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Typhoon-Induced SST Cooling and Rainfall Variations: The Case of Typhoon CHAN-HOM and Nangka

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Abstract

This paper focuses on the investigation of sea surface temperature (SST) and the rainfall variations due to typhoon CHAN-HOM and Nangka occurred in 2015 over Northwest Pacific Ocean (NPO). On 7-13 July, the SST cooling area occurred mainly in the middle of the two typhoons track, the maximum SST decline reached more than 4˚C during typhoon CHAN-HOM and Nangka passage. Due to the collective effect of typhoon CHAN-HOM and Nangka, the SST cooling phenomenon maintained for about 15 days. Typhoon CHAN-HOM and Nangka produced heavy rainfall and the maximum daily rainfall was 120 mm (8 July) and 130 mm (11 July). In a1, c area, the average temperature and rainfall basically showed a positive correlation with correlation coefficient of 0.54, while on area a2, the correlation coefficient was −0.6.

Subject Areas

Atmospheric Sciences, Oceanology

Keywords

Typhoon, SST, Rainfall

1. Introduction

Typhoons are extremely high wind events, which can produce strongest mixed layer velocity, mixed layer deepening, strong mixing and entrainment, transient upwelling, air-sea interaction, internal wave generation and so on. Typhoons are highly occurring and most damaging type of natural disasters in the world, especially over North West Pacific. There are much research doing on the SST cooling and rainfall (Lau and Zhou 2012 [1]; Kim *et al.*, 2006 [2]). The SST decrease can affect storm forecasting (Cione *et al.*, 2003 [3]) and it is also important in climate research for estimating the ocean's heat transport (Emanuel *et al.*, 2001 [4]). Depending on typhoon intensity, cooling of surface water can exceed 3˚C and in some cases even up to 7˚C - 9˚C (Price *et al.*, 1981 [5]). The ocean's response processes to a typhoon includes forced and relaxation stages (Price *et al.*, 1994 [6]). Several researchers are paying more attention to the ocean environment response to the typhoon passing such as sea surface salinity, SST, budget of moist static energy, kinetic energy, rain flux etc (Gray 1968 [7]; Merrill 1988 [8]; Titley and Elsberry 2000 [9]; Hanley *et al.* 2001 [10]).

Previously, various satellite remote sensing data were widely used to study the upper ocean responses to typhoons in recent years (Lin *et al.*, 2003a [11]; Sun *et al.*, 2009 [12]; Yang *et al.*, 2010 [13]; Sun *et al.*, 2012 [14]). Variations in upper-ocean conditions can elucidate the effect of typhoon intensity and affects the magnitude of typhoon (Shay *et al.* 2000 [15]; Wu *et al.* 2007 [16]; Lin *et al.* 2008, 2009 [17] [18]; Vincent *et al.* 2014 [19]). Surface cooling strongly depends on mixed layer depth and stratification in thermocline during pre-storm and also depend on typhoon intensity and translation speed (Price 1981 [5]; Lin *et al.* 2009b [20]; Knaff *et al.* 2013 [21]; Mei and Pasquero 2013 [22]). Typhoon-induced rainfall size and distribution are affected by many factors, such as typhoon moving speed, track, latent heat of vaporization, and underlying conditions. Many studies have found that the rainfall distribution is asymmetric on both sides of the typhoon track (Shapiro 1983 [23]; Bender 1997 [24]; Frank and Ritchie 1999 [25]; Lonfat *et al.* 2004 [26]), which is due to the vertical shear. This paper studies the changes of ocean surface temperature and rainfall characteristics in the northwest Pacific Ocean, and hopes to provide some effective basis for future typhoon forecasting. The goal of this work is to reveal the SST cooling conditions during the two typhoons passage. Besides providing insight into the SST cooling and rainfall, it is of great scientific and practical significance to improve the prediction accuracy of typhoon and understand the role of typhoon in the climate system. Few people reveal the true relationship between rainfall and SST cooling. The advantage of study method is to calculate the correlation coefficient between rainfall and SST cooling, so it will clear to know the relationship (the advantage of your research compared with the others).

2. Data and Methodology

In the study, we used the typhoon track information which is from JTWC (The Joint Typhoon Warming Center). The impact of the East China Sea (ECS) typhoon on upper ocean SST pattern was studied using OISST (Optimum Interpolation Sea Surface Temperature). The daily SST was used for this study with the resolution of 0.25˚ × 0.25˚and provided by NOAA's Meteorological Center. Rainfall data is obtained by a tropical rain sensor (TRMM) jointly developed by the United States and Japan. The satellite is equipped with five remote sensing instruments, VIRS (Visible and Infrared Scanner), TRMM Microwave Image

TMI (TRMM Microwave Imager) and Precipitation Radar are the basic precipitation measuring instruments for TRMM satellites. The time resolution is 0.25˚ × 0.25˚. This data is indicative of daily rainfall. We can use it to analyze how much rainfall happened by typhoon CHAN-HOM and how SST decreased due to rainfall.

The aim of this work is to check the SST cooling due to Typhoon CHAN-HOM and Nangka, analyze the impact of rainfall on SST cooling in different places. The data has been chosen with OISST and TRMM data for the study area (10˚N - 40˚N; 110˚E - 160˚E). Both SST data and TRMM data have been plotted for comparison. The relationship between SST and rainfall from June 30th to July 17th over study area will be checked. We choose 4 regains where represent typical areas and consider rainfall variation. We have chosen three areas over the typhoon track, A1 and a2 were at the landfall area of Typhoon CHAN-HOM and Nangka, over the coastal area. B was in the middle of the study area and two typhoons passed this area with higher intensity. C was the genesis area of Typhoon CHAN-HOM and Nangka. Variations of SST and rainfall have been checked at the genesis of two typhoons, higher intensity and landfall area (coasta region). Finally, find the relationship between rainfall and SST cooling over the 4 areas. (the reason why the “four regions a1, a2, b, c” are chosen as the research points).

