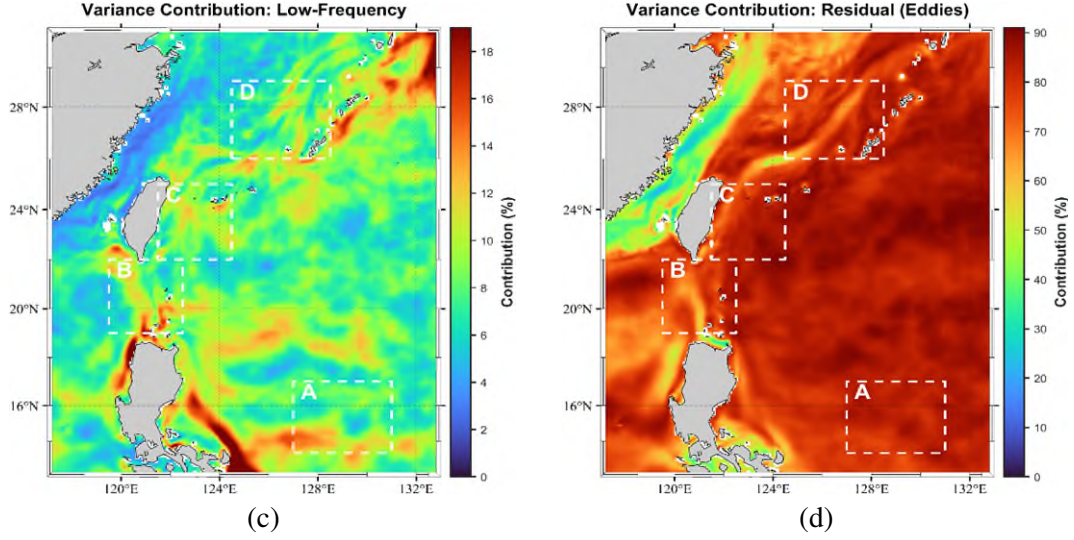


Figure 1 Spatial and energy distribution of the Kuroshio Front. a) Climate-mode-averaged structure of the surface flow field; b) Seasonal cycle; c) Low-frequency variability; d) High-frequency residuals

3.2 Spatial Coherence of Low-Frequency Evolution: Long-Term Trends and Interannual Oscillations

Although local flow field variations in the Kuroshio front zone depend largely on the nonlinear evolution of high-frequency mesoscale vortices (as discussed in Section 3.1), the large-scale path patterns of the Kuroshio (e.g., the looping/bypassing of the Strait and the offset of the East China Sea main axis) and background flow rates are governed by the slow adjustment of the ocean's low-frequency climate state. Thus, as SSH anomalies (SSHAs) directly encapsulate the internal baroclinic structure (thermocline fluctuations) and the dynamical height of the water column, this study used low-frequency SSHA data with the long-term linear trends removed. By applying an EOF analysis to obtain the dominant low-frequency modes in the study area, and combining this with the spatial distribution of long-term trends in the original SSHA, we analyzed the spatial co-evolution patterns of the Kuroshio system.

As shown in Fig. 2, the first dominant mode extracted by EOF analysis accounted for up to 50.4% of the total low-frequency variance, verifying the existence of extremely strong spatial co-evolution characteristics in the study area on an interdecadal timescale. This mode exhibited a dipole structure spatially: With a boundary near 20°N, the tropical ocean region to the south (covering the NEC branching zone) was dominated by large-scale negative anomalies (blue region), while the subtropical oceanic region to the north (encompassing the area east of Taiwan and the outer side of the Kuroshio front in the East China Sea) was dominated by notable positive anomalies (red region). This dipole structure spanning latitudinal zones reflected the volume transport distribution and water mass exchange processes at the boundary between the North Pacific subtropical circulation and the tropical cyclonic circulation [25]. Specifically, when this mode was in the positive phase, the dynamic height anomaly decreased in the tropical region (the thermocline became shallower) and increased in the subtropical region (the thermocline became deeper). This meridional variation in the baroclinic gradient directly altered the geostrophic shear and initial PV distribution in the Kuroshio source region.

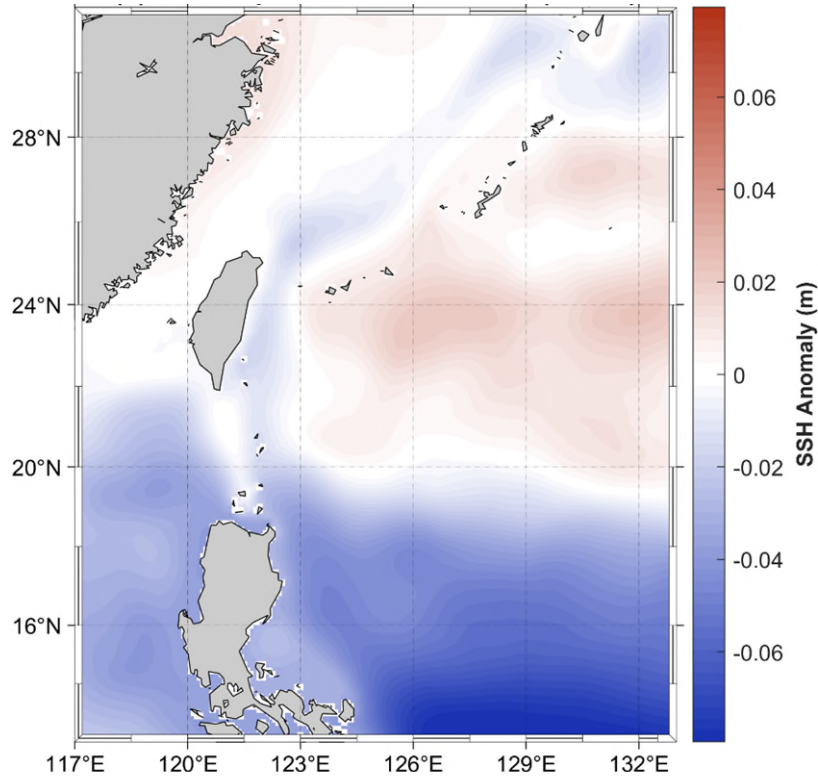


Figure 2 Spatial structure of sea surface height EOF1 (50.4%)

Moreover, the principal component time series corresponding to the EOF1 spatial mode (line data in Fig. 3) exhibited significant interannual-to-decadal oscillation characteristics. The time series was in a strong positive phase during 2003–2005 and 2014–2016, while it exhibited a negative phase during 2008–2009, 2012–2013, and 2022–2024. This time series closely matched the POD (bar data in Fig. 3) and extreme El Niño-Southern Oscillation (ENSO) events. Taking the 2015–2016 super El Niño event as an example, we found that PC1 exhibited the most prominent positive anomaly peak across the period. Combined with the spatial mode shown in Fig. 2, we found that the SSHAs in the NEC source region reached a minimum at this time, which precisely corresponded to the physical response during the El Niño warming event—that is, the eastward discharge of heat from the Western Pacific Warm Pool and the rapid lifting of the local thermocline. Oceanic climate modes propagated from east to west toward the western boundary precisely through such interannual/decadal baroclinic waves (see Section 4.1 on Rossby wave mechanisms), thus altering the zonal and meridional transport ratios in the Kuroshio Current field east of Taiwan and the Strait.

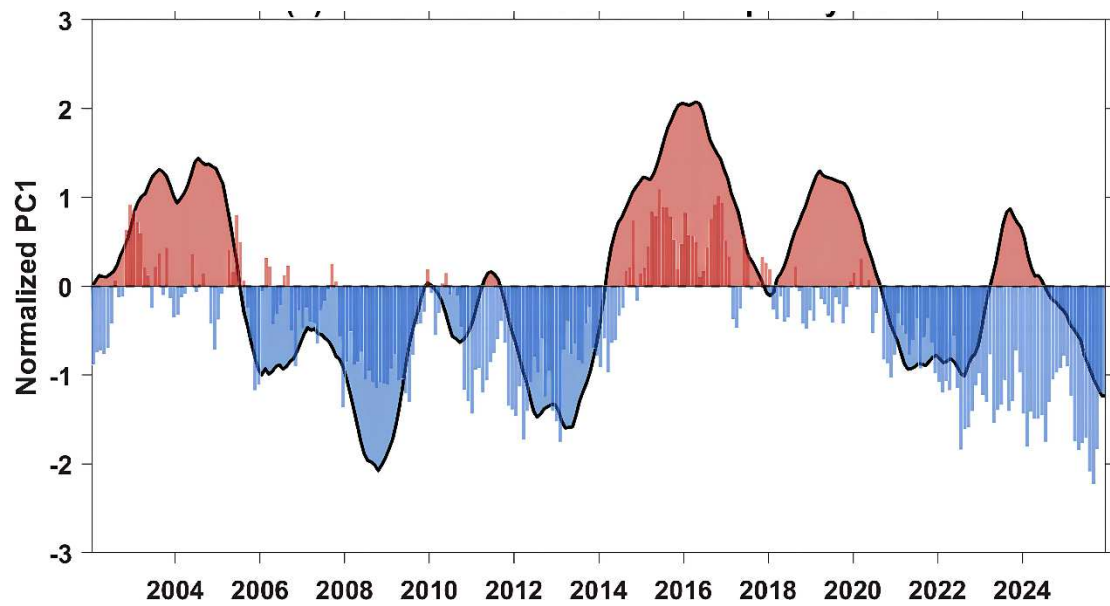


Figure 3 Time series of the low-frequency sea surface height principal component (line data) and POD (bar data)

Against the background of low-frequency oscillations, the spatial distribution of the long-term linear trend in raw SSH from 2002 to 2024 (Fig. 4) revealed another key long-term dynamical limitation. SSH exhibited a positive upward trend (sea level rise) across the western boundary region of the northwestern Pacific, but the rate of increase showed strong spatial variability. The Fig. overtly shows that in the subtropical front zone traversed by the main branch of the Kuroshio Current (east of Taiwan and the East China Sea continental slope region), the rate of SSH rise was relatively steep (> 0.05 m/decade, dark red areas). In contrast, in the nearshore areas on the inner side of the Kuroshio Current and the Strait (Region B), the rate of SSH rise was relatively gentle. This uneven dynamic elevation rise led to a continuous strengthening of the horizontal pressure gradient force across the main Kuroshio axis over the past two decades. According to geostrophic equilibrium dynamics, the intensification of the cross-current geostrophic gradient will force the main branch of the Kuroshio east of Taiwan and in the East China Sea to exhibit a long-term trend of strengthening and path straightening. At the same time, this adjustment of the large-scale background field effectively suppresses the westward penetration of the Kuroshio into the interior of the South China Sea Basin, thus providing dynamic support for a long-term decline in the intensity of Kuroshio intrusion into the Strait (Section 3.4).

