AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

10.1002/2017JC012944

Key Points:

- A 52 year coral $\delta^{18}O$ record of Kuroshio Current transport was constructed from southern Taiwan
- Asynchronous changes were observed in different meridional sections of the Kuroshio Current, even in upstream regions
- A complicated relationship exists between the Kuroshio Current and atmospheric/oceanic patterns in the Pacific

Supporting Information:

- Supporting Information S1
- Data Set S1

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Citation:

Li, X., Y. Liu, Y.-C. Hsin, W. Liu, Z. Shi, H.-W. Chiang, and C.-C. Shen (2017), Coral record of variability in the upstream Kuroshio Current during 1953–2004, *J. Geophys. Res. Oceans*, *122*, 6936–6946, doi:10.1002/2017JC012944.

Received 31 MAR 2017
Accepted 3 AUG 2017
Accepted article online 11 AUG 2017
Published online 30 AUG 2017

Coral record of variability in the upstream Kuroshio Current during 1953–2004

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Abstract The Kuroshio Current (KC), one of the most important western boundary currents in the North Pacific Ocean, strongly affects regional hydroclimate in East Asia and upper ocean thermal structure. Limited by few on-site observations, the responses of the KC to regional and remote climate forcings are still poorly understood. Here we use monthly coral $\delta^{18}O$ data to reconstruct a KC transport record with annual to interannual resolution for the interval 1953–2004. The field site is located in southern Taiwan on the western flank of the upstream KC. Increased (reduced) KC transport would generate strong (weak) upwelling, resulting in relatively high (low) local coral $\delta^{18}O$. The upstream KC transport and downstream transport, off Tatsukushi Bay, Japan, covary on interannual and decadal time scales. This suggests common forcings, such as meridional drift of the North Equatorial Current bifurcation, or zonal climatic oscillations in the Pacific. The intensities of KC transport off southeastern and northeastern Taiwan are in phase before 1990 and antiphase after 1990. This difference may be due to a poleward shift of the subtropical western boundary current as a response to global warming.

Plain Language Summary The connection between climate and oceanic circulation has long been recognized, particularly with regard to western boundary currents such as the Gulf Stream and the Kuroshio Current (KC). These systems play a crucial role in transferring solar energy from the subtropical regions to the poles. As we begin to experience the impacts of global climate change, it is critical that we understand the affect global change has on variability leading to significant changes in the structure and heat transport of such currents. Current knowledge of the KC is limited to observations over individual 10 year periods or to paleorecords of very low resolution (one sample per roughly 1000 years). Neither data set allows for a detailed understanding of the natural variability of the KC, nor does it allow for a thorough investigation of potential driving forces in ocean circulation, such as the Pacific Decadal Oscillation (PDO) or the El Nino Southern Oscillation (ENSO). Here we reconstruct a long-term record of KC transport since 1950 using high-resolution coral records from southeastern Taiwan, to provide new insights into KC dynamics under the current global warming trend.

1. Introduction

The western boundary currents (WBCs) of global oceans play a key role in the interhemispheric and intrahemispheric coupling of climate change between the tropical and high-latitude realms [*Hogg and Johns*, 1995; *Hu et al.*, 2015; *Seager and Simpson*, 2016; *Yang et al.*, 2016]. The Kuroshio Current (KC) is one of the most important WBCs globally. It originates in the northern branch of the North Equatorial Current (NEC) in the Pacific and carries warm tropical water masses poleward. It is an important source of heat and moisture to the atmosphere and strongly influences regional hydroclimate and carbon cycling [*Wu et al.*, 2012].

Oceans are taking up ~90% of the expected energy imbalance associated with increasing greenhouse gases [*Trenberth and Fasullo*, 2013]. The potential effects of global warming on the KC and other WBCs have raised significant concerns [*Ridgway et al.*, 2008; *Goni et al.*, 2011; *Wu et al.*, 2012; *Hu et al.*, 2015; *Yang et al.*, 2016]. For example, enhanced warming in the path of subtropical WBCs is 2–3 times faster than the global mean [*Wu et al*., 2012]. A decreasing trend in downstream KC transport since the 1900s has been inferred from the abrupt freshening of surface waters off the Ogasawara Islands, possibly caused by weakened winds [*Felis et al*., 2009]. The volume transport of the Loop Current, part of the North Atlantic WBC, has been reduced considerably, by 20–25%, in the 21st century [*Liu et al*., 2012].

Current knowledge about KC drift is based mainly on intermittent individual surveys, satellite data, and numerical models [*Hwang and Kao*, 2002; *Hsin et al*., 2008, 2013; *Chang and Oey*, 2011; *Yang et al*., 2012; *Hsin*, 2015]. The history of the KC beyond the timeframe covered by instrumental observations has been reconstructed primarily using proxy records in marine sediments [*Sawada and Handa*, 1998; *Ujiié and Ujiié*, 1999; *Liu et al*., 2013]. Planktonic foraminiferal assemblages, and the stable isotope compositions of their calcium carbonate tests, have been used to reconstruct past KC intensities and flow paths since the Last Glacial Maximum [*Li et al*., 1997; *Jian et al*., 2000; *Ijiri et al*., 2005]. A comprehensive analysis of planktonic foraminifera, clay minerals, and geochemical characteristics of sediment cores from the northeastern South China Sea (SCS) has provided evidence for the impact of the KC intrusion in the region [*Liu et al*., 2013].

Instrumental and paleodata have significantly advanced our understanding of the structure of the KC, its seasonal to interannual variability, how it changes on millennial to glacial-interglacial time scales, and its climatic impacts. However, the lack of continuous on-site records hinders an in-depth understanding of the natural variability of the KC over the past decades. *Yamazaki et al*. [2016] used annually resolved coral skeletal nitrogen isotope (δ^{15}N) records to reconstruct changes in the KC transport pathway off Tatsukushi Bay, Japan (32°47′N, 132°52′E) for the interval 1859–2008. However, the upstream and downstream components of the KC might not drift concurrently [*Qiu*, 2001; *Hsin*, 2015]. Studies have shown that the intensity of the KC in the area bordering Taiwan is similar to that in the southern East China Sea (ECS) [*Soeyanto et al*., 2014; *Hsin*, 2015]; while the intensity of the KC east of Luzon fluctuates in the opposite sense of that off eastern Taiwan [*Hsin*, 2015]. Multidecadal, high-resolution, upstream on-site KC records are required to fully understand the entire Kuroshio system.

