

Numerical study on the evolution of tropical cyclone size: Sensitivity to the radial distribution of latent heating

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Sensitivity to the radial distribution of latent heating

辻 宏樹

Abstract

The size of tropical cyclones (TCs) is one of their most important characteristics along with intensity. However, far fewer studies have examined TC size than have considered the intensity, genesis and development of TCs and the mechanism of TC size change has not been understood yet.

In this study, to clarify the mechanism governing the size change of tropical cyclones (TCs), we firstly perform idealized numerical experiments using the primitive equation system on an f -plane to understand the correspondence between the thermal forcing mimicking cumulus heating and the size change of TC-like vortices. We investigate the sensitivity of vortex size change to the location of forcing, strength of forcing, scales of forcing, and the structure of initial vortex. Additionally, we also examine the vortex size change when forcing is applied to two regions. Then, based on the results obtained from the idealized experiments, we examined the relationship between TC size change and precipitation distribution by using satellite observation data. The vortex size is defined as the radius of 15 m s^{-1} wind speed (R15). R15 is calculated by using the wind speed at the model lowest level in the idealized experiments and the wind speed over the ocean surface obtained from microwave scatterometer on QuikSCAT satellite in the analyses of satellite observation data. We use precipitation data obtained by Tropical Rainfall Measuring Mission Microwave Imager (TRMM/TMI) and Global Satellite Mapping of Precipitation (GSMaP) data.

From the results of the idealized experiments, we found that the vortex size change depends on the location and strength of forcing but does not depends on the scales of forcing. The size change of vortices is small when the forcing is applied near the center of vortices, whereas the vortex grows in size when the forcing is located at the outer part of vortices but still inside R15, and the vortex size decreases when the forcing is applied to the outside of R15. The vortex size becomes larger as the forcing is stronger. Moreover, in most of the results of experiments in which forcing is applied to two regions, we found that the size change of vortices can be understood by the sum of the contribution of

the effects of each forcing on the size change of vortices. However, when the outer of the two forcings is applied just outside R15, the change rate of R15 varies in the latter period of integration if the forcing applied outside R15 is located near the initial R15. In this case, the outer forcing contributes to the increase of R15 even if the forcing is located outside R15. We also found that the structure of initial vortices affects the size change of vortices. The initial vortex with small radial gradient of tangential wind becomes larger than that with large radial gradient of tangential wind for the same forcing.

The temporal evolution of tangential wind and radial advection of absolute angular momentum (AAM) at R15 contribute to the change of vortex size defined by R15. The former is mainly controlled by the radial advection of AAM at R15. Therefore, the results of the idealized experiments by using the same initial vortex are explained by considering the radial transport of AAM at R15 by the heat-induced secondary circulation (SC). The amount of the radial advection of AAM at R15 is related to the location and strength of forcing. When the forcing is applied near the center of the vortex, the horizontal extent of the heat-induced SC becomes narrow and the inflow near R15 does not strengthen due to the large inertial stability in the forcing region. Therefore, the radial advection of AAM becomes small and the vortex size hardly changes. When the forcing is located at the outer part of vortices but still inside R15, the horizontal extent of the heat-induced SC becomes wide and the inflow near R15 becomes strong due to the small inertial stability in the forcing region. Therefore, the radial advection of AAM becomes large and the vortex size grows in size. When the forcing is applied to the outside of R15, the radial advection of AAM becomes negative because the direction of the heat-induced SC at R15 is outward. Therefore, the vortex size decreases. When the forcing location is fixed, the vortex size becomes larger in proportion to the strength of forcing because the heat-induced radial flow at the lower level is proportional to the strength of forcing. In contrast, when the amount of forcing is the same, the change of the vortex size does not depend on the scales of forcing. Because there are an approximately linear relationship between the amount of forcing and the strength of heat-induced SC at R15, the change of vortex size in the experiments in which forcing is applied to two

regions can be understood by the sum of the contribution of each effect of forcing to the size change of vortices when the radial gradient of AAM does not change. However, in the experiments in which forcing is applied to the inside and outside of R15 and the outer forcing is located near the initial R15, vortex size becomes larger than the sum of the increase of each forcing because the increase rate of tangential wind increases by the contribution of asymmetric component of the radial advection of AAM in the latter period of integration. The change of R15 is related to the radial advection of AAM through the radial gradient of tangential wind speed. Therefore, if the amount of the radial advection of AAM is the same, the vortex having smaller gradient of tangential wind becomes larger than that having larger gradient of tangential wind due to the large efficiency of increasing R15.

From the results of the analyses of satellite observation data, we found that there are differences between the precipitation distribution in size increase period and that in size stationary period of TCs. It is consistent with the results of the idealized experiments, i.e., the precipitation in the size increase period is greater than that in the size stationary period at the location far from the center inside R15. The precipitation in the size increase period is also greater than that in the size stationary period at the outside of R15, which is seemingly inconsistent with the results of the idealized experiments that vortex size decreases when the forcing is applied outside R15. This can be explained by considering the results of the idealized experiments in which forcing is applied to two regions, which indicate that the effects of the inner forcing on the increase in size of vortices are larger than those of the outer forcing on the decrease in size of vortices and the forcing located at just outside R15 contributes to the increase of R15 when the forcing is applied to the inside and outside R15. We also found that this relationship between TC size change and precipitation distribution does not depend on the TC intensity and intensity change of TCs.

The results of this study shown above have a possibility to clarify the relationship between the structure change of TCs including TC size change and TC intensity change and precipitation distribution by considering the discussion of many previous studies which investigated the effects of the structure of TC near the center on precipitation distribution.

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Chapter 1

General Introduction

1 Size of tropical cyclones and its importance

Tropical cyclones (TCs) are interesting phenomena in meteorology and various studies about TCs have been performed for a long time. Moreover, TCs have a significant social impact because TCs cause human and social damage by heavy rain, high winds, storm surge, and storm waves. The damage by TCs is closely related to the maximum wind speed and horizontal extent of TCs. Therefore, the structure change of TCs is a significant subject.

According to Merrill (1984), the structure change of TCs can largely occur in three different modes: intensity, which is indicated by the extreme value of some meteorological variable in a TC, strength, which is indicated by the average wind speed in the cyclone circulation, and size, which is indicated by the areal extent of a cyclone circulation. Among these modes, it is known that the correlation between strength and size is high (the correlation coefficient 0.9, Chan and Chan 2012). Therefore, we do not discuss the strength of TCs in the following.

The intensity of TCs is defined by the maximum sustained wind speed or the minimum sea level pressure. Research on TC intensity has studied most frequently in the subject of TC research as the mechanism about TC intensity has been studied since the 1960s (e.g., Ooyama 1964). In the aspect of disaster prevention, TC intensity is important because the damage by high winds, storm surge, and

storm waves is larger as TCs are intensified more.

In contrast, the size of TCs is defined by the radius of a certain surface wind speed or the average radius of the outer closed isobar. Many studies have shown that the correlation between size and intensity is very weak (e.g., Merrill 1984). However, far fewer studies have been examined for TC size than have been considered about the intensity of TCs. In particular, studies about the mechanism of the size change of TCs lag far behind that of the intensity of TCs. In the aspect of disaster prevention, TC size is important because larger TC size causes larger damage by increasing the duration of heavy rainfall and high winds, and total amount of precipitation. Moreover, Irish et al. (2008) showed that in the TCs having a certain intensity, at most 30% of the variation of storm surge is explained by TC size.

As described above, the size of TCs is one of their most important characteristics aside from intensity and one of the primary subjects in TC research. The goal of this study is to clarify the mechanism governing the size change of TCs.

2 Definition of TC size

Before discussing the size change of TCs, we firstly consider the definition of TC size. Traditionally, there have been two definitions of TC size. One is the radius of a certain wind speed, which is an index of the extent of high wind regions. The radius of gale force wind (over 15 or 17 m s⁻¹, R15 or R17) is often used. TC size defined by the radius of a certain wind speed has been used not only in many studies about TC size (e.g., Lee et al. 2010; Chan and Chan 2012), but also in the besttrack data produced by Japan Meteorological Agency. The other is the average radius of the outer closed isobar, which is an index of distinguishing between TC and environment. There are some other similar definitions such as the radius where the mean tangential wind at 850 hPa is 5 kt (R5) used in Knaff et al. (2014) as the radius where the circulation of TCs cannot be distinguished by the climatological background flow, the radius of vanishing wind (R0) used in Dean et al. (2009) and Chavas and Emanuel (2010) as the radius where surface wind disturbance related to storm is vanished, and the

mean radius at which the relative vorticity decreases to $1 \times 10^{-5} \text{ s}^{-1}$ from the center used in Liu and Chan (1999, 2002) as the boundary of the cyclone circulation.

These two types of definitions are closely related. Merrill (1984) showed that larger TCs defined by the average radius of the outer closed isobar have stronger tangential wind to a far distance. This result indicates that the average radius of the outer closed isobar is related to the radius of a certain wind speed. Furthermore, R0 or R5 mentioned above are actually diagnosed using radius of gale force winds. For example, R0 used in Dean et al. (2009) and Chavas and Emanuel (2010) is estimated by using the outer wind structure model produced by Emanuel (2004) and the radius of 34 kt winds (R34, which is almost the same as R17) included in the dataset of Demuth et al. (2006) and Kossin et al. (2007) in Dean et al. (2009), and the radius of 12 m s^{-1} wind speed (R12) calculated by using satellite observation data obtained from QuikSCAT in Chavas and Emanuel (2010), respectively. Thus, R0 is a function of R34 or R12. R5 used in Knaff et al. (2014) is estimated by using the climatological mean value of R5 calculated by using tangential wind speed at 850 hPa at 500 km from the center obtained from infrared satellite information by using the regression equation of the Statistical Hurricane Intensity Predictions Scheme and Global Forecast Model -based model analyses, and the climatological mean values of tangential wind at 500 km and 1000 km. R5 and R34 can be associated by a regression equation which is a function of the maximum wind speed and the root mean square errors, and mean absolute errors of the regression equation are 74 km and 55 km, respectively (Knaff et al. 2014). According to Knaff et al. (2014), these errors are almost the same as those in the previous studies, which indicates that R5 is related to R34. Liu and Chan (1999) calculated the horizontal distribution of vorticity by using wind data observed by microwave scatterometer on satellites and defined TC size as the mean radius at which the relative vorticity decreases to $1 \times 10^{-5} \text{ s}^{-1}$ from the center. They also calculated R15 by using the same data and showed that the TC size defined by using vorticity is closely related to R15 (correlation coefficient 0.82). This indicates that the TC size defined by using vorticity corresponds to R15. As described above, the definitions of TC size, which distinguish TC from environment, are related to the radius of a certain wind speed.

Therefore, the physically meaningful size change of TCs can be considered by using either definition.

In this study, TC size is defined by R15. There are the following two reasons. The first is that R15 can be calculated easily and without obscuration in both modeling study and analyses of observation data. The second is that as mentioned previously, TC size defined by R15 is highly related to that defined by vorticity as shown in Liu and Chan (1999).

3 Review of researches on the size of tropical cyclones

One of the most important findings about TC size is that the correlation between size and intensity is very weak. Merrill (1984) showed that the correlation coefficient between the maximum wind speed and the radius of the outer closed isobar is 0.28. This conclusion has been supported by many other studies after his study (e.g., Chavas and Emanuel 2010; Chan and Chan 2012). Another important study was conducted by Lee et al. (2010). They statistically investigated TC size before and after development, finding that TCs initially larger (smaller) than others remain larger (smaller) after development, even though size increases with development. This means that TC sizes do not change relative to each other throughout their lifetimes.

The most well-researched subject regarding TC size is its seasonal and regional dependence. Merrill (1984) statistically investigated the size of hurricanes (TCs over the Atlantic) and typhoons (TCs over the western North Pacific), finding that the average size of hurricanes is 1.5 latitudes larger than that of typhoons. Merrill (1984) also found that both hurricanes and typhoons are largest in October and smallest in midsummer. Similar results were obtained by Liu and Chan (1999) using satellite observational data. Weatherford and Gray (1988a, b), using aircraft observations, showed that larger typhoons are found at higher latitudes. Liu and Chan (2002) reports that many large typhoons are seen under southwesterly surge synoptic patterns, which frequently appear in the end stage of the TC season (October and November). They also showed that many small typhoons are found south of the subtropical ridge and at the eastern ridge of the monsoon gyre. Yuan et al. (2007) obtained the same conclusion. This result indicates that the synoptic environments surrounding TCs differ between

large and small typhoons. Kimball and Mulekar (2004) investigated TC size over the Atlantic, finding that size is larger at higher latitudes and reaches a maximum in September. Seasonal and regional differences of size were also indicated by Chan and Chan (2012) and Knaff et al. (2014).

Numerical research has also been conducted on the factors affecting TC size. Hill and Lackmann (2009) investigated the effect of humidity in the outer rainbands on TC size, demonstrating that higher humidity in these rainbands makes TCs larger. Sawada and Iwasaki (2010) showed that diabatic heating associated with rainband which is generated by cold pool associated with evaporative cooling at the mature stage of TCs makes TCs larger. Fudeyasu and Wang (2011) also pointed out the importance of diabatic heating on the size change of TCs. Xu and Wang (2010) investigated the effect of the radius of maximum wind (RMW) on size using initial vortices with different RMWs, showing that initial vortices with larger RMW grow larger and the effects of the inner core size on the size change is more heavily than that of humidity of the environment. This dependence of size on the structure of initial vortices (large-scale disturbances in tropical cyclogenesis) is consistent with the theoretical work of Rotunno and Emanuel (1987). Fang and Zhang (2012) showed that the β -effect alters TC size. Radu et al. (2014) demonstrated that the growth of the TC size is linearly related to the sea surface temperature (SST) and air temperature; when these variables are higher, the latent heat flux inside TCs increases, which they argue makes TC larger. Chen et al. (2014) found that typhoons possessing long-lasting principal rainbands due to the effect of a monsoon have larger sizes. Smith et al. (2011) investigated the effect of the Coriolis parameter on TC size using an axisymmetric numerical model, whose results indicated the existence of an optimal Coriolis parameter for maximizing TC size. Chan and Chan (2014) also obtained the same result using a three-dimensional model. Conversely, other work has shown that TC size monotonically increases with latitude (e.g., DeMaria and Pickle 1988; see also Weatherford and Gray 1988a, b, and Kimball and Mulekar 2004). It thus remains uncertain how the Coriolis parameter influences TC size.

As reviewed above, various studies about TC size have been performed from various point of view and they have identified various factors that affect the size of TCs. However, many of the studies above

only state the factor affecting the size without mentioning about the mechanism.

Some of more recent studies mentioned the mechanism governing the size change of TCs. Chan and Chan (2014, 2015) investigated the size change of TCs in terms of absolute angular momentum (AAM). According to their research, TC size grows when the initial size, tangential wind outside the TC, and/or Coriolis parameter are large. They concluded that the inward AAM flux, which strengthens the tangential wind, is large in these cases. However, Chan and Chan (2014, 2015) did not explain the origin of the inflow that transports AAM into TCs. In other words, they did not explain from where the inflow is induced. Sawada and Iwasaki (2010) and Fudeyasu and Wang (2011) pointed out that the diabatic heating associated with rainband is important for the size change of TCs. The mechanism is that the secondary circulation induced by the diabatic heating associated with rainband causes the inflow in the lower layer to transport AAM into the TC from the outside, which strengthen the tangential wind at the outer region of TCs and thus the TC size grows. However, they did not investigate the quantitative relationship between TC size change and heating. Moreover, the mechanism proposed by Fudeyasu and Wang (2011) is about the tangential wind in the middle layer, which does not necessarily correspond to TC size because it is generally defined by the tangential wind near the surface.

4 Difficulty of the study on the size of tropical cyclones and approach of the present study

Research on TC size change is fewer in number than that on TC intensity and lags far behind that on intensity. The reason is considered to arise from the difference in the regions within a TC which size and intensity are mainly concerned. In considering intensity, mainly the structure near the center of a TC needs to be considered because the maximum tangential wind speed and minimum pressure, both of which characterize the intensity, occur near the center. Conversely, in considering size, the structure of outer regions receives greater focus because the change in TC size occurs around there. The structure of TCs generally becomes complex as the distance from the center increases. Compared with a nearly axisymmetric structure near the center of TCs, such as an eye and eyewalls, the outer

portion of TCs is characterized by non-axisymmetric structures such as rainbands and has a large variety. Therefore, research on TC size related to the structure of outer regions of TCs becomes more complicated and should be performed from more number of directions than those used in the research on the intensity of TCs related to the dynamical structure near the TC center. In fact, previous studies have shown that many factors related to the dynamical structure of TCs as a whole affect TC size; e.g., environmental humidity (Hill and Lackmann 2009), evaporation from raindrops (Sawada and Iwasaki 2010), initial vortex size (Xu and Wang 2010; Chan and Chan 2014), heating in anvil clouds (Fudeyasu and Wang 2011), cloud-radiative forcing (Bu et al. 2014), and sea surface temperature and air temperature (Radu et al. 2014).

The fact that TC size is connected to the structure of the outer region of TCs raises a further difficulty. Because many external environmental factors affect the outer region of TCs, TC size is affected more by the number of external factors than TC intensity. In fact, many previous studies have indicated that various external factors affect TC size; examples are ocean basins and seasons (e.g., Merrill 1984; Chan and Chan 2012; Knaff et al. 2014), synoptic environments (e.g., Liu and Chan 2002; Yuan et al. 2007), β -effect (Fang and Zhang 2012), and latitude (e.g., Weatherford and Gray 1988a, b; Kimball and Mulekar 2004). The involvement of so many external environmental factors complicates the quantitative evaluation of the relationship between TC size and those factors. This “foggy” outlook of the issue on TC size contrasts to that on TC intensity, where a much more integrated and systematic approach, such as the maximum potential intensity theory associated with basic principles of thermodynamics proposed by Emanuel (1986), is possible.

The fact that TC size change is the change of wind speed at the outer part of TCs also causes a difficulty for dealing with the observation data. The useful data to analyze TCs are the observation data obtained from aircraft or satellite, which cannot observe extensive area in TCs due to the limitation of instrument. Therefore, the data covering outer regions of TCs are far insufficient than those observing the center of TCs. This restriction of data have hindered research on TC size approaching from observational data.

Bearing such situation in mind, we consider that the understanding of the mechanism governing TC size-change is difficult to achieve only through observational analyses of the real TCs, which have complicated structure embedded in diverse and complex environments, or numerical experiments that reproduce things as they are. To reach a fundamental understanding of the mechanism governing TC size, an alternative strategy is more promising. After essential elements affecting TC size change are identified, we simplify the identified elements, implement them in an idealized numerical model, perform numerical experiments systematically, and examine the results. This strategy not only leads us to the understanding of a fundamental mechanism but also serves as an indispensable basis on which the understanding of the size evolution of real TCs proceeds by adding back the elements that were eliminated in the process of simplification.

5 Structure of this paper

In this study, based on the above strategy, we firstly perform idealized numerical experiments systematically in chapter 2. In the idealized experiments, thermal forcings mimicking cumulus convection is applied to only a limited region at a certain distance from the center of simplified TC-like vortices and the size evolution of the vortices is examined. We firstly mention the justification of idealized experiments in section 1. In section 2, the basic equations of the idealized model, method to apply forcing, classification of experiments, and direction of analyses are explained. We demonstrate the temporal evolution of the vortex structure in section 3. Then, the results and consideration of experiments in which sensitivity of vortex size change to the location of forcing, to the strength and scales of forcing, and to the structure of the initial vortex in sections 4, 5, and 6, respectively. In section 7, the results and consideration of experiments in which forcing is applied to two regions are shown. The conclusions of the idealized experiments are offered along with a discussion in section 8.

Then, we examine the mechanism governing the size change of vortices. In chapter 3, to investigate the applicability of the mechanism obtained from the idealized experiments to real TCs, satellite observation data analyses are performed. In the analyses, we investigate the difference of precipitation

distribution in size increase period and size stationary period and discuss the correspondence between the results of analyses and those of the idealized experiments. We firstly mention the significance to compare the results of the idealized experiments with the size change of actual TCs and review the research on TCs by using satellite observation data. In section 2 and section 3, we explain about the data used in the analyses and method of the analyses. We show the results of analyses in section 4. In section 5, we discuss the results of analyses with those of idealized experiments in chapter 2. The conclusions of the analyses are summarized in section 6.

The content of this study is summarized in chapter 4.

Chapter 2

Size change of Tropical cyclone-like vortices

1 Justification of idealized experiment

In research on TCs in the past, approaches by idealized experiments have often been performed (e.g., Shapiro and Willoughby 1982; Guin and Schubert 1993). Presently, on the other hand, machine power is developed and numerical models are elaborated, with which larger number of studies have employed realistic and/or complicated settings. Still, however, idealized experiments with simple settings provide us with many insightful knowledge (e.g., Smith et al. 2009; Moon and Nolan 2010). In particular, the framework of idealized experiments is useful to examine complicated problems such as TC size change, in separating contributions of various different controlling factors.

In this chapter, we perform idealized experiments to identify and investigate the essential mechanism governing the size of TCs based on the strategy stated the previous chapter. To perform idealized experiments, we need to simplify TC structure and extract essential elements affecting TC size change carefully. In this study, TCs are simplified as a simple vortex lacking complicated structures. Then, we only consider dynamical factors inside a TC and exclude external factors such as seasonal and regional dependences and synoptic patterns because the TC size change caused by external factors

should be interpreted as that these factors affect TC size indirectly through the change of dynamical structure in the outer region of TCs. For example, the effect of southwesterly-surge synoptic patterns investigated by Liu and Chan (2002) may be grasped as a system of angular momentum supply from the synoptic-scale fields to the outer edge of TCs, and the supply of angular momentum affects TC size through the change of dynamical structure in the outer region of TCs.

To narrow down the dynamical factors to essential ones affecting TC size, we review recent modeling studies. Musgrave et al. (2012), using a balanced vortex model, showed that diabatic heating applied to the outside and inside of the radius of maximum wind (RMW) affects TC size and intensity, respectively. Fudeyasu and Wang (2011), using a fullphysics tropical cyclone model, showed that in their simulated TC, diabatic heating in the outer rainband contributes to the spin-up of the tangential wind in the mid troposphere of outer core region (outside of the outer rainband) by the transport of absolute angular momentum (AAM) by the inflow constituting secondary circulation (SC). This mechanism has been supported by Didlake and Houze (2013) using airborne Doppler radar data. Chan and Chan (2014, 2015) performed numerical experiments with changing initial vortex size, planetary vorticity, vortex intensity, and outer wind of TCs using a fullphysics model. Their results indicate that the TC size becomes larger as the initial size of TCs and the tangential wind at the outside of TCs are larger, attributing the cause to the largeness of AAM flux coming into TCs. Moreover, Sawada and Iwasaki (2010), using a non-hydrostatic model, found that evaporation from raindrops affects TC size through the change of AAM transport driven by rainbands. From the above findings, we identify radial AAM flux induced by SC driven by cumulus heating as an essential element in considering the mechanism governing TC size.