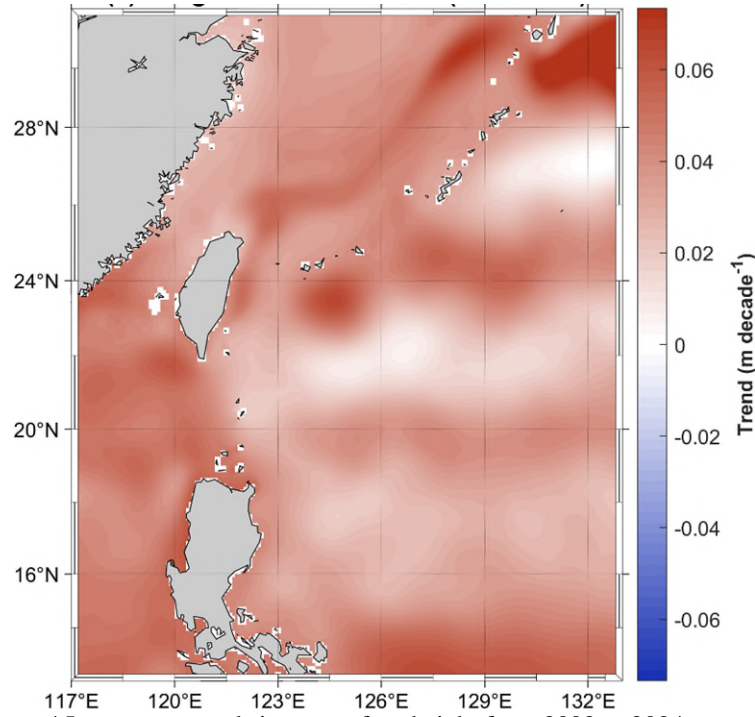


Figure 4 Long-term trends in sea surface height from 2002 to 2024

3.3 Seasonal Oscillations of the Kuroshio Main Branch and Thermocline Adjustments

Variations in the western boundary current system of the northwestern Pacific are reflected both in changes in the strength of two-dimensional horizontal flow and in seasonal variations in the upper-ocean dynamical axis, thermodynamic fronts, and mixed-layer thickness. To clarify the “dynamic–thermodynamic” coupling response mechanism of the Kuroshio front zone under East Asian monsoon forcing, this section conducts multi-parameter spatial synthesis and cross-axis profile analysis of the climatic state characteristics during winter (DJF) and summer (JJA) based on SST, SSH, and density mixing layer thickness. A comparison of Fig. 5a (winter) and Fig. 5b (summer) clearly revealed a seasonal reversal in the Kuroshio front east of Taiwan and in the Strait, characterized by a strong coupling between the flow axis shift and the front’s formation and dissipation [26].

During winter (DJF), under the strong forcing of the northeastern monsoon, the surface waters of the northwestern Pacific undergo sustained westward Ekman transport. This behavior forces the SSH isoclines, which are the main axis of the Kuroshio geostrophic current, to shift toward the coast, resulting in a “loop” type intrusion in the Strait region, where large amounts of Kuroshio surface water flow into the northern South China Sea. More importantly, in winter, the convergence of a strong cold water mass and the warm water carried by the main Kuroshio current off the East China Sea continental slope and east of Taiwan forms an extremely intense SST front. The superposition of this onshore flow axis with the strong cold–warm front considerably enhances mesoscale instability along the front, driving a powerful material exchange between the surface and subsurface layers [7]. In contrast, in summer (JJA), with the transition from the East Asian monsoon to the southwest monsoon, local Ekman transport shifts to an easterly direction, and isobars of SSH generally retreat toward the open ocean. At this time, the path of the Kuroshio’s main axis straightens

and smooths out (Leap path), and the westward intrusion into the Strait is notably suppressed. Moreover, intense solar radiation in summer causes the surface temperature difference between the Kuroshio and the surrounding shelf/marginal waters to sharply decrease, and the horizontal temperature gradient essentially dissipates. The surface water is stabilized by strong thermodynamic stratification, and the upper ocean tends toward a stratified-stable state [7].

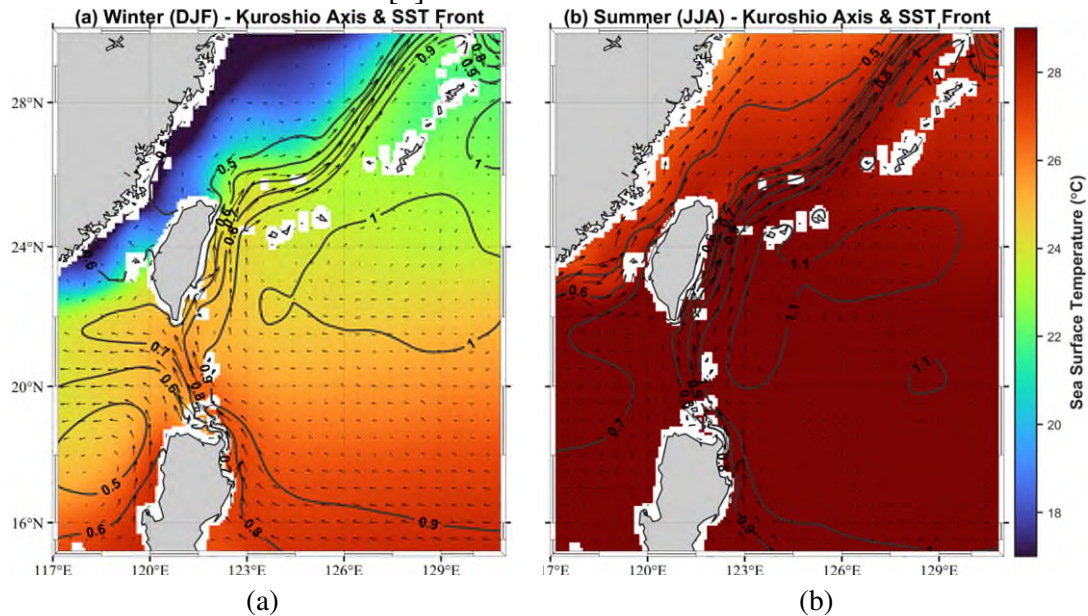


Figure 5 Distribution of sea surface temperature and sea surface height in the waters east of Taiwan and the Luzon Strait during winter (a) and summer (b) (black lines represent sea surface height)

Additionally, the thermodynamic state and dynamic oscillations of the Kuroshio main branch are driven by wind fields but also directly modulate the vertical stratification of the upper ocean. By extracting seasonal profiles of the mixed-layer depth (MLD) across the Kuroshio front zone in the Strait (21°N, 119°E–123°E) (Fig. 6), we aimed to quantify the upper-ocean adjustment process under air–sea interactions. The profile clearly revealed that the MLD in this region exhibited highly regular seasonal characteristics, being deeper in winter and shallower in summer, along with a significant cross-current gradient.

In winter (DJF, blue solid line in Fig. 6), the strong northeasterly monsoon not only generated intense mechanical turbulence through surface wind stress but was also accompanied by strong heat loss at the sea surface (the buoyancy flux becomes negative), leading to deep convective overturning in the upper water column. Moreover, under the combined forcing of wind and heat, the winter MLD deepened significantly, generally reaching depths of 45–60 m in the core region. Particularly in the eastern waters (121.5°E–123°E) traversed by the main branch of the Kuroshio Current, the mixed layer exhibited a continuous eastward deepening gradient owing to the influence of deep-water convergence by the warm Kuroshio Current. In contrast, during summer (JJA, red solid line in Fig. 6), the southwest monsoon winds were relatively weak, limiting mixing. Furthermore, intense solar radiation created an extremely stable density stratification in the upper ocean. This strong stratification stability effectively suppressed vertical turbulent exchange, causing the summer mixed layer depth to contract sharply. The MLD remained stable at a shallow depth of 13–16 m across the

entire profile, and the meridional gradient across the current axis nearly disappeared.

