Chapter

Response of the Coastal Ocean to Tropical Cyclones

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Abstract

The Northwest Pacific and the South China Sea region are the birthplaces of most monsoon disturbances and tropical cyclones and are an important channel for the generation and transmission of water vapor. The Northwest Pacific plays a major role in regulating interdecadal and long-term changes in climate. China experiences the largest number of typhoon landfalls and the most destructive power affected by typhoons in the world. The hidden dangers of typhoon disasters are accelerating with the acceleration of urbanization, the rapid development of economic construction and global warming. The coastal cities are the most dynamic and affluent areas of China's economic development. They are the strong magnetic field that attracts international capital in China, and are also the most densely populated areas and important port groups in China. Although these regions are highly developed, they are vulnerable to disasters. When typhoons hit, the economic losses and casualties caused by gale, heavy rain and storm surges were particularly serious. This chapter reviews the response of coastal ocean to tropical cyclones, included sea surface temperature, sea surface salinity, storm surge simulation and extreme rainfall under the influence of tropical cyclones.

Keywords: tropical cyclones, typhoons, coastal ocean dynamics, sea surface temperature, sea salinity, extreme rainfall; air-sea interaction

1. Introduction

Tropical cyclones are some of the most destructive natural disasters, which often bring huge losses to people's life and property. The Northwest Pacific and the South China Sea regions are the birthplaces of most monsoons and typhoons and are important channels for the generation and transmission of water vapor [1–3]. The influence of a typhoon on a region is often not only a heavy wind disaster. At the same time, the heavy rain, extreme waves, storm surges, and coastal inundation that are produced will also have a huge impact on the region, which will result in the formation of a typhoon disaster chain [4–6].

There are more than 20 typhoons in the Pacific Northwest each year, which is the region with the most frequent typhoon activity in the world. China, which has a long coastline on the west coast of the Pacific Ocean, is the country with the most frequent typhoon attacks in the world, with an average of 9.3 per year, resulting in a direct economy every year. The losses exceeded 100 billion yuan and the number of casualties reached thousands. Therefore, a comprehensive understanding and in-depth study of the typhoon process, especially the improvement of typhoon monitoring and early warning capabilities, is an inevitable requirement for the disaster reduction work of our national defense platform.

In the past few decades, from the perspective of atmospheric science, the research on the mechanisms of typhoon development, numerical simulation and forecasting has made great progress. However, as a strong atmospheric process, typhoons have violent disturbances, the cumulative effects of many typhoons will also have a significant impact on the ocean's thermo-salt structure and ocean circulation and global ocean heat transport. These effects will counteract typhoons, affect not only the intensity and path of specific typhoons, but also the global the low-frequency variation characteristics of the typhoon. But so far, the lack of on-site observation data during the typhoon has made the study of multi-scale response and feedback mechanism of typhoon not deep enough. People cannot simulate the interaction process between the ocean and typhoon well. The reliable initial ocean field required for typhoon forecasting has greatly limited the further improvement of typhoon research and forecasting capabilities.

The typhoon is a devastating natural disaster that has long been a focus of attention in the field of atmospheric and oceanic research [7, 8]. With the rapid development of computers, the numerical simulation of typhoons is becoming increasingly developed, and the model resolution is getting higher and higher [9]. The Pacific Northwest is the most concentrated area of global tropical cyclones (also known as typhoons in the Pacific Northwest). China is located on the west coast of the Pacific Ocean, with a long coastline and a special geographical position on the southeast coast. It has been hit by typhoons frequently, with an average annual rate of 9.3, ranking first in the world. The typhoon is one of the most serious natural disasters in China [10–12]. The annual direct economic losses caused by the typhoon are nearly 100 billion yuan, and the number of casualties is thousands. On the one hand, the strong winds and heavy rains that landed in the typhoon brought huge meteorological disasters to the vast areas of China, posing a huge threat to the people's lives, property and production activities. On the other hand, huge waves and storm surges caused by typhoons have also caused serious marine disasters, which have caused major safety hazards and economic losses to offshore operations and transportation, coastal protection projects, marine fisheries and marine aquaculture. Coastal areas are one of China's most economically developed regions, which are vulnerable to the effects of marine disasters [13–16].