In this chapter, we perform idealized experiments to clarify the relationship between thermal forcing and vortex size change. Specifically, an external thermal forcing is applied to only one or two limited region at a certain distance from the vortex center. We aim to understand the effects of the strength, scales and location of forcing on the size change of vortices. To achieve this purpose, cumulus parameterization and water vapor are excluded. We also exclude the effect of surface friction. This

simplification becomes possible because the feedback loop between SC driven by surface friction and heating is disconnected in our framework, in which thermal forcing is applied externally. Musgrave et al. (2012) and the present study employ external forcing in common. Musgrave et al. (2012) investigate only the effect of forcing near the RMW, but we investigate that in a wider range of distances from the vortex center, considering the effect of rainbands as well. Moreover, our simplification is justified by the fact that radial convergence of AAM flux above the boundary layer is also important for the surface-wind change in the outer region of TCs (e.g., Smith et al. 2009). By eliminating all but the most essential elements, i.e., the vortex and heating, the essential mechanism governing TC size will be much more easily understood.

2 Summary of numerical model and design of experiments

In this section, we describe the model used in this study and the design of the numerical experiments.

2.1 Basic equations and design of numerical model

The numerical model is based on the primitive equation system on an f -plane in the σ coordinate. This model does not include the boundary layer turbulence, surface friction, moist processes (including cumulus parameterization), and latent heat flux from the sea surface for the purpose of simplification.

The equation system of the model is as follows:

$$\frac{\partial u}{\partial t} = (f + \zeta)v - \frac{\partial}{\partial x}(K + \phi) - \dot{\sigma} \frac{\partial u}{\partial \sigma} - \sigma \alpha \frac{\partial \pi}{\partial x} + k_h \nabla^2 u + F_u, \quad (2.1)$$

$$\frac{\partial v}{\partial t} = -(f + \zeta)u - \frac{\partial}{\partial y}(K + \phi) - \dot{\sigma} \frac{\partial v}{\partial \sigma} - \sigma \alpha \frac{\partial \pi}{\partial y} + k_h \nabla^2 v + F_v, \quad (2.2)$$

$$\frac{\partial(\pi\theta)}{\partial t} = -\nabla \cdot (\pi \mathbf{V} \theta) - \frac{\partial}{\partial \sigma}(\pi \dot{\sigma} \theta) + \pi Q_F + \pi R + \pi k_h \nabla^2 \theta, \quad (2.3)$$

$$\frac{\partial \pi}{\partial t} = -\nabla \cdot (\pi \mathbf{V}) - \frac{\partial}{\partial \sigma}(\pi \dot{\sigma}) \quad (2.4)$$

$$\frac{\partial \phi}{\partial(p\kappa)} = c_p \theta, \quad (2.5)$$

where $x, y, t, \mathbf{V} = (u, v), f, \zeta, \phi, K, \alpha, c_p$, and θ designate the eastward coordinate, northward coordinate, time, horizontal wind, Coriolis parameter, relative vorticity, geopotential, kinetic energy, specific volume, specific heat of dry air at constant pressure, and potential temperature, respectively. Furthermore, $\pi = p_s - p_t$, $\sigma = (p - p_t)/\pi$, and $\kappa = R_c/c_p$, where p, p_s, p_t , and R_c represent the pressure, surface pressure, model-top pressure (80 hPa), and gas constant, respectively. Q_F is the thermal forcing term, which is explained in Subsection 2.3.

The model domain is $12\,800\text{ km} \times 12\,800\text{ km}$ with a resolution of 20 km, and the number of vertical levels is five ($\sigma^* = 0.95, 0.72, 0.43, 0.24$, and 0.12 , where $\sigma^* = p/p_s$). The coarseness of the vertical resolution is due to the demands of computational time, which is very important in our study because of a large number of numerical experiments conducted. To check the effect of the coarse vertical resolution, a model with 11 vertical levels ($p_t = 50\text{ hPa}$, and $\sigma^* = 0.95, 0.845, 0.74, 0.63, 0.52, 0.42, 0.33, 0.25, 0.18, 0.12$, and 0.07) is used in some experiments. The setting of the 11-level model is presented at subsection 2.5. As is shown in Subsection 4.5, the five-level model gives qualitatively similar results as those of the 11-level model. Therefore, we show the results of the five-level model unless otherwise specified. The horizontal boundary condition is cyclic, whereas the vertical boundary condition is $\dot{\sigma} = 0$ at $\sigma = 0$ and 1 , where $\dot{\sigma}$ is $D\sigma/Dt$. The value of the Coriolis parameter is $3.8 \times 10^{-5}\text{ s}^{-1}$, which corresponds to the value at 15° latitude.

The integration time is 240 h with a time step of 20 s. Data is output every one hour.

R is the net radiation, assumed as

$$R = -h_0(\theta - \theta_e), \quad (2.6)$$

where θ_e is the potential temperature in radiative balance, set to 294.2, 296.2, 302.6, 343.9, and 410.7 K at $\sigma^* = 0.95, 0.72, 0.43, 0.24$, and 0.12 , respectively. $h_0 = 1/8\text{ day}^{-1}$ is the reciprocal of the time constant of Newtonian cooling. k_h is the horizontal diffusion coefficient, which is a constant value of $2.5 \times 10^4\text{ m}^2\text{ s}^{-1}$ within 3500 km from the center, $2.5 \times 10^5\text{ m}^2\text{ s}^{-1}$ outside of 6000 km from the center, and follows a linear increase between 3500 and 6000 km. For u and v , Rayleigh damping is also set

to prevent reflection from boundary. The coefficient of Rayleigh damping changes with the distance from the center; this coefficient has a constant value of 0 inside 3500 km and 2 day^{-1} (time constant is 0.5 day) outside of 6000 km, with a linear increase between 3500 and 6000 km. F_u represents the vertical diffusion of the u -component as follows:

$$F_u = \frac{g}{p_s} \frac{\partial \tau_u}{\partial \sigma}, \quad (2.7)$$

where τ_u is

$$\tau_u = \frac{\rho^2 g}{p_s} k_v \frac{\partial u}{\partial \sigma}, \quad (2.8)$$

except at the lowest level, where g and ρ are the gravitational acceleration and density, respectively. F_v , vertical diffusion of v -component, is defined in the way similar to F_u . To exclude the effect of surface friction, τ is set to 0 at the lowest model level. k_v is the vertical diffusion coefficient and is set to $k_v = 1 \text{ m}^2 \text{ s}^{-1}$.

2.2 Method for making the initial vortices and structure of the vortices

Initial vortices are given by axisymmetric tangential wind fields and temperature and pressure conditions which are assumed to be in the gradient wind balance. The axisymmetric tangential wind fields are given by

$$v_\varphi(r, p) = v_\varphi(r)g(p) \quad (2.9)$$

$$v_\varphi(r) = \begin{cases} v_m \frac{r}{r_m} \left[\exp \frac{1 - \left(\frac{r}{r_m}\right)^b}{b} - \frac{|r - r_m|}{r_{tc} - r_m} \exp \frac{1 - \left(\frac{r_{tc}}{r_m}\right)^b}{r_m} \right] & , r < r_{tc} \\ 0 & , r > r_{tc} \end{cases} \quad (2.10)$$

$$g(p) = \begin{cases} 1 & , p > 850 \\ 0.5 - 0.5 \cos \frac{\ln(p/100)}{\ln(8.5)} \pi_c & , 100 \leq p \leq 850 \\ 0 & , p < 100 \end{cases} \quad (2.11)$$

which is used in Chan and Chan (2014), where v_φ , v_m , r_m , b , r , r_{tc} , and π_c denote tangential wind, the maximum tangential wind, the radius of maximum wind, a shape parameter, radial distance from the center, the vanishing-wind radius of the vortex, the circular constant, respectively. The given vortices are not perfectly balanced because of finite difference errors. Thus, the size of the vortex oscillates despite the lack of forcing (not shown). To minimize the effect of these oscillations on vortex size, we integrate the model for 24 h without forcing. The vortex modeled at this time is used as the initial vortex in each of the experiments.

The structure of initial vortices is controlled by the values of parameters v_m , r_m , and b in Eq. (2.10). In this study, we use four types of initial vortices whose parameters are set as shown in Table 2.1. Initial vortices Gentle, Moderate, and Steep are only used in parameter experiments shown in Section 6 in which the dependence of the vortex size evolution on the structure of initial vortex is investigated. In the other parameter experiments, we use the initial vortex Nominal. The radial distributions of tangential wind of these initial vortices at the lowest level are shown in Fig. 2.1. The radial-vertical distributions of tangential wind of the initial vortices are shown in Fig. 2.2. We also show the radial-vertical distributions of inertial stability, which is an index of the difficulty of radial movement and an important parameter to understand the size change of vortices, in Fig. 2.3.

2.3 The specification of thermal forcing

The thermal forcing, Q_F , is specified so as to represent the collective effect of a large number of heating events mimicking cumulus convection. The thermal forcing in each single heating event (Q_c) is represented as

$$Q_c(r_0, \sigma^*, t_f) = Q \times \eta(\sigma^*) \times \left(\frac{S_0}{S}\right)^2 \times \cos\left(\frac{r_0}{S} \frac{\pi_0}{2}\right) \sin\left(\frac{t_f}{t_d} \pi_0\right) \quad (2.12)$$

for $0 < r_0 \leq S$ and $0 < t_f \leq t_d$,

where Q and $\eta(\sigma^*)$ represent the strength of forcing and the vertical structure of the forcing, respectively, and are described later. S and S_0 are the horizontal scale of heating and its standard value (100

km), respectively. The third factor on the right-hand side of Eq. (2.12) is introduced to keep the total amount of heating independent of S . r_0 is the distance from the center of a heating event. t_f and t_d are the elapsed time after the start of a heating event and the duration of the heating (30 minutes), respectively. Each of the heating elements is generated randomly in time, centered at an azimuthally arbitrary point at a certain prescribed distance from the center of the model domain, i.e., the location where the center of the initial vortex is located (Fig. 2.4). We hereafter call the distance as $2l_q$ ‘location of the forcing’. The frequency of the generation of heating events in the entire domain is once in 20 min on average, and Q_F is obtained by adding the contributions of all the abovementioned generated heating events.

For some parameter experiments, to help our understanding, we also performed supplementary experiments in which forcing does not change in time and space (annulus forcing experiment). In this case, Q_F is represented as

$$Q_F(r_0, \sigma^*) = \left[\frac{S}{2L} \left(1 - \frac{2}{\pi} \right) \right] \times Q \times \eta(\sigma^*) \times \left(\frac{S_0}{S} \right)^2 \times \cos\left(\frac{r_0}{S} \frac{\pi_0}{2} \right) \sin\left(\frac{1}{2} \pi_0 \right) \quad (2.13)$$

for $0 < r_0 \leq S$,

where L represents distance of forcing from the center (location of forcing). In the annulus forcing experiment, twice the horizontal scale of forcing, $2S$, corresponds to the width of forcing region.

The vertical structure of forcing, $\eta(\sigma^*)$, is taken from averaged vertical structure of heating in a TC which is simulated by using the primitive equation system on an f -plane in the σ coordinate. This model, which is the underlying model used in this study, is the same as that in Itoh and Ghil (1988) except for the f -plane and cyclic boundary conditions. The details of the simulation of the TC to calculate the ratio of heating are shown in Appendix. The specific values of calculated $\eta(\sigma^*)$ are 2.0, 16.870, 23.734, 5.134, and 0 from the lowest level upward. Because the heating is averaged without classifying into components associated with eyewalls and rainbands, the vertical structure of heating corresponds to the averaged one between them.

2.4 Method of calculating R15

The vortex size change is investigated by applying an external thermal forcing to the initial vortex. Throughout this study, the vortex size is defined as the radius of 15 m s^{-1} lowest model level wind speed (R15). Note that this definition is not the same as that of real TCs, whose R15 is defined by the surface wind speed located inside boundary layer.

In general, the contours of 15 m s^{-1} wind speed appear in two places: near the center and outer region of a vortex. Because our target is the outer region, R15 is estimated as

$$R15 = \sqrt{\frac{n(\Delta x)^2}{\pi_0}}, \quad (2.14)$$

where n and Δx are the number of grid points inside the outer contour and the grid interval of the model, respectively.

2.5 Classes of experiments and direction of analysis

In this study, we performed five types of parameter experiments described below.

Series L The parameter experiment to investigate the sensibility of change of R15 to the location of forcing. In this parameter experiment, the location of forcing (L , standard: 400 km) is changed and strength and scales of forcing are set to the standard values.

Series Q The parameter experiment to investigate the sensibility of change of R15 to the strength of forcing, in which the strength of forcing (maximum magnitude of forcing at the lowest level (Q), standard: $1 \times 10^{-4} \text{ K s}^{-1}$) is changed and other parameters are set to the standard values.

Series S The parameter experiment to investigate the sensibility of change of R15 to the scales of forcing. In the parameter experiment, the scales of forcing (S , standard (S_0): 100 km) is changed and other parameters are set to the standard values.

Series V The parameter experiment to investigate the effect of structure of initial vortex on the change of R15.

Series D The parameter experiment in which forcing region is increased in two places. The details of the settings of each parameter experiment are shown in the beginning of each section in which the results and discussions are demonstrated.

In some experiments, to investigate the effects of the coarse vertical resolution, the model with 11 vertical levels is used. In experiments using the 11-level model, the structure of the initial vortex and each parameter in this model are created by interpolation from the five-level model except for the top level. On the top level, u and v are set to the same value as those at $\sigma^* = 0.12$, T at the σ surface is determined by the thermal wind relation, and ϕ is calculated from the hydrostatic balance equation. The radiative equilibrium temperature and thermal forcing are that in the stratosphere (198.0 K) and 0, respectively.

Some of the following analyses are performed on the cylindrical coordinate (r - φ - σ coordinate). In these cases, coordinate transformation is executed by cubic spline interpolation. The grid intervals of the r and φ directions are 20 km and 5° , respectively.

Table 2.1: Initial R15 and Values of v_m , r_m , and b of initial vortices.

Initial vortices	v_m	r_m	b	Initial R15
Nominal	30	200	1.0	535 km
Gentle	30	100	0.3	675 km
Moderate	30	200	0.7	670 km
Steep	30	300	1.5	655 km

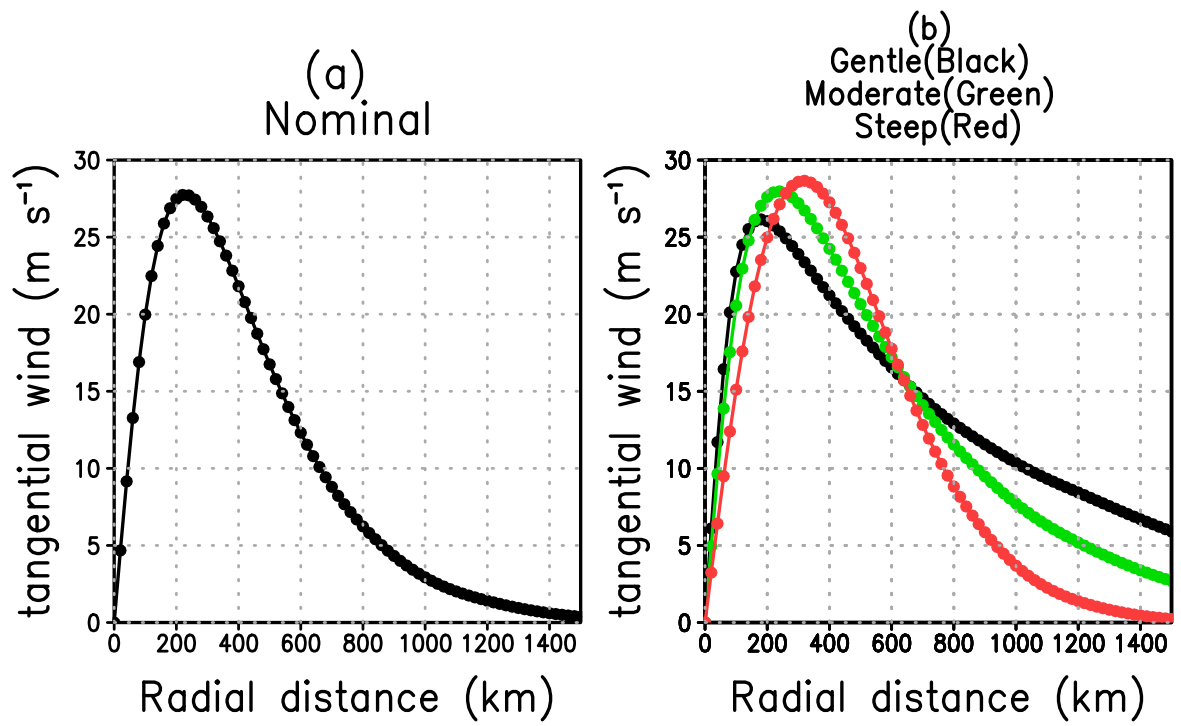


Figure 2.1: Radial structure of tangential wind at the lowest level in four types of vortices (a)Nominal, (b)Gentle, Moderate, Steep. The abscissa and the ordinate indicate the distance from the center of the vortex (km) and tangential wind speed (m s^{-1}), respectively.

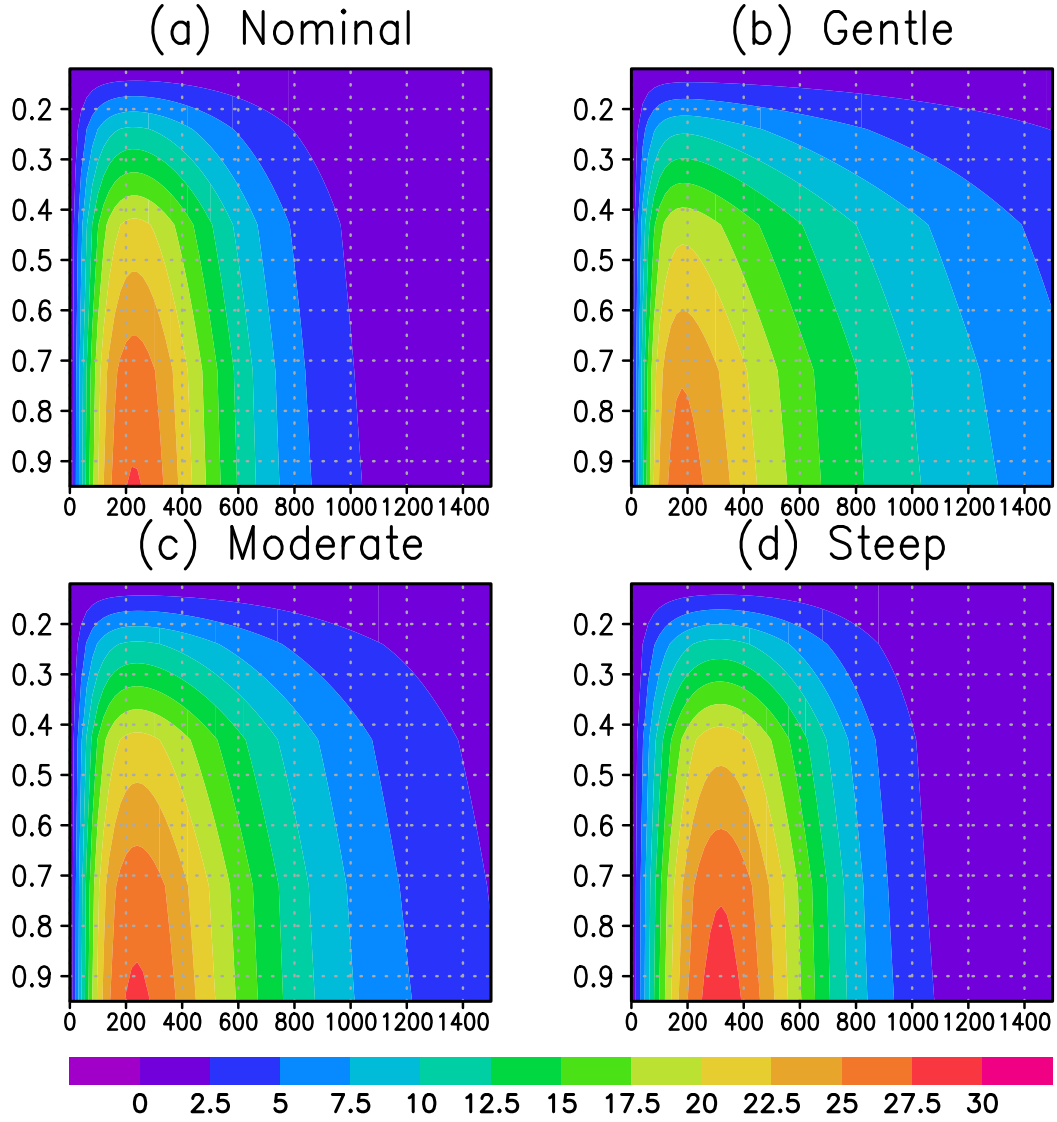


Figure 2.2: Radial-vertical distribution of the tangential wind speed in the initial vortices (a)Nominal, (b)Gentle, (c)Moderate, and (d)Steep. Color shows tangential wind speed (m s^{-1}). The ordinate and the abscissa represent σ^* and the distance from the center of the vortex (km), respectively.

