atmosphere

MDPI

Review

A Review of Typhoon Inner Core Characteristics and Their Relationship with Intensity Changes

Shumin Chen [1,*] and Weibiao Li [2,*]

[1] Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai 519082, China
[2] School of Atmospheric Sciences and Key Laboratory of Tropical Atmosphere-Ocean System, Ministry of Education, Sun Yat-sen University, Zhuhai 519082, China
* Correspondence: chenshumin@sml-zhuhai.cn (S.C.); eeslwb@mail.sysu.edu.cn (W.L.)

Abstract: The inner core of a typhoon plays a crucial role in storm intensification and is especially critical for rapid increases in storm intensity. Most of the energy exchange occurs in the inner core, including the eyewall. Moist air rising from the warm ocean releases latent heat, increasing wind speeds and sustaining the warm-core structure through secondary circulations. A deeper understanding of the physical processes in the inner core is essential for improving intensity forecasts and disaster preparedness and mitigation. This paper reviews key studies on the inner core. We focus on lead–lag relationships, eyewall replacement cycles, and waves and oscillations, which are topics that can greatly enhance forecasting capabilities. We highlight limitations of current research and propose key scientific questions that would provide essential insights to improve forecasts and support disaster reduction strategies. These include: (1) what are the physical processes that drive the lead–lag relationship between eyewall convection and intensity changes, and how does the time lag vary across typhoons? (2) What conditions favor merging of the inner and outer eyewalls and completion of the eyewall replacement cycle, potentially leading to rapid intensification before landfall? (3) How do waves and oscillations in the eyewall influence typhoon intensity variations?

Keywords: typhoon; inner core; intensity change; eyewall

check for updates

Citation: Chen, S.; Li, W. A Review of Typhoon Inner Core Characteristics and Their Relationship with Intensity Changes. *Atmosphere* **2024**, *15*, 1522. https://doi.org/10.3390/atmos15121522

Academic Editor: Mario Marcello Miglietta

Received: 27 November 2024
Revised: 17 December 2024
Accepted: 19 December 2024
Published: 20 December 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Typhoons are intense low-pressure systems that form over warm tropical oceans [1] and are the cause of some of the most severe weather disasters [2]. Their destructive potential stems from a combination of strong winds, heavy rainfall, and storm surges, which cause widespread damage to human communities in affected regions [3]. Globally, the number of landfall typhoons is the highest in China, which has suffered devastating impacts. Figure 1 shows the tracks of a total of 528 westward, northwestward, and recurving landfall typhoons from 1979 to 2018, obtained from the China Meteorological Administration (CMA) Best Track data [4]. The categorization of typhoon tracks is based on Chan and Gray's study [5]. According to the China Climate Bulletin for 2019 and 2023, on average, seven to eight typhoons make landfall in China each year. In addition to loss of life, the social impacts of typhoons include displacement of communities, disruption to infrastructure, and an estimated annual economic loss of approximately CNY 60 billion. These factors underscore the importance of enhancing our understanding of these extreme weather events.

The complexity of typhoon characteristics, such as track, intensity, and structure, presents significant challenges for meteorological forecasting and research. Track prediction has improved substantially in recent years due to advancements in numerical weather models [6]. However, intensity forecasting remains challenging, especially in the case of rapid changes in intensity [7], which are often associated with complex inner core dynamics [8]. The inherent difficulty lies in the intricate interplay between the physical processes governing typhoon development and intensification. Consequently, research on typhoon intensity remains a key focus in meteorology.

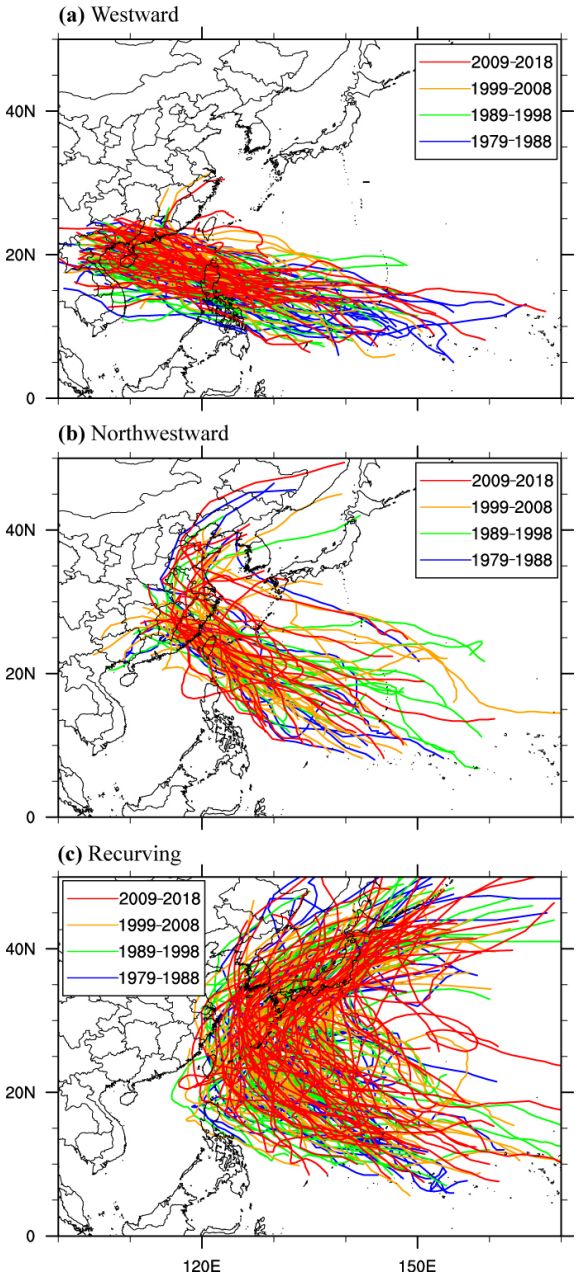


Figure 1. Tracks of (**a**) westward, (**b**) northwestward, and (**c**) recurving landfall typhoons during 1979–2018 from China Meteorological Administration (CMA) Best Track data.

The structural components of a typhoon include the eye, the eyewall, and the outer spiral rainbands (Figure 2) [9]. The eye, located at the storm's center, is characterized by descending air and relative calmness; it is warmer than the surrounding environment. The eyewall is a ring of intense convection surrounding the eye; it contains the strongest winds and the heaviest rainfall, making it the most destructive part of the storm. Extending outward are the spiral rainbands, which can span hundreds of kilometers; they can bring heavy precipitation to areas that are far away from the storm center. Collectively, these structural components define the typhoon's behavior and influence its impact. The inner core—typically defined as the region within 100 km of the storm center and includes the eye and eyewall—is particularly important for understanding intensity variations.

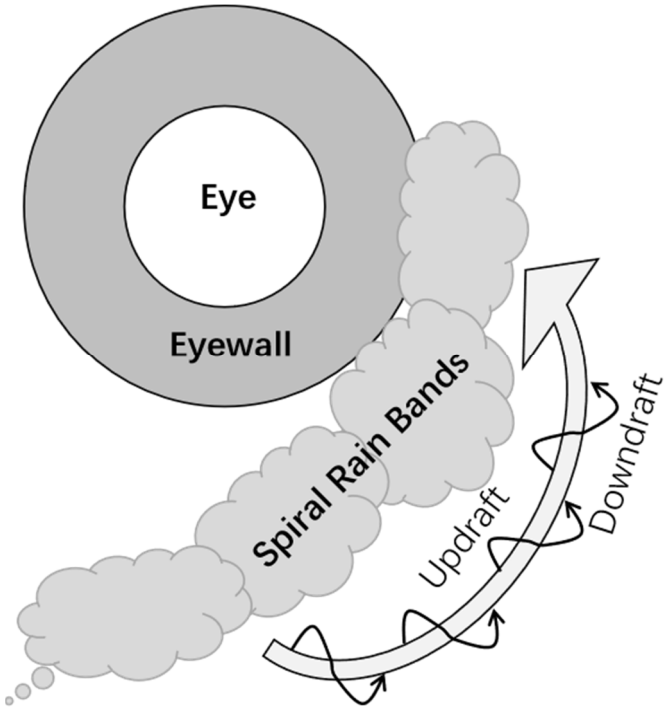


Figure 2. A schematic diagram of the structural components of a typhoon: the eye, eyewall, and outer spiral rain bands. The thick gray arrow indicates the overall direction of the low-level flow in the typhoon, which is counterclockwise. The thin black spiral lines around the arrow represent the small-scale upward and downward motions, which are in connection with the horizontal winds, in the cloud systems of the inner core and outer rainbands.