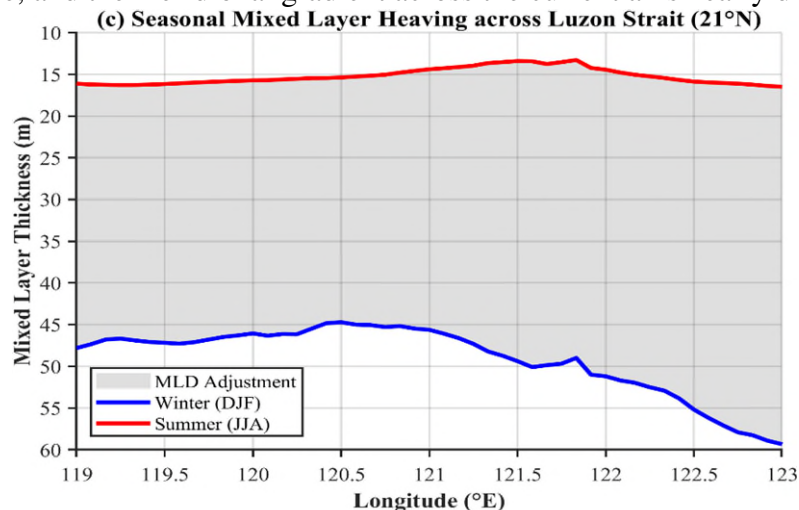


Figure 6 Seasonal profiles of the mixed-layer depth

3.4 Characteristics of Sudden Path Changes and Spatial Patterns of the Kuroshio Invasion in the Strait

To better reveal the nature of the path abrupt change of the Kuroshio in the Luzon Strait, based on the previously defined Kuroshio westernmost intrusion index, two extreme flow regimes — “strong intrusion (LoopPath)” and “weak intrusion (LeapPath)” — were identified, and multi-parameter spatial composites of their sea surface height (SSH), surface flow field, and mixed layer depth (MLD) were generated (Figures 7 and 8). These composite results not only visually demonstrate the dramatic oscillations in the horizontal position of the flow axis but also clearly illustrate the coupling relationship between the main branch of the Kuroshio Current and the three-dimensional thermodynamic structure of the upper ocean.

As shown in Figure 7, under the strong intrusion flow regime, the SSH isoclines (white solid lines) representing the geostrophic main axis of the Kuroshio experienced severe instability and deflection while crossing the Luzon Strait. The flow field vectors reveal a massive anticyclonic “loop,” the core of which extends beyond 119° E and penetrates deep into the South China Sea basin. Notably, the spatial geometric center of this anticyclonic loop aligns spatially with the region of maximum mixed-layer depth (MLD) (the deep red area in Figure 7, where the depth exceeds 45 – 50 m). From an oceanodynamic perspective, when large volumes of warm, low-density Kuroshio subsurface water intrude into the South China Sea, intense anticyclonic velocity shear drives significant upper-layer Ekman convergence. This dynamic convergence forces the surface water to undergo intense subsidence, causing the isodensity surface to drop sharply, thereby forming the extremely deep mixed layer and warm-core structure shown in the figure [27, 28]. This process is accompanied by the release of massive baroclinic energy into the South China Sea [3].

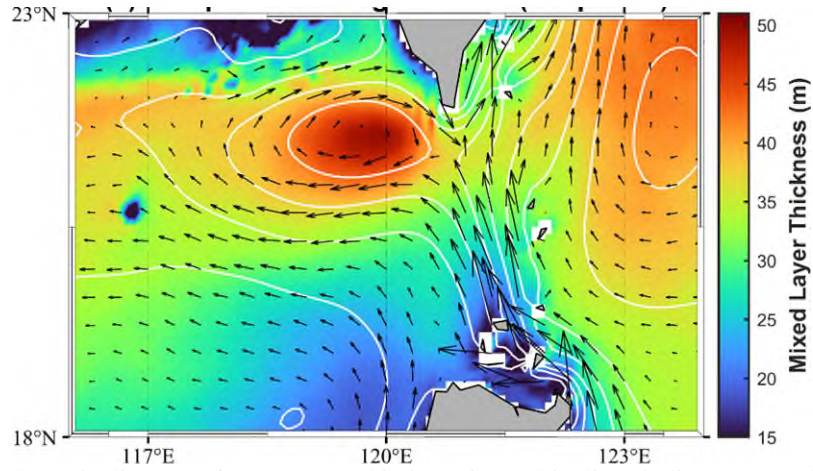


Figure 7 Schematic diagram of strong Kuroshio intrusion (white lines indicate sea surface height)

In contrast, when the Kuroshio was in a weak intrusion phase (Fig. 8), the flow pattern in the Strait changed. Specifically, the SSH isoclines became dense, compact, and parallel to the meridian direction; the main branch of the Kuroshio hugged the Philippine coast, “leaped” across the Strait, and reached the east coast of Taiwan. The straightening of the current axis directly cut off the advective transport of warm water from the western Pacific to the South China Sea. Against this backdrop, Fig. 8 shows extensive “shallow adjustment” in the MLD across the western and central parts of the Strait and the northern South China Sea (extensive blue-green areas, with MLD generally retreating to below 20–30 m). This shallowing reflected the “dynamic shielding effect” of the Kuroshio main branch on the marginal sea: Owing to the lack of strong convergence and subsidence from warm waters in the open ocean, local water masses in the South China Sea could maintain relatively shallow thermodynamic stratification or generate a certain degree of compensatory upwelling due to local wind vorticity.

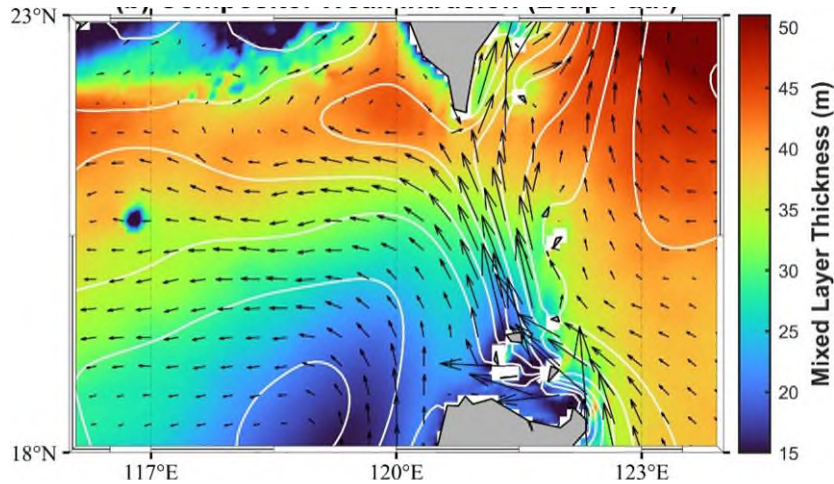


Figure 8 Schematic diagram of weak Kuroshio intrusion (white lines indicate sea surface height)

4. Mechanism Analysis

In response to the multiscale spatiotemporal variability of the Kuroshio front east of Taiwan, the path-shifting patterns of Kuroshio intrusion into the Strait, and their associations with large-scale climate oscillations revealed by the above observations, this section presents a systematic analysis of the dynamical mechanisms underlying the multiscale variability of the Kuroshio front. The effort ranged from ocean-basin-scale remote forcing to local nonlinear dynamical processes within the front zone. First, based on classical wind-driven circulation theory, we elucidated how large-scale climate modes in the North Pacific (PDO, ENSO) drove adjustments in Sverdrup

transport through wind-induced vorticity anomalies, and how baroclinic Rossby waves facilitated the transoceanic propagation of climate signals toward the western boundary, ultimately recognizing the remote control mechanism for low-frequency variations in the Kuroshio. Second, within a Reynolds-averaged framework, we analyzed the energy supply to mesoscale vortex activity from barotropic and baroclinic instability processes in the Kuroshio front zone through energy conversion, identifying the driving role of high-frequency eddy variations. Subsequently, based on the principle of PV conservation, we clarified the coupling relationship between adjustments in the thickness of the upper water column and variations in relative vorticity, clarifying the hydrodynamic limitations on the abrupt transition of the Kuroshio's "sleeve-jump" path in the Strait. Finally, by integrating air–sea interaction processes, we analyzed the seasonal effects of Ekman suction and frontal secondary circulation driven by the East Asian monsoon, revealing the seasonal regulatory mechanisms of physico–ecological coupling processes in the Kuroshio front zone.

4.1 Large-Scale Wind-Driven Circulation Mechanisms and Rossby Wave Propagation

4.1.1 Dominant Modes of Oceanic Wind Field Forcing and Coupling with the PDO

The long-term, low-frequency variability of the western boundary current is mainly driven by the long-term cumulative dynamical response to wind-stress vorticity in the ocean basin, rather than being controlled solely by local wind fields [29]. To that end, an EOF analysis of wind stress vorticity anomalies in the central North Pacific (0°N–40°N, 115°E–125°W) over 2002–2024 showed that the first spatial mode (EOF1, accounting for 16.0% of the variance) exhibited a typical meridional dipole distribution (Fig. 9): It manifested as a positive anomaly zone in the mid-latitude region around 28°N, while in the subtropical waters around 12°N, it appeared as a significant negative anomaly zone.

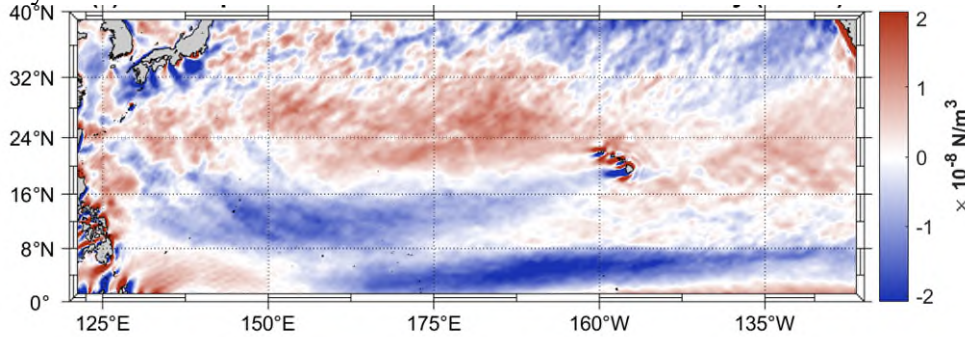


Figure 9 Spatial structure of the empirical orthogonal decomposition of the wind stress curl anomaly field (16.0%)

Further time-series analysis (Fig. 10) revealed a highly significant negative correlation between the first principal component (PC1) of this mode and the Pacific Decadal Oscillation (PDO) index. Specifically, the phase relationship manifested as follows: During the strong warm phase of the PDO from 2014 to 2017, PC1 showed significant negative anomalies, during the cold phases of the PDO from 2008 to 2013 and from 2020 to 2024, PC1 showed persistent strong positive anomalies. This result indicates that the dominant mode of large-scale, low-frequency wind field forcing in the North Pacific is governed by the interdecadal climate system represented by the PDO [30], which also directly explains the observed high correlation between the SSH principal component series and ENSO and PDO extreme events discussed in Section 3.2.