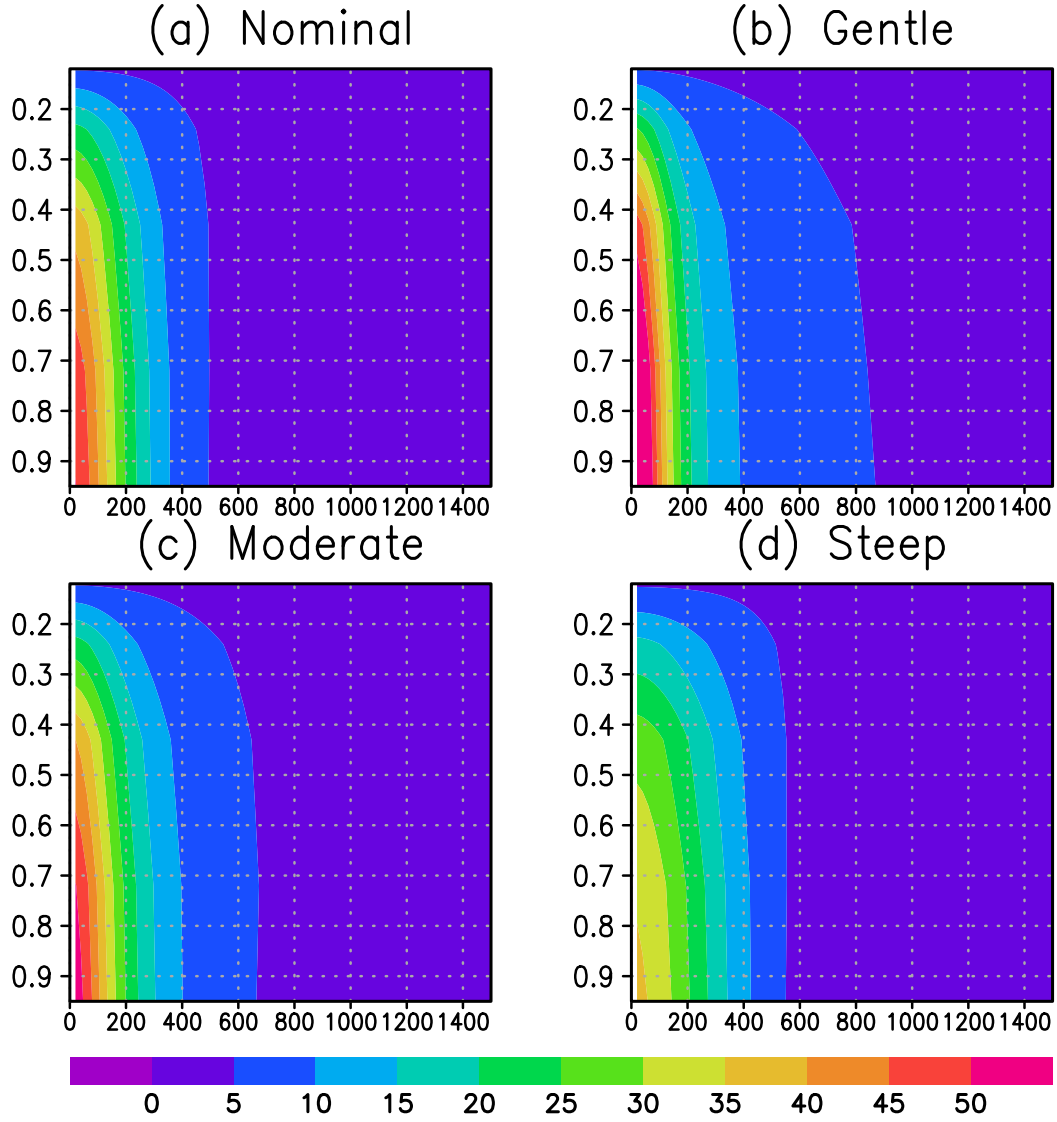


Figure 2.3: Radial-vertical distribution of inertial stability in the initial vortices (a)Nominal, (b)Gentle, (c)Moderate, and (d)Steep. Color shows inertial stability ($\times 10^{-5} \text{ s}^{-1}$). The ordinate and the abscissa represent σ^* and the distance from the center of the vortex (km), respectively.

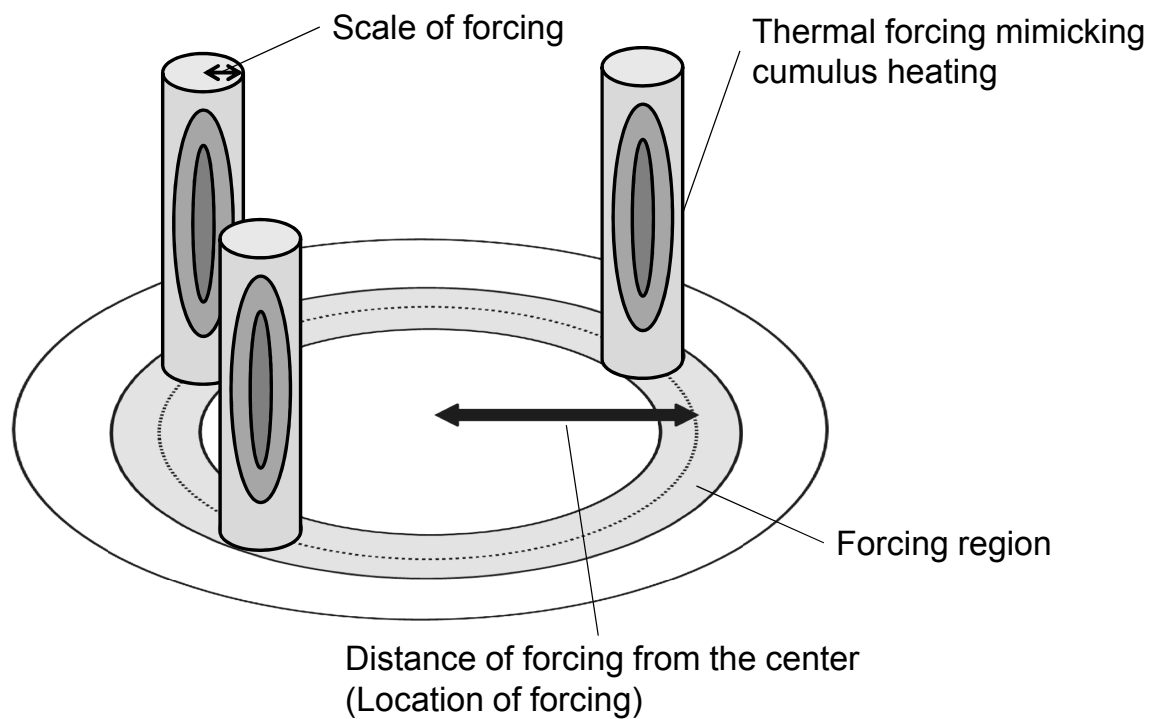


Figure 2.4: Schematic of the method of applying forcing. Circular forcings are applied in annulus regions (shaded) at a certain distance from the domain center. A forcing is illustrated as a cylinder. Shades in a cylinder show the vertical profile of the forcing strength schematically.

3 Temporal evolution of vortices

First, the evolution of vortex structure in an experiment in which forcing having width of 100 km and strength of 1.0Q is applied to 400 km from the center of initial vortex Nominal is shown as a representative case in the present study. Figure 2.5 shows wind speeds and vectors at the lowest level in this model. As seen in the comparison between Figs. 2.5a and 2.5b, R15 gradually grows with time. However, after approximately 120 h, the vortex begins to distort with a wavenumber-2 component (Fig. 2.5c), and this state is persistent (Fig. 2.5d). At this stage, R15 no longer grows and levels off.

The distortion of the vortex like that described above is likely caused by two kinds of instability. One is barotropic instability, which requires the reversal of radial vorticity gradient. Figure 2.6 shows time-radius view of the radial gradient of vorticity. Radial gradient of vorticity is negative in most of the the region inside R15 initially, but the region of positive radial gradient of vorticity appears in the inside of forcing region (about 300 km from the center) after $t = 40$, suggesting the possibility of barotropic instability. The development of positive radial gradient of vorticity is caused by the increase of vorticity by stretching in the forcing region and the decrease by diffusion nearer to the center.

The other is inertial instability. Inertial stability I^2 is defined by

$$I^2 = (f + \bar{\zeta}) \left(f + \frac{2\overline{v_\varphi}}{r} \right), \quad (2.15)$$

where overline designates azimuthally average. I serves as an index of the difficulty of radial movement. Representing AAM as $M(\equiv r\overline{v_\varphi} + \frac{1}{2}fr^2)$, I and M are related as

$$I^2 = \frac{1}{r^3} \frac{\partial M^2}{\partial r}. \quad (2.16)$$

Therefore, the vortex becomes inertially unstable when radial gradient of AAM becomes negative.

Figure 2.7 shows time-radius view of the amplitude of the asymmetric component of wind speed ($\sqrt{v_\varphi'^2 + v_r'^2}$) at $\sigma^* = 0.95$ and $\sigma^* = 0.43$, where v_r designates radial velocity. At $\sigma^* = 0.43$, an iner-

tially unstable region (inside red line of Fig. 2.7b) emerges from around $t = 20$. With the emergence of unstable region, the amplitude of the asymmetric component becomes large from around $t = 60$. The amplitude of the asymmetric component around $r = 300$ km at the model lowest level ($\sigma^* = 0.95$) also becomes large from around $t = 100$.

The radial gradient of AAM becomes negative outside the forcing location (400–600 km) around $\sigma^* = 0.4$ – 0.6 (Fig. 2.8). This inversion of AAM gradient is caused by the increases of AAM around the forcing region (300–500 km) and decreases beyond 500 km from the center of the vortex. These changes result from radial advection of AAM by the secondary circulation induced by the applied heating, whose detail will be discussed in the next section. Distortion of a vortex like that described above is commonly observed among the experiments conducted in this study. In some of the cases, the vortex strains to the extent that the region of weak-wind ($|\mathbf{V}| < 15 \text{ m s}^{-1}$) containing the vortex center connects to the weak-wind region outside of the vortex. This situation is inappropriate for the present experiment. Therefore, the analysis is stopped at this point unless the inner and outer weak-wind regions disconnect within 4 h. In some other cases, the center of the vortex moves far from the center of the model domain; such cases are also inappropriate. Thus, the analysis is terminated when the vortex center, defined as the point of the nine-grid averaged minimum surface pressure, moves outside of 200 km from the model center for longer than 5 h. The two criteria are referred to as the condition for terminating the analysis.

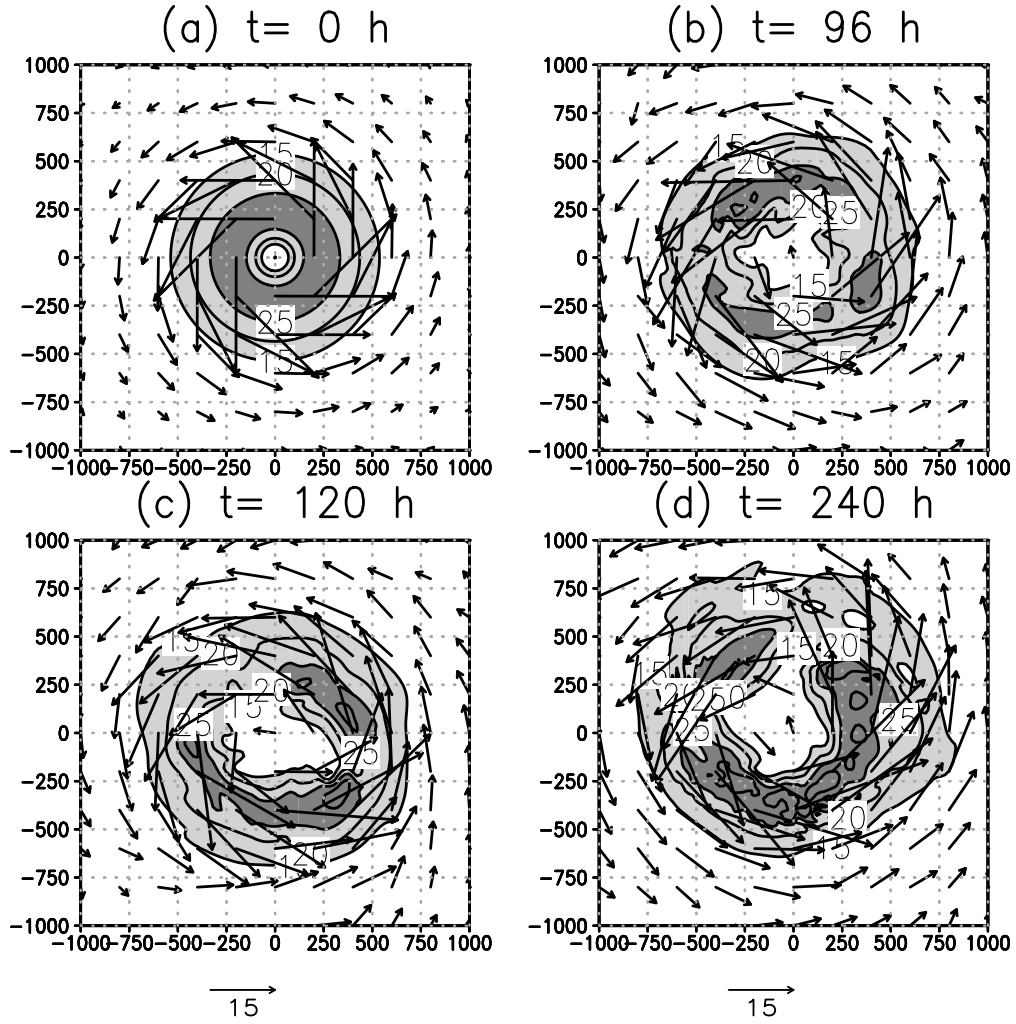


Figure 2.5: Wind speeds (contour) and vectors at the lowest level in L400 at (a) the initial time, (b) 96 h, (c) 120 h and (d) 240 h. The scale of the vectors is shown at the lower right of each figure. The contour interval is 5 m s^{-1} starting from 15 m s^{-1} . Light and dark shading show the areas in which the wind speed exceeds 15 m s^{-1} and 25 m s^{-1} , respectively. The abscissa and the ordinate indicate the distance from the domain center. The vortex initially exists at the origin.

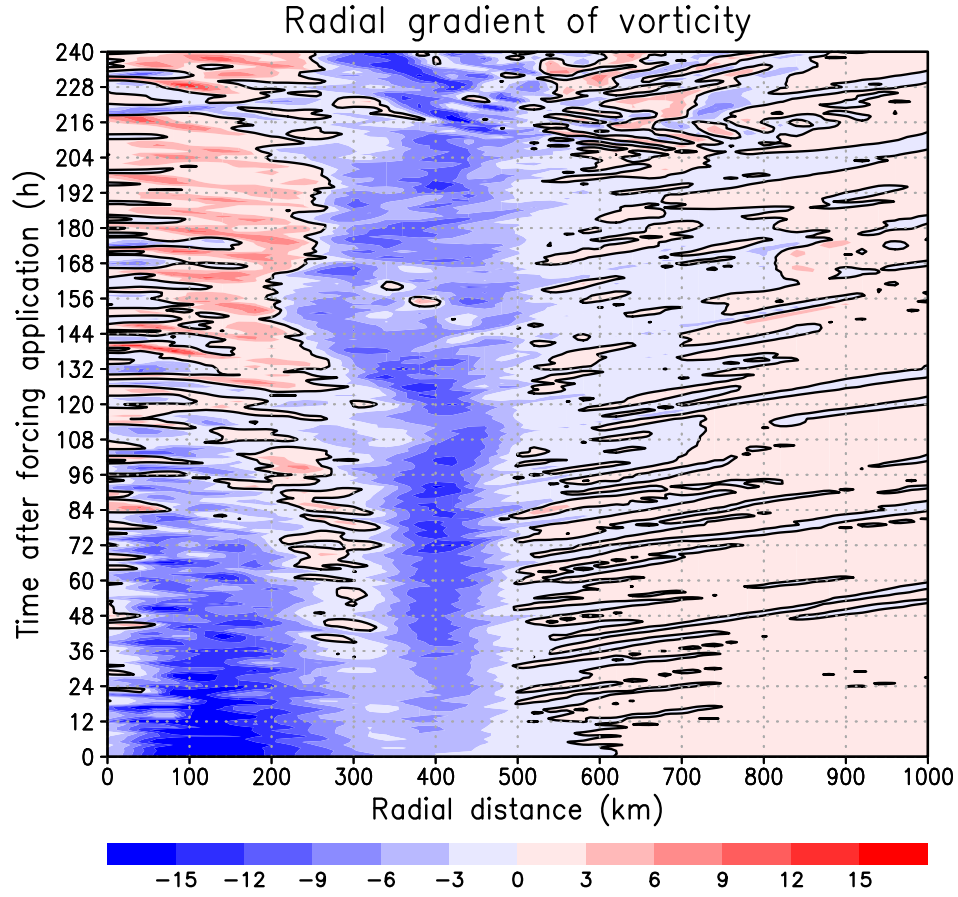


Figure 2.6: Time-radius view of the radial gradient of vorticity (color, unit $\times 10^{-10} \text{ s}^{-1}$) in the experiment in which forcing having width of 100 km and strength of 1.0Q is applied to 400 km from the center of initial vortex Nominal. The ordinate and the abscissa represent time (hour) after forcing application and radial distance from the center (km), respectively. The black line designates the contour of zero.

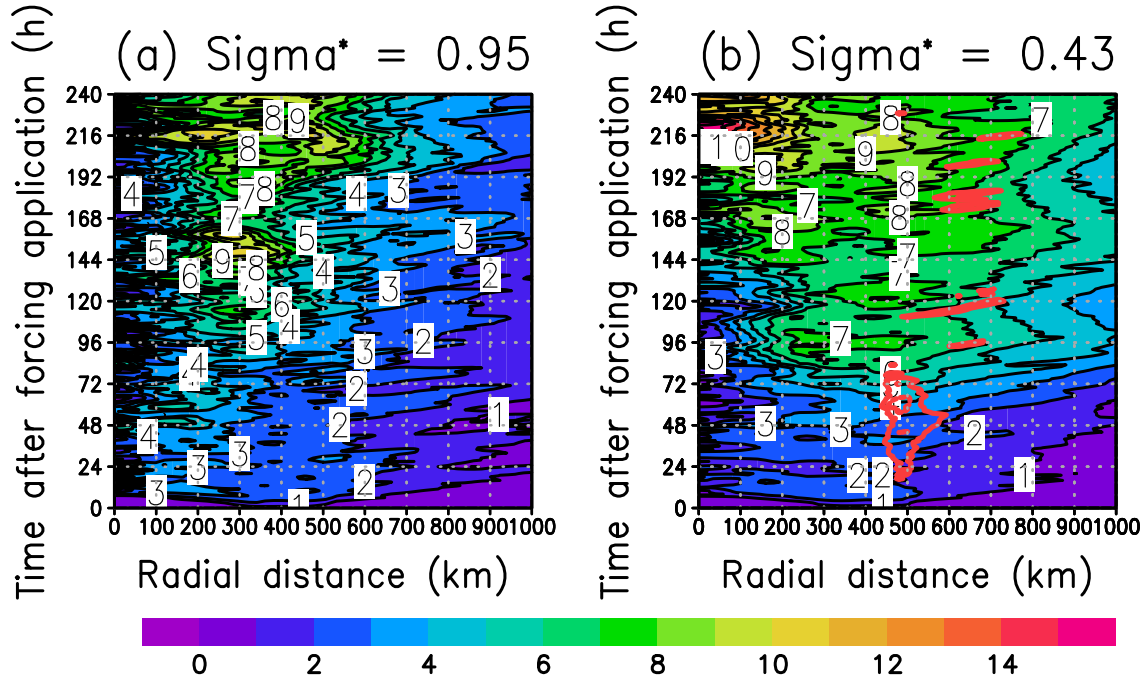


Figure 2.7: Time-radius view of the amplitude of the asymmetric component of wind speed ($\sqrt{v_\phi'^2 + v_r'^2}$, m s^{-1}) at (a) $\sigma^* = 0.95$ and (b) $\sigma^* = 0.43$ in the experiment in which forcing having width of 100 km and strength of 1.0Q is applied to 400 km from the center of initial vortex Nominal. The ordinate and the abscissa represent time (hour) after forcing application and radial distance from the center (km), respectively. The red line in (b) designates inertial stability I^2 ($\times 10^{-9} \text{ s}^{-2}$). Only the region of $I^2 < 0$ is designated.

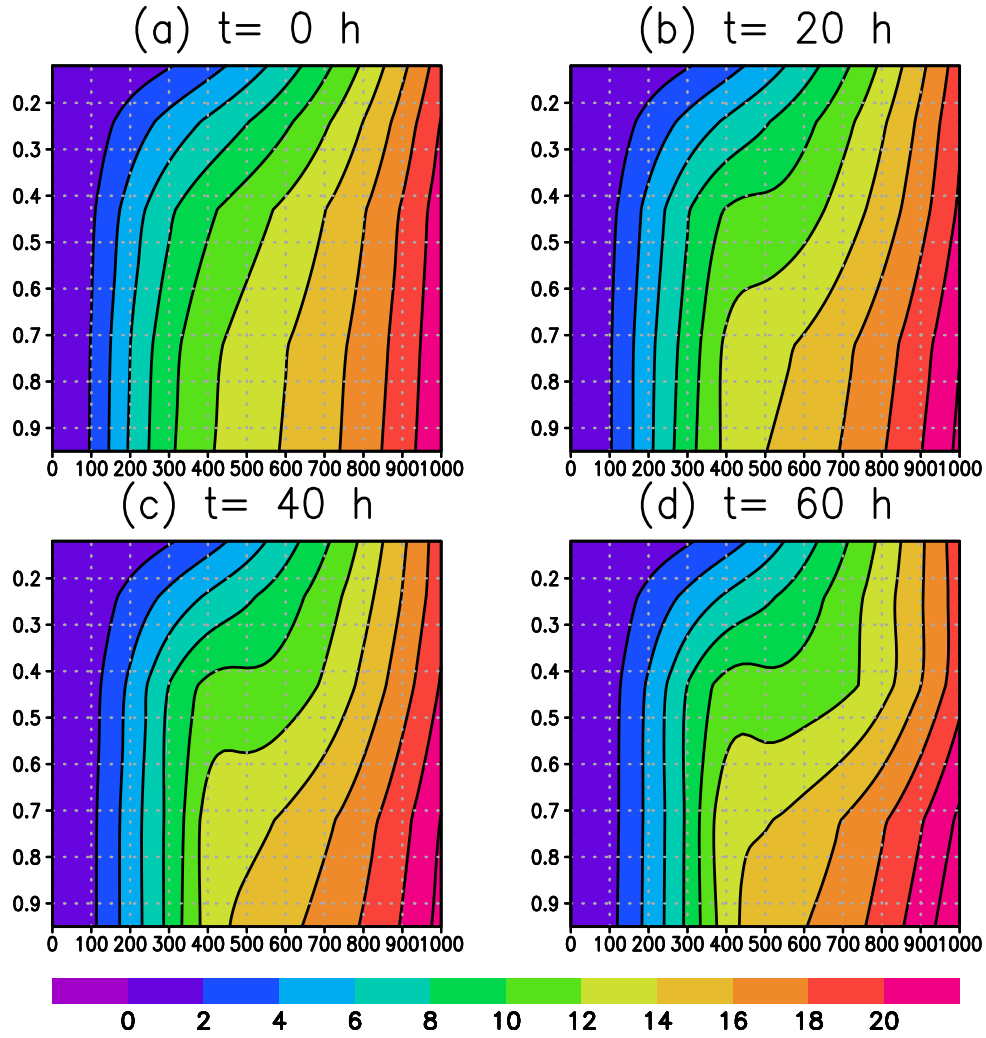


Figure 2.8: Radial-vertical distribution of AAM at (a) $t = 0$, (b) $t = 20$, (c) $t = 40$, and (d) $t = 60$ in the experiment in which forcing having width of 100 km and strength of $1.0Q$ is applied to 400 km from the center of initial vortex Nominal. The color represents AAM ($\times 10^6 \text{ m}^2 \text{ s}^{-1}$). The ordinate and abscissa represent σ^* and radial distance from the center (km), respectively.

