INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **32**: 481–488 (2012)
Published online 6 January 2011 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.2295

RMetS
Royal Meteorological Society

Inter-annual and inter-decadal variability of Kuroshio heat transport in the East China Sea

Qilong Zhang,[a,c] Yijun Hou[a] and Tingzhuang Yan[b]*
[a] *Key Laboratory of Ocean Circulation and Waves, Institute of Oceanology, Chinese Academy of Sciences, 7 Nanhai Road, Qingdao 266071, P. R. China*
[b] *Department of Marine, Earth and Atmospheric Sciences, NC State University, Raleigh, NC 27695-8208, USA*
[c] *National Key Laboratory for Satellite Marine Environment Dynamics, Hangzhou 310012, P. R. China*

ABSTRACT: High inter-annual and inter-decadal variability was identified in the Kuroshio heat transport (KHT), primarily following 5.4-, 22- and 2-year cycles. The KHT experienced a sharp climatic jump around 1976. Inter-decadal variability of the KHT was strongly associated with the Pacific Decadal Oscillation (PDO). A linear long-term KHT upward trend was identified from 1956 to 2003, and the KHT increased 0.65×10^{15} W in this period. The northeastward volume transport of the Kuroshio made a greater contribution to the KHT across the PN section than sea temperature did. Correlation and composite analyses showed that the meridional wind anomalies over the Kuroshio area and the southern portion of the South China Sea were responsible for the inter-annual variability of the KHT in the East China Sea, i.e. the KHT increased (decreased) when the southerly (northerly) anomalies strengthened. Copyright © 2011 Royal Meteorological Society

KEY WORDS East China Sea; Kuroshio; heat transport; climate jump; volume transport

Received 28 December 2009; Revised 22 June 2010; Accepted 10 December 2010

1. Introduction

The Kuroshio is one of the most well known ocean currents in the world, and is one of the most important poleward heat transport pathways to adjusting the world climate. Originating from the east Philippines, the Kuroshio heads northward along the western boundary of the Pacific Ocean, enters the East China Sea (ECS) between the Taiwan and Ishigaki islands, passes by the Okinawa Trough, and then flows back to the Pacific through Tokara Strait. Hence, the Kuroshio is the dominant current in the ECS, and controls the hydrological characteristics and coastal ecosystems, as well as climate conditions surrounding southeast China. Thus, investigations of variability of the Kuroshio are of great importance, both for academic and practical reasons.

The Kuroshio in the ECS has been extensively studied since the 1960s (Guan, 1964; 1979; Konaga *et al*., 1980; Isami, 1981; Guan, 1982; Nishizawa *et al*., 1982; Saiki, 1982; Guan, 1983; Li *et al*., 1983; Pu and Xu, 1986; Yuan *et al*., 1991, 1992, 1994, 2000; Ichikawa and Beardstey, 1993; Sun and Kaneko, 1993; Tang and Tashiro, 1993; Weng *et al*., 1996; Liu and Yuan, 1999; Ichikawa and Chaen, 2000). Bryden *et al*. (1991) estimated the Kuroshio heat transport while studying ocean heat transport across 24°N in the North Pacific from the 1985 transpacific hydrographic section. Yuan *et al*. (1992) and Liu and Yuan (1999) estimated the ECS KHT based on hydrographic data from several research cruises. Weng *et al*. (1996) and Zhang *et al*. (1999, 2001) studied the variability of the ECS KHT and its influence on China summer rainfall based on hydrographic data obtained in winters between 1956–1990. However, no study has examined the long-term variability of the KHT based on a nearly 50-year record. Clearly long-term observations are necessary to analyse the long-term variability of the KHT. Thus, the objectives of this paper are to provide a scientific basis for study of the influences of the northwestern Pacific on Chinese coastal environments, and to investigate air–sea interactions in middle latitudes.

2. Data and methodology

2.1. Data

The ECS PN section observation data (1956–2003) used in this study was derived from the Japan Meteorological Agency. The PN section was located in the northwestern portion of Okinoerabujima Island, from 27°30′N, 128°15′E to 29°36′N, 125°05′E, where the Kuroshio passes through the East China Sea (Figure 1). The PN section is one of the most representative and systematically observed sections in the Kuroshio area. However, only summer and winter observations are available before 1972. For example, there were 48 cases in winter and summer, respectively, but 38 cases (except 1956–1960, 1966–1969, 1971) in spring and

* Correspondence to: Tingzhuang Yan, Department of Marine, Earth and Atmospheric Sciences, NC State University, Raleigh, NC 27695-8208, USA. E-mail: tyan@ncsu.edu

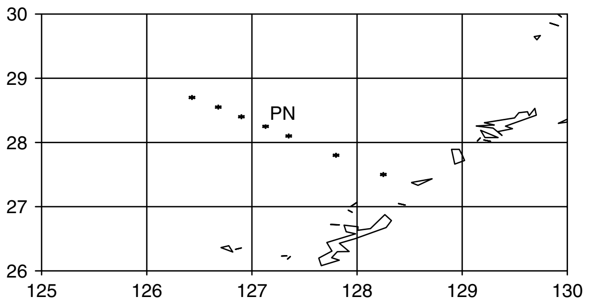

Figure 1. Station location map.

