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Key Points:
- A systemwide weakened Kuroshio is found during 1993–2013, capable of redistributing mass and energy between the marginal seas and Pacific
- Weakened westerlies and cyclonic wind stress curl are the most responsible for the weakened Kuroshio
- The basin wind stress curl may be a potent indicator for the Kuroshio strength in the future

Supporting Information:
- Supporting Information S1

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Warming and weakening trends of the Kuroshio during 1993–2013

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Abstract Global warming seems leveling off somewhat during 1993–2013 despite increasing atmospheric greenhouse gases. What has happened to the Kuroshio Current system concurrently? Available independent data sets from 1993 to 2013 point to a single answer. Here we show a systemwide weakened Kuroshio during the period despite enhanced warming along its path. The Pacific warm pool upstream of the Kuroshio is still becoming warmer during the period. It injects more heat into the Current despite the weakened Kuroshio, which is associated with weakened westerlies and cyclonic trends of basin-scale wind stress curl. The weakened Kuroshio will modulate heat and mass exchanges between the tropics and extratropics, impacting the energy balance of climate system. It will also significantly influence mass, heat, salinity, and nutrient exchanges between the Pacific and adjacent marginal seas, which in turn impacts the regional weather, fisheries, and environments.

1. Introduction

As solar heating preferentially warms the tropical ocean, the Kuroshio is vitally important to transport excess heat poleward in the North Pacific. In the last century, global warming seemed to have enhanced the transport and heat of the Kuroshio Current Extension; poleward path shift and/or strength intensification of the Kuroshio Current were suspects [*Wu et al*., 2012]. Since late 1990s, the global warming rate has been approaching a slowing down or nearly hiatus state despite increases in atmospheric greenhouse gases [*Easterling and Wehner*, 2009; *England et al*., 2014]. This slowdown shares many traits but may not be exactly synonymous with the negative phase of the well-known Pacific Decadal Oscillation (PDO) [*Mantua et al*., 1997], as weak solar activity [*Hansen et al*., 2011], stratospheric water vapor decrease [*Solomon et al*., 2010], volcanic eruptions [*Santer et al*., 2014], stratospheric aerosols increase [*Solomon et al*., 2011], enhanced ocean heat uptake [*Chen and Tung*, 2014], and cooling of central-eastern tropical Pacific [*England et al*., 2014 ; *Kosaka and Xie*, 2013; *Trenberth et al*., 2014] may also contribute to the former. These advances, through diverse, mostly point to the negative PDO and the associated trade wind strengthening around the late 1990s as two potent factors. Ideally, an accelerating Kuroshio would serve us better by transporting more heat poleward. In reality, the wind stress curl and PDO, rather than the net heat input, had more influence on the Kuroshio strength. This complicated the issue.

Even more recent studies suggest that decadal variability contributes to the global warming quasi-pause, but anthropogenic warming still dominates [*Watanabe et al*., 2014]. The global warming quasi-pause may only be a precursory artifact of upcoming warming events [*Karl et al*., 2015] still waiting to play out. Our understanding, still murky at the present time, may become increasingly clear as future samples grow in number. Pronounced changes in atmospheric circulation and surface winds came with PDO. Over the Pacific, a canonical negative PDO normally contains enhanced trade winds [*England et al*., 2014; *Kosaka and Xie*, 2013; *Trenberth et al*., 2014] and weakened westerlies [*Mantua and Hare*, 2002]. The former may enhance tropical upwelling and surface cooling, and sustain global warming quasi-pause [*England et al*., 2014]. The Kuroshio also changes in response to the changing planetary wind system.

The Kuroshio modulates the climate by transporting excess heat from tropics poleward [*Nitani*, 1972; *Kwon et al*., 2010] (Figure 1). It also affects typhoon development [*Wu et al*., 2008], fishery economy [*Tsukamoto*, 2006], and ocean circulation [*Hsin et al*., 2013; *Wu*, 2013] in surrounding marginal seas such as the East China Sea (ECS) and South China Sea (SCS) (Figure 1a). In fact, the Kuroshio exerted a stronger impact on both the ECS and SCS with more intrusion events when it weakened [*Hsin et al*., 2013; *Wu*, 2013]. Empirical correlations among satellite altimeter and tidal gauge data, Kuroshio transport and PDO along a few lines across the