Therefore, studying the movement mechanism of typhoon, accurately forecasting the influence of typhoon and reducing storm surge disasters have important social value for the protection of national economic development and people's lives and property safety.

From the perspective of practical application, improving the monitoring and forecasting ability of typhoon is the fundamental goal of typhoon research. Due to the multi-scale characteristics of the interaction between ocean and typhoon, the ocean data assimilation for the typhoon process should also be multi-scale. Due to extreme sea conditions under typhoon conditions Harsh, satellite remote sensing data has become an important data source for assimilation. However, remote sensing can only provide sea surface information. At present, people usually use the projection mapping method and multiple dynamic constraints to map surface information to the ocean subsurface and assimilate. Some assimilation methods still lack universality. How to establish a sea surface data assimilation method that considers more dynamic constraints and is more suitable for typhoon conditions is an important part of the future sea-air coupled data assimilation research. For the actual operational forecast of the typhoon, International or domestic still rely mainly on numerical weather patterns. After long-term exploration and improvement, the main forecasting modes are for atmospheric processes (such as atmospheric boundary layer physical properties, cloud physical processes, atmospheric turbulent energy calculations, cumulus convective parameterization schemes, etc.). There has been considerable progress in simulation and forecasting capabilities. The understanding of ocean feedback is insufficient. The current typhoon numerical (weather) forecasting model still has significant errors, especially for typhoon intensity and wind and rain distribution forecast. The United States is the first to develop a sea-air coupled hurricane (the Atlantic called hurricane, the Pacific Ocean). After years of operational operation, the improved air-sea coupled model has improved both the intensity of the hurricane and the path prediction compared with the traditional atmospheric model.

In summary, the interaction between the ocean and typhoon has obvious scientific significance and important practical value. At various time and space scales, people's understanding of the mechanism of the ocean response to typhoon and modulation is obviously insufficient. At present, air-sea coupling The model's ability to simulate, assimilate and forecast the typhoon process is still very limited, which has become a bottleneck problem to further improve the typhoon forecasting capability.

2. Sea surface temperature response to tropical cyclones

With an increase in sea surface temperature (SST), the total number of tropical cyclones in the North Pacific, Indian Ocean, and southwest Pacific Ocean decreases, and the cyclone development period shortens, but the number and proportion of tropical cyclones reaching super typhoon intensity increases greatly [17].

In the study of air-sea interaction, the response of the upper ocean to typhoons is a hot topic [18]. Typhoon transit can cause ocean mixing and upwelling, and sea surface cooling is the main feature [19]. The cooling caused by a typhoon is mainly related to the intensity, propagation speed of the typhoon, and the ocean condition before typhoon arrival, such as the location of cold vortices, the thermodynamic structure of the upper ocean, the position of the 26°C isotherm, etc.

Cyclonic wind stress results in the upwelling of sea water in the center of the path, the decrease of sea surface temperature, and the heat transfer from the surface to the atmosphere. Strong winds cause turbulent mixing of the ocean, entraining cold water from the lower layer into the mixing layer, resulting in cooling of the upper sea water and deepening of the mixing layer [10–21]. Inclusive mixing disturbances cause 85% of irreversible ocean heat to enter the atmosphere; direct air-sea interaction plays a minor role in surface cooling. Mixed layer plays an important role in sea surface cooling [22–24]. After typhoon transit, the ocean response is mostly the internal nonlocal baroclinic process caused by wind stress. In baroclinic driving stage, the flow of mixing layer 1 m/s is induced by vertical mixing, and the flow of near-inertial oscillation frequency wave into thermocline, which lasts for 5–10 days. The barotropic driving process usually results in geostrophic currents and associated sea surface height changes.

Using the observed data to study the ocean response to typhoons is a common research method. However, due to the severe weather conditions during the transit of tropical cyclones, it is very difficult to obtain fixed-point observation data. There is a strong mass transport, energy exchange, and interaction between the atmosphere and the ocean during a typhoon process [25, 26] (**Figure 1**).

