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RESEARCH LETTER

Radiocarbon variability recorded in coral skeletons from the northwest of Luzon Island, Philippines

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Abstract

The North Equatorial Current (NEC) bifurcates at the eastern coast of the Philippines and moves northward as the Kuroshio, a North Pacific western boundary current. The NEC bifurcation point and Kuroshio variability are known to be affected by changes in climate such as the El Niño–Southern Oscillation and the pacific decadal oscillation. However, observational data are not sufficient to examine the mechanisms of decadal fluctuation. Here, we report seasonal radiocarbon data recorded from 1968 to 1995 in coral skeletons northwest of Luzon Island. The data suggest that the East Asian winter monsoon is a dominant factor in the seasonal fluctuations in water mass northwest of Luzon Island. Compared with other coral records reported for Guam, Ishigaki, Con Dao, and Hon Tre Island, the data suggest that the area of the Kuroshio loop current through the Luzon Strait decreased from the 1970s to 1980s as a result of the change in Kuroshio transport and the migration of the NEC bifurcation latitude after a regime shift in 1976.

Keywords: Luzon Strait, South China Sea, Radiocarbon, Corals, Kuroshio, Kuroshio loop current

Background

The South China Sea (SCS) is the largest marginal sea in southeastern Asia where the moisture of Asian summer monsoon originates (Yokoyama et al. 2011). The surface ocean circulation in the SCS, which is mainly driven by the East Asian monsoon, is cyclonic in winter and anticyclonic in summer. To the north, the SCS connects with the Pacific Ocean through the Luzon Strait, where the Kuroshio intrudes into the SCS through the Luzon Strait. The Kuroshio is one of the western boundary currents in the North Pacific and originates from the North Equatorial Current (NEC), which bifurcates at the eastern coast of the Philippines (e.g., Nitani 1972; Toole et al. 1990; Qiu and Lukas 1996; Lukas et al. 1996). The migration of the NEC bifurcation latitude has seasonal and interannual variation and affects the path and transport of the Kuroshio through the Luzon Strait. As a result, transport through the Luzon Strait is generally higher in summer and lower in winter (e.g., Qu 2000; Chu and Li 2000; Qu et al. 2004; Potemra and Qu 2009). The mechanism of Kuroshio intrusion into the SCS is still controversial but is thought to be primarily related to the East Asian monsoon and the El Niño–Southern Oscillation (Yuan et al. 2014). However, an accurate, observation-based estimate of the variation in Luzon Strait transport is not available (Qu et al. 2009). Furthermore, the frequency and characteristics of Kuroshio intrusions and their effects on circulation patterns in the northeast SCS are not well understood (Qu et al. 2009).

A complete understanding of the entire current system in the SCS is difficult to obtain because most existing observations are focused on flows in particular locations and in particular seasons (Potemra and Qu 2009). Although numerical models have recently been improved, no agreement has been established on the circulation mechanism in the SCS (Hu et al. 2000; Gan

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et al. 2006; Liu et al. 2009; Hsin et al. 2012). For example, Wyrtki (1961) estimated the mean Luzon transport as 0.5 Sv, whereas model estimates based on long-term hydrographic data, wind stress, geostrophic velocity, and other data range between 0.6 and 10.2 Sv westward (e.g., Chu and Li 2000; Qu et al. 2000; Lan et al. 2004; Hsin et al. 2012). Estimates based on short-term cruises from 1992 to 2007 also have large uncertainties (e.g., Tian et al. 2006; Liao et al. 2008; Yang et al. 2010; Hsin et al. 2012). Satellite altimeter data show that Kuroshio intrusion takes different pathways through the Luzon Strait as a result of eddies of various timescales (e.g., Yuan et al. 2006; Caruso et al. 2006). However, Caruso et al. (2006) reported that a longer time series of satellite data is necessary to identify the effects of local and remote forcing on the variability in Kuroshio intrusion. Long-term, high-vertical-resolution observations are needed to improve these models and our understanding of the SCS current system.

The radiocarbon (^{14}C) composition of seawater is a reliable tracer of water mass advection and vertical mixing (Matsumoto and Yokoyama 2013). Because of the atmospheric nuclear bomb testing in the 1950s, atmospheric ^{14}C rapidly increased after 1955 and nearly doubled in the mid-1960s (Hua et al. 2013). ^{14}C in the atmosphere quickly oxidizes to become ^{14}CO$_2$, which diffuses into the surface ocean through air–sea CO$_2$ exchange; the deep ocean is isolated from direct CO$_2$ exchange with the atmosphere.