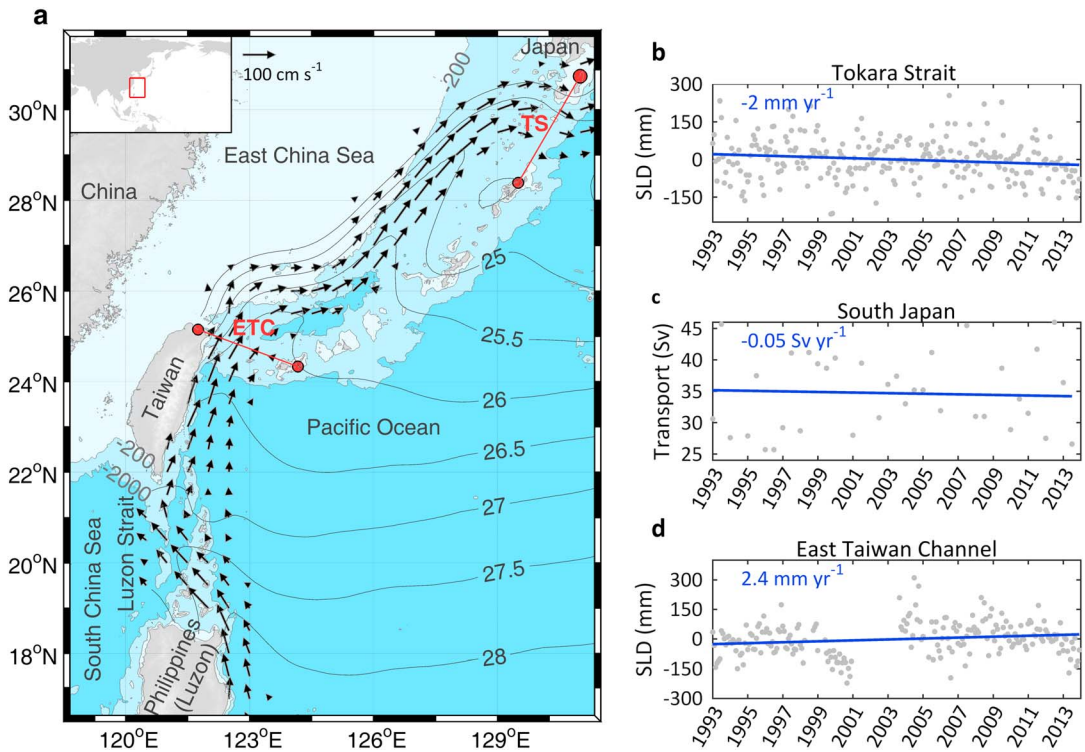

Figure 1. (a) Study area (top left), mean surface Kuroshio velocities from Argos and mean SST contours (°C) from OISST. Red dots indicate tidal stations: Naze (129.5°E, 28.383°N), Nishinoomote (131°E, 30.733°N), Ishigaki (124.17°E, 24.333°N), and Keelung (121.75°E, 25.15°N). Ocean depth contours (200 m and 2000 m), Tokara Strait (TS), and East Taiwan Channel (ETC) are shown. (b–d) Regional Kuroshio intensities from observations (dots) and linear trends (blue lines). Figure 1b shows demeaned time series and its linear trend of monthly sea level difference (SLD) across the Kuroshio in Tokara Strait (statistically significant over 90% confidence level). Figure 1c shows the Kuroshio transport inferred from hydrological cruises south of Japan along 137°E (with statistical significance below 90% confidence level). Figure 1d shows the same as Figure 1b but for the East Taiwan Channel (statistically significant over 90% confidence level).

Kuroshio indicated Kuroshio deceleration during negative PDOs [*Gordon and Giulivi*, 2004; *Andres et al*., 2009; *Han and Huang*, 2008]. On the other hand, inferred interannual changes of atmospheric forcing, a global ocean model and a coupled climate model led to the conclusion of an accelerating Kuroshio for 1992–2011 [*England et al*., 2014]. Both outcomes seem dynamically possible at a glance, depending on whether weakened westerlies or enhanced easterlies predominate. In the present study, however, our analyses of eight independent data sets point to a decelerating Kuroshio instead during 1993–2013. Section 2 describes data sets used in this study. Section 3 shows main results. Section 4 discusses basin wind field during 1993–2013 and its effect on the weakened Kuroshio, summarizing this work.