The inner core encompasses the towering convective clouds of the eyewall [10], which are at various stages of development [11]. This region is critical for the transfer of energy between the typhoon and its surroundings. According to established theories, the intensification of a typhoon is driven by warm, moist air being drawn into the inner core through boundary-layer inflow. As this air ascends, it cools adiabatically, leading to condensation and the release of latent heat. This heat release warms the mid-to-upper levels of the atmosphere, creating a warm-core structure that lowers central pressure and intensifies the storm [12]. Oceanic thermal conditions, as expressed through the sea surface temperature (SST), are key determinants of this process. The wind-induced surface heat exchange (WISHE) mechanism sets up positive feedback between the intensifying typhoon and the surface fluxes of heat and moisture; as wind speed increases, more moisture is drawn into the storm center; latent heat release further intensifies pressure drop and wind speed, driving additional intensification of the typhoon [13]. However, other elements, such as the atmospheric boundary-layer structure [14] and the large-scale circulation patterns [15,16], also modulate energy transfer and influence intensity changes.

Secondary circulations in the inner core play a critical role in sustaining typhoon intensity (Figure 3) [12]. These include radial inflow at the surface, upward motion in the eyewall, and outward flow in the upper troposphere. Together, they facilitate the continuous transport of heat and moisture into the system, reinforcing the storm's warm core. Processes such as eyewall replacement cycles [17] and vortex Rossby waves [18] also induce significant structural changes in the inner core, leading to intensity fluctuations. For instance, eyewall replacement cycles involve the development of a secondary eyewall, which temporarily intensifies the storm as the original eyewall compresses and is eventually replaced. Similarly, vortex Rossby waves, which propagate radially within the typhoon, can enhance eyewall convection and contribute to the evolution of the storm structure.

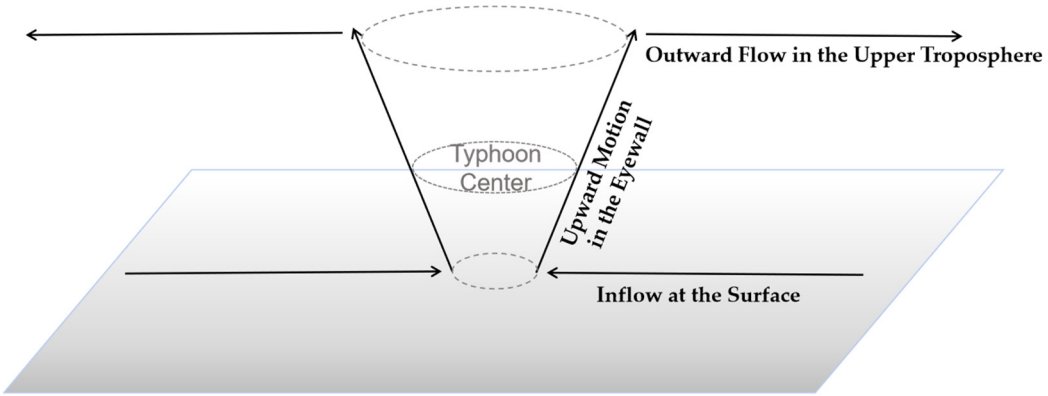


Figure 3. A schematic diagram of the secondary circulation of a typhoon.

The study of typhoon intensity in special areas, such as the South China Sea, poses unique challenges. Typhoons traversing the South China Sea often encounter rapid variations in ocean heat content, SST [19], and environmental wind shear [20], leading to complex changes in typhoon intensity. For example, Typhoon Rammasun (2014) intensified substantially over the South China Sea because of favorable interactions with monsoonal flows and oceanic eddies. This demonstrates the influence of regional factors on inner core processes [21] and underscores the need to improve our understanding of typhoon intensity changes over the South China Sea by conducting targeted studies.

Observational and modeling studies have advanced our understanding of inner core dynamics [22,23]. High-resolution satellite data, airborne reconnaissance, and in situ measurements, such as dropsondes, provide invaluable insights into the physical processes occurring inside the inner core. Additionally, numerical models, particularly those with cloud-resolving capabilities, have improved our ability to simulate complex interactions, such as latent heat release, secondary circulation patterns, and microphysical processes in the eyewall [24]. However, challenges remain; these include the accurate representation of the role of small-scale convection and the interaction between the typhoon and its larger-scale environment.

A deeper understanding of the physical mechanisms of the inner core is crucial for improving intensity forecasts. It will contribute toward disaster mitigation and preparedness and has significant scientific and practical value. Therefore, in this paper, we review studies on the inner core with a particular focus on lead–lag relationships, eyewall replacement cycles, and waves and oscillations. An understanding of these topics could greatly improve forecasting capabilities. We also highlight limitations in these studies and raise several key scientific questions. Our objective is to enhance the understanding of the inner core and improve typhoon forecasting to support disaster prevention and reduction.

2. Inner Core as the Hub of Energy Transfer in Typhoons

The inner core of a typhoon plays a central role in the storm's energy dynamics, particularly in vertical energy transport. The energy required to sustain and intensify a typhoon is the most highly concentrated in this region [25]. As the hub of energy transfer, the inner core is responsible for maintaining the storm's structural integrity and dynamics. Its primary energy source is the ocean surface through latent heat release. The latent heat released in the inner core contributes to the establishment of the storm center, which is a prominent low-pressure system in the lower troposphere, and plays a pivotal role in sustaining the convective processes that fuel storm intensification [12,13].

Li reproduced this process in an analytical study, in which he derived solutions for a dynamic typhoon model. He showed that the latent heat release in the inner core is crucial for maintaining the low-pressure storm structure; these results are consistent with those derived from observation data [26]. Latent heat release causes the temperature of the middle troposphere to rise; this initiates a positive feedback loop in which the thermal wind

effect is enhanced, driving stronger lower-level winds and increased heat and moisture fluxes. This is a key mechanism underlying the intensification of typhoons [27].

Knowledge of the energy dynamics in the inner core is critical to understanding the evolution of typhoon intensity. Comprehensive understanding of the physical processes in the inner core is indispensable for accurate typhoon forecasting [28]. The evolution of typhoon intensity is substantially influenced by interactions between typhoon structure and the surrounding environment. Studies have shown that variations in typhoon intensity are closely linked to changes in the structure of the inner core, particularly in the symmetry of the eyewall [29]. The eyewall is typically symmetric around the storm center. Under certain conditions such as vertical shear, the eyewall can become asymmetric. Because of their irregular structure, asymmetric eyewalls can have varying effects on typhoon intensity [30,31]. In particular, during the intensification phase, the formation of an outer eyewall or the development of peripheral rainbands can lead to significant fluctuations in storm intensity; periods of weakening can be followed by rapid reintensification [32]. This complex interplay between structural changes and intensity variations highlights the need for more refined modeling and observational techniques to capture the nuanced processes at play in the inner core.

The physical processes occurring in the inner core are not only influenced by the storm's internal dynamics but also by large-scale atmospheric and oceanic conditions [33]. The exchange of heat and moisture between the ocean and atmosphere is closely tied to changes in typhoon intensity [34]. The rapid intensification of typhoons depends on the availability of heat in the ocean surface layer and the moisture content in the atmosphere. Studies have shown that rapid intensification is often associated with higher SSTs and abundant atmospheric moisture, both of which supply essential energy for storm development [35]. Interactions between these factors are particularly crucial during the initial formation and intensification of a typhoon. A moist atmosphere and sufficiently high SST allow the storm to draw substantial amounts of heat and moisture into the inner core, fueling further intensification. Typhoons substantially lower SST because high wind stress induces Ekman divergence and results in cold wakes. As a result, improved typhoon intensity forecasts and storm surge predictions rely on the use of coupled atmosphere–ocean models, which can simulate the interactions between typhoons and the ocean with higher accuracy.

