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Long-term variability of sea surface temperature in Taiwan Strait

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Abstract Long-term variability of sea surface temperature (SST) in the Taiwan Strait was studied from the U.K. Met Office Hadley Centre climatological data set HadISST1. In 1957–2011, three epochs were identified. The first epoch of cooling SST lasted through 1976. The regime shift of 1976–1977 led to an extremely rapid warming of 2.1 °C in 22 years. Another regime shift occurred in 1998–1999, resulting in a 1.0 °C cooling by 2011. The cross-frontal gradient between the China Coastal Current and offshore Taiwan Strait waters has abruptly decreased in 1992 and remained low through 2011. The long-term warming of SST increased towards the East China Sea, where the SST warming in 1957–2011 was about three times that in the South China Sea. The long-term warming was strongly enhanced in winter, with the maximum warming of 3.8 °C in February. The wintertime amplification of long-term warming has resulted in a decrease of the north–south SST range from 5 to 4 °C and a decrease in the amplitude of seasonal cycle of SST from 11 to 8 °C.

1 Introduction

The Taiwan Strait is one of the world's most important passages. Oceanographically, it connects two major marginal seas, the East China Sea (ECS) and South China Sea (SCS) (Fig. 1, top). Biogeographically, it's a migration route for many fish species (Chang et al. 2013). Economically, it's one of the busiest sea lanes, with 58,279 cargo vessels crossing the Strait in 2012 (MOTS 2013), and home to captive marine fishing grounds and mariculture

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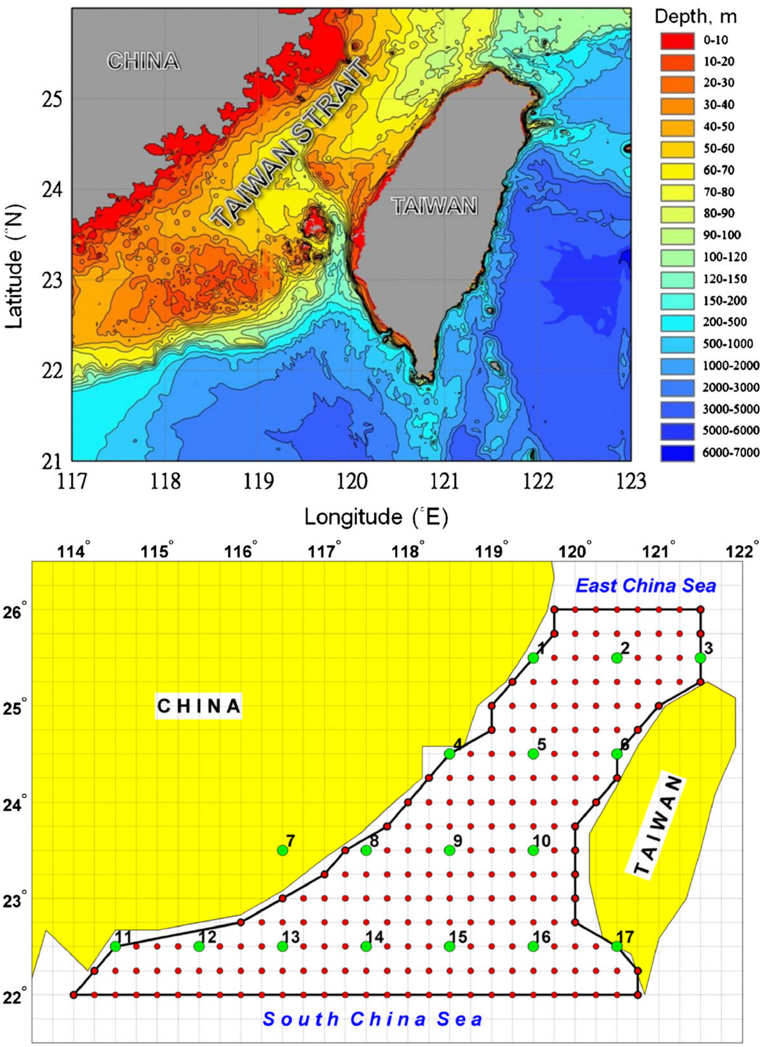

Fig. 1 (*Top*) Bathymetry of the Taiwan Strait. (*Bottom*) Base map of the Taiwan Strait region approximated by a polygon (*black solid line*) on a 0.25°×0.25° grid (*small red dots*). Hadley SST data are defined on a 1°×1° grid (large green circles with numbers) and interpolated onto the 0.25°×0.25° grid

(Chang et al. 2013). Demographically, 164 million people live on the shores of the Strait, including most of Taiwan's 23 million (http://en.wikipedia.org/wiki/Taiwan), and the entire Guangdong (104 million) and Fujian (37 million) provinces in China (http://en.wikipedia.org/wiki/List_of_Chinese_administrative_divisions_by_population). Yet very few studies focused on the maritime climate of the Taiwan Strait (Kuo and Ho 2004; Kuo and Lee 2013; Oey et al. 2013).