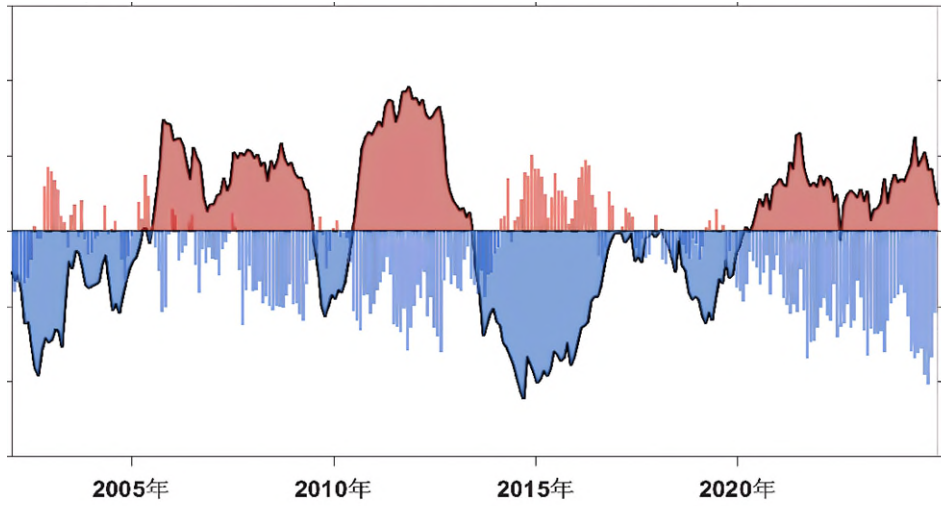


Figure 10 Principal component time series of wind stress vorticity anomalies (line data) and PDO (bar data)

4.1.2 Sverdrup Transport Anomalies and Dynamical Compensation of the Western Boundary Current

Based on the classical Sverdrup balance theory, wind-stress vorticity in the ocean directly spurs meridional water transport. By performing a path integral from east to west, this study extracted the Sverdrup transport anomaly field corresponding to the EOF1 mode (Fig. 11).

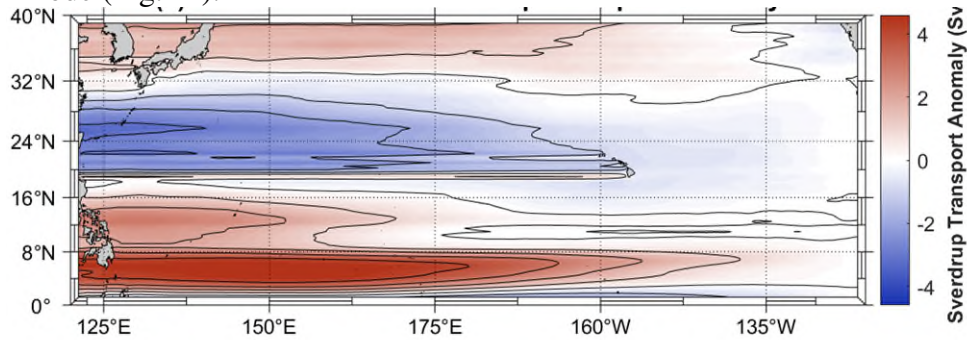


Figure 11 Spatial structure of the empirical orthogonal decomposition of the Sverdrup transport anomaly field

As shown in the Fig., in PC1 positive phase (i.e., the warm phase of the PDO, such as 2014–2020), a significant negative wind-stress vorticity anomaly occurred in the subtropical region (20°N–30°N). This anomaly caused a strong southward Sverdrup transport anomaly within the Pacific. Based on the principles of mass conservation and vorticity limitations in the ocean basin, an internal southward mass transport anomaly requires the western boundary current (Kuroshio) to generate an equal northward transport anomaly to realize dynamical compensation. Furthermore, the overall strengthening of the subtropical circulation and the southward shift of the North Equatorial Current (NEC) bifurcation point caused an increase in the main Kuroshio current velocity and a tendency toward a straighter path. This large-scale dynamical adjustment effectively suppressed the evolution of the Kuroshio “loop” intrusion into the Strait, thus revealing the cause of the long-term declining trend in Kuroshio intrusion into the Strait on a climatological timescale.

4.1.3 Rossby Wave Delay in the Westward Propagation of Climate Signals

Furthermore, the response of the western boundary current to the forcing of the mid-ocean wind field is not instant but, rather, governed by dynamic adjustment processes within the ocean’s baroclinic structure [31]. A Hovmöller plot of SSHAs

along the 15.0°N–18.0°N latitude band (covering the North Equatorial Current to the Kuroshio source region) (Fig. 12) visually illustrates this process. The alternating positive and negative anomaly bands sloping from east to west, as shown in the Fig., provided direct observational evidence for the westward propagation of the first baroclinic Rossby wave. When combined with the superimposed theoretical Rossby wave velocity reference line (dashed line), we observed that the phase velocity of the observed signal was consistent with classical long-wave theory.

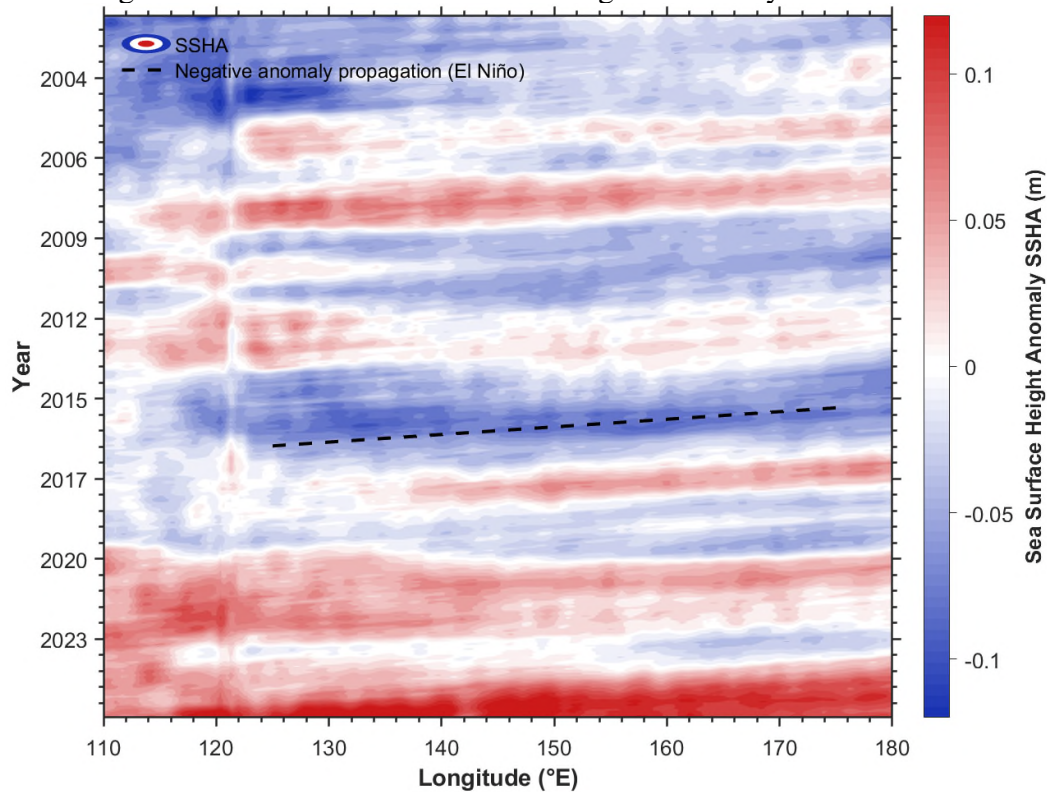


Figure 12 Sea Surface Height Anomaly (SSHA) Hovmöller plot (15.0°N–18.0°N)

Taking the strong El Niño event of 2015–2016 as an example, we observed that anomalies in the trade winds over the central and eastern equatorial Pacific led to localized abnormal upwelling in the thermocline, which, in turn, generated a significant negative SSHA signal (the dark blue region in Fig. 12). This wave carried large-scale vorticity anomalies and after transoceanic propagation lasting approximately 1–1.5 years, it finally reached the western boundary waters between 120°E and 130°E in late 2016 to early 2017. The arrival of the baroclinic signal at the boundary mediated the local baroclinic gradient and thermocline depth in the Kuroshio front zone, thus driving adjustments in the geostrophic flow field.

Based on the above analysis, large-scale climate modes such as the PDO and ENSO first triggered a low-frequency reorganization of the wind stress curl field in the North Pacific (EOF1 mode). This oceanic wind field forcing then drove internal Sverdrup transport anomalies and excited baroclinic fluctuations in sea surface height. Subsequently, the anomalous signal propagated westward across the ocean in the form of first-order baroclinic Rossby waves. Further, after a propagation delay of 1–1.5 years upon reaching the western boundary, it ultimately regulated the multiscale spatiotemporal variability of the Kuroshio front by changing the local dynamic height and water column stratification.

4.2 Baroclinic Instability and Vorticity–Current Interaction

Based on the results of the multiscale variance decomposition discussed earlier, the overall variability of the flow field in the Kuroshio front east of Taiwan and the

Strait is largely controlled by high-frequency residual components (contributing approximately 70% of the variance). To investigate the physical driving mechanisms and energy sources of these high-frequency fluctuations (mainly manifested as mesoscale vorticity and frontal instability processes), this study performed a quantitative analysis of the distribution characteristics of EKE in the Kuroshio strong current zone and the energy conversion process between it and the mean flow, based on a Reynolds-averaged framework.