Furthermore, processes in the upper ocean and atmospheric boundary layer can substantially influence cloud structure in the inner core; they can influence the development of the eyewall and the overall storm structure [36,37]. Warm SSTs and a moist atmospheric boundary layer favor the growth and persistence of convection in the inner core, thus promoting intensification [38,39]. These conditions facilitate the upward motion of moist air into the storm center, where condensation and latent heat release further fuel convection, driving intensification [12]. Moreover, a typhoon can intensify, and its structure can stabilize under favorable atmospheric conditions, such as lower vertical wind shear and higher relative vorticity at lower levels [40,41]. On the other hand, high vertical wind shear or low SSTs can disrupt inner core structure, weaken the upward motion of warm moist air, and hinder storm intensification.

Large-scale atmospheric circulation can also impact typhoon intensity by interacting with atmospheric moisture [42]. Opening moisture channels between the upper and lower levels of the typhoon and increasing moisture convergence in the inner core facilitate intensification [43]. However, unfavorable atmospheric conditions, such as the injection of dry air into the storm, can suppress typhoon development by drying out the atmosphere and reducing convection [44].

Topographic factors also play a significant role in the evolution of typhoon intensity, structure, and trajectory. At landfall, typhoons weaken rapidly because of the absence of evaporation from the sea surface and increased surface friction; islands and other land features can also influence the intensity and evolution of the inner core through dynamic processes such as orographic lifting and wave interaction [45,46]. For instance, when a

typhoon encounters an island, the topography can lead to changes in the storm's wind patterns, contributing to the development of secondary circulations in the inner core. In some cases, the interaction between a typhoon and islands can lead to changes in storm intensity; the intensity may increase or decrease, depending on the size and orientation of the landmass. These topographical influences are especially important when typhoons make landfall or interact with smaller islands and archipelagos in coastal regions.

In conclusion, knowledge of the inner core of a typhoon is critical for understanding both the dynamics and energy transfer processes that govern storm intensity. The interplay between latent heat release, oceanic conditions, atmospheric moisture, and large-scale circulation patterns is complex, and each of these factors can have a substantial influence on storm intensity and evolution. Moreover, structural variations in the inner core, such as the symmetry of the eyewall and the formation of outer eyewalls or rainbands, can result in dramatic changes in typhoon intensity. Therefore, improving the accuracy of typhoon intensity forecasts requires a deeper understanding of these processes and the environmental factors that modulate them. Further research, particularly in regions where rapid intensification occurs with high frequency, such as the South China Sea, is needed to enhance our predictive capabilities and mitigate the impacts of these devastating storms.

3. Lead–Lag Relationship Between Inner Core Structural Change and Intensification

The inner core of a typhoon serves as the central hub for energy transfer within the system. Energy is transported from the core to the mid-troposphere and subsequently fed back into the lower atmosphere, driving a gradual decrease in central pressure and increase in maximum wind speeds near the core. This sequential and interdependent process highlights the intricate relationship between the evolution of the inner core structure and changes in typhoon intensity. Importantly, changes in the inner core structure often precede observable intensity variations and can be used as early indicators of the intensification or weakening of the storm.

According to numerous research studies, the inner core contains precursory signals of impending intensity changes, such as rapid increase or decrease. These signals offer valuable opportunities to forecasters to anticipate and prepare for significant changes in typhoon behavior. For instance, during phases of rapid intensification, there are frequent bursts of lightning activity in the inner core. They typically occur hours before the typhoon reaches its maximum intensity, making them a reliable early signal of intensification. Pan et al. observed that such lightning bursts are particularly pronounced in the eyewall region during rapid intensification [47]. This heightened convective activity indicates intense energy exchange in the inner core and highlights the critical role of the eyewall in typhoon evolution.

Further insights into inner core dynamics were provided by Li et al. in their numerical simulation study of Typhoon Fitow (2013) [48]. Their work revealed the formation of a distinctive tower in the inner core during the storm's mature phase. This tower had a hollow annular structure; the potential vorticity was high around the perimeter. The hollow tower gradually filled in and the typhoon entered a phase of rapid weakening. The evolution of the tower provided critical insights into how structural changes in the inner core can offer early warnings of a shift from intensification to weakening.

Numerical simulations of Typhoon Hagupit (2008) conducted by Chen et al. allowed further analysis of the relationship between eyewall convection in the inner core and changes in typhoon intensity [49]. Simulation results brought to light a clear sequence of events: the intensification of eyewall convection is followed by the strengthening of the warm core, which ends with an overall increase in storm intensity. Notably, the intensification of the upward convection in the eyewall preceded the observable strengthening of the typhoon by more than 2 h. There was no obvious lead–lag relationship between downward convection and typhoon intensification (Figure 4), but there was a general synchrony between changes in the warm core and changes in typhoon intensity. This time lag highlights inner core convection as a precursor to intensity changes. It provides

valuable early signals and additional time for forecasting. Their sensitivity experiments and subsequent studies have demonstrated that this time lag varies significantly between typhoons. Variations are influenced by the structural characteristics of the typhoon, including the size and configuration of the inner core, as well as external environmental conditions such as vertical wind shear and moisture availability. For example, time lags of larger typhoons with broader inner cores may be longer than those of smaller and more compact systems. However, the factors and mechanisms governing these variations remain poorly understood and improved understanding is crucial for advancing our predictions of rapid intensity changes.

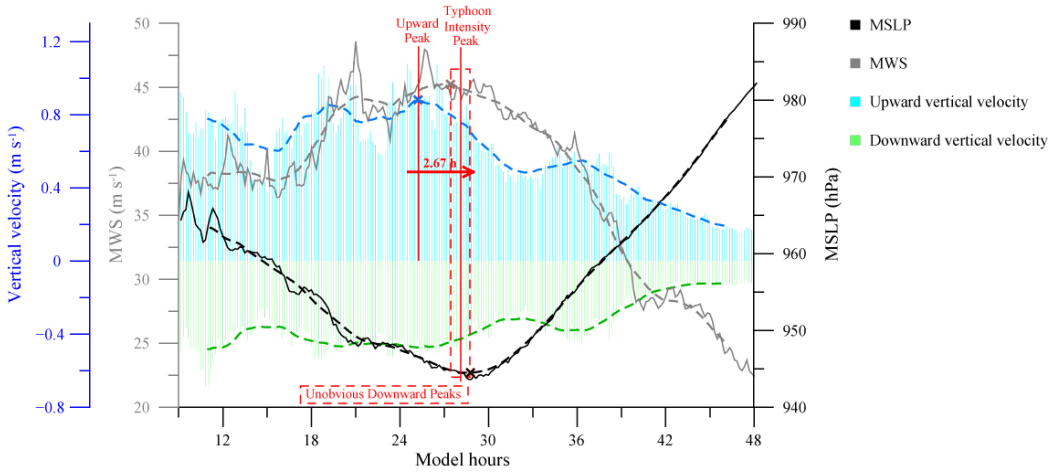


Figure 4. Lead–lag relationships between vertical velocity, inner core temperature, and typhoon intensity. Intensity is indicated by mean sea level pressure (MSLP) (black, unit: hPa) and maximum wind speed (MWS) (gray, unit: m/s). Solid lines indicate model output at 10 min intervals and dashed lines indicate 4 h running means. Solid red bars indicate peak values. Peak typhoon intensity is defined as the midway point between the peaks of MSLP and MWS. Red arrows show the lead (lag) relationships and the corresponding lead (lag) times. Blue and green bars indicate upward and downward vertical velocity, respectively; blue and green dashed lines show 4 h running mean upward and downward velocities, respectively. The figure is adapted from Ref. [49].

