What caused the record-breaking warming in East China Seas during August 2016?

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The East China Seas (ECS) encountered its warmest monthly mean sea surface temperature (SST) in August 2016, based on the high-resolution satellite SST product (1982–2016). The area-averaged monthly SST over the ECS (28°–39°N, 120°–130°E) reached up to 28.3 °C, 2 °C above normal that exceeds two times of SD. The isotherms of 28.5 and 30 °C extended to 36° and 32°N, respectively, both reaching their unprecedented northernmost locations. The heat budget analysis indicated that this extreme warming event in the ECS was predominantly attributable to the combined effects of oceanic advection (0.18 °C, ~24%) and net heat flux (0.44 °C, ~58%), with the latter being the dominant contributor. Further, the extreme ECS warming is induced by the strong adiabatic descent motion with increased downward solar radiation due to the anomalous anticyclonic circulation over the north western Pacific, which is closely linked to the negative phase of the Indian Ocean Dipole (IOD) with robust heating over the tropical eastern Indian Ocean and western Pacific. Additionally, the anticyclonic circulation anomalies promoted the intrusion of warm water of the Kuroshio across the ECS shelf, which also contributed to the forming of enhanced ECS warming. It is further found that most of the ECS warming events can be explained by the precursor signals of negative IOD with 1–3 months ahead, which have important implications for prediction.

KEYWORDS
East China Sea, extreme SST, the Indian Ocean dipole

1 | INTRODUCTION

The global sea surface temperature (SST) has been rising rapidly during the last several decades, however, the warming magnitude is not spatially homogeneous but shows rather great regional differences (Hoegh-Guldberg et al., 2014). For example, an enhanced warming trend with frequent extreme SST events was observed in the East Asian seas, especially the East China Seas and adjacent seas (referred to as ECS, Park et al., 2015; Cai et al., 2017). The substantial increase in SST during the extreme warming events can potentially disrupt local established physical, chemical and biological processes, leading to myriad changes in coastal marine ecosystems. For instance, the warming conditions in the ECS have been linked to frequent occurrences of harmful algae blooms and northward shifts of marine fishes in the East Asian seas (Cai et al., 2016). Hence, identifying, understanding and predicting the regional ocean warming, especially the extreme events, are important for assessing their socioeconomic and environmental impacts.

Previous studies have proposed several processes responsible for the variability and change of SST in the ECS, including oceanic advection transport (Oey et al., 2013), air–sea heat flux exchange (Wu et al., 2014), diluted water discharge of the Yangtze River (Kako et al., 2016),...
and local vertical mixing effect (Xie et al., 2002). Among these factors, oceanic advection and air–sea heat flux are widely considered as the major driving factors (Cai et al., 2017). The former is associated with the Kuroshio Current (KC), one of the strongest western boundary currents, which carry warm tropical water to the mid-latitudes. The vigorous spreading of warm water from the KC has been proven to favor decadal warming in the ECS (Qiu, 2000; Oey et al., 2013). The latter is dominated by the variations of East Asian Monsoon and the western North Pacific subtropical high through modulating the turbulent heat fluxes and solar shortwave radiation (Cai et al., 2017). Strong solar radiation during summer results in increased positive (downward) net surface heat flux, heating upper sea water in the ECS (Liu et al., 2014). However, the relative contributions of ocean dynamics process and surface heat flux to changes of ECS SST varied largely in different seasons and cases (e.g., Zhang et al., 2010).

Besides the local environmental variables, the remoted large-scale air–sea variability, such as El Niño Southern Oscillation (ENSO), may also affect SST changes in the coastal China seas through atmospheric circulation and ocean dynamics processes (Wang et al., 2006; Tan and Cai, 2014). For example, the South China Sea experienced an extreme warm event during 1997/1998, which may be caused by the strong 1997/1998 El Niño (Wang et al., 2006). In addition, previous studies suggested that ENSO together with the subsequent warming in the tropical Indian Ocean (IO) tend to modulate the location and intensity of the western North Pacific subtropical high, and in turn affect summer extreme high temperature events over eastern China mainland (Xie et al., 2009; Hu et al., 2011). Nevertheless, their influence on SST extremes in the adjacent ECS is less concerned.