Coral skeletons, which are composed of CaCO$_3$ (aragonite), record the Δ^{14}C content in the surface ocean when they incorporate dissolved inorganic carbon from ambient seawater. After the atmospheric nuclear bomb testing in the 1950s, the Δ^{14}C in coral skeletons also increased because excess ^{14}C was absorbed from the atmosphere into the ocean surface through air–sea gas exchange. This feature is known as the "bomb peak" or the "bomb curve" (Grottoli and Eakin 2007; Hua 2009). Because of the bomb ^{14}C in the corals, Δ^{14}C records in coral skeletons can be used as a sensitive water mass tracer and contribute to our understanding of ocean circulation, thereby improving ocean circulation models, especially in the post-bomb period.

High-resolution ^{14}C measurements of coral skeletons can be used to reconstruct continuous and seasonal/interannual variability in ocean conditions (Guilderson et al. 2000; Druffel et al. 2014; Andrews et al. 2016). However, post-bomb ^{14}C data are scarcely available for the SCS (e.g., Mitsuguchi et al. 2007; Shen et al. 2003). Recent studies employed Iodine-129 (^{129}I) in coral skeleton obtained from SCS as a tracer of 1950s nuclear bomb test (Bautista et al. 2016; Chang et al. 2016). Chang et al. (2016) reported ^{129}I data in the SCS corals (Con Dao and Xisha) and showed that ^{129}I is a useful environmental tracer to reconstruct physical oceanography in the past, though their resolution is much coarser than that from the ^{14}C-based study. For example, variations of ^{129}I trend at Con Dao and Xisha are similar to each other, whereas high-resolution ^{14}C records have apparent difference due to the upwelling in the central SCS (Chang et al. 2016). This can be attributed to the residence times of those nuclides namely ~2 years and ~10 years, respectively, for ^{129}I and ^{14}C in the atmosphere. ^{129}I bomb peak recorded in the corals are less influenced by oceanic process (Bautista et al. 2016), while ^{14}C bomb curve varies both in timing and magnitude among different coral locations, depending on local differences in the air–sea CO$_2$ exchange rate and physical oceanic processes (Druffel 2002; Grottoli and Eakin 2007).

In this study, we report high-resolution data for modern corals from Currimao, a municipality on the northwest coast of Luzon Island, Philippines. We also compare these data with the coral data reported from Ishigaki (Hirabayashi et al. 2017a), Guam (Andrews et al. 2016), Con Dao (Mitsuguchi et al. 2007), and Hon Tre Island (Bolton et al. 2016) to understand the relationship between North Pacific western boundary currents and SCS circulation around the Luzon Strait.

Methods

A modern coral (*Porites lutea*) core, PCURIN03, was taken from the coast of Currimao (17°59.098′N, 120°E28.809′E) at a water depth of 4.8 m in November 2004 (Fig. 1). PCURIN03 was micro-sampled at 0.8-mm intervals, and the Sr/Ca ratios were measured to determine sample age using the method of Hirabayashi et al. (2013). Each sample (2–5 mg) from PCURIN03 was prepared using a specially designed vacuum line for small samples (Yokoyama et al. 2010; Hirabayashi et al. 2017b),

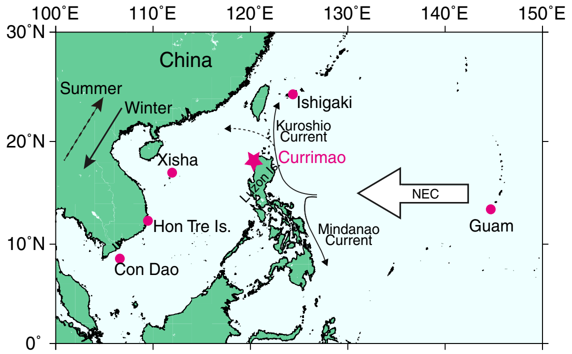

Fig. 1 Map of the South China Sea and coral sampling site (*star*). *Black solid and dotted arrows* indicate the wind directions of the East Asian monsoon during winter and summer, respectively

and 6–10 mg of each sample from PCURIN03 was prepared following the method of Yokoyama et al. (2007) (Additional file 1: Table S1). We measured 55 samples with ages ranging from 1968 to 1994. Graphite target samples were then analyzed with single-stage accelerator mass spectrometry (Yamane et al. 2014; Yokoyama et al. 2016) at the Atmosphere and Ocean Research Institute, The University of Tokyo.

