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孟加拉湾春季小型暖池对热带气旋的影响研究

摘要

本文研究了2017年春季孟加拉湾小型暖池对热带气旋Maarutha(4月14—17日)以及热带气旋Mora(5月27—30日)的影响.利用卫星遥感和现场观测数据分析发现,尽管春季孟加拉湾热带气旋确实能引起海洋上层冷却效应,但是其冷却强度受到暖池强度的影响.本文进一步对比孟加拉湾小型暖池对两个热带气旋的响应情况,发现当春季小型暖池的温度大于31 ℃(热带气旋Mora期间),暖池效应能有效抑制海洋上层混合层的加深,降低热带气旋引起的潜热通量损失带来的冷却效应,并在一定程度上加强了热带气旋.

关键词

热带气旋;春季小型暖池;海表温度;孟加拉湾

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0 Introduction

Tropical cyclones (TCs) are one of the disastrous natural hazards which cause numerous ecological/economical losses under favorable conditions. As TCs are capable of bringing catastrophic losses, examining, understanding and predicting of the TCs has practical importance in terms of minimizing their damages. Nearly 7% of TCs in the world are thought to occur in the Northern Indian Ocean (NIO), which holds unique characteristics compared to the Atlantic and Pacific Oceans. Singh et al.[1] noted an increasing trend in TC genesis during November and May in the NIO, while Webster et al.[2] suggested an increase in the intensified TCs in the region. Mohanty et al.[3] pointed out that the Bay of Bengal (BoB) contributes around 75% of TCs (in each category) towards total of the Indian Ocean. Due to its regional importance, many studies has been carried out to understand the TC activity (formation, intensification and propagation) in the BoB[4-5], however, predicting TC intensities in the region has been a challenging problem[6]. The BoB holds unique characteristics under the influence of Asian Monsoon with its seasonality being defined as, summer monsoon (June-September), winter monsoon (December-February), pre-summer monsoon (March - May) and post-summer monsoon (October- November). Occurrence of TCs is a common feature in the BoB, which experiences intense TCs during April-early June (secondary TC peak season) and during late September-December (primary TC peak season)[7-8].

Six major factors (low-level relative vorticity, the Coriolis Effect, weak vertical wind shear, warmer sea surface temperature (SST), thermodynamically unstable atmosphere, and mid-level relative humidity) have been pointed out as the primary requirement for TC genesis[9-10], which are well evident during the two TC peak seasons in the BoB[11], and many recent studies have highlighted the importance of higher SST[12-13], deepening of mixed-layer depth (MLD)[14], and latent heat flux (Q_L) between the air-sea interfaces[15], which influence the TC intensification. Furthermore, the role of seasonal barrier-layer (BL)[16], the effect of positive and negative sea surface height anomalies (SSHA)[6,17], and the importance of cyclone heat potential (CHP)[18], have been discussed in terms of TC intensification in the BoB.Several earlier studies have pointed out the significance of TC-induced SST cooling on TC intensification[19],while Sengupta et al.[7] argued that the TC-induced SST cooling is larger during secondary TC peak season compared to that during primary TC peak season in the BoB.Furthermore,Shen and Ginis[20] and Lin et al.[21] have suggested that any processes which could influence the TC-induced SST cooling,may play an important role in TC intensification.

The existence of southwest-northeast oriented spring warm pool in the BoB with SST> 31 ℃ and its impact on the onset of Asian Summer Monsoon have been pointed out by Wu et al.[22].After examining the intensification of monsoon trough and associated TC activity over the BoB during spring,Wang et al.[23] have proposed that the increasing of SST in the BoB has contributed to an increase in TC intensity.Though previous studies have examined the role of different influencing factors,none of them have examined the effect of spring mini-warm pool (MWP) on TCs in the BoB.Consecutive,recent extreme TC events and associated damages noted during spring in the BoB have motivated us to continue this study.Therefore,by utilizing multiple data sources,we examined the effect of spring MWP on TC intensity change in the BoB. We have selected two recent cases (TC Maarutha and TC Mora) (Fig.1) based on their known impacts and the availability of high-quality datasets (including in-situ observations). The noted recent extreme TC events during spring in the BoB have motivated us to focus on the influence of spring MWP on TCs which has not been discussed before. The paper is organized in 4 sections. Data and methodology used in the study are described in section 2,followed by results and discussion in section 3,and major conclusions are stated in section 4.

1 Data and methodology

Existing data from multiple sources are utilized to highlight the development of the spring MWP in the BoB and its impact on TC's intensity change.Best track data from Joint Typhoon Warning Center (JWTC) (http://www.metoc.navy.mil/jtwc/jtwc.html) are utilized to track the passages of TC Maarutha and TC Mora over the BoB.SST variability have been examined using Optimum Interpolation Sea Surface Temperature (OISST) data (https://www.esrl.noaa.gov/psd/data/gridded/). The pre- and post-conditioning of atmosphere-ocean during TC events have been examined using European Centre for Medium-Range Weather Forecasts (ECMWF) data (wind, vorticity, and RH) (http://apps.ecmwf.int/datasets/), TropFlux data (Q_L) (http://www.incois.gov.in/tropflux/), Hybrid Coordinate Ocean Model (HYCOM) data (temperature) (http://apdrc.soest.hawaii.edu/dods/public_data/Model_output/HYCOM/global), Sea Surface Height Anomaly (SSHA) data from Jet Propulsion Laboratory (JPL) (https://opendap.jpl.nasa.gov/opendap/SeaSurfaceTopography/merged_alt/L4/cdr_grid_interim/contents.html), and wind data from Advanced Scatterometer (ASCAT) (http://apdrc.soest.hawaii.edu/dods/public_data/satellite_product/ASCAT).Furthermore,we utilize the observations (temperature and salinity) from the Research Moored Array for African－Asian－Australian Monsoon Analysis and Prediction (RAMA) mooring at 15°N,90°E (https://

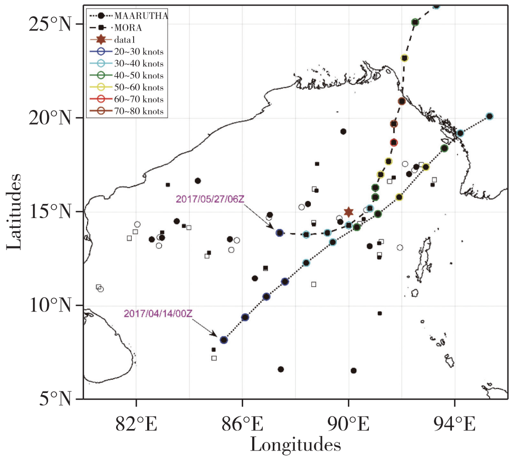

Fig. 1 Tracks of TC Maarutha and TC Mora during spring 2017 in the BoB.The circles marked with colors along the trajectories indicate the wind speed and values are presented in the figure legend.The star (brown color) represents the RAMA mooring at 15°N,90°E.The black shaded (non-shaded) squares represent the Argo observations noted before (after) TC Mora, and the black shaded (non-shaded) circles represent the Argo observations noted before (after) TC Maarutha

www. pmel. noaa. gov/tao/drupal/disdel/) with Argo (http://www.argodatamgt.org/) to examine the in-situ conditions during the TC events.