36 cases (except 1956–1959, 1962–1963, 1965–1967, 1969–1971) in fall.

The Pacific Decadal Oscillation (PDO) indices (1955–2003) were obtained from the Climate Diagnostics Center of the United States. The 850 hPa wind data (1955–2003) used in this study were derived from the National Centers for Environmental Prediction (NCEP) of the United States. The horizontal resolution was 2.5° × 2.5°.

2.2. Methodology

Direct-computation methodology (Weng *et al.*, 1996) was applied to estimate the ECS KHT. Suppose X and Y axes are perpendicular and parallel to the PN section, respectively, and the Z axis is downward, then heat transport (Q_T) passing through the PN section could be obtained by

$$Q_T = \int\int C_P \cdot \rho \cdot T \cdot U dy dz \tag{1}$$

Where, C_p is the specific heat capacity of seawater at constant pressure, ρ is the density of seawater, U is the horizontal component of velocity across the PN section, and T is the *in situ* temperature.

Because the Kuroshio volume transport across the PN section has been calculated, Equation (1) can be expressed as

$$Q_T = C_P \cdot \rho \cdot T_W \cdot V \tag{2}$$

where, T_W is the mean temperature over the PN section, and V is the Kuroshio volume transport cross-section. Since C_p is between 0.93 and 0.96 and ρ is between 1.022 and 1.027, for simplicity, $C_p \cdot \rho$ takes the value of 1.

As described above, the Kuroshio volume transport (KVT) that passes through the PN section has been extensively analysed by Chinese and Japanese scientists. Here, we used the Kuroshio volume transport across the PN section (1956–2003) calculated by Isami (1981) and the Nagasaki Marine Observatory of Japan (2003), using a dynamic method based on temperature and salinity data from station PN_1 (27°30′N, 128°15′E) to station PN_5 (28°42′N, 126°28′E) (Figure 1). The reference level for the Kuroshio volume transport was 700 dbar. Thus, the average temperatures of the PN section were computed based on temperature data at the same stations and reference level from 1956 to 2003.

3. Basic characteristics of the KHT

From computation, the annual mean of the KHT passing across the PN section over the 48 years (1955–2003) was 1.69×10^{15} W, larger than the northward ocean heat transport (0.76×10^{15} W) across 24°N in the North Pacific (Bryden *et al.*, 1991), and also slightly larger than the mean KHT (1.57×10^{15} W) across the PN section during 1956–1990 (Weng *et al.*, 1996). From Table I, the KHT varied between 1.63×10^{15} W and 1.75×10^{15} W, and its seasonal variation was weaker, which is quite consistent with a previous KHT estimation during 1956–1990 (Weng *et al.*, 1996).

From the definition of heat transport, the KHT was dominated by the KVT and sea temperature. Therefore, we first examined the KVT and mean temperature over the PN section. The overall mean KVT and mean temperature for 170 cases were 24.61 Sv (1 Sv $\approx 10^6$ m^3/sec) and 16.34 °C, respectively. The mean KVT from 1955 to 2003 was quite close to the mean KVT of 24.9 Sv during 1989–1991 (Sun and Kaneko, 1993). However, our calculated mean KVT across the PN section was larger than the mean KVT (19.7 Sv) estimated by Nishizawa *et al.* (1982) for the period of 1955–1980, and also larger than the mean KVT (22.8 Sv) reported by Tang and Tashiro (1993) for 1955–1990, and smaller than the mean KVT of 27.1 Sv calculated by Liu and Yuan (1999) during 1993–1994. These different results primarily arise from different methodologies applied to obtain the data. Note that the seasonal variation of the KHT across the PN section was weaker and similar to that of the KVT and the average temperature across the PN section. From computational analyses of this study, the mean KVT reached

Table I. KHT ($\times 10^{15}$ W) across the PN section.

Category	Winter	Spring	Summer	Fall	Seasonal mean
Multi-year mean	1.64	1.73	1.75	1.63	1.69
Standard deviation	0.42	0.28	0.38	0.30	0.26
Number of samples	48	38	48	36	170
Maximum	2.38 (2002)	2.28 (1977)	2.39 (2001)	2.18 (2000)	2.13 (2001)
Minimum	0.43 (1974)	1.20 (1970)	0.76 (1968)	0.77 (1964)	1.11 (1969)
Maximum variation	1.95	1.08	1.63	1.41	1.02

a maximum (25.64 Sv) in spring and minimum (23.30 Sv) in fall, with a difference of 2.24 Sv. Conversely, the mean temperatures were highest (16.76 °C) in summer and lowest (15.83 °C) in winter, with a difference of 0.97 °C. Nishizawa *et al.* (1982) calculated the KVT across the PN section during 1955–1980 based on data from 'Prompt Reports of the Sea Condition of Maritime Safety Agency of Japan'. Their study concluded that seasonal variation of the KVT was not apparent, which is consistent with the results presented here. This weak seasonal variation of the KHT may be caused by the difference in seasonal variability of heat transport in each individual year. In 1974, for example, heat transport is stronger in summer (1.80×10^{15} W) than in winter (0.43×10^{15} W); in 1986, however, heat transport is stronger in winter (2.38×10^{15} W) than in summer (1.44×10^{15} W). Similar cases hold for average temperature and Kuroshio transport volume. More discussion on seasonal variation was added.