2. Data

In Figure 1, monthly tidal gauge data at Naze, Nishinoomote, Ishigaki, and Keelung (fast-delivery version) from University of Hawaii Sea Level Center (http://uhslc.soest.hawaii.edu/) were used. The sea level difference across the Tokara Strait and East Taiwan Channel was defined as deviation of Naze minus Nishinoomote and deviation of Ishigaki minus Keelung, respectively. Transport data from 137°E hydrological cruises were provided by Japan Meteorological Agency (http://www.data.jma.go.jp/gmd/kaiyou/shindan/b_2/kuroshio_-flow/kuroshio_flow.html).

Ocean surface velocities from five data sets were used, including Argos drifters data (Global Drifter Program; http://www.aoml.noaa.gov); Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO; DT-MADT "two sat merged" version, http://www.aviso.altimetry.fr); National Centers for Environmental Prediction (NCEP) Global Ocean Data Assimilation System (GODAS; http://www.esrl.noaa.gov) [*Behringer et al*., 1998]; Japan Coastal Ocean Predictability Experiment 2 (JCOPE-2; http://www.jamstec.go.jp/e/) [*Miyazawa et al*., 2009]; and Hybrid Coordinate Ocean Model (HYCOM; https://hycom.org) [*Bleck and Boudra*, 1981] (GLBu0.08 data set: "reanalysis" version from 1993–2012 and extended to 2013 by "analysis"

version). Argos data were gridded on 0.5° meshes to obtain monthly mean; meshes with gridded data occupancy less than 24 months were ignored. Argos drifters measure oceanic surface current near 15 m depth; thus, velocity data from GODAS, JCOPE-2, and HYCOM were chosen at 15 m or near 15 m depth for the monthly mean.

Six sea surface temperature (SST) data sets were used: Argos; NOAA Optimum Interpolation Sea Surface Temperature (OISST; http://www.esrl.noaa.gov/) V2 high resolution data set [*Reynolds et al*., 2007]; International Comprehensive Ocean-Atmosphere Data Set release 2.5 (ICOADS; http://icoads.noaa.gov/) [*Woodruff et al*., 2011] ("1°×1° standard" version from 1993 to 2007 plus extension to 2013 by "1°×1° standard preliminary" version); Hadley Center Sea Ice and Sea Surface Temperature data set version 1 (HadISST; http://www.metoffice.gov.uk/) [*Rayner et al*., 2003]; Group for High Resolution Sea Surface Temperature (GHRSST) ("CMC0.2deg-CMC-L4-GLOB-v2.0" version; https://podaac.jpl.nasa.gov/); and Extended Reconstructed Sea Surface Temperature v3b (ERSST; https://www.ncdc.noaa.gov/) [*Smith et al*., 2008]. The monthly mean is first derived for all data before analysis. Argos SST data were gridded on 0.5° meshes to derive monthly mean and meshes with gridded data occupancy less than 24 months were ignored.

Three surface wind stress data sets were used: National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis 1 (NCEPr1; http://www.esrl.noaa.gov) [*Kalnay et al*., 1996]; National Centers for Environmental Prediction-Department of Energy Atmospheric Model Intercomparison Project II (NCEP-DOE AMIP-II) Reanalysis (NCEPr2; http://www.esrl.noaa.gov) [*Kanamitsu et al*., 2002]; and European Centre for Medium-Range Weather Forecasts (http://www.ecmwf.int) Reanalysis Interim (ERA-Int) [*Dee et al*., 2011].

3. Results

3.1. Weakened Trend of the Kuroshio

The sea level difference (SLD) across the Kuroshio is often a good proxy for its intensity [*Kawabe*, 1988; *Yang et al*., 2001]. Based on geostrophy, the surface Kuroshio intensifies or weakens as SLD increases or decreases. Several logical estimates of the Kuroshio intensity have been made using the SLD from tide gauge measurements in the Tokara Strait [*Kawabe*, 1988] (marked as "TS" in Figure 1a) and the East Taiwan Channel [*Yang et al*., 2001] ("ETC" in Figure 1a). We applied this method to derive the long-term tendency of the surface Kuroshio intensity.

