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Key Points:

- Kuroshio transport in the Tokara Strait south of Japan decreased by ~4% during 1998–2013, indicating a rate of about 0.05 Sv year⁻¹
- Shoaling of the offshore pycnocline in the Kuroshio was due to vertical thermocline displacement rather than to modified water mass
- Dynamic-topography propagation pathways from the northern and southern interior regions caused weakened Kuroshio transport in the hiatus

Supporting Information:

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

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Comprehensive Observational Features for the Kuroshio Transport Decreasing Trend During a Recent Global Warming Hiatus

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Abstract Linear trends in Kuroshio transport during a recent global warming hiatus (1998–2013) were evaluated using long-term ferryboat ADCP (acoustic Doppler current profiler) data and tidal gauge data in the Tokara Strait south of Japan. The Kuroshio exhibited a remarkable weakening trend of approximately 0.05 Sv year⁻¹ (1 Sv = 10⁶ m³ s⁻¹). The pycnocline in the weakened Kuroshio was relaxed and displayed shoaling at the offshore edge, which was attributed to vertical thermocline displacement rather than to water mass modification. Importantly, Kuroshio transport trends in the Tokara Strait were affected by sea surface height anomalies, which were driven by the combined effects of the clockwise baroclinic-mode coastal trapped wave propagation along the southern coast of Japan and downstream Kuroshio advection in the East China Sea. Both features were induced by wind stress curl changes related to the global warming hiatus over the North Pacific.

Plain Language Summary The Kuroshio is the western boundary current in the wind-driven subtropical circulation of the North Pacific. It exits the East China Sea and flows into the North Pacific through the Tokara Strait between the Yakushima and Amami Oshima Islands to the south of Kyushu, Japan. This study revealed that the Kuroshio transport through the Tokara Strait showed a remarkable weakening trend along with a northward shift during 1998–2013. Changes in the wind stress curl in the high (low)-latitude band over the North Pacific during the global warming hiatus exhibited negative (positive) tendencies, leading to anomalously high (low) sea surface heights. The high (low) sea surface height anomaly arrived at the onshore (offshore) side of Tokara Strait from the high (low)-latitude band decreasing Kuroshio transport because of geostrophy.

1. Introduction

Subtropical western boundary currents have shifted poleward and/or strengthened in the last century under global warming (L. Wu et al., 2012; Yamazaki et al., 2016). Particularly, the Kuroshio in the western North Pacific has intensified remarkably (Chen et al., 2019; Cheon et al., 2012; Sakamoto et al., 2005; Sasaki & Umeda, 2021).

However, the globally averaged surface warming had slowed down from the late 1990s to the early 2010s (Figure 1a), a period commonly referred to as the global warming hiatus (England et al., 2014; Kosaka & Xie, 2013; Watanabe et al., 2014). Concurrent with this hiatus, the Kuroshio experienced an obvious weakening trend from the east of Taiwan to the East China Sea (ECS; Han & Huang, 2008; Wang & Wu, 2018; Wang et al., 2016; Y. Zhang et al., 2020). Using various independent data sets, Wang et al. (2016) showed that weakening of the Kuroshio in this region was attributed to weakened westerlies and related weakening of negative basin-scale wind stress curl over the subtropical North Pacific. Furthermore, Wang and Wu (2018) demonstrated that the Kuroshio intensified east of Luzon Island and slowed east of Taiwan during the hiatus. This discordant trend was associated with changes in basin-scale surface winds and oceanic mesoscale eddy activity around the Subtropical Countercurrent-North Equatorial Current (STCC-NEC) zone.