The Taiwan Strait's climate is defined by the East Asia's land mass, being strongly affected by the Siberian High, especially in winter (Cohen et al. 2001). The Strait's seasonal variability is driven by the East Asian summer-winter monsoons (Zhang et al. 1997; Gong et al. 2001; Ding and Chan 2005). The seasonal switch in wind direction is amplified by the Strait's SW-

NE orientation. The Strait's climate is sensitive to large-scale interannual variations originating in the Tropical Pacific (Wang et al. 2000; Kuo and Ho 2004). The Strait is a meeting place and a conduit of warm waters of the Kuroshio and SCS, and cold waters of the China Coastal Current (CCC) (Jan et al. 2002; Hong et al. 2011; Fig. S1 in online supplementary material), with a strong north–south gradient of sea surface temperature (SST), especially in winter (Fig. S2), when the Strait features the maximum north–south SST gradient in the entire western North Pacific (Jin and Wang 2011, Fig. 1a; see also Baumann and Doherty 2013).

The ECS Large Marine Ecosystem (LME) warmed rapidly in 1982–1998, whereas the adjacent SCS LME warmed much slower (Belkin 2009). The strong regional variability of global warming observed in the late 20th century across the East Asian seas begs a few questions: Which sea does the Taiwan Strait climate gravitate to, ECS or SCS? Has the Taiwan Strait warmed very fast (as ECS) or rather moderately (as SCS)? Has the late 20th century warming continued into the 21st century?

The first modern studies of long-term SST variability in the China Seas were based on repeat oceanographic sections (Table 1). Lin et al. (2005) reported rapid warming in the Yellow Sea in 1976–2000. Ning et al. (2009) documented rapid warming of the South China Shelf in 1976–2004. Ning et al. (2011) found a significant warming in 1975–1995 in the Yellow Sea. Tang et al. (2009) found a relatively small warming (~0.5 °C) between 1957–76 and 1977–96 in the northern ECS. Wang et al. (2013) extended this data set through 2001 and analyzed a broader area of 23°–41°N, 117°–130°E, where they found a significant warming after 1985.

The above studies were based on in situ data. Meanwhile, inclusion of satellite SST made possible creation of global data bases that lend themselves to studies of global and regional climate change.

The U.K. Met Office Hadley Centre SST climatology HadISST1 has gained recognition in climate studies owing to its superior spatial (1°×1°) and temporal (monthly) resolution and time span that goes back to 1870 (Rayner et al. 2003). The IPCC-2007 Report (Trenberth et al. 2007) was based on this data set. Alongside with global studies, the potential of Hadley climatology for regional climate assessments was realized early on (Sheppard and Rayner 2002; Sheppard 2004; Sheppard and Rioja-Nieto 2005). Belkin (2009) computed SST time series in 1957–2006 for 63 LMEs that has revealed an extremely rapid warming in the ECS, where SST rose by 2.5 °C in 22 years, the fastest warming rate in the World Ocean. This study has also revealed strong regional variations in long-term trends of SST, which stimulated further applications of HadISST1 for regional climate assessments, particularly in the China Seas (Jin and Wang 2011; Liu and Zhang 2013).

The above works provide a strong incentive for using HadISST1 in regional climate assessments. Our goal is to document long-term variability of SST, study its spatial variations across the Taiwan Strait, and elucidate seasonality of the long-term variability. Figures S1 through S5 are found in Online Supplementary Material.

2 Data and methods

A global SST climatology HadISST1 compiled by the U.K. Met Office Hadley Centre consists of global fields with 1°×1° spatial resolution and monthly temporal resolution, from 1870 till present (Rayner et al. 2003). The present study uses the same methodology and data set as in Belkin (2009), updated through 2011.

There are only 17 one-degree cells that fall within the boundary of the Strait (Fig. 1, bottom). Nonetheless, this data set revealed a distinct spatial gradient of long-term trends of SST within the Strait. To study regional variations of such trends, monthly time series of SST

