Numerical Studies on the Effects of Atmospheric Radiation on the Evolution of Tropical Cyclones

大気放射が台風の発達に及ぼす影響に関する数値的研究

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1. Introduction

Tropical cyclones (TCs) are extremely dangerous, even when they are just starting to form. They bring a range of severe weather that can each be highly destructive. For instance, they can produce storm surges, which will lead to sea level rise, potentially inundating coastal regions. They can also spawn flooding from heavy rainfall, especially in low-lying areas or places near rivers and lakes. TCs also generate extreme winds that can damage or destroy buildings, trees, and power lines. A TC is a vast, low-pressure meteorological system originating over warm ocean. It has a warm core and lacks frontal boundaries. TC features organized thunderstorm activity surrounding an eye where there is nearly no cloud. Over warm tropical oceans, clusters of thunderstorms sometimes form.

Diurnal variations of TCs are widely observed in different ocean basins. Using satellite data, several studies have investigated the cloud coverage around TCs and found that there is a diurnal cycle of the area of cold cloud tops. The diurnal cycle of TCs is presumably influenced by daytime shortwave radiation as well as longwave radiation, leading to diurnal variations in radiative heating/cooling, which can cause TCs to exhibit diurnal variation. The diurnal cycle of TCs implies that radiative processes impact TC behavior.

By conducting numerical experiments, previous studies illustrated that radiative processes play a crucial role in the formation and intensification of TCs. Generally, radiation significantly influences TC development when the intensity is low, but its effect diminishes as the intensity increases. Before substantial cloud cover develops, clear sky cooling can increase humidity, favoring the development of moist convection. In the cloud area, at nighttime, longwave radiative cooling almost predominates at all levels, and it is the strongest in the upper troposphere. This leads to decreased stability and promotes deep moist convection. At daytime, shortwave radiative heating and longwave radiative cooling coexist. The net effect is radiative heating at all levels, which is the strongest in the upper troposphere. This enhances stability, making conditions less favorable for storm development. The differential radiation effect between the TC and the clear sky environment generates circulations that influence convective activity within the TC core.

The overarching purpose of this dissertation is to analyze the radiative impacts on TCs from numerical experiments. This work is structured into two methodical components: real-case simulations and idealized experiments. Each component serves a distinct but complementary investigative purpose, forming a comprehensive inquiry into the physical processes governing TC evolution under radiative process.

The first component (chapter 3) involves real case simulations aimed at revealing how existing TCs are modulated by shortwave and longwave radiation. These simulations strive to simulate the actual atmospheric conditions under which TCs develop, with varying shortwave or longwave radiation. Through comparing the results of the sensitivity experiments in a series of numerical experiments, how shortwave and longwave radiation influence the TC development can be analyzed. This approach is inspired by previous studies that have provided views of the TC response to radiation most notably by examining nighttime conditions without shortwave radiation. Although it is found that the TC is stronger with a lack of shortwave radiation, how TC evolves with weaker or stronger shortwave/longwave radiation has not yet been investigated. The present work proposes to vary both shortwave and longwave radiation to simulate real case TCs.

The second component (chapter 4) utilizes an idealized framework, aiming to exclude external environmental influences such as synoptic scale disturbances and other meteorological conditions. This simplification enables a concentrated examination of the impact of the radiative forcing on the TC evolution and its diurnal cycle. Observational studies have highlighted the existence of a diurnal cycle within mature TCs, but the amplitude and phase of this diurnal cycle vary across different basins and individual TCs, suggesting a complex interplay between internal dynamics and external environmental factors. Previous studies did not focus on the diurnal cycle of TCs during the cyclogenesis and intensification stages. Therefore, in this dissertation, TCs are simulated from the cyclogenesis stage to the mature stage under diurnally varying solar radiation, allowing for an analysis of the diurnal cycle features at different stages. Moreover, the effect of the diurnal cycle of radiation on the developmental characteristics of TCs, apart from the diurnal cycle of convection, has not been investigated. In this dissertation, experiments with constant solar radiation are also carried out. By comparing the simulation results with both constant and diurnally varying solar radiation, the impacts of the diurnal cycle on the developmental features of TCs can be analyzed. The idealized simulations conducted in this research offer a purified view of TC behavior, providing important insights into the diurnal effects on TCs