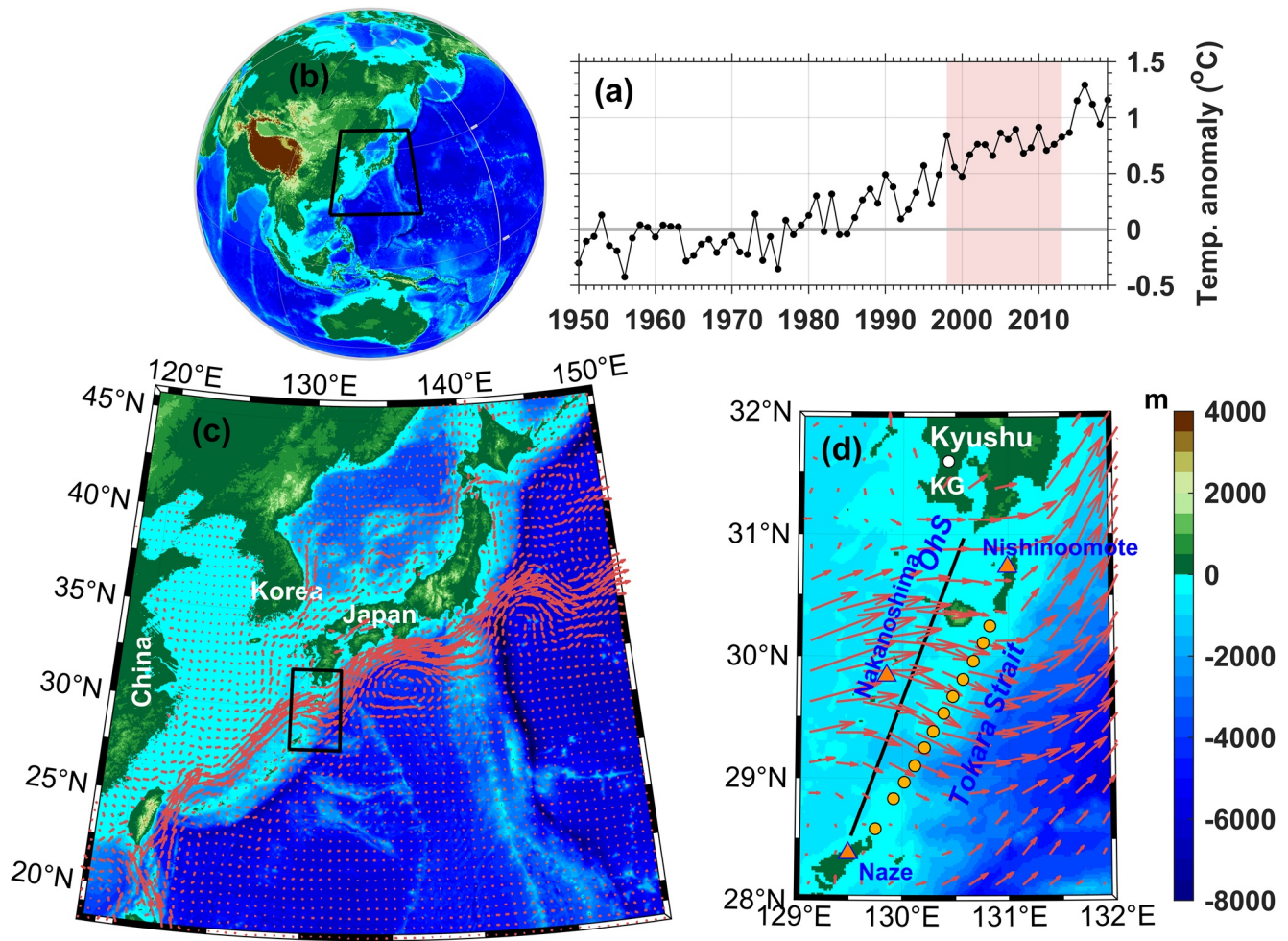


Figure 1. (a) Global temperature anomaly with respect to the 1961–1990 mean value obtained from the Hadley Centre–Climate Research Unit combined with land SAT and SST (HadCRUT) version 4.1.1.0. The shaded area denotes the analysis period (1998–2013) used in this study. (b) Global view of the western North Pacific. (c) Mean surface geostrophic velocity (m s^{-1} ; vectors) in the western North Pacific derived from Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO) daily data during 1998–2013. (d) Close-up of the Tokara Strait area inside the square box in (c). Also shown is the cruise line (black line) of the ferryboat Naminoue along which current measurements by acoustic Doppler current profiler (ADCP) were performed during 2003–2012. OhS indicates the Ohsumi Strait; the white closed circle indicates Kagoshima City located on the island of Kyushu; red triangles mark the locations of the tide-gauge stations at Naze, Nakanoshima, and Nishinoomote; and yellow closed circles indicate the positions of Japan Meteorological Agency (JMA) CTD stations.

For the changes in the oceanic eddies around the STCC-NEC zone, cyclonic (anticyclonic) eddies were more active than anticyclonic (cyclonic) eddies, which contributed to Kuroshio weakening (strengthening) east of Taiwan (Luzon Island) from 1993 to 2013. Recently, Y. Zhang et al. (2020) also found that Kuroshio transport in the area from the east of Taiwan to the ECS was noticeably weakened during 1993–2014, and the reduction in upstream transport east of Taiwan was greater than the reduction in downstream transport in the ECS. This was attributed to an increased number of cyclonic eddies that appeared around the STCC-NEC zone due to the intensified tropical cyclone during 1993–2014.

In terms of the influence of wind stress changes on long-term variations in the Kuroshio transport east of Taiwan to the ECS, most studies have focused on wind stress curl changes over the interior region for the same latitudinal band as the affected Kuroshio or the entire North Pacific. However, Kuroshio transport at a given latitude cannot be predicted simply by the Sverdrup balance along the same latitudinal band. For example, Andres et al. (2011), using a Kuroshio transport time series derived from satellite sea surface height (SSH) data from 1993 to 2008, showed that Kuroshio transport in the ECS was positively correlated with wind stress curl in the high-latitude ($\sim 35^\circ\text{N}$) interior region without a lag time. This correlation was explained as a remote response due to the barotropic Rossby wave that emanated from the central North

Pacific near 35°N and propagated along an ambient potential vorticity contour. However, this no-lag relationship has disappeared since 2005 (C.-R. Wu et al., 2019); hence, the process underlying the Kuroshio transport response in the ECS to the interior wind stress curl variation is still unclear at a decadal time scale.