The response mechanism of the ocean to typhoon can be considered from two levels. First, the typhoon-driven mesoscale three-dimensional ocean circulation will have a significant impact on the local dynamics and thermal processes. The resulting near-inertial internal waves and vortices can input a large amount of mechanical

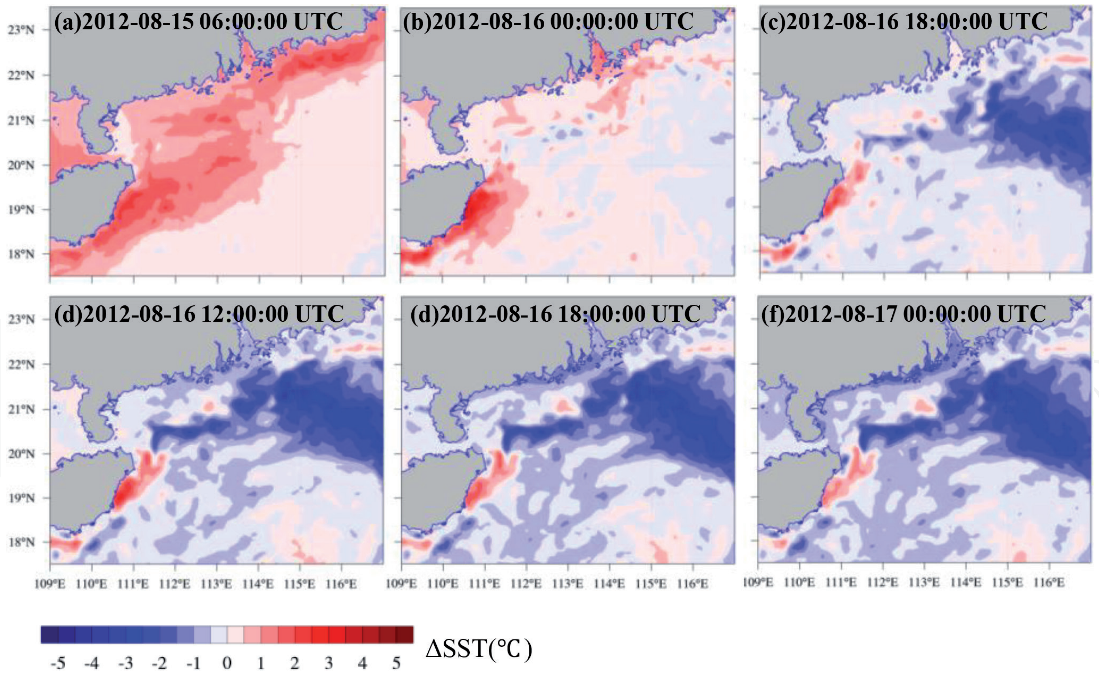

Figure 1.
The spatial distribution of change in sea surface temperature (ΔSST) in the northern area of the South China Sea under the influence of typhoon Kai-tak (2012).

energy into the ocean, thus significantly enhancing the local The ocean mixes and changes the warm salt structure of the upper ocean. Second, in the interior of the ocean, the energy input into the ocean by typhoons in the form of near-inertial internal waves travels along the oceanic thermocline to distant places, such as the entire tropical Pacific. During the propagation process, they interact nonlinearly with the original internal waves and near-inertial oscillations inside the ocean, which affects the ocean basin scale and even the global energy distribution, and leads to an increase in ocean mixing rate in some specific regions. The modulation of the typhoon by the ocean can also be considered from two scales. On the weather scale, the ocean plays a very important role in the movement and action of typhoons.

The maturity stage is mainly characterized by negative feedback that reduces the sea surface temperature. However, when the upper ocean warm water is thicker, the typhoon transit will not cause obvious sea temperature anomaly, and the lack of negative ocean feedback can cause the typhoon to strengthen. The interaction between the ocean mesoscale process and the typhoon is currently a focus of typhoon research. Usually, the warm vortex can quickly strengthen the typhoon, and the cold vortex can quickly weaken the typhoon. At the climate scale, global warming and interannual and interdecadal variations of climate can cause changes in ocean circulation and thermal conditions, resulting in low-frequency modulation of the intensity and frequency of typhoons.