Here, we identified an episode of record-breaking SST event in the ECS during August 2016 over the past decades, diagnosed the potential atmospheric and oceanic physical processes at play, and explored their association with large-scale tropical drivers.

2 | DATA AND METHODS

The SST data used in this study is Optimum Interpolation 0.25° × 0.25° daily analysis product, which is obtained from National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (http://www.ncdc.noaa.gov/oisst/data-access). The atmospheric circulation data, including horizontal wind field and vertical velocity, geopotential height, and surface heat fluxes (latent heat flux, sensible heat flux, solar shortwave radiation and longwave radiation) is derived from the newly released ERA Interim, with 1.5°×1.5° spatial resolution spanning the period 1979–present (Dee et al., 2011). The three-dimensional ocean variables, including potential temperature, zonal, meridional, and vertical velocities of ocean currents, were obtained from the National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS) Reanalysis (CFSR, 1979–2010, Saha et al., 2010), and extended CFS Version 2 analysis (CSFv2, 2011–2016, Saha et al., 2014). The monthly CFSR ocean product considers the coupled process of atmosphere and ocean, and assimilates all available conventional and satellite observations, with unparalleled spatial resolution 0.25° at the equator and 0.5° beyond the tropics.

We focused our research on the monthly SST anomaly from 1982 to 2016. The anomaly is defined as the departure of the SST for a particular month from the long-term monthly mean (1982–2016). The SD of SST is calculated by

\[ SD = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (A_i - \overline{A})^2} \]

where \( A_i \) is the area-averaged SST at each time, \( n \) is the number of variable \( A \), \( \overline{A} \) is the mean of \( A \). Composite analysis method was used to examine the linkage of extreme ECS warming events to large-scale air–sea factor, such as El Niño and the Indian Ocean Dipole (IOD, defined as difference between SST of the tropical south eastern and western IO, Saji et al., 1999). The Niño 3.4 index and IOD index are from https://stateoftheocean.osmoc.noaa.gov/sur/. The statistical confidence level is estimated using the Student's t test. In addition, the atmospheric forcing and ocean dynamics processes were diagnosed in terms of the seawater temperature budget equation, which will be described in detail in the following section.

3 | RESULTS AND DISCUSSION

3.1 | Observed characteristics

Figure 1 shows the characteristic of extreme warming in the coastal China Sea in August 2016 based on the NOAA’s high-resolution (0.25° × 0.25°) SST product. Significantly positive SST anomaly during August 2016 was observed in the ECS, and the maximum value reached up to 2.5 °C, over the northern part of ECS (Figure 1a). For quantitative analysis, an index was constructed based on the area-averaged SST over the ECS (28°–39°N, 120°–130°E, blue box in Figure 1a). Climatologically, the sea surface in the ECS starts to warm up in February, reaches its peak in August with mean SST value at 26.3 °C, and follows by cooling down from September to next February. As such, August is particularly prone to experiencing record-breaking high temperature. In August 2016, ECS encountered its warmest monthly mean SST, with the area-averaged SST index up to 28.3 °C, 2 °C above the normal which exceeds the two times of the SD (Figure 1b). The anomalous warming event is unprecedented during summer (June to August) in the satellite era. The ECS SST anomaly in August 2016 exceeded the long-term mean of August temperature (1982–2016) by more than 2 °C (Figure 1b) and exceeded the previous warmest August of 2013 by 0.4 °C (Figure 1c). There was no observational precedent for this level of warming even
extending the research period to the late-19th century, based on other SST datasets (see Figure S1, Supporting Information).

In addition, the robust warming is generally accompanied by a large northward shift of the sea surface isotherms. We focused here on the 28.5 and 30°C isotherms, as they have important implications, for example, 28.5°C is generally the scope of Indo-Pacific warm pool and threshold of atmospheric deep convection (Graham and Barnett, 1987). In August 2016, the 28.5°C isotherm reaches northward to 36°N, near the China Shandong Peninsula and south of Korean Peninsula (Figure 1a). The 30°C isotherm also extends northward to the Kagoshima, Japan (~32°N). We defined an index of the north edge where 28.5 and 30°C isotherms reached within the coastal China Sea for 1982–2016. The northernmost locations (since 1982) of both the 28.5 and 30°C isotherms are reached in August 2016. The second record occurred in the August 1998, with the 28.5 and 30°C isotherms extending to 34.5° and 30.5°N, respectively.