With a linear fit from 1993 to 2013, the monthly SLD across Tokara Strait decreased by 2 mm per year (Figure 1b), suggesting a weakening Kuroshio during the period. Analysis of repeated, long-term hydrographic survey results along 137°E to the south of Japan may lend further support, although they are not statistically significant above 90 % significance level; the inferred geostrophic Kuroshio transport was decreasing by 0.05 sverdrup (Sv) per year (Figure 1c, $1\,\mathrm{Sv} = 10^6\,\mathrm{m}^3\,\mathrm{s}^{-1}$). However, the SLD derived from tide gauges in the ETC is inconsistent, increasing at the rate of 2.4 mm per year (Figure 1d). The anomalous increase in the Kuroshio intensity appears to be highly localized phenomena that do not reflect the overall tendency; further analyses below bear this out.

Additional five data sets are used to calculate the spatial pattern of the surface Kuroshio velocity tendency, including satellite-tracked Argos drifters to derive ocean currents at 15 m depth, satellite altimeters (AVISO) for surface geostrophic currents, and ocean reanalysis products (GODAS; JCOPE-2; HYCOM) that are independent of each other in assimilation method or simulation setting. Figures 2a and 2b show the tendency pattern of the Kuroshio based on Argos drifters and altimeter-derived surface geostrophic currents, respectively. Both indicate a weakened Kuroshio (blue band) during 1993–2013, except for two localized anomalies (in red) near the northern tip of Taiwan and east of Luzon and Luzon Strait.

Weakened Kuroshio main stream is also evident in all three reanalysis products with varying magnitudes (Figure S1 in the supporting information), regardless of the shift of Kuroshio axis (Figure S2). The Kuroshio main stream means seaward of the maximum speed axis and excludes shelf. Starting from the Kuroshio main axis mostly along the 200 m isobaths, we track the Kuroshio main stream area for each data set mesh-by-mesh seaward, until the northeastward current vanishes or reverses. In Figure S2, each estimate

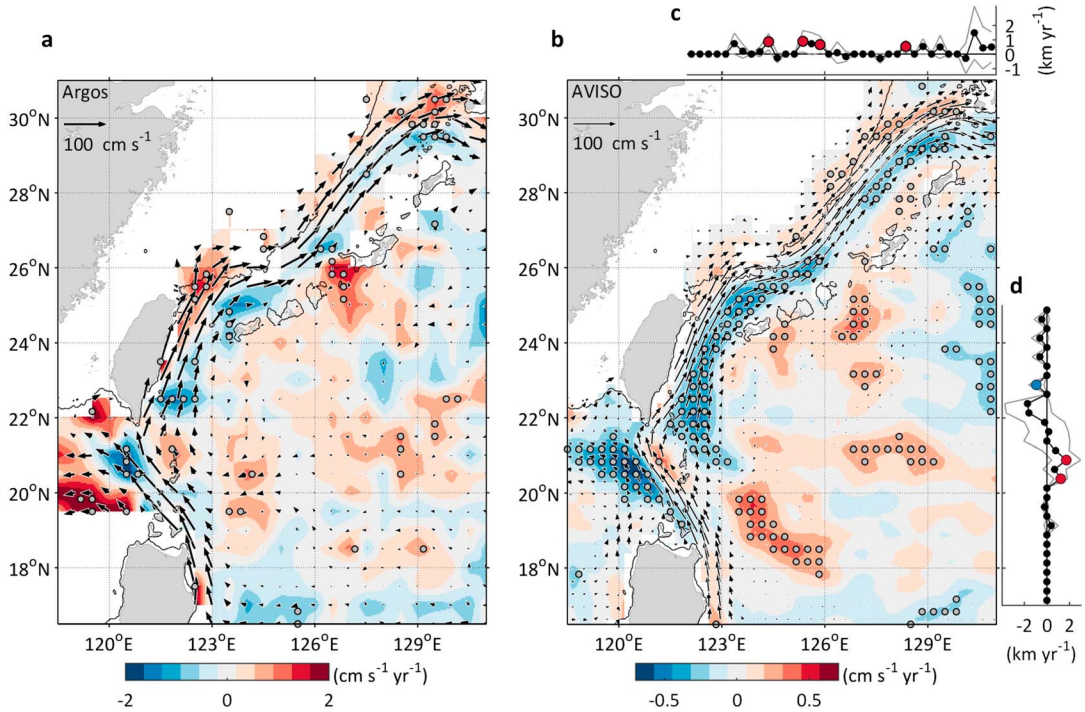

Figure 2. (a and b), Linear trends of the Kuroshio velocity (colors) and the average Kuroshio velocity (vectors) from various data sets. Gray dots indicate statistical significance above 90% confidence level. (c and d) The Kuroshio axis meridional (north of 25°N region) and zonal migration rates (south of 25°N region) with 90% confidence envelopes. Black dots are below 90% confidence level. (c) Red dots indicate higher statistical significance with northward migration. (d) Same as Figure 2c but with red and blue dots indicating eastward and westward migrations, respectively.

is a linear fit of Kuroshio velocity averaged over the time-dependent main stream (from southern tip of Taiwan to Tokara Strait) from 1993 to 2013.