In summary, the dynamic evolution of the inner core provides valuable indicators of changes in typhoon intensity, although the timing and mechanisms of these signals can vary between storms. However, several scientific questions remain: (1)what are the physical processes that drive the lead–lag relationship between strong eyewall convection and changes in typhoon intensity? (2) How does the time lag between convection and intensity change vary across typhoons? Using advanced observational and numerical tools to explore these questions will improve our understanding and predictions of typhoon behavior.

4. Eyewall Replacement Cycle in the Inner Core

When typhoon intensity reaches a certain threshold, the outer rainbands often act as a conduit for the transfer of heat and vortex energy toward the center of the storm. This energy transport gradually leads to the development of a secondary eyewall, which has been observed in many strong typhoons [50,51]. The primary and secondary eyewalls are generally concentric. The secondary eyewall is typically on the outside. In typhoons with high levels of intensity and organization, the secondary eyewall results from the energy exchange between the outer rainbands and the inner core. While secondary eyewalls are most often seen in symmetric typhoons, recent studies have shown that they can also develop in asymmetric typhoons under certain conditions [52]. In their numerical experiments, Wang et al. found that secondary eyewalls can form in complex storm structures as well, challenging earlier assumptions and opening new avenues for understanding the development of secondary eyewalls in more realistic, asymmetric storm systems.

The eyewall replacement cycle typically begins once the primary eyewall has reached a certain strength; this indicates that the typhoon has accumulated enough energy to develop a secondary structure. Formation of the secondary eyewall exerts pressure on the primary eyewall; as a result, the intensity of the primary eyewall decreases, and the typhoon weakens temporarily. Once the secondary eyewall reaches a sufficient size and strength, it begins to merge with the primary eyewall, resulting in a potentially substantial increase in storm intensity. The eyewall replacement cycle includes the following crucial sequence of events: a growing secondary eyewall draws energy away from the primary eyewall, overall storm intensity decreases, and the primary and secondary eyewalls eventually merge.

During the cycle, there are three distinct phases of intensity fluctuation: intensification, weakening, and reintensification. Initially, the influx of heat and moisture from the outer rainbands creates the secondary eyewall and increases storm intensity. This intensification period is often short-lived, as the growing secondary eyewall soon begins to weaken the primary eyewall. During the weakening phase, storm intensity decreases as the primary eyewall loses energy to the newly developing eyewall. This phase can last for several hours, during which the storm may appear to lose strength. However, once the two eyewalls merge, the storm rapidly regains strength and reintensifies. The entire eyewall replacement cycle typically lasts around 36 h (Figure 5). The intensification, weakening, and reintensification phases take approximately 9, 16, and 11 h, respectively [32]; but for many typhoons, the cycle can take over 48 h. Variability in the duration of eyewall replacement cycles increases the challenge of intensity forecasting; it can be difficult to predict the exact timing of the reintensification phase or the end of the cycle.

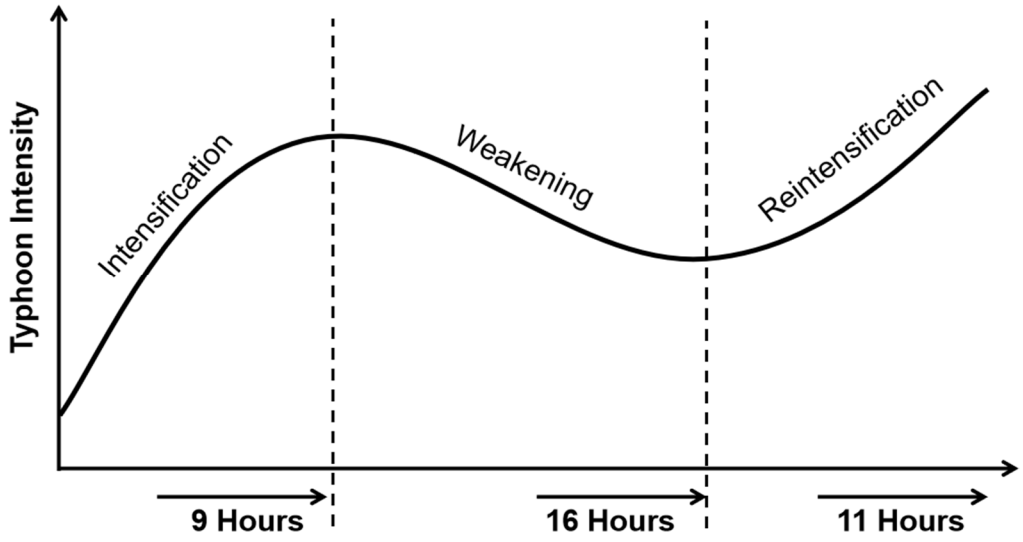


Figure 5. Schematic of maximum intensity evolution during the three phases of an eyewall replacement cycle. The average amount of time to complete each phase is shown for the start and end of the eyewall replacement cycle and for the transitions between phases. The figure is adapted from Ref. [53].

Accurate forecasting of storm intensity at landfall relies on accurate forecasting of the completion of the final phase of the eyewall replacement cycle; the timing of this phase, which includes merging of the primary and secondary eyewalls and rapid intensification, has significant implications for potential storm damage. It determines whether the typhoon will make landfall as a stronger or weaker system. For example, Super Typhoon Usagi (2013) had triple eyewalls, but did not complete the full eyewall replacement cycle before landfall [53]. It weakened gradually over 24 h before landfall in Guangdong. This slow weakening likely spared the coastal communities from more devastating impacts. Had the eyewall replacement cycle been completed in time for landfall, the storm would have intensified rapidly; a much more powerful storm could have led to far greater destruction.

This example highlights the critical importance of accurate forecasts of the completion of the eyewall replacement cycle; the timing of this critical phase influences the strength and impacts of a typhoon at landfall.

Variability in eyewall replacement cycles also underscores the inherent unpredictability of typhoon behavior and the complexity of intensity forecasting. While much has been learned about the processes involved in secondary eyewall formation and eyewall replacement, significant challenges in predicting the timing and outcome of these cycles remain. For instance, while eyewall replacement cycles typically involve a period of weakening followed by reintensification, the specific timing of these phases can vary greatly from one storm to another. Factors such as SST, atmospheric moisture, and wind shear all play important roles in determining how quickly a secondary eyewall can form and how it will interact with the primary eyewall. They can introduce substantial variability in the evolution of the eyewall replacement cycle, making it difficult to make accurate intensity forecasts. Usagi demonstrated the impact of the timing of the different phases of the eyewall replacement cycle on the characteristics of a typhoon at landfall, especially in terms of wind speed, storm surge, and rainfall distribution.

Furthermore, the relationship between eyewall replacement cycle and landfall timing is crucial for emergency management and disaster preparedness. If a typhoon completes its eyewall replacement cycle before landfall, the storm may come ashore with significantly stronger winds and more intense rainfall, which can result in greater damage to infrastructure and more severe impacts on coastal populations. On the other hand, if the eyewall replacement cycle is not complete before landfall, the typhoon may weaken and have potentially lower overall impact. This unpredictability is one of the reasons why forecasting typhoon intensity at landfall remains one of the most challenging aspects of tropical cyclone prediction.

In conclusion, the eyewall replacement cycle is a crucial aspect of typhoon dynamics and has significant implications for forecasts of storm intensity and potential storm impacts. It involves complex interactions between the primary and secondary eyewalls, which cause fluctuations in storm intensity. The timing of the completion of the cycle is a key determinant of intensity at landfall and, consequently, of potential storm damage. As demonstrated by Super Typhoon Usagi, failing to complete the eyewall replacement cycle before landfall can result in a weaker typhoon with less severe impacts, while completing the cycle can lead to a more powerful storm. The key scientific questions are: (1) What conditions favor the merging of the inner and outer eyewalls and the completion of the eyewall replacement cycle? (2) How can we accurately predict the respective timing of eyewall merging, rapid intensification, and landfall? Accurate predictions of the timing of the different phases of the eyewall replacement cycle are, therefore, essential for improving typhoon forecasting and disaster preparedness. Continued research into the dynamics of eyewall replacement will be crucial for improving the accuracy of intensity forecasts in the future.