In summary, the ECS experienced an extreme warming event in August 2016, both the area-averaged SST anomaly

FIGURE 1 (a) Characteristic of extreme warming in the coastal China Sea. SST anomaly (color in °C) in August 2016 superimposed by 28.5 and 30°C isotherms (blue lines). The black box in (a) denotes the East China Sea (ECS, 28°–39°N, 120°–130°E) for area-averaged SST index. (b) Monthly evolved SST in the ECS for the year 2016 and climatology (1982–2016), with the light blue shading representing their range of ±2.0 SD. (c) The monthly ECS SST anomaly in August for 1982–2016. (d) The northernmost location where 28.5 and 30°C isotherms reached within the coastal China Sea for 1982–2016. The missing value for 30°C isotherm denotes no criterion met within 0°–45°N, 100°–140°E.
(>1.5 °C, exceeding ±2.0 SD) and isotherms (28.5 and 30 °C) reaching their unprecedented levels. The above results seem to have higher reliability, as they are derived from the satellite-derived SST product with unparalleled spatial resolution and temporal continuity. Prolonged periods (months or longer) of anomalously high SST may have severe impacts on marine ecosystems and fisheries and aquaculture industries (e.g., Wernberg et al., 2013).

### 3.2 Dynamics processes

To examine the relative contribution of atmospheric and oceanic processes to this extreme warming event, the upper-ocean heat budget in the ECS during August 2016 was calculated based on the three-dimensional heat conservation equation,

\[
\frac{\partial T}{\partial t} = -\bar{v} \nabla T - \int_0^h \frac{\partial}{\partial z} w T dz + \frac{1}{\rho_c} \frac{\partial h}{\partial t} Q_{\text{net}} + R
\]  

(1)

where \(T\) and \(\bar{v}\) are seawater temperature and horizontal velocity \((u; v)\), respectively, vertically averaged in the upper mixed layer, and \(w\) is vertical velocity. The mixed layer depth \((h)\) is defined as the depth at which the temperature is 0.5 °C below the near-surface value. \(\rho\) is the mean density of seawater, and \(c_p\) is the specific heat. \(\nabla\) is the horizontal gradient operator \((\nabla \equiv \frac{\partial}{\partial x}; \frac{\partial}{\partial y})\). Net surface heat flux \(Q_{\text{net}}\) is the sum of the latent heat flux \(Q_{\text{LH}}\), sensible heat flux \(Q_{\text{SH}}\), net shortwave radiation flux \(Q_{\text{SW}}\), and net longwave radiation flux \(Q_{\text{LW}}\):

\[
Q_{\text{net}} = Q_{\text{LH}} + Q_{\text{SH}} + Q_{\text{SW}} + Q_{\text{LW}}.
\]  

(2)

The surface heat flux is defined as positive downward, indicative of a positive value when the ocean gains heat from atmosphere. Equation (1) denotes that the local change of \(T\) is affected by the oceanic horizontal advection, vertical mixing, \(Q_{\text{net}}\), and residual terms \((R)\). \(R\) may comprise diffusive heat flux, entrainment, and so on. Previous studies suggested these terms are much less than ocean advection and \(Q_{\text{net}}\) (Zhang et al., 2010), and hence will not be estimated here. Note that Equation (1) is just a simplified version of primitive equation, and one can refer to Moisan and Niiler (1998) for the formal derivation. The heat fluxes and oceanic variables are derived from monthly ERA interim and NCEP-CFSR reanalysis, respectively.