4. Inter-annual variability of the KHT

During the period of 1955–2003, the maximum seasonal mean heat transport occurred in 2001, and was 2.13×10^{15} W, while the minimum value occurred in 1969, and was 1.11×10^{15} W, with a maximum deviation as large as 1.02×10^{15} W (Table I).

From Table I, the inter-annual variability of the ECS KHT in each season varied widely, such that the maximum average variation reached 1.95×10^{15} W in winter and then decreased by an order of magnitude from summer to fall and then to spring.

Figure 2 demonstrates the significant inter-annual variation of the seasonal mean heat transport anomaly during 1956–2003. The heat transport anomalies were negative before 1976, and changed to positive after 1976. The maximum anomaly (0.48×10^{15} W) occurred in 2001. The minimum anomaly was observed in 1969 (-0.54×10^{15} W), with a difference of 1.02×10^{15} W.

Performing discriminate analysis based on the KHT anomaly and its standard deviation of the multi-year average ($\sigma = 0.26 \times 10^{15}$ W), allowed classification of years into two categories: stronger ($\Delta Q > \sigma$) and weaker ($\Delta Q < -\sigma$) KHT years. Stronger years were 1981, 1986, 1988, 1997, 1998, 2000, 2001, and 2003; weaker years were 1956, 1957, 1963, 1964, 1966–1969, 1971, and 1974. Clearly, all weaker years occurred before 1976, while all stronger years were observed after 1976.

To further analyse the variability of the ECS KHT, Maximum Entropy Spectral analysis was applied to the seasonal-averaged heat transport anomaly across the PN Section during the period 1956–2003. Results showed that the primary periods of the ECS Kuroshio heat transport were 5.4, 16.6, 26.5, and 2.6 years (not shown), respectively. Since both peaks of 26.5 and 16.6 years belonged to inter-decadal variations, we obtained one 22.1-year peak by averaging two peaks (26.5 and 16.6 years). The KHT not only contains a 5-year and a quasi-biennial oscillation, but a 22-year inter-decadal variation as well.

To examine contributions of the KVT and the mean temperature to the KHT, we evaluated the inter-annual variations of three time series (Figure 3). It is clear that inter-annual variations of the KHT and the KVT varied widely, and were closely correlated. From computations, the inter-annual variation of the mean temperature was relatively small, with a maximum deviation of 1.85 °C. Maximum Entropy Spectral analysis showed that the primary periods of the ECS KVT were 21, 5.4, and 2.6 years (not shown), respectively, and were similar to those of the KHT. While the primary periods of the mean temperature were 2 and 23.4 years (not shown), these values differed from those of the KHT. The correlation coefficient between the KHT and KVT was 0.98, while the coefficient between KHT and the mean temperature was 0.76, and both exceed 99% confidence levels. This result indicates that the Kuroshio volume transport from lower latitudes made a greater contribution to the KHT across the PN section than sea temperature did.

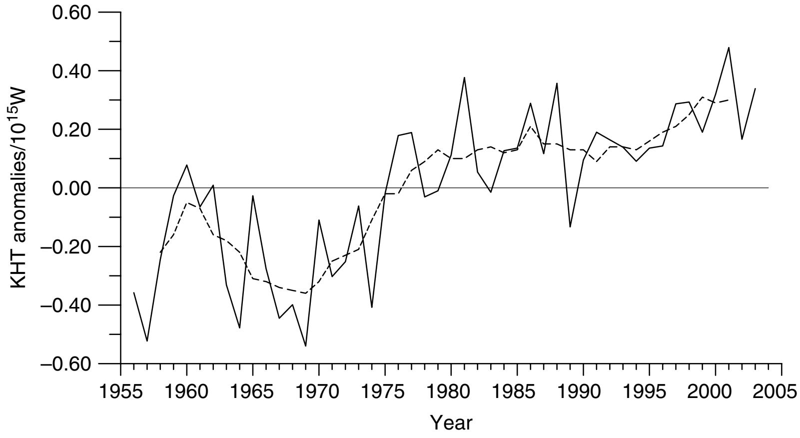

Figure 2. Inter-annual (solid line) and inter-decadal variations (dashed line) of the KHT anomalies.