4.2.1 Spatial Concentration Characteristics of EKE

Fig. 13 visualizes the spatial correspondence between surface EKE in the study area and the mean axis of the Kuroshio Current. The results show that regions of high EKE were concentrated along the boundaries on either side of the mean axis of the Kuroshio Current (black contour lines) and at points where the flow lines bended. Specifically, in the southern and eastern parts of the Strait, east of Taiwan, and in the area where the Kuroshio's path deviates across the East China Sea continental slope, EKE exhibited a distinct band-like enrichment pattern [32]. This result indicates that instability processes in the main Kuroshio current field are the primary energy source sustaining the active eddy field in this region [13].

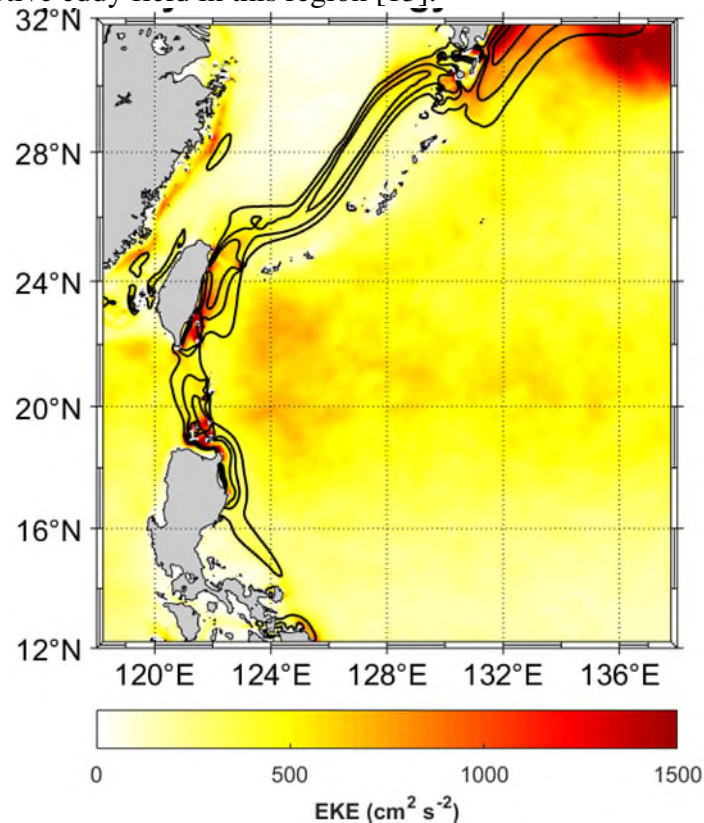


Figure 13 Spatial relationship between surface EKE and the mean main axis of the Kuroshio

4.2.2 Barotropic Instability and Kinetic Energy Cascade (BTR)

The BTR shown in Fig. 14 depicts the conversion process from MKE to EKE. On both sides of the Kuroshio main axis in the waters east of Taiwan and along the continental slope of the East China Sea, the BTR exhibited a distinct alternating positive–negative dipole distribution. Specifically, a broad region of strong positive BTR ($BTR > 0$) was observed in the offshore front zone of the Kuroshio main axis. This spatial distribution indicates that the Kuroshio is accompanied by strong horizontal velocity shear as it flows through these regions. This strong shear background induces barotropic instability, causing the mean flow field to become unstable and spurring the continuous conversion of MKE into EKE. This release of MKE into EKE delivers a

critical energy source for the formation and development of Kuroshio frontal eddies [13].

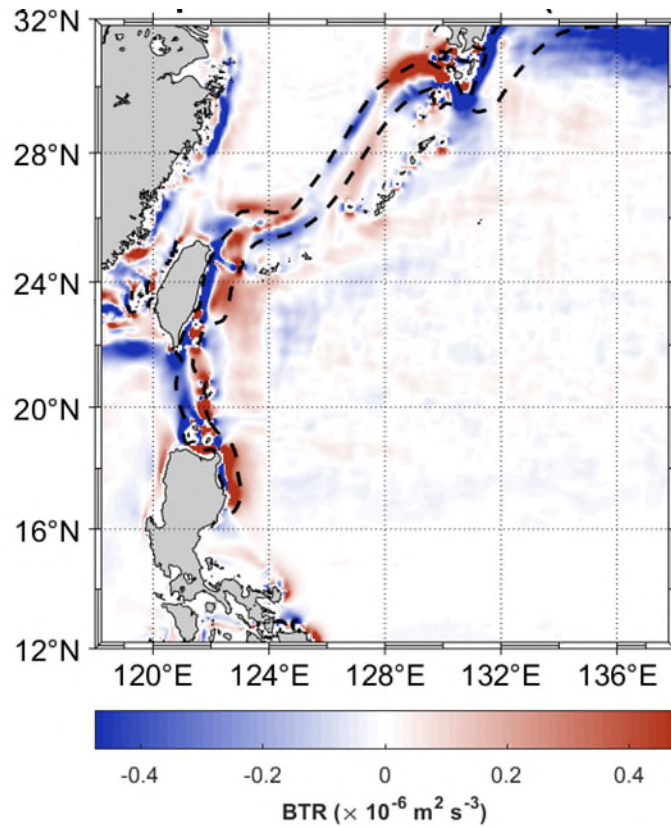


Figure 14 Barotropic energy conversion rate (MKE→EKE)

4.2.3 Baroclinic Instability and Release of Effective Potential Energy (BCR)

Besides the barotropic shear mechanism, as a typical western boundary current system, the main Kuroshio front zone is also accompanied by strong cross-frontal temperature and density gradients. The spatial distribution of the baroclinic eddy heat flux (represented as the conversion rate of mean available potential energy to eddy energy) shown in Fig. 15 shows that significant positive energy conversion was widespread in the main Kuroshio current region east of Taiwan and along the eastern continental slope. Mesoscale disturbances in the positive baroclinic eddy heat flux surface transported heat in the direction of the background temperature gradient, thus extracting energy from the MAPE of the background field and converting it into EKE. This characteristic indicates that baroclinic instability is highly active in the aforementioned sea area and that the strong tilt of isopycnal surfaces in the Kuroshio front zone provides an abundant source of potential energy for the generation and evolution of mesoscale vortices [33, 34].

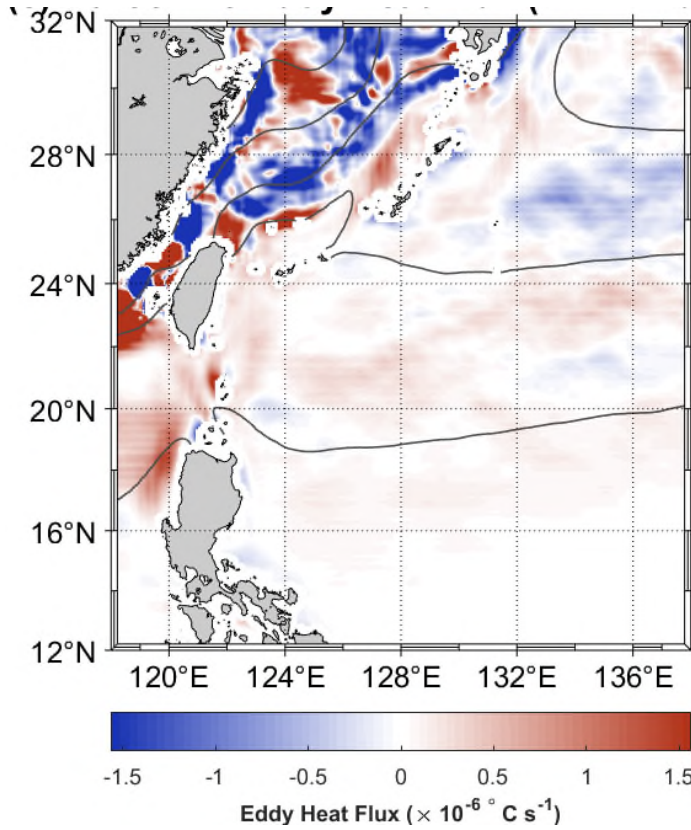


Figure 15 Baroclinic eddy kinetic energy flux (MAPE→EKE)

Based on the above results, evidently, the extremely high proportion of high-frequency variability variance (approximately 70%) in key sea areas east of Taiwan and the Strait is governed by the following mechanisms: Under the limitations of complex continental slopes, the extreme horizontal velocity shear in the Kuroshio current band triggers barotropic instability. Simultaneously, the thermal gradient formed by the convergence of cold and warm water masses excites baroclinic instability. The synergistic interaction of barotropic and baroclinic instability mechanisms induces the continuous energy cascade and conversion from the Kuroshio's MKE and MAPE to EKE, thus triggering and sustaining the highly active high-frequency mesoscale processes in the Kuroshio front zone.

4.3 Dynamical Limitations on Kuroshio Invasion Patterns Imposed by PV Conservation

To thoroughly investigate one of the reasons for the transition between the two typical paths of the Kuroshio in the Strait, the “Loop” (strong intrusion) and the “Leap” (weak intrusion), this study performed a quantitative analysis based on the principle of PV conservation in frictionless upper-ocean fluids. In this framework, as the Kuroshio water column crosses the Strait, its relative vorticity ζ (which determines streamline curvature: $\zeta > 0$ corresponds to cyclonic westward deflection, and $\zeta < 0$ corresponds to anticyclonic straightening) is constrained by the local Coriolis parameter f and the thickness of the upper water column H (defined here as the depth of the thermocline/mixing layer), i.e., $(f + \zeta)/H = \text{const.}$

Fig. 16 illustrates the flow field and vorticity spatial structure during a typical period of strong intrusion. The results show that during this period (e.g., when modulated by positive baroclinic Rossby wave anomalies triggered by large-scale climate anomalies), significant subsidence occurred in the local thermocline of the Strait, leading to a marked increase in the upper water column thickness H (the black contour lines in the figure show that the H values in the core region increased to 64–84 m).