3. Results

3.1. The Description of Typhoon CHAN-HOM and Nangka

The study area is within a range of 10˚N - 40˚N and 110˚E - 160˚E (**Figure 1**). On 30 June, 2015, a tropical depression was generated on the Pacific Ocean. At 21:00 on 1 July, tropical cyclone at 11.7˚N, 154˚E upgraded to the tropical storm which was named typhoon CHAN-HOM. The center pressure was 985 hPa. On 3 July, typhoon CHAN-HOM appeared center reorganization phenomenon and intensified into a strong tropical storm. On July 4, typhoon Nangka was generated on the Pacific Ocean (9.9˚N, 170.3˚E) with a maximum wind speed of 18 m/s and gradually moved northwest. On 7 July, typhoon Nangka developed into a super typhoon, the maximum wind speed was 58 m/s. On 10 July at 20:00, typhoon CHAN-HOM strengthened with high wind speed 90 m/s which was the largest in its life period. From Zhejiang Meteorological Observatory message, on 10 July, typhoon CHAN-HOM gradually closed to the coastal Zhejiang Province, and would be held in Wenling around Zhoushan coastal area where was near the center of the maximum wind speed 45 m/s. Under the influence of the southwest monsoon, there was sufficient water vapor transport, so the rainfall induced by typhoon CHAN-HOM increased in Zhejiang Province and Fujian Province, resulting in direct economic losses of 1.947 billion yuan. After landing, the intensity of typhoon CHAN-HOM gradually weakened. However, it changed its direction and moved to northeast. At last, Typhoon CHAN-HOM weakened to tropical low pressure in the southwest of Korea on the morning of July 13th. Typhoon CHAN-HOM experienced a total of 12 days, was a long period of life in

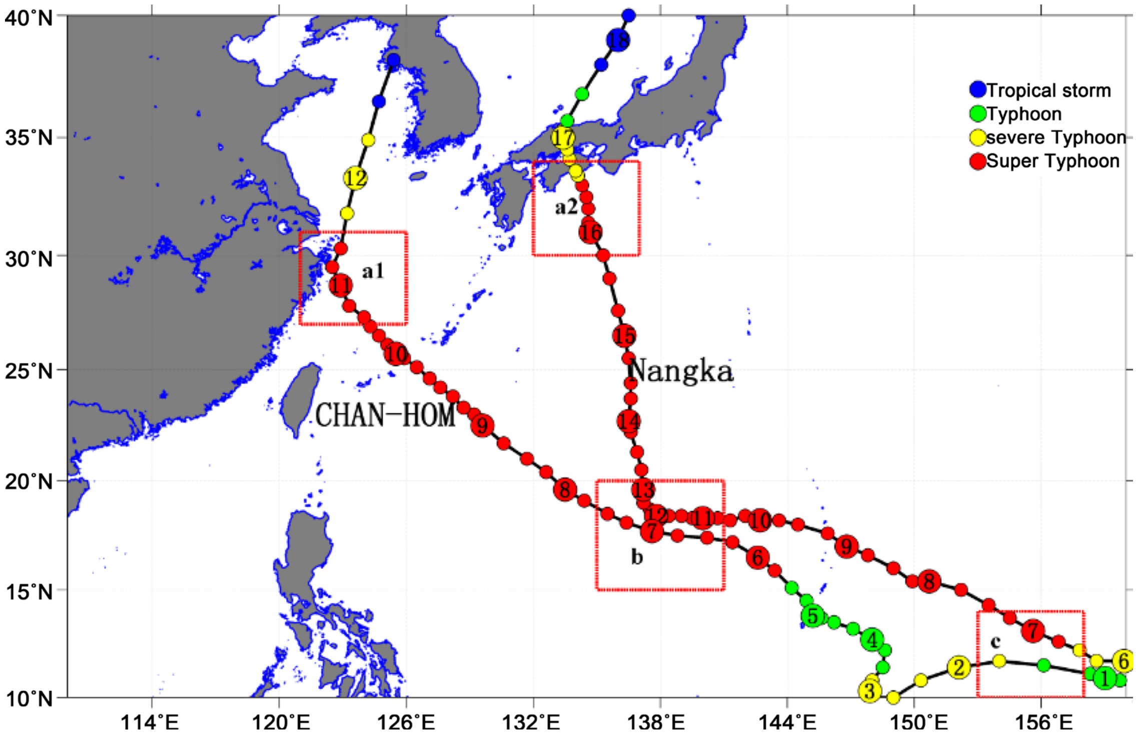

Figure 1. Typhoon tracks of CHAN-HOM and Nangka. The colors within the circles indicating central pressure of the typhoon at each position from JTWC. a1, a2, b, c are four regions. The domain of a1 is 27˚N - 31˚N; 134˚E - 126˚E; The domain of a2 is 30˚N - 34˚N; 132˚E - 137˚E; The domain of b is 15˚N - 20˚N; 134˚E - 142˚E; The domain of c is 10˚N - 14˚N; 153˚E - 158˚E.

history. On 12 July, the maximum wind speed near typhoon Nangka's core was 42 m/s at the location 137.4˚E; 18.8˚N with the central pressure of 955 hPa, next it moved northward. In addition, the intensity of typhoon Nangka enhanced to super typhoon. On 17 July, typhoon Nangka moved into the Sea of Japan and caused heavy rainfall.