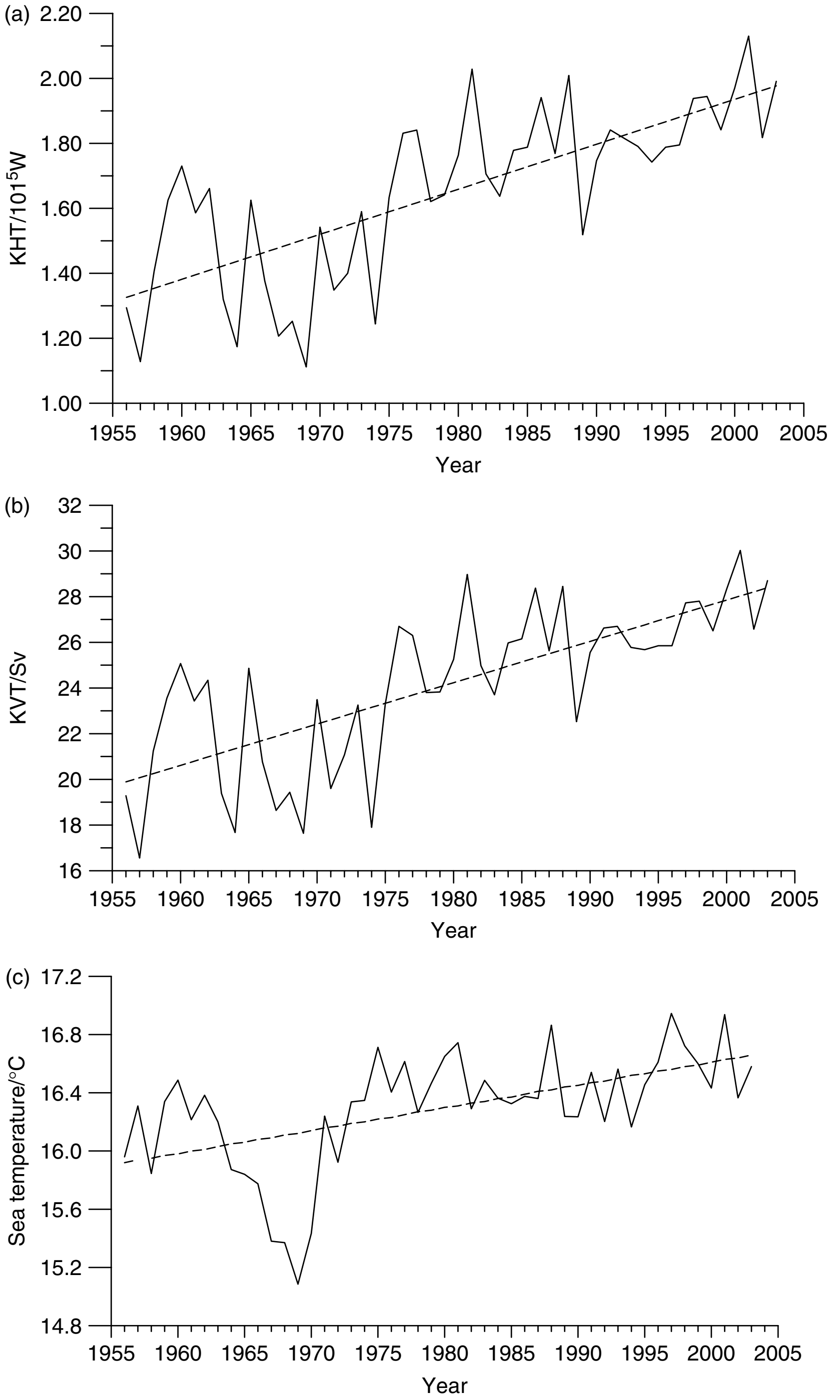

Figure 3. Inter-annual variations (solid line) and long-term trends (dashed line) of seasonal mean heat transport, a, volume transport, b, and sea temperature, c, across the PN section.

5. Inter-decadal and long-term variability of the KHT

The dashed lines in Figure 2 represent the inter-decadal time series of the ECS KHT after passing a 5-year moving average filter. The heat transport anomalies were negative prior to the middle of the 1970s and became positive after the mid-1970s. A question is then raised as to whether there was a climate jump associated with the KHT around the mid-1970s? With a 10-year-sliding t-test (Ding and Jiang, 1998), a diagnostic analysis was made on the KHT anomaly time series. Results showed that the statistical t-value (5.844) in 1976 exceeded the 0.001 confidence level (3.922). We can therefore conclude that the KHT experienced a climate jump (from weak to strong) around 1976, during the 48-year (1956–2003) time period. Before the jump (1956–1976), the mean KHT was 1.43×10^{15} W, and after the jump (1977–2003), the mean value was 1.82×10^{15} W. This value then increased by 27.3%, which coincided with the climate jump time of the North Pacific SST and western

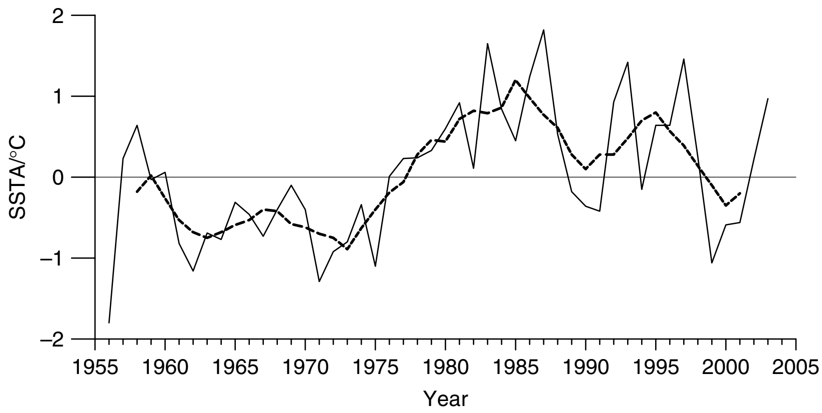

Figure 4. Inter-annual (solid line) and inter-decadal variations (dashed line) of the Pacific Decadal Oscillation index.