In addition to changes in eddies and winds, several studies have highlighted that isopycnal steepness changes due to water mass modification can play an active role in enhancing or weakening the upper layer of the Kuroshio (e.g., Sun et al., 2013). Chen et al. (2019) recently suggested that sea surface warming was responsible for the Kuroshio intensification in the ECS rather than wind stress changes. This process can be explained by stronger warming to the east of the Kuroshio compared to the west, due to ocean subduction and advection processes affected by sea surface warming. Hence, isopycnal slope changes due to water mass modification must be applicable to longer time scale Kuroshio transport changes.

In recent years, increasing studies of the linear trends of Kuroshio transport have been performed in the upstream region from the east of Luzon Island to the continental slope area in the northeastern ECS where the Japan Meteorological Agency (JMA) repeat hydrographic PN-section exists. However, the Kuroshio response to climate change in the region downstream of the PN-section was only touched lightly.

The Tokara Strait to the south of Kyushu Island is a choke point in the Kuroshio stream, and significant heat, nutrients, and organic matter are carried by the Kuroshio from the ECS into the North Pacific through the Tokara Strait (Feng et al., 2000; Nakamura et al., 2003; Nitani, 1972). Recently, Kida et al. (2020) suggested that the long-term trend in Tsushima Warm Current transport during the hiatus period was forced by the SSH anomaly formed by a shift of the Kuroshio axis south of Japan that propagated through the Tokara Strait from the North Pacific to the ECS. Hence, investigating the Kuroshio transport trends in the Tokara Strait under global warming conditions would deepen our understanding of the Kuroshio changes south of Japan and provide a basis for understanding the changes in the Tsushima Warm Current due to climate change. So far, extensive observational data are available in the Tokara Strait, including long-term tide-gauge sea-level records (Kawabe, 1995), approximately 9 years of ferryboat acoustic Doppler current profiler (ADCP) data (Zhu et al., 2017), and JMA repeat hydrographic TK-section data (Nakamura et al., 2006; Wei et al., 2013). These data enable analysis of decadal–interdecadal variations in the Kuroshio transport.

In this study, we derived an empirical regression formula between the observed Kuroshio transport using ferryboat ADCP data and sea-level differences based on tide gauges. Using this formula, we obtained a continuous time series of the Kuroshio transport through the Tokara Strait during 1998–2013 to investigate linear trends in Kuroshio transport and their potential mechanisms.

1.1. Data and Methods

From January 2003 to March 2012, a 38.4-kHz ADCP, mounted on the ferryboat *Naminoue*, measured full-depth velocity during round trips across the Kuroshio mainstream between Kagoshima and Naze once every 4 days (Figure 1d). Velocity profiles were averaged over a horizontal distance of 2 km with a 24 m vertical bin length. There were 146 mean profiles with 50 vertical bins spanning the Kuroshio mainstream across the Tokara Strait. A total of 1,234 velocity data tracks were available, of which 364 tracks had issues with missing data. Details of the ADCP data processing methodology have been reported in previous studies (Liu et al., 2017; Zhu et al., 2017). Using this data set, absolute Kuroshio transport through the Tokara Strait was obtained more accurately compared to previous estimates. Daily mean sea-level data during the hiatus period at three tide-gauge stations (Nishinoomote, Nakanoshima, and Naze; Figure 1d) near the ADCP tracks were also used. Tide-gauge data sets were obtained from the Japan Oceanographic Data Center at the Hydrographic Department of the Maritime Safety Agency, Japan. To further investigate long-term changes in the Kuroshio axis position, we used tide-gauge sea-level data to derive the position of the Kuroshio axis in the Tokara Strait following Yamashiro and Kawabe (1996).

To empirically establish a long-term continuous Kuroshio transport time series, only daily sea-level data that were strictly consistent with the ADCP data time frame were used. Because the Kuroshio mainstream through the Tokara Strait exhibits a nearly permanent double-core structure located south and north of Nakanoshima (Feng et al., 2000; Liu et al., 2019), we calculated regression formulas for the two sections spanning the northern and southern Kuroshio current cores. Therefore, the observed transport was divided into northern and southern sections.