3.2. The Response of Sea Surface Temperature to Typhoon CHAN-HOM and Nangka

In this paper, the sea surface temperature from 1 July to 17 July, 2015 is subtracted from the temperature of 27˚C. The response of the sea surface temperature of typhoons was studied based on the remote temperature dataset shown in Figure 2. It was very clear that there was SST cooling phenomenon (Figure 2) induced by typhoon CHAN-HOM and Nangka. During the period of 1 July to 6 July, water temperature in the south of the Taiwan Strait was basically higher than 27˚C, which provided sufficient heat for the development of typhoon at the beginning of typhoon period. Typhoon CHAN-HOM has a strong intensity, long life, and bulky body and also has been connected with the southwest monsoon, which had more adequate water vapor transport. On 7 July, Typhoon CHAN-HOM moved faster, we could find that there happened a cold patch below 27˚C at 13.8˚N, 145.2˚E. It was because the marine upper environment carried out a strong disturbance and let the bottom of the cold sea water rise up re-

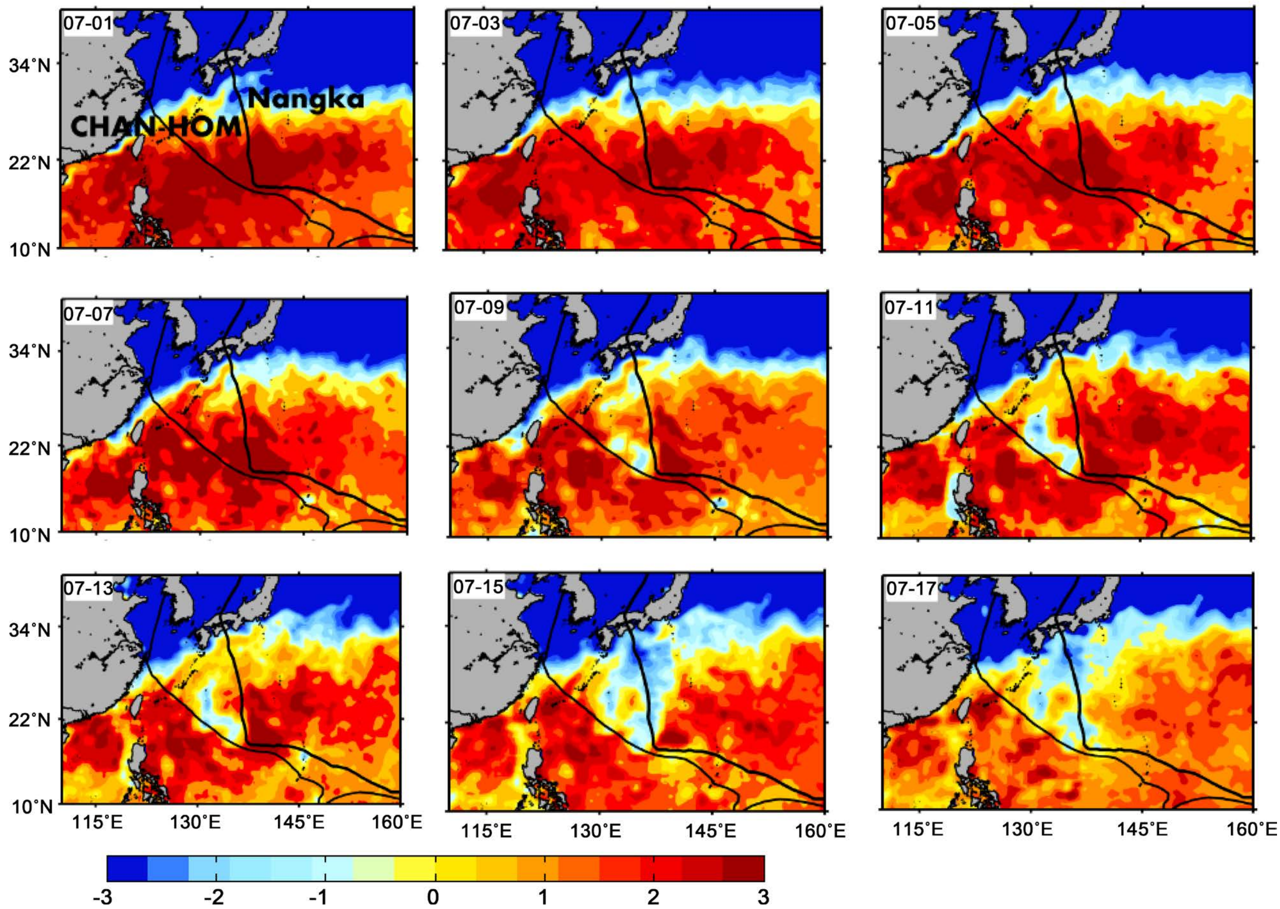

Figure 2. Variation of OISST (˚C) (color shading) on 1 to 17 July 2015 during the passage of two typhoons CHAN-HOM and Nangka. The colors within the circles indicate the central pressure of the typhoon at each position along the best track.