Weakened (strengthened) Kuroshio usually enhances (retards) intrusions to its left [*Hsin et al.*, 2013; *Wu*, 2013], and this can explain why there is enhanced northward tendency (in red) over the ECS shelf in Figures 2a and 2b. Inferring from AVISO data, the Kuroshio axis (defined by its maximum speed) north of 25°N migrates northward by 0–1 km per year during 1993–2013 (Figure 2c), indicating enhanced Kuroshio intrusion onto the ECS shelf. To the east of Luzon Strait (~21°N), zonal migration rate of the Kuroshio axis is eastward instead (Figure 2d). The enhanced northward acceleration of Kuroshio off east Luzon (in red in Figures 2a and 2b) reduced its intrusion into the Luzon Strait during 1993–2013 [*Sheu et al.*, 2010]. The foregoing conclusion bears out in all six data sets.

Observation-validated HYCOM reanalysis product also confirms that the Kuroshio mainstream is weakening. Figure S3 shows 12 sections used to calculate the Kuroshio transport, and results are listed in Table S1, indicating that the Kuroshio transports bordering the ECS are weakened (decreasing at about 0.1 Sv yr^{-1} with statistical significance above 90% confidence level). Furthermore, basin-scale wind stress curl provides dynamical weakening condition for the weakened transport of Kuroshio according to Sverdrup transport (decreasing by about 0.4–0.5 Sv yr^{-1} with statistical significance above 90% confidence level) (Figure S4). Based on these, we conclude that the Kuroshio is weakened due to changes in the basin wind field rather than the migration of Kuroshio axis.

3.2. Ocean and Atmospheric Conditions in the North Pacific

In the face of a weakening Kuroshio, warming continues along its path northward. This somewhat counter-intuitive result is illustrated in Figures 3a and S5, in which the surface Kuroshio warming (red patches) is almost contiguous along its path (green line) northward at rates ranging up to 0.03°C per year. The warming trend also spills onto the ECS shelf. Among surface or near-surface temperature in Figure S5, the Argos drifter data differ more from others because they are at 15 m depth and gridded from near instantaneous