Mixed-Layer Depth (MLD) is defined as the depth at which density is equal to sea surface density plus the increment in density equivalent to a desired net increase of 0.8 ℃. This criterion takes into account temperature and salinity effects on stratification and is considered to be more reliable compared to 0.5 ℃ or 1 ℃ criterion [24]. Top of Thermocline Depth (TTD) is calculated as the depth where temperature is 0.8 ℃ lower than the SST ($\Delta T = 0.8$ ℃) [25], and barrier layer thickness as the difference between the MLD and the TTD. The CHP is computed using Eq.(1) [26],

$$CHP = \rho C_p \int_0^{D26} \Delta T d_z, \tag{1}$$

where, ρ is the density of seawater column ($\rho = 1\,024$ kg·m^{-3}), C_p is specific heat capacity of seawater at constant pressure ($C_p = 4$ kJ·kg^{-1}·K^{-1}), $D26$ is the depth of 26 ℃ isotherm, ΔT is the temperature difference between mean temperature of two consecutive layers and 26 ℃, and d_z is the depth increment. Ekman pumping velocity (W_e) is estimated using Eq.(2), following Chacko and Zimik[27]:

$$W_e = \frac{Curl(\tau)}{\rho \times f}, \tag{2}$$

where, $Curl(\tau)$ is the wind stress curl (N·m^{-3}) and f is the Coriolis parameter. The vertical wind shear (s) is computed following Gray[9]:

$$s = \sqrt{((U_{200} - U_{850})^2 + (V_{200} - V_{850})^2)}, \tag{3}$$

where, U, V represent the atmospheric vector wind speeds at 200 and 850 hPa levels.

2 Results and discussion

2.1 Formation of spring MWP in the BoB

Generally, SST peaks in the BoB during monsoon transition periods as a part of the seasonal cycle. During pre-summer monsoon (hereafter spring), a large quantity of solar radiation reaches into the BoB under favorable conditions and supports the seasonal heat buildup in the region. As a result, an anomalous warming condition is noted during spring in the BoB with SSTs mostly exceeding 31 ℃. Seasonal warming analyzed by utilizing daily SST observations from OISST is displayed in Figure 2. SST anomaly is computed after removing the annual mean SST (28.66 ℃) for the year 2017. During the month of May, almost the entire BoB experiences a warmer SST (> 30 ℃) compared to other months. As this anomalous warming condition appears in March and continues up to June, daily SST observations at 7-day interval have been selected to examine the development of spring MWP in the BoB during 2017. Here, the spring MWP is defined as a patch of warm water with SST exceeding 29.5 ℃ which exists in the BoB.

The snapshots of daily SST from 15th March to 28th June of 2017 are illustrated in Figure 3. The boundary of the spring MWP is determined using 29.5 ℃ isotherm, which is ~1 ℃ higher than the annual mean of 28.66 ℃ (2017). The spring MWP appears from the southern BoB during late March and gradually expands towards the northern BoB during April. It occupies most of the BoB during the month of May with the highest SSTs (>31 ℃) and disappears during early June (Fig. 3). Warmer SSTs are supported by thermal stratification and weaker winds during this season in the BoB and favor the formation of the spring MWP. Warmer SST is one of the six major factors contributing to TC genesis[9] and also one of the main influencing factors for TC intensification[12]. The selected two recent TC events and their details are discussed in the next section.

2.2 Tracks of TC Maarutha and TC Mora

Two TCs (TC Maarutha and TC Mora) have been selected for the current study considering the data availability, and their development at different stages of the spring MWP. Figure 1 illustrates the trajectories and features of TC Maarutha and TC Mora in the BoB. TC Maarutha existed over the BoB during 14th–17th April 2017. Initially it formed as a low-pressure system in the southern BoB and developed into a tropical storm over the central BoB at 1200 UTC on 15th April 2017 with a central pressure of ~996 hPa. Under favorable conditions, it reached its peak intensity at early 16th April 2017 attaining a maximum sustained wind speed of ~50 knots and was intensified into a named cyclonic storm Maarutha at 0600 UTC on 16th April. After the landfall at

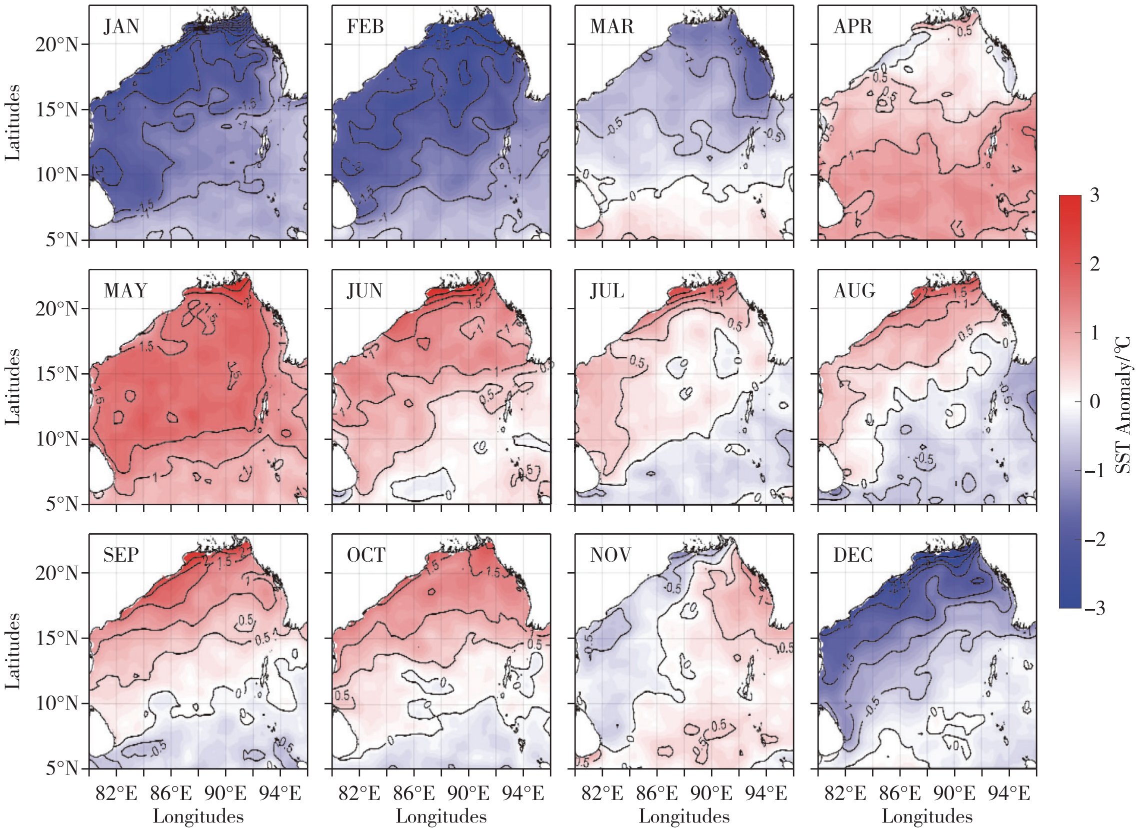

Fig. 2 Variability of monthly SST anomaly estimated by removing the annual mean of 28.66 ℃ during 2017 in the BoB