4 Sensitivity of vortex size change to the location of forcing

4.1 Specifications of the experiments

In this section, the results and discussion of the parameter experiment in which sensitivity of the size change of vortices to the location of forcing is investigated (Series L) are shown. In the parameter experiment, strength and scales of forcing are set to the standard values (1.0Q and 100 km) and location of forcing is changed. The initial vortex Nominal, whose R15 is 535 km is used. We represent, for example, an experiment in which forcing is applied to 400 km as L400.

To exclude the effects of the distortion of the vortex, only the data obtained earlier than 96 h are used. Additionally, because R15 changes with an oscillation of small amplitude (Fig. 2.9), the data are time-averaged to investigate average characteristics.

In this section, we discuss the mechanism governing the change of R15. At first, the results of experiments in which forcing is applied to the inside of R15 are discussed in subsection 4.3 to subsection 4.6. In subsection 4.7, the results of experiments in which forcing is applied outside R15 are discussed. In subsection 4.8, we summarize the results and discussions of Series L.

4.2 Temporal evolution of vortex size

Figure 2.9 illustrates the time evolution of R15 in the experiments in Series L. Vortex size changes depending on the location of forcing. Specifically, when the forcing location is inside the initial R15 (535 km), vortices with forcing applied near the initial R15 become larger than those to which forcing is applied near the center. However, when the location is near the initial R15 (e.g., L500; L525), the size increases less as the forcing is located further from the vortex center. Moreover, when the forcing is located outside the initial R15, i.e., when the entire forcing region is outside the initial R15 (L700 – L900), the vortex size decreases.

Another feature of these results is that when the location of forcing is within 500 km of the vortex center, leveling-offs of vortex size are commonly observed. The time at which the size reaches a limit depends on the forcing location and seems to be earlier in cases for which the location is more

interior. Close examination reveals that this leveling-off phenomenon is caused by the distortion of the vortex induced by inertial instability shown in section 3. However, the detail is omitted, because the explanation of its cause deviates from the object of this paper.

4.3 Radial wind and budget analyses of absolute angular momentum at R15

Many previous studies have shown that the transport of AAM into a TC (radial convergence of AAM) results in the increase in the tangential wind in the outer region (e.g., Bui et al. 2009; Smith et al. 2009; Sawada and Iwasaki 2010; Fudeyasu and Wang 2011; Chan and Chan 2014, 2015). The same may apply to the idealized experiments in the present study, in which a TC is simplified. Therefore, we first examine the relation between the increase in R15 and the radial velocity at R15 which causes AAM advection.

Figure 2.10 shows the relation between the increase in R15 and time-averaged $\overline{v_r}$ at R15 in each experiment. Inflow is observed in the most of the experiments for which R15 increases (forcing location within 600 km), while outflow is observed in the experiments for which R15 decreases (forcing location over 625 km). Additionally, the change of R15 is roughly proportional to $\overline{v_r}$ at R15 except for the experiments whose forcings are applied near R15 (L550 – L650). This strong relationship between these two variables is found not only in the time-averaged results but also in the segmented time data (not shown).

To examine this relationship quantitatively, budget analyses of AAM are performed. The equation for the time evolution of AAM in a cylindrical coordinate is

$$\frac{\partial(\pi M)}{\partial t} = -\nabla \cdot (\pi M \mathbf{v}) - \frac{\partial}{\partial \sigma} (\pi M \dot{\sigma}) - \frac{\partial(\pi \phi)}{\partial \varphi} + \frac{\partial(\sigma \phi)}{\partial \sigma} \frac{\partial \pi}{\partial \varphi} + r\pi(K_h + K_v), \quad (2.17)$$

where $\mathbf{v} = (v_r, v_\varphi)$, and K_h and K_v are the horizontal and vertical diffusion terms, respectively. By expanding Eq. (2.17), taking azimuthal averages and using the continuity equation, we have the

equation for azimuthally averaged tangential velocity tendency as

$$r\pi \frac{\partial v_\phi}{\partial t} = -\pi v_r \frac{\partial M}{\partial r} - \pi \dot{\sigma} \frac{\partial M}{\partial \sigma} + \frac{\partial(\sigma\phi)}{\partial \sigma} \frac{\partial \pi}{\partial \phi} + r(\pi K_h + \pi K_v). \quad (2.18)$$

Figure 2.11 describes time-averaged magnitude of each term in Eq. (2.18) between 1 and 96 h at R15. The third term on the right-hand side is omitted because its magnitude is three orders smaller than that on the left-hand side in all the experiments. Figure 2.11 indicates that the radial and vertical advection of AAM explains the evolution of the left-hand side of Eq. (2.18) at R15 except for the experiments in which forcing is located around R15 (500–650 km). The contribution of the diffusion term becomes large in the experiments in which forcing is located around R15 because the spatial variation of wind speed at R15 becomes large when the forcing is applied near R15.

In contrast, different characteristics are confirmed in the annulus forcing experiments (Fig. 2.12). The evolution of the left-hand side of Eq. (2.18) is explained by the radial advection of AAM, and the vertical advection of AAM and diffusion term hardly contribute to the evolution of the left-hand side except for the experiments in which forcing is located around R15. The difference of the results of the budget analyses between the standard experiments and annulus forcing experiments is related to the contribution of the asymmetric components of the radial and vertical advection of AAM, the details of which are discussed in section 5. The vertical advection does not have the axisymmetric component except for the region near forcing and is constituted of the asymmetric component. Therefore, the vertical advection of AAM is almost zero at R15 and the radial advection of AAM corresponds to the left-hand side of Eq. (2.18) in the annulus forcing experiments. Based on these results and the relationship between the radial velocity at R15 and the increase in R15 (Fig. 2.10), we can conclude that the radial advection of AAM governs the size change of vortices and its dependence on the forcing location.

4.4 Trajectory analyses

In subsection 4.3, we showed that the increase in vortex size is larger when the inflow at R15 is stronger. We also pointed out that the radial advection of AAM mainly contribute to the increase of the tangential wind at R15. This could be supposed to result from that larger AAM located outside R15 can come to the inside of R15 when the inflow at R15 is strong. In this subsection, we confirm this idea by using the backward trajectory analysis.

In the analyses, 360 parcels, distributed uniformly in azimuth, are placed at the initial R15 (540 km) and $\sigma^* = 0.95$ (approximately 400 m) at $t = 96$ h. After time interpolation for every 10 min from the hourly output, backward time integration of the parcel position is performed to $t = 0$ h using the fourth-order Runge-Kutta method. We use linear interpolation for time and cubic spline interpolation for space.

First, we examine the relationship between the increase of R15 and the average radial movement of all parcels in the trajectory analyses. Figure 2.13 illustrates the relationship between time-averaged increase of R15 and the averaged radial movement of the parcels in the trajectory analyses in each experiment. The distance of inward movement tends to be longer as the increase of R15 is larger. In other words, the vortex size becomes larger as the parcels come from farther distances outside R15.

Next, time evolution of the radial movement of the parcels in the trajectory analyses is investigated. Figure 2.14 shows the radial movement of the parcels in 48 hours and 96 hours. When the forcing is applied inside 250 km, there is no appreciable difference between the radial movement of the parcels in 48 hours and 96 hours. This result indicates that the parcels hardly move in the latter part of the analyses. Conversely, the radial distance of the movement of the parcels in 96 hours is twice as long as that in 48 hours when the forcing is applied further than 300 km. This result indicates that the parcels come from farther distances with time, that is, this result suggests that the parcels come from farther distance when the analyses are performed longer than 96 hours.

Next, the AAM change along the parcel trajectories is investigated. Figure 2.15 illustrates the relationship between the average parcel positions and AAM in L100 and L400. The AAM at the end

of the analyses (i.e., at the start of the experiments) at the average position of the parcels (the rightmost marks) is almost the same as that of the initial AAM in both experiments. In L400, we can see the parcels moving toward R15 while conserving AAM. On the other hand, the parcels hardly move and the change of AAM is small in L100. In accordance with this contrast, the line of azimuthally averaged AAM at $t = 96$ h moves to as long as 150 km from the initial R15 in L400, whereas it hardly moves in L100.

From the above, it is demonstrated that when the forcing is located on the outer part of the vortex but still inside R15 like L400, the transport of larger AAM located at farther distance strengthens the tangential wind near R15 and then the vortex size grows. We also demonstrated that when forcing is applied near the center of the vortex like L100, the inflow at R15 is weak and the transport of AAM becomes small. Additionally, when the forcing is located on the outer part of the vortex but still inside R15, we showed that there is a possibility that the parcels come from farther distance when the analyzing period is extended. Based on the fact that AAM is larger as the distance from the center is longer, these results indicate that where the origins of the parcels coming to R15 are is important for the change of R15.

4.5 Secondary circulation and the change of R15

In the previous subsection, we showed from the trajectory analyses that the vortex size becomes larger as the parcels come from farther distance outside R15, transporting larger AAM inward to R15. The movement of parcels at the lower level is related to not only the strength of the radial wind at R15, but also the spatial distribution of the radial wind, which is connected to the structure of the secondary circulation (SC) induced by forcing. Therefore, we can expect that there is a relationship between the vortex size change and the structure of the SC induced by forcing. In this subsection, we investigate the relationship between the structure of the SC and the change of R15.

a) Horizontal extent of secondary circulation

To deal with the overall structure of SC, we first consider its horizontal extent in the low level.

We define the extent of the SC at the lowest level as the distance between the location of forcing and the outer edge of the descending region of the SC. The outer edge is defined as the point where the divergence of radial wind, $\frac{1}{r} \frac{\partial(r\overline{\pi v_r})}{\partial r}$, is 1/10 of its maximum outside the location of forcing, i.e., the point where the descending flow becomes weak. Note that $\overline{\pi v_r}$ can be expanded as $\overline{\pi} \overline{v_r} + \overline{\pi' v_r'}$, but the second term is small enough to be neglected.

The divergence of radial wind is the same as the first term on the right-hand side of the azimuthally averaged continuity equation:

$$\frac{\partial \overline{\pi}}{\partial t} = -\frac{1}{r} \frac{\partial(r\overline{\pi v_r})}{\partial r} - \frac{\partial(\overline{\pi \dot{\sigma}})}{\partial \sigma}. \quad (2.19)$$

Thus, the divergence of radial wind is nearly equals to the convergence of vertical velocity when $\partial \overline{\pi} / \partial t$ is small. In fact, it is two to three orders smaller than the other terms, which means that it is sufficiently small to be neglected.

Examples of the horizontal scale of the SC are represented in Fig. 2.16, which shows the divergence of radial wind at the lowest level in L100 and L400. In L100 (Fig. 2.16a), the divergence of radial wind has a positive peak at $r \sim 200$ km. Beyond this peak, the divergence of radial wind becomes negative at $r \sim 300$ km, so that the extent of the SC is about 200 km, as obtained by the subtraction of the forcing location from 300 km. In L400 (Fig. 2.16b), the divergence of radial wind has a positive peak at approximately 700 km and reaches 1/10 of its maximum near 1000 km. The extent of the SC is thus 600 km.

We first examine the dependence of the horizontal scale of SC on the forcing location. Figure 2.17 shows the location of the outer edge of the SC in each in Series L. In the experiments in which forcing is applied near the center of the vortex (L100–L250), the edge of the SC is mostly located at the inside of R15. L150 and L200 are exceptions. However, even in these experiments, the edge of SC scarcely extends beyond initial R15. In contrast, in the experiments in which forcing is applied to the outer part of the vortex but still inside R15 (L275–L450), the edge of the SC is located outside R15. Moreover, the location of the edge of the SC tends to be located further as the forcing is located further out.

Next, we compare the extent of the SC beyond the initial R15 and the increase in R15. Figure 2.18 shows the relationship between the extent of the SC beyond the initial R15 and the increase in R15; it is evident that the increase in R15 is larger as the outer edge is located further out. This result indicates that when the SC extends beyond R15, the vortex size grows because the inflow constituting the SC near R15 becomes strong, whereas when the SC does not extend beyond R15, the vortex size hardly changes because the inflow near R15 is weak.

As described above, we can conclude that the horizontal scales of the SC is related to the large or small of the increase in R15. When the forcing is applied inside R15, vortex size grows more as the SC induced by forcing extends further beyond R15, from which large AAM is transported inward.

b) Structure of secondary circulation

Next, to further consider the difference between the cases in which the SC extends beyond R15 and that does not, the structure of the SC including the upper-level flow is examined. In the following, only the results of L100 and L400 are compared as the representatives of the cases. Figure 2.19 shows the SC ($\overline{v_r}, \overline{\sigma}$) and the radial velocity in the (r, σ^*) cross sections in the two cases. The inflow region (for example, the region where the radial velocity is under -0.25 m s^{-1} in L400 whose SC extends wider than that in L100. Comparing the altitudes of the outflow layer in L100 and L400, we find the levels of the most intense outflow are located on $\sigma^* = 0.24$ in L100 and $\sigma^* = 0.43$ in L400, respectively, so that the outflow layer in L100 is located more upper level than that in L400. Additionally, focusing on the distribution of the downward flow, the downward flow in L400 is prominent in a wider range outside forcing region (500 – 1000 km from the center), whereas that in L100 exists only a narrow region just outside forcing region (200–250 km, $\sigma^* = 0.95\text{--}0.72$).

These characteristics can be confirmed in the experiments with higher vertical resolution. Figures 2.19c and d illustrate the SC and AAM distribution in L100 and L400, respectively obtained by the 11-level model. The results of 11-level model shows that the altitude of the outflow layer in L100 ($\sigma^* = 0.33$) is located more upper level than that in L400 ($\sigma^* = 0.43$). We can also confirm from the results that the downward flow region in L400 is wider than that in L100. These characteristics found

in the results of 11-level model are the same as those of five level model.

In summary, in the experiments in which the SC exceeds the initial R15, the SC has a horizontally broad structure. Therefore, the inflow accompanying with the SC becomes strong near R15 and the parcels having larger AAM come from further distance. As a result, the vortex size grows. In contrast, in the experiments in which the SC does not reach the initial R15, horizontal extent of the SC is narrow. Therefore, the inflow and thus tangential wind near R15 does not much strengthen. As a result, the vortex size hardly change.

4.6 Secondary circulation and inertial stability

In the previous subsection, we demonstrated that whether the SC exceeds the initial R15 or not is important for the size change of the vortex. In this subsection, from the perspective of the inertial stability, we consider what determines the structure and horizontal extent of the SC.

As mentioned in section 3, inertial stability I , which is defined in Eq. (2.15), serves as an index of the difficulty of horizontal movement. This is paired with static stability (Brunt-Väisälä frequency), N , which serves as an index of the difficulty of vertical movement. The distribution of these two constrains SC: when I is relatively large, SC becomes a vertically elongated structure, while in the opposite case, the structure expands horizontally (Holland and Merrill 1984). Parcel trajectory analyses by Miyamoto and Takemi (2013), which pointed out the important role of increased inertial stability in confining high enthalpy air within close to the TC center prior to rapid intensification, also support the above relationship.

Figure 2.20 shows I and N in L100 and L400. In both cases, the radial variation of N is not large, except around the forcing region in L100, but I exhibits a large radial variation. In the lower layer, I exhibits a large gradient inside 400 km from the vortex center and is almost constant outside this point. Examining more closely, the distribution of I differs between L100 and L400, being very large near the vortex center in the former. Its maximum value is approximately $140 \times 10^{-5} \text{ s}^{-1}$ in L100, which is four times larger than that in L400. This larger maximum in L100 results from the stronger

tangential wind near the vortex center.

The distributions of I provide clues on the difference in the structure of the SC between the cases in which the SC does not exceeds the initial R15. In the former, I is very large near the vortex center, especially in the lower layer. Near the forcing region, because I becomes relatively larger than N , air parcels are limited to move radially. Therefore, the SC tend to become vertically tall. As a result, in the case of L100, for example, the outflow layer tend to be located at high altitude and the extent of the SC becomes narrow.

4.7 Analyses of the results of experiments when forcing is applied outside R15

When the forcing is applied outside the initial R15, R15 decreases with time (Fig. 2.9). The mechanism of decreasing R15 is fundamentally the same as that of the increase of R15 in the cases where the forcing is located at the inside of the initial R15, discussed in the previous section. The radial flow at the lowest level at R15 is outward associated with the heat-induced SC located at the inner side of the forcing location. Because the evolution of AAM at R15 in the experiments when the forcing is located at the outside of initial R15 is also dominated by the radial advection of AAM (Fig. 2.11), smaller AAM located near the center of the vortex transported to around R15 decreases AAM at R15, resulting in the decreases of tangential flow and R15.

The absolute degree of the change of R15 when the forcing is applied outside R15 is smaller than that when the forcing is located at the inside of R15. The reason is that the heat-induced SC located at the inner side of the forcing location is weaker than that located outside the forcing location (see also Fig. 2.19) so that the radial flow at the lowest level at R15 in the case when the forcing is applied to the outside of R15 is weaker than that in the case when the forcing is applied to the inside of R15 (See Fig. 2.10).

There are two reasons for the difference between the intensities of SC inside and outside of the forcing location. The first reason is the asymmetry of the radial distribution of inertial stability. The inertial stability scarcely changes outside the forcing location, whereas that becomes larger as the

location is closer to the center of the vortex (Fig. 2.21). As mentioned in subsection 4.6, the radial movement is prohibited when the inertial stability is large. Thus, the heat-induced SC located at the inner side of the forcing location is weak. The other reason is the geometrical effect of the basically axisymmetric heating, the flow induced by forcing affects the flow at an azimuthally different location from the forcing. In the induced flow at the azimuthally different location, the tangential component is canceled by that at the opposite side, whereas the radial component directed to the center remains. Thus, the azimuthally averaged inflow strengthens and the azimuthally averaged outflow weakens (e.g., Schubert and McNoldy 2010). The radial wind speed at forcing location not becoming just zero is due to the geometrical effect.

Both of the two effects above are weak when the location is far from the center of the vortex. In fact, in the case when forcing having width of 100 km and strength of $1.0Q$ is applied to 2000 km from the center of the initial vortex, the radial distribution of the inertial stability is not much difference between the inner and outer sides of the forcing location (Fig. 2.21). In fact, in a supplementary experiment in which forcing is applied to 2000 km from the center, the strength of the heat-induced SC in both the inner and outer sides of the forcing location is almost the same (Fig. 2.22). As described above, we can conclude that the asymmetry of the heat-induced SCs inside and outside of the forcing is caused by the radial inhomogeneity of the distribution of the inertial stability and the geometrical effect.

4.8 Summary

From the results of the parameter experiment in which sensitivity of the size change of vortices to the location of forcing (Series L), we clarified that the change of R_{15} depends on the location of forcing. The dependence can be understood by considering radial transport of absolute angular momentum (AAM) at R_{15} by the heat-induced secondary circulation (SC), whose structure is governed by the distribution of inertial stability, I . Figure 2.23 schematically illustrates the relationship between the SC, radial advection of AAM, and R_{15} . When forcing is applied near the center of the vortex (Fig.

2.23a), the structure of the SC becomes horizontally narrow because inertial stability near the forcing region is high. Therefore, the inflow near R15 is weak and, hence, the radial advection of AAM becomes small. Thus, R15 hardly changes. Next, when forcing is located on the outer part of vortex but still inside R15 (Fig. 2.23b), the horizontal extent of the SC becomes wide because inertial stability near the forcing region is low. Therefore, strong inflow exists near R15, which causes strong radial AAM advection there. Thus, the vortex size becomes large. Finally, when the forcing location is outside R15, the flow direction of the SC induced by the forcing near R15 is opposite from the others (Fig. 2.23c). Thus, this outflow near R15 causes negative radial AAM advection and the vortex size decreases.

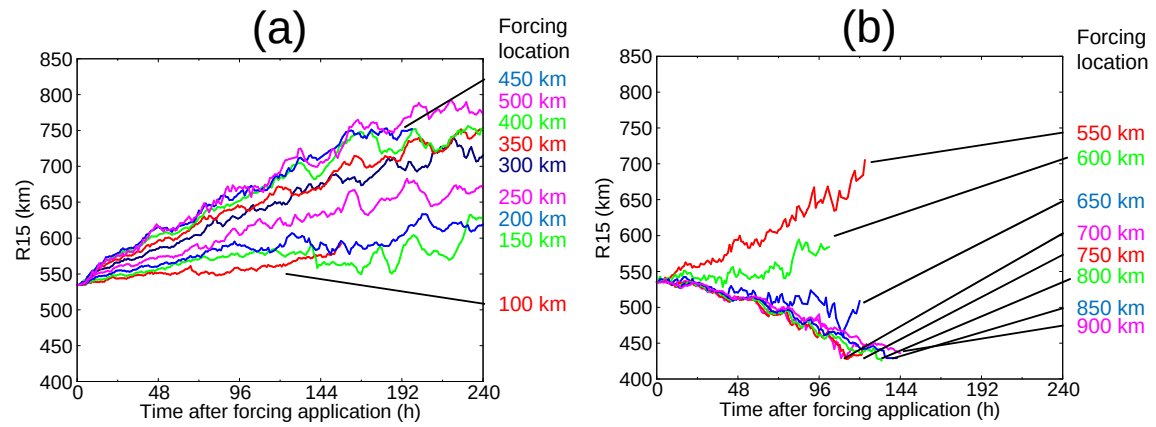


Figure 2.9: Time evolution of R15 in the experiments in which locations of forcing are changed. The left and right panels show the cases in which the forcing locations are (a) 100–500 km and (b) 550–900 km, respectively. For ease of view, only the results of every 50 km are shown. The ordinate and the abscissa represent R15 (km) and time (hour) after forcing application, respectively.