Results

The $\Delta^{14}C$ values in the Currimao coral skeletons increased from 1968 to 1970, in agreement with the bomb ^{14}C curve (Fig. 2; Additional file 1: Table S1). In the 1970s, seasonal variation in $\Delta^{14}C$ was observed, with higher values in the summers than in the winters (Fig. 3a). The average $\Delta^{14}C$ value in the 1970s was 146.7 ‰, which lies between the average $\Delta^{14}C$ values in Guam (Andrews et al. 2016) and Ishigaki (Hirabayashi et al. 2017a) and is lower than that in Con Dao (Mitsuguchi et al. 2007) (Fig. 2). A limited number of $\Delta^{14}C$ data are available for the 1970s in coral obtained from Hon Tre Island, yet the averaged $\Delta^{14}C$ is slightly higher than that in Currimao. Although each point of data from Hon Tre Island is represents annual average of respective years, comparisons are made for other locations in SCS in Figs. 2 and 4b, c. To estimate seasonal changes in the magnitude of $\Delta^{14}C$, we referred to the seasonal variation in 1969 in Hon Tre Island reported by Bolton et al. (2016). They showed that $\Delta^{14}C$ in spring/summer is lower than that in autumn/winter. Thus, it is likely that higher values were marked in summer and lower values in winter than the annual value (Fig. 4b, c). After 1986, $\Delta^{14}C$ in Currimao was lower than the values in Guam (Andrews et al. 2016), Ishigaki (Hirabayashi et al. 2017a), and Con Dao (Mitsuguchi et al. 2007) (Fig. 2). The seasonality in $\Delta^{14}C$ in Currimao also decreased from 1975 to 1995 (Fig. 3a).

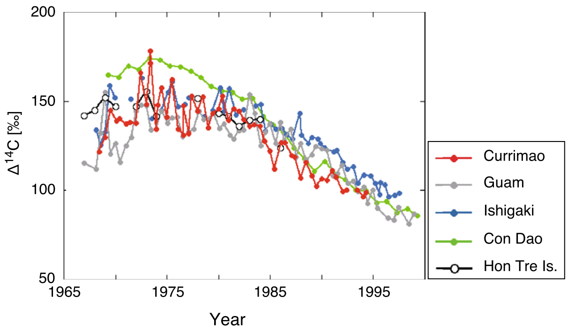

Fig. 2 $\Delta^{14}C$ recorded in coral skeletons collected from Currimao (this study), Guam (Andrews et al. 2016), Ishigaki (Hirabayashi et al. 2017a), Con Dao (Mitsuguchi et al. 2007), and Hon Tre Island (Bolton et al. 2016)

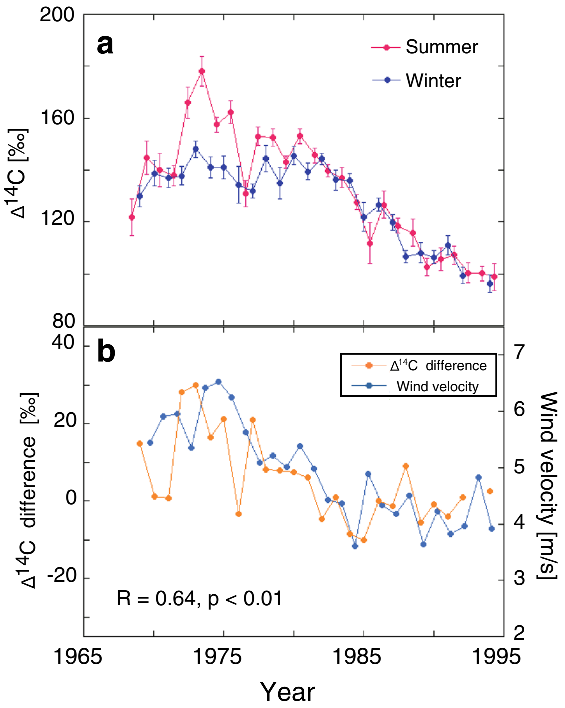

Fig. 3 **a** Seasonal $\Delta^{14}C$ of Currimao coral. **b** Comparison of seasonal $\Delta^{14}C$ difference of Currimao coral and the average winter monsoon wind velocity from December to February reported in Song et al. (2012)

From 1972 to 1975, when $\Delta^{14}C$ in Currimao exhibited significant seasonal variability (Fig. 3a), the $\Delta^{14}C$ level increased to the levels observed in Con Dao in the summers of 1972 and 1973 (Fig. 4b). The winter $\Delta^{14}C$ in Currimao decreased to the level in Guam during this period (Fig. 4c). It is difficult to compare the $\Delta^{14}C$ values of Ishigaki during this period with other regions because of the lack of data in the 1970s; however, the $\Delta^{14}C$ level of Ishigaki fluctuated between that of Guam and Currimao, whereas the $\Delta^{14}C$ values in Ishigaki in the 1980s and 1990s were higher than those in Currimao (Fig. 2). The $\Delta^{14}C$ values of both Ishigaki and Guam did not show clear seasonal differences from 1972 to 1975 (Fig. 4b, c).