Myanmar, it dissipated in the early hours of 17th April 2017. TC Mora existed over the BoB during 27th−30th May 2017. Initially it formed as a low-pressure system in the southeastern BoB and developed into a tropical storm over the central BoB on late 27th May. Under favorable conditions, it was intensified into a named cyclonic storm Mora at 0600 UTC on 29th May 2017. TC Mora was intensified further into a severe cyclonic storm at 1 800 UTC on 29th May 2017 with a central pressure ~970 hPa and a maximum sustained wind speed of ~70 knots. In the late hours of 30th May 2017, it dissipated after the landfall on the southern coast of Bangladesh. Based on climatological data, Maneesha et al.[8] pointed out that during pre-summer monsoon (spring) most of the TCs existed in the BoB have moved westward and then northward during 1945−1970, while after 1970 their movements are directed towards north/northeastward. The moving direction of TC Maarutha and TC Mora from its genesis location indicates a pattern similar to that stated by Maneesha et al.[8]. However, in this study we mainly focus on the intensity change of the TC Mora comparatively with TC Maarutha and examine the effect of spring MWP. The atmospheric and oceanic conditions during their genesis and just before their land-fall are examined to understand the influencing factors associated with their intensity changes, which are discussed in the next section.

2.3 Atmospheric-oceanic conditions during TC Mora

Presence of warmer SSTs (> 28 ℃), weak tropospheric wind shear and thermodynamically unstable atmosphere are evident during the two TC peak seasons in the BoB, which favors the TC development in the region [11]. Though TC genesis in the BoB during secondary TC peak season is known, many studies have been focused on the TC activity during primary TC peak season in the BoB. Hence two TCs have been selected as a case study to examine major influencing factors for the TC activity (change in intensity) in the BoB during secondary TC peak season.

First, the conditioning during TC Mora is discussed due to its intensification and the presence of the devel-

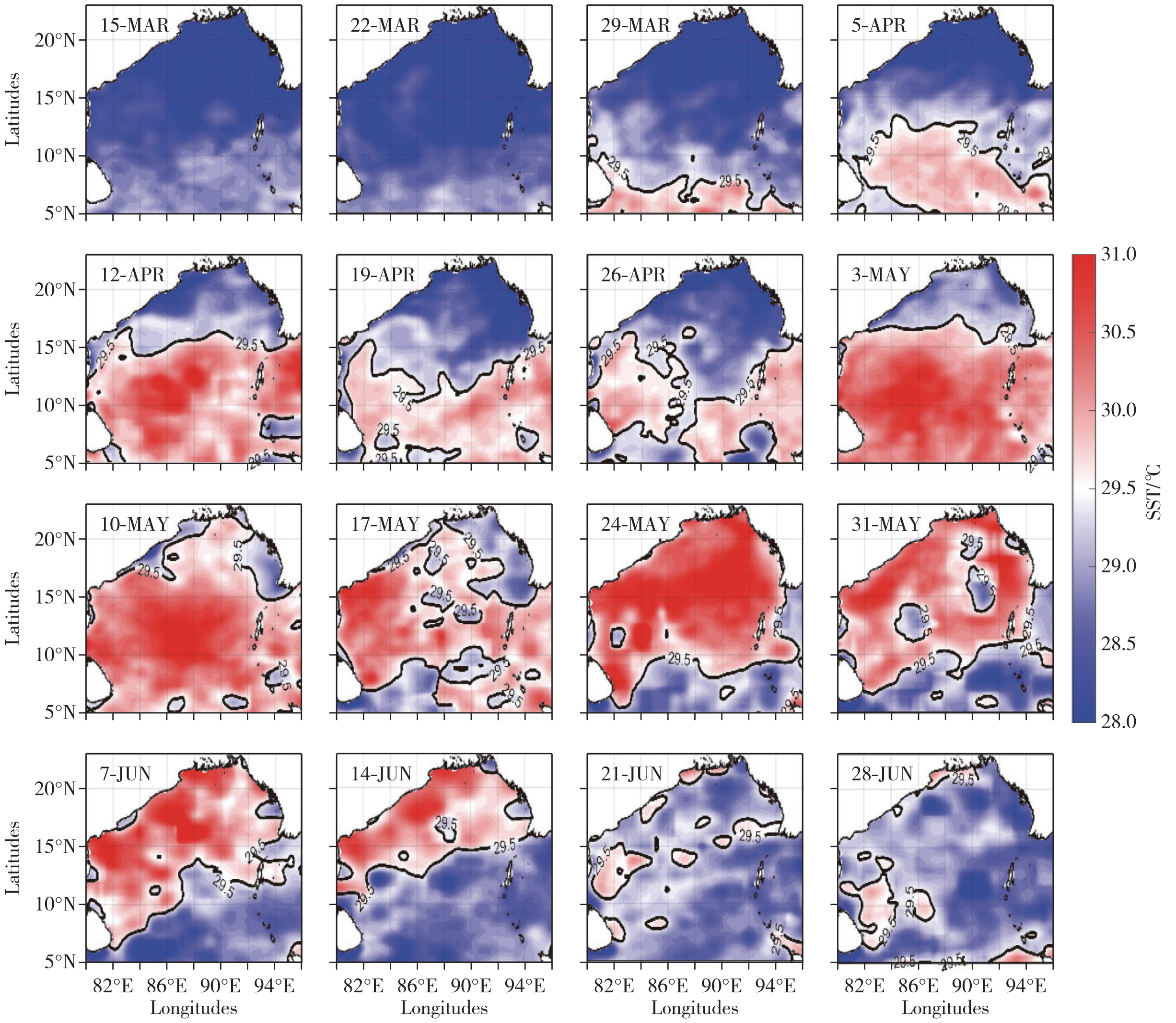

Fig. 3 Development of the spring MWP during March–June 2017 in the BoB.The boundary of the spring MWP has been determined using 29. 5 ℃ isotherm，which is ~1 ℃ higher than the annual mean of 28. 66 ℃ observed during 2017