Table 1 Long-term warming in the China Seas

Authors	Region	Years	Seasons	Data	Parameter	Warming rate, °C /10a
Lin et al. 2005	YS: 36 N, 121–124.5E	1976–2000	Annual	In situ	SST	0.94
Lin et al. 2005	YS: 36 N, 121–124.5E	1976–2000	Winter	In situ	SST	0.83
Lin et al. 2005	YS: 36 N, 121–124.5E	1976–2000	Summer	In situ	SST	0.81
Lin et al. 2005	YS: 36 N, 121–124.5E	1976–2000	Annual	In situ	VAT	0.68
Lin et al. 2005	YS: 36 N, 121–124.5E	1976–2000	Winter	In situ	VAT	0.81
Lin et al. 2005	YS: 36 N, 121–124.5E	1976–2000	Summer	In situ	VAT	0.56
Lin et al. 2005	YS: 36 N, 121–124.5E	1976–2000	Annual	In situ	BT	0.38
Lin et al. 2005	YS: 36 N, 121–124.5E	1976–2000	Winter	In situ	BT	0.67
Lin et al. 2005	YS: 36 N, 121–124.5E	1976–2000	Summer	In situ	BT	0.48
Ning et al. 2009	NSCS: SE of Hong Kong	1976–2004	Annual	In situ	SST	0.78
Ning et al. 2009	NSCS: SE of Hong Kong	1976–2004	Annual	In situ	VAT	0.90
Tang et al. 2009	ECS: 28–32 N, 122–128E	1957–1996	Winter	In situ	SST	0.12[a]
Tang et al. 2009	ECS: 28–32 N, 122–128E	1957–1996	Summer	In situ	SST	0.23[a]
Ning et al. 2011	ECS: 32 N, 122–127E	1975–1995	Annual	In situ	SST	0.34
Ning et al. 2011	ECS: 32 N, 122–127E	1975–1995	Annual	In situ	VAT	0.45
Ning et al. 2011	ECS: 32 N, 122–127E	1975–1995	Annual	In situ	BT	0.53
Xu et al. 2013	ECS: 29–32 N, 122–123.5E	1959–2009	May	In situ	SST	~1.0[b]
Wang et al. 2013	23–41 N, 117–130E	1957–2001	Feb	In situ	SST	0.67
Wang et al. 2013	23–41 N, 117–130E	1957–2001	Aug	In situ	SST	0.01
Wang et al. 2013	23–41 N, 117–130E	1985–2001	Feb	In situ	SST	1.96
Wang et al. 2013	23–41 N, 117–130E	1985–2001	Aug	In situ	SST	0.31
Belkin 2009	ECS	1982–2006	Annual	HadISST1	SST	0.5
Belkin 2009	ECS	1982–1998	Annual	HadISST1	SST	1.4
Jin and Wang 2011	China Seas	1870–2007	Annual	HadISST1	SST	Max=0.12
Liu and Zhang 2013	ECS and around Taiwan	1900–2006	Winter	HadISST1	SST	0.27
This study	Taiwan Strait	1957–2011	Feb	HadISST1	SST	Max=0.7[c]
This study	Taiwan Strait	1957–2011	Aug	HadISST1	SST	Max=0.2[c]
This study	Taiwan Strait	1976–1998	Annual	HadISST1	SST	1.0

Acronyms: *VAT* vertically-averaged temperature; *BT* bottom temperature; *YS* Yellow Sea; *ECS* East China Sea; *NSCS* Northern South China Sea

[a] Tang et al. (2009) estimated an SST difference between the cold period of 1957–1976 and the warm period of 1976–1996. The decadal rates in this table are obtained from Tang et al.'s numbers given the 20-year separation between the center years of the cold (1966) and warm (1986) periods

[b] Xu et al. (2013) used data from 1959, 1981, and 1999–2009

[c] Maximum rates in the Taiwan Strait; rates vary by factor of 3 across the Strait

were extracted for each 1° node. Time series of annual SSTs were calculated from monthly SSTs for each 1° node. Linear trends were estimated from time series of annual SSTs for each 1° node.

To accurately estimate the area-mean SST trend in the Taiwan Strait, we approximated the Strait area by a polygon defined on a 0.25°×0.25° grid between 22 and 26°N (Fig. 1, bottom) and interpolated SST onto this grid. The 0.25°×0.25° gridded data were used to calculate areaweighted Strait-wide mean monthly SST for each individual month, 01/1957-12/2011. The individual mean monthly SSTs were averaged over 1957–2011 for each month to produce long-term mean monthly SSTs. The same individual mean monthly SSTs were averaged for each year to produce mean annual SSTs for the entire Taiwan Strait and estimate long-term trend for this area in 1957–2011. We only used data from 1957 on (as in Belkin 2009) since data density has sharply increased in 1957 thanks to the International Geophysical Year 1957–1958.

3 Results

The time series of area-mean annual SST revealed three epochs and two regime shifts (Fig. 2, top), the latter coincident with large-scale events, a trans-Pacific regime shift in 1976–1977 (Hare and Mantua, 2000) and the 1997–1998 El Niño (McPhaden 1999). The SST warming rate varies three-fold along the Taiwan Strait, from 0.7 °C off Hong Kong up to 2.1 °C east of Kinmen (Fig. 2, bottom).