2. Descriptions of numerical model

In this chapter, the numerical model, physics schemes, and the general design of the simulations in this work are described. The Weather Research and Forecasting (WRF) model is utilized, with version 4.1 used in Chapter 3 and version 4.2 in Chapter 4. The

WRF model is a non-hydrostatic model, and can well simulate the vertical motion, which is essential for modeling severe weather events such as thunderstorms and TCs. In the simulations, the following physical processes were calculated through parameterizations: microphysics, cumulus, radiation, planetary boundary layer, and surface layer.

In chapter 3, real case simulations were conducted. In real case simulations, reanalysis data are used as initial and boundary conditions for the numerical experiments. By modifying the configuration of the shortwave and longwave radiation, the model can simulate the evolution of the TC cases under different atmospheric radiative conditions.

In chapter 4, idealized rotating radiative-convective equilibrium (RCE) simulations were conducted. In the simulations, the atmospheric system is allowed to evolve under the influence of radiation and convection, while rotation is included to mimic the Coriolis effects. The absence of large-scale external forces allows to focus on the analysis of internal diurnal cycle of a TC.

3. Simulations of Typhoon Hagibis and Lionrock with varying radiative heating rates

In this chapter, the effects of varying radiative forcing on the evolution of Typhoon Lionrock (2016) and Typhoon Hagibis (2019) are examined using the WRF model. Hagibis was a rapidly intensifying and quickly moving TC; while Lionrock was a slowly developing, long-lived TC. Radiation presumably has different effects on the two typhoon cases with different characteristics, so these two cases are chosen.

Because this study focuses on the effects of radiative heating processes on the evolution of typhoons, we specifically investigated the sensitivity of the simulated typhoons to radiative parameterizations by intentionally changing the magnitudes of shortwave and longwave heating/cooling. We designed four experiments with different radiative heating rates, in addition to the control experiment (CTL). The radiation heating rates are modified by changing the temperature tendency due to shortwave or longwave radiative heating/cooling. The CTL experiment is conducted with standard (i.e., unmodified) settings for radiative processes.

The sensitivity experiments include no shortwave radiation (NSW), no longwave radiation (NLW), double the temperature tendency due to longwave radiation (DLW), and double the temperature tendency due to shortwave radiation (DSW) experiments. The NSW experiment is the same as that in the nighttime-only experiment of Tang and Zhang (2016) and is intended to examine how a TC develops in the absence of solar radiative heating. The NLW experiment is designed to examine longwave radiative effects because a differential longwave cooling effect from cloud and atmosphere has been suggested in previous studies (Gray and Jacobson, 1977; Nicholls, 2015); this experiment can verify how this effect works. Both the DLW and DSW experiments apply extremely strong radiative heating rates not investigated in previous studies; we expect shortwave or longwave heating/cooling to be elucidated under these enhanced radiative effects. We analyze the influences of radiation by comparing the different sensitivity experiments.

The simulation results of the CTL are compared with the best track and satellite observation data. The CTL captures the time evolution reasonably well; hence it can be regarded as a proxy of the real typhoon cases. Analysis of TC intensity changes among the experiments shows that for the Hagibis simulations, the central pressure in the NLW decreases more slowly, whereas it decreases more rapidly in the other experiments. Compared with the CTL, the central pressures in the NSW and the DLW are higher whereas the value of the DSW is lower. The maximum wind speeds of these sensitivity experiments are very close, except for the NLW which is the smallest. For the Lionrock simulations, generally the features of the sensitivity experiments are similar to the Hagibis simulations. The deviations of each experiment are much larger than in the Hagibis simulations. The intensity of the Lionrock NLW is extremely weak, indicating that the Lionrock NLW fails to become a TC. The analysis of evolution of cloud structure shows that in all the experiments initial disturbances develop into stronger TCs, except for the Lionrock NLW which does not form TC structure. The differences among the sensitivity experiments indicate the simulated TCs are strongly affected by radiation.