5. Waves and Oscillations in the Inner Core

In addition to long-period processes, such as eyewall replacement cycles, that shape a typhoon's overall structure, there are also short-period oscillations in the inner core. These rapid, short-period activities are typically associated with storm rotation and the internal dynamics of the eyewall. They are often driven by environmental factors, most notably vertical wind shear. Vertical wind shear can induce asymmetric convective development in the typhoon's cloud systems [54], resulting in a series of periodic fluctuations in the eyewall convection. Storm rotation creates oscillations of convection and intensity reduction, which have a considerable influence on the internal structure and overall intensity of a typhoon over relatively short timescales.

The interaction between storm rotation and surrounding environmental conditions is one of the primary mechanisms responsible for these oscillations. As the typhoon rotates, convection and wind shear vary in different parts of the eyewall. This asymmetry results

in the development and suppression or periodic expansion and contraction of convective activity in the eyewall. These are often referred to as eyewall oscillations. They can have a significant influence on the storm's internal dynamics, including upward mass flux and heat and moisture distribution. Storm intensity can fluctuate in relatively short bursts and can contribute to short-term changes in the overall strength of the typhoon.

Reasor et al. (2009) conducted a detailed analysis of airborne Doppler radar data and found convective burst cycles in the eyewall [55]. Convective bursts, or cycles, are short-period oscillations. As the storm rotates in environmental vertical shear, periodic intensification and weakening occur, with typical periods of approximately 0.6–2 h. These rapid phenomena contribute to the dynamic nature of storm intensity. During a convective burst, eyewall convection intensifies, temporarily increasing the storm's energy output. However, bursts are often followed by the suppression of convection as the storm rotates into a less favorable position relative to the environmental shear. These rapid cycles play an important role in the short-term variability of storm intensity and have been observed across different types of storms.

Using radar data, station measurements, and numerical simulations, Chen et al. and Fang et al. detected eyewall oscillations in several intense typhoons over the western North Pacific. By using the upward mass flux in the eyewall as an indicator of convection strength, they provided additional insights into eyewall oscillations (Figure 6) [56–58]. They analyzed the short-period fluctuations in the upward mass flux and found that upward mass flux was closely related to typhoon intensification rate. Each cycle (or oscillation period) had three stages (or phases). For each cycle, the total mass flux was always highest (lowest) in stage 2 (3); similarly, the maximum (minimum) intensification rate was always in stage 2 (3). The oscillation period was approximately 1.5–5 h, which is slightly longer than that of the convective bursts identified by Reasor et al. The oscillations in Figure 6 are also driven by storm rotation, but they differ from convective bursts in that they involve more complex interactions between the internal dynamics of the typhoon and surrounding environmental parameters, such as wind shear, moisture distribution, and SST. As the typhoon rotates, regions of the eyewall may experience periods of enhanced convection, followed by phases of convection suppression because of unfavorable environmental conditions. This variability in convection leads to periodic changes in intensification rate, resulting in oscillatory fluctuations in storm intensity over several hours.

These short-period oscillations in the eyewall differ from long-period oscillations, such as vortex Rossby waves, that were presented in earlier theoretical studies [59]. While vortex Rossby waves are typically associated with long-period oscillations in the storm's circulation, the eyewall oscillations discussed here involve more rapid, localized fluctuations in convection and wind. Eyewall oscillations are driven by the more immediate and localized interactions between the internal dynamics of the typhoon and the surrounding environment. Unlike more traditional wave phenomena like vortex Rossby waves, the integral of the oscillatory variables, such as vertical wind speed in the eyewall, around the typhoon center is non-zero. Instead, eyewall oscillations fluctuate over time, leading to variations in typhoon intensification rate. As a result, the eyewall convection does not simply oscillate symmetrically but has complex, time-dependent variations that can influence the overall structure and intensity of the typhoon over shorter timescales.

The rotation period of a typhoon is relatively stable. It establishes a predictable timeframe for eyewall oscillations. As the storm rotates, there are periodic changes in convection in different parts of the eyewall, leading to increases or reductions in storm intensity. Understanding these oscillations is crucial for improving the accuracy of intensity forecasting, particularly for short-term variations in intensity. The impact of these oscillations is not only evident in the convection itself but also in the storm's overall mass flux, wind speed, and vertical structure. These short-period intensity fluctuations can significantly influence the prediction of typhoon behavior, especially as storms approach landfall or interact with other weather systems.

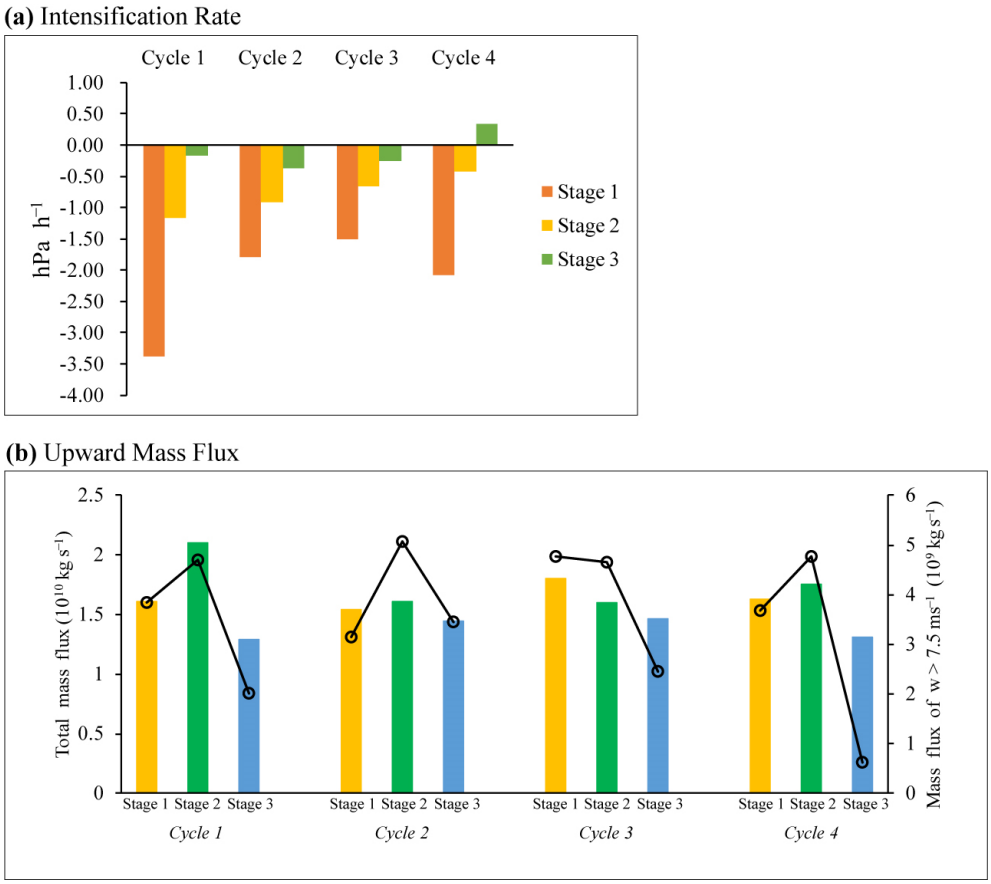


Figure 6. (**a**) Typhoon intensification rate and (**b**) total mass fluxes at a height of 12.7 km in the eyewall (bars) and mass fluxes as a result of vertical velocity (w) > 7.4 m s^{-1} (lines) for each of the three stages across four cycles. A cycle refers to one oscillation period, and each stage corresponds to a different phase within the same cycle. Each stage lasts for approximately 0.5–1.5 h. The figure is adapted from Ref. [58].