Discussion

Relationship between the East Asian winter monsoon and the $\Delta^{14}C$ of the SCS

Circulation in the SCS, which is mainly controlled by the East Asian monsoon, is cyclonic in winter and anticyclonic in summer (Wyrtki 1961; Hu et al. 2000). Because of this seasonal change in circulation, the water mass reaching northwest Luzon is different in summer and winter (Additional file 1: Figure S1). To discuss the seasonality of $\Delta^{14}C$ in Currimao, we calculated the difference

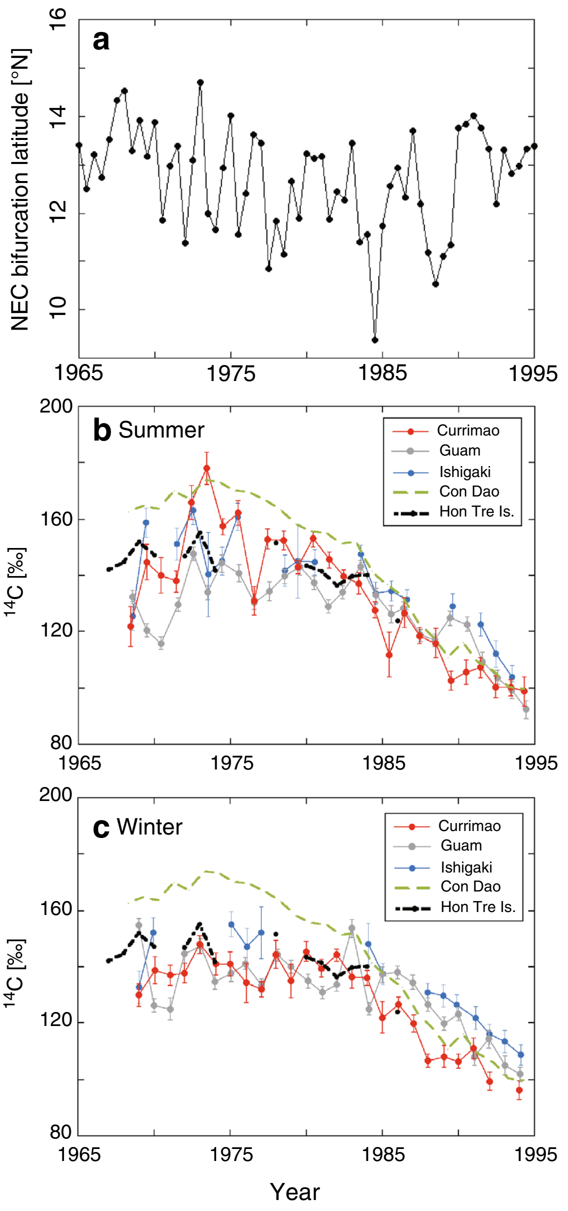

Fig. 4 **a** Seasonal average NEC bifurcation latitudes from 1965 to 1995 based on Zhao et al. (2013). Summer averaged latitude refers to the average latitude value of June and July. Winter averaged latitude refers to the average value of January and February. Δ^{14}C in **b** summer and **c** winter recorded in the corals sampled from Currimao (this study), Guam (Andrews et al. 2016), and Ishigaki (Hirabayashi et al. 2017a). Δ^{14}C in Con Dao (Mitsuguchi et al. 2007) and Hon Tre Island are annual

in Δ^{14}C between summer and winter within the same year. We used the average wind velocity from December to February measured at Xisha as the East Asian winter monsoon velocity (Song et al. 2012). The winter monsoon velocity and the winter Δ^{14}C were positively correlated from 1968 to 1995 ($R = 0.64$, $n = 25$, $p \ll 0.01$) and strongly positively correlated after 1973 ($R = 0.75$, $n = 21$, $p \ll 0.01$). Song et al. (2012) reported that the winter monsoon velocity decreased after the 1976 regime shift. Seasonal Δ^{14}C differences were smaller after 1976, which is related to the winter monsoon velocity.