According to the PV conservation law, against the backdrop of an increase in H , to maintain the conservation of PV (assuming that local f changes are small), the relative vorticity ζ of the flow field had to undergo a significant compensatory increase. Fig. 16 clearly shows that a broad band of strong positive vorticity (red region, $\zeta > 0$) was generated in the main channel of the Strait between 120°E and 122°E. The abrupt influx of positive vorticity forced the main axis of the Kuroshio to undergo a strong cyclonic torque, causing the flow field vectors to exhibit a sharp westward deflection of the Kuroshio main branch into the South China Sea basin, thus creating a classic “loop” pattern of strong intrusion.

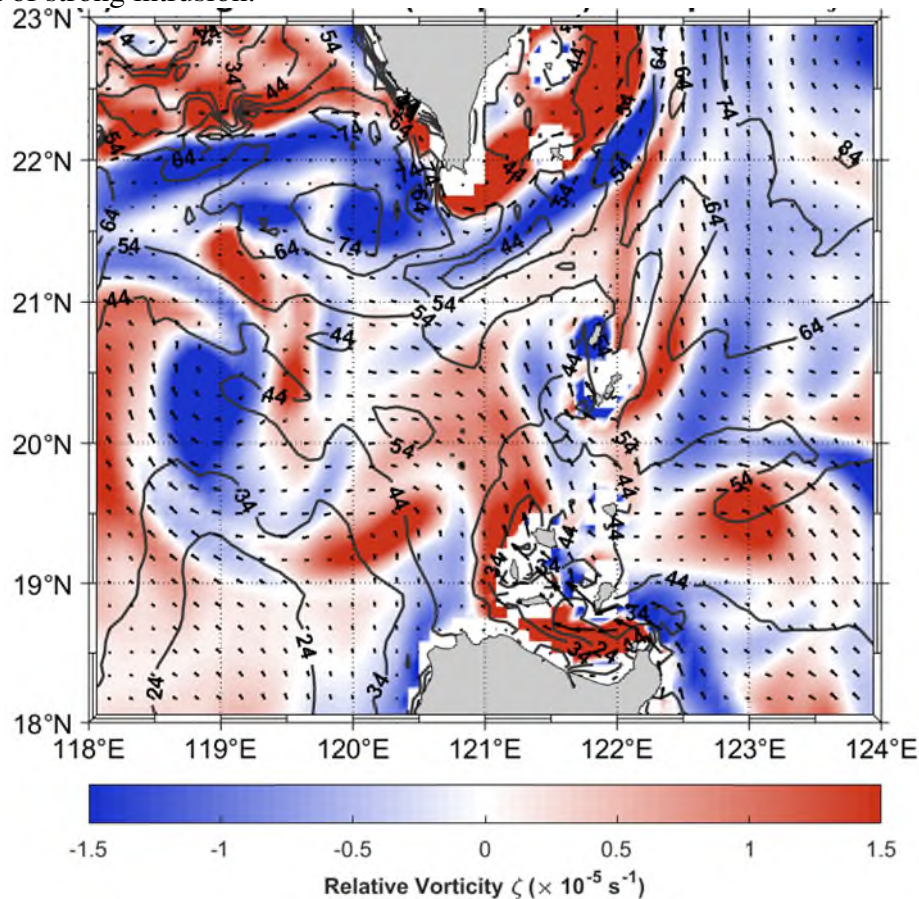


Figure 16 Spatial structure of the flow field and vorticity during the period of strong intrusion

In contrast, Fig. 17 illustrates the characteristics of a typical weak intrusion phase. During this phase, the local thermocline rose abnormally, and the water column thickness H decreased significantly (with isobath values in the core region dropping to 34–54 m). The shallowing of the water column forced a corresponding decrease in the numerator of the PV equation, leading to a sharp drop in relative vorticity ζ and a widespread shift to negative values. As illustrated in Fig. 17, the eastern side of the Strait, through which the main axis of the Kuroshio passes, was extensively occupied by a strong negative vorticity band (blue region, $\zeta < 0$). Negative vorticity indicates that the current was significantly controlled by an anticyclonic torque. This anticyclonic shear effectively suppressed the westward momentum of the Kuroshio’s intrusion, forcing the streamlines to become straight. In terms of flow field vectors, the Kuroshio appeared to “leap” directly northward along the eastern side of the Strait, resulting in a substantial reduction in the meridional volume transport into the South China Sea.

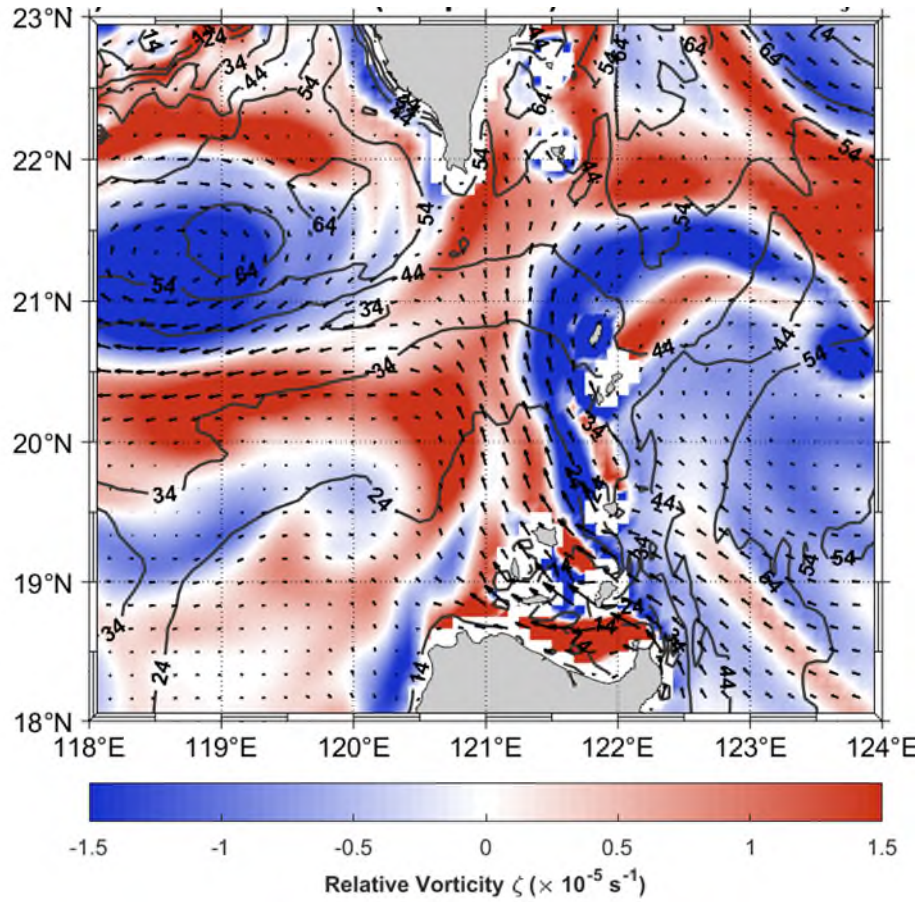


Figure 17 Spatial structure of the flow field and vorticity during the weak intrusion period

A thorough comparison of extreme periods revealed that the multiscale variability and changes in the Kuroshio's intrusion path through the Strait were mainly governed by the coupled interaction between large-scale baroclinic signals (fluctuations in thermocline depth H) and local hydrodynamics (adjustments in relative vorticity ζ) [27]. Changes in the thickness of the upper water column were directly converted into alternating cyclonic and anticyclonic torques in the flow field through the PV conservation mechanism. This is the primary mechanism governing the transition of the Kuroshio between the “sleeve” and “leap” flow modes. To verify this, we focused on the core front zone of the Kuroshio's intrusion into the South China Sea (119°E–120°E, 21°N–22°N) and conducted a quantitative statistical analysis using full-period observational data from 2002 to 2024. After removing seasonal cycles and applying low-pass filtering (to retain interannual–decadal signals), we extracted upper water column thickness anomalies (ΔH) and relative vorticity anomalies ($\Delta \zeta$) for this core region, and plotted a long-series scatter plot of correlation statistics (Fig. 18).