The north–south SST gradient along the Strait decreased from 5 °C in 1957 to 4 °C in 2011 as the colder northern Strait warmed much more than the warmer southern Strait (Fig. 2, bottom)(also see Lima and Wethey 2012; Baumann and Doherty 2013). The long-term warming of SST is seasonal: It is strongest in winter (January-March) and weakest in summer (July–September) (Figs. 3, 4 and 5). The maximum warming (SST_{2011} minus SST_{1957}) calculated by linear regression of annual SST for each of 17 grid nodes peaked in February, reaching 3.8 °C at node 4 (Fig. 4, bottom). Long-term time series of monthly SST show the maximum warming rate reaching 1 °C/ decade in wintertime. Indeed, the coldest winter SST was observed around 1968, when the average minimum winter SST dropped to nearly 16 °C (Fig. 5, top). By 1999, the average minimum winter SST reached 21 °C, a 5 °C increase in 31 years (Fig. 5, top). The winter amplification of long-term SST warming has resulted in a substantial decrease in the amplitude of seasonal cycle of SST, from 11 °C in 1960s–1970s to 8 °C in 2011 (Fig. 5, top). Time series of SST in 17 grid nodes, while synchronous across the Strait, reveal a major regime shift in 1992, when the SST gradient between nodes 7–8 and 9–10 has almost vanished (Fig. 4, top), suggesting a sharp weakening of a front between the China Coastal Current (CCC) and offshore waters (Belkin et al. 2009). The CCC front remained weak through 2011.

4 Discussion

4.1 Comparisons with independent in situ data sets

Our results are consistent with other regional studies based on independent in situ data (Table 1). In this respect, studies based on People's Republic of China (PRC) data are especially valuable because PRC data from ECS and Taiwan Strait are virtually absent in the World Ocean Database (WOD) maintained by the National Oceanographic Data Center (NODC/NOAA) (www.nodc.noaa.gov). Since the HadISST1 includes all available data from WOD, it means that PRC data from ECS and Taiwan Strait are largely absent in HadISST1 and therefore can be used for comparison. For example, Xu et al. (2013, Figs. 2–3) found a 2 °C warming between 1981 and 2001, which penetrated to the bottom (maximum depth, 60 m) in the study area. The same conclusion (surface-to-bottom penetration of warming signal) is evident from Lin et al. (2005). Wang et al. (2013) documented a sharp increase in warming rate