In this study, we generated δ^{18}O profiles with biweekly resolution from a core taken from a living *Porites lutea* from southern Taiwan, on the western flank of the upstream KC. Our main goals are to (1) explore the possibility of using local coral δ^{18}O data to infer changes in transport in the upstream KC; (2) reconstruct a KC transport history back to the 1950s; and (3) evaluate the relationship between upstream KC transport and other hydroclimatic subsystems, such as those linked to the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO), as well as changing oceanic currents that are associated with current global warming.

2. Methodology and Sampling

2.1. Climatology of the Study Site

The KC off eastern Taiwan is 100–150 km wide with a speed of up to 100 cm s^{-1}, as shown by instrumental data from profiles through the current [*Liang et al*., 2003]. The estimated volumetric rate of northward KC transport is 15–47 Sv (1 Sv = 10^{6} m^{3} s^{-1}) [*Nitani*, 1972; *Chu*, 1976; *Liu*, 1983; *Lee et al*., 2001; *Liang et al*., 2003; *Hsin et al*., 2008]. Significant seasonal and interannual variations of the KC off the eastern coast of Taiwan are also observed. The intensity of surface Kuroshio is relatively weak in winter ($\sim$8 $\times$ 10^{4} m^{2} s^{-1}) and strong in summer ($\sim$10 $\times$ 10^{4} m^{2} s^{-1}) [*Hsin et al*., 2013]. On interannual scales, KC transport may become more intense during PDO warm-phase periods; e.g., during the intervals 1995–1997 and 2004–2007 [*Hsin et al*., 2013].

Nanwan Bay (21°56′N, 120°44′E), a semienclosed bay located at the southern tip of Taiwan, opens southward to face the Luzon Strait, with a submerged reef located $\sim$5 km south of the coast [*Shen et al*., 2005a, Figure 1b]. The warm KC strongly affects the hydrographic conditions of the sea surface offshore from southern Taiwan [*Chiang et al*., 2010; *Hsin*, 2015]. Strong upwelling along the path of the KC could be induced by a combination of turbulence and topography [*Ito et al*., 1995; *Kaneko et al*., 2012]. Southern Taiwan is subjected to a high degree of interannual variability in sea surface temperature (SST) (Figure 2). In addition to natural seasonality, this variability is associated mainly with cold upwelling induced by the KC [*Chen et al*., 2004; *Shen et al*., 2005a; *Jan et al*., 2012]. Monthly mean SSTs at Nanwan range from 24.4°C in

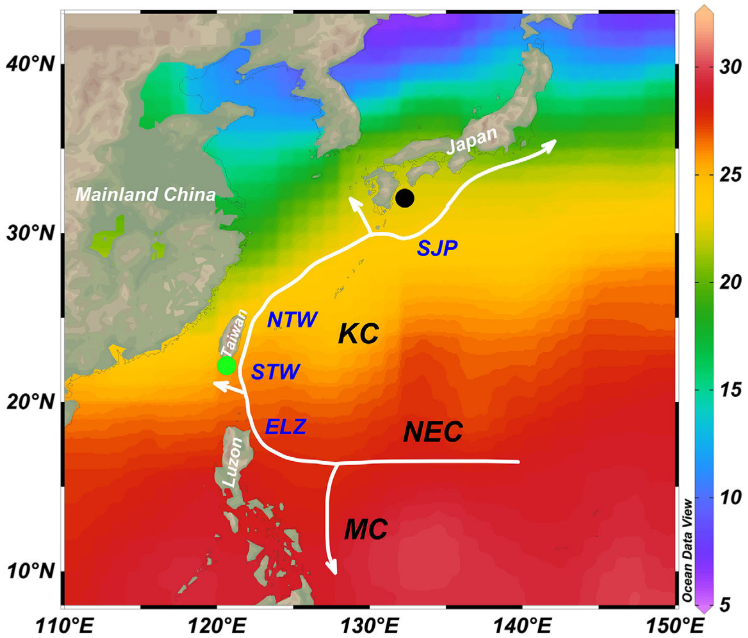

Figure 1. A SST map with the North Equatorial Current (NEC) and its branches of the Kuroshio Current (KC) and the Mindanao Current (MC). Green circle shows the collection site of the Nanwan coral. Black circle is the collection site of Tatsukushi Bay coral [*Yamazaki et al.*, 2016]. ELZ, STW, NTW, and SJP respectively denote four sectors of east of Luzon, southeast of Taiwan, northeast of Taiwan, and south of Japan along the KC path. Average SST image was created with Ocean Data View [*Schlitzer*, 2008] and data in the period of 1982–2016 are obtained from *Reynolds et al.* [2002], http://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/.monthly/.sst.

January to 29.2°C in July (Figure 2a). More than 90% of the local annual rainfall (2000 ± 500 mm: 1971–2000) falls in the summer rainy season [*Shen et al.*, 2005b; *Chiang et al.*, 2010].