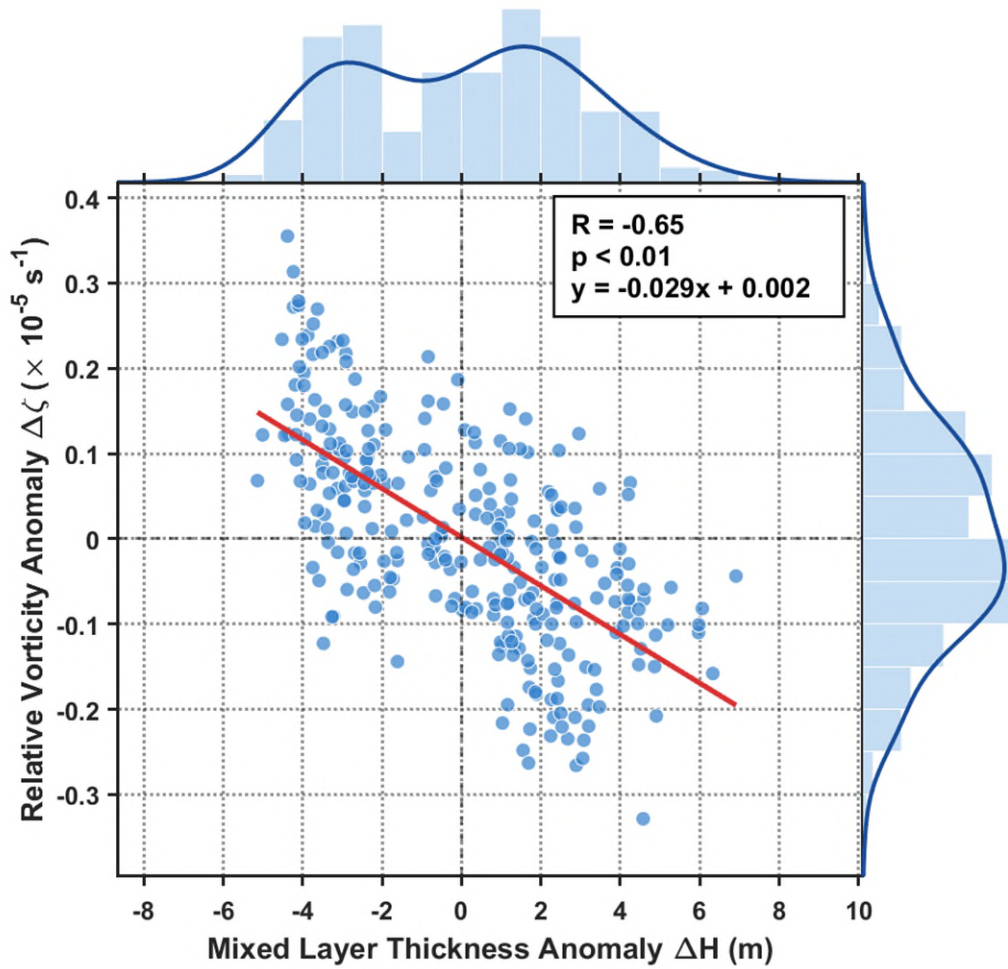


Figure 18 Correlation analysis of thermocline thickness anomalies (ΔH) and relative vorticity anomalies ($\Delta \zeta$)

Statistical results show that in the core region of the Kuroshio intrusion, anomalies in the water column thickness exhibited a significant negative correlation with anomalies in relative vorticity ($R = -0.64, p < 0.01$). This strong negative correlation indicates the mechanism of baroclinic geostrophic adjustment during the Kuroshio intrusion process. From a hydrodynamic perspective, when modulated by oceanic climate anomalies (e.g., Rossby wave propagation during the warm phase of the PDO), the Kuroshio underwent a vigorous “loop” intrusion into the interior of the South China Sea, causing a large volume of warm, low-density Kuroshio subsurface water to converge and accumulate in this region. This led to a rapid deepening of the local thermocline and a significant rise in the dynamic height (i.e., $\Delta H > 0$). This thickness anomaly established a strong local high-pressure center in the upper ocean. According to the geostrophic balance criterion ($\zeta \propto \nabla^2 H$), the high-pressure bulge inevitably forced the flow field to generate strong anticyclonic (clockwise) geostrophic shear, thus causing a sharp, widespread shift to negative relative vorticity ($\Delta \zeta < 0$). Conversely, during “Leap” type periods of weak intrusion, Kuroshio warm water retreated, and the region was occupied by local cold water from the South China Sea ($\Delta H < 0$), causing the anticyclonic torque to dissipate and relative vorticity to rebound toward positive values.

In summary, based on statistical evidence spanning more than 20 years ($R = -0.64$), it can be inferred that the evolution of Kuroshio patterns within the Strait is not simply a two-dimensional oscillation of horizontal streamlines but is accompanied by intense three-dimensional mass transport and vorticity reorganization. Variations in the

upper layer thickness (H) induced by oceanic forcing, through geostrophic adaptation, impose an anticyclonic vorticity (ζ) structure on the intruding flow, driving the multiscale variability in Kuroshio water mass exchange in the Strait.

4.4 Seasonal Modulation of the Kuroshio Front Zone Habitat by Frontal Dynamics and Ekman Suction

Multiscale variations in physical oceanographic currents and front zones often exert great influence on the biological habitats and chemical cycles of the surrounding waters. To elucidate the impact of monsoon evolution on the hydrobiological environment of the Kuroshio, this study performed a multifactorial analysis of wind-driven Ekman suction rates (W_e), SST frontal intensity ($|\nabla SST|$), and SSH (Figs. 19 and 20). The results show that the physico–ecological coupling mechanisms in the study area exhibited significant seasonal reversals and spatial heterogeneity.

Fig. 19 illustrates the scenario dominated by the winter northeastern monsoon. Along the East China Sea continental slope traversed by the Kuroshio Current (25°N–28°N), the oceanic background wind field exhibited weak Ekman subsidence (light blue region, $W_e < 0$). From the perspective of wind pumping alone, such a subsidence environment is inherently unfavorable for the upwelling of deep-water nutrients, which contradicts the high chlorophyll concentrations observed in Chinese coastal waters in winter. However, the Fig. clearly shows that surrounding this region of weak subsidence, immediately adjacent to the main axis of the Kuroshio (area of dense gray contour lines), there was a strong SST thermodynamic front (green solid line; temperature gradient $> 3\text{ }^{\circ}\text{C}/100\text{ km}$). The intense winter atmospheric cooling and the warm water carried by the Kuroshio converged violently here, creating a strong thermodynamic boundary. This result indicates that the abundance of habitats in the Kuroshio front zone in winter is not mainly driven by wind fields but by frontal dynamics. Stronger SST fronts induce active mesoscale processes; this locally intense vertical nonlinear mixing successfully overcomes the Ekman subsidence suppression imposed by the background wind field, transporting nutrients to the surface and retaining them [35], thus providing the material basis for the phytoplankton bloom in the following spring.

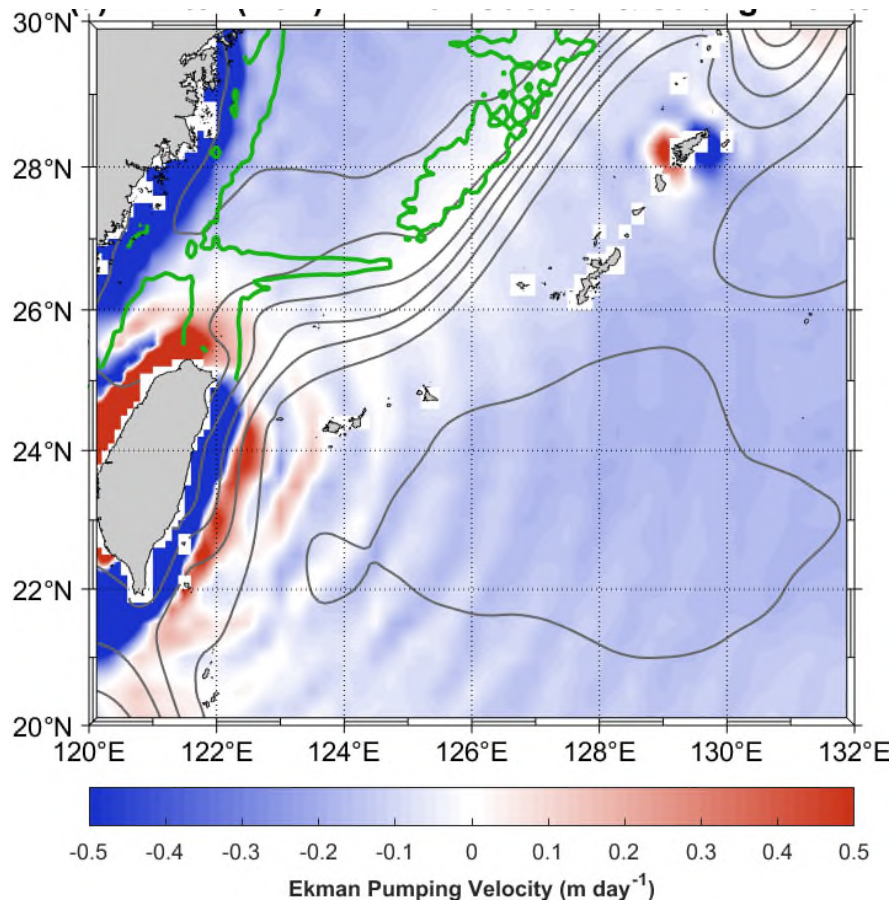


Figure 19 Schematic diagram of winter Ekman suction rates (shaded areas), sea surface temperature fronts (green solid lines), and sea surface height (gray solid lines) in the waters east of Taiwan

Fig. 20 reveals a starkly different scenario dominated by the summer southwest monsoon. A marked positive Ekman suction zone (red area) persisted in the waters east of Taiwan during summer. This was not a computational error but rather the result of the island's wake effect. Specifically, after being blocked by Taiwan's towering Central Mountain Range, the summer southwest monsoon induced strong positive wind stress vorticity in the leeward region east of Taiwan, thus driving localized Ekman upwelling. However, although the physical upwelling mechanism persisted, the summer SST front completely disappeared (the green contour lines in the Fig. are no longer visible). This is because intense summer solar radiation heats the sea surface uniformly, causing the surface temperature difference between the Kuroshio and the surrounding water to sharply decrease and the horizontal temperature gradient to be virtually eliminated or become very weak. More importantly, intense summer surface heating forms a stable density stratification in the upper ocean [36]. At this time, even if the wind field (island wake) generates upward Ekman suction (red patches) east of Taiwan, its weak kinetic energy cannot penetrate the summer thermocline. Consequently, deep-water nutrients are trapped beneath the sub-surface layer. Under the dual limitations of strong stratification and the absence of a front, the surface layer of the summer Kuroshio front zone enters an oligotrophic state.