In practice, understanding the dynamics of eyewall oscillations is crucial for improving typhoon forecasting models. Since typhoon rotation is relatively stable, the periodicity of eyewall oscillations provides an opportunity to refine intensity predictions over short timescales. By incorporating observations of convection cycles, vertical wind shear, and other relevant environmental factors into forecasting models, the accuracy of short-term intensity predictions can be improved. This is particularly important when predicting rapid fluctuations in storm intensity, which can have significant impacts on coastal communities in the hours leading up to landfall. Furthermore, these oscillations contribute to both the intensification and weakening phases of a typhoon. Short- and long-term forecasting and storm prediction will advance with improved understanding of the role of eyewall oscillations in typhoon intensification and structure.

In summary, eyewall oscillations are a critical aspect of typhoon dynamics. They drive short-term fluctuations in storm intensity. They are caused by the interaction between storm rotation and the surrounding environment. They result in periodic changes in convection, mass flux, and wind in the eyewall. Understanding the periodicity and underlying mechanisms of these oscillations is essential for improving typhoon intensity forecasts, particularly in the context of short-term intensity variations. The key scientific questions are: (1) What are the differences and relationships between the various waves and oscillations in the eyewall? (2) What causes these fluctuations, and how do they influence typhoon intensity variations? Continued research into these phenomena, leveraging high-resolution radar data and numerical simulations, will be crucial for enhancing

our understanding of the high-speed dynamics in the inner core and refining forecasting techniques for tropical cyclones.

6. Precipitation and Strong Winds in the Inner Core

Heavy precipitation and strong winds are hallmarks of the inner core. They are closely linked to the dynamics of this central region of the storm. Convection is intense in the inner core. It plays a pivotal role in the development of typhoons. Strong convective activity in the eyewall is often associated with the formation of heavy rainfall and powerful winds, both of which are major contributors to the damage caused by typhoons [56]. Because the interactions between convection, precipitation, and wind in the inner core determine the overall typhoon intensity and impact, they are a key focus in meteorological research. Extremely heavy rainfall can occur at landfall. A single storm can bring 300–500 mm of precipitation. Precipitation is reduced by frictional convergence and topographical features. However, Guangdong is relatively flat, and a single typhoon can bring more than 1000 mm of precipitation in extreme cases [60]. Such extreme rainfall can lead to catastrophic flooding, landslides, and significant disruption to infrastructure, agriculture, and communities.

In addition to heavy rainfall, the strong winds in the inner core of a typhoon can have devastating impacts. Wind speeds are typically highest in the eyewall, where the most intense convective bands are located. As the typhoon intensifies over time, its wind field becomes increasingly asymmetric because of both environmental and internal factors. This asymmetry can amplify wind speeds in certain regions of the storm; the strongest winds are often found in the right-front quadrant. Wind speed and the direction of the storm track are key factors determining the severity of the impact of the storm at landfall. South China is particularly vulnerable to strong winds. It has many coastal communities and typhoons frequently traverse the nearby South China Sea. Winds exceeding 100 km/h in the inner core can cause severe damage to buildings, infrastructure, and vegetation, and pose significant risks to human safety.

In terms of typhoon landfalls in South China, research has shown that the topography of the area where landfall occurs, such as mountainous or coastal features, has little to no impact on the overall precipitation structure of most typhoons [61]. In other regions, mountainous terrain can enhance precipitation by forcing moist air upwards and triggering orographic rainfall. In South China, topographical features have little effect on the precipitation patterns of typhoons. This suggests that other atmospheric and oceanic processes, such as the availability of high SST and atmospheric moisture, are dominant determinants of rainfall distribution.

The wind field in the inner core of typhoons over the South China Sea is strongly asymmetric [62]. Using multi-mission satellite data and drifting buoy data, Fan et al. examined the wind field structure of typhoons in this region. They found notable asymmetries that influenced the overall wind distribution and intensity in the affected areas [63]. Similarly, in their analysis of wind profiler data, Zhou et al. found that the effects of underlying surface factors on typhoon wind field structure varied across the northern South China Sea [64]. These findings underscore that the wind field structure of a typhoon is influenced by a combination of variable factors, including storm size and intensity and surrounding environmental conditions. As a result, the wind field in the inner core can vary significantly with regional factors, making accurate forecasting of wind intensity and direction a challenge.

Despite significant progress in understanding the dynamics of precipitation and strong winds in the inner core, much of current research remains limited in scope. The patterns and mechanisms linking these core processes, precipitation, and wind distribution are still not fully understood. Further research to explore these complex interactions is essential in order to enhance our ability to predict typhoon behavior. A deeper understanding of the influence of inner core dynamics on precipitation and wind fields will be critical for improving typhoon forecasts. This, in turn, will strengthen preparedness and response

efforts in regions that are vulnerable to typhoons. With more comprehensive data and refined models, it will be possible to predict the impact of typhoons with greater accuracy, ultimately reducing risk to human life and property.

7. Summary and Perspective

In summary, the inner core of a typhoon plays a crucial role in storm intensification and is especially critical for rapid increases in storm intensity. Inside a typhoon, most of the energy exchange occurs in the inner core, including the eyewall. Moist air rising from the warm ocean releases latent heat, which increases the temperature in the mid-levels of the atmosphere. As the wind speeds increase, the secondary circulations, such as inward flow and upward motion, help sustain the warm-core structure. Forecasters can use the organized convection near the eyewall as early signals of rapid intensification. External factors, such as vertical wind shear and ocean heat content, can influence inner core dynamics.

The number of studies focusing on the structure of the inner core remains limited. Despite significant progress in our understanding, the main mechanisms of different processes remain unclear. Key scientific questions that still need to be addressed include:

1. Time lag between convection and intensity changes: what are the physical processes that drive the lead–lag relationship between strong eyewall convection and changes in typhoon intensity? How does the time lag between convection and intensity change vary across typhoons?
2. Eyewall replacement cycle and rapid intensification: what conditions favor the merging of the inner and outer eyewalls and completion of the eyewall replacement cycle? How can we accurately predict the respective timing of eyewall merging, rapid intensification, and landfall?
3. Waves and oscillations in the eyewall: what are the differences and relationships between the various waves and oscillations in the eyewall? What causes these fluctuations, and how do they influence typhoon intensity variations?

Our recommendations for future research include: further development of ocean and atmospheric observation networks, integrated platforms, and dual-polarization radar and satellite technologies; numerical simulation studies will also enhance our ability to understand the inner core structure of typhoons. These advances will contribute toward improving our understanding and enhancing our ability to forecast typhoon intensification.

Author Contributions: Conceptualization, S.C. and W.L.; investigation, S.C.; writing—original draft preparation, S.C.; writing—review and editing, W.L.; supervision, S.C.; project administration, S.C.; funding acquisition, W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Guangdong Major Project of Basic and Applied Basic Research, grant number 2020B0301030004, the Innovation Group Project of Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), grant number 311022006, and the project supported by Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), grant number SML2023SP212.

Data Availability Statement: Shanghai Typhoon Institute of China Meteorological Administration [4]. Available online: http://tcdata.typhoon.org.cn (accessed on 11 December 2024).