oped spring MWP.Figures 4 and 5 illustrate the atmosphere-ocean conditions of pre- and post-TC Mora in the BoB.TC Mora started to form on early 27th May and supported by cyclonic winds around a low-pressure zone ~1 000 hPa (Fig.4a).The development was further favored with the presence of weak vertical wind shear of ~5 m/s (Fig.4b)，strong low-level positive vorticity of ~1×10^{-4} s^{-1} (Fig.4c)，and ~100% mid-tropospheric relative humidity (Fig. 4d). The atmospheric conditioning for the genesis of TC Mora was further enhanced with positive condition of the upper-ocean at the same time.Presence of warmer SST (> 30 ℃) as a result of seasonal warming (Fig.4e) positively impacted TC Mora.Furthermore，the presence of a slightly positive SSHA close to the initial center of TC Mora was observed (Fig.4f).The CHP，which is estimated by referring to the depth of 26 ℃ isothermal layer，also indicates a positive impact with values ranging between 80–100 kJ/cm^2(Fig.4g).The variability of MLD，BLT，and CHP are further examined using available in-situ Argo profiles during 26th–27th May in the BoB (Fig.4h).Existence of MLD around 15–25 m，BLT around 0–5 m (almost zero)，and CHP> 40 kJ/cm^2 is evidently close to the track of TC Mora.Thus，the pre-conditions of atmosphere and ocean during 26th–27th May favored the genesis of TC Mora. However，TC Mora had favorable conditions in comparison with ocean-atmosphere preconditioning during TC Maarutha in the BoB (Supplementary Fig.1).

Furthermore，the post-conditioning of atmosphere and ocean just before the landfall is examined in order to understand the effect of potential influencing factors for the intensity change in TCs. The replacement of cyclonic winds by winds directed towards the northeast (Fig.5a), and increased vertical wind shear up to 10 m/s (Fig.5b) were observed during the post-conditioning of TC Mora. In addition, the noted low-level vorticity was reduced up to zero (Fig.5c), and mid-level relative humidity decreased up to less than 50% (Fig.5d). Similar changes were observed during TC Marutha and the results are given in Supplementary Figure 2. On 30th May SST remained higher than 30 ℃ in most part of the BoB (Fig.5e), which is higher compared to that we observed on 17th April (< 28 ℃). The SSHA, an indicator for upwelling/downwelling of cold/warm water, showed that the track of TC Mora followed over a cyclonic eddy, while similar observations (negative SSHA) have been noted close to the track of TC Marutha (Fig.5f). Furthermore, on 30th May the estimated CHP has decreased up to < 80 kJ/cm² close to the track of TC Mora (Fig.5g), while the Argo observations indicated a deepening in MLD (40-50 m), almost zero change in BLT, and a decrease in CHP (Fig.5h).

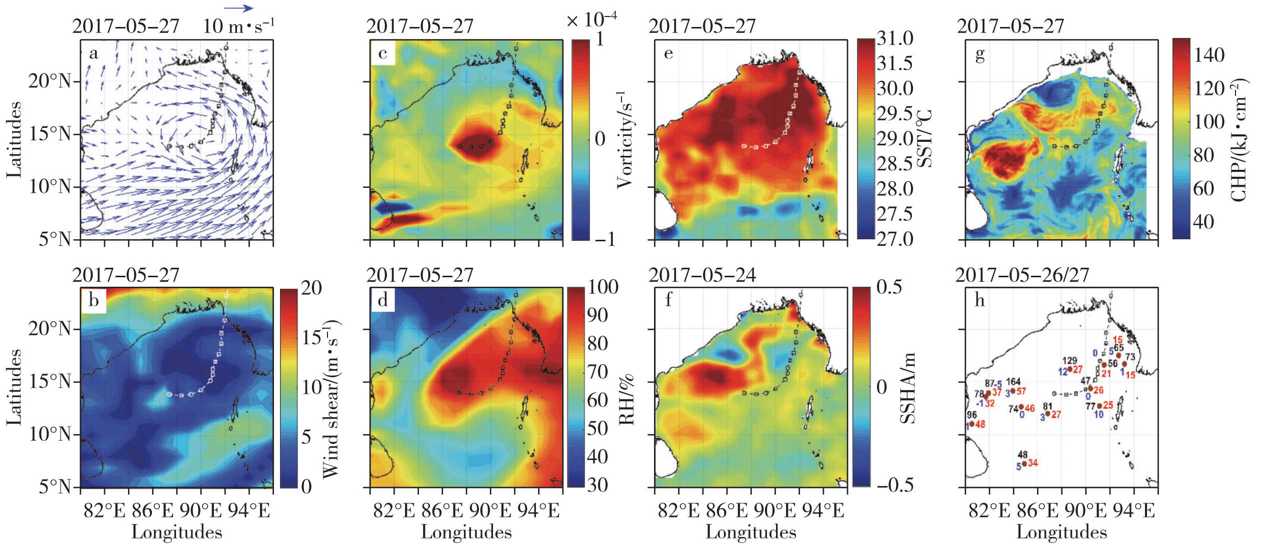

Fig.4 The atmospheric and oceanic preconditioning of (a) winds, (b) vertical wind shear, (c) low-level relative vorticity, (d) mid-level relative humidity, (e) SST, (f) SSHA, (g) CHP, and (h) Argo observations (MLD (red), BLT (blue), and CHP (black)) during TC Mora in the BoB. The dashed line with squares in each figure represents the track of TC Mora during May 2017 in the BoB