Pacific warm pool (Yu and Lin, 1997; Zhao *et al*., 2002; Zhang *et al*., 2004).

Is the 22-year period of the ECS KHT related to the Pacific Decadal Oscillation (PDO)? Figure 4 shows the inter-annual and inter-decadal variations of the average PDO indices. By comparing Figure 2 with Figure 4, we find that the inter-decadal variability of the ECS KHT was consistent with the PDO, i.e. the KHT anomaly was below (above) zero when the PDO was negative (positive). The correlation coefficient of the two time series was 0.45 (exceeding the 99% confidence level), which indicates that the PDO can explain 20.2% of the total variance of the KHT.

The coefficient increases to 0.72 after the moving-average (exceeding the 99% confidence level). This means that the PDO can explain 51.8% of the total variance of the KHT. The above relationship indicates that the inter-decadal variability of the ECS KHT may be associated with the PDO. However, further investigations are needed to understand the underlying physical process.

From the above analysis, we noticed that both the inter-annual and inter-decadal variations of the ECS KHT varied widely. Thus, a stepwise regression analysis was applied to further investigate long-term variability of the KHT. The seasonal-averaged heat transport was considered as a linear combination of polynomial functions of time t.

$$y(t) = c_0 + c_1 t + c_2 t^2 + c_3 t^3 + c_4 t^4 + c_5 t^{1/2} + c_6 t^{-1} + c_7 t^{-1/2} + c_8 t^{-2} + c_9 e^{-t} + c_{10} \ln t \qquad (3)$$

where, t is the year; and $c_0 \sim c_{10}$ are the regression coefficients.

Coefficients in Equation (3) could be obtained from regression analysis. In the case of $f = 5.5$, the optional regression equation of the KHT was:

$$y(t) = 1.312288 + 0.0138573t \qquad (4)$$

From Equation (4), the long-term variation of KHT followed a linear function with a ratio of 0.0138573×10^{15} W/year. As displayed in Figure 3a (dashed line), the KHT experienced a strong (linear) upward trend during the period of 1956–2003, with a 0.65×10^{15} W increase.

Similarly, we could obtain the optimal regression equations of the KVT and mean temperatures across the PN section

$$y_v(t) = 19.70896 + 0.1809018t \qquad (5)$$

and

$$y_t(t) = 15.90396 + 0.01569993t \qquad (6)$$

Figure 3b and c (dashed lines) showed that the KVT and sea temperature experienced a linear upward trend from 1956 to 2003. From Equations (5) and (6), we know that the KVT and mean temperature increased 8.50 Sv and 0.74 °C in this period, respectively. It is clear that the long-term variability of the KHT also was dominated by the KVT and sea temperature across the PN section. Furthermore, KVT seemed to have contributed more to the KHT than the mean temperature.

6. Inter-annual variabilities of heat transport and the meridional wind anomaly

Previous studies have shown that the wind stress vorticity over the subtropical North Pacific can affect the KVT 1 year in advance (Guan, 1982). Yao and Wang (1993) explained this remote connection using sea level data and concluded that the increase in anti-cyclone wind stress vorticity enhanced the north equator current, and increased the KVT in the East China Sea. However, Kim *et al*. (2004) obtained an inverse relationship between inter-annual variations of the KVT and the North Equator Current. It is still not clear what the main factor that affects the KHT variation is. Below, we discuss the relationship between inter-annual variability of the KHT in summer and winter, and the meridional wind anomaly over the northwest Pacific.

Correlation analysis indicated that the winter KHT was significantly correlated with the meridional wind anomaly over the northwest Pacific in August of the previous year (Figure 5a), especially in the southern portion of the South China Sea (5°–15°N, 100°–120 °E) where a high