The local tendency of \(T\) \((\partial T/\partial t)\), defined as the difference of sea temperature over upper mixed layer between August and July in 2016, indicates a rapid warming in ECS and an obvious cooling in the northern South China Sea and Taiwan Strait (Figure 2a). Also shown in Figure 2a is the anomalous upper ocean circulation (30 m above) in the coastal China sea. Significant northward current anomalies were observed along the east coast of China from the northeast of Taiwan, where warm water of the KC intrudes across the ECS shelf. The poleward warm water could extend to south of Shandong Peninsula and form an anomalous anticyclonic circulation, encouraging the massive accumulation of warm water and thus leading to a positive SST anomaly in the ECS. Linked to the circulation anomalies is the oceanic horizontal advection (Figure 2b), that is, sum of zonal and meridional advects. Robust warm advection was found in the northeast of Taiwan and north part of ECS. Furthermore, most of the total horizontal advection was dominated by the meridional advection (Figure 2c), which is associated with anomalous meridional current. On the other hand, the net heat flux \(Q_{\text{net}}\) also contributed largely to the ECS warming (Figure 2c). Heating center is located over the north part of ECS, consistent with the center of positive SST anomaly. Previous studies have reported that there is usually positive \(Q_{\text{net}}\) over the ECS in summer, which indicates that ocean receives heat from the atmosphere, due to intense insolation over the subtropical Northwest Pacific (Liu et al., 2014; Cai et al., 2017). In August 2016, \(Q_{\text{net}}\) over the ECS was largely accounted for by the net shortwave radiation flux anomaly, with the maximum anomaly of nearly 100 W/m² (Figure 2f). Sea surface in ECS could be warmed efficiently by the powerful insolation due to absence of cloud, which was associated with the anomalous sinking motion over this region (Figure 3). Therefore, the heat effect is radiative in nature and amplified by the strong descending motion.

To quantitatively measure the relative contributions of oceanic advection and heat flux, we calculated their area-averaged values over the ECS (28°–39°N, 120°–130°E). In August 2016, the ECS experienced a rapid warming (relative to July), with the upper sea temperature increasing by 0.76 °C. The net heat flux seems to contribute largely to this warming (0.44 °C, 58%), while the ocean horizontal advection played a secondary role of 0.18 °C (24%). It should be noted that the contribution of ocean advection may be underestimated, because warm advection along the east coast of China was partially offset by the cold advection offshore (Figure 2b). In addition, the vertical advection was also estimated according to the second term on the right side of the Equation (1). However, the vertical advection-induced change of temperature is much less than other two terms with at least one order of magnitude (\(-0.008\) °C). This may result from shallow mixed layer depth (30 m) and small vertical velocity due to enhanced stratification during August 2016 (see Figure S2). Also noted is that the heat budget is not completely closed, suggesting that other factors, such as entrainment and runoff of the Yangtze River, may also play some roles.

In summary, based on the upper ocean heat budget analysis, the extreme ECS warming in August 2016 can be explained by the combined effects of oceanic advection and \(Q_{\text{net}}\), with the latter being the dominant contributor. In particular, \(Q_{\text{net}}\) is largely attributable to the intense solar radiation, associated with the anomalous descending motion over ECS. We recognized that the estimated values shown above
FIGURE 2  Heat budget in the ECS during August 2016. (a) Tendency of sea temperature (color, °C) over upper mixed layer, superimposed anomalous upper 30 m ocean circulation (vector, m/s). Contributions of total horizontal advective heat transport (b, °C), and net heat flux (c, °C). The horizontal advection is the sum of zonal (d, °C) and meridional (e, °C) advection. (f-i) Denote net shortwave, longwave, latent heat, and sensible heat fluxes (W/m²), defined as positive downward.
have great uncertainty, which may depend on the choice of reanalysis data. The aim here is not to seek an accurate SST budget but rather to understand the relative importance of $Q_{\text{net}}$ and oceanic advection.

### 3.3 Linkage to tropical drivers

The record-breaking high-temperature in the ECS occurred after the strong 2015/2016 El Niño. Likewise, the extreme ECS warming in August 1998, as shown in Figure 1c, also took place during the decay of the 1997/1998 El Niño event. Both events suggest a potential linkage to El Niño. In addition, previous studies have suggested an increasingly important role of the IO in the East Asian summer climate, especially after the El Niño, through the capacitor effect (Xie et al., 2009; Wu et al., 2012). Lu et al. (2018) have reported an extreme negative IOD event in the summer of 2016, which may be related to the ECS warming. In the following, we focused on the associations of large-scale climatic environments of ECS warming with El Niño and IOD events.