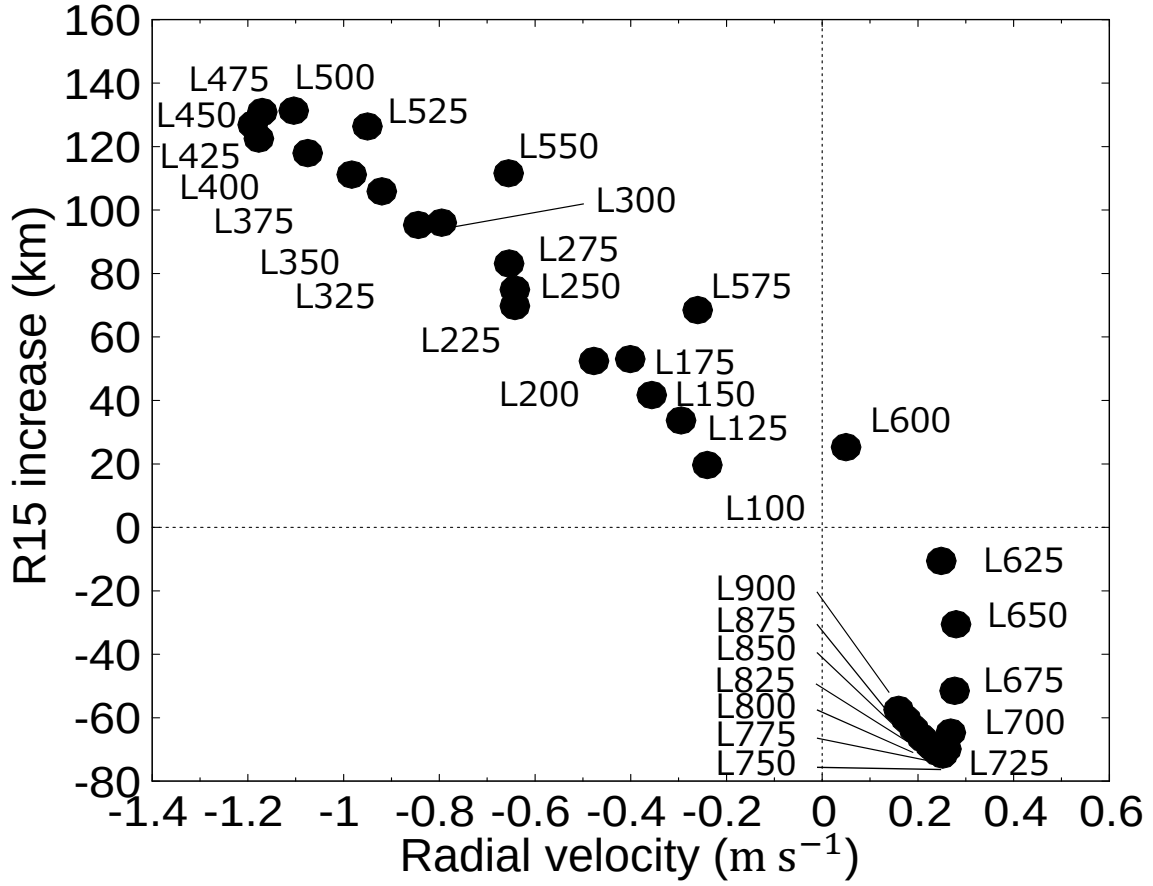


Figure 2.10: Relation between the increase in R15 (ordinate) and time-averaged v_r at R15 (abscissa) in each experiment in Series L. The increase in R15 is calculated as the difference between the 84 to 108-h average and initial R15, and v_r is averaged between 1 and 96 h. The ordinate and the abscissa represent the time-averaged increase of R15 (km) and time-averaged radial velocity at R15 (m s⁻¹), respectively.

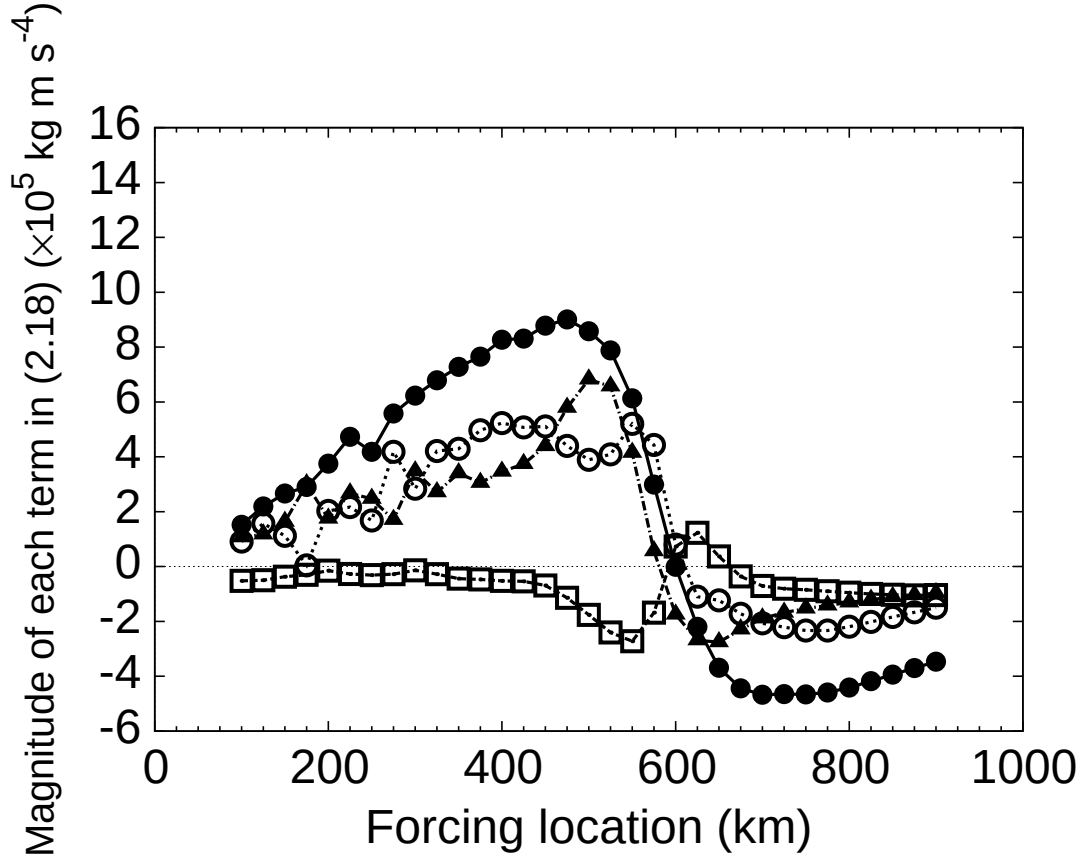


Figure 2.11: Magnitudes of each term in Eq. (2.18) of each experiment in Series L (ordinate, unit: 10^5 kg m s^{-4}). The abscissa shows the forcing location. These values are averaged between 1 and 96 h at R15. The solid line with closed circles represents the left-hand side, while the dotted line with open circles, dash-dotted line with triangles, and dashed line with squares indicate the first term ($-\pi \nu_r \frac{\partial M}{\partial r}$), the second term ($-\pi \sigma \frac{\partial M}{\partial \sigma}$), and the sum of the fourth and fifth terms (diffusion term), respectively, on the right-hand side. The third term on the right-hand side is omitted because its value is negligible.

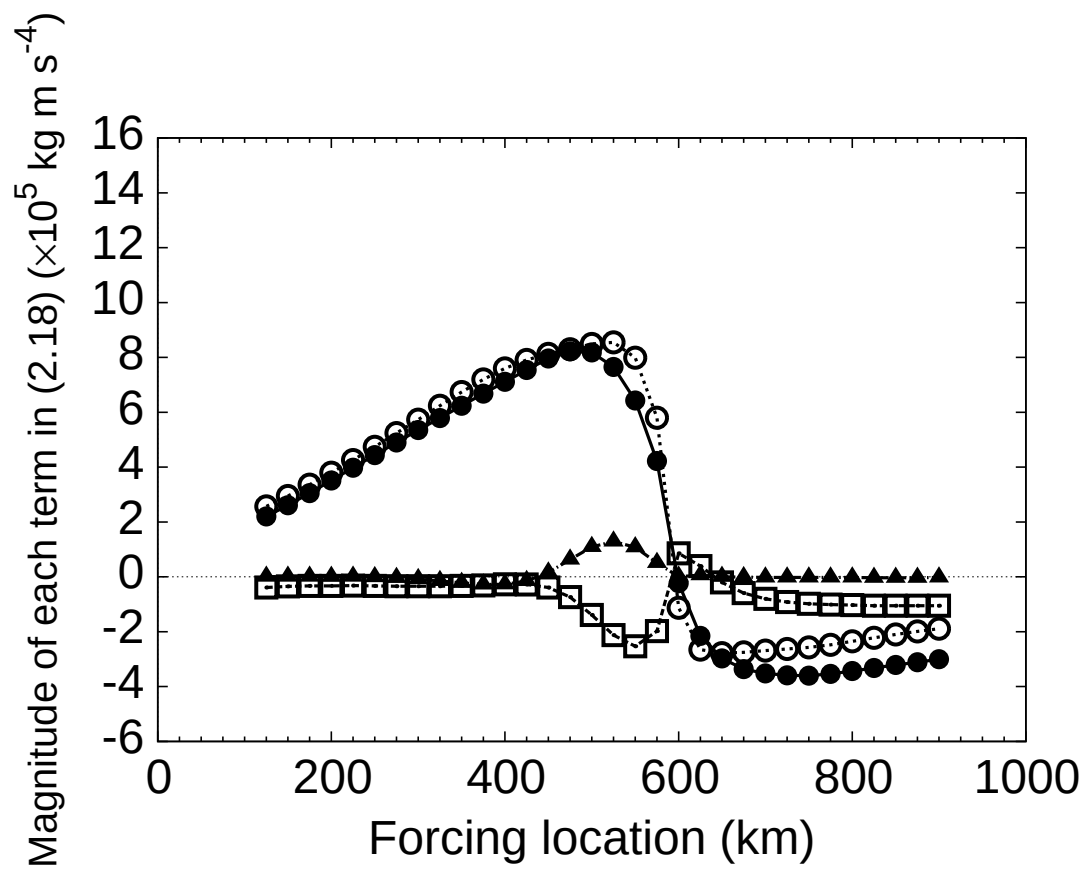


Figure 2.12: As in Fig. 2.11, but for the annulus forcing experiments in Series L.

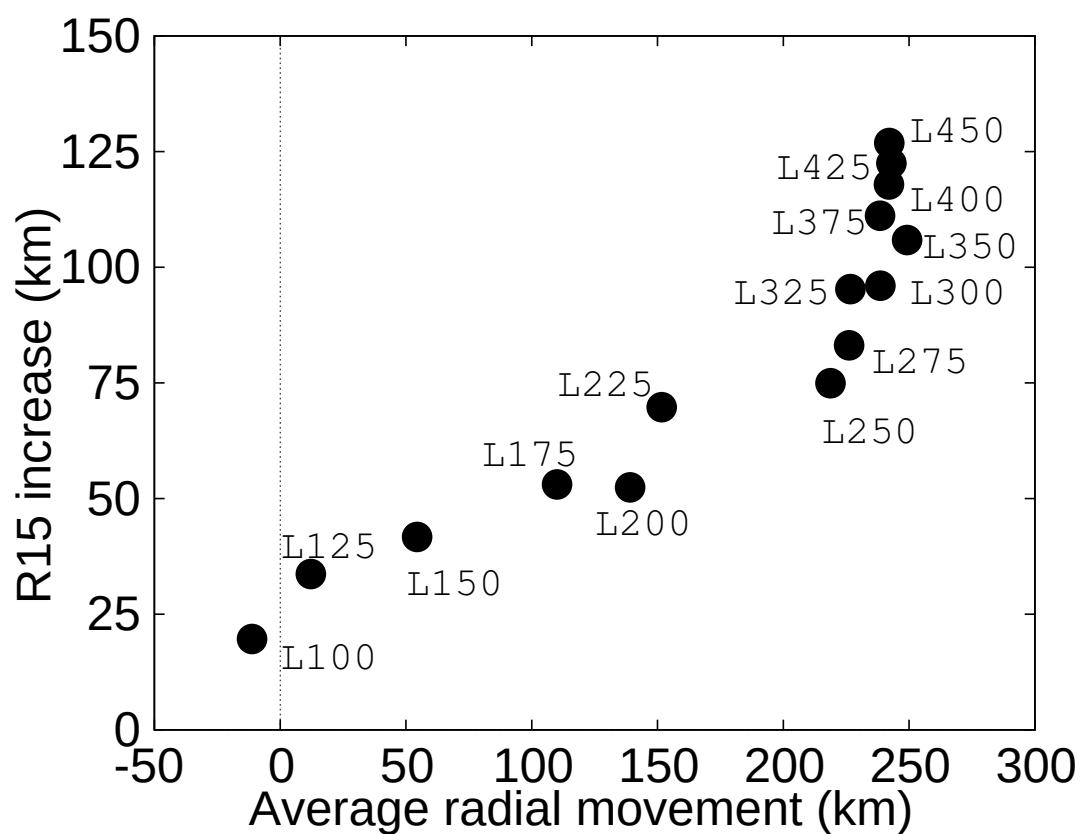


Figure 2.13: Relationship between time-average increase in R15 between 84 and 108 h (ordinate) and the average radial movement of all parcels in 96 hours in the trajectory analyses (abscissa). Symbols (L plus numerals) indicate each experiment (L100–L450).

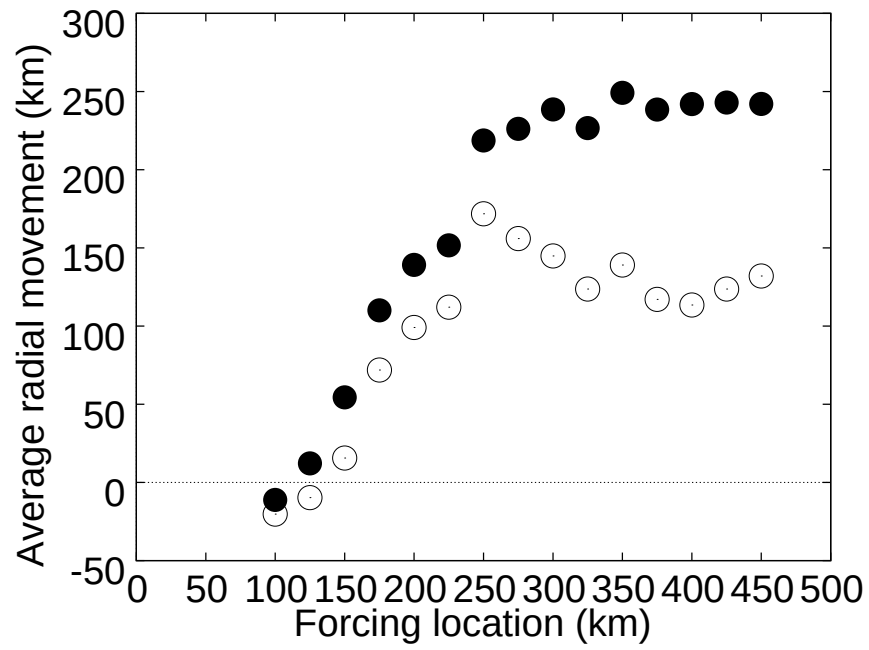


Figure 2.14: Average radial movement of all parcels in 48 hours (open circle) and 96 hours (closed circle) in the trajectory analyses. The ordinate and the abscissa represent forcing location (km) and average radial movement of parcels (km), respectively.

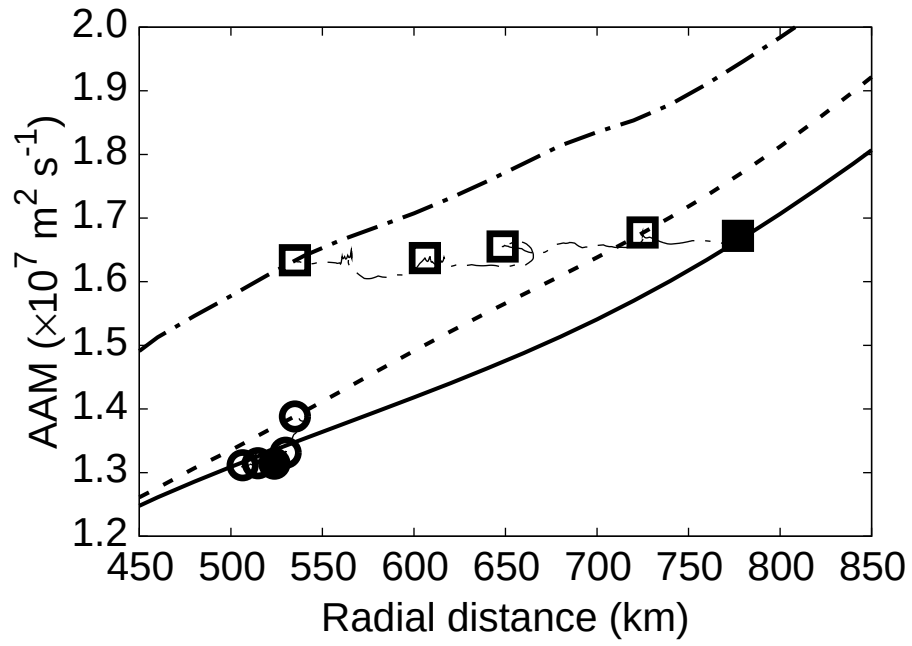


Figure 2.15: Average positions of the 360 parcels from $t = 96$ to $t = 0$ and AAM in L100 (dotted line) and L400 (dash-dotted line). Thick and thin lines represent the azimuthally averaged AAM at $t = 96$ and the averaged parcel positions, respectively. The open circles and squares on the thin lines designate the positions at each 24 h, and the filled marks indicate the positions at the end of the analyses, i.e., positions at $t = 0$. The thick, solid line shows the azimuthally averaged initial AAM.

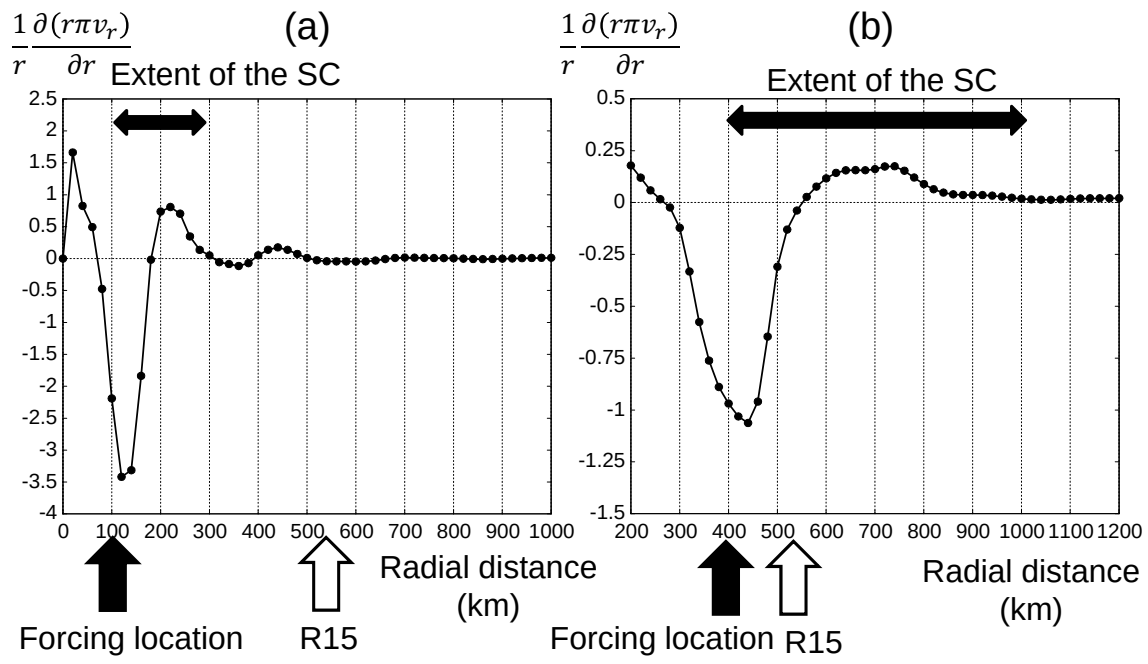


Figure 2.16: Divergence of radial wind at the lowest level in (a) L100 and (b) L400. These values are temporally and azimuthally averaged between 1 and 96 h. The ordinate represents the divergence of radial wind ($\text{kg m}^{-1} \text{s}^{-3}$). The black and white arrows show the forcing location and initial R15, respectively. The double-headed arrows designate the extent of the SC.

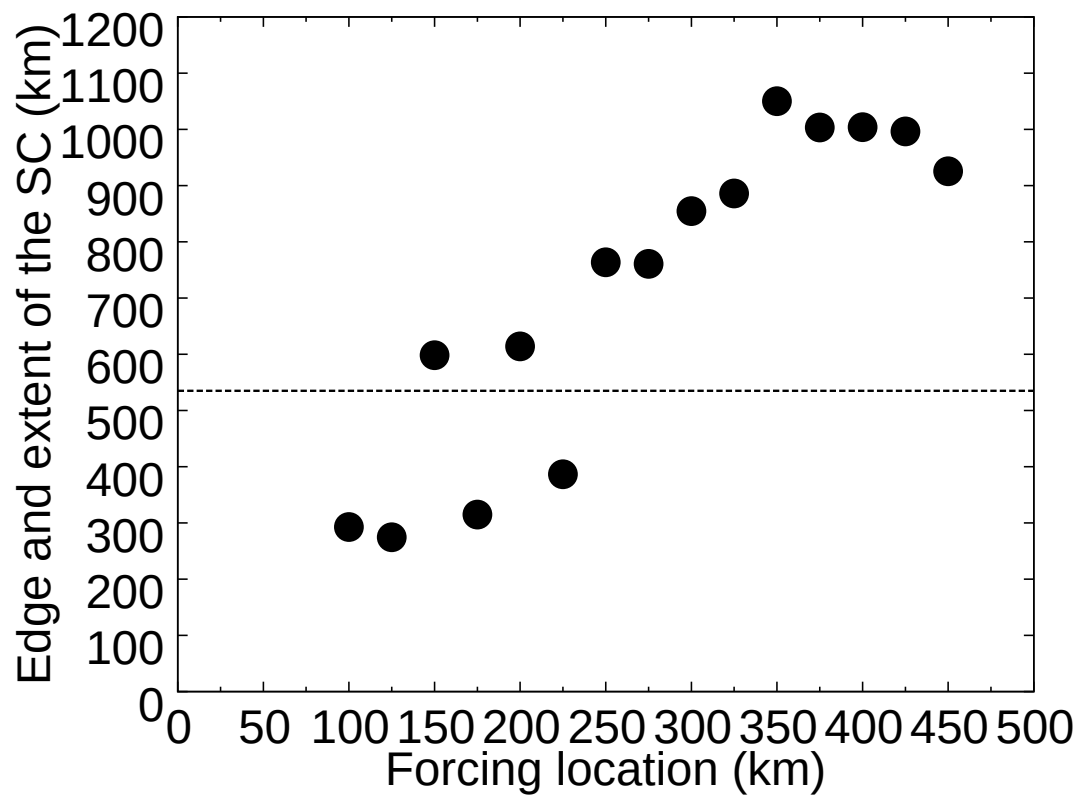


Figure 2.17: Location of the edge of the SC for each forcing location (abscissa). The dotted line shows the initial R15.