2.2. Coral Sampling and Methods

On 9 May 2006, a vertical coral core, 100 cm in length and 8 cm in diameter, was drilled from the vertical maximum growth axis of a living massive *P. lutea* coral colony 5 m below the sea surface in Nanwan Bay (Figure 1). Using the method described in *DeLong et al.* [2013], the core was sliced longitudinally along the axis of growth to reveal medial transects of the corallites. Once retrieved, the core was washed with pure water and dried. Five millimeter-thick slabs were

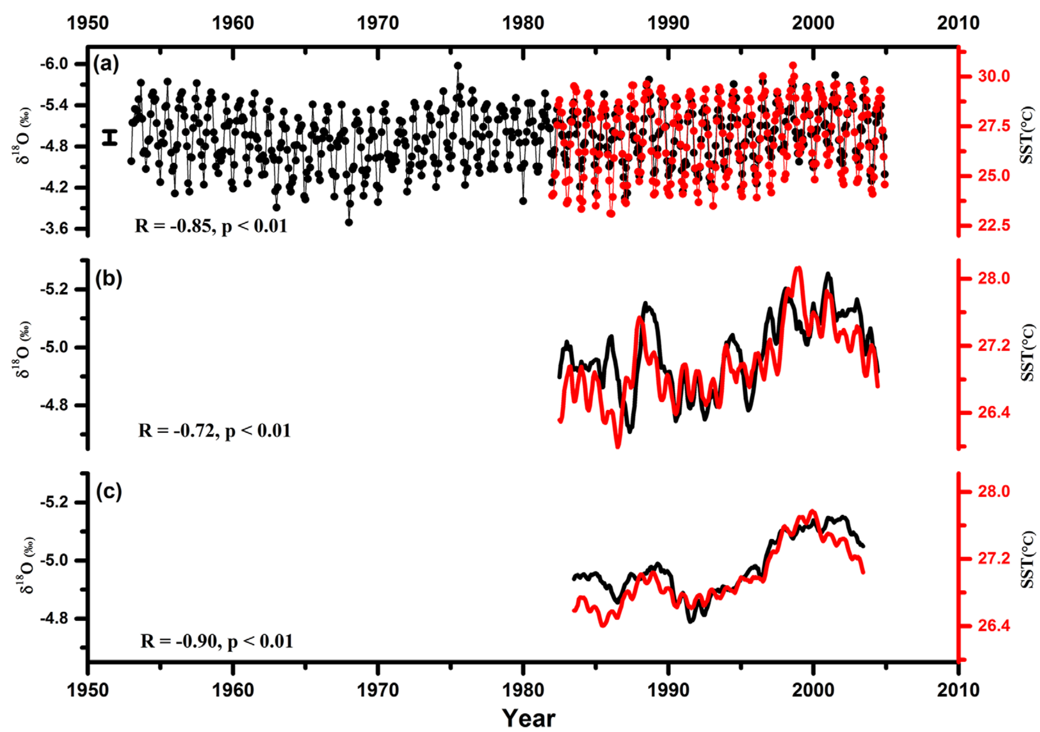

Figure 2. Comparison of coral δ^{18}O and Nanwan SST time series from the Integrated Global Ocean Services System (IGOSS) [*Reynolds et al.*, 2002]. (a) Monthly time series of δ^{18}O (solid black dot) and SST (solid red dot). Error bar represents analytical precision (1σ), positioned on the means. (b) One year running averages of δ^{18}O (black curve) and SST (red curve). (c) Same as Figure 2b but for 3 year running averages.

cut, washed with ultrapure water, and dried. Coral slabs were kept in 10% H_2O_2 for 24 h to decompose organic matter and were then washed with ultrapure water by ultrasonic cleaning for 15–20 min 3 times. X-ray images reveal clear annual density bands in the slab (supporting information Figure S1a), spanning the interval 1953–2006. Based on the width of each band, the average growth rate of the coral was 19.4 mm yr^{-1}. The top 20 mm segment, which included the tissue layer, was not used in our analyses.

Powdered subsamples, 150 μg each, were taken at 0.9 mm intervals (>22 subsamples/yr). The sampling paths are along the central axis of the corallite fan (supporting information Figure S1a), and the corallite are parallel to the surface. Stable oxygen isotope ratio was measured using a Finnigan MAT-252 gas-sourced mass spectrometer housed at the Institute of Earth Environment, Chinese Academy of Science, Xi'an, China. The results are expressed using delta (δ) notation relative to the Vienna Pee Dee Belemnite (V-PDB) standard. Stable isotope precision for $\delta^{18}O$ determined by analysis of the Chinese national standard calcite sample GBW04405 over the course of 2 months was $\pm 0.09‰$ (1σ; n = 138). Sr/Ca ratios of the same powdered subsamples for $\delta^{18}O$ over the period from 1980 to 2004 were determined on an inductively coupled plasma sector field mass spectrometer (ICP-SF-MS), Thermo Electron ELEMENT II, housed at the High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University [*Lo et al.*, 2014]. External precision for Sr/Ca determination by analyzing the in-house standard CORAL-M [*Shen et al.*, 2007] over the course of 1 month was ± 0.02 mmol/mol (1σ; n = 519).

A chronology for coral geochemical records was established by assigning $\delta^{18}O_{coral}$ maxima to SST minima in January (based on on-site SST data) [*Shen et al.*, 1996; *Chiang et al.*, 2010] for each annual cycle and then interpolating monthly intervals (12 points/yr) following the approach of *Charles et al.* [1997] and *Al-Rousan et al.* [2002]. We also followed previous studies [*Felis et al.*, 2009; *Yamazaki et al.*, 2016] to build 1 and 3 year running averaged records to suppress local intraannual variability of solar insolation and SST. Smoothing was performed using the Paleontological Statistics (PAST) software [*Hammer et al.*, 2001].

2.3. Hydroclimatic and Oceanic Data

We used the 1° × 1° Integrated Global Ocean Services System (IGOSS) SST data [*Reynolds et al.*, 2002] (http://iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/.Reyn_SmithOIv2/.monthly/.sst) in this study. Monthly precipitation data from 1965 to 2004 at 0.5° spatial resolution were obtained from [*Becker et al.*, 2011] (https://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html). Monthly KC transport data offshore southeastern Taiwan (KT_{STW}) for the interval 1993–2004 came from *Hsin et al.* [2013] and were based on gridded altimeter-based absolute geostrophic velocity data. A data set of NEC bifurcation latitude (NBL) came from *Qiu and Chen* [2010b] and was based on sea surface height anomalies. The record of PDO index poleward of 20°N, appears to be the leading driver of monthly SST anomalies in the North Pacific Ocean [*Mantua et al.*, 1997] (http://research.jisao.washington.edu/pdo/PDO.latest). The ENSO index time series is based on Niño-3.4 SST data and is used to calculate the Extended Reconstruction of Global Sea Surface Temperature Anomaly (ERSSTA) over the region 5°S–5°N, 170°W–120°W [*Smith et al.*, 2008].