We first extracted eight extreme ECS warming events that occurred in August, that is, 2016, 2013, 2010, 2006, 2004, 2001, 1998, 1990, based on the analysis results of Figure 1c. It is found that three events occurred during the decay period of El Niño (2015/2016, 2009/2010, 1997/1998 El Niño events). The three El Niño events are all well-defined and strong episodes, with their Niño3.4 indices peaking in the winter and attenuating after spring (Figure 4a). And yet, other warming events in the ECS respond to negative Niño3.4 indices during the former winters, indicating large uncertainties in the relationship between El Niño and extreme ECS warming. By contrast, there are more consistent connections to IOD events. The extreme ECS warming events seem to happen after negative IOD episodes in summer, with lagging period of 1–3 months. That is, there are in general negative IOD events during May to July, before the outbreak of extreme warming events in August. In particular, the record-breaking warming event in the ECS during August 2016 followed the extreme negative IOD event in July (Figure 4b). Further, almost all of the warming events can be explained by the precursor signals of negative IOD indices. Most of the IOD events generally develops in summer, peaks in autumn, and collapses in winter (Liu et al., 2017), as shown in Figure 4b. The significant seasonal phase locking of IOD has large predictability, with higher skillful predictions being made one season (3 months) ahead (Luo et al., 2005; Lu et al., 2018). The 3 months lag is a common characteristic of the atmospheric bridge and is the approximate time needed for ocean surface heat content and SST to respond to the cumulative atmospheric forcing (Alexander et al., 2002). Therefore, the development of negative IOD may be a potential predictor for the extreme warming in the ECS.

To unravel the potential mechanisms underlying the relationship between IOD and extreme ECS warming, the composite analysis was performed to illustrate SST and low-level circulation anomalies over the tropical IO and northwestern Pacific Ocean in summer (June to August), based on the eight extreme ECS warming events, relative to the climatological mean condition (1982–2016). Significantly positive SST anomalies were observed over the tropical eastern IO and western Pacific Ocean, whereas negative SST anomalies over the tropical western IO, indicative of typical negative phase of IOD (Figure 5). The anomalous warming is particularly remarkable along the offshore areas of Sumatra, Indonesia. This strong heating initiates a Matsuno–Gill (Matsuno, 1966; Gill, 1980) pattern of anomalous atmospheric circulation in tropical low-level troposphere (at 850 hPa) with a Kelvin wave propagating into the tropical western Pacific. In addition, an anomalous anticyclonic circulation developed over the northwestern Pacific Ocean with its center anchoring to the ECS. Because circulation and vertical velocity are generally coupled, the anticyclonic circulation anomalies may force the strong adiabatic descent motion, as shown in Figure 3, which favor surface warming through intense insolation and suppressing convective activity. On the other hand, the low-level anticyclonic circulation anomalies promoted the warm water of the KC to intrude across the ECS shelf via Ekman effect, which also contribute to the enhanced ECS warming. Besides, the composited contour line for 5.870 gpm at 500 hPa, a proxy of position of western Pacific subtropical high, denoted a pronounced northward shift to north of 30°N, in accordance to the low-level anticyclonic circulation. The prevailed subsidence within the areas controlled by the subtropical high suppressed the local convection and feedback, despite of robust surface warming, and helped to maintain anomalous warming in the ECS.

In summary, the extreme ECS warming is closely linked to the tropical large-scale drivers, especially the negative phase of IOD. The anomalous anticyclonic circulation over the northwestern Pacific, which may be associated with strong heating over the tropical eastern IO and western
Pacific, played a crucial role in forming of enhanced ECS warming. The precursor signals of negative IOD with 1–3 months ahead have important implications for prediction of the extreme warming events. Despite this, the negative IOD was not absolutely doomed to follow by an extreme ECS warming. For example, the summer of 1996 witnessed a significantly negative IOD; however, the extent of the ECS warming in August, in spite of displaying positive SST anomaly, was not as large as other events (see Figure S3). Therefore, other mechanisms, such as mid-latitude atmospheric circulation forcing, may also be considered in future work.