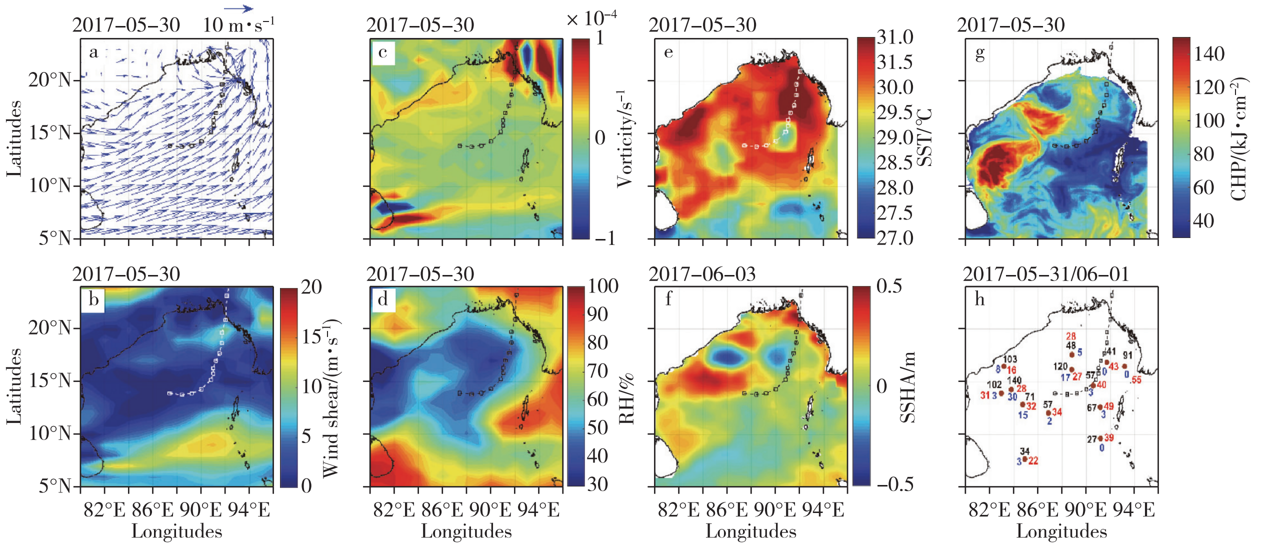

Fig.5 Same as in Fig.4, but for atmosphere and ocean post-conditioning during TC Mora

Thus, the post-conditioning observed during both TC events indicated a negative impact on intensity change except SST. In addition, it is found that the change in SST (post-pre) close to the TC tracks displays differences. As suggested by previous studies, a decrease in CHP, deepening of the MLD, and the decrease of Q_L are thought to inhibit the TC intensification. A possible decrease in CHP and deepening of MLD is noted during the landfall of both TCs. Therefore, considering the differences observed during two TCs before their landfall, the influence of spring MWP is discussed in the next section.

2.4 Effect of spring MWP on TCs in the BoB

Both TCs started as tropical depressions over the BoB, and TC Mora was intensified into a severe tropical storm (~70 knots) while TC Maarutha into a tropical storm (~50 knots). Hence, the influence of spring MWP on the intensity change of TCs are discussed with respect to the SST variability and other potential factors. As mentioned in section 3.1, SST remains larger than 30 ℃ during spring in comparison with that in other seasons. The OISST data provides evidence for the gradual expansion of spring MWP during April (occurrence of TC Maarutha), and its existence in most of the BoB during May with the highest SST (occurrence of TC Mora).

Furthermore, the noted differences in parameters were compared with observations at the RAMA mooring (hereafter buoy) (15°N, 90°E), located to the left of the tracks of TCs, and the results are presented in Figure 6. In agreement with OISST data, the buoy indicates a warmer SST (SST > 28 ℃) during the TC events, where the SST during the genesis of TC Mora is ~1 ℃ higher (30.92 ℃) than that observed with TC Maarutha (29.39 ℃) in the BoB (Fig. 6a). In contrast, the timeseries data illustrates a TC-induced SST cooling during both TC events, in which the noted cooling at the buoy is larger during TC Mora (~1.27 ℃) compared to that during TC Maarutha (~0.66 ℃). MLD deepens during both TC events and is larger during TC Mora (~23 m) than during TC Maarutha (~11 m) (Fig. 6b). The estimated 20 ℃ isothermal layer (D20) indicates an upward movement (upwelling) during TC Maarutha while the change in the D20 during TC Mora remains unchanged (Fig. 6c). Observed CHP is relatively high during TC Mora (> 80 kJ/cm^2) compared to that of TC Maarutha (< 80 kJ/cm^2), but the noted decrease in the CHP is larger during TC Maarutha (~24.1 kJ/cm^2) than that during TC Mora (~15.2 kJ/cm^2) (Fig. 6d). Thus, considering the observations at the buoy, the BoB region experienced a warmer condition during spring.

In addition, to understand the impact of the development stage of spring MWP on TCs, the differences in major factors have been comparatively examined. The differences in SST, CHP, MLD, and Q_L of both TCs are calculated as conditions just before the landfall minus conditions during the genesis of TCs. Existence of SST cooling of ~2.5 ℃ (Fig. 7a), a decrease in CHP of 20–60 kJ/cm^2 (Fig. 7b), and a decrease in Q_L of 50–100 W·m^2 (Fig. 7c) are observed close to the trajectory of TC Mora. Similar changes are also observed during

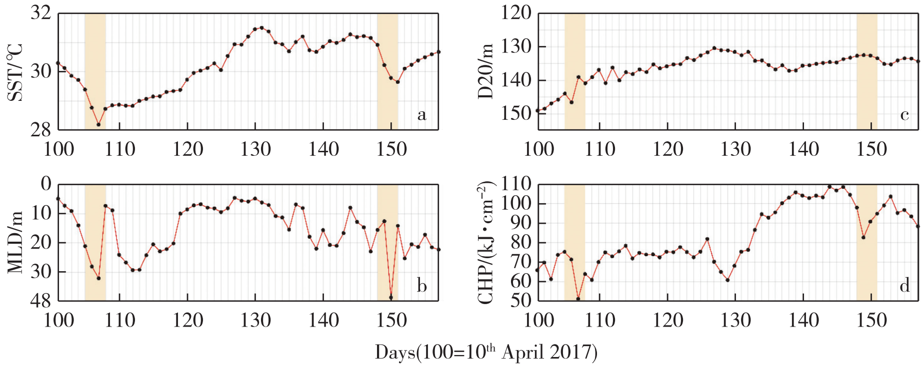

Fig. 6 The variability of (a) SST, (b) MLD, (c) D20, and (d) CHP during TC Maarutha (14th–17th April) and TC Mora (27th–30th May) observed by the RAMA mooring at 15°N, 90°E in the BoB. The shaded areas represent time periods of the two TCs