The extremely weak development of the Lionrock NLW is thought to be due to latent heating because latent heating is one of the most important diabatic heating source for TC development. Analysis of latent heating rates shows that there is a pronounced cold pool in early stage for the Lionrock NLW. Cold pool suppresses the pressure drop and prevents intensification, which can explain the extremely weak development for the Lionrock NLW. The relative humidity in the Lionrock NLW experiment is lower than in the Lionrock CTL experiment, which is favorable for the evaporation in the lower troposphere and hence generate the cold pool. The smaller relative humidity for the Lionrock NLW is caused by the lack of longwave radiation. The analysis of longwave radiation in early stage shows that the atmosphere at the cloud-base is shown to experience relatively weak longwave cooling; by contrast, outside the cloud area, longwave cooling is stronger. This differential longwave cooling in the radial direction enhances the radial pressure contrast and hence the pressure gradient toward the TC center, thereby increasing low-level convergence below the cloud base. This stronger low-level convergence near the surface can bring more water vapor to the cloud region and increase relative humidity. Therefore, the lack of longwave radiation in the NLW leads to smaller relative humidity in early stage. The initial humidity for Hagibis is higher than that for Lionrock. For the Hagibis NLW, without differential longwave cooling effect, the relative humidity is still high. This is the reason for the lack of the cold pool in the Hagibis NLW.

The analysis of radiative heating rates distribution shows that the magnitude of radiative heating/cooling is strongest near cloud top for the sensitivity experiments of both Hagibis and Lionrock cases. The magnitude of radiative heating/cooling near cloud top is two to three times larger than that in low-level. This leads to vertical temperature gradients, affecting the stability of the atmosphere. For the NSW, there is no shortwave heating near cloud top, so cloud top radiative cooling is stronger than the CTL. For the NLW, the lack of longwave radiative cooling near cloud top leads to stronger cloud top heating than the CTL. For the DLW and the DSW, because of the doubling the radiative heating/cooling rate, the increase of the radiative heating/cooling rate is stronger in the cloud top layer than below the cloud top. As a result, compared to the CTL, the stability is lower for the NSW and the DLW, and is higher for the NLW and the DSW. Compared to the CTL, the convection for the NSW and the DLW is stronger, and the convection for the NLW and the DSW is weaker. The results indicate that cloud top radiation can affect stability, and hence influence convection.

In the eye region, because of the lack of convection and latent heating, the radiative heating becomes a predominant diabatic heating source. In the DLW and the NSW, strong longwave cooling occurs in the eye region, and the central pressure drop is reduced because of the cooling. This effect makes the central pressure higher in the DLW and the NSW than in the other experiments for both typhoon cases. However, the DSW case indicates stronger warming in the eye region among the experiments, which enhances the central pressure drop.

The conclusions of this chapter can be briefly summarized as follows: In early stage, the differential cooling effect, which indicates that longwave cooling rates between cloud clusters and clear sky differ, can promote low-level inflow, and increase relative humidity in the cloud clusters. This effect is particularly important if the initial humidity is low. After eyewall formation, both the change in temperature lapse rate due to a vertical gradient of radiative heating/cooling and the change in the warm core due to radiative heating/cooling can affect the intensity of a TC; however, the net effect may depend on the magnitude of these influences.

4. Idealized experiments of TCs in rotating convective-radiative equilibrium framework

In this chapter, rotating RCE experiments using the WRF Model are conducted to explore the effects of the diurnal cycle of radiation on TCs. The vertical structure of the atmosphere at the initial time is determined as a RCE state achieved after a long-time integration of a RCE simulation in a smaller domain. The initial condition is horizontally homogenous and no initial wind. A random low-level temperature perturbation is introduced to initiate convection. It means there are no large-scale or external forcings in the simulations.