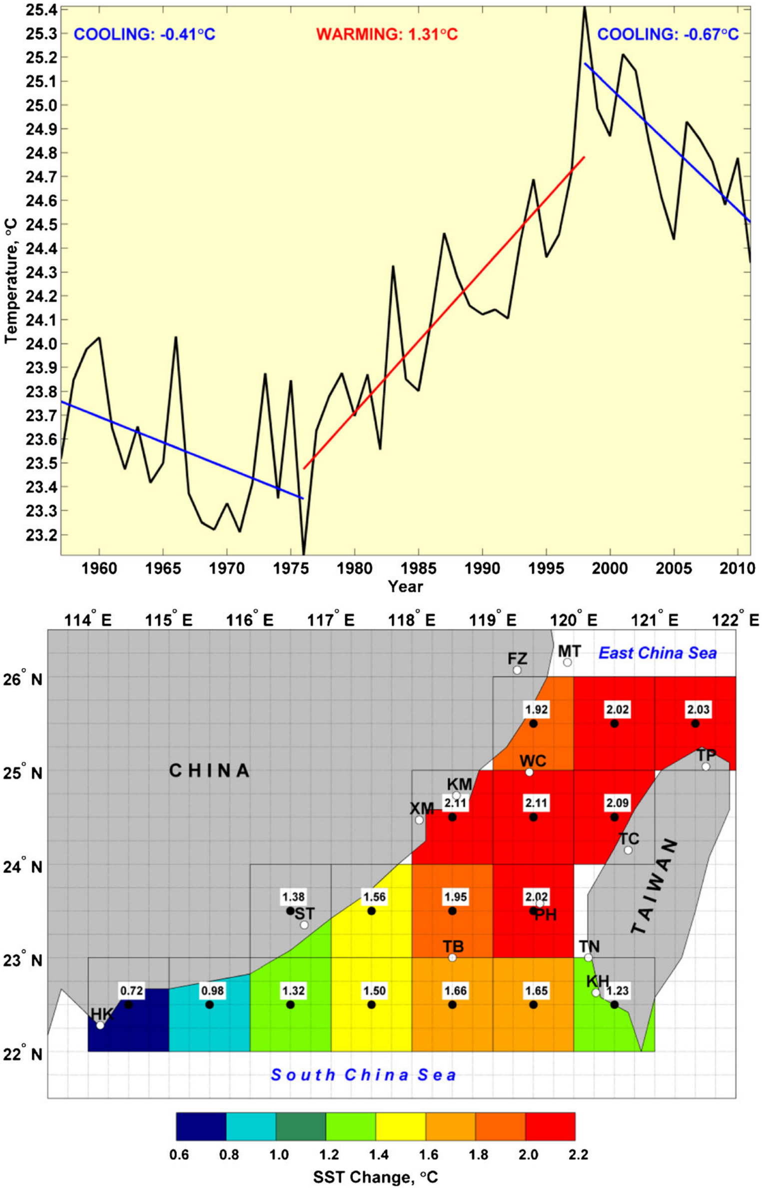

Fig. 2 (*Top*) Long-term variability of annual mean area-averaged SST in the Taiwan Strait region (bounded by a polygon in Fig. 4). Shown are three epochs: cooling in 1957–1976, warming in 1977–1998, and cooling in 1999–2011. (*Bottom*) Long-term SST trends in the Taiwan Strait. Shown are net SST changes (°C) between 1957 and 2011 according to linear regression trends of annual data. The warming rates increase three-fold from the southwest (0.7 °C) to the northeast (2.1 °C). Acronyms: FZ, Fuzhou; HK, Hong Kong; KM, Kinmen; KH, Kaohsiung; MT, Matsu; ST, Shantou; TB, Taiwan Bank; TC, Taichung; TN, Tainan; TP, Taipei; PH, Penghu; WC, Wuchiu; XM, Xiamen

(up to 2 °C/10a) near the northern entrance to the Strait, especially in winter. These results are consistent with this study; they reinforce the usefulness of winter SST as a climate indicator representative of the entire upper mixed layer.

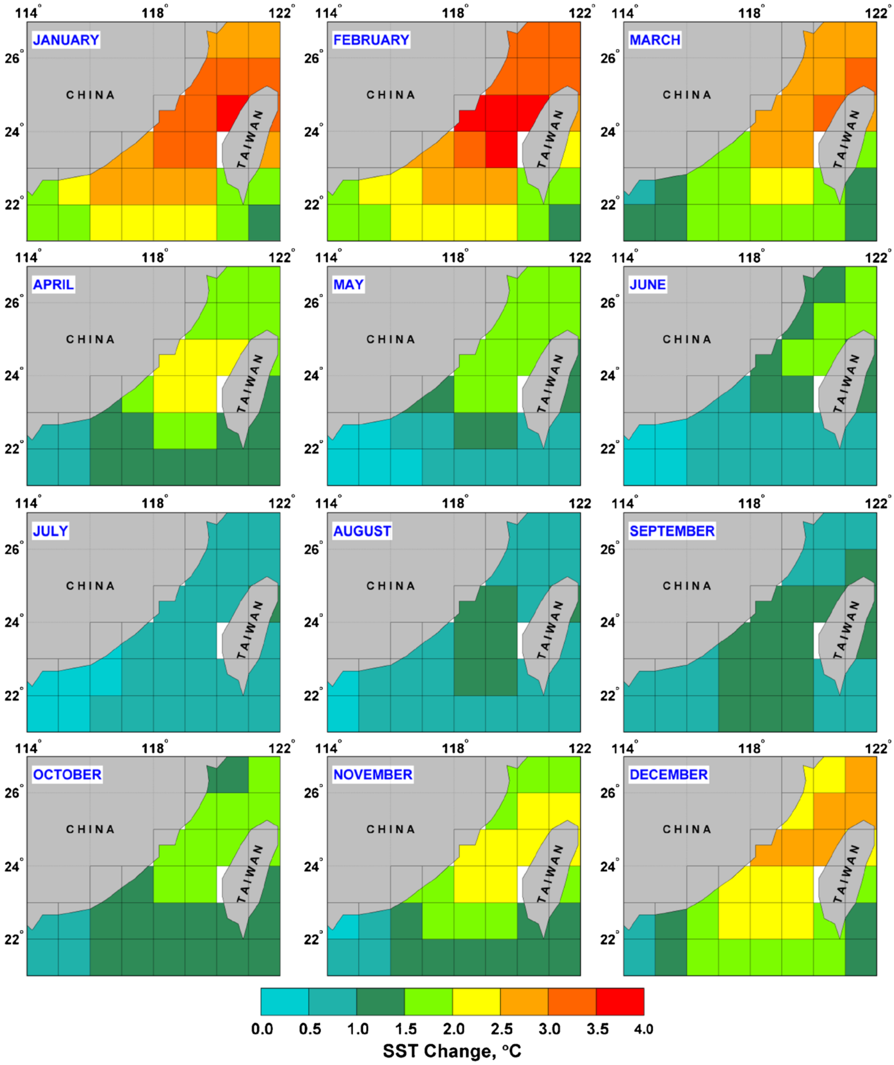

Fig. 3 Monthly maps of SST trends in the Taiwan Strait. Shown are net SST changes between 1957 and 2011 according to linear regression trends of monthly data

Coastal and offshore SST is routinely measured at fixed stations around Taiwan maintained by the Central Weather Bureau (CWB), Taipei (Fig. S3). The CWB has kindly made available to us this data. For this study we selected several stations in the eastern Taiwan Strait that have relatively long time span and no obvious instrumental problems or data gaps. Time series of SST at these stations (e.g., Fig. S4) reveal the post-1998 cooling consistent with the Strait-wide cooling in 1998–2011 (Fig. 2, top). A detailed analysis of the CWB data will be reported elsewhere.