sulting in upwelling. On the 8th, there was a patch of significant SST drop of 1˚C around the typhoon CHAN-HOM center (Fig omitted) because of upwelling and rainfall. On 9 July, in the middle of the two typhoon path area, although the typhoon moving speed weakened, SST cooling phenomenon became more obvious with maximum 4˚C decrease, the range was also expanded, which was mainly the impact of typhoon CHAN-HOM. The longer typhoon effected on the sea, the more obvious the phenomenon of SST cooling. The moving speed of the typhoon determined the wind stress acting length time on the ocean, so the SST change magnitude and range were very sensitive to the speed. On 10 July, the typhoon CHAN-HOM moved to the vicinity of the Ryukyu Islands, the right side of the cooling area extended to the north (Fig omitted). The Taiwan Strait and the north sea area showed lower amplitude of the SST cooling phenomenon, about 3˚C. In the west side of Philippines, there was a cooling area because typhoon Nangka acted on the ocean. On 11 July, the typhoon CHAN-HOM landed in Zhoushan, cooling area still maintained on the right side of the typhoon path, did not disappear. On 12 July, after typhoon CHAN-HOM landing, it did not move to the northwest and cyclone did not dissipate, but changed the track to the northeast direction through the Yellow Sea. This anomalous phenomenon may be related to the unique island terrain of Zhoushan. According to the sea surface temperature display, we can conclude that the cooling phenomenon can be maintained for nearly 15 days after the typhoon passage (**Figure 2**). For typhoon Nangka, SST cooling occurred on the left side of its track and it was the first time that appeared on the right side on 11, 13 July. On 17 July, due to the role of two typhoons, the average temperature of the upper ocean reached to minimum.

3.3. Characteristics of Rainfall Influenced by Typhoon CHAN-HOM and Nangka

Typhoon-induced rainfall distribution is affected by internal power and external environmental flow (Chen *et al.*, 2006 [27]; Miller 1958 [28]; Marks 1985 [29]; Burpee and Black 1989 [30]). **Figure 3** shows the daily rainfall distribution for the period from 1 July to 17 July. It can be seen from the **Figure 3**, on the 3rd, typhoon CHAN-HOM through sea area brought rainfall more than 80 mm, and mainly distributed on the left of the typhoon track. On 5 July, at the Bashi

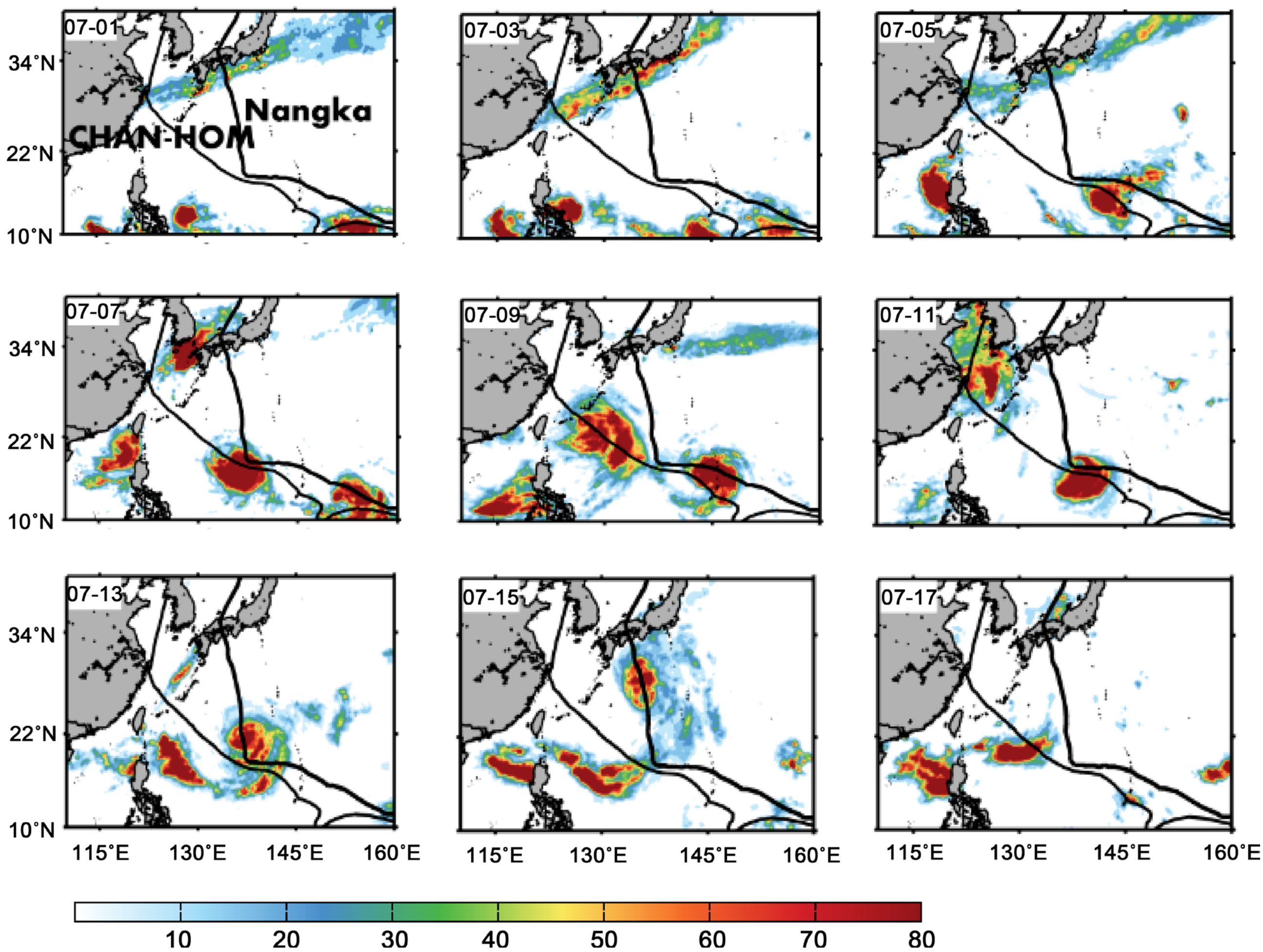

Figure 3. Variation of TRMM precipitation (color shading) on 1 to 17 July 2015 during the passage of two typhoons CHAN-HOM and Nangka. The two lines indicate the central pressure of the typhoon at each position along the best track. The unit is mm/d.