Since the microphysics scheme and the SST influence convection behavior and may affect the diurnal cycle of convection, to test the robustness of the simulated behavior, sensitivity experiments with two different microphysics schemes (i.e., the WSM6 and the Morrison) and two different SSTs (i.e., 305 K and 299 K) are conducted. The corresponding experiments are abbreviated as Morrison_305K, Wsm6_305K, Morrison_299K, and Wsm6_299K.

Based on the evolution features of the TCs in these experiments, the simulation period can be divided into cyclogenesis, intensification, and mature stages, according to the daily mean maximum surface wind speed. The analysis of convection shows that for all the sensitivity experiments, the diurnal cycle of convection is statistically significant in the cyclogenesis and mature stage, but insignificant in the intensification stage.

The analysis of radiative heating rates shows that in the cloud region, the radiative heating is predominant in the daytime and radiative cooling is predominant in the nighttime. The strongest radiative heating/cooling rates appear at high-levels near the cloud tops. Beneath the cloud top, the magnitude of radiative heating/cooling is smaller than that near cloud top levels. The vertical differences in radiative heating/cooling can affect the stability of the atmosphere, which in turn influences the convection activity. The temperature lapse rate shows a clear diurnal cycle with a maximum around the early morning. The longwave cooling is strongest near high level in nighttime; thus, the temperature in the high level continuously decreases in nighttime, resulting in a larger temperature lapse rate near early morning. This effect makes convective activity stronger in the early morning.

In the cloud-free region, generally, the features of predominant cooling in nighttime and predominant heating in daytime is similar to those in the cloud region, but the distribution is more vertically homogenous. The radiative heating/cooling in the high-level is much weaker than that in the cloud region. The differential radiation effect between the cloud region and cloud-free region is considered to influence the airflow between the cloud region and cloud-free region. Therefore, the vertically averaged massweighted radiative heating rate in the cloud region minus that in the cloud-free region is analyzed. Throughout the day, the value is positive, which means that the temperature tendency of the whole vertical column due to the radiation is greater in the cloud region than in the cloud-free region. Thus, the inflow to the cloud region can be enhanced by the differential radiation effect, which transports more surface sensible and latent heat to the cloud region and hence strengthens convection. Because shortwave heating decreases the differential radiation effect, the value is larger in the nighttime than in daytime. Therefore, this effect is considered to enhance convection more significantly in the nighttime than in the daytime.

The radiation leads to a diurnal variation of temperature lapse rate and differential radiation effect, and hence causes the diurnal cycle of convection. Although there are some deviations among the sensitivity experiments, these radiative effects are similar for these sensitivity experiments, indicating the results are robust against different microphysics schemes and SSTs.

In the intensification stage, the surface pressure drop is strong, so the pressure gradient force is increasing. As a result, the surface wind speed continuously increases, surface heat and moisture flux also increase, and are transported to the TC center, that can promote persistent convection within the TC irrespective of the time of day. This effect outweighs that of radiative forcing, so the diurnal cycle of convection becomes not obvious in the intensification stage.

Moreover, in addition to the diurnal cycle of convection, the effects of the diurnal cycle on general TC development are also examined, particularly through comparisons with results from experiments using constant shortwave radiation. These experiments are denoted as NDC, and those with normally diurnally varying radiation are denoted as DC. In the cyclogenesis stage, for both the Morrison and Wsm6 experiments, the cyclogenesis rate is greater in the DC than in the NDC. In the intensification stage, for the Morrison experiments, the intensification rate is larger for the NDC than for the DC; however, for the Wsm6 experiments, it is the opposite in that the intensification rate is smaller for the NDC than for the DC.