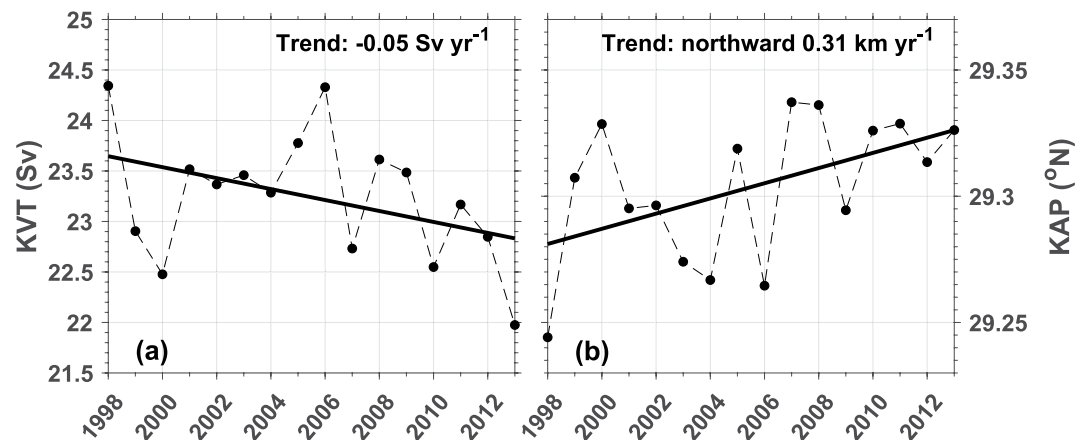


Figure 2. Yearly mean (a) Kuroshio volume transport (KVT; dots) and (b) Kuroshio axis position (KAP; dots) in the Tokara Strait. The solid lines indicate the linear trend during 1998–2013 (statistically significant over the 90% confidence level).

The linear regression relationship between the observed northern Kuroshio volume transport (hereafter, KVTn) and the sea-level difference in the northern Kuroshio stream (SLDn, Nakanoshima minus Nishinomotote) during January 2003 to March 2012 yielded a correlation coefficient of 0.77 (statistical significant at the 95% confidence level, RMS = 1.24 Sv), with bias 8.97 Sv and slope 0.18 Sv cm⁻¹ (Figures S1a and S1c). Hence, KVTn was estimated using $KVTn = 0.18 \times SLDn + 8.97$ Sv. Meanwhile, linear regression analysis on the observed southern Kuroshio volume transport (KVTs) and the sea-level difference in the southern Kuroshio stream (SLDs, Naze minus Nakanoshima) provided $KVTs = 0.24 \times SLDs + 10.16$ Sv with a correlation coefficient of 0.65 (statistically significant at the 95% confidence level) and RMS 2.96 Sv (Figures S1b and S1d). Then, KVTn and KVTs during 1998–2013 were estimated using the corresponding linear regression formulas. Consequently, the total Kuroshio volume transport through the Tokara Strait during 1998–2013 was obtained by summing KVTn and KVTs.

To examine the contribution of wind stress to the Kuroshio transport trends during 1998–2013, 5-hourly ERA-Interim wind data (Dee et al., 2011) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF, <http://apps.ecmwf.int/datasets/>) were used. The ERA-Interim wind data, which have a global grid spacing of 0.75°, were produced with a sequential data assimilation scheme. Moreover, SSH data from Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO, <http://www.aviso.oceanobs.com>, Ducet & Le Traon, 2001) were used to investigate SSH trends along with basin-scale wind stress curl changes.

The pycnocline steepness of the Kuroshio stream across the Tokara Strait during 1998–2010 was evaluated using historical quarterly hydrographic data (pressure, temperature, and salinity data from 12 stations; <http://www.jodc.go.jp>) from the JMA repeat hydrographic TK-section shown in Figure 1d. Note that these quarterly data have been unavailable since 2011; hence, we calculated the annual mean using quarterly data during 1998–2010, which spans the main part of the hiatus period, to avoid seasonal signals in the trend.

2. Results

2.1. Weakened Kuroshio Trend in the Tokara Strait

Yearly mean Kuroshio transport through the Tokara Strait estimated by regression analysis revealed that the Kuroshio transport decreased by ~4% (approximately 0.05 Sv year⁻¹) during 1998–2013 (Figure 2a). Generally, a weakened Kuroshio is associated with a shoreward shift of the Kuroshio path over the ECS continental slope (Hsin et al., 2013; C.-R. Wu, 2013). Figure 2b shows that the weakened Kuroshio in the Tokara Strait showed a shoreward (i.e., northward) shifting tendency during 1998–2013, at a rate of ~0.31 km year⁻¹. This may be attributed to the impact of topographic steering on the Kuroshio jet when it exits the ECS through the Tokara Strait. This is because the western boundary current follows isobaths on the continental slope;

however, it loops when the current flows past a boundary gap and exhibits weaker transport owing to potential vorticity conservation (Andres et al., 2009; Sheremet, 2001).

Previous studies suggested that the decreasing Kuroshio transport trend east of Taiwan during the hiatus period may be due to changes in eddy activity around the STCC-NEC zone, basin-scale surface winds over the North Pacific, or water mass modifications due to thermodynamic processes. Wang and Wu (2018) statistically analyzed the linear trend of mesoscale eddy numbers around the STCC during the hiatus period and found that a relatively large (small) number of cyclonic (anticyclonic) eddies led to a weakened Kuroshio east of Taiwan. This situation, more or less, caused the downstream Kuroshio transport to decrease. In this study, we focused on the relative contributions of the following two factors: (a) pycnocline structure changes due to water mass modification in the western subtropical gyre (Chen et al., 2019; X. Zhang et al., 2014) and (b) the SSH change related to the westward-propagating Rossby wave that is excited by the wind stress curl changes over the interior North Pacific (Wang et al., 2016).