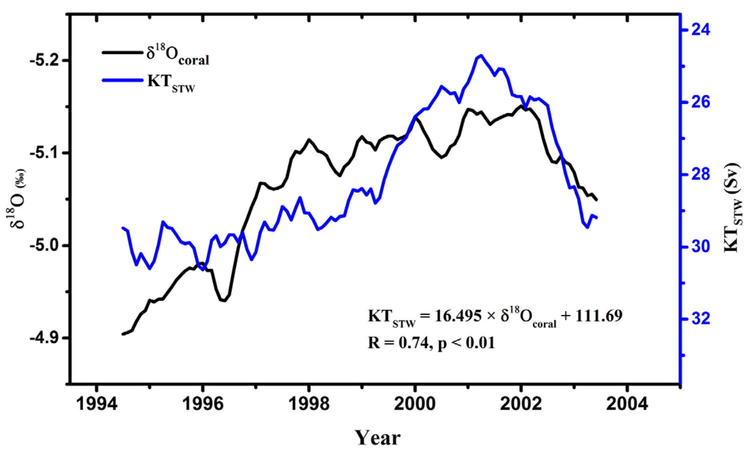

Figure 3. Comparison of 3 year running averages of Nanwan coral $\delta^{18}O$ (black curve) with the KC transport off the STW. KT_{STW} data (blue curve) are based on gridded altimeter-based absolute geostrophic velocity in 1993–2004 [*Hsin et al.*, 2013].

3. Results and Discussion

3.1. Coral $\delta^{18}O$ Record and SSTs

A total of 52 annual cycles (1953–2004) of the measured Nanwan $\delta^{18}O_{coral}$ sequence are illustrated in supporting information Figure S1b, where they are matched with the annual light and dark (low and high density) couplets identified on the X-ray image (supporting information Figure S1a). Resampled monthly resolved

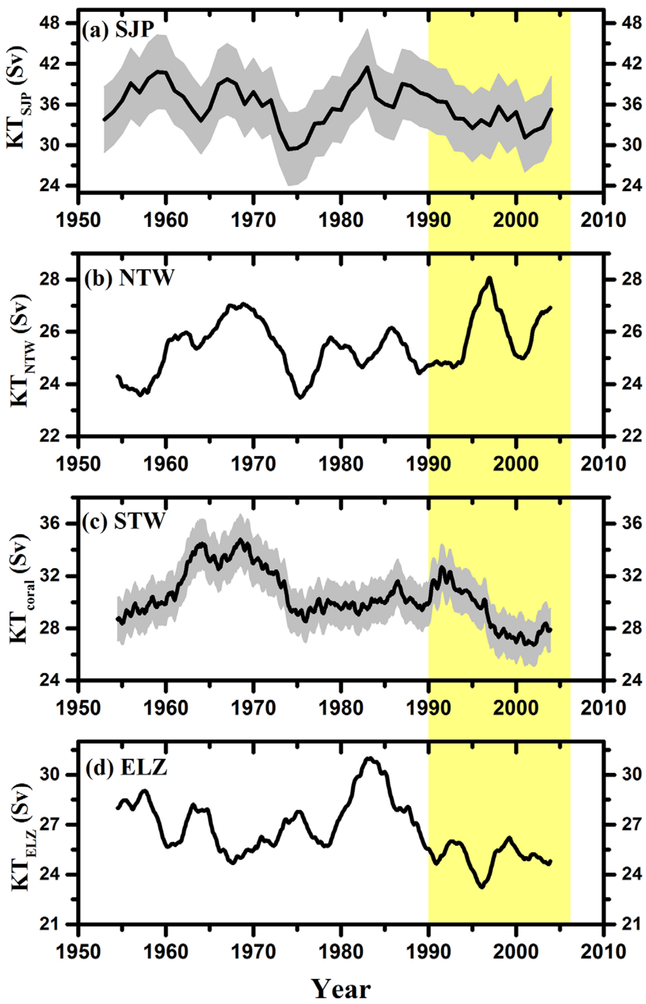

Figure 4. Three year (black curve) running averages of the KC transport in the four sectors along the KC path: (a) SJP record [*Yamazaki et al.*, 2016], (b) NTW [*Hsin*, 2015], (c) STW (KT_{coral}) in this study, and (d) ELZ [*Hsin*, 2015]. Yellow shaded area denotes the period after 1990. Regression errors ($\pm 1\sigma$, Sv) are shown in the gray areas of Figures 4a and 4c. The detailed descriptions about methods for the reconstruction error of KC transport are shown in the supporting information.

$\delta^{18}O_{coral}$ data (Figure 2a) averaged $-4.9 \pm 0.4‰$ and varied from $-5.49‰$ in summer to $-4.32‰$ in winter. Changes in $\delta^{18}O_{coral}$ are governed by both SST and seawater $\delta^{18}O$, with the latter relating primarily to salinity [*McCulloch et al.*, 1994; *Pfeiffer et al.*, 2006; *Goodkin et al.*, 2008; *Felis et al.*, 2009]. The regional sea surface salinity (SSS) is controlled mainly by freshwater input [*Shen et al.*, 2005a]. There is no river near Nanwan Bay. The mass contribution of freshwater in the bay, primarily from precipitation and surface runoff, is very low, representing only $\sim$2% of the total bay water mass in the summer rainy season [*Shen et al.*, 2005b]. On average, SSS values vary from 33.5 psu in the wet season to 34.4 psu in the dry season, yielding a small seasonal variability of only 0.9 psu or less [*Shen et al.*, 2005b]. The seasonal change in bay water $\delta^{18}O$ was only $0.20 \pm 0.05‰$ in 1993 and 1995 [*Shen et al.*, 2005b], accounting for <17% of the seasonal $\delta^{18}O_{coral}$ variation. A negligible correlation (R = −0.03) between precipitation and $\delta^{18}O_{coral}$ is observed (supporting information Figure S2). Hence, the $\delta^{18}O_{coral}$ data primarily reflect seasonal SST changes of about 5°C (IGOSS SST; Figure 2a).