Acknowledgments: We thank Tina Tin for editing the English text of a draft of this manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Lin, C.H.; Hou, S.K.; Shih, F.F.Y.; Su, S. The effect of tropical cyclones (typhoons) on emergency department visits. *J. Emerg. Med.* **2013**, *45*, 372–379. [CrossRef] [PubMed]
2. Spiridonov, V.; Ćurić, M. Tropical storms. In *Fundamentals of Meteorology*; Springer: Cham, Switzerland, 2021. [CrossRef]
3. Lin, N.; Smith, J.A.; Villarini, G.; Marchok, T.P.; Baeck, M.L. Modeling extreme rainfall, winds, and surge from Hurricane Isabel (2003). *Weather Forecast.* **2010**, *25*, 1342–1361. [CrossRef]

4. Ying, M.; Zhang, W.; Yu, H.; Lu, X.; Feng, J.; Fan, Y.; Zhu, Y.; Chen, D.J. An overview of the China Meteorological Administration tropical cyclone database. *J. Atmos. Ocean. Technol.* **2014**, *31*, 287–301. [CrossRef]
5. Chan, J.C.L.; Gray, W.M. Tropical cyclone movement and surrounding flow relationships. *Mon. Weather Rev.* **1982**, *110*, 1354–1374. [CrossRef]
6. Heming, J.T.; Prates, F.; Bender, M.A.; Bowyer, R.; Cangialosi, J.; Caroff, P.; Coleman, T.; Doyle, J.D.; Dube, A.; Faure, G.; et al. Review of recent progress in tropical cyclone track forecasting and expression of uncertainties. *Trop. Cyclone Res. Rev.* **2019**, *8*, 181–218. [CrossRef]
7. Leroux, M.-D.; Wood, K.; Elsberry, R.L.; Cayanan, E.O.; Hendricks, E.; Kucas, M.; Otto, P.; Rogers, R.; Sampson, B.; Yu, Z. Recent advances in research and forecasting of tropical cyclone track, intensity, and structure at landfall. *Trop. Cyclone Res. Rev.* **2018**, *7*, 85–105. [CrossRef]
8. Chen, X.; Wang, Y.; Fang, J.; Xue, M. A numerical study on rapid intensification of Typhoon Vicente (2012) in the South China Sea. Part II: Roles of inner-core processes. *J. Atmos. Sci.* **2018**, *75*, 235–255. [CrossRef]
9. Xu, Y.; Wu, R. The conservation of helicity in hurricane Andrew (1992) and the formation of the spiral rainband. *Adv. Atmos. Sci.* **2003**, *20*, 940–950.
10. Stevenson, S.; Corbosiero, K.; Demaria, M.; Vigh, J. A 10-Year Survey of Tropical Cyclone Inner-Core Lightning Bursts and Their Relationship to Intensity Change. *Weather Forecast.* **2018**, *33*, 23–36.10. [CrossRef]
11. Jiang, H. The Relationship between Tropical Cyclone Intensity Change and the Strength of Inner-Core Convection. *Mon. Weather Rev.* **2012**, *140*, 1164–1176. [CrossRef]
12. Charney, J.G.; Eliassen, A. On the growth of the hurricane depression. *J. Atmos. Sci.* **1964**, *21*, 68–75. [CrossRef]
13. Emanuel, K.A. An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *J. Atmos. Sci.* **1986**, *43*, 585–605. [CrossRef]
14. Huang, Y.; Duan, Y.; Chan, J.C.L.; Bao, X. A method for diagnosing the secondary circulation with saturated moist entropy structure in a mature tropical cyclone. *Adv. Atmos. Sci.* **2019**, *36*, 804–810. [CrossRef]
15. Xiao, Z.; Cai, Y.; Luo, X.; Sun, H. A Comparative Study on the Offshore Intensification of Supertyphoon Rammasun (2014) and Typhoon Rumbia (2013): The Role of Summer Monsoon. *Asia-Pac. J. Atmos. Sci.* **2021**, *57*, 405–420. [CrossRef]
16. Wu, Y.; Chen, S.; Li, W.; Fang, R.; Liu, H. Relative vorticity is the major environmental factor controlling tropical cyclone intensification over the Western North Pacific. *Atmos. Res.* **2020**, *237*, 104874. [CrossRef]
17. Fischer, M.S.; Rogers, R.F.; Reasor, P.D. The rapid intensification and eyewall replacement cycles of Hurricane Irma (2017). *Mon. Weather Rev.* **2020**, *148*, 981–1004. [CrossRef]
18. Montgomery, M.T.; Kallenbach, R.J. A theory for vortex Rossby waves and its application to spiral bands and intensity changes in hurricanes. *Q. J. R. Meteorol. Soc.* **1997**, *123*, 435–465. [CrossRef]
19. Zhang, Y.; Zhang, H.; Tang, X.; Yang, S.; Wang, Y.; Lin, X.; Tian, D.; Chen, D. Oceanic response to tropical cyclone in the northern South China Sea observed by underwater gliders during 2018 and 2020. *Deep. Sea Res. Part I Oceanogr. Res. Pap.* **2024**, *213*, 104387. [CrossRef]
20. Wang, G.; Su, J.; Ding, Y.; Chen, D. Tropical cyclone genesis over the South China Sea. *J. Mar. Syst.* **2007**, *68*, 318–326. [CrossRef]
21. Zhang, X.; Wei, N.; Wang, Q. Influence of radiation diurnal variation on the rapid intensification process of super Typhoon Rammasun (1409) in the South China Sea. *Front. Earth Sci.* **2022**, *10*, 940418. [CrossRef]
22. Ueno, M. Observational analysis and numerical evaluation of the effects of vertical wind shear on the rainfall asymmetry in the typhoon inner-core region. *J. Meteorol. Soc. Jpn. Ser. II* **2007**, *85*, 115–136. [CrossRef]
23. Wang, H.; Wang, Y.; Xu, H. Improving simulation of a tropical cyclone using dynamical initialization and large-scale spectral nudging: A case study of Typhoon Megi (2010). *Acta Meteorol. Sin.* **2013**, *27*, 455–475. [CrossRef]
24. Guichard, F.; Couvreux, F. A short review of numerical cloud-resolving models. *Tellus A Dyn. Meteorol. Oceanogr.* **2017**, *69*, 1. [CrossRef]
25. Callaghan, J. Asymmetric inner core convection leading to tropical cyclone intensification. *Trop. Cyclone Res. Rev.* **2017**, *6*, 55–66. [CrossRef]
26. Li, X. Analytic Solutions of Dynamic Model and Dynamic Mechanism of the Formation and Maintenance of Typhoon (Part I). *J. Trop. Meteorol.* **1987**, *3*, 266–273. (In Chinese)
27. Wang, D.; Lin, Y. Potential role of irreversible moist processes in modulating tropical cyclone surface wind structure. *J. Atmos. Sci.* **2020**, *21*, 709–725. [CrossRef]
28. Qin, X.; Duan, W.; Xu, H. Sensitivity to tendency perturbations of tropical cyclone short-range intensity forecasts generated by WRF. *Adv. Atmos. Sci.* **2020**, *37*, 291–306. [CrossRef]
29. Zhang, D.; Zhu, L.; Zhang, X.; Tallapragada, V. Sensitivity of Idealized Hurricane Intensity and Structures under Varying Background Flows and Initial Vortex Intensities to Different Vertical Resolutions in HWRF. *Mon. Weather Rev.* **2015**, *143*, 914–932. [CrossRef]
30. Qu, Y.; Qu, B.; Chen, B.H.; Ming, J.; Lynn, B.H.; Yang, M.-J. Aerosol impacts on the structure, intensity, and precipitation of the landfalling Typhoon Saomai (2006). *J. Geophys. Res. Atmos.* **2017**, *122*, 11825–11842. [CrossRef]
31. Yu, Z.; Wang, Y.; Xu, H.; Davidson, N.; Chen, Y.; Chen, Y.; Yu, H. On the relationship between intensity and rainfall distribution in tropical cyclones making landfall over China. *J. Appl. Meteorol. Climatol.* **2017**, *56*, 2883–2901. [CrossRef]