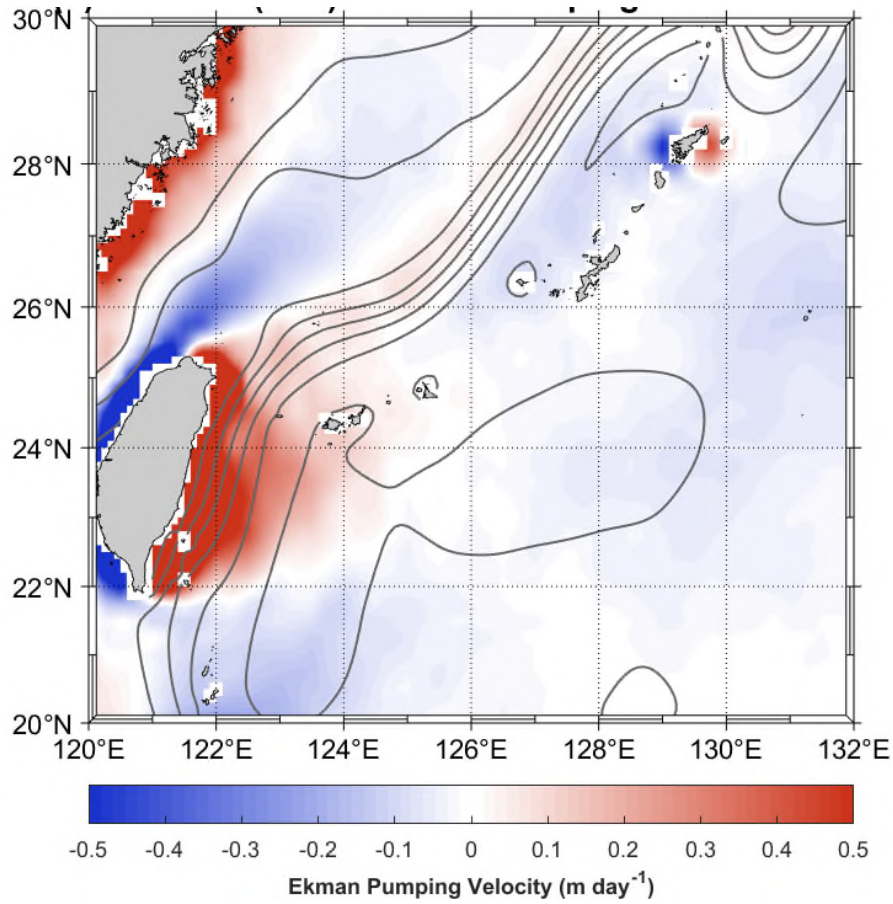


Figure 20 Schematic diagram of summer Ekman suction rates (colored) and sea surface height (gray shading) in the waters east of Taiwan

5. Conclusion

This study examines the multiscale spatiotemporal variability of the Kuroshio Front Zone from the Luzon Strait to the East China Sea continental slope, using eddy-resolving reanalysis and satellite data for the period 2002–2024. The analysis provides a quantitative characterization of variance contributions across temporal scales and explores the dynamical mechanisms linking basin-scale climate forcing to local frontal processes.

The variance decomposition reveals marked spatial heterogeneity in the flow field. In the Kuroshio main stream and adjacent deep-water regions, high-frequency signals (predominantly associated with mesoscale eddy activity) account for over 70% of the total variance, indicating that local variability is largely governed by nonlinear eddy processes. Seasonal signals are most pronounced over shallow shelves and coastal areas, where they contribute up to 60% of the variance, consistent with monsoon-driven wind stress forcing. Low-frequency (interannual to decadal) variations contribute modestly to local velocity variance but appear to modulate the large-scale path and transport of the Kuroshio. The leading EOF mode of sea surface height anomalies (50.4% of the low-frequency variance) exhibits a meridional dipole structure, and its principal component shows covariability with ENSO and PDO indices. The spatially nonuniform sea level rise trend over the study period suggests a strengthening of the cross-stream geostrophic gradient, which may have contributed to the intensification of the Kuroshio east of Taiwan and a reduction in Luzon Strait intrusion. However, this interpretation remains correlational and does not establish causation.

Seasonal dynamical-thermodynamic coupling is evident in the frontal system. In winter, northeasterly monsoon forcing drives an onshore shift of the Kuroshio axis,

intensifies the looping intrusion into the Luzon Strait, and enhances the SST front and mixed-layer depth. In summer, the southwesterly monsoon is associated with an offshore retreat and straightening of the Kuroshio path, a weakening of frontal gradients, and strong thermal stratification. These seasonal contrasts are robustly captured by the data.

The study explores several dynamical mechanisms. At the basin scale, PDO- and ENSO-related wind stress curl anomalies appear to drive Sverdrup transport adjustments, and the associated signals propagate westward as first-mode baroclinic Rossby waves with a lag of approximately 1–1.5 years. This provides a plausible, though not definitive, explanation for the low-frequency modulation of Kuroshio transport and Luzon intrusion. At the frontal scale, both barotropic instability (associated with horizontal velocity shear) and baroclinic instability (associated with cross-frontal density gradients) are active and appear to contribute to the forward energy cascade from mean kinetic and potential energy to eddy kinetic energy. This energy conversion pathway is consistent with the observed dominance of high-frequency eddy variability.

For the path transitions of Kuroshio intrusion into the Luzon Strait, the analysis based on potential vorticity conservation indicates a negative correlation between upper-layer thickness anomalies and relative vorticity anomalies ($R = -0.64$, $p < 0.01$) in the core intrusion region. This suggests that thermocline depth fluctuations, through geostrophic adjustment, may modulate the cyclonic or anticyclonic tendency of the flow, thereby influencing the transition between looping and leaping states. While consistent with the PV framework, this relationship is based on reanalysis data and does not constitute direct observational verification of the mechanism.

Regarding seasonal physico-ecological coupling, winter frontal dynamics appear to enhance vertical mixing and nutrient supply despite background Ekman downwelling, whereas summer thermal stratification and frontal dissipation limit surface nutrient availability even where Ekman upwelling is present. These patterns are consistent with existing understanding of monsoon-driven ecosystem responses.

Several limitations warrant emphasis. First, this study relies entirely on reanalysis and satellite-derived products; direct in situ observations are not used for validation of the multiscale decomposition or the proposed mechanisms. Second, the analysis is restricted to upper-ocean dynamics; the role of deeper circulation in modulating the front and its variability remains unexplored. Third, the proposed energy conversion pathways are derived from diagnostic calculations using Reynolds-averaged fields and should be interpreted as indicative rather than definitive. Fourth, the PV-based interpretation of path transitions, while statistically supported, is based on a simplified two-layer framework and does not account for three-dimensional effects or nonlinear interactions that may be important in the Luzon Strait. Finally, the findings are based on a 23-year record and may not fully capture decadal to multidecadal variability; projections of future changes under warming scenarios are beyond the scope of this work.

In summary, this study provides a spatially resolved, scale-dependent characterization of Kuroshio Front variability and identifies plausible dynamical linkages to both remote climate forcing and local instability processes. However, the causal relationships proposed remain tentative and require further testing with higher-resolution observations, targeted process studies, and coupled modeling approaches. Future work should also examine the vertical structure of energy transfer, the influence of deep-ocean variability, and the responses of the Kuroshio system to ongoing climate change.

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Data Availability

The datasets supporting the results and analyses presented in this study are openly available in the Zenodo repository under the Creative Commons Attribution 4.0 International (CC-BY) licence. The repository contains the processed datasets and derived variables required to replicate all research findings reported in this article.

Primary Datasets:

1. **Satellite Sea Surface Temperature (SST) Data:** The daily, high-resolution (0.09°) MW_IR OI SST product (v5.1) developed by Remote Sensing Systems, Inc. (REMSS) is available via the REMSS data portal (<https://www.remss.com/measurements/sea-surface-temperature/>). These data were used to construct climatological mean states, seasonal cycle analyses, and frontal intensity calculations ($|\nabla \text{SST}|$) presented in Figures 1, 5, 19, and 20.

2. **Ocean Reanalysis Data:** The GLORYS12V1 global eddy-resolving ocean reanalysis dataset, produced by the Copernicus Marine Environment Monitoring Service (CMEMS), is accessible through the CMEMS data portal (https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030). This dataset provided three-dimensional ocean current velocities (u, v components), sea surface height (SSH), mixed layer depth (MLD), thermocline thickness, temperature, and salinity fields used for multiscale variance decomposition, EOF analysis, Sverdrup transport calculations, eddy kinetic energy (EKE) diagnostics, potential vorticity (PV) analysis, and Ekman pumping velocity computations. The horizontal resolution is 1/12° with 50 vertical layers, covering the period 1993–present.

Processed Data and Replication Materials:

All processed datasets, including:

- Multiscale decomposed variance components (seasonal, low-frequency, and high-frequency residuals) derived from Reynolds-like decomposition of surface velocity fields;
- Area-weighted EOF spatial modes and principal component time series (PC1) of

SSH anomalies;

- Sverdrup transport anomaly fields and wind stress curl EOF modes;
- EKE, barotropic conversion rate (BTR), and baroclinic conversion rate (BCR) calculations;
- PV conservation analysis variables (relative vorticity ζ , water column thickness H);
- Ekman pumping velocity (W_e) and frontal intensity indices;
- Statistical correlation matrices and regression coefficients;

are archived in the Zenodo repository: <https://zenodo.org/records/21787337> ; DOI[10.5281/zenodo.21787337]

Software and Code Availability: All analytical scripts for data processing, statistical analysis, and figure generation (implemented in MATLAB) are available upon request.

Restrictions: No ethical, privacy, or security restrictions apply to the datasets used in this study. All source data are publicly available under open licences. The authors confirm that all data underlying the means, standard deviations, variance contributions, and graphical representations reported in this article are included in the repository. Should further supplementary materials be required, please feel free to contact me at your earliest convenience. I shall spare no effort in furnishing them without delay.

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