A linear regression between monthly $\delta^{18}O_{coral}$ values and SST results in the following equation: $\delta^{18}O_{coral} = -0.176$ (± 0.007, 1σ) $\times$ SST – 0.225 (± 0.180, 1σ) (R = −0.85, n = 276, $p < 0.01$, 1982–2004). The strong correlation supports our argument that changes in $\delta^{18}O_{coral}$ are controlled mainly by temperature, rather than by seawater $\delta^{18}O$. Annual $\delta^{18}O_{coral}$ values are also strongly correlated with SST [$\delta^{18}O_{coral} = -0.208$ (± 0.013, 1σ) $\times$ SST + 0.618 (± 0.338, 1σ) (R = −0.72, n = 264, $p < 0.01$, 1982–2004)], as shown in Figure 2b. The $\delta^{18}O_{coral}$ time series data, expressed as 1 year running averages, ranges from a minimum of $-5.23‰$ in 2000 to a maximum of $-4.71‰$ in 1987. This time series shows synchronous fluctuations with those in the annual SST data, which range from 26.1°C to 28.1°C, showing that $\sim$80% of the annual change in $\delta^{18}O_{coral}$ values can be attributed to SST. A very strong correlation (R = −0.90, n = 240, $p < 0.01$) illustrated in Figure 2c for 3 year running averages indicates that our $\delta^{18}O_{coral}$ values primarily reflect thermal conditions on annual-interannual time scales. A significant correlation (R = 0.84, $p < 0.01$) between $\delta^{18}O_{coral}$ and Sr/Ca (supporting information Figure S1b), considered to be primarily controlled by SST [*Shen et al.*, 1996; *Yu et al.*, 2005; *DeLong et al.*, 2007, 2012], also supports this view.

3.2. Reconstruction of Kuroshio Current Transport

Kuroshio-induced upwelling is one of the major features of the KC path, as demonstrated by satellite observations, cruise data, and modeling results [*Liu et al.*, 1992; *Ito et al.*, 1995]. Owing to the presence of two pronounced meridional ridges (the Heng-Chun Ridge and the Luzon Island Arc), baroclinic tides can be

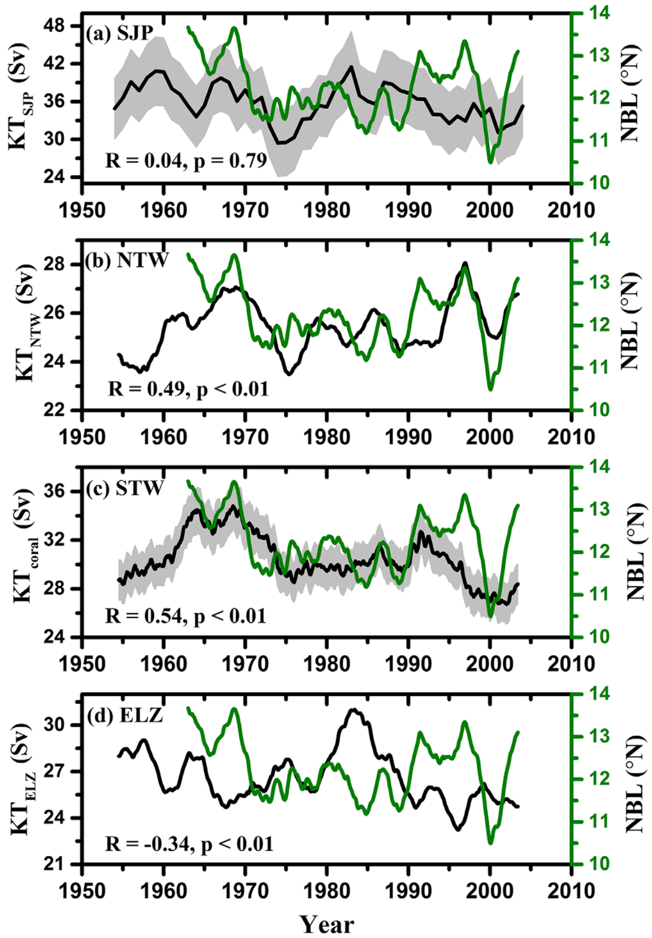

Figure 5. Comparison of 3 year running averages of the KC transport (black curve) in the four sectors along the KC path: (a) SJP [*Yamazaki et al*., 2016], (b) NTW [*Hsin*, 2015], (c) STW (KT_{coral}) in this study, and (d) ELZ [*Hsin*, 2015] with the NBL record (olive curve), derived from the sea surface height anomalies during 1962–2004 [*Qiu and Chen*, 2010b]. Regression errors ($\pm 1\sigma$, Sv) are shown in the gray areas of Figures 5a and 5c.

generated in Nanwan Bay [*Chao et al*., 2007; *Jan et al*., 2012]. In the velocity field of westward-propagating baroclinic tides, the northward-flowing KC can enhance upwelling at the velocity convergence zone by increasing the northward compensation flow at the density hump [*Jan et al*., 2012]. At present, up to 75% of Nanwan water is from the upwelled water mass and 23–25% from offshore surface waters [*Shen et al*., 2005a]. SSTs in the bay are therefore about 1°C lower than those outside of the bay [*Chen et al*., 2004]. Increased (reduced) KC transport is expected to generate strong (weak) upwelling, resulting in relatively low (high) SSTs recorded in the coral skeleton in the bay. The local temperature-dominated $\delta^{18}O_{coral}$ signal can therefore be used as a proxy for KC transport. The 1 and 3 year running average time series for Nanwan $\delta^{18}O_{coral}$ values and KT_{STW} [*Hsin et al*., 2013] show significantly positive linear correlations during the interval 1993–2004. A better correlation is obtained for 3 year running averages (R = 0.74, Figure 3) than for 1 year running averages (R = 0.58, supporting information Figure S3). Agreement between variations in the $\delta^{18}O_{coral}$ data and the modern KC transport time series supports the use of our local $\delta^{18}O_{coral}$ record as a proxy for KC transport: where high $\delta^{18}O_{coral}$ values reflect strong upwelling associated with a strong KC, and vice versa.