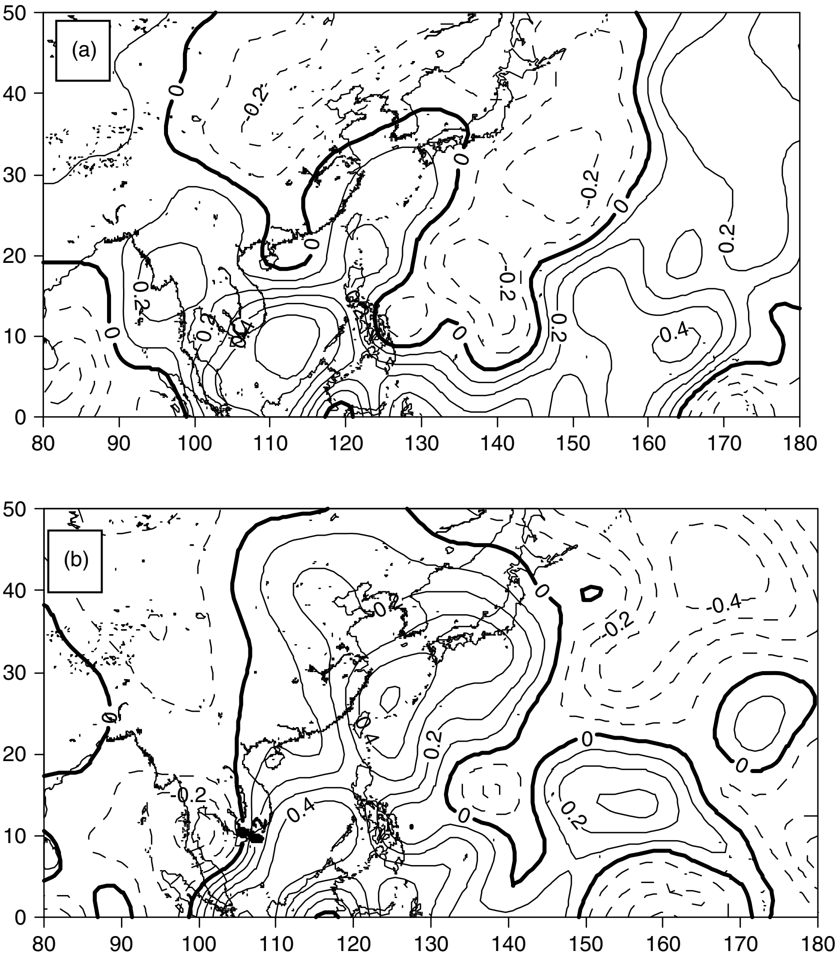

Figure 5. Distribution of correlation coefficients between the KHT and meridional wind anomaly fields: a, Winter KHT and meridional wind anomaly in August of the previous year; b, Summer KHT and meridional wind anomaly in June.

positive correlation (>0.4) area was identified. The maximum correlation coefficient reached 0.57, and exceeded the 99% confidence level. A positive correlation was also identified between the summer KHT and the meridional wind anomaly over the northwest Pacific in June of the concurrent year (Figure 5b). The maximum correlation coefficient was 0.54 and the most significant correlation occurred around the Kuroshio area (20°–30°N, 120°–130 °E). The summer correlation area was about 15° North and 10° East of the winter correlation area. Meridional wind anomalies can affect the winter (summer) KHT 5 (1) months ahead, respectively. This means that the influence on the KHT of the meridional wind anomaly over the northwest Pacific has a regional dependence.

To further investigate the influence of the meridional wind anomaly on the KHT, a composite analysis was conducted for the meridional wind anomalies during stronger/weaker KHT years in winter and summer, respectively. Note that the stronger/weaker KHT years were determined by the combination the KHT anomaly of individual years and their deviations from multiple year averages.

Figure 6 shows the inter-annual variations of the KHT in winter and summer. In winter, the year was defined to be a stronger (weaker) KHT year if its KHT anomaly was greater (less) than the standard deviation of the multiple-year mean $\sigma = 0.418$ ($\sigma = -0.418$). From Figure 6, stronger KHT years were: 1959, 1981, 1986–1988, 1999, and 2002; weaker KHT years were: 1956, 1957, 1963, 1966, 1967, 1971, 1974, and 1977. Similarly, in summer we took those years with KHT anomalies higher (lower) than the standard deviation $\sigma = 0.418$ ($\sigma = -0.418$) of the KHT anomaly of a multi-year mean to be stronger (weaker) KHT years. The strong KHT years were: 1970, 1975, 1976, 1977, 1985, 1988, 1990, 1991, 1992, 1994, and 2001. Years 1957, 1958, 1959, 1962, 1968, 1969, and 1972 were classified as weaker KHT years.

Following the above definitions, composite analyses were conducted for meridional winds in the previous August and concurrent June, respectively, in those stronger and weaker winter/summer KHT years. Results (Figure 7) showed that meridional wind anomalies over the southern South China Sea and the Kurishio area were positive during those stronger KHT years (winter and summer), with a maximum anomaly of 0.6 m/s in winter and 0.8 m/s in summer (i.e. southerly enhanced). However, during the weaker KHT years, meridional wind anomalies were negative, with a maximum anomaly of -1.0 m/s (not shown) (i.e. northerly strengthened).

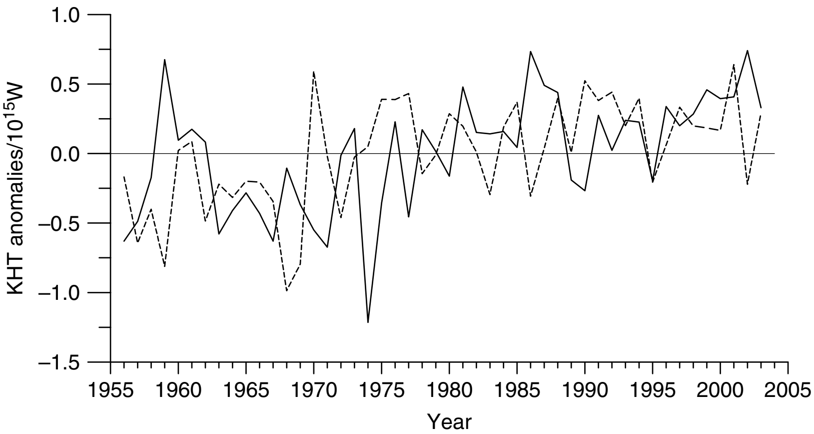

Figure 6. Inter-annual variability of KHT anomalies in winter (solid line) and summer (dashed line).