Channe, there also appeared heavy rainfall which was induced by typhoon Linfa. Typhoon Linfa brought great uncertainty to the development of typhoon CHAN-HOM. On 7 July, three typhoons (CHAN-HOM, Linfa and Nangka) appeared in the Northwest Pacific Ocean, this phenomenon was extremely rare in history. With the increase of center wind speed for typhoon CHAN-HOM, a large number of water vapor evaporation resulted in rainfall. Due to the role of typhoon Nangka, the rainfall area was mainly distributed on the right side of its track. However, rainfall caused by typhoon CHAN-HOM was mainly distributed on the left side of its track. On 8 to 10 July, the maximum rainfall 120 mm happened, which located in the southeast of the Ryukyu Islands (Fig omitted). On 11 July, typhoon CHAN-HOM landed Zhoushan and carried heavy rainfall. On 11 July, the position of rainfall area caused by typhoon Nangka was basically the same with that caused by typhoon CHAN-HOM on the 7 July and was mainly on the left side of Nangka's track. And the rainfall induced by typhoon Nangka reached 130 mm which was the maximum. After 11 July, with the weakness of typhoon Nangka's intensity, the daily rainfall decreased.

3.4. The Relationship of Rainfall and SST

In order to analyze the relationship between SST cooling and rainfall, four representative regions a1, a2, b and c are selected to show the rainfall and temperature of each region, as shown in **Figure 4**. In the (a1), (c) region, the average temperature and rainfall basically showed a positive correlation and the correlation coefficient were both 0.54 which meant the sea surface temperature roused with the increase of rainfall (**Figure 4(a1)** & **Figure 4(c)**). In regain (a2) (coastal area), rain on the ocean played a mixed role, probably because the heavy rainfall delivered the mechanical energy to the ocean, so that the flow velocity in the right oceanic mixing layer increased, resulting in a vertical mixing in the upper ocean, causing a entrainment effect, the entrainment and aspiration of the lower water into the mixed layer, So that SST reduced, so the sea surface temperature decreased. The correlation coefficient between SST and rainfall was −0.38. However, in the b region, the correlation between mean temperature and rainfall was not very obvious, which indicated the impact of rainfall on sea surface temperature was not very large on the open ocean, the rainfall factor was not the main factor of causing sea surface cooling. It was generally believed that the sea surface cooling was mainly caused by upwelling or the vertical mixing caused by typhoon (D'Asaro 2003 [31]; Subrahmanyam 2002 [32]; Price *et al.*, 1981 [5]). On the whole, in the high latitude of coastal area (a2), rainfall can cause and enhance SST cooling. In the low latitude of coastal area (a1) and typhoon started area (c), rainfall can restrain the intensity of SST cooling. (relationship between of the "Variation of OISST and TRMM precipitation") On 7 and 11 July, Typhoon CHAN-HOM and Nangka brought rainfall more than 80 mm in the same area, and a large amount of rain released much latent heat which provided sufficient energy for the maintenance of typhoon intensity.