2.2. Thermocline Changes Within the Kuroshio

Figure 3a shows the potential density section averaged for 1998–2010 along the TK-section (yellow dots in Figure 1d). The σ_{θ} 26.8 isopycnal is used to define the pycnocline depth. The steepness of the σ_{θ} 26.8 isopycnal was defined as $\left| (D_s - D_n) / dx \right|$, where D_s and D_n are depths of σ_{θ} 26.8 isopycnal at the southern and northern positions of the Kuroshio, respectively, and dx is the distance between the two positions. Notably, the steepness decreased by approximately $0.03 \text{ m km}^{-1} \text{ year}^{-1}$ during this period (Figure 3c), suggesting that the Kuroshio weakened through the Tokara Strait. We also calculated the trends in D_s and D_n and found that the pycnocline tended to shoal in the southern (i.e., offshore) position, whereas it remained relatively steady in the northern (i.e., onshore) position (Figure 3b). This suggests that the relaxed thermocline was caused by the shoaling of the pycnocline in the southern position. The upward shift of the pycnocline can occur through the following two processes: (a) horizontal advection of the water mass modified in the subtropical gyre and (b) the dynamical response of the Kuroshio to wind stress curl changes over the North Pacific.

To determine how much of the total upward shift of the pycnocline could be attributed to the above two factors during 1998–2010, we calculated the temperature trend on the isopycnal surface (Figure 3e) using JMA data from 1998 to 2010. This kind of trend is considered to be caused by horizontal advection of the modified water mass (hereafter, $\text{Trend}_{\text{adv}}$). The temperature trend due to vertical thermocline displacement, which is the dynamic response of the Kuroshio to wind changes (hereafter, $\text{Trend}_{\text{dyn}}$; Figure 3f), corresponds to the difference between the total temperature trend ($\text{Trend}_{\text{total}}$; Figure 3d) and $\text{Trend}_{\text{adv}}$ (Figure 3e). Details of the calculations are provided in the Supporting Information S1. During 1998–2010, $\text{Trend}_{\text{dyn}}$ reproduced the major features of $\text{Trend}_{\text{total}}$ indicating that the upward shift of the pycnocline (relaxed thermocline) was mainly caused by the dynamical response of the Kuroshio to wind stress changes, and not the horizontal advection of the modified water mass.

2.3. Wind Stress Changes

Studies have found that long-term variations in the western boundary current are controlled by the wind stress curl over the North Pacific (Wang et al., 2016; Y. Zhang et al., 2020). The weakened tendency of the Kuroshio in the Tokara Strait revealed in this study is also attributable to changes in the basin-scale wind stress curl response to the global warming hiatus. More specifically, weakening in the Tokara Strait was forced by wind stress curl changes in two latitudinal bands (Figure 4a) as opposed to the wind stress curl changes along the same latitude as the Tokara Strait. Statistically significant linear trends were found in two latitude bands during 1995–2013 (Figure 4b); the first band lies slightly north of the Kuroshio Extension (35°N – 45°N) and shows a negative trend (statistical significance at the 90% confidence level), while the second band (20°N – 30°N) corresponds with the northern area of the STCC zone and shows a positive trend (statistical significance at the 90% confidence level). Note that the analysis period of 1995–2013 was adopted in this section because the response of Kuroshio transport to wind stress changes in the interior ocean is a remote process with a lag of several years.