4.2 Validation of satellite-derived SST with in situ data

Satellite SST data in waters around Taiwan were previously validated with in situ data (Lee et al. 2005, 2010). The AVHRR SST data were found to have a small bias of <0.01 °C (Lee

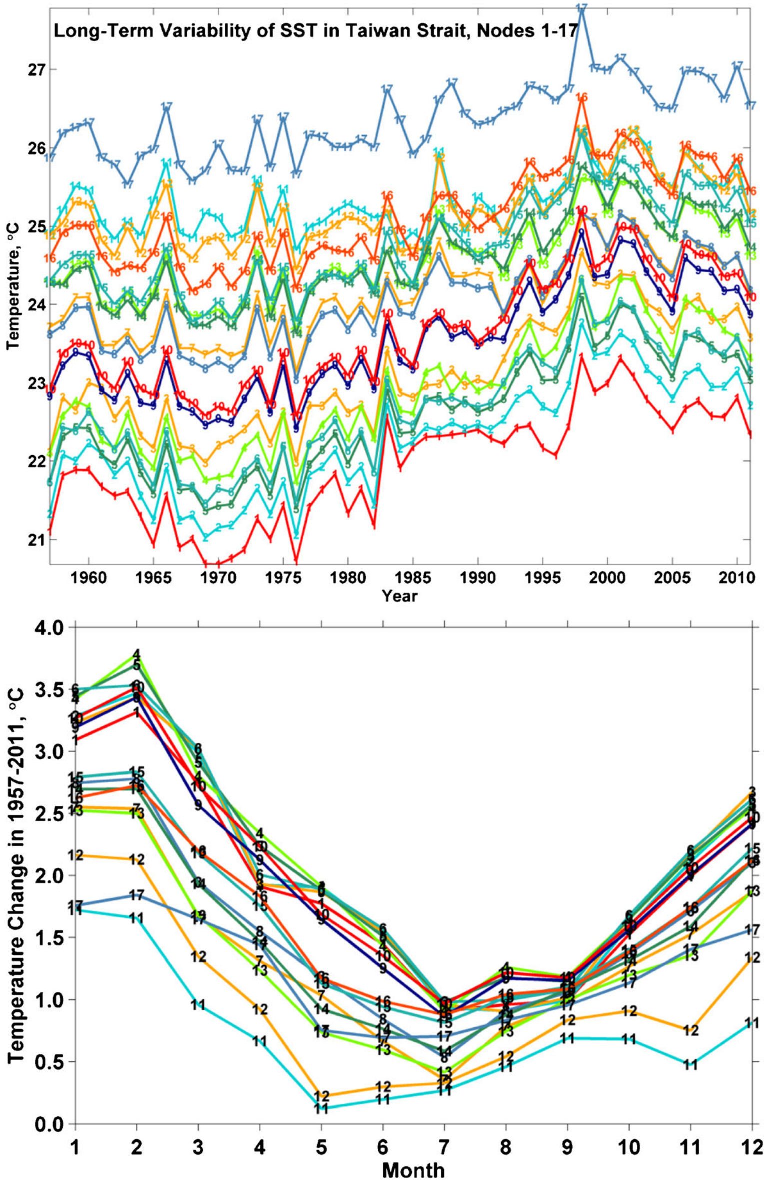

Fig. 4 (*Top*) Time series of SST in 17 nodes of Hadley 1°×1° grid in the Taiwan Strait, 1957–2011. The nodes are shown with large green circles in Fig. 4. During an abrupt regime change in 1992, the previously distinct SST gradient between nodes 7–8 (China Coastal Current) and 9–10 (offshore Taiwan Strait) has almost vanished. The entire zonal band (nodes 7–10) remained thermally uniform through 2011. (*Bottom*) Seasonal change of SST trends in 17 nodes of Hadley 1°×1° grid (large green circles in inset and in Fig. 4). The most rapid warming is observed in February along 24.5°N (nodes 4–6), with the maximum SST change in 1957–2011 exceeding 3.8 °C (node 4)

et al. 2005). The MODIS Aqua and Terra SST data were found to have generally small biases, although larger than those of AVHRR SST (Lee et al. 2010). These biases, fortunately, are negligible relative to the rapid warming in 1976–1998, which occurred before Terra and Aqua