A 52 year coral-reconstructed KC transport (KT_{coral}) record for the interval 1953–2004 was constructed using the linear regression equation, $KT_{STW} = 16.495$ ($\pm$1.393, 1σ) $\times$ $\delta^{18}O_{coral} + 111.69$ ($\pm$7.05, 1σ) (R = 0.74, $p < 0.01$), for the 3 year smoothed KT_{STW} and $\delta^{18}O_{coral}$ records (black curve in Figure 4c). This inferred KT_{coral} record displays interannual and decadal variations with amplitudes of 1–3 Sv. The KT_{coral} values are relatively low in the 1950s, and during 1973–1977, 1987–1991, and 1998–2002, whereas they are relatively high in the intervals 1962–1972, 1985–1987, and 1992–1995. Detailed calculation of the regression error is given in the supporting information.

3.3. Meridional KC Transport

Our reconstructed half-century regional KC transport records (Figure 4) reflect the different interannual and decadal dynamics at each site. The possible forcings for this variability can be evaluated by comparing time series of other upstream and downstream KC transport records, and of the NBL, PDO, and ENSO indices [*Qiu and Lukas*, 1996; *Wu*, 2013; *Hsin*, 2015; *Hu et al*., 2015; *Yamazaki et al*., 2016].

It has been suggested that KC intensity varies regionally [*Wei et al*., 2013; *Soeyanto et al*., 2014; *Hsin*, 2015]. A comparison of KT_{coral} data with direct KC transport observations is limited by the absence of in situ multidecadal observations and local tide gauge records. At present, surface geostrophic velocity records derived from

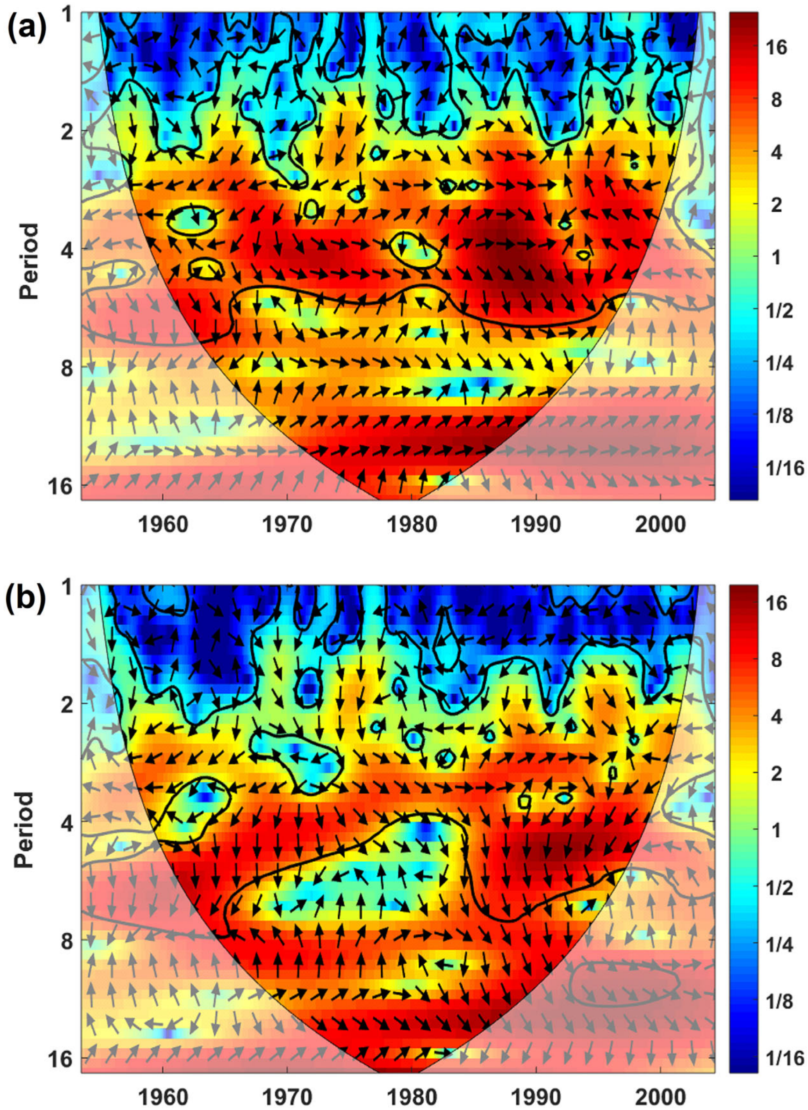

Figure 6. Cross-wavelet transform results [*Grinsted et al.*, 2004] of 1 year running averages of (a) KT_{coral} with Niño-3.4 index [*Smith et al.*, 2008] and (b) KT_{coral} with PDO index [*Mantua et al.*, 1997]. The 5% significance level against red noise is shown as a thick contour. Relative phase relationship is expressed as arrows (with in-phase pointing right, antiphase pointing left, and climate index leading KT_{coral} by 90° pointing straight down).

reconstructed sea level data [*Hsin*, 2015] can provide alternative data pertaining to past transport of the upstream KC in the northwestern Pacific Ocean. These data sets provide continuous records of upstream KC transport since 1950 in two regions near Nanwan: offshore eastern Luzon (KT_{ELZ}) in the south and offshore northeastern Taiwan in the north (KT_{NTW}; Figure 1). Figure 4 shows that before 1990 (1954–1989), KT_{coral} data were negatively correlated with the KT_{ELZ} times series ($R = -0.46$, $p < 0.01$; compare Figures 4c and 4d) and positively correlated with the KT_{NTW} data ($R = 0.79$, $p < 0.01$; compare Figures 4b and 4c).

After 1990, the relationship between KT_{coral} and KT_{ELZ} changed (Figures 4c and 4d, yellow shaded area). Both KT_{coral} and KT_{ELZ} decreased during the following 10+ years. The interannual KT_{coral} record however, followed an opposite trend to that of the KT_{NTW} record ($R = -0.37$, $p < 0.01$; compare Figures 4b and 4c). This trend is also supported by observations in a previous study based on 7 year time series of TOPEX/Poseidon altimeter data and a gravimetric geoid [*Hwang and Kao*, 2002].