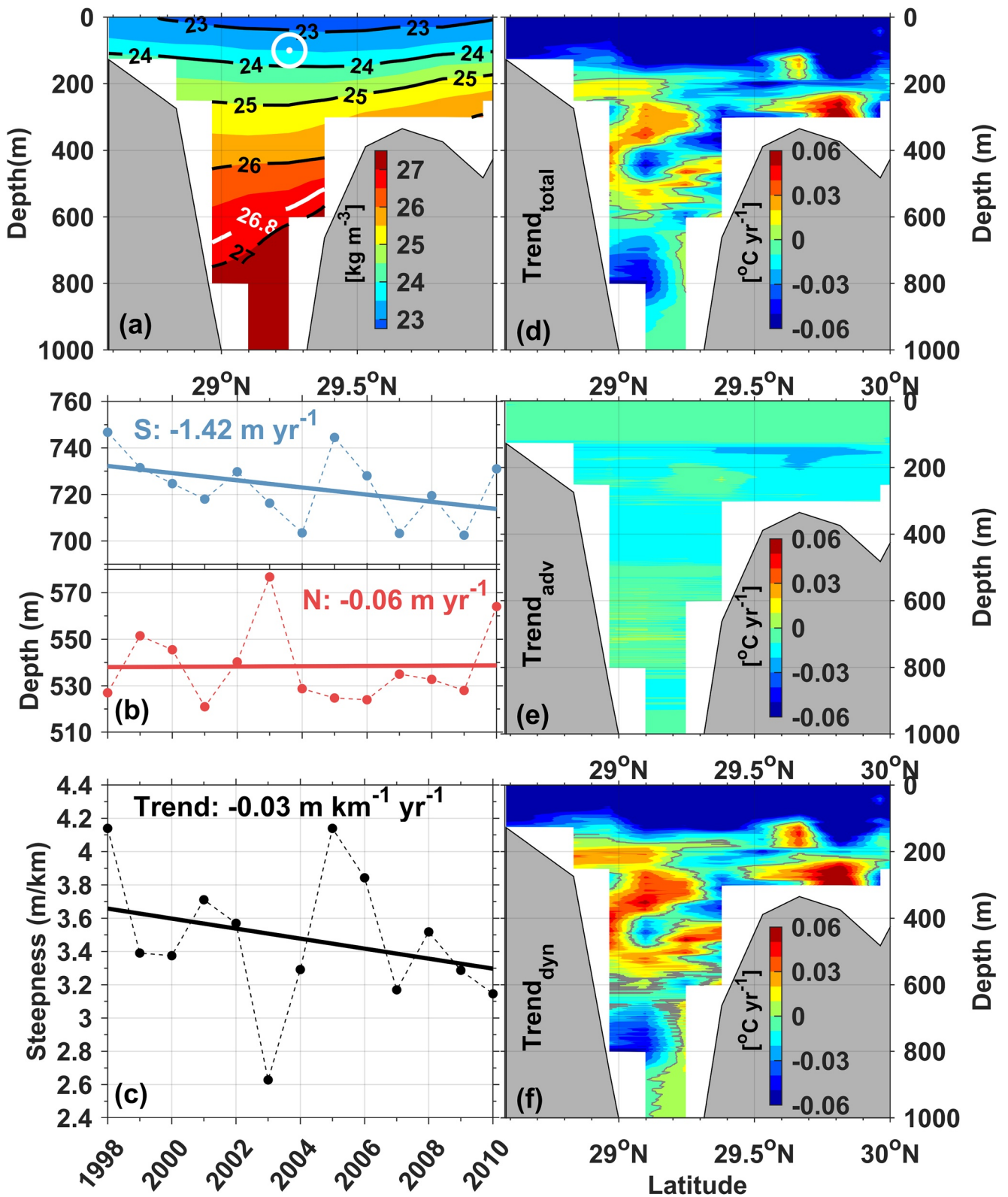


Figure 3.

The negative trend of the wind stress curl in the northern band generated a positive SSH anomaly due to enhanced Ekman flux convergence (Figure 4c). This anomaly propagated westward and arrived at the eastern coast of mainland Japan. Then, the signal propagated in the clockwise direction around the mainland of Japan as baroclinic-mode coastal trapped waves, such as Kelvin waves (Figure 4e). Consequently, this signal raised the sea level on the onshore (i.e., northern) side of the Tokara Strait when it passed through the southern coast of Kyushu from east to west, causing the Kuroshio transport to decrease in the Tokara Strait. Conversely, enhanced Ekman divergence forced by the positive wind stress curl trend over the southern band resulted in negative SSH anomalies. Figure 4c shows that the band structures of the negative SSH trend in the southern area are not exactly zonal; rather, they extend westward with a southward tendency, accompanied by a weak positive trend band in the same direction as the negative trend bands. This feature suggests that the negative SSH anomalies over the southern area are propagated along characteristics for the second baroclinic mode as opposed to the first baroclinic mode (Nakamura, 1998). Notably, the baroclinic modes used here are not the same as the normal modes derived from the linear equations because the SSH anomaly propagation in the second baroclinic mode is due to the combined effect of the second baroclinic-mode Rossby wave and the subtropical gyre circulation. This process well explains why the band structure of the weak positive SSH trend emanates from the positive SSH trend area near 30°N, 160°W and extends westward with a southward tendency. Figure 4e shows that the main pathway of negative SSH anomaly propagation extends westward with a southward tendency from the north of the Hawaiian Islands along approximately 20°N. Importantly, when this signal arrived at the offshore side of the Kuroshio in the ECS, it would be advected downstream along the Kuroshio, decreasing the sea level on the southern side of the Tokara Strait. The seesaw-like sea-level changes across the Tokara Strait led to a weakened Kuroshio (Figure 4f).

Sea levels recorded by tide gauges provide direct evidence of the seesaw-like response of sea level across the Kuroshio (Figure 4d). The sea level on the northern side (Nishinoomote) of the Tokara Strait depicted an increasing trend (approximately 0.37 mm year⁻¹) during 1995–2013, while the sea level on the southern side (Naze) of the strait decreased by approximately 1.96 mm year⁻¹. Although the increasing tendency of the sea level at Nishinoomote was not statistically significant at the 90% confidence level, the sea level along the southern coast of Japan exhibited a significantly increasing trend during 1995–2013 (Figure S2 and Table S1). The decreasing trend in the sea-level difference across the Tokara Strait can weaken the Kuroshio transport through geostrophy.