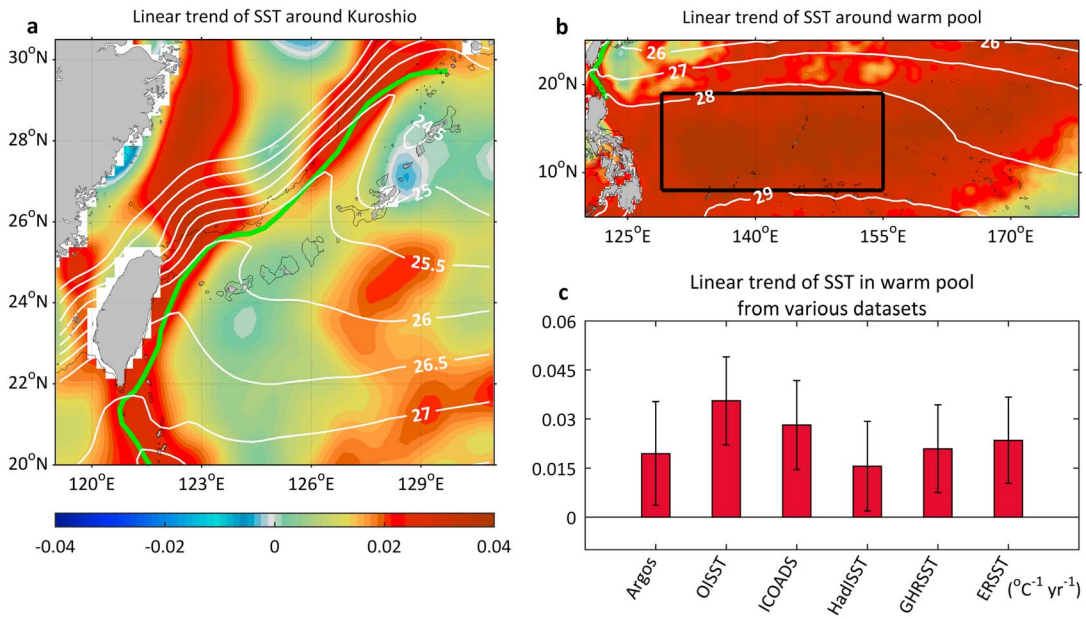

Figure 3. (a and b) Mean (white contours, in units of °C) and linear trend (colors, in units of °C yr^{-1}) of SST from OISST around Kuroshio in Figure 3a and around warm pool in Figure 3b. Green curve indicates the mean axis of Kuroshio based on AVISO. Thin black curve indicates 200 m isobath. (c) Linear trend of SST in the proxy area of warm pool (delineated by a black rectangle in Figure 3b) from various data sets. Error bars indicate 90% confidence interval.

measurements that lack time resolution at gridded meshes in space. Tracing back to the source region of the Kuroshio, Figure 3b shows an even higher warming rate (up to 0.04°C per year) in the western Pacific warm pool, consistent with recent findings [*England et al.*, 2014]. We further demonstrate this warming trend using six SST data sets including Argos, OISST, ICOADS, HadISST, GHRSST, and ERSST; all suggested enhanced warming in the warm pool (Figures 3c and S6). It is therefore entirely feasible for the slower conveyor duct (the Kuroshio) to move more heat away from a warmer source (the warm pool).

Figures 4a–4c show the weakened westerlies tendency over the Pacific based in three wind products (NCEPr1, NCEPr2, and ERA-Int). The familiar climatology wind stress pattern and its linear trend are also shown in Figure S7. With westerlies in the north and trade winds in the south, the consequent negative wind stress curl (WSC) drives the Kuroshio. This negative WSC weakens during the 1993–2013. The dominance of positive (less negative) WSC trend shows up as patches (Figures 4a–4c and S7). After zonal averaging, all three wind products show positive WSC trend (10^{-9} N m^{-3} yr^{-1}, statistical significance at 90% confidence level) in major latitudes of interest (20–30°N, gray shading in Figures 4d–4f). In other words, the weakened tendency of the surface Kuroshio can be attributed to changes in westerlies and WSC in the North Pacific. However, the Pacific warm pool upstream of the Kuroshio is getting warmer and injects more heat into the Kuroshio despite its weakened transport.

4. Discussion and Conclusion

The so-called global warming hiatus can be redeemed in the context of Pacific Decadal Oscillation. Since mid-1990s, the PDO has been oscillating about a decreasing trend from positive to negative, during which one expects weaker westerlies, strengthened easterlies, warmer Kuroshio Extension Current, and cooler tropical Pacific. Trends during 1993–2013 retained these features. However, no two negative PDOs are exactly alike. The weakened westerlies and strengthened easterlies waxed and waned during a negative PDO. If stronger trade winds predominate, the negative WSC and Kuroshio will likely be strengthened. This is the scenario put forth recently [*England et al.*, 2014]. As we check for consistency among three wind products (NCEPr1, NCEPr2, and ERA-Int), only one (ERA-Int) shows predominance of enhanced trade winds and may have led to the speculation of strengthening Kuroshio [*England et al.*, 2014]. Our investigation points to the predominance of decelerating westerlies instead (Figures 4a–4c), leading to weaker negative WSC and weaker Kuroshio. In addition to 1993–2013 trends (Figures 4a–4c), we also constructed a composite,