The causal mechanism behind the observed different regional trends of KC transport off eastern Luzon, southeastern Taiwan, and northeastern Taiwan before and after 1990 is not clear. Eddy activity plays a major role in KC transport off northeastern Taiwan, while wind stress curl dominates KC transport off eastern Luzon [*Hsin*, 2015].

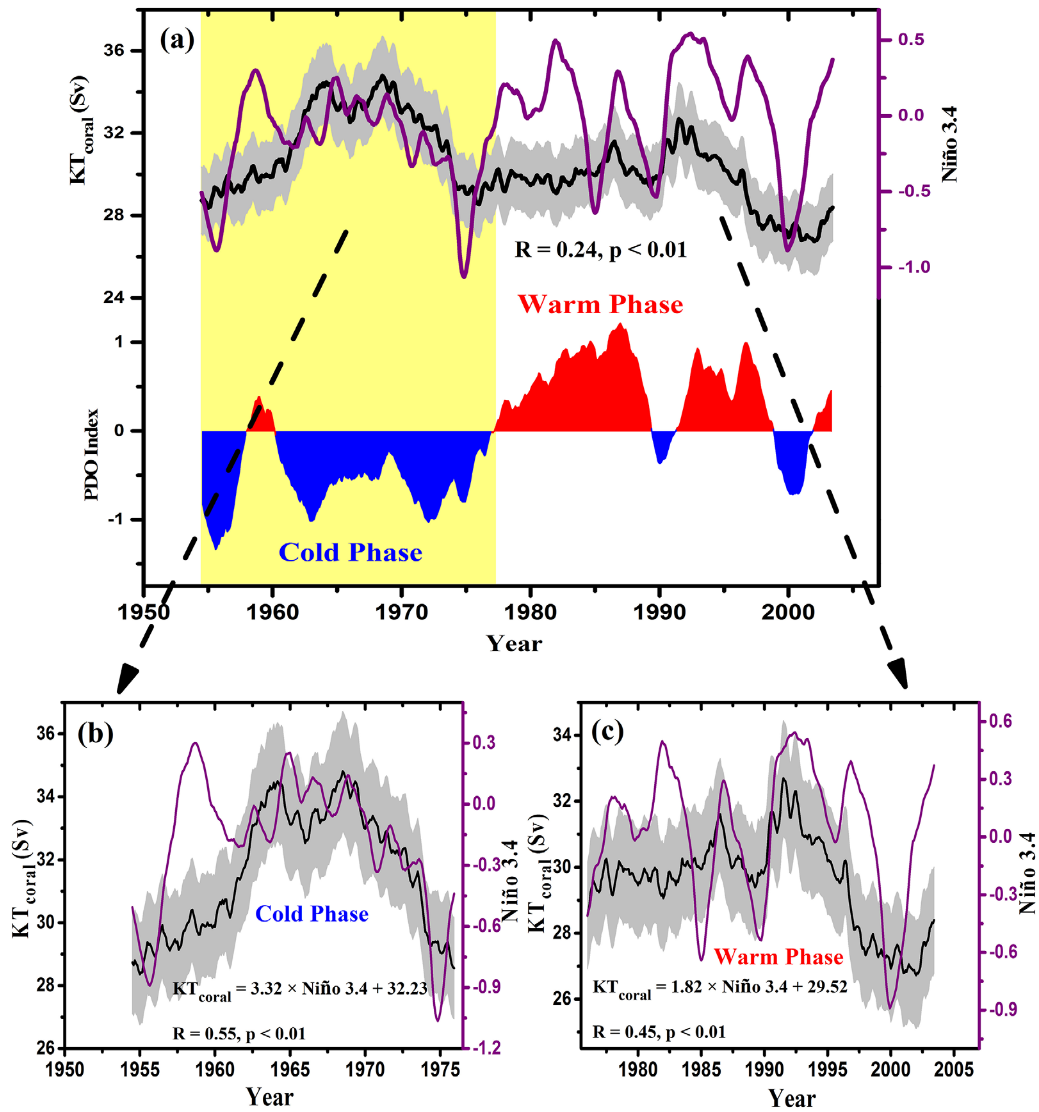

Figure 7. Comparison of 3 year running averages KC transport of STW (KT_{coral}, black curve) with 3 year running averages time series of the Niño-3.4 (purple curve) [*Smith et al.*, 2008] (http://climexp.knmi.nl) and PDO (blue and red shading) [*Mantua et al.*, 1997] (http://research.jisao.washington.edu/pdo/PDO.latest) indices in the periods of (a) 1954–2003, (b) 1954–1975, and (c) 1976–2003. Regression errors ($\pm 1\sigma$, Sv) are shown in the gray areas. Blue and red shaded areas show cold and warm phases of the PDO, respectively.

We speculate that a poleward shift of subtropical western boundary currents under modern global warming (attributed to the migration of wind fields) [*Wu et al.*, 2012] can explain the post-1990 covariance between KC transport off southeastern Taiwan and eastern Luzon (instead of northeastern Taiwan). That is, KC transport off southeastern Taiwan might be more affected by eddy activity (wind stress curl) before (after) 1990.

Simultaneous changes are also found in KT_{coral} and KC transport off southern Japan (KT_{SJP}) ($R = 0.34$, $p < 0.05$, compare Figures 4a and 4c) [*Yamazaki et al.*, 2016], with troughs centered at 1955, 1975, and 2000 for both regions. This suggests similar forcings were dominant at the two sites over the past 50 years.