3. Conclusion and Discussion

Comprehensive observational results showed that the Kuroshio transport through the Tokara Strait was noticeably weakened during 1998–2013, decreasing by approximately 4% of the mean total transport (approximately 0.05 Sv year⁻¹), while its path shifted northward by approximately 0.31 km year⁻¹. Concurrently, the Tsushima Warm Current west of Kyushu increased by approximately 0.21 Sv (Kida et al., 2020). Bearing in mind the baroclinic-mode coastal trapped wave propagating along the mainland of Japan in the clockwise direction, the SSH anomaly that originated from the northern band (35°N–45°N) first passed through the Tokara Strait and then through the Tsushima Strait. Consequently, wind stress changes over the northern band caused the Kuroshio transport through the Tokara Strait to weaken by approximately 0.21 Sv during 1998–2013; this effect accounted for approximately 26% of the weakened Kuroshio transport in the Tokara Strait (approximately 0.05 Sv year⁻¹ × 16 years = 0.80 Sv). Hence, signals from the STCC-NEC zone accounted for approximately 0.59 Sv of the weakened Kuroshio transport through the Tokara Strait during 1998–2013, that is, approximately 41% of the weakened Kuroshio transport east of Taiwan (Wang & Wu, 2018). These findings may be consistent with those of Y. Zhang et al. (2020), who found that the upstream Kuroshio transport was reduced more than the downstream transport because the latter was

Figure 3. (a) Cross-sectional potential density (σ_θ) during 1998–2010 derived from JMA data. The white contour indicates the σ_θ 26.8 isopycnal, which is used to define the pycnocline depth. (b) Yearly mean pycnocline depths (dots) at the south (blue) and north (red) sides of the Tokara Strait. The linear trends are shown by solid lines. (c) Steepness of the σ_θ 26.8 isopycnal (dots) and its linear trend (solid line), which is statistically significant at the 90% confidence level. (d) Linear trends of temperature (°C year⁻¹) across the Tokara Strait during 1998–2010. Gray contours indicate no trend. (e) Same as (d), but for temperature trends estimated on isopycnal surfaces, which are regarded as the contribution of horizontal advection of the modified water mass. (f) Difference between (d) and (e), indicating temperature trends due to vertical thermocline displacement, caused by the dynamical response of the Kuroshio to wind stress curl changes.