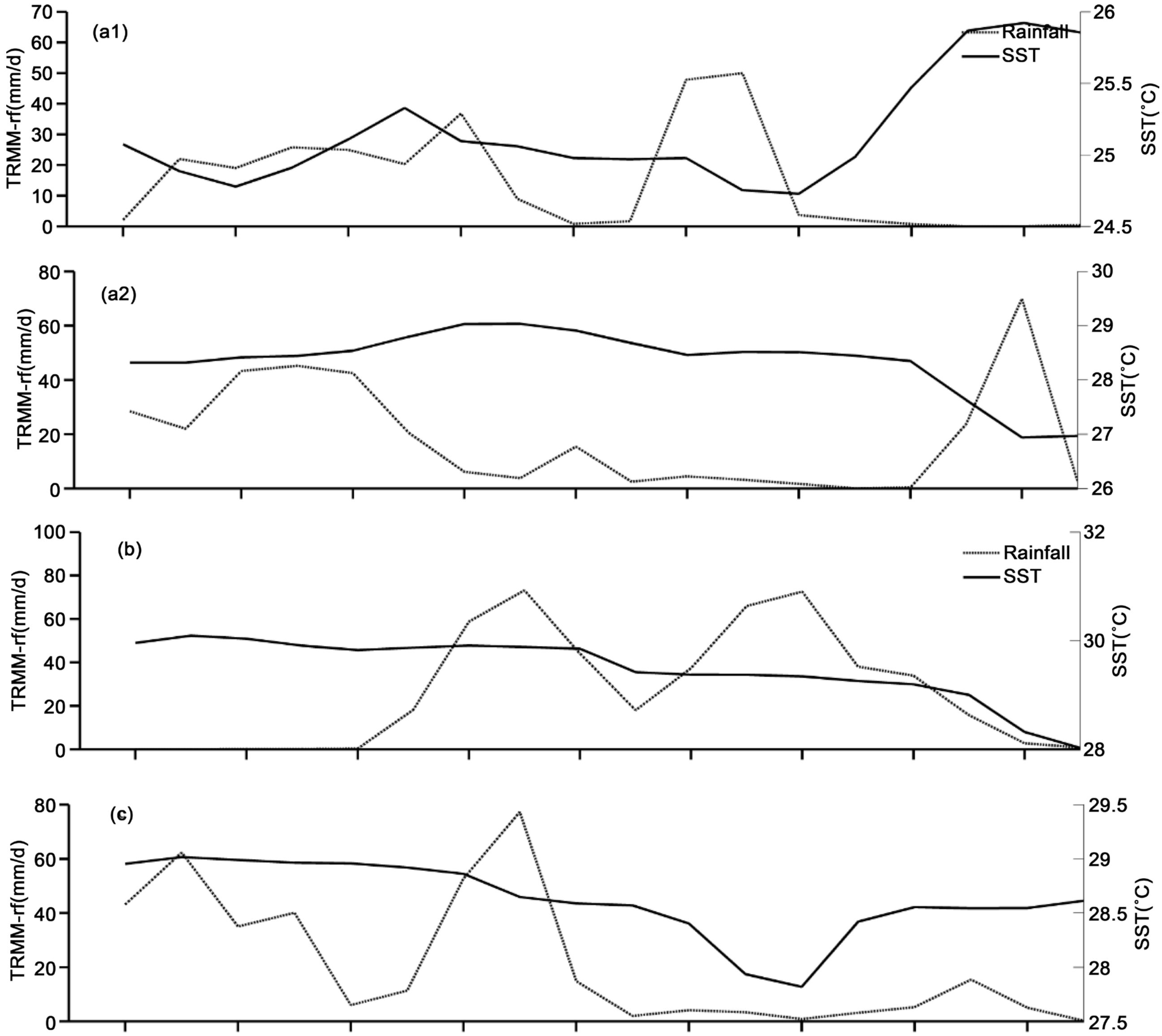

Figure 4. Variation of rainfall and SST on 30 June to 17 July 2015, dashed line indicates rainfall and solid line indicates SST. The domain of (a1), (a2), (b), (c) is same in **Figure 1** shown.

4. Discussion

There has been a lot of research on SST cooling phenomenon caused by typhoon (Price 1994 [6]; Tsai *et al.*, 2008 [33]; Lin *et al.*, 2003a [11]). Typhoon is a great strong wind event. Air-sea fluxes will reduce the SST cooling happened due to typhoon at the surface to prevail pre-typhoon condition, however for sub-surface will take longer time. A distinctive feature of this response is the decrease in SST to the right of a moving storm. Due to the lack of observation data, even with the Argo buoy observation data, it is also very limited in time and space distribution and this problem hindered the human further study of typhoons. The research of this paper has the following problems: First, when we studied the typhoon phenomenon, we only used the satellite remote sensing data, and did not combine the measured data, so the results might be with some limitations. Second, this paper only studied the distribution characteristics of rainfall induced by typhoon CHAN-HOM and Nangka, but there was another typhoon Linfa on the sea during typhoon CHAN-HOM and Nangka passage. Its appearance would affect typhoon CHAN-HOM and Nangka surrounding environment flow field, and also influenced the movement direction and rainfall distribution. The interaction of the three typhoons need further study. Third, there were many factors that affected the sea surface temperature cooling, such as upwelling, vertical mixing, entrainment, rainfall, etc. The cyclonic wind stress induced by the typhoon causes subsurface cold water upwelling over a large region. Higher intensity typhoons usually resulted in the decreasing of the SST and the near-surface temperature, but the warming of the subsurface water. Due to strong cyclonic wind stress curl during typhoons pushed heat downward and brought cold water upward by Ekman pumping. Surface water was moved away from the center due to strong wind which brought the cold water to surface, which was known as upwelling. This paper only study the impact of rainfall on the sea surface cooling, without considering the impact of multiple factors, so there was a accidental chance. In addition, in the coastal area, large rainfall on the sea surface temperature played a cooling effect, probably because the huge rainfall on the sea had a slight stirring effect to strengthen the mixing of seawater, the lower cold sea water roused to the sea surface through mixing. However, in the open ocean, the typhoon absorbed a lot of heat from the ocean and caused heavy rainfall, large amount of rainfall released latent heat which provided sufficient energy and played a significant role on maintaining the intensity of typhoons. In addition, on 15, 17 July, the right side bias of SST cooling phenomenon was not obvious with the influence of typhoon Nangka. It was the comprehensive effect by typhoon CHAN-HOM and Nangka. Typhoon CHAN-HOM and Nangka led to heavy rainfall which mainly all distributed the left track of typhoons. (Subrahmanyam 2015 [34]; Blackwell 2000 [35]). Finally, when typhoon CHAN-HOM landed in Zhoushan, the direction of movement reversed to the northeast and was different from previous typhoon track. Then typhoon CHAN-HOM moved forward quickly to the Yellow Sea region. There was a hypothesis that Zhoushan special terrain caused the strange track of typhoon. This gave an impression that typhoon forecasts may benefit from the conclusion of more strange tracks of typhoon, the reason of sudden change in the track need to be studied in the further.

5. Conclusions

In this paper, we focus on SST cooling and rainfall pattern induced by typhoon CHAN-HOM and Nangka. Analysis of rainfall data during typhoon passage as well as a high-resolution OISST data, the relationship of SST cooling and rainfall will be shown and explained. These results can be concluded into five parts.

1) During typhoon CHAN-HOM and Nangka passage, there were SST cooling

phenomenon caused by typhoons; on 7-13 July, the cooling area occurred mainly in the middle of the two typhoons path, the maximum decline reached more than 4˚C.