3.4. Relationship With NBL

Previous studies have shown that a shift of the NBL can affect KC transport on interannual to decadal scales [*Qiu and Lukas*, 1996; *Wu*, 2013; *Hu et al.*, 2015]. Derived from sea surface height anomalies [*Qiu and Chen*, 2010b], the NBL is characterized by multidecadal fluctuations over the past 50 years [*Qiu and Chen*, 2010b; *Chen and Wu*, 2012; *Hu et al.*, 2015; *Hsin*, 2016]. Accompanied by a northward shift in the NBL, a positive wind stress curl anomaly generally induces a weakened upstream KT_{ELZ} (Figure 5d) [*Qiu* *and Chen*, 2010a]. The northward NBL shift also results in strengthened eddy activity in the Subtropical Counter Current (STCC) by changing vertical shear in the STCC-NEC system. The westward-propagating eddies in the STCC enhance KC transport off eastern Taiwan (Figures 5b and 5c) [*Qiu and Chen*, 2010a; *Chang and Oey*, 2012; *Hsin et al*., 2013; *Hsin*, 2015]. The KT_{coral} record is generally consistent with the NBL during the period 1962–2004 ($R = 0.54$, $p < 0.01$, Figure 5c), suggesting that the increased KT_{coral} off southeastern Taiwan is associated with northward migration of the NBL, and vice versa. This consistency indicates that large-scale tropical ocean circulation affects KC transport on multidecadal time scales.

3.5. Relationship With Hydroclimate in the Pacific

Interannual and multidecadal climate dynamics of ENSO and PDO in the Pacific have been suggested as influences on KC behavior [*Chiang et al*., 2010; *Hsin et al*., 2013; *Wu*, 2013; *Hu et al*., 2015; *Yamazaki et al*., 2016]. During El Niño years, a positive wind stress curl anomaly, resulting in a negative sea surface height anomaly, can cause a northward shift in the NBL [*Zhai and Hu*, 2013], further enhancing KC transport off eastern Taiwan [*Wu*, 2013]. Cross-wavelet transform analysis [*Grinsted et al*., 2004] shows that KT_{coral} is highly coherent with the ENSO index (2–7 years, Figure 6a) and PDO index (7–16 years, Figure 6b). Surprisingly, the correlation coefficient between the entire 52 year KT_{coral} and contemporaneous Niño-3.4 index data sets is positive, although only weakly so ($R = 0.24$, $p < 0.01$), off southeastern Taiwan (Figure 7a). It is however, as high as 0.55 for the first time window from 1954 to 1975 ($KT_{coral} = 3.32$ (± 0.32, 1σ) $\times$ Niño 3.4 + 32.23 (± 0.12, 1σ); Figure 7b) and 0.45 for the second interval from 1976 to 2003 ($KT_{coral} = 1.82$ (± 0.20, 1σ) $\times$ Niño 3.4 + 29.52 (± 0.07, 1σ); Figure 7c) before and after the transition year of 1975/1976 for PDO cold and warm phases [*Mantua et al*., 1997]. A regression slope gradient of 3.3 in the cold PDO phase is about double that in the following warm PDO phase (1.8). Comparisons between KT_{ELZ} off eastern Luzon, KT_{NTW} off northeastern Taiwan, KT_{SJP} off southern Japan, and the ENSO index (supporting information Figure S5) show similar nonstationary relationships between regional KC transport and ENSO. This multidecadal relationship was also noted in a previous study [*Wu*, 2013]. The NBL is situated farther to the south during the cold phase of the PDO than the warm phase, and the NBL could move a substantial distance to the north in an El Niño state from this more southerly position [*Hu et al*., 2015]. The KC transport is thus more sensitive to ENSO during the cold PDO phase before 1976 than during the warm PDO phase after 1976. The greatest KC transport off the STW during the interval 1960–1970, as shown in the KT_{coral} record, could be attributable to the farthest northward shift in the NBL during an El Niño and cold PDO phase.

4. Conclusions

Nanwan coral $\delta^{18}O$ is a robust proxy for SSTs on interannual and decadal scales and is controlled by KC transport. Results suggest that coral $\delta^{18}O$ records in this region provide a promising archive for reconstructing interannual changes in KC transport off southeastern Taiwan beyond the period of instrumental observations and satellite altimeter data. Our new reconstruction reveals that the maximum KC transport off southeastern Taiwan since 1950 was observed during the interval 1960–1970. The paleoclimatological reconstructions described here provide long-term insights into the interannual variability of the KC in the context of larger-scale processes. The KC does not show simultaneous changes in the upstream area to the changes east of Luzon and in the downstream area to the south of Japan. In the upstream KC area, KC transport off southeastern Taiwan shows interannual out-of-phase/in-phase fluctuations with those east of Luzon and offshore northern Taiwan before 1990. However, after 1990 the long-term records of KC transport off southeastern Taiwan show a similar decreasing trend to that of the KC transport record off eastern Luzon, and fluctuate in the opposite sense to that of offshore northeastern Taiwan. We also find that the KC transport off southeastern Taiwan and southern Japan have nearly simultaneous interannual changes, suggesting the same dominant forcing(s) for the entire KC system. Northward migration of the NBL could cause an increase in the KC transport off southeastern Taiwan. The interannual variability in KC transport off southeastern Taiwan has also been related to the ENSO and PDO. The impact of ENSO on KC transport is not stationary, and depends on the transition of the PDO phase. During a cold PDO phase, ENSO has a relative strong impact on the KC off southeastern Taiwan. Further work is needed to understand the KC system with respect to interannual to decadal climate variability and the influences of global warming. A recommended and promising approach is to establish an expanded network of coral records across the whole KC region extending back in time, to before the start of the Industrial Revolution.

Acknowledgments
We thank Bo Qiu for providing the bifurcation latitude of the North Equatorial Current data and Atsuko Yamazaki for providing the Kuroshio transport data at the 137°E line. We thank G. Burr for giving valuable suggestions and polishing the English. We thank Kefu Yu and another anonymous reviewer for their helpful comments and constructive suggestions. This research was supported by the National Key Basic Research Program of China (2013CB956102), National Science Foundation of China (441572148), Open Foundation of State Key Laboratory of Loess and Quaternary Geology (SKLLQG1613), and fund from the Youth Innovation Promotion Association, CAS (2017498). Funding was also provided by grants from Taiwan ROC MOST (104-2119-M-002-003 and 105-2119-M-002–001 to C.-C.S.) and the National Taiwan University (105R7625 to C.-C.S.). Data of the coral $\delta^{18}O$ and Sr/Ca are available in the supporting information.

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