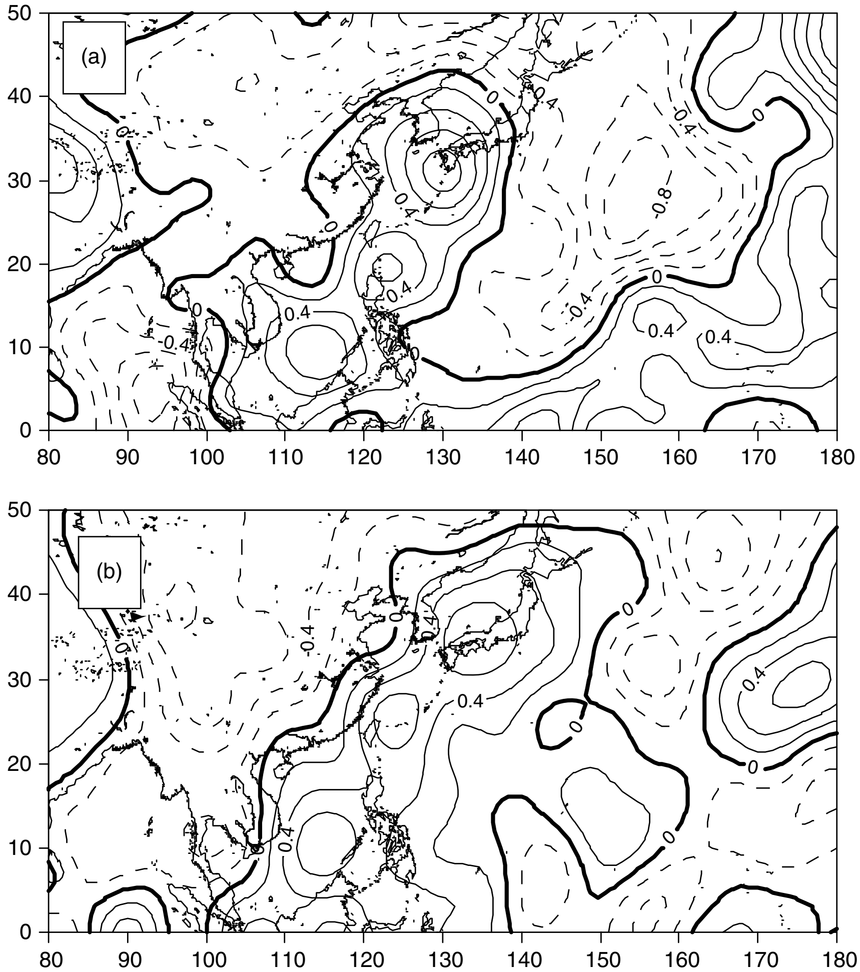

Figure 7. Distributions of meridional wind anomalies in stronger KHT years: a, winter, and b, summer.

From the above discussion, we conclude that meridional wind anomalies over the southern South China Sea and the Kuroshio area, are one of the most important dynamical climate factors, and have significant impacts on the KHT in the East China Sea. The KHT increases (decreases) when southerly (northerly) wind anomaly enhances. This topic deserves further investigation to clarify the physical mechanism that links the winter KHT to the meridional wind anomaly over the southern portion of the South China Sea.

7. Conclusions

From the above discussion, we can summarise the following. Through the PN Section, seasonal mean heat energy transported by the Kuroshio from low to high latitudes could be 1.69×10^{15} W. Its seasonal variation is weaker, but the climatological seasonal KHT is a little larger in spring and summer than in fall and winter. Both inter-annual and inter-decadal variations of the KHT in the ECS have a wide range. During the 48-year (1956–2003) study interval, maximum variability of the seasonal mean KHT in the East China Sea was 1.02×10^{15} W. The primary periods of the KHT variations were 5.4, 22 and 2 years, respectively. The KHT experienced a climate jump around 1976, while the mean KHT was below (above) normal before (after) the jump. Long-term variability of the ECS KHT followed a linear function, with a ratio of 0.0138573×10^{15} W/year. This value increased 0.65×10^{15} W during the period of 1956–2003, which was associated with increases of both the KVT and the mean temperature in the PN Section. Northeastward Kuroshio volume transport made greater impact on the KHT across the PN section than sea temperature did. The KHT in the East China Sea is significantly affected by meridional wind anomalies over the southern South China Sea and Kuroshio area. This trend increases (decreases) as southerly (northerly) strengthens. Additionally, the inter-decadal variability of the KHT is closely associated with the Pacific Decadal Oscillation (PDO).

Acknowledgments

The authors acknowledge support for this study from the Key Fund of Chinese Academy of Sciences (KZCX2-YW-201),the Knowledge Innovation Program of Chinese Academy of Sciences (KZCX2-YW-Q11-02), Chinese National Special Marine Fund (908-02-01-02), and the Open Fund (SOED0601) from the State Key Laboratory of Satellite Ocean Environment Dynamics (Second Institute of Oceanography, State Oceanic Administration).

References

Bryden HD, Roemmich H, Church JA. 1991. Ocean heat transport across 24°N in the Pacific. *Deep-Sea Research* **38**(3): 297–324.

Ding YG and Jiang ZH. 1998. *Meteorological data time series signal processing [M]*. Beijing: Meteorological Press: 18–50.