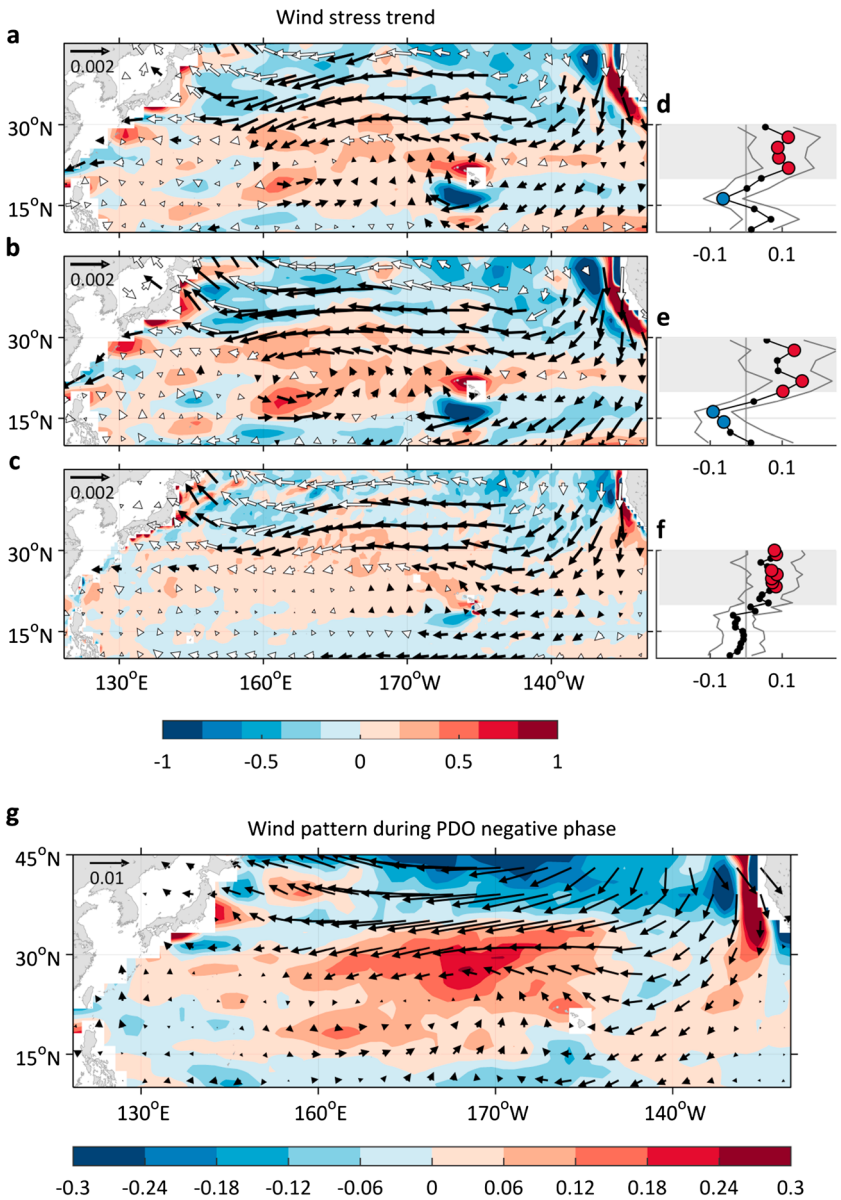

Figure 4. (a–c) Linear trends of wind stress vectors in units of N m^{-2} yr^{-1} and wind stress curl (WSC, colors in units of 10^{-8} N m^{-3} yr^{-1}) from various data sets. Black (white) arrows are above (below) 90% confidence level. (d–f) Corresponding linear trends of zonally (118.5–240°E) averaged WSC (10^{-8} N m^{-3} yr^{-1}) with 90% confidence envelopes. Shading indicates 20–30°N region. Red (blue) dots indicate positive (negative) trend above 90% confidence level. Black dots are below 90% confidence level. (g) The 1950–2013 composite of PDO negative phase from NCEPr1. Vectors and colors indicate wind stress in units of N m^{-2} and WSC in units of 10^{-7} N m^{-3}, respectively.

canonical negative PDO wind stress, and WSC anomalies during 1950–2013 (Figure 4g). Relevant data are demeaned for each month and averaged for all negative PDOs during the period. The 1950–2013 negative PDO anomalies (Figure 4g) are strikingly similar to 1993–2013 trends (Figures 4a–4c), implying that the wind trend during 1993–2013 is dominated by a negative PDO regime shift.

We conclude with a weaker and warmer Kuroshio during 1993–2013, capable of redistributing mass and energy between the marginal seas and Pacific by conveying less heat into the SCS but more heat into the ECS, from the warming western North Pacific warm pool. The redistribution may trigger regional climate changes and extreme events. For instance, enhanced warming in the western North Pacific warm pool may feed the growth of extreme tropical cyclones, such as the "Category-6" supertyphoon event in 2013

[*Lin et al*., 2014]. A warmer ECS may enhance precipitation in surrounding areas [*Manda et al*., 2014]. The PDO phase change still rules this episode [*England et al*., 2014; *Trenberth et al*., 2014]. The basin wind stress curl may be a potent indicator for the Kuroshio strength in the future. Climate models should reproduce the wind pattern to monitor long-term variability in the western North Pacific.

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