Con Dao Island lies on the Sunda Shelf in the southwestern SCS, where the waters are very shallow (Mitsuguchi et al. 2007). Mitsuguchi et al. (2007) suggested that the Δ^{14}C record in Con Dao is primarily related to monsoon-induced air–sea gas exchange in the semi-enclosed shallow waters. After the East Asian winter monsoon regime shift in 1976, monsoon-induced air–sea gas exchange weakened, and the Δ^{14}C value in Con Dao became the same as, or lower than, that of Guam after 1985. This 10-year time lag is consistent with the time of CO_2 absorption from the atmosphere into the ocean surface through air–sea gas exchange with a ~10-year delay for isotopic equilibrium (Broecker and Peng 1982; Druffel and Suess 1983; Druffel 1987).

Comparison of our data with the Δ^{14}C data from Ishigaki, Guam, and Con Dao by season and period

We examined the mixing of water masses northwest of Luzon Island based on the Δ^{14}C values of Guam and Con Dao (representing water masses from the Pacific Ocean and the SCS, respectively; see Additional file 1: Figure S1). Hon Tre Island is located on a coastal shelf surrounded by less than 100-m-deep waters (Bolton et al. 2016). Comparing with the Con Dao Δ^{14}C record reported by Mitsuguchi et al. (2007), Δ^{14}C in Con Dao is consistently higher than that in Hon Tre Island. This is attributed to the fact that Hon Tre Island coral site is affected by shallow coastal upwelling at ~12°N during the summer, whereas this upwelling-originated water mass does not reach Con Dao. The Δ^{14}C value of Ishigaki was affected by the mixing of water masses from the Pacific Ocean and Luzon Strait because of the variation in the Kuroshio path (Hirabayashi et al. 2017a). Because Kuroshio intrusion in the Pacific water mass takes different paths through the Luzon Strait because of eddies on various timescales (e.g., Li et al. 1998; Hu et al. 2000; Wu and Chiang 2007; Qu et al. 2009), and because surface circulation in the SCS exhibits seasonal variation, we discuss the changes in water masses separately for different seasons (summer and winter) and decades (1970s and 1980s) (Fig. 5).

Decadal comparison

Because of above-described reasons, Con Dao coral records Δ^{14}C signature of the SCS surface water. In contrast, the Δ^{14}C of Guam coral represents the value of Kuroshio water reaching the eastern coast of the