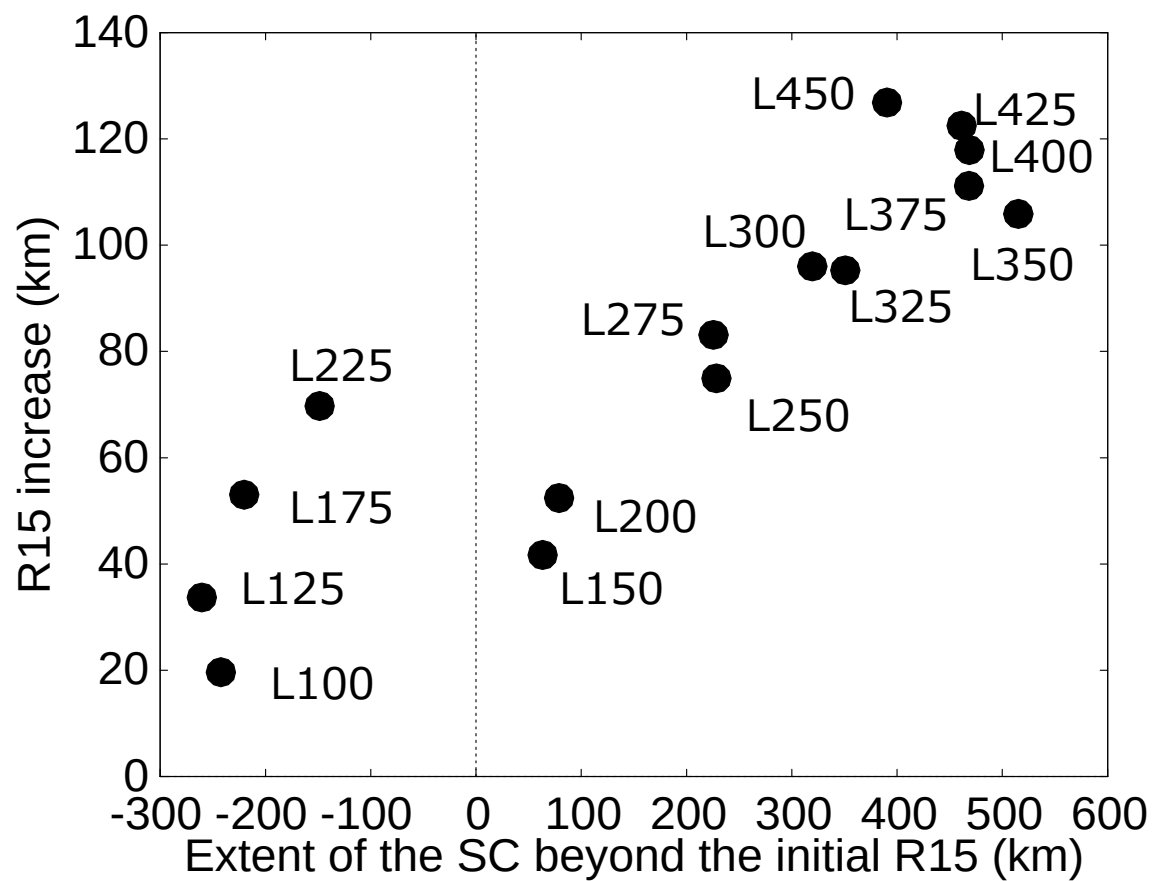


Figure 2.18: Relationship between the extent of the SC beyond the initial R15 (abscissa) and the increase in R15 (ordinate). Symbols (L plus numerals) indicate each experiment (L100–L450).

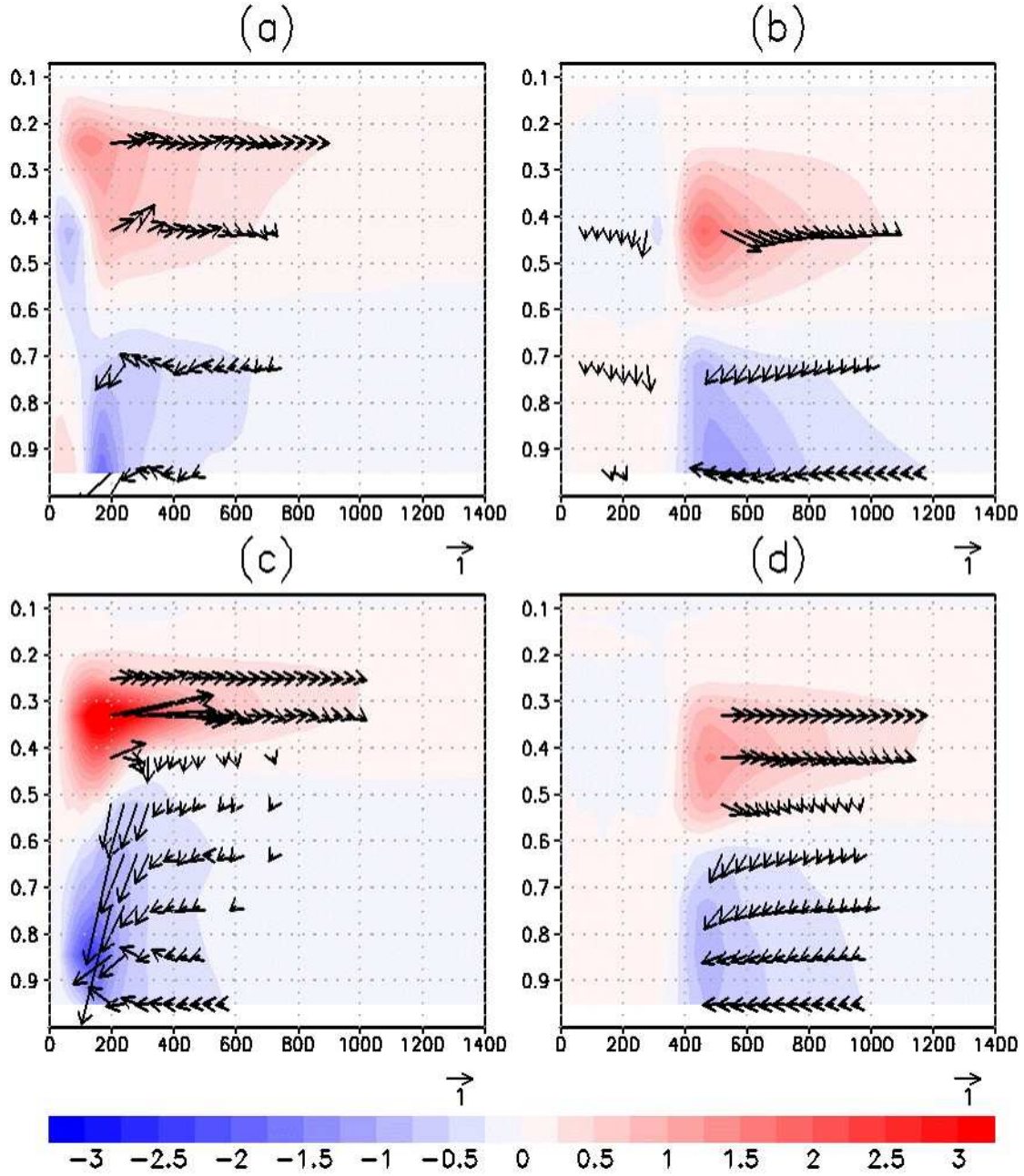


Figure 2.19: $\bar{v}_r$ and $\bar{\sigma}_r$ (arrows) and the azimuthally averaged radial wind (color; unit: m s^{-1}) in (a), (c) L100 and (b), (d) L400; (c) and (d) show the results of the experiments using the 11-level model. These values are temporally averaged between 1 and 96 h. The scale of the arrows is shown at the lower left of each figure and normalized in each coordinate. The arrows in the region of the forcing and of $|\bar{v}_r| < 0.25 \text{ m s}^{-1}$ (and their corresponding $\bar{\sigma}_r$) are not depicted. The ordinate and the abscissa represent σ^* and radial distance from the center (km), respectively.

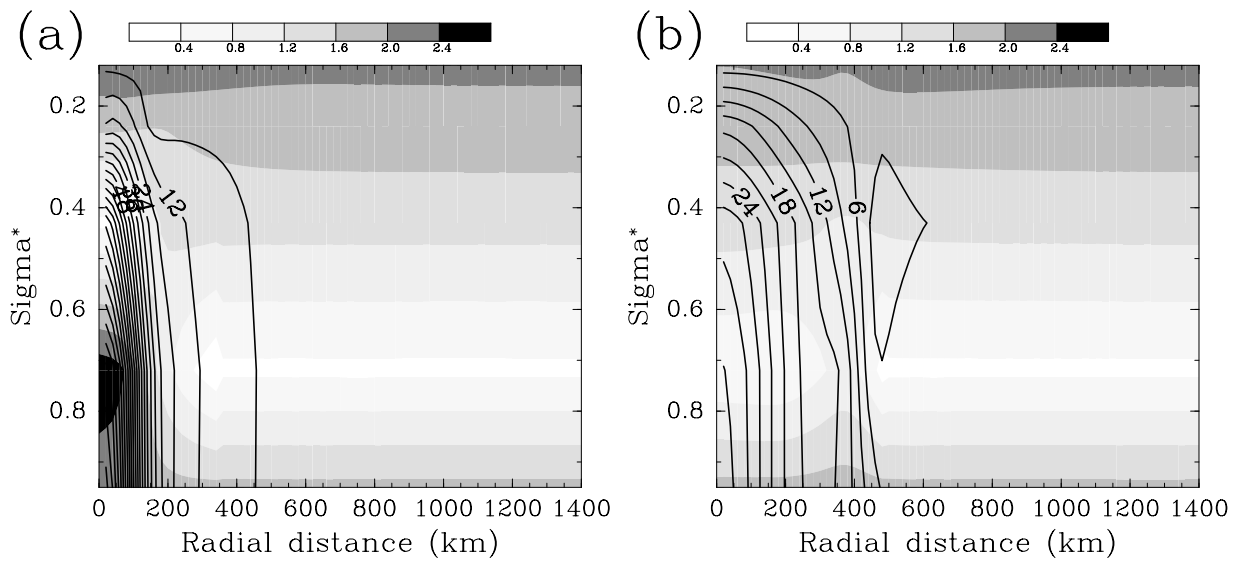


Figure 2.20: Inertial stability (I ; solid line; unit: 10^{-5} s^{-1}) and static stability (N ; shading; unit: 10^{-2} s^{-1}) in (a) L100 and (b) L400. These values are temporally and azimuthally averaged between 1 and 96 h. The contour interval is $6 \times 10^{-5} \text{ s}^{-1}$ in (a) and $3 \times 10^{-5} \text{ s}^{-1}$ in (b).

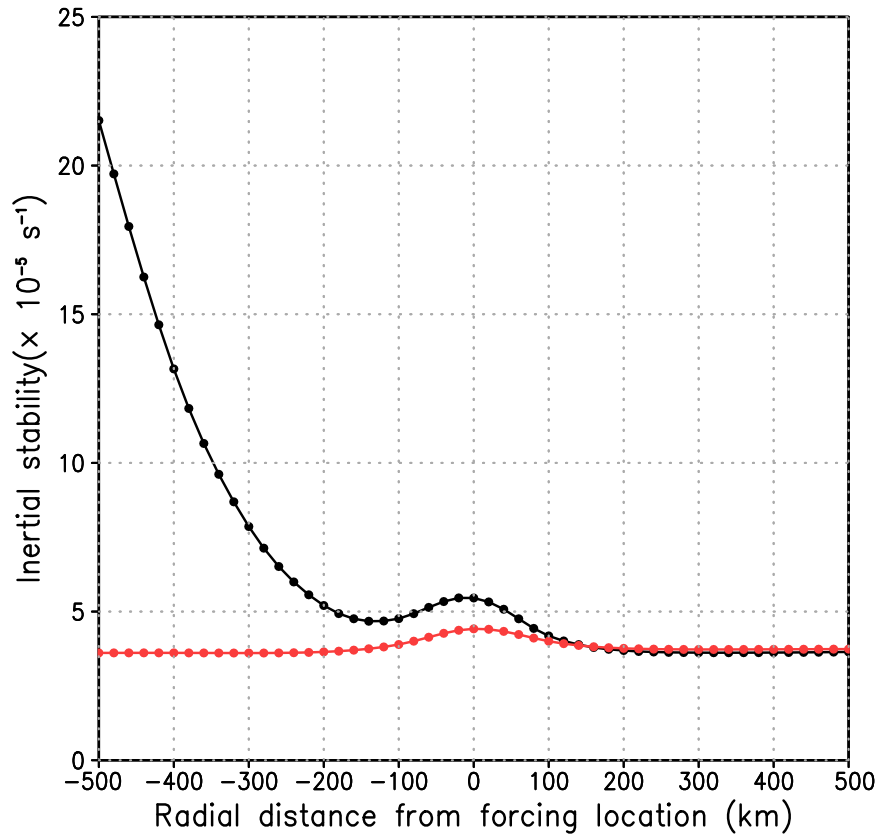


Figure 2.21: Radial distribution of inertial stability (I) in the experiments in which forcing is applied to 700 km (black line) and 2000 km (red line) at the lowest level around forcing region. These values are temporally and azimuthally averaged between 1 and 96 h. The ordinate and the abscissa represent inertial stability I (s^{-1}) and radial distance from forcing locations (km), respectively.

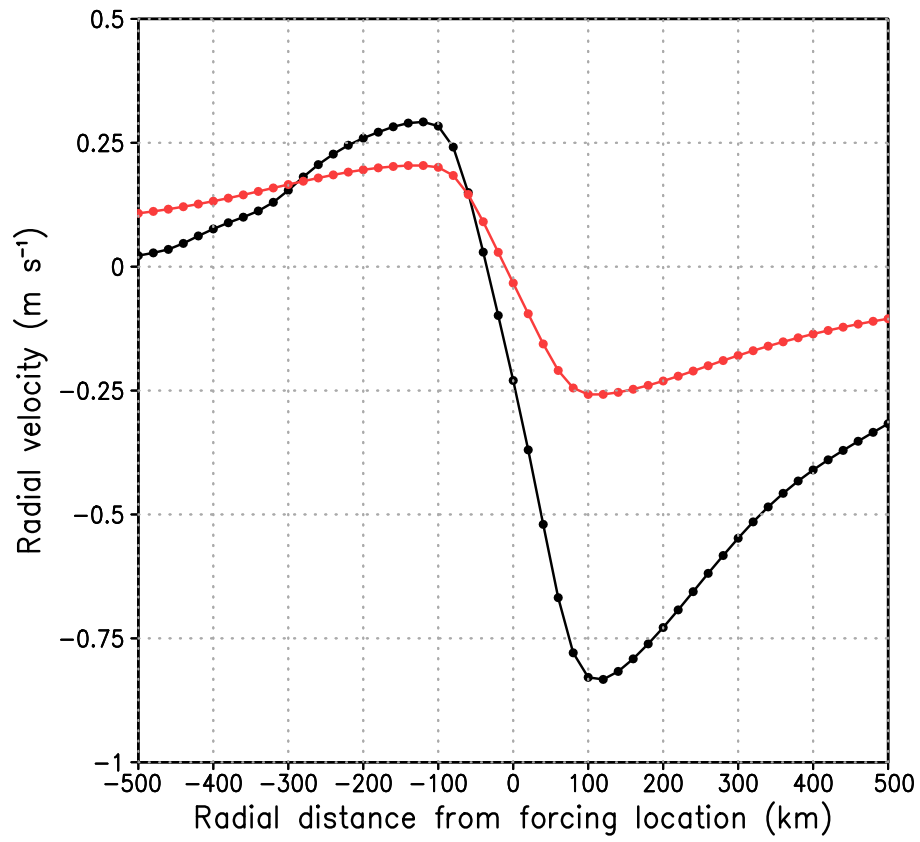


Figure 2.22: Radial distribution of radial velocity in the experiments in which forcing is applied to 700 km (black line) and 2000 km (red line) at the lowest level around forcing region. These values are temporally and azimuthally averaged between 1 and 96 h. The ordinate and the abscissa represent radial velocity (m s^{-1}) and radial distance from forcing locations (km), respectively.

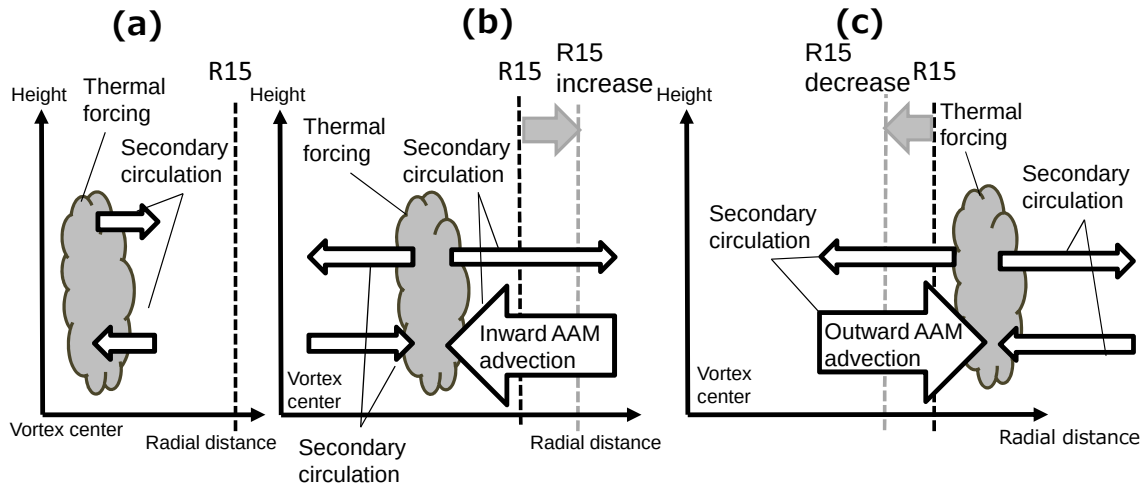


Figure 2.23: Schematics of explaining the SC induced by thermal forcing and the change of R15 in the cases that forcing is applied (a) near the center, (b) a relatively outer region inside R15, and (c) outside R15. The dark and thin dashed lines indicate the initial R15 and R15 at some time later, respectively.

5 Sensitivity of vortex size change to the strength and scales of forcing

5.1 Specifications of the experiments

In this subsection, we investigate the sensitivity of the size change of vortices to the strength and scales of forcing. In the parameter experiment in which the sensitivity to the strength of forcing is investigated (Series Q), the location and scales of forcing are set to the standard values (400 km, 100 km) and the strength of forcing is changed. On the other hand, in the parameter experiment in which the sensitivity to the scales of forcing is investigated (Series S), the location and strength of forcing are set to the standard values (400 km, 1.0Q) and the scales of forcing is changed. We also perform parameter experiments in which the location of forcing is set besides the standard value. The initial vortex Nominal, whose initial R15 is 535 km, is used in both parameter experiments.

The names of the parameter experiments and each experiment are summarized in table 2.2. We refer the names of each parameter experiment as, for example, “S-L500”, where “S” indicates Series S and “L500” represents a forcing location 500 km. We refer the names of each experiment as, for example, “S60-L500”, where “S60” represents a scales of forcing 60 km in Series S and “L500” designates that forcing is applied to 500 km from the center.

5.2 Temporal evolution of vortex size

First, we show the results of each experiment in Series Q. Figure 2.24 illustrates the time evolution of R15 in each experiment in parameter experiment Q-L400. R15 changes with time by a constant rate. This characteristic can also be seen in the other parameter experiments in which forcing location is set besides 400 km. Additionally, the strength of forcing is almost proportional to the change of R15 from the initial in any forcing location (Fig. 2.25).

Next, we represent the results of each experiment in Series S. Figure 2.26a illustrates the time evolution of R15 in each experiment in parameter experiment S-L400. R15 also increases with time by a constant rate, same as Series Q but the change rate of R15 does not depend on the scales of forcing, which indicate that the change of R15 does not have the sensitivity to the scales of forcing

(see also Fig. 2.27). Excepting for, for example, parameter experiments S-L500 and S-L600 in which forcing is applied near R15, this is true even for parameter experiments in which forcing is applied besides 400 km. However, as in parameter experiment S-L200 shown in Fig. 2.26b, the change of R15 varies with the scales of forcing after 72 hours, according to the scales of forcing. This variation of the change of R15 results from that the vortex tends to be unstable and thus to be deformed when the scales of forcing is wide. The instability of the vortex after 72 hours can be confirmed in some parameter experiments in Series S. Therefore, in the analyses of Series S, we use only the data before 72 hours.

Figure 2.27 shows the increase in R15 from the initial in each experiment in each parameter experiment. In parameter experiment S-L500, R15 increases with the scales of forcing when the scales of forcing is narrower than 100 km. Moreover, in parameter experiment S-L600, R15 increases as the scales of forcing becomes wide. In the other parameter experiments, the change of R15 does not depend on the scales of forcing.

In summary, the change of R15 is proportional to the strength of forcing and does not depend on the scales of forcing except some experiments in which forcing is applied near R15.

5.3 Radial wind and budget analyses of absolute angular momentum at R15

In the previous subsection, we clarified that the change of R15 is larger as the strength of forcing is larger, but does not depend on the scales of forcing except for some experiments. In this subsection, we examine the reason by investigating the radial wind at R15 and performing budget analyses of AAM at R15.