3. Sea surface salinity response to tropical cyclones

The typhoon is one of the most serious natural disasters that affects the coastal ocean environment in China [35, 36], especially in the eastern and southern estuaries, such as the Yangtze River Estuary [37] and the Pearl River Estuary [27, 28, 38, 39]. During a typhoon, the coupling of various dynamic factors, such as wind, waves, storm surges, and river runoff, greatly enhances the mass and energy exchange of various interfaces in the ocean and is accompanied by heavy rain and storm runoff on the surface [31, 32, 34, 40]. Scouring can transport a large amount of minerals from the land to an estuary offshore, causing sudden changes in the water quality of the estuary, which may have an important impact on the marine ecological environment [41–43].

On the one hand, typhoon transit strengthens the mixing process of offshore water [44–46]. On the other hand, the heavy rainfall brought by a typhoon rapidly increases river runoff into the sea, and a large amount of land-based materials are washed away and brought into the estuary offshore area [47–50]. These changes due to the influence of a typhoon significantly affect the physical, chemical and biological processes of estuarine offshore waters, which in turn have an impact on the structure and function of the ecosystem [51–53]. Studying the changes of the estuarine nearshore environment under the influence of a typhoon and its ecological effects are of great importance for further understanding the evolution process of ecosystems in this region on a long-term scale [8, 54].

Field observations show that the salinity of the surface water of an estuary usually shows a sharp change during a typhoon and the resulting rain, which gradually rises after entering the recovery period [8, 55–57]. During typhoon crossing, the disturbance caused by strong winds strengthens the mixing process of the estuary and its adjacent waters. However, this process has a passing impact on the water environment, and the runoff diluting water expansion and the external seawater intrusion play a greater role in changing the water environment after a typhoon. Among these, the strengthening of a typhoon after the expansion of fresh water greatly affects the upper water, the upper salinity decreases after the typhoon, and the nutrient salt concentration increases significantly. External seawater intrusion substantially changes the bottom water environment. The salinity of the bottom