32. Sitkowski, M.; Kossin, J.P.; Rozoff, C.M. Intensity and structure changes during hurricane eyewall replacement cycles. *Mon. Weather Rev.* **2011**, *139*, 3829–3847. [CrossRef]
33. Chen, L.; Meng, Z.; Cong, C. An overview on the research of typhoon rainfall distribution. *J. Mar. Meteorol.* **2017**, *37*, 1–7. (In Chinese) [CrossRef]
34. Choi, H.Y.; Park, M.S.; Kim, H.S.; Lee, S. Marine heatwave events strengthen the intensity of tropical cyclones. *Commun. Earth Environ.* **2024**, *5*, 69. [CrossRef]
35. Nadimpalli, R.; Mohanty, S.; Pathak, N.; Osuri, K.K.; Mohanty, U.C.; Chatterjee, S. Understanding the characteristics of rapid intensity changes of tropical cyclones over North Indian Ocean. *SN Appl. Sci.* **2021**, *3*, 68. [CrossRef]
36. Yue, C.; Cao, Y.; Gu, W.; Tan, J.; Li, X. Study on the genesis of asymmetrical distribution characteristics of precipitation associated with the typhoon Haitang (2005) from the view of atmospheric factor. *J. Trop. Meteorol.* **2016**, *22*, 265–276. [CrossRef]
37. Bi, X.; Chen, G.; Zhou, W.; Shen, X.; Cao, X. Research in long-term tendency of tropical cyclone position reaching different intensities over the Western North Pacific. *Clim. Chang. Res.* **2017**, *13*, 31–40. (In Chinese) [CrossRef]
38. Oyama, R.; Wada, A. The relationship between convective bursts and warm-core intensification in a nonhydrostatic simulation of Typhoon Lionrock (2016). *Mon. Weather Rev.* **2019**, *147*, 1557–1579. [CrossRef]
39. Shi, D.; Chen, G. Modulation of asymmetric inner-core convection on midlevel ventilation leading up to the rapid intensification of Typhoon Lekima (2019). *J. Geophys. Res. Atmos.* **2023**, *128*, e2022JD037952. [CrossRef]
40. Zhao, H.; Chen, S.; Raga, G.B.; Klotzbach, P.J.; Wu, L. Recent decrease in genesis productivity of tropical cloud clusters over the Western North Pacific. *Clim. Dyn.* **2019**, *52*, 5819–5831. [CrossRef]
41. Zhao, J.; Zhan, R.; Wang, Y. Global warming hiatus contributed to the increased occurrence of intense tropical cyclones in the coastal regions along East Asia. *Sci. Rep.* **2018**, *8*, 6023. [CrossRef]
42. Feng, Q.; Zhang, Q. Statistics of environmental vertical wind shear and water vapor field on the change of tropical cyclone structure in northwest Pacific Ocean from 2001 to 2014. *Acta Sci. Nat. Univ. Pekin.* **2018**, *54*, 713–720. (In Chinese) [CrossRef]
43. Shi, H.; Yu, J.; Wang, C.; Qiu, J. Influence of boreal summer intraseasonal oscillation on tropical cyclone heavy rain in southeastern coast China. *J. Meteorol. Sci.* **2018**, *38*, 11–18. (In Chinese) [CrossRef]
44. Bian, J.; Fang, J.; Chen, G.; Liu, C. Circulation features associated with the record-breaking Typhoon Silence in August 2014. *Adv. Atmos. Sci.* **2018**, *35*, 1321–1336. [CrossRef]
45. Wang, M.; Xue, M.; Zhao, K. An investigation on how inner-core structures obtained through radar data assimilation affect track forecasting of Typhoon Jangmi (2008) near Taiwan Island. *J. Geophys. Res. Atmos.* **2016**, *121*, 10601–10616. [CrossRef]
46. Zhang, X.; Tang, J.; Wu, C.; Wu, D. An observational study of the inner core structure of Typhoon Meranti (2016) near landfall. *Atmos. Sci. Lett.* **2020**, *21*, e962. [CrossRef]
47. Pan, L.X.; Qie, X.S.; Liu, D.X.; Wang, D.F.; Yang, J. The lightning activities in super typhoons over the Northwest Pacific. *Sci. China Earth Sci.* **2010**, *40*, 252–260. (In Chinese) [CrossRef]
48. Li, Q.H.; Lu, H.C.; Huang, X.G.; Zhong, W.; Liu, J.W.; Shi, W.L. Diagnosis on the characteristics of the mesoscale inner core potential vorticity in intensity maintaining typhoons. *Chin. J. Geophys.* **2019**, *62*, 2821–2834. (In Chinese) [CrossRef]
49. Chen, S.; Li, W.; Wen, Z.; Lu, Y.; Zhou, M.; Qian, Y.-K.; Chen, G. Vertical motions prior to the intensification of simulated Typhoon Hagupit (2008). *J. Geophys. Res. Oceans* **2019**, *124*, 577–592. [CrossRef]
50. Guan, L.; Ge, X. How does tropical cyclone size affect the onset timing of secondary eyewall formation? *J. Meteorol. Res.* **2018**, *32*, 124–134. [CrossRef]
51. Qiu, X.; Tan, Z.-M. The roles of asymmetric inflow forcing induced by outer rainbands in tropical cyclone secondary eyewall formation. *J. Atmos. Sci.* **2013**, *70*, 953–974. [CrossRef]
52. Wang, H.; Wang, Y.; Xu, J.; Duan, Y. The axisymmetric and asymmetric aspects of the secondary eyewall formation in a numerically simulated tropical cyclone under idealized conditions on an f plane. *J. Atmos. Sci.* **2019**, *76*, 357–378. [CrossRef]
53. Zhao, K.; Lin, Q.; Lee, W.-C.; Sun, Y.Q.; Zhang, F. Doppler radar analysis of triple eyewalls in Typhoon Usagi (2013). *Bull. Am. Meteorol. Soc.* **2016**, *97*, 25–30. [CrossRef]
54. Shu, S.; Xu, Y.; Song, J.; Yu, Z. An observational study on distribution of precipitation associated with landfalling tropical cyclones affecting China. *J. Trop. Meteorol.* **2012**, *18*, 275–283. [CrossRef]
55. Reasor, P.D.; Eastin, M.D.; Gamache, J.F. Rapidly intensifying Hurricane Guillermo (1997). Part I: Low-wavenumber structure and evolution. *Mon. Weather Rev.* **2009**, *137*, 603–631. [CrossRef]
56. Chen, S.; Lu, Y.; Li, W.; Wen, Z. Identification and analysis of high-frequency oscillations in the eyewalls of tropical cyclones. *Adv. Atmos. Sci.* **2015**, *32*, 624–634. [CrossRef]
57. Chen, S.; Li, W.; Wen, Z.; Zhou, M.; Lu, Y.; Qian, Y.-K.; Liu, H.; Fang, R. Variations in high frequency oscillations of tropical cyclones over the western North Pacific. *Adv. Atmos. Sci.* **2018**, *35*, 423–434. [CrossRef]
58. Fang, R.; Chen, S.; Zhou, M.; Li, W.; Xiao, H.; Zhan, T.; Wu, Y.; Liu, H.; Tu, C. Periodic cycles of eyewall convection limit the rapid intensification of Typhoon Hato (2017). *Adv. Meteorol.* **2021**, *d22*, 1–18. [CrossRef]
59. Lin, Y.; Li, Y.; Li, Q.; Chen, M.; Xu, F.; Wang, Y.; Huang, B. A long-lasting vortex Rossby wave–induced rainband of Typhoon Longwang (2005). *Bull. Am. Meteorol. Soc.* **2018**, *99*, 1127–1134. [CrossRef]
60. Liu, Y.-J.; Yan, J.-Y.; Song, Y.-L. Features of climate change over the Xishan Island in the South China Sea in the recent 50 years. *Sci. Geogr. Sin.* **2008**, *28*, 804–810. (In Chinese) [CrossRef]

61. Wen, G.; Huang, G.; Huang, H.; Liu, C.; Bi, X. Observed rainfall asymmetry of tropical cyclone in the process of making landfall in Guangdong, South China. *Int. J. Climatol.* **2019**, *39*, 3379–3395. [CrossRef]
62. Abbas, S.; Nichol, J.E.; Fischer, G.A.; Wong, M.S.; Irteza, S.M. Impact assessment of a super-typhoon on Hong Kong's secondary vegetation and recommendations for restoration of resilience in the forest succession. *Agric. For. Meteorol.* **2020**, *280*, 107784. [CrossRef]
63. Fan, S.; Zhang, B.; Perrie, W.; Mouche, A.; Liu, G.; Li, H.; Wang, C.; He, Y. Observed ocean surface winds and mixed layer currents under tropical cyclones: Asymmetric characteristics. *J. Geophys. Res. Ocean.* **2022**, *127*, e2021JC017991. [CrossRef]
64. Zhou, X.; Liang, J.; Huang, J.; Liao, F. A study on wind structure of Typhoon Goni and Koppu during landing. *J. Trop. Meteorol.* **2012**, *28*, 809–818. (In Chinese)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.