First, we investigate the characteristics of the radial wind at R15 in Series Q. Figure 2.28 represents the relationship between the strength of forcing and the time-averaged radial wind at R15. In all the parameter experiments, the radial wind is proportional to the strength of forcing. From these results and the increase of R15 (Fig. 2.25), it is indicated that the stronger the strength of forcing is, the stronger the radial wind at R15 is and then the larger the change of R15 is.

Next, the characteristics of the radial wind at R15 in Series S is examined. Figure 2.29 shows the relationship between the scales of forcing and the time-averaged radial wind at R15 in each experiment in each parameter experiment. The radial wind at R15 does almost not depend on the scales of forcing except for the parameter experiments in which forcing is applied near R15 like parameter experiments S-L500 and S-L600. These results are consistent with that the increase of R15 does not depend on the scales of forcing except for the parameter experiments in which forcing is applied near R15 (Fig. 2.27). Conversely, in parameter experiments S-L500 and S-L600, the radial wind at R15 becomes weak as the scales of forcing is wide (Fig. 2.29).

To clarify the reason why the radial wind at R15 becomes weak as the scales of forcing is wide in parameter experiments S-L500 and S-L600, the radial distribution of radial wind is investigated. Figure 2.30 shows the time-averaged radial distribution of radial wind at the lowest level in the experiments in which the scales of forcing is set to 100 km, 140 km, and 180 km in parameter experiments S-L500 and S-L600. In the outside of the forcing region, the distribution of radial wind in each experiment is overlapped in both inflow and outflow regions, whereas the distribution is different in the inside of the edge of the forcing region. In the inside of the forcing region, the inflow in the outer side than the forcing location becomes weaker as the scales of forcing is wider, whereas the outflow in the inner side than the forcing location becomes weak and, especially near the forcing location, becomes inflow as the scales of forcing is wider. The radial flow is not just zero at forcing location because of the geometrical effect mentioned in subsection 4.7.

Taking this distribution of the radial wind into consideration, we can understand the dependence of the radial wind at R15 on the scales of forcing in parameter experiments S-L500 and S-L600. In parameter experiment S-L500, because the initial R15 is located on the inside of the forcing region, the inflow at R15 becomes weaker as the scales of forcing is wider, as shown in Fig. 2.29. In parameter experiment S-L600, the outflow at R15 becomes weaker and, especially in the cases when the scales of forcing is wider than 140 km, the outflow at R15 becomes inflow as the scales of forcing is wider on the same reason of parameter experiment S-L500.

Next, we investigate the budget of AAM at R15. Figure 2.31 shows the results of the budget analyses of AAM in each experiment in parameter experiment Q-L400. When the forcing is weak, the change of the left-hand side of Eq. (2.18) is mainly controlled by the radial advection of AAM and the contribution of the vertical advection and diffusion term is small. In contrast, when the forcing is strong, the contribution of vertical advection becomes large and that of radial advection decreases. The decrease of the contribution of radial advection and the increase of the contribution of vertical advection do not occur in the annulus forcing experiments (Fig. 2.32). In the annulus forcing experiments, the change of the left-hand side is explained by the radial advection of AAM and the contribution of vertical advection and diffusion term is small, which is the same as the results of the budget analyses of AAM in Series L (section 4.3).

The results which the contribution of the radial advection of AAM decreases and that of the vertical advection of AAM increases when the forcing is strong and the contribution of the vertical advection of AAM is small in the annulus forcing experiments are related to the contribution of asymmetric components. Fig. 2.33 shows the axisymmetric and asymmetric components of radial advection term and vertical advection term. Focusing on the radial advection term (Fig. 2.33a), the axisymmetric component contributes to the increase of tangential wind and the asymmetric component contributes to the decrease of tangential wind. Both axisymmetric and asymmetric components become larger as the forcing is stronger. In contrast, in the vertical advection term (Fig. 2.33b), the axisymmetric component is almost zero regardless of the strength of forcing, whereas the asymmetric component contributes to the increase of tangential wind and becomes larger as the forcing is stronger. Additionally, comparing the asymmetric component of radial advection term with that of vertical advection term, the magnitudes of both asymmetric components are almost the same but the signs are opposite. Counteracting tendency of the asymmetric components can be confirmed not only at R15, but also at the most part of the model lowest level except for the forcing region (Fig. 2.34).

Next, we investigate the budget of AAM in Series S. Figure 2.35a shows the results of the budget analyses of AAM at R15 in each experiment in parameter experiment S-L400. Basic characteristics

are the same as the results of other experiments shown previously. When the scales of forcing is narrow, the radial advection is small and the vertical advection is large. This can be explained by the same reason as the case when the forcing is strong in Series Q, i.e., the asymmetric components becomes larger as the scales of forcing is narrower because the high frequency, high wavenumber variation of wind speed becomes large, resulting from strong forcing applied in the narrow forcing region. As a result, the contribution of the radial advection term decreases and that of the vertical advection term increases.

Such a characteristic of the budget analyses of AAM can be also observed when the forcing is applied to different distance from the center of vortices. However, a little different characteristics are confirmed when forcing is applied near R15. Figure 2.35b shows the results of the budget analyses of AAM at R15 in each experiment in parameter experiment S-L500. The magnitude of diffusion term depends on the scales of forcing in parameter experiment S-L500 and the contribution of the diffusion term in S60-L500 is two times larger than that in S200-L500. This result indicates that when the scales of forcing is wide, the contribution of diffusion term becomes small even if forcing is applied around R15 because the region where wind speed is changed by forcing becomes wider as the scales of forcing is wider.

5.4 Summary and discussion

a) Summary

From the results of experiments in which the sensitivity of the size change of vortices to the strength of forcing (Series Q), we clarified that the change of R15 depends on the strength of forcing. The inflow at the lowest model level at R15 becomes stronger and thus the radial advection of AAM increases more as the forcing becomes stronger. As a result, vortex size grows more. Because the strength of forcing is proportional to the strength of inflow, the increase of R15 is also proportional to the strength of forcing.

From the results of experiments in which the sensitivity of the size change of vortices to the scales

of forcing (Series S), we clarified that the change of R15 does not depend on the scales of forcing except for some parameter experiments in which the forcing is applied near the initial R15. The reason why the scales of forcing does not affect the change of R15 is that because the given amount of heating does not depend on the scales of forcing, the strength of radial wind induced by forcing does not change with the scales of forcing.

b) Factors generating the asymmetric components

From the results of Series Q, we showed that the magnitude of asymmetric components of radial and vertical advection terms increases with the strength of forcing. We can observe from the investigation of the time-radius distribution of the asymmetric components (Fig. 2.36) that the asymmetric components seems to consist of three components; the component arising just after starting experiments and propagating to a further distance from the center, the component arising just after starting experiments and existing only near the forcing region, and the component arising after a while and having large amplitude. The component arising just after starting experiments and propagating to a further distance from the center in the radial advection is distributed in a similar range as that in the vertical advection. Additionally, both radial and vertical advection tend to counteract each other. This characteristic can be interpreted as the influence of conservatively propagation (Nonacceleration theorem, e.g., Charney and Drazin 1961) of disturbances having large group velocity, specifically, inertia-gravity waves. The component arising just after starting experiments and existing only near the forcing region is anticipated to be generated by disturbances having small group velocity, specifically, vortex Rossby wave. Moreover, because the diffusion term is large near the forcing region due to large spatial variation of wind speed, it is considered that such vortex Rossby waves are likely to dissipate. The component arising after a while and having large amplitude seems to be caused by barotropic instability and/or inertial instability because this component appears only in the radial advection term and the timing of appearing this component corresponds to that of appearing inertially unstable region and barotropically unstable region shown in section 3 (see also Figs. 2.6 and 2.7). As discussed above, the asymmetric components are generated by overlapping contributions of different factors. It is diffi-

cult to separate and analyze the factors quantitatively. Thus, the analyses of the factors generating the asymmetric components are future works.

Table 2.2: Settings and names of parameter experiments in Series Q and Series S.

Series Q				
Name of parameter experiment	Forcing location L (km)	Forcing strength Q ($\times 10^{-4} \text{ K s}^{-1}$)	Forcing scales S (km)	Name of each experiment
Q-L100	100	Variable (0.1-1.0)	100	Q0.1-L100 etc.
Q-L400	400	Variable (0.1-1.0)	100	Q0.5-L400 etc.
Q-L700	700	Variable (0.1-1.0)	100	Q0.9-L700 etc.
Series S				
Name of parameter experiment	Forcing location L (km)	Forcing strength Q ($\times 10^{-4} \text{ K s}^{-1}$)	Forcing scales S (km)	Name of each experiment
S-L200	200	1.0	Variable (60-200)	S60-L200 etc.
S-L300	300	1.0	Variable (60-200)	S80-L300 etc.
S-L400	400	1.0	Variable (60-200)	S100-L400 etc.
S-L500	500	1.0	Variable (60-200)	S120-L500 etc.
S-L600	600	1.0	Variable (60-200)	S140-L600 etc.
S-L700	700	1.0	Variable (60-200)	S160-L700 etc.
S-L800	800	1.0	Variable (60-200)	S180-L800 etc.

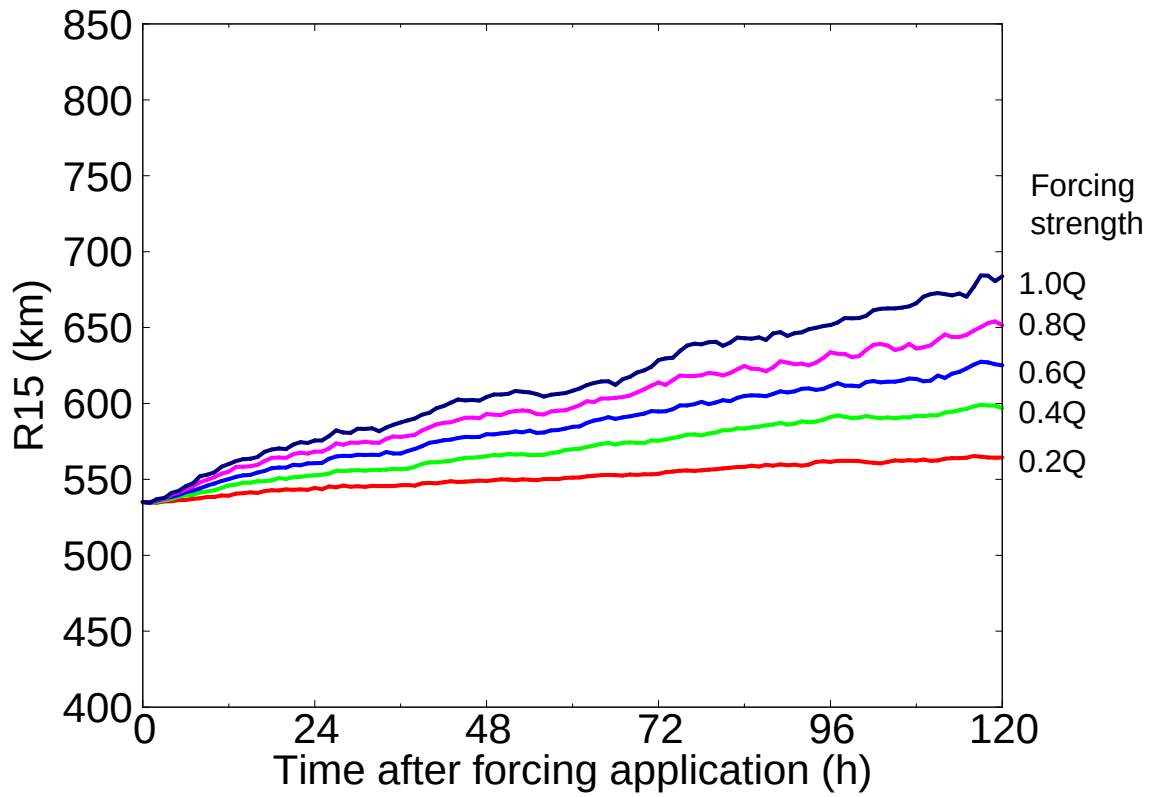


Figure 2.24: Time evolution of R15 in each experiment in parameter experiment Q-L400. For case of view, only the results on Q0.2-L400, Q0.4-L400, Q0.6-L400, Q0.8-L400, and Q1.0-L400 are shown. The ordinate and the abscissa represent R15 (km) and time (hour) after forcing application, respectively.

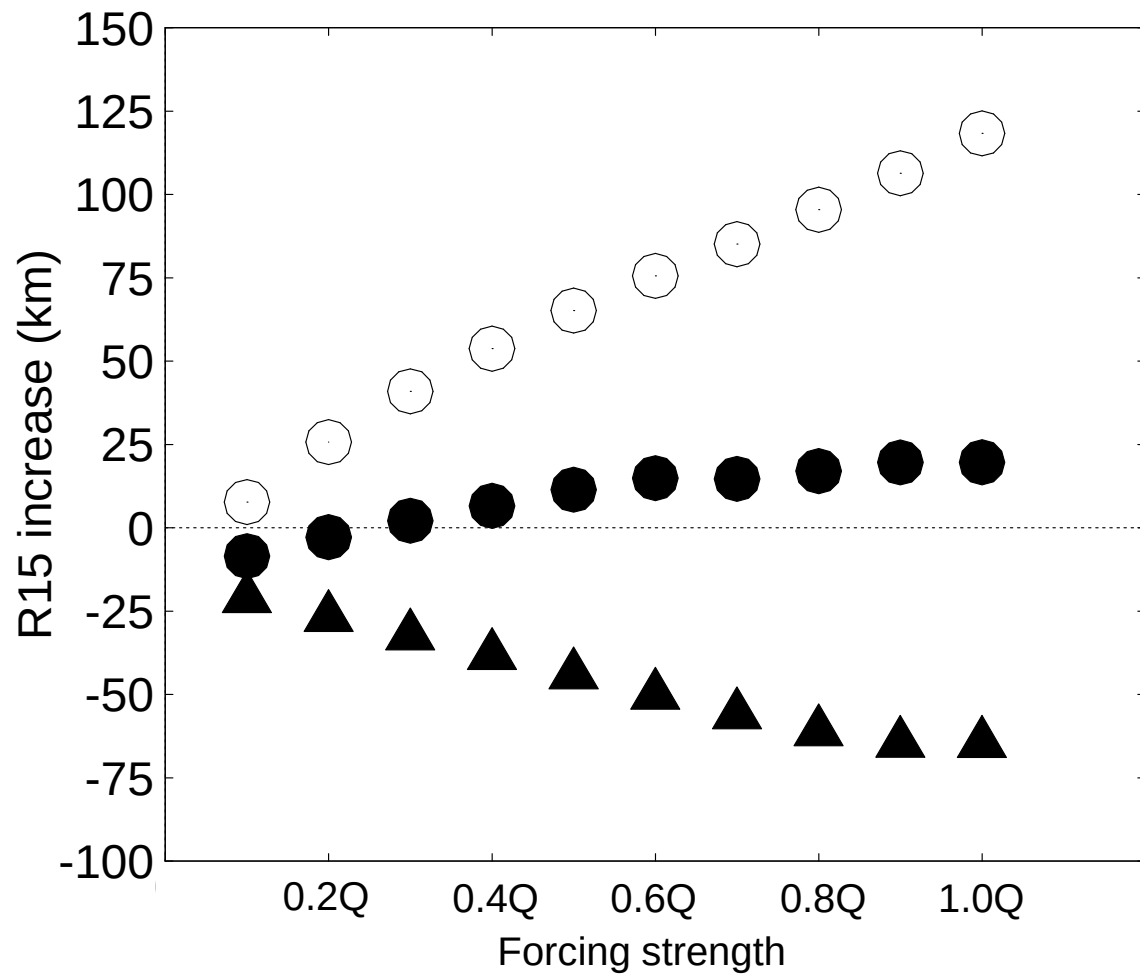


Figure 2.25: Time-average increase in R15 between 84 and 108 h in each experiment in parameter experiments Q-L100 (closed circle), Q-L400 (open circle), and Q-L700 (closed triangle). The ordinate and the abscissa represent time-averaged increase in R15 (km) and strength of forcing, respectively.

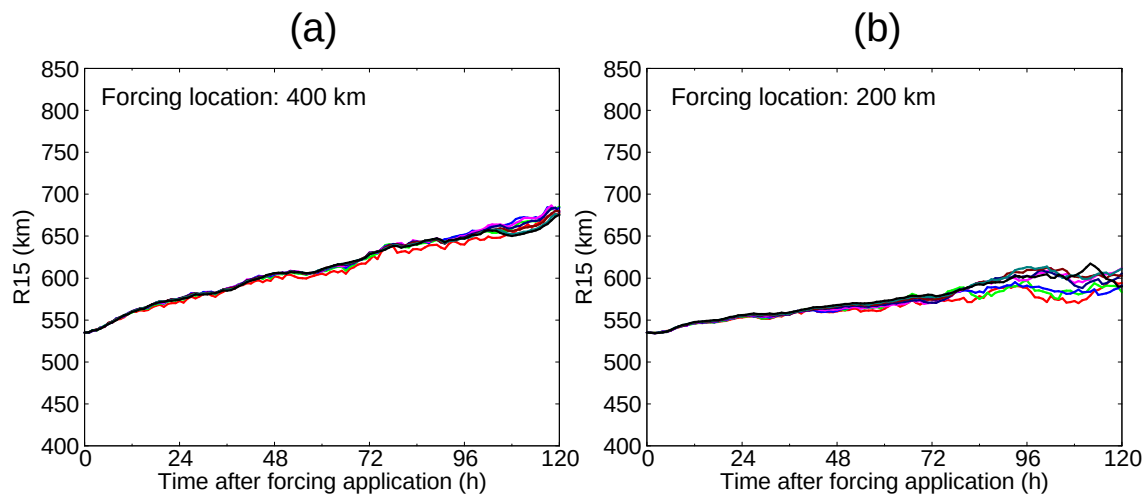


Figure 2.26: Time evolution of R15 in each experiment in parameter experiments (a)S-L400 and (b)S-L200. The ordinate and the abscissa represent R15 (km) and time (h) after forcing application, respectively.

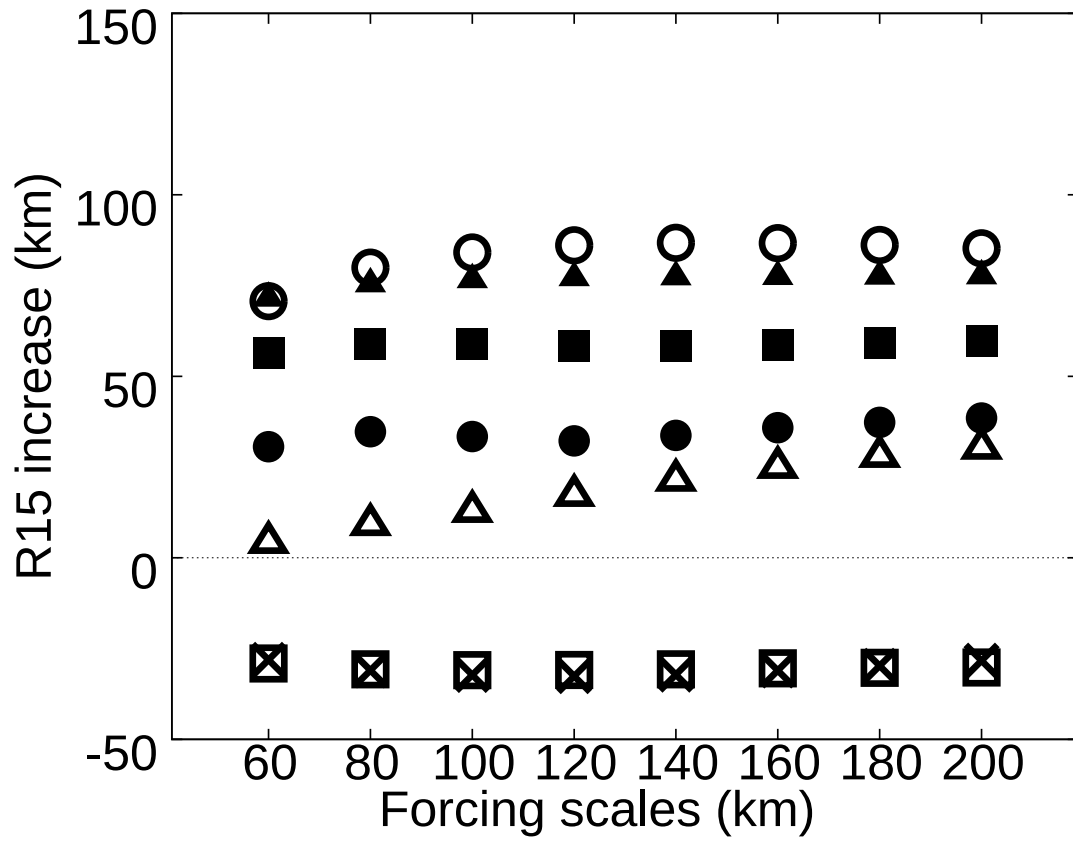


Figure 2.27: Time-average increase in R15 between 48 and 72 h in each experiment in parameter experiments S-L200 (closed circle), S-L300 (closed square), S-L400 (closed triangle), S-L500 (open circle), S-L600 (open triangle), S-L700 (cross), and S-L800 (open square). The ordinate and the abscissa represent time-averaged increase in R15 (km) and scales of forcing, respectively.