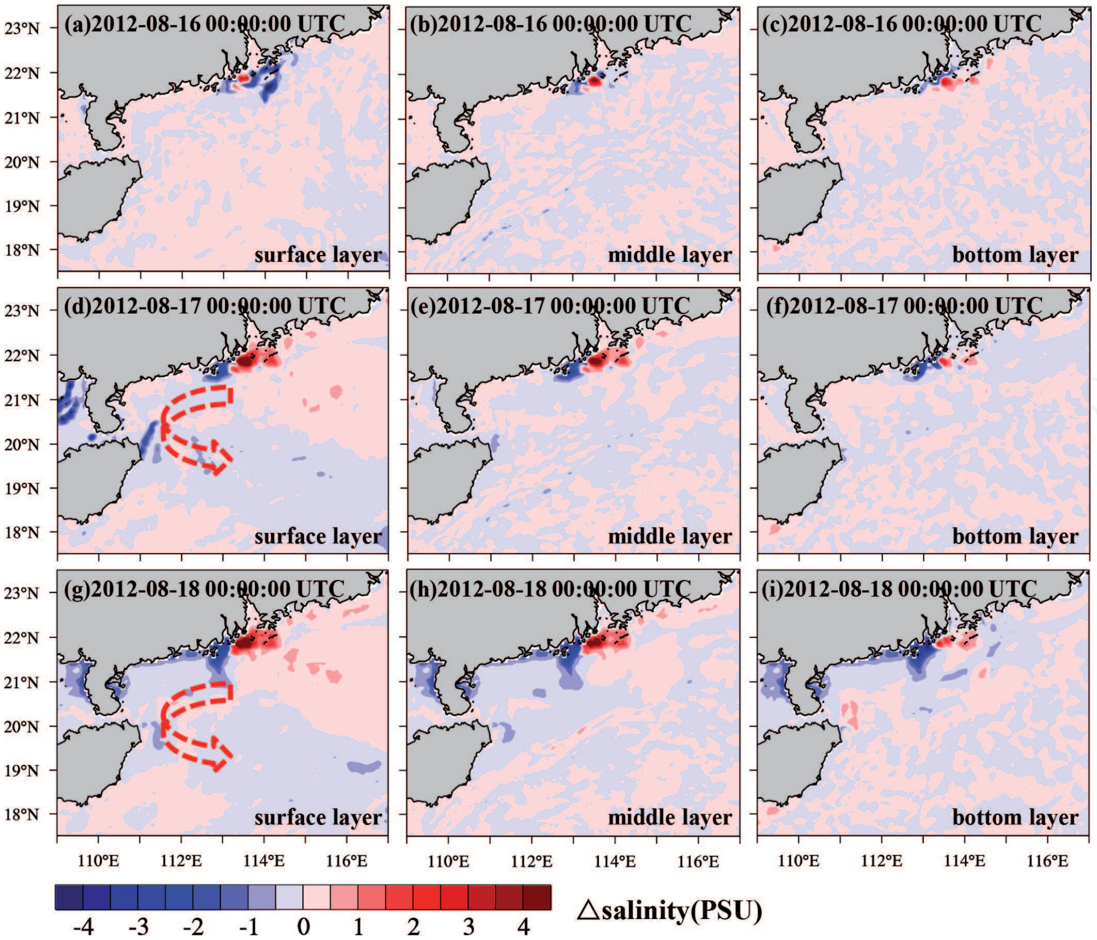

Figure 2.
Changes in stratifications salinity influenced by typhoon Kai-tak based on the fully coupled WRF-SWAN-ROMS model (beginning on 2012-08-15 00:00:00 UTC).

layer increases after a typhoon, and the nutrient concentration of nitrogen and silicon decreases.

Typhoons or tropical cyclones are strong wind events in the climate system and are a strong form of air-sea interaction. The strong vertical mixing and wind field generated by a typhoon has a major impact on the upper ocean dynamics and ecosystem [58]. Due to typhoons, there is a decrease in sea level, a decrease in sea surface temperature, an increase in phytoplankton blooms and a decrease in primary productivity, which also affect marine fisheries [59–61]. Typhoons mainly affect the marine ecological environment through two physical mechanisms: (1) after a typhoon, a cold vortex is formed, causing seawater to upwell and the lower layer of cold nutrient water is transported to the upper layer [62, 63]; and (2) the typhoon intensifies the vertical mixing of the upper ocean by a strong wind process [64–67].

At present, most research on the sea surface salinity (SSS) response to typhoons is limited to the estuary area. According to the physical and biochemical environmental conditions of the estuary, SSS may show an upward or downward trend after typhoon transit [2, 22, 29, 30, 68–76]. However, studies on marine ecological factors, especially SSS and the response to typhoon transit, are limited and have not been discussed in detail [77–80]. The South China Sea (CSC) is the largest marginal sea in the Pacific Northwest, and is also a frequent typhoon zone, but it is difficult to obtain measured data during typhoons.

Due to the harsh meteorological conditions during typhoon transit, the use of on-site observation methods in an estuary to study the changes in the marine environment before and after a typhoon is very limited. The numerical simulation method is an effective way to study the distribution characteristics of fresh and salt water in an estuary under the influence of a typhoon (**Figure 2**).

4. Storm surge modeling during tropical cyclones

The Northwest Pacific and the South China Sea region are the birthplaces of most monsoons and typhoons and are an important channel for the generation and transmission of water vapor [18, 81–85]. The Northwest Pacific plays a major role in regulating interdecadal and long-term changes in climate [49, 86, 87]. China is the region with the largest number of typhoons and the most destructive power affected by typhoons in the world [88, 89].

Compared with large-scale phenomena such as global climate change, small- and medium-scale phenomena such as typhoons and thunderstorms have an even greater impact on people's production and life [6, 90, 91]. Typhoons and hurricanes present some of the greatest threats to life and damage to property [92]. The influence of a typhoon on a region is often not only a heavy wind disaster. At the same time, the heavy rain, extreme waves, storm surges and beach erosion [24] that are produced will also have a huge impact on the region, which will result in the formation of a typhoon disaster chain [19, 33, 93, 94]. Therefore, studying the movement mechanism of typhoon, accurately forecasting the influence of typhoon and reducing storm surge disasters have important social value for the protection of national economic development and human and property safety.