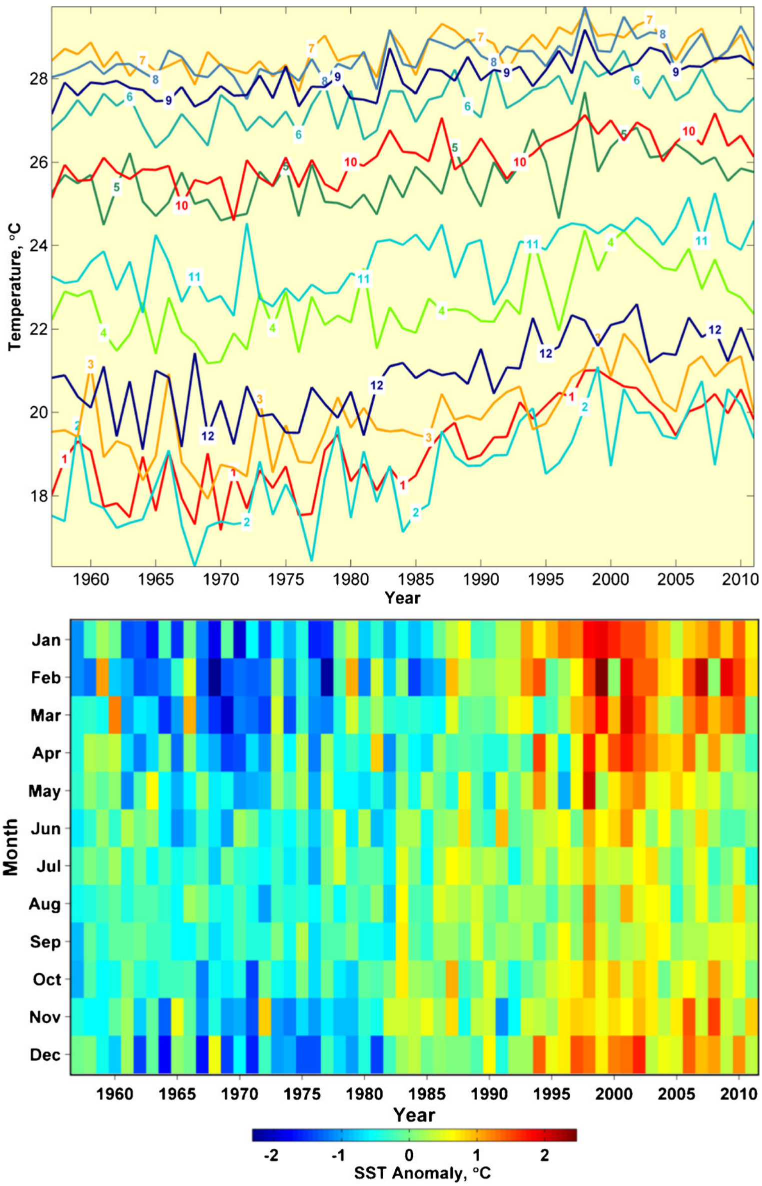

Fig. 5 (*Top*) Long-term variability of monthly SST in the Taiwan Strait. Numbers denote months (January, 1; February, 2; and so forth). (*Bottom*) Monthly area-averaged SST anomalies in the Taiwan Strait, 1957–2011. The anomalies have been calculated relative to the 1957–2011 means

have been launched. Even more important is the absence of any significant temporal drift in satellite-derived SST acquired from AVHRR and MODIS. A comparison of HadISST1 vs. HadSST2 (un-interpolated in situ data set) revealed a good agreement between the two (Rayner et al. 2006).

4.3 Comparison with Reynolds SST climatology

The high-resolution (0.25°) daily satellite SST climatology by Reynolds et al. (2007) lends itself to comparison with our results. Lima and Wethey (2012) used this data set to study global coastal SST in 1982–2011. Our results compare favorably with those of Lima and Wethey (2012). Confirmed are (a) extremely rapid warming in ECS and Taiwan Strait; (b) southward decrease in warming rates toward SCS; (3) winter amplification of warming rates in a broad Taiwan Strait area. A close inspection of warming rates in Lima and Wethey (2012, supplementary data) reveals a discontinuity off the Yangtze Estuary, suggestive of a key role played by the Yangtze River discharge (Belkin 2009).

4.4 Winter amplification of long-term SST warming

The above-documented winter amplification of long-term SST warming can be explained by the seasonally-reversing, monsoon-driven circulation (Jan et al. 2002; Fig. S1). In winter, the regional circulation is dominated by the southward flow from ECS toward SCS. Since the ECS has been warming much faster than SCS, it explains the wintertime amplification of the long-term warming in the Taiwan Strait. Seasonality of SST warming in the China Seas has been studied by several researchers (Table 1). Mechanisms responsible for the enhanced winter warming in the western North Pacific were investigated by Yeh and Kim (2010), Heo et al. (2012) and Park et al. (2012). Clearly, the East Asian winter monsoon and its intensification (combined with the concomitant relaxation of the summer monsoon) play key roles. Even though predominant winter warming has been reported in most Northern Hemisphere coastal gradients (Baumann and Doherty 2013, Fig. 4), this phenomenon is exceptionally strong in the eastern China Seas (Lima and Wethey 2012, Figs. 3–8).