In the cyclogenesis stage, the analysis of the temporal mean of radiative heating rates shows that in the cloud region, in lower levels, the heating rate is larger in the DC than in the NDC; however, in higher levels, it is smaller in the DC than in the NDC. In the cloud-free region, throughout the entire vertical levels, it is larger for the NDC than for the DC. The differences in the radiative heating rates for the DC and the NDC will produce those in differential radiation effect. Analysis shows that the differential radiation effect for the DC is stronger than that for the NDC. The stronger differential radiation effect for the DC results in stronger moisture convergence into the cloud areas, leading to more rapid cyclogenesis.

In intensification stage, the analysis of radiative heating rates in the inner region of TC shows that for the Morrison experiments, the cloud top cooling is stronger for the NDC than for the DC; however, this feature is the opposite for the Wsm6 experiments in that the cloud top cooling is weaker for the NDC than for the DC. These differences in cloud top cooling leads to different stability changes for the DC and the NDC. Stronger cloud top cooling causes lower stability promoting convection and latent heating released in the TC. Stronger latent heating leads to more rapid central pressure drop and greater intensification rate.

The conclusions of this chapter can be briefly summarized as follows: The contribution of the diurnal cycle depends on the stages of TC development, being significant in the cyclogenesis and mature stages but insignificant during the intensification stage. This diurnal cycle remains robust across different microphysics schemes and SSTs. There are two primary mechanisms that influence the diurnal cycle in the cyclogenesis and mature stages: variations in the temperature lapse rate due to diurnal shifts in radiative heating/cooling, and the diurnal variation of the differential radiative heating/cooling effect. The intensification stage experiences continuous convection intensification, making the diurnal cycle less significant. In the presence of the diurnal cycle, the differential radiation effect is stronger. The effect of the diurnal cycle on cloud top cooling depends on the specific microphysics schemes used in the experiments.

5. Conclusions

Atmospheric phenomena evolve under the impact of both shortwave and longwave radiation. The radiative processes are important in determining atmospheric temperature field and circulation, thereby influencing the development of TCs.

Numerous observational studies have indicated the statistical significance of diurnal variation in many TC cases, underscoring the importance of radiative impacts on TC evolution. Advancements in computational technology have led to the development of sophisticated atmospheric numerical models capable of handling radiative transfer equations. These models enable researchers to simulate and analyze the radiative effects on TCs. In this dissertation, the real case simulations reveal how existing TCs are modulated by varying shortwave/longwave radiations; the idealized simulations demonstrate the intrinsic diurnal radiative impacts on TCs. Based on the analysis of the simulation results and discussions, the following general conclusions are obtained.

During nighttime, the absence of shortwave radiation makes longwave radiation the primary factor, resulting in predominant radiative cooling. Conversely, in the daytime, the coexistence of shortwave and longwave radiation leads to net radiative heating, peaking at noon when the solar zenith angle becomes maximum. The radiative heating/cooling rate is contingent upon droplet sizes in the atmosphere, leading to distinct characteristics in cloud and clear sky regions. In the cloud region, the most intense radiative heating/cooling occur at the cloud top, with significantly less intensity beneath the cloud top. In contrast, the clear sky region exhibits a more uniform vertical distribution of radiative heating /cooling rates.

The vertical differences in radiative heating and cooling within the cloud region can significantly affect atmospheric stability, which in turn may impact convection activity. At night, strong radiative cooling at higher altitudes leads to a larger temperature lapse rate, conducive to convective activity. In the daytime, radiative heating predominates, and the opposite effects become significant. Despite the strong cloud top cooling at night and heating during the day, the net effect over the entire day is cloud top cooling, which generally destabilizes the atmosphere.

Eliminating the diurnal cycle of radiation by maintaining shortwave radiation at a constant value, equivalent to the daily average of its diurnal variation, the cloud top cooling becomes stronger or weaker with the specific microphysics scheme employed in the experiments. The diurnal cycle can amplify or attenuate cloud top cooling, depending on the microphysics scheme used, establishing a critical link between diurnal cycle effects and the chosen microphysics scheme. This implies that while the diurnal cycle significantly influences convection, its exact impact is closely tied to the microphysics scheme.