2) Due to the collective effect of typhoon CHAN-HOM and Nangka, the SST cooling phenomenon maintained for about 15 days. On 17 July, the average temperature of the upper ocean reached to minimum.

3) Typhoon CHAN-HOM through sea area brought rainfall 120 mm (8 July), Typhoon Nangka also brought heavy rainfall and the maximum daily rainfall was 130 mm (11 July). These rainfall induced by two typhoons mainly distributed on the left of the typhoons track.

4) Four representative regions a1, a2, b and c are selected to show the rainfall and temperature of each region. In a1, c area, the average temperature and rainfall basically showed a positive correlation (0.54), the sea surface temperature roused with the increase of rainfall. While on area a2, the correlation coefficient was −0.6 between SST cooling and rainfall.

5) All in all, the relationship between rainfall and SST cooling was different in different latitude as typhoons passage. In the high latitude of coastal area (a2), rainfall can cause and enhance SST cooling. However, the low latitude of coastal area (a1) and typhoon started area (c); rainfall can restrain the intensity of SST cooling.

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References

[1] Lau, W.K.-M. and Zhou, Y.P. (2012) Observed Recent Trends in Tropical Cyclone Rainfall over the North Atlantic and the North Pacific. *Journal of Geophysical Research*, **117**, D03104. https://doi.org/10.1029/2011JD016510

[2] Kim, J.-H., Ho, C.-H., Lee, M.-H., Jeong, J.-H. and Chen, D. (2006) Large Increase in Heavy Rainfall Associated with Tropical Cyclone Landfalls in Korea after the Late 1970s. *Geophysical Research Letters*, **33**, L18706. https://doi.org/10.1029/2006GL027430

[3] Cione, J.J. and Uhlhorn, E.W. (2003) Sea Surface Temperature Variability in Hurricanes: Implications with Respect to Intensity Change. *Monthly Weather Review*, **131**, 1783-1796. https://doi.org/10.1175//2562.1

[4] Emanuel, K.A. (2001) Contribution of Tropical Cyclones to Meridional Heat Transport by the Oceans. *Journal of Geophysical Research*, **106**, 14771-14781. https://doi.org/10.1029/2000JD900641

[5] Price, J.F. (1981) Upper Ocean Response to a Hurricane. *Journal of Physical Oceanography*, **11**, 153-175. https://doi.org/10.1175/1520-0485(1981)011<0153:UORTAH>2.0.CO;2

[6] Price, J.F., Sanford, T.B. and Forristall, G.Z. (1994) Forced Stage Response to a Moving Hurricane. *Journal of Physical Oceanography*, **24**, 233-260.

https://doi.org/10.1175/1520-0485(1994)024<0233:FSRTAM>2.0.CO;2

[7] Gray, W.M. (1968) Global View of the Origin of Tropical Disturbances and Storms. *Monthly Weather Review*, **96**, 669-700. https://doi.org/10.1175/1520-0493(1968)096<0669:GVOTOO>2.0.CO;2

[8] Merrill, R.T. (1988) Characteristic of the Upper-Tropospheric Environment Flow around Hurricanes. *Journal of the Atmospheric Sciences*, **45**, 1665-1677. https://doi.org/10.1175/1520-0469(1988)045<1665:COTUTE>2.0.CO;2

[9] Titley, D.W. and Elsberry, R.L. (2000) Large Intensity Changes in Tropical Cyclones: A Case Study of Supertyphoon Flo during TCM-90. *Monthly Weather Review*, **128**, 3556-3573.

[10] Hanley, D.E., Molinari, J. and Keyser, D. (2001) A Composite Study of Theinteractions between Tropical Cyclones and Upper Tropospheric Troughs. *Monthly Weather Review*, **129**, 2570-2584. https://doi.org/10.1175/1520-0493(2001)129<2570:ACSOTI>2.0.CO;2

[11] Lin, I.I., Liu, W.T., Wu, C.C., Chiang, J.C.H. and Sui, C.H. (2003a) Satellite Observations of Modulation of Surface Winds by Typhoon-Induced Upper Ocean Cooling. *Geophysical Research Letters*, **30**, 1131.

[12] Sun, L., Yang, Y.J. and Fu, Y.F. (2009) Impacts of Typhoons on the Kuroshio Large Meander: Observation Evidences. *Atmospheric and Oceanic Science Letters*, **2**, 45-50. (In Chinese)

[13] Yang, Y.J., Sun, L., Liu, Q., *et al.* (2010) The Biophysical Responses of the Upper Ocean to the Typhoons Namtheun and Malou in 2004. *International Journal of Remote Sensing*, **31**, 4559-4568. https://doi.org/10.1080/01431161.2010.485140

[14] Sun, L., Yang, Y.J., Xian, T., Lu, Z.-M. and Fu, Y.-F. (2012) Strong Enhancement of Chlorophyll A Concentration by a Weak Typhoon. *Marine Ecology Progress Series* (*MEPS*), **404**, 39-50. (In Chinese)

[15] Shay, L.K., Goni, G.J. and Black, P.G. (2000) Role of a Warm Ocean Feature on Hurricane Opa*l. Monthly Weather Review*, **128**, 1366-1383. https://doi.org/10.1175/1520-0493(2000)128<1366:EOAWOF>2.0.CO;2

[16] Wu, C.-C., Lee, C.-Y. and Lin, I.-I. (2007) The Effect of the Ocean Eddy on Tropical Cyclone Intensity. *Journal of the Atmospheric Sciences*, **64**, 3562-3578. https://doi.org/10.1175/JAS4051.1

[17] Lin, I.I., Wu, C.C., Pun, I.F. and Ko, D.S. (2008) Upper-Ocean Thermal Structure and the Western North Pacific Category-5 Typhoons. Part I: Ocean Features and Category-5 Typhoon's Intensification. *Monthly Weather Review*, **136**, 3288-3306. https://doi.org/10.1175/2008MWR2277.1

[18] Lin, I.I., Chen, C.H., Pun, I.F., Liu, W.T. and Wu, C.C. (2009) Warm Ocean Anomaly, Air Sea Fluxes, and the Rapid Intensification of Tropical Cyclone Nargis (2008). *Geophysical Research Letters*, **36**, L03817.