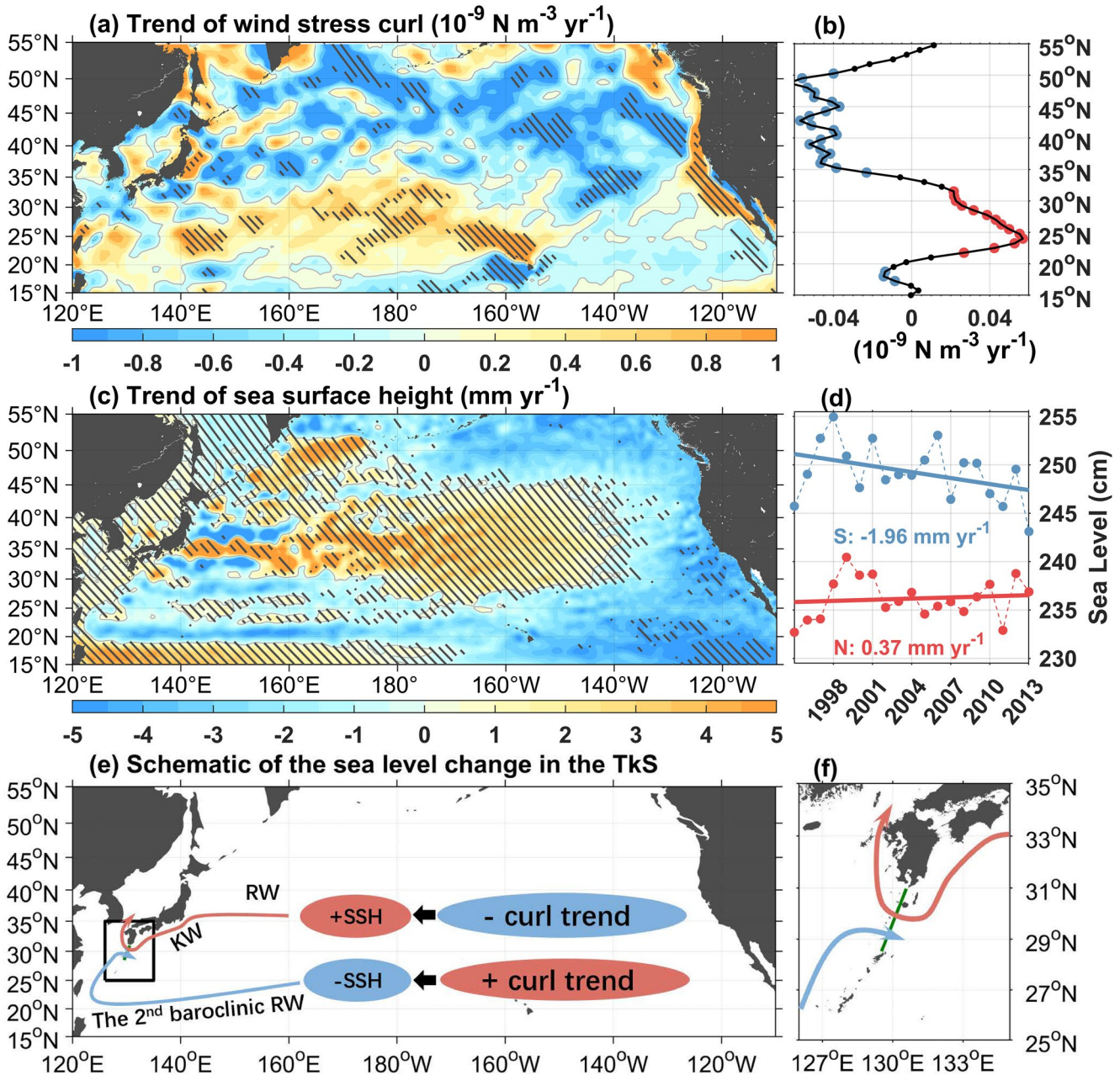


Figure 4. (a) Linear trends of wind stress curl (colors in units of $10^{-9} \text{ N m}^{-3} \text{ year}^{-1}$). Hatchings indicate statistical significance at the 90% confidence level. (b) Linear trends of zonal mean wind stress curl. Blue (red) dots denote negative (positive) trends above the 90% confidence level. (c) Linear trend of the sea surface height (SSH; mm year^{-1} ; color shading) derived from satellite data during 1995–2013. The linear trend in the global mean SSH (approximately $0.24 \text{ cm year}^{-1}$) has been removed. Hatchings indicate statistical significance at the 90% confidence level. Gray contours indicate no trend. (d) Sea-level linear trend based on tide-gauge data at Naze (blue) and Nishinoomote (red). The global mean sea level has been removed. (e, f) Schematics of the sea-level changes in the North Pacific and around the Tokara Strait. In (f), the green line indicates the cruise line of the ferryboat ADCP as shown in Figure 1d.

suppressed by the increased number of cyclonic eddies around the STCC-NEC zone due to intensified tropical cyclones during the hiatus period. Moreover, water exchange between the North Pacific and the ECS through the Ryukyu Islands chain likely led to a different weakening tendency between the Kuroshio east of Taiwan and that in the Tokara Strait. To address this issue, further studies are necessary.

Decadal pycnocline changes in the weakened Kuroshio were related to the Rossby wave adjustment, and not to advection of the modified water mass. This is probably because the nonuniform warming of the

subsurface ocean temperature, caused by ocean subduction and advection processes (Chen et al., 2019), may be the primary reason for the phenomena with much longer time scale spanning nearly 100 years.

Wind stress changes in the North Pacific provide the dynamical conditions for the weakened Kuroshio transport according to Sverdrup theory (Wang et al., 2016). Our study showed that the weakened Kuroshio across the Tokara Strait was attributable to remote wind stress curl changes in two latitudinal bands: the northern (35°N–45°N) and the southern (20°N–30°N) bands. Because of the decreasing wind stress curl in the northern band, a positive SSH anomaly formed, propagated to the west, and then arrived at the eastern coast of mainland Japan. The signal then propagated in the clockwise direction around the mainland Japan as baroclinic-mode coastal trapped waves and raised sea level on the northern side of the Tokara Strait. Conversely, the negative SSH anomaly caused by the increasing wind stress curl in the southern band tended to extend westward with a southward tendency, which was attributed to the propagation of the SSH anomaly along the characteristics for the second baroclinic mode. This signal would be advected downstream along the Kuroshio, decreasing the sea level on the southern side of the Tokara Strait. The opposing sea-level trends across the Tokara Strait led to the weakened Kuroshio transport. The increasing sea-level trend along the southern coast of Japan was also clarified by Kida et al. (2020), who suggested that the increasing trend was forced by a northward shift of the Kuroshio axis south of mainland Japan. Northward shifts of the Kuroshio axis south of mainland Japan are induced by westward-propagating jet-trapped Rossby waves (Sasaki et al., 2014). Hence, the coastal sea-level rise is under the direct influence of upper ocean changes caused by wind forcing changes.

The wind stress curl changes associated with weakened westerlies and intensified easterlies during 1995–2013 are considered as an aspect of the global warming hiatus and are related to the negative phase of the Pacific Decadal Oscillation, as reported in previous studies (Trenberth et al., 2014; Wang & Wu, 2018). According to Hu and Fedorov (2017) and Wang and Wu (2018), the hiatus ended around 2012–2013, after which global warming accelerated again. The Kuroshio transport through the Tokara Strait during 1998–2018 was weakened by approximately 0.03 Sv year⁻¹ (Figure S3), less than the 0.05 Sv year⁻¹ observed during 1998–2013. Hence, the Kuroshio transport may have increased as in the period before the hiatus, and this remains to be determined in future studies.

Data Availability Statement

The data used in this study are available from https://figshare.com/articles/dataset/data_in_Tokara_Strait/14221940.

Acknowledgments

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