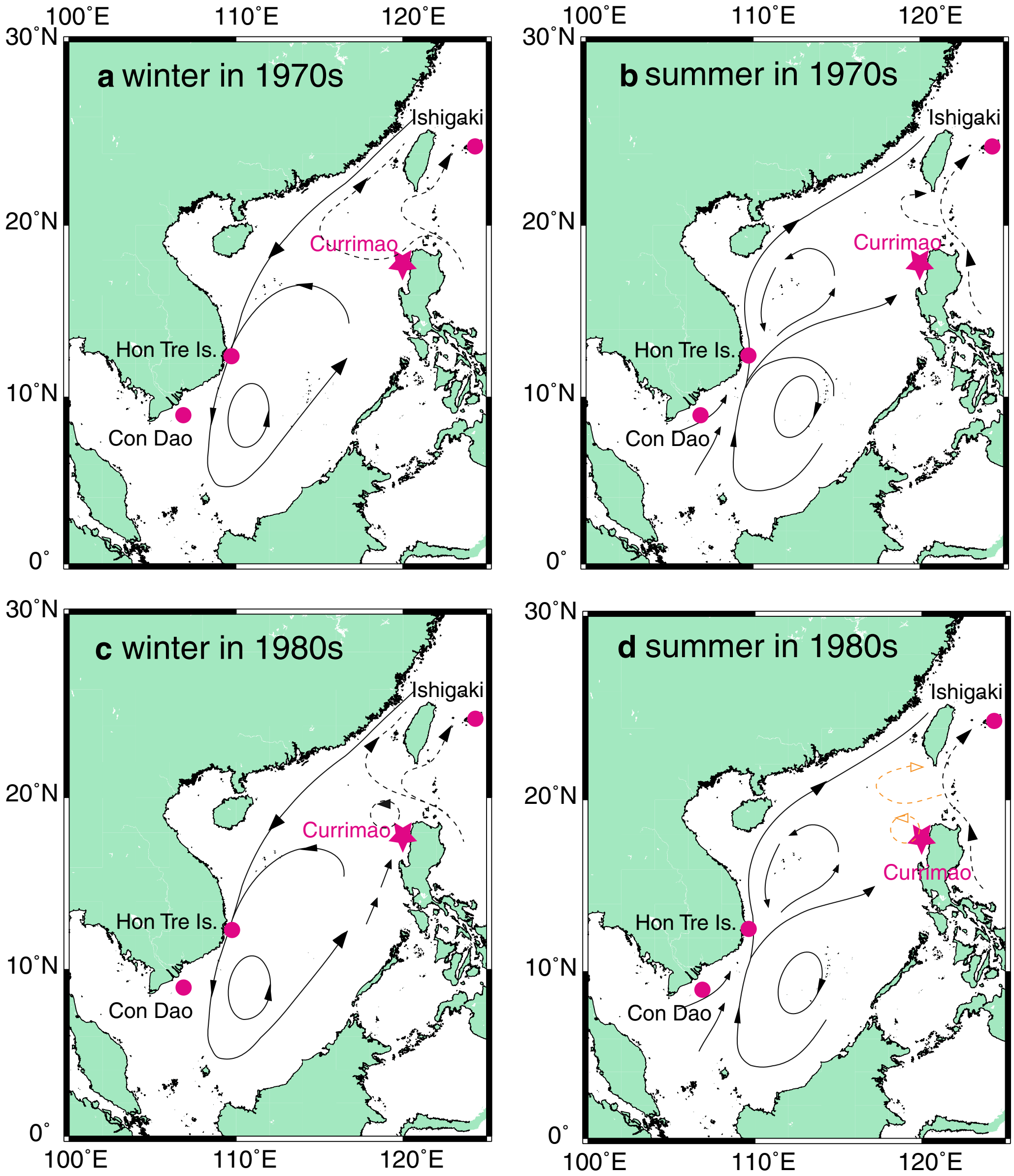

Fig. 5 Schematic illustration of surface ocean circulation in the South China Sea. The main current (*black solid lines*) of the South China Sea is based on Wang and Li (2009). The path of the Kuroshio loop current (*black dotted line*) fluctuated in (**a**, **b**) the 1970s and (**c**, **d**) the 1980s. The *orange arrows* in **d** are for the periods 1985 and 1989–1990

Philippines. Thus, the degrees of changes in two water masses, both from Kuroshio and SCS, reaching the Currimao coast are responsible for fluctuations observed in $\Delta^{14}C$ of Currimao corals in the 1970s and early 1980s (Fig. 2). It seems likely also that the area of mesoscale eddies changed between 1970s and 1980s. The coral record from Currimao indicates that the site was less influenced by vertical mixing driven by mesoscale eddies in 1970s because $\Delta^{14}C$ in Currimao during this period was constantly higher than/or the same as that of Guam (Fig. 2). After the mid-1980s, the $\Delta^{14}C$ in Currimao was the lowest among Guam, Con Dao, and Ishigaki although there are no data except for 1986 from the Hon Tre Island, because vertical mixing related to mesoscale eddies driven by Kuroshio intrusion likely diluted $\Delta^{14}C$ at the ocean surface.

Seasonal comparison

The intrusion of the Kuroshio loop current into the Luzon Strait is generally observed from November to March as a result of the northeast monsoon during the winter (e.g., Hsin et al. 2012; Nan et al. 2015). Observational data show that the anticyclonic intrusion of the Kuroshio can occur during any season, although winter is the most favorable time of the year (Yuan et al. 2006). This Kuroshio intrusion is affected by the bifurcation of the NEC on seasonal and interannual timescales. Kuroshio intrusion into the Luzon Strait tends to be stronger during El Niño years because bifurcation of the NEC migrates northward during El Niño years; this results in a weaker Kuroshio current east of Luzon, which provides a favorable condition for the intrusion of Pacific waters through the Luzon Strait (Sheremet 2001; Yaremchuk and Qu 2004; Qu et al. 2004).

Summers in the 1970s

Comparing $\Delta^{14}C$ among five sites depicted in Fig. 2, the highest and the lowest sites are Con Dao and Guam, respectively. Because of coarse resolution of coral record obtained from Hon Tre Island (i.e., annual instead of seasonal), we cannot compare directly with other coral $\Delta^{14}C$ results. However, Bolton et al. (2016) reported seasonal variability for 1969 and found that summer $\Delta^{14}C$ marked lowest in the year because of local upwelling. Assuming this upwelling had persisted during summers in the 1970s, $\Delta^{14}C$ in surface water around Hon Tre Island would possibly have been lower than that of Guam during the summer. Currimao coral $\Delta^{14}C$ during summers in the 1970s, in particular between 1972 and 1975, records as high $\Delta^{14}C$ as Con Dao coral. It seems unlikely that the water mass traveled via the area near the Hon Tre Island to Currimao. According to Zhao et al. (2013), the average NEC bifurcation latitude in summer is 12.5°N, which is almost identical to the normal bifurcation point in summer (12.4°N from 1968 to 1994). Kuroshio intrusion into the Luzon Strait tends to be stronger during strong El Niño years (Ho et al. 2004). However, the $\Delta^{14}C$ of Currimao from 1972 to 1973, which were strong El Niño years, was higher than that in Guam. The NEC bifurcation latitudes in the summers of 1972 and 1973 were 13.1°N and 12.0°N, respectively (Fig. 4a). The most northward migration of the NEC occurred in the winter of 1972/1973, when the NEC bifurcation latitude was 14.7°N (Fig. 4a). The NEC bifurcation latitude in the summer of 1973 was not favorable for the intrusion of Pacific waters into the Luzon Strait. In the summer of 1972, Kuroshio intrusion into the Luzon Strait was stronger than usual because of the higher NEC bifurcation latitude; however, the higher $\Delta^{14}C$ of Currimao compared with Guam indicates that the intrusion did not reach Currimao. Therefore, we suggest that the $\Delta^{14}C$ of Currimao was mainly affected by water mass advection from the central SCS via the East Asian summer monsoon rather than by Kuroshio intrusion or vertical mixing induced by mesoscale eddies.