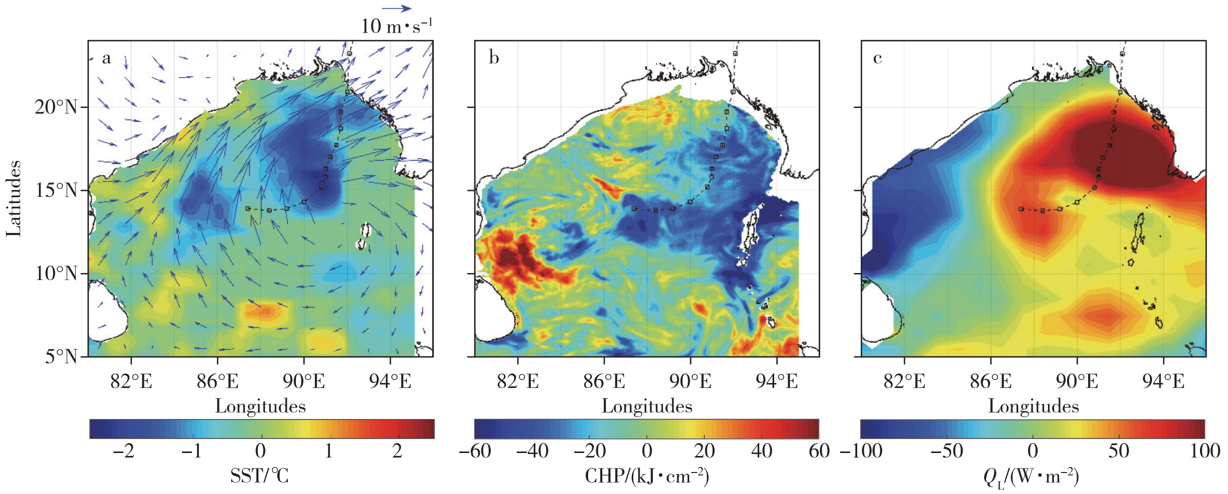

Fig. 7　The variability of (a) SST, (b) CHP, and (c) Q_L during TC Mora in the BoB. The differences have been calculated as, condition before the landfall of TC minus condition at the TC genesis. The dashed line with squares in each figure represents the track of TC Mora during May 2017 in the BoB

TC Maarutha with different magnitudes. The noted differences in all the factors negatively influence the two TCs, despite the stage of the spring MWP. Furthermore, the wind-induced Ekman pumping velocity (W_e), which is an index for upwelling ($+W_e$) and downwelling ($-W_e$) in the ocean are examined (Fig. 8). The presence of $+W_e$ along the tracks of the two TCs clearly indicated the existence of upwelling in the region. In general, the cold water upwelling from the subsurface into the mixed-layer favors the SST cooling, and the impact may differ with the strength of the winds. Thus, the negative impact of the atmosphere-ocean conditioning on the two TCs is observed.

However, SST cooling is not strong along the track of TC Mora. TC induced SST cooling, and SST just before the landfall of both TCs are given in Figure 9. Though TC induced SST cooling is evident during both events, SST is relatively high just before the landfall of TC Mora in the BoB. Hence, the observed warmer conditions are primarily due to the existence of spring MWP. Also, the negative feedback from MLD and CHP is suppressed due to the spring MWP. Therefore, it can be argued that the spring MWP suppressed the negative feedback of MLD deepening, CHP decreasing, and cold-water upwelling, and enhanced the intensification of TC Mora. Thus, based on this case study, the importance of spring MWP in the BoB is highlighted.

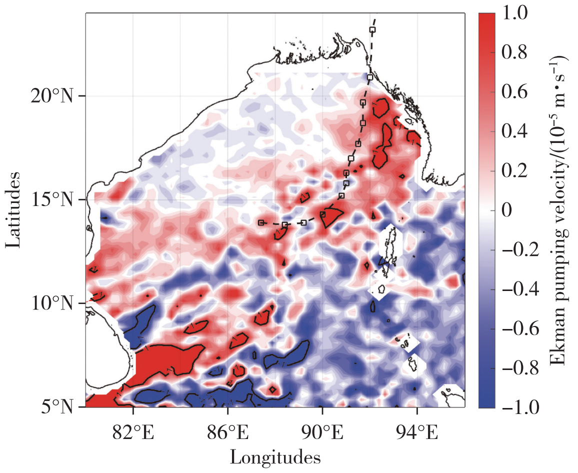

Fig. 8　Ekman pumping velocity (W_e) averaged during the period of TC Mora (27th-30th May) in the BoB. The dashed line with squares represents the track of TC Mora during May 2017 in the BoB

3　Conclusion

Utilizing multiple datasets, the impact of spring MWP on TCs in the BoB has been examined. Two TCs (TC Maarutha and TC Mora) during spring 2017 have been selected based on the known impacts and available data. The development of the spring MWP during 2017 in the BoB is evident from late March to early June with a maximum SST exceeding 31 ℃. Inconsistent with earlier studies, favorable atmospheric and oceanic conditions for TC genesis during spring (secondary TC

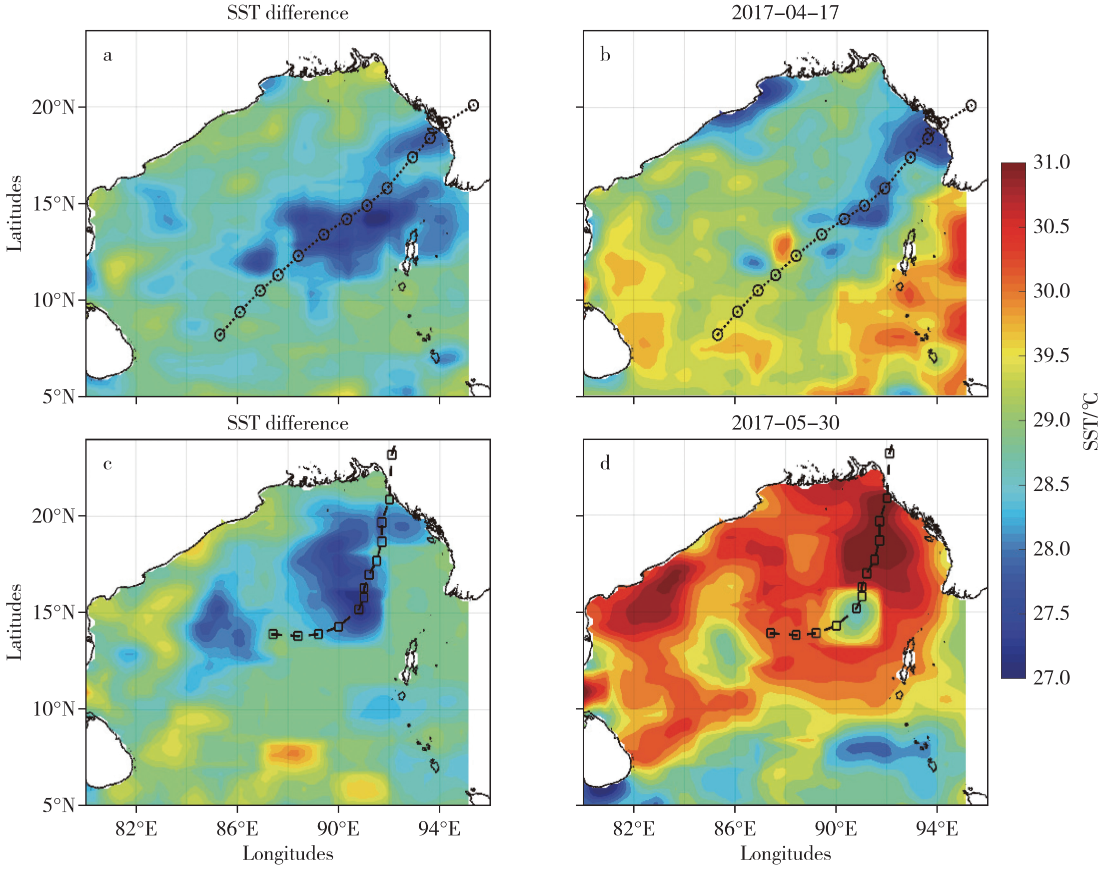

Fig. 9 TC-induced SST cooling during Maarutha (a) and Mora (c), SST just before the land-fall of TC Maarutha (b) and TC Mora (d) in the BoB. The dashed line with circles/squares in each figure represents the track of TC Maarutha/Mora during April/May 2017 in the BoB