The features of radiative heating and cooling in the cloud region and clear sky region differ markedly. This differential radiation effect can influence the airflow between the cloud region and clear sky region. At night, the longwave cooling throughout the entire column is less intense in the cloud region compared to the clear sky region. This indicates that the inflow to the cloud region can be enhanced by this effect, transporting more surface sensible and latent heat to the cloud region, and increasing convection. During the daytime, the presence of shortwave heating in both the cloud and clear sky regions reduces the differential radiation effect. However, throughout the entire day, the differential radiation effect remains positive, enhancing the low-level convergence in the cloud region. Removing the diurnal cycle of radiation by keeping the shortwave radiation constant at its daily mean value reduces the differential radiation effect. Thus, the diurnal cycle can enhance the differential radiation effect.

After the formation of a TC's eyewall structure, the radiation in the eye region becomes the predominant diabatic heating due to the lack of convection and latent heating. Radiative cooling in this region can reduce the central pressure drop, while radiative heating can enhance it.

Without large-scale external forcings, in the cyclogenesis stage, the diurnal cycle of convection is pronounced, with maximum activity from midnight to early morning. This cycle is primarily driven by the diurnal variation of the temperature lapse rate and the differential radiation effect. Moreover, the enhanced low-level convergence, influenced by the differential radiation, boosts cloud aggregation, leading to faster cyclogenesis. The differential radiation effect is more pronounced with the presence of the diurnal cycle of radiation, suggesting that the diurnal cycle can accelerate the cyclogenesis process. This effect becomes evident if the chosen microphysics scheme produces weaker latent heating.

In the early stages of TC intensification, especially under conditions of low relative humidity, the differential radiation effect becomes important. Without this effect, reduced low-level convergence leads to decreased water vapor and low humidity, promoting the evaporation of falling precipitation and the generation of cold pools, which inhibits further TC development.

As a TC intensifies, latent heating consistently increases, reducing surface pressure and amplifying the pressure gradient. This leads to increase the inflow into the TC, enhancing convection. This intensification process overwhelms the diurnal cycle of the radiation, rendering the diurnal variation less significant.

Cloud top cooling influences the TC intensification rate. Stronger cloud top cooling increases the temperature lapse rate, favoring convection and boosting intensification rate. The presence of diurnal cycle of the radiation can weaken or strengthen cloud top cooling, depending on the microphysics scheme. It indicates the complex interaction between radiative and microphysical processes.

If there are no large-scale external forcings, in the mature stage of a TC, a significant diurnal cycle of convective activity occurs. This cycle is driven by the diurnal variation in the temperature lapse rate and differential radiation effect. Radiative cooling in the eye region is stronger at night, potentially increasing central pressure and negatively impacting TC convection. The simulations show that TC convection peaks from midnight to early morning, indicating that the positive radiative effects increasing the temperature lapse rate and differential radiation outweigh its negative effect increasing central pressure, resulting in maximum convection during the early morning.

The findings in this dissertation provide valuable insights into the radiative impacts on TC evolution. However, several points remain unclear. Future works are desirable to deepen the understanding of radiative impacts on TCs.

The simulation results indicate that the radiative heating rate seems to be different for different microphysics schemes. However, the relationship between radiation and microphysics schemes is still unclear. Therefore, interactions between radiation and microphysics need to be further investigated.

In this dissertation, there is no temporal change of SST in the numerical experiments. In the real world, the SST is influenced by radiation or mixing of the ocean surface layer with deeper water, which could influence the TC development. Future numerical studies that incorporate changes in SST due to radiation and mixing processes can help to understand how the diurnal cycle of SST affects TC development.

Large-scale forcings such as vertical wind shear or an upper tropospheric trough might influence the symmetric structure of a TC, leading to asymmetric cloud distribution and radiative heating/cooling. This asymmetry in diabatic heating patterns could influence TC development. Future numerical studies that include specific large-scale forcings can provide insights into how these forcings affect the radiative effects on TC development.

The complexity of these interactions means that the radiative effects on TC development are still not fully understood, making future studies in this area highly desirable.