Tropical cyclones (TCs) present some of the greatest threats to life [25, 95–98] and damage to property [99]. The SLOSH model was widely used in storm surge simulation in seas, lakes, and on land. Blumberg and Mellor (1987) developed the POM model to simulate large-scale ocean and coastal water levels, and flow field changes. Many ocean models have been developed and used for the simulation of storm surges, such as the ECOM model, ROMS model, CH3D-IMS model, CEST model, SELFE model, Delft3D model, ADCIRC model and FVCOM model. They have achieved very good results and laid the foundation for understanding the dynamic mechanism of storm surges. The development of a coupled atmospheric and ocean model had significant effects on improving the accuracy of numerical prediction. The establishment of a coupled atmosphere and ocean model is an effective method to solve this problem (**Figure 3**).

The typhoon numerical model is the focus of typhoon research and the key to typhoon forecasting. The modern model has a certain forecasting ability for the typhoon path, but the forecast of typhoon intensity is still a recognized problem in the international meteorological community. The reason is that, besides the understanding and simulation of the atmospheric environment and the structure of the typhoon itself is not accurate enough, it is also one of the important reasons for the lack of understanding of the complexity and feedback of related ocean dynamics and thermal processes. When the typhoon transits, it exerts a great shearing force on the sea surface. The related wave breaking and the interaction between the wind field and the Stokes drifting can generate a large amount of turbulent kinetic energy, which produces a wave below the sea surface. The turbulent enhancement zone enhances the rate of turbulence dissipation in the upper ocean. Therefore, the establishment of a relatively complete marine hybrid scheme is an important way to improve the maritime-coupled typhoon model. In addition, improving the sea surface flux parameterization scheme under strong wind conditions is also an urgent need to improve the model prediction capability. With the rapid increase of computing power and technology, the air-sea coupled typhoon model has broken through the limitations of the early axisymmetric typhoon model and the mixed-layer ocean model, and replaced it with a complete fully coupled ocean