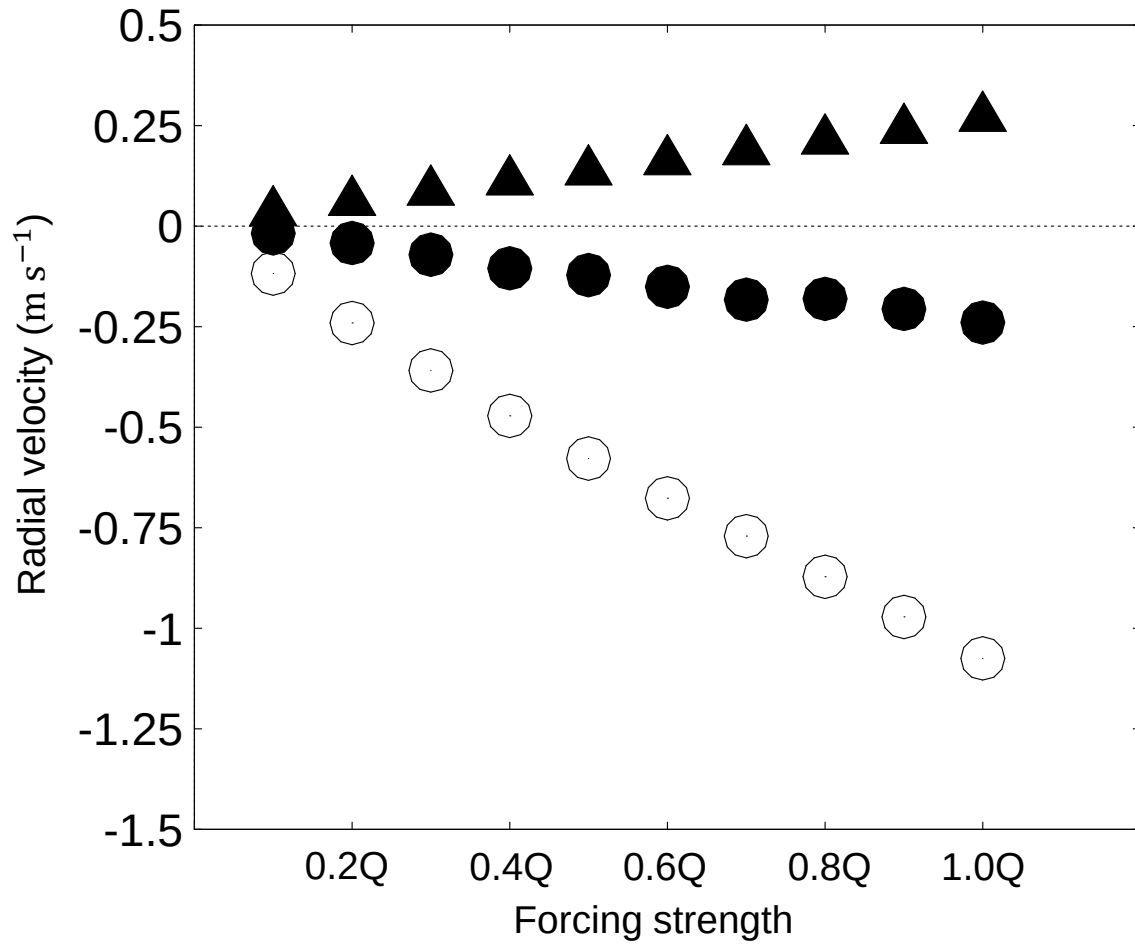


Figure 2.28: Relationship between the strength of forcing and radial wind at R15 in each experiment in parameter experiments Q-L100 (closed circle), Q-L400 (open circle), and Q-L700 (closed triangle). The ordinate and the abscissa represent time-averaged radial wind between 1 and 96 h (m s^{-1}) and forcing strength, respectively.

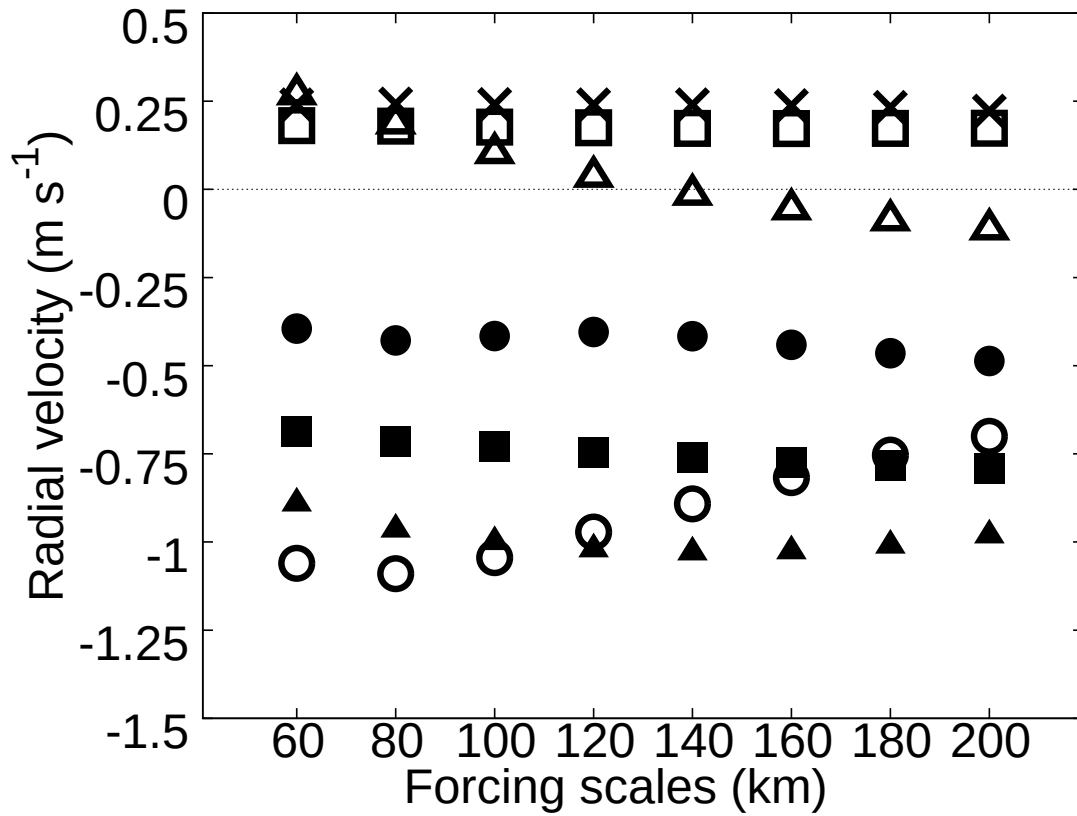


Figure 2.29: Relationship between the scales of forcing and radial wind at R15 in each experiment in parameter experiments S-L200 (closed circle), S-L300 (closed square), S-L400 (closed triangle), S-L500 (open circle), S-L600 (open triangle), S-L700 (cross), and S-L800 (open square). The ordinate and the abscissa represent time-averaged radial wind between 1 and 60 h (m s^{-1}) and forcing scales (km), respectively.

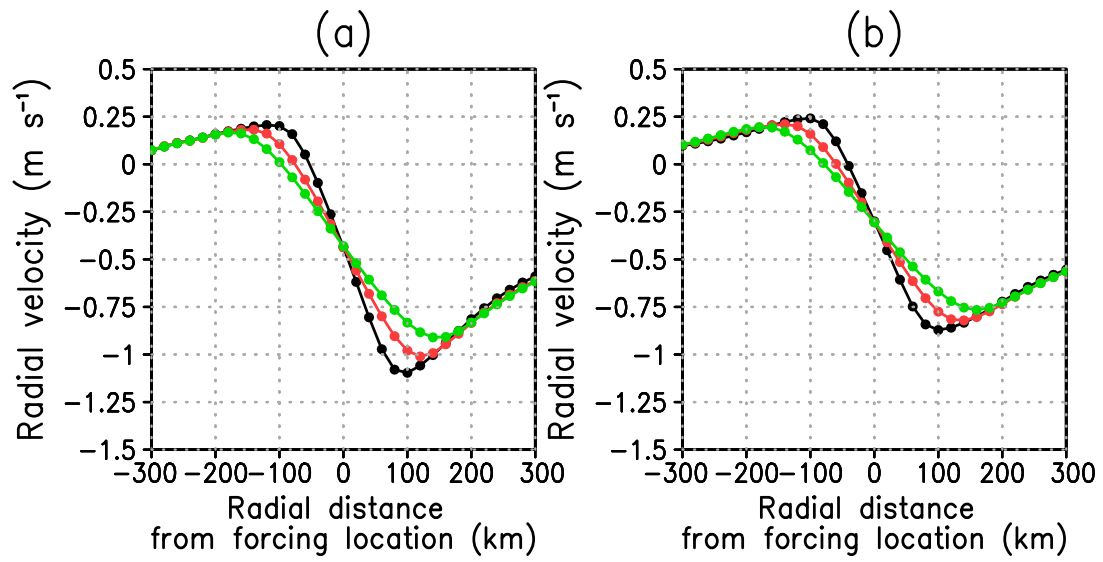


Figure 2.30: Time-averaged radial wind between 1 and 60 h at the lowest level in experiments (a) S100-L500 (black line), S140-L500 (red line), and S180-L500 (green line) in parameter experiment S-L500 and (b) S100-L600 (black line), S140-L600 (red line), and S180-L600 (green line) in parameter experiment S-L600. The ordinate and the abscissa represent time-averaged radial velocity at the lowest level (m s^{-1}) and radial distance from forcing location (km), respectively.

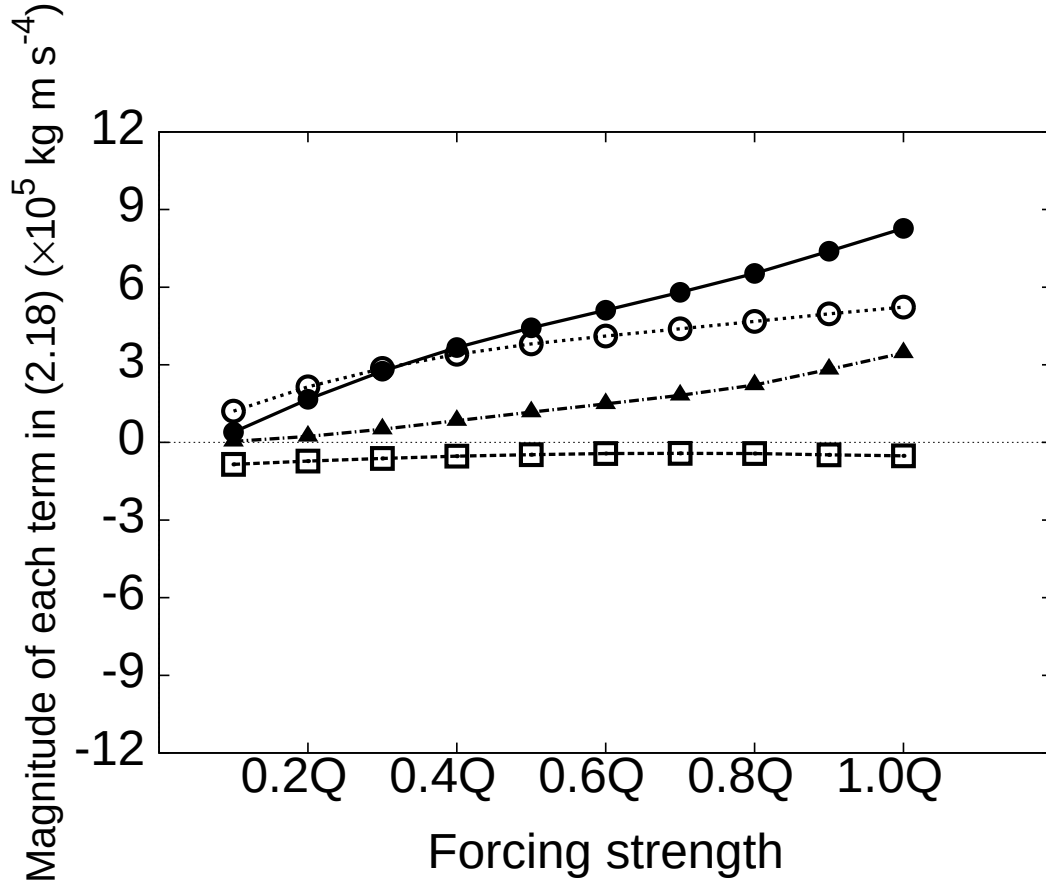


Figure 2.31: Magnitudes of each term in Eq. (2.18) of each experiment in parameter experiment Q-L400 (ordinate, unit: 10^5 kg m s^{-4}). The abscissa shows the forcing strength. These values are averaged between 1 and 96 h at R15. The solid line with closed circles represents the left-hand side, while the dotted line with open circles, dash-dotted line with triangles, and dashed line with squares indicate the first term ($-\pi \nu_r \frac{\partial M}{\partial r}$), the second term ($-\pi \sigma \frac{\partial M}{\partial \sigma}$), and the sum of the fourth and fifth terms (diffusion term), respectively, on the right-hand side. The third term on the right-hand side is omitted because its value is negligible.

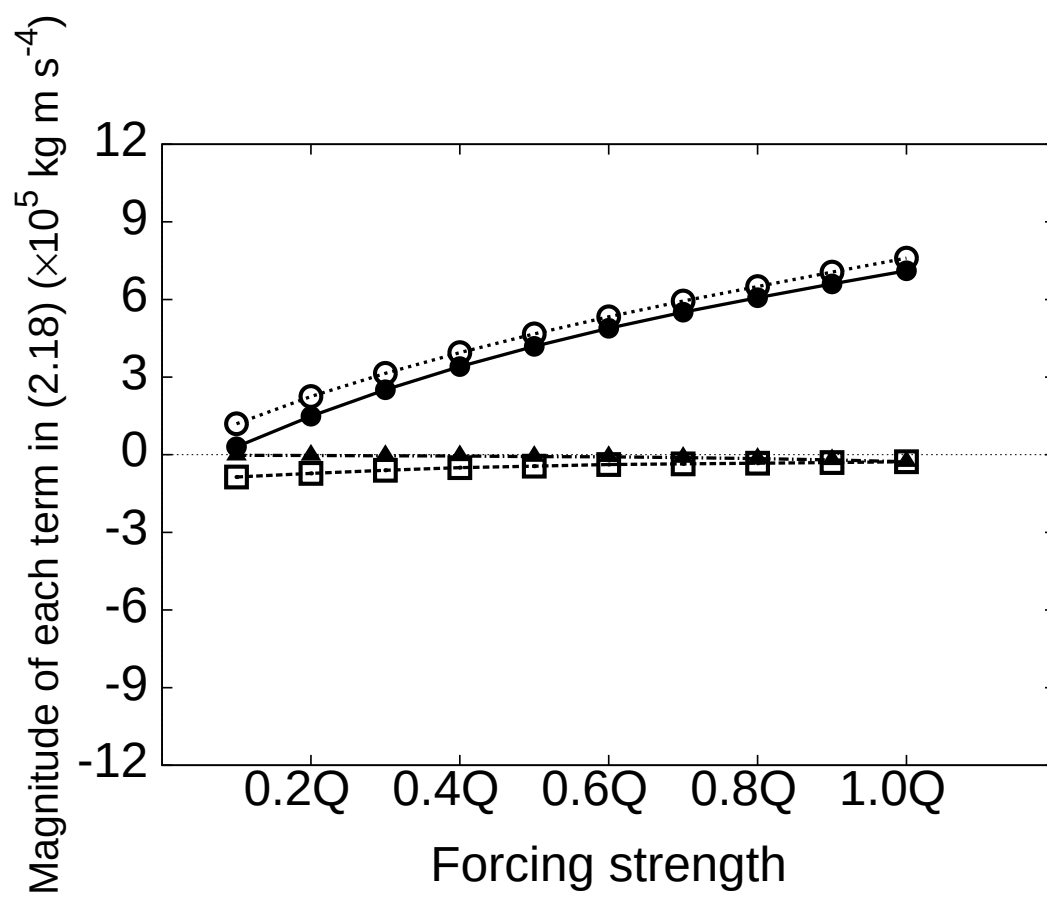


Figure 2.32: As in Fig. 2.31, but for annulus forcing experiment.

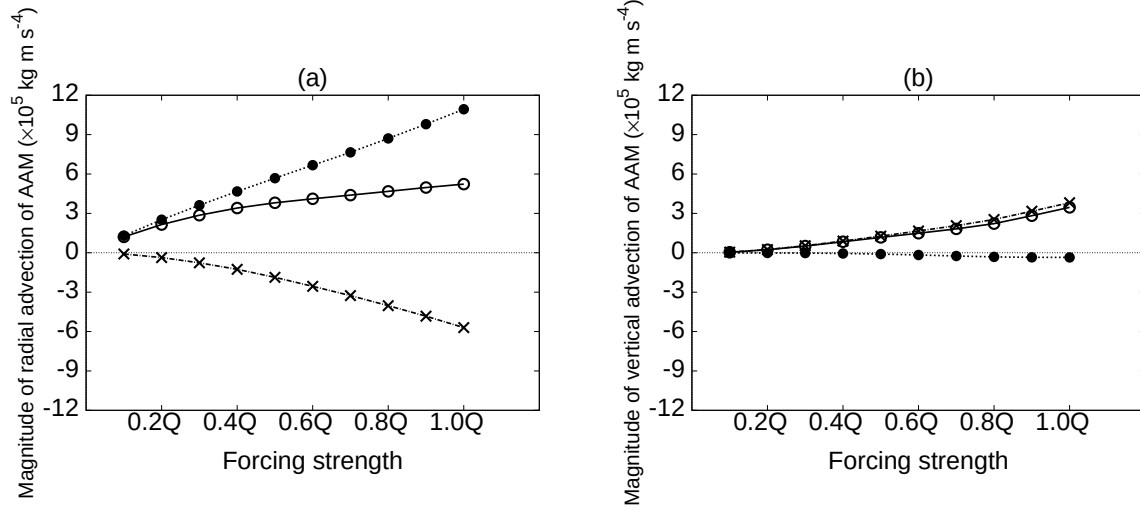


Figure 2.33: Axisymmetric and asymmetric components of (a) radial advection term and (b) vertical advection term in each experiment in parameter experiment Q-L400. The dotted line with closed circle, solid line with open circle, and dash-dotted line with cross indicate radial advection term in (a) and vertical advection term in (b), axisymmetric component, and asymmetric component, respectively. These values are averaged between 1 and 96 h. The ordinate and the abscissa represent the magnitude of each term ($\times 10^5 \text{ kg m s}^{-4}$) and the forcing strength, respectively.

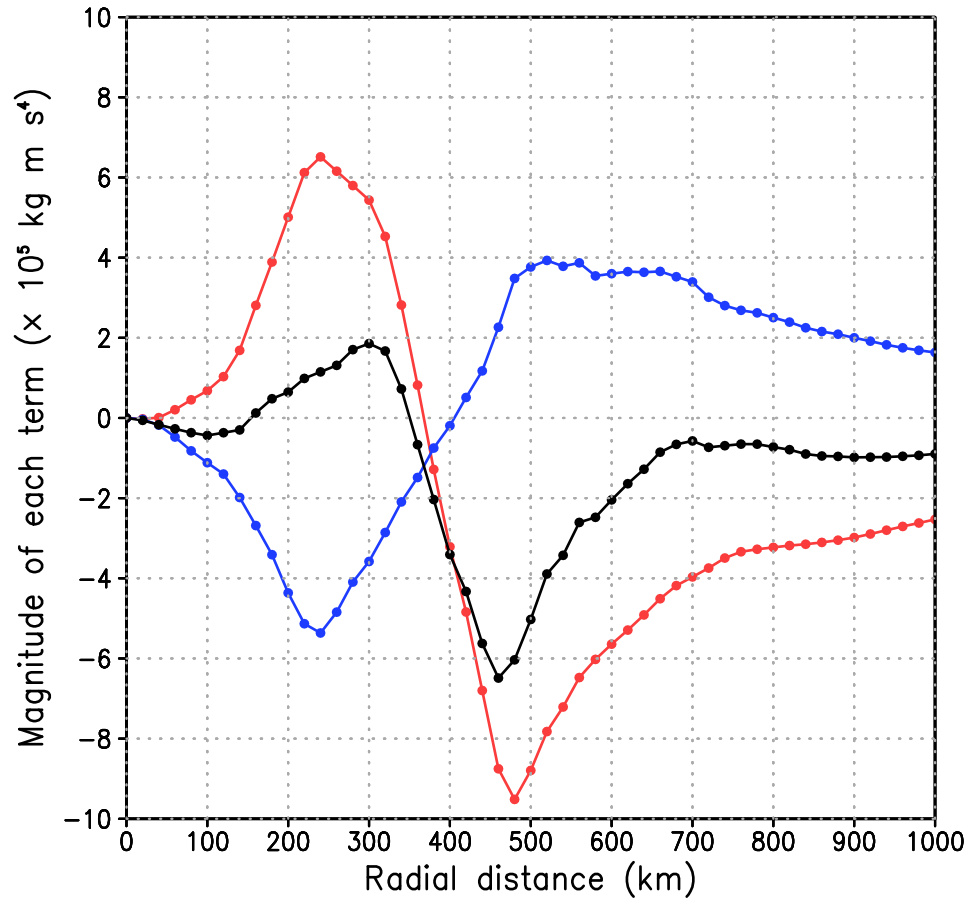


Figure 2.34: Time-averaged magnitudes of the asymmetric components of radial advection term (red line), the asymmetric components of vertical advection term (blue line), and the sum of the asymmetric components of radial and vertical advection terms (black line) between 1 and 96 hours at the lowest level in the experiment in which the strength of forcing is set to 1.0Q in parameter experiments Q-L400.

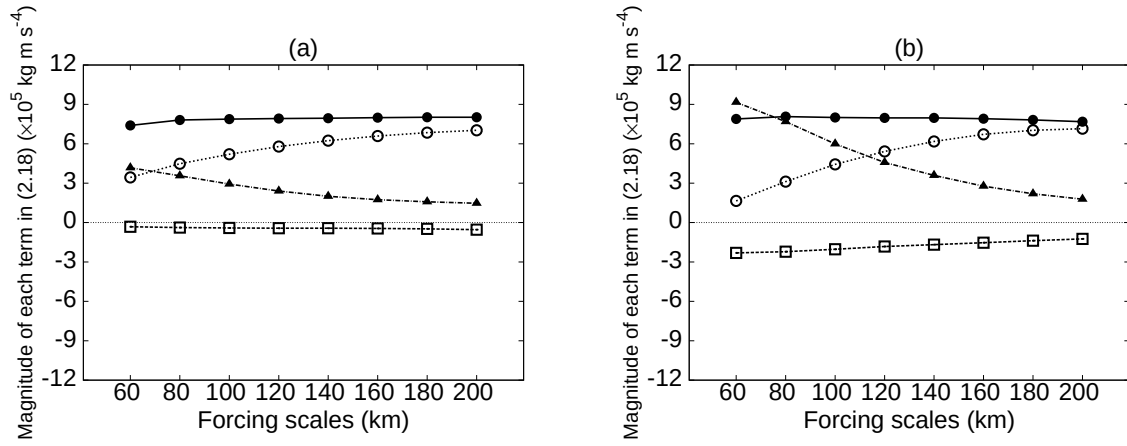


Figure 2.35: Magnitudes of each term in Eq. (2.18) of each experiment in parameter experiments (a) S-L400 and (b) S-L500 (ordinate, unit: 10^5 kg m s^{-4}). The abscissa shows the forcing scales. These values are averaged between