The $\Delta^{14}C$ level in Ishigaki fluctuated between those of Currimao and Guam (Fig. 4b). The $\Delta^{14}C$ value in Ishigaki reached that of Luzon Island in 1971, 1972, and 1975 and that of Guam in 1973, 1974, and 1978. No $\Delta^{14}C$ value was recorded in Ishigaki from 1976 to 1977. The sample site at Ishigaki is known for seasonal upwelling (Sowa et al. 2014; Hirabayashi et al. 2017b). The higher $\Delta^{14}C$ value of Ishigaki likely resulted from the water mass that passed through the Luzon Strait via the Kuroshio loop current; the lower $\Delta^{14}C$ values likely resulted from the water mass that did not pass through the Luzon Strait and was transported directly to Ishigaki.

Summers after the mid-1980s

Among the four locations except Hon Tre Island, the $\Delta^{14}C$ levels decreased in the following order: Ishigaki > Guam > Con Dao > Currimao. This trend is different from that observed in the 1970s. Only 1986 data are available for Hon Tre Island but it is likely that the boreal summer value in $\Delta^{14}C$ was lower than that of Currimao because of upwelling reported by Bolton et al. (2016). It is difficult to ascertain the origin of the water mass that reached Currimao because the difference in $\Delta^{14}C$ between Guam and Con Dao became smaller after the mid-1980s compared with that in the 1970s, although the $\Delta^{14}C$ value in Con Dao was annual.

The average NEC bifurcation latitude from 1985 to 1994 was 12.5°N, which migrated southward comparing to the average bifurcation latitude of 12.9°N from 1968 before the regime shift in 1976/1977. Southward shift of the NEC bifurcation corresponds to a stronger Kuroshio transport off the Philippines (Qu et al. 2004). Considering Kuroshio transport off the Philippines in the 1970s and 1980s, Kuroshio intrusion into the Luzon Strait was probably weaker in the 1980s because stronger Kuroshio transport is not favorable for the penetration of Pacific waters into the SCS through the Luzon Strait (Qu et al. 2004). Therefore, we suggest that the water mass reaching northwest of Luzon in the 1980s originated from the SCS.

We also suggest that different water masses reached northwest Luzon in 1985, 1989, and 1990. The $\Delta^{14}C$ in Currimao decreased during these years; this trend was not observed in the other studied locations. Abrupt northward migration of the NEC bifurcation latitude was also observed in 1985, 1989, and 1990 (Fig. 4a). Hu et al. (2015) reported that Kuroshio intrusion into the Luzon Strait becomes stronger when the NEC bifurcation latitude migrates north. Thus, we suggest the following scenario during 1985, 1989, and 1990. Kuroshio intruded into the SCS but did not reach the region northwest of Luzon Island. Additionally, Kuroshio intrusion induced mesoscale eddies around Luzon Island (Nan et al. 2011, 2015), causing the Δ^{14}C of Currimao to decrease as a result of vertical mixing.

Winters in the 1970s

The fact that the Δ^{14}C values in Currimao were similar to those in Guam during the 1970s indicates that the water mass that reached this area may have originated from the Kuroshio loop (Fig. 4c). It is difficult to compare Currimao data with Con Dao and Hon Tre Island because of coarse resolution for latter sites; however, we can conclude that SCS water masses did not reach Currimao given that Δ^{14}C in Hon Tre Island would have been higher than the values in Fig. 4c.