[19] Vincent, E., Emanuel, K., Lengaigne, M., Vialard, J. and Madec, G. (2014) Influence of Upper Ocean Stratification Interannual Variability on Tropical Cyclones. *Journal of Advances in Modeling Earth Systems*, **6**, 680-699. https://doi.org/10.1002/2014MS000327

[20] Lin, I.-I., Pun, I.-F. and Wu, C.-C. (2009b) Upper-Ocean Thermal Structure and the Western North Pacific Category 5 Typhoons. Part II: Dependence on Translation. *Monthly Weather Review*, **137**, 3744-3757.

[21] Knaff, J.A., DeMaria, M., Sampson, C.R., Peak, J.E., Cummings, J. and Schubert, W.H. (2013) Upper Oceanic Energy Response to Tropical Cyclone Passage. *Journal*

of Climate, **26**, 2631-2650. https://doi.org/10.1175/JCLI-D-12-00038.1

[22] Mei, W. and Pasquero, C. (2013) Spatial and Temporal Characterization of Sea Surface Temperature Response to Tropical Cyclones. *Journal of Climate*, **26**, 3745-3765. https://doi.org/10.1175/JCLI-D-12-00125.1

[23] Shapiro, L.J. (1983) Asymmetric Boundary Layer Flow under a Translating Hurricane. *Journal of the Atmospheric Sciences*, **40**, 1984-1998. https://doi.org/10.1175/1520-0469(1983)040<1984:TABLFU>2.0.CO;2

[24] Bender, M.A. (1997) The Effect of Relative Flow on the Asymmetric Structure in the Interior of Hurricanes. *Journal of the Atmospheric Sciences*, **54**, 703-724. https://doi.org/10.1175/1520-0469(1997)054<0703:TEORFO>2.0.CO;2

[25] Frank, W.M. and Ritchie, E.A. (1999) Effects of Environmental Flow upon Tropical Cyclone Structure. *Monthly Weather Review*, **127**, 2044-2061. https://doi.org/10.1175/1520-0493(1999)127<2044:EOEFUT>2.0.CO;2

[26] Lonfat, M., Marks Jr., F.D. and Chen, S.S. (2004) Precipitation Distribution in Tropical Cyclones Using the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager: A Global Perspective. *Monthly Weather Review*, **132**, 1645-1660. https://doi.org/10.1175/1520-0493(2004)132<1645:PDITCU>2.0.CO;2

[27] Chen, S.S., Knaff, J.A. and Marks Jr., F.D. (2006) Effects of Vertical Wind Shear and Storm Motion on Tropical Cyclone Rainfall Asymmetries Deduced from TRMM. *Monthly Weather Review*, **134**, 3190-3208. https://doi.org/10.1175/MWR3245.1

[28] Miller, B.I. (1958) Rainfall Rates in Florida Hurricanes. *Monthly Weather Review*, **86**, 258-264. https://doi.org/10.1175/1520-0493(1958)086<0258:RRIFH>2.0.CO;2

[29] Marks Jr., F.D. (1985) Evolution of the Structure of Precipitation in Hurricane Allen (1980). *Monthly Weather Review*, **113**, 909-930. https://doi.org/10.1175/1520-0493(1985)113<0909:EOTSOP>2.0.CO;2

[30] Burpee, R.W. and Black, M.L. (1989) Temporal and Spatial Variations of Rainfall near the Centers of Two Tropical Cyclones. *Monthly Weather Review*, **117**, 2204-2218. https://doi.org/10.1175/1520-0493(1989)117<2204:TASVOR>2.0.CO;2

[31] D'Asaro, E.A. (2003) The Ocean Boundary Layer below Hurricane Dennis. *Journal of Physical Oceanography*, **33**, 561-579. https://doi.org/10.1175/1520-0485(2003)033<0561:TOBLBH>2.0.CO;2

[32] Subrahmanyam, B., Rao, K.H., Srinivasa Rao, N., *et al.* (2002) Influence of a Tropical Cyclone on Chlorophyll-A Concentration in the Arabian Sea. *Geophysical Research Letters*, **29**, 22-1-22-4.

[33] Tsai, Y., Chern, C.S. and Wang, J. (2008) The Upper Ocean Response to a Moving Typhoon. *Journal of Oceanography*, **64**, 115-130. https://doi.org/10.1007/s10872-008-0009-1

[34] Subrahmanyam, M.V. (2015) Impact of Typhoon on the North-West Pacific Sea Surface Temperature: A Case Study of Typhoon Kaemi (2006). *Natural Hazards*, **3**, 77. https://doi.org/10.1007/s11069-015-1733-7

[35] Blackwell, K.G. (2000) The Evolution of Hurricane Danny (1997) at landfall: Doppler Observed Eyewall Replacement, Vortex Contraction/Intensification, and Low Level Wind Maxima. *Monthly Weather Review*, **128**, 4002-4016. https://doi.org/10.1175/1520-0493(2000)129<4002:TEOHDA>2.0.CO;2