4 | CONCLUSION

Based on the high-resolution satellite SST product, we identified a record-breaking warming event over the ECS in August 2016. The area-averaged monthly SST over ECS reached up to 28.3 °C (2 °C above normal), exceeding two times of SD, and the isotherms of 28.5 and 30 °C extended to 36° and 32°N, respectively, both reaching their northernmost locations. The heat budget analysis indicated that this extreme warming can be attributable to the combined effects of oceanic advection (∼0.18 °C, 24%) and net heat flux (∼0.44 °C, 58%), with the latter being the dominant contributor due to the intense shortwave radiation flux. Further, the extreme ECS warming is closely linked to the negative phase of IOD. The anomalous anticyclonic circulation over the north western Pacific, which may be associated with robust heating over the tropical eastern IO and western Pacific, induced the strong adiabatic descent motion with powerful heating over the tropical eastern IO and western Pacific, resulting in the anomalous warming over the ECS. On the other hand, the anticyclonic circulation anomalies promoted the intrusion of warm water of the KC across the ECS shelf via Ekman effect, which also contributed to the forming of enhanced ECS warming. Moreover, most of the ECS warming events can be explained by the precursor signals of negative IOD with leading periods of 1–3 months, which have important implications for extreme warm event prediction.

Prolonged periods (month or longer) of extremely high SST, like the presented event in August 2016, may have severe impacts on marine ecosystems and local climatic conditions (e.g., Wernberg et al., 2013; Cai et al., 2016). In particular, the northward migration of 28.5 °C isotherms may change regional air–sea interaction and affect marine biological processes. The air–sea interactions and follow-up ecological consequence induced by this warming event remains unknown but deserves further investigation in future studies. In addition, given that the continued global warming in the future seems inevitable as a result of anthropogenic greenhouse gases, the increased mean upper ocean temperature is expected to result in more frequent and more extreme warming events (Hobday et al., 2016). Therefore, it is important, ecologically and climatically, to understand the physical process and predictability of marine extreme warming events.

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**REFERENCES**

Alexander, M.A., Bladé, I., Newman, M., Lanzante, J.R., Lau, N.C. and Scott, J.D. (2002) The atmospheric bridge: the influence of ENSO teleconnections on air–sea interaction over the global oceans. *Journal of Climate*, 15(16), 2205–2231.

Cai, R., Tan, H. and Qi, Q. (2016) Impacts of and adaptation to inter-decadal marine climate change in coastal China seas. *International Journal of Climatology*, 36(11), 3770–3780.

Cai, R., Tan, H. and Kontoyiannis, H. (2017) Robust surface warming in offshore China seas and its relationship to the east Asian monsoon wind field and ocean forcing on interdecadal time scales. *Journal of Climate*, 30(22), 8987–9005.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balsamo, M.A., Balsamo, G., Bauer, D.P. and Bechtold, P. (2011) The ERA–interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(656), 553–597.

Gill, A.E. (1980) Some simple solutions for heat-induced tropical circulation. *Quarterly Journal of the Royal Meteorological Society*, 106, 447–462.

Graham, N. and Barnett, T. (1987) Sea surface temperature, surface wind divergence, and convection over tropical oceans. *Science*, 238, 657–659.

Hobday, A.J., Alexander, L.V., Perkins, S.E., Smale, D.A., Straub, S.C., Oliver, E.C., Benthusen, J.A., Burrows, M.T., Donat, M.G., Feng, M. and Holbrook, N.J. (2016) A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, 141, 227–238.

Hoegh-Guldberg, O., Cai, R., Poloczanska, E.S., Brewer, P.G., Sundby, S., Hilmi, K., Fabry, V.J. and Jung, S. (2014) The ocean. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects*, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York, NY: Cambridge University Press, pp. 1655–1731.

Hu, K., Huang, G. and Huang, R. (2011) The impact of tropical Indian Ocean variability on summer surface air temperature in China. *Journal of Climate*, 24(20), 5365–5377.