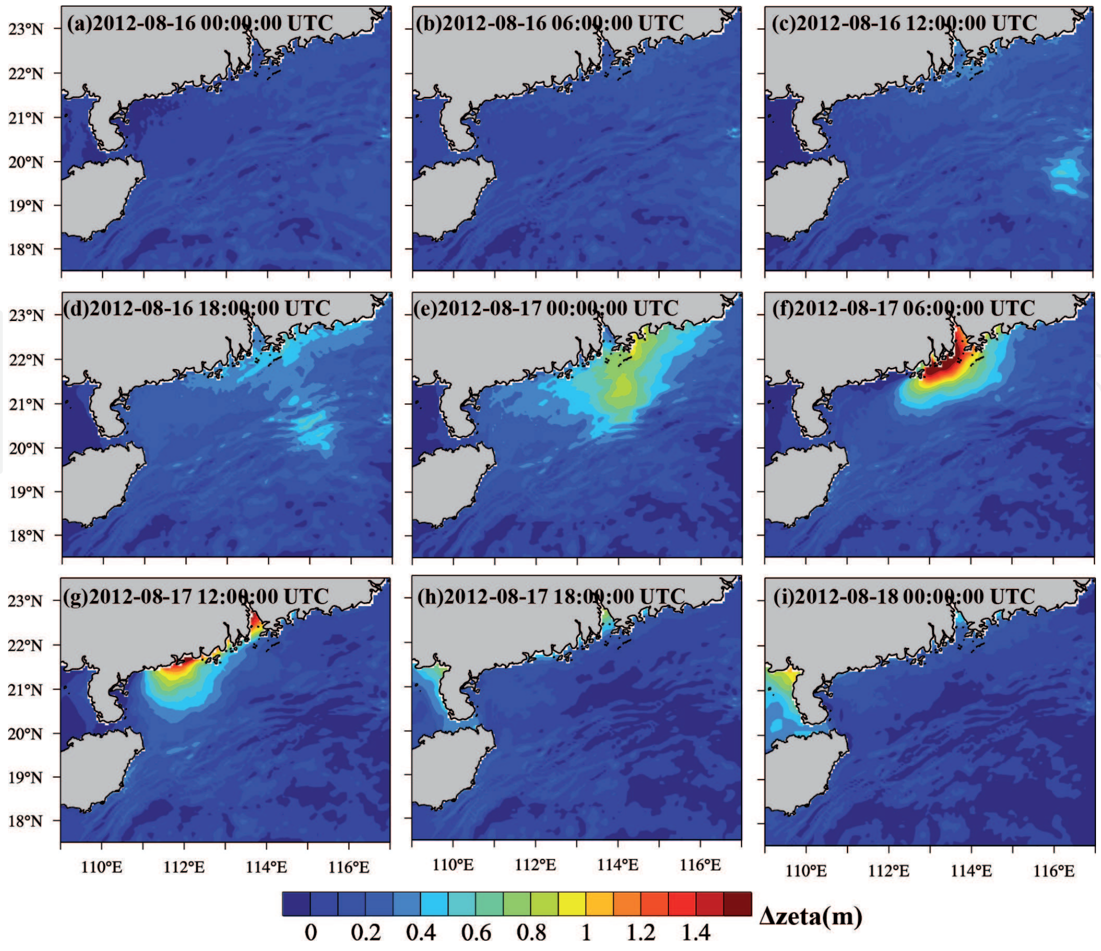

Figure 3.
Spatial distribution of storm surge level influenced by typhoon Kai-tak (start at 2012-08-15 00:00:00 UTC).

and atmosphere model. At present, the world's 1/32 to 1/900 degree resolution ocean model is being developed, which will provide strong support for the study of small-scale processes in the ocean and the multi-scale interaction between ocean and typhoon.

5. Future plans

The interaction between the ocean and the typhoon is a major scientific issue with significant scientific significance and important practical value. In recent years, with the support of national major scientific research projects, China has comprehensively utilized on-site observations from the perspective of air-sea interaction. Research methods such as theoretical analysis, data assimilation, and model prediction systematically study the response and modulation mechanism of the upper ocean to the typhoon, the interaction between the ocean and atmospheric observation system for the typhoon, the ocean mesoscale process and the typhoon, and the ocean to the typhoon. A series of innovations have been achieved in low-frequency response and modulation, physical mechanisms and parameterization of typhoons affecting the upper oceans, ocean multi-source data assimilation and parameter estimation during the typhoon, and ocean-air coupled prediction technology and applications in typhoons and marine environments. These research results will provide a solid theoretical foundation and technical support for further improving the forecast level of typhoon business in China, and make substantial contributions to the major national needs of disaster prevention and reduction.

However, it must also be recognized that China is still very lacking in the research field of interaction between ocean and typhoon, and there is still a big gap with the international advanced level. Compared with the national demand for disaster prevention, there are still obvious deficiencies. Based on the research results, we believe that the major scientific problems and major challenges in the interaction between oceans and typhoons are mainly reflected in the following points.

a. On-site observations are still very scarce. As described in this paper, China has already made important practices in ocean monitoring of typhoon processes and has obtained valuable on-site observations. Especially in the field of sea-air coordinated observation, China has launched A useful attempt. After the technology and security conditions are more mature, the typhoon observations coordinated by the sea-air will provide the necessary information for deepening the typhoon research. In addition, due to the harsh sea conditions during the typhoon, the long-term monitoring system for the typhoon process is still missing. The Pacific region and the northern part of the South China Sea are the regions with the highest typhoon in the world, and are almost the only way for typhoons that cause major disasters in our country. Therefore, long-term observation networks are built and maintained in the region (for example, the cross buoy/potential system) An array of observations for the basic structure is an effective means of enhancing ocean and atmospheric monitoring during the typhoon.

b. The response mechanism of the multi-scale circulation system of the upper ocean to the typhoon needs to be deepened. The circulation system of the upper ocean is very complicated. The typhoon prevailing in the northwestern Pacific includes the North Pacific subtropical circulation and tropical circulation driven by the trade wind, by buoyancy flux. The shallow transfected circulation of the North Pacific, the monsoon-driven circulation of the South China