peak season) in the BoB are observed. After examining the major factors, it is noted that the ocean-atmosphere conditioning negatively impacts on both TCs during spring 2017. TC-induced SST cooling is evident along the tracks of TC Maarutha and TC Mora with $+W_e$, decrease in CHP, Q_L, and deeper MLD. However, warmer SST is evident (> 30 ℃) just before the land-fall of TC Mora compared with TC Maarutha, as a result of the well-developed spring MWP during May in the BoB. The warmer SSTs noted during TC Mora, may have suppressed the negative impacts from MLD deepening, CHP decreasing, Q_L decreasing and upwelling of subsurface cold water (W_e), and positively impact on the intensification of TC Mora. Thus, the study points out the importance of spring MWP, which mainly influences the ocean-conditioning during TC events. However, it will be interesting to examine how atmosphere-conditioning responds to the influence of spring MWP during TC events in the BoB.

Furthermore, the averaged SST during April and May from 1990 to 2017 indicates a warming trend and the mean SST remains larger than 28.8 ℃ in the BoB. However, due to the lack of higher vertical resolution data, vertical extend of the spring MWP has not been studied. Also, the conclusion in this study is obtained based on just two TC cases and therefore, a systematic study is required to understand the complete role of spring MWP on TC activity in the BoB.

References

[1] Singh O P, Khan T M A, Rahman M S. Has the frequency of intense tropical cyclones increased in the north Indian Ocean? [J]. Current Science, 2001, 80(4): 575-580

[2] Webster P J, Holland G J, Curry J A, et al. Changes in tropical cyclone number, duration, and intensity in a warming environment [J]. Science, 2005, 309(7542): 1844-1846

[3] Mohanty U C, Osuri K K, Pattanayak S, et al. An observational perspective on tropical cyclone activity over Indian seas in a warming environment [J]. Natural Hazards,

2012,63(3):1319-1335

[4] Hoarau K,Bernard J,Chalonge L.Intense tropical cyclone activities in the northern Indian Ocean[J].International Journal of Climatology,2012,32(13):1935-1945

[5] Girishkumar M S, Ravichandran M. The influences of ENSO on tropical cyclone activity in the Bay of Bengal during October－December[J]. Journal of Geophysical Research,2012,117:C02033

[6] Ali M M,Jagadeesh P S V,Jain S.Effects of eddies on Bay of Bengal cyclone intensity[J]. EOS Transactions American Geophysical Union,2007,88(8):93-104

[7] Sengupta D,Goddalehundi B R,Anitha D S.Cyclone-induced mixing does not cool SST in the post-monsoon north Bay of Bengal[J]. Atmospheric Science Letters, 2008,9(1):1-6

[8] Maneesha K,Murty V S N,Ravichandran M,et al.Upper ocean variability in the Bay of Bengal during the tropical cyclones Nargis and Laila[J].Progress in Oceanography, 2012,106:49-61

[9] Gray W M.Tropical cyclone genesis[C]//Department of Atmospheric Science, Colorado State University, 1975, Paper No:234

[10] Henderson-Sellers A,Zhang H,Berz G,et al.Tropical cyclones and global climate change: a post-IPCC assessment[J]. Bulletin of the American Meteorological Society,1998,79(1):19-38

[11] McPhaden M J,Foltz G R,Lee T,et al.Ocean-atmosphere interactions during cyclone Nargis[J].EOS Transactions American Geophysical Union,2009,90(7):53-60

[12] Arora K,Dash P.Towards dependence of tropical cyclone intensity on sea surface temperature and its response in a warming world[J].Climate,2016,4(30):1-19

[13] Kanada S, Tsujino S, Aiki H, et al. Impacts of SST patterns on rapid intensification of typhoon Megi (2010) [J]. Journal of Geophysical Research: Atmospheres, 2017,122(24):13245-13262

[14] Zhao X H,Chan J C L.Changes in tropical cyclone intensity with translation speed and mixed-layer depth: idealized WRF-ROMS coupled model simulations[J]. Quarterly Journal of the Royal Meteorological Society, 2017,143(702):152-163

[15] Emanuel K A. Thermodynamic control of hurricane intensity[J].Nature,1999,401(6754):665-669

[16] Balaguru K,Chang P,Saravanan R,et al.Ocean barrier layers' effect on tropical cyclone intensification[J].Proceedings of the National Academy of Sciences of the United States of America,2012,109(36):14343-14347

[17] Ma Z, Fei J, Liu L, et al. An investigation of the influences of mesoscale ocean eddies on tropical cyclone intensities[J].Monthly Weather Review,2017,145(4): 1181-1201

[18] Sadhuram Y,Rao B P,Rao D P,et al.Seasonal variability of cyclone heat potential in the Bay of Bengal[J].Natural Hazards,2004,32(2):191-209

[19] Jourdain N C,Lengaigne M,Jérome V,et al.Observation-based estimates of surface cooling inhibition by heavy rainfall under tropical cyclones[J]. Journal of Physical Oceanography,2013,43(1):205-221

[20] Shen W,Ginis I.Effects of surface heat flux-induced sea surface temperature changes on tropical cyclone intensity [J]. Geophysical Research Letters, 2003, 30(18): 159-171

[21] Lin I I,Chun-Chieh W U,Emanuel K A,et al.The interaction of supertyphoon Maemi (2003) with a warm ocean eddy[J]. Monthly Weather Review, 2005, 133(9): 2635-2649

[22] Wu G X,Guan Y,Wang T M,et al.Vortex genesis over the Bay of Bengal in spring and its role in the onset of the Asian Summer Monsoon[J]. Science China Earth Sciences,2011,54(1):1-9

[23] Wang S Y,Buckley B M,Yoon J H,et al.Intensification of premonsoon tropical cyclones in the Bay of Bengal and its impacts on Myanmar[J].Journal of Geophysical Research:Atmospheres,2013,118:4373-4384

[24] Chacko N, Ravichandran M, Rao R R, et al. An anomalous cooling event observed in the Bay of Bengal during June 2009[J]. Ocean Dynamics,2012,62(5): 671-681