Because of the lack of data for Ishigaki, it is difficult to deduce the mechanism of changes in the water mass around Ishigaki; however, the higher Δ^{14}C in Ishigaki, at least from 1975 to 1977, suggests that this region was not affected by mesoscale eddies around Taiwan or the Luzon Strait. The average NEC bifurcation latitude in the 1970s before the regime shift in 1976/1977 was 13.1°N, whereas the average latitude after 1985 was 12.7°N (Fig. 4a). During the winter of 1972/1973, which fell during a strong El Niño year, the NEC bifurcation latitude was 14.7°N (Fig. 4a), which is favorable for the intrusion of Pacific waters through the Luzon Strait (Sheremet 2001; Yaremchuk and Qu 2004; Qu et al. 2004). Because of this, Δ^{14}C in Currimao was similar to that in Guam, indicating that the Pacific water mass reached Currimao via a strong Kuroshio intrusion in the winter of 1972/1973. The Kuroshio loop current may have expanded southwestward to include the area northwest of Luzon Island because of the northward migration of the NEC bifurcation latitude (Fig. 4a) (Hu et al. 2015).

Winters after the mid-1980s

During winters after the mid-1980s, the Δ^{14}C values were lowest in Currimao among the studied locations, and the Δ^{14}C values in Guam and Ishigaki were similar (Fig. 4c). In this period, Δ^{14}C data in 1986 are the only data reported from Hon Tre Island. Annual Δ^{14}C data in 1986 in Hon Tre Island are the same as those in Currimao, but considering the seasonal variation, winter Δ^{14}C in Hon Tre Island would be higher than Currimao. Therefore, during winters after the mid-1980s, the Δ^{14}C values were lowest in Currimao among the studied locations. Although the Con Dao data are annual, the Δ^{14}C value in Con Dao was higher than that in Currimao during winter because of vertical mixing induced by mesoscale eddies northwest of Luzon Island. These mesoscale eddies are thought to be induced by Kuroshio intrusion into the Luzon Strait. The average NEC bifurcation latitude after 1985 was 12.7°N, which is located south of the bifurcation point in the 1970s (Fig. 4a). Therefore, Kuroshio intrusion into the Luzon Strait was weaker in the 1980s than in the 1970s, and the water mass of the Kuroshio did not reach northwest of Luzon Island. However, Kuroshio intrusion induced mesoscale eddies in that area, which caused the Δ^{14}C in Currimao to be the lowest among the five studied locations. According to Tseng et al. (2009), weakening of the monsoon decreases the extent of vertical mixing in the northern SCS. The East Asian winter monsoon velocity decreased from the 1970s to the 1980s (Song et al. 2012); thus, the area of mesoscale eddies decreased in size after 1976. However, we suggest that the mesoscale eddies lingered in the area northwest of Luzon Island.

Conclusion

High-resolution Δ^{14}C data were generated from a coral skeleton collected in Currimao, northwest of Luzon Island. We examined the variability in the Kuroshio loop current and the effects of climate change and the East Asian monsoon by comparing the seasonal and annual variations in Δ^{14}C in Currimao with previously reported data for Guam, Ishigaki, Con Dao, and Hon Tre Island. The seasonal variation in Δ^{14}C in Currimao, which indicates seasonal fluctuation in the water mass northwest of Luzon Island, correlated with the East Asian winter monsoon velocity in the SCS from 1968 to 1995. The lower Δ^{14}C at Currimao in the 1970s and 1980s compared with the other locations was attributed to the transport of an SCS water mass to the northwest of Luzon Island. This transport was triggered by the overall southward shift of the bifurcation latitude associated with the 1976 regime shift, which led to a decrease in the magnitude of Kuroshio intrusion into the Luzon Strait. Additional investigation is required to understand the detailed mechanism of the relationship between Kuroshio intrusion and the regime shift. However, the data presented herein contribute to our understanding of the physical oceanography of the North Pacific western boundary current.

Additional file

Additional file 1: Table S1. Radiocarbon data in the PCURIN03 coral. For the samples which includes (s) in the Lab No., we conducted small-scale radiocarbon dating with the sample amount of 2–5 mg. For the samples of (*), we measured same samples twice and took an average of them. **Figure S1.** Schematic illustration of surface ocean circulation in the South China Sea. The main current (black solid lines) of the South China Sea is based on Wang and Li (2009).

Authors' contributions

YY designed the research and collected coral samples. SH carried out experiments and wrote paper with YY. AS advised ICP-AES measurements YM and TA ran AMS. YM and FS conducted fieldwork in Philippines with YY. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

Radiocarbon data of the Currimao coral are shown in Additional File 1: Table S1. Any additional data may be obtained from SH (s-hirabayashi@aori.u-tokyo.ac.jp) and YY (yokoyama@aori.u-tokyo.ac.jp).

Consent for publication

All the authors agree for publication.

Ethics approval and consent to participate

We consent to participate and have no competing interests.

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