4.5 China Coastal Current vs. Kuroshio

Our results demonstrate that the Taiwan Strait is heavily influenced by ECS through the China Coastal Current and its offshore branches. Indeed, the warming rate of the Taiwan Strait is comparable with that of the ECS and much exceeds the warming rates of the Kuroshio and SCS (Belkin 2009). The crucial role of CCC in regulating the hydrography of the Taiwan Strait was amply demonstrated by the 2008 cold disaster caused by southward invasion of the CCC waters, when SST dropped by almost 8 °C vs. a 12-year mean February SST, causing substantial mortality of wild fish and a 80 % loss of caged mariculture fish (Chang et al. 2009, 2013). The Kuroshio impact is limited by the southeastern part of the Strait, where in summer the SCS Warm Current flows northward alongside the Kuroshio branch (Jan et al. 2002; Fig. S1).

4.6 Rapid warming in 1977–1998 and possible role of the Yangtze River discharge

The extremely rapid warming of the ECS in 1976–1998 begs for explanation. Belkin (2009) suggested a key role of the Yangtze River outflow. Indeed, the Yangtze River and its tributaries act together to integrate terrestrial warming over a huge basin of 1,808,500 km^2 and inject it into ECS. The annual discharge of up to 1,000 km^3 (Yang et al. 2010) creates a buoyant plume that spreads across ECS. In summer, the plume is warmer than the ambient offshore water. The combined effect of low salinity and warm temperature results in the plume water's density being substantially less than that of the ambient water, thereby enhancing the plume's vertical stability and its capacity for trapping the incoming solar radiation. Thus, the Yangtze River runoff in summer should enhance surface warming. The above-described conceptual model of the Yangtze River discharge-driven enhancement of regional warming has been corroborated by Park et al. (2011).

Moreover, the Yangtze River outflow per se is an important seasonal heat source to ECS (Belkin 2009) since (a) the Yangtze discharge peaks in summer when riverine water is warmer than the ambient offshore water (Zhang et al. 2007), and (b) the Yangtze stream temperature in the estuary increased by 2 °C since the late 1960s (Fig. S5 after Zhou et al. 2005, Fig. 4), thereby enhancing the rapid warming east of the estuary (Ho et al. 2004; Belkin 2009, Fig. 4). The rapid increase of the Yangtze River stream temperature is consistent with the recent amelioration of winter climate in East Asia (e.g., Wang and Gong 2000), which is especially pronounced in the middle and lower reaches of the Yangtze River and in the Yangtze River Delta (e.g., Chen et al. 2006; Su et al. 2006). Another reason for a local maximum warming rate in the ECS is topographic trapping of the Yangtze discharge over the Yangtze Shoal, inside the Yangtze Shoal Ring Front (Belkin et al. 2009).

Among several factors that control the regional climate of the Taiwan Strait, the East Asian winter monsoon appears as one of the most important. Indeed, the recent amelioration of the North Pacific climate occurred thanks to a significant warming of the winter season, whereas the summer season temperatures remain fairly stable and even cooled slightly (Schneider and Held 2001; Thompson and Wallace 2001; Belkin et al. 2002). Particularly, the frequency of cold surges decreased dramatically between 1979–80 and 1994–95 (Zhang et al. 1997). These surges bring extremely cold and dry air from Central Asia, resulting in extreme heat loss by the sea to the atmosphere. The decrease in the total number of cold surges means higher winter SST in ECS and Taiwan Strait.

4.7 Post-1998 cooling

The global warming has slowed down after the global temperature peaked in 1998. Currently, the reasons for this sharp slowdown are not understood yet. In many regions around the world, the SST decreased after 1998 (Belkin 2009). Perhaps, nowhere was the post-1998 cooling as prominent as in the Taiwan Strait region, including ECS (Belkin, I.M., 2014. Rapid warming in Large Marine Ecosystems: An update through 2013, in preparation). Since the Taiwan Strait climate is strongly affected by the Siberian High, especially in winter, the Arctic is expected to be responsible for the post-1998 cooling. Outten and Esau (2012) suggested a link between the recent loss of the Arctic Ocean sea ice cover and the concurrent cooling trend over mid-latitude Eurasia. The loss of Arctic sea and extremely fast warming over Northern Eurasia and North-Western Canada, up to 5.8 °C/10a in the Kara Sea, decrease the mean north–south temperature gradient, thereby weakening zonal winds and allowing cold Arctic air to escape south.

5 Summary

Multi-decadal variability of SST in the Taiwan Strait was studied from 1°×1° monthly climatology HadISST1. In 1957–2011, three epochs (regimes) were identified. The first epoch of cooling SST lasted through 1976. The regime shift of 1976–1977 led to a rapid warming of 2.1 °C in 22 years. The regime shift of 1997–1998 led to a 1.0 °C cooling by 2011. In the midst of the warming epoch, a sharp decrease of cross-frontal gradient between the China Coastal Current and offshore Taiwan Strait waters occurred in 1992–2011. The long-term net warming of SST in the Taiwan Strait increased three-fold from SCS to ECS and was pronounced in winter and weak in summer. The winter amplification of SST warming peaked along 24.5°N, where February SST warmed in 1957–2011 at >0.7 °C/decade.

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