[25] Du Y,Qu T,Meyers G,et al.Seasonal heat budget in the mixed layer of the southeastern tropical Indian Ocean in a high-resolution ocean general circulation model[J]. Journal of Geophysical Research,2005,110(C4).DOI: 10. 1029/2004JC002845

[26] Sarma Y,Murty V,Rao D.Distribution of cyclone heat potential in the Bay of Bengal[J].Indian Journal of Marine Sciences,1990,19:102-106

[27] Chacko N,Zimik L.Effect of cyclone Thane in the Bay of Bengal explored using moored buoy observations and multi-platform satellite data[J].Journal of the Indian Society of Remote Sensing,2018,46(5):821-828

Effect of spring mini-warm pool on the tropical cyclones in the Bay of Bengal:case studies

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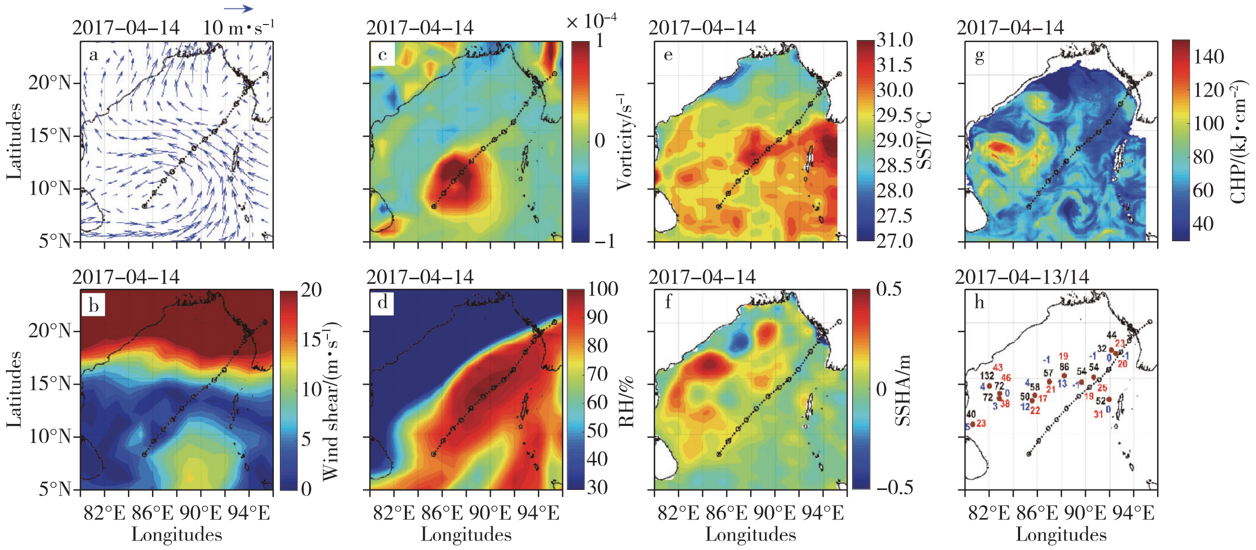
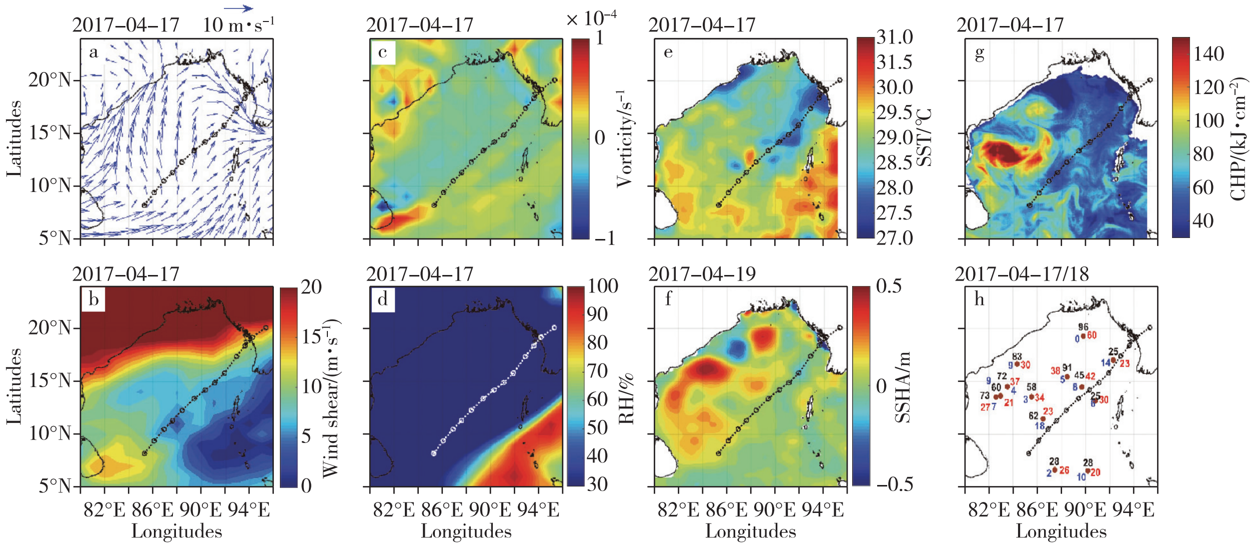
Abstract Two tropical cyclones (TCs) during spring 2017 have been selected as case studies to examine the effect of spring mini-warm pool (MWP) on TCs in the Bay of Bengal (BoB).The TC Maarutha existed over the BoB from 14th to 17th April of 2017,while TC Mora existed from 27th to 30th May of 2017.Existing datasets have been utilized to analyze major factors which influence TC activity in the region.It is identified that the TC-induced sea surface temperature (SST) cooling is evident during spring,but SST is relatively high just before the landfall of the TC Mora in the BoB.This observed warmer conditions are primarily due to the existence of spring MWP in the BoB. When the spring MWP is stronger (SST> 31 ℃),TC Mora induced mixing does not have any major influence on removing of the TC energy.In addition,the study reveals that the spring MWP suppresses the TC-induced negative effect by deepening the mixed-layer,decreasing cyclone heat potential and latent heat flux during spring in the BoB.

Key words tropical cyclones; spring mini-warm pool; sea surface temperature; the Bay of Bengal



Supplementary Fig. 1 The atmosphere and ocean pre-conditioning of (a) winds, (b) vertical wind shear, (c) low-level relative vorticity, (d) mid-level relative humidity, (e) SST, (f) SSHA, (g) CHP, and (h) Argo observations (MLD (red), BLT (blue), and CHP (black)) during TC Maarutha in the BoB. The dashed line with circles in each figure represents the track of TC Maarutha during April 2017 in the BoB



Supplementary Fig. 2 Same as in Supplementary Fig.1, but for atmosphere and ocean postconditioning during TC Maarutha