Guan BX. 1964. Primary analysis of the relationship between variations of Kuroshio velocity, volume transport and topography. *Oceanologia et Limnologia* **6**(3): 229–251.

Guan BX. 1979. The Kuroshio Variability in East China Sea. *Oceanologia et Limnologia* **10**(4): 297–306.

Guan Bingxian. 1982. Analysis of the variations of volume transports of the Kuroshio in the East China Sea. *Proceedings of the 1980 Symposium on Hydrometeology of the Chinese Society of Oceanolology and Limnology*. Beijing: Science Press: 103–116.

Guan BX. 1983. Analysis of variation of volume transport of the Kuroshio in the East China Sea. *Chinese Journal of Oceanology and Limnology* **1**(2): 156–165.

Ichikawa H and Beardsley RC. 1993. Temporal and spatial variability of volume transport of the Kuroshio in the East China Sea. *Deep-sea Research* **40**(4): 583–605.

Ichikawa H and Chaen M. 2000. Seasonal variation of heat and freshwater transport by the Kuroshio in the East China Sea. *Journal of Marine Systems* **24**: 119–129.

Isami Fujiwara. 1981. Characteristics of East China Sea. *Ocean Science (Japan)* **23**(4): 264–270.

Kim YY, Qu T, Jensen T, Miyama T, Mitsudera H, Kang HW, Ishida A. 2004. Seasonal and interannual variations of the North Equatorial Current bifurcation in a high-resolution OGCM. *Journal of Geophysical Research* **109**: C03040 : 1–19.

Konaga S, Nishiyama K, Ishizaki H. 1980. Geostrophic transport in the East China Sea and southeast of Yakushima Island? A case study. *The Oceanographical Magazine*.

Li RD, Zhao XK, Jing CC. 1983. Influences of Kuroshio variability on subtropical high. *Journal of the Ocean* **5**(3): 284–291.

Liu YG and Yuan YC. 1999. Variability of the Kuroshio in the East China Sea in 1993 and 1994. *Acta Oceanologica Sinica* **18**(1): 17–36.

Nagasaki marine observatory station. 2003. *Ocean Express (Japan)* **188**: 2–8.

Nishizawa JM, Eamihira AM, Komura K. 1982. Estimation of the Kuroshio mass transport flowing out of the East China Sea to the North Pacific. *La Mer* **20**: 37–40.

Pu YX and Xu XY. 1986. Kuroshio flow in East China Sea (PN Section) during 1972–1983. *Journal of the Ocean* **8**(1): 14–21.

Saiki M. 1982. Relation between the geostrophic flux of the Kuroshio in the eastern China Sea and its large meanders in south of Japan. *Oceanographical Magazine* **32**: 11–18.

Sun XP and Kaneko I. 1993. Variations of the Kuroshio during the period of 1989–1991. In *Proceedings of Investigation of the Kuroshio*. China Ocean Press: Beijing, 52–68.

Tang YX and Tashiro T. 1993. Variations of the current conditions of the Kuroshio at PN section in the East China Sea. In *Proceedings of Investigation of the Kuroshio*. China Ocean Press: Beijing, 69–76.

Weng XC, Zhang QL, Yang YL. 1996. The Kuroshio heat transport and its relationship to precipitation in North China. *Oceanologia et. Limnologia Sinica* **27**(3): 237–245.

Yao JX, Wang ZS. 1993. Preliminary investigation on the relations between the circulation and wind-stress field at the North Pacific Ocean. *Oceanography in China* **4**: 15–19.

Yu SQ, Lin XC. 1997. Relationships between Pacific decadal oscillation (PDO) and climate variability in China. *Journal of Tropical Meteorology* **13**(3): 265–275.

Yuan YC, Masahira E, Hiroshi I. 1991. The study of the Kuroshio in the East China Sea and the currents east of the Ryukyu Islands. *Acta Oceanologica Sinica* **10**(3): 373–391.

Yuan YC, Su JL, Pan ZQ. 1992. Volume and heat transports of the Kuroshio in the East China Sea in 1989. *La Mer* **30**: 251–262.

Yuan YC, Takano K, Pan ZQ. 1994. The Kuroshio in the East China Sea and the currents of the Ryukyu Island during Autumn 1991. *La Mer.* **32**: 235–244.

Yuan YC, Liu YG, Wang HQ. 2000. The Kuroshio in east of Taiwan and in the East China Sea in July 1997. *La Mer.* **38**: 173–178.

Zhang QL, Weng XC, Cheng MH. 1999. Precipitation in North China and its associations with tropical western Pacific warm pool and the Kuroshio. *Plateau Meteorology* **18**(4): 575–583.

Zhang QL, Weng XC, Cheng MH. 2001. Preliminary prediction of precipitation trend in North China. *Plateau Meteorology* **20**(2): 121–126.

Zhang QL, Weng XC, Hou YJ. 2004. Zonal movement of surface warm water in the western Pacific warm pool. *Chinese Journal of Oceanology and Limnology* **26**(1): 33–39.

Zhao YP, Wu AM, Chen YL. 2002. The climatic jump of the western Pacific warm pool and its climatic effects. *Journal of Tropical Meteorology* **18**(4): 317–326.