Sea, and the small-scale circulation and vortex superimposed on these large-scale circulations. Typhoons can not only affect and even drive small- and medium-scale ocean circulation and vortex on the weather scale. The rotation can also affect the large-scale ocean circulation of the climatic state by changing the thermal salt structure of the upper ocean. Therefore, the response of the multi-scale circulation system of the upper ocean to the typhoon includes various dynamic processes, thermal processes, and nonlinearities between them. Interactions, these are major challenges in the study of the interaction between ocean and typhoon. Reveal the propagation, transfer and dissipation mechanisms of near-inertial energy input into the ocean by typhoons, and understand the mesoscale processes such as ocean vortex and internal waves during typhoon transit. Response characteristics and excitation mechanism to determine the "heat pump" and "cold suction" of the typhoon. The different effects on ocean stratification are the core of solving these problems.

c. A quantitative study on the modulation of typhoon intensity by the dynamic and thermal structures of the upper ocean. The dynamic and thermal structure of the upper ocean determines the magnitude of sensible heat and latent heat flux at the air-sea interface during typhoon transit. The maintenance and development of typhoons, especially the changes in typhoon intensity, depending on the energy and water vapor provided by these fluxes. Therefore, the dynamic and thermal structures of the upper oceans can play an important role in modulating the intensity of typhoons. The path and intensity are closely related, but since the typhoon intensity is directly affected by the energy provided by the ocean and is the weak link of the current typhoon forecast, we should pay special attention to the modulation of the typhoon intensity by the ocean. If the marine environment does not change, this modulation can be easily estimated from the upper maritime structure of the climatic state. But the problem is that the dynamic and thermal structures of the upper ocean are constantly changing at various spatial and temporal scales. Understand the feedback mechanism of the maritime mesoscale process on the typhoon on the weather scale, reveal the climate. The low-frequency variation of the upper ocean circulation and heat content under changing background should be solved by this question. The key to the question.

In short, based on the existing research foundation and experience, we suggest that in the future research on the interaction between ocean and typhoon. On the basis of the mechanism, the typhoon intensity and the forecasting ability of the marine environment are improved, and the predictability of typhoon low-frequency variability is evaluated, making China one of the world's leading researchers in the interaction between ocean and typhoon.

6. Summary

Observations over the past few decades have shown that the frequency, intensity, and duration of tropical cyclones vary over the interannual, interdecadal, and even longer timescales. Global warming caused by human activities and low-frequency natural oscillations in the Earth's climate system may have an impact on typhoons, but the relative importance of the two is still controversial. Whatever the case, the role of the ocean is unquestionable. Because on a long-term scale, the memory of the climate system is mainly stored in the ocean, any low-frequency variation must be related to the ocean. Previous studies on the low-frequency modulation of tropical cyclones in the ocean have focused on the correlation analysis between tropical sea surface temperature and typhoon parameters, but such analysis has its limitations. For example, the variation of the total power consumption of the Atlantic tropical cyclone has a good correlation with the variation of the sea surface temperature. If this empirical relationship is brought into the climate model, the total power consumption of the Atlantic tropical cyclone will increase by 3 times by the end of the 21st century. However, if a similar empirical relationship is established by subtracting the global tropical average from the tropical Atlantic sea surface temperature variation, the total tropical Atlantic cyclone power consumption predicted by the climate model remains essentially unchanged. This shows that the Atlantic tropical cyclone has been mainly modulated by natural low-frequency oscillations for the past 30 years.

In addition to high-resolution models, advanced data assimilation techniques are also essential to improve the simulation and forecasting capabilities of the typhoon model. Data assimilation can assimilate data from different sources, different time and space, and different elements into the dynamic model, and obtain an analysis field that is more detailed than the observation data and more realistic than the model results. For the assimilation of ocean data in the typhoon process, the most important problem is how to achieve multi-scale, multi-variable assimilation, extract the information reflecting the multi-scale interaction between ocean and typhoon in the observation system, and ensure the consistency of the model state field correction; The determination of the dependent background field error covariance matrix is also a problem.

In summary, the response and modulation mechanism of the ocean to typhoons is an international frontier proposition for marine and atmospheric science research. It is extremely challenging in terms of theoretical methods, observation techniques, model development and data assimilation. Taking this as an entry point, it is expected to achieve breakthrough basic research results, develop and improve marine science theories, and promote the interdisciplinary and common development of marine and atmospheric sciences while meeting the major needs of the country.

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