Kako, S., Nakagawa, T., Takayama, K., Hirose, N. and Iseobe, A. (2016) Impact of Changjiang River discharge on sea surface temperature in the East China Sea. *Journal of Physical Oceanography*, 46(6), 1735–1750.

Luo, J.J., Masson, S., Behera, S., Shingu, S. and Yamagata, T. (2005) Seasonal climate predictability in a coupled OAGCM using a different approach for ensemble forecasts. *Journal of Climate*, 18(21), 4474–4497.

Matsuno, T. (1966) Quasi-geostrophic motions in the equatorial area. *Journal of the Meteorological Society of Japan*, 44, 25–43.

Moisan, J.R. and Nüller, P.P. (1998) The seasonal heat budget of the North Pacific: net heat flux and heat storage rates (1950–1990). *Journal of Physical Oceanography*, 28, 401–421.

Oey, L.Y., Chang, M.C., Chang, Y.L., Lin, Y.C. and Xu, F.H. (2013) Decadal warming of coastal China Seas and coupling with winter monsoon and currents. *Geophysical Research Letters*, 40, 6288–6292. https://doi.org/10.1002/2013GL058202.

Park, K.A., Lee, E.Y., Chang, E. and Hong, S. (2015) Spatial and temporal variability of sea surface temperature and warming trends in the Yellow Sea. *Journal of Marine Systems*, 143, 24–38.

Qu, B. (2000) Interannual variability of the Kuroshio extension system and its impact on the wintertime SST field. *Journal of Physical Oceanography*, 30, 1486–1502.

Saha, S., Moorthi, S., Pan, H.L., Wu, X., Wang, J., Nadiga, S., et al. (2010) The NCEP climate forecast system reanalysis. *Bulletin of the American Meteorological Society*, 91(8), 1015–1058.

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., et al. (2014) The NCEP climate forecast system version 2. *Journal of Climate*, 27(6), 2185–2208.

Saji, N.H., Goswami, B.N., Vinayachandran, P.N. and Yamagata, T. (1999) A dipole mode in the tropical Indian Ocean. *Nature*, 401(6751), 360–363.

Tan, H. and Cai, R. (2014) A possible impact of El Niño Modoki on sea surface temperature of China’s offshore and its adjacent regions. *Journal of Tropical Meteorology*, 20, 1–7.

Wang, C., Wang, W., Wang, D. and Wang, Q. (2006) Interannual variability of the South China Sea associated with El Nino. *Journal of Geophysical Research-Oceans*, 111, C03023. https://doi.org/10.1029/2005JC003333.

Wernberg, T., Smale, D.A., Tuya, F., Thomsen, M.S., Langlois, T.J., De Bettignies, T., Bennett, S. and Rousseaux, C.S. (2013) An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nature Climate Change*, 3(1), 78–82.

Wu, R., Yang, S., Wen, Z., Huang, G. and Hu, K. (2012) Interdecadal change in the relationship of southern China summer rainfall with tropical indo-Pacific SST: *Theoretical and Applied Climatology*, 108(1–2), 119–133.

Wu, R., Chen, W., Huang, G. and Hu, K. (2014) Relative contribution of ENSO and East Asian winter monsoon to the South China Sea SST anomalies during ENSO decaying years. *Journal of Geophysical Research-Atmospheres*, 119(9), 5046–5064.

Xie, S.P., Hafner, J., Tanimoto, Y., Liu, W.T., Tokinaga, H. and Xu, H. (2002) Bathymetric effect on the winter sea surface temperature and climate of the Yellow and East China seas. *Geophysical Research Letters*, 29(24), 2228–814. https://doi.org/10.1029/2002GL015884.

Xie, S.P., Hu, K., Hafner, J., Tokinaga, H., Du, Y., Huang, G. and Sampe, T. (2009) Indian Ocean capacitor effect on Indo–western Pacific climate during the summer following El Niño. *Journal of Climate*, 22(3), 730–747.

Zhang, L., Wu, L., Lin, X. and Wu, D. (2010) Modes and mechanisms of sea surface temperature low-frequency variations over the coastal China seas. *Journal of Geophysical Research-Oceans*, 115, C08031. https://doi.org/10.1029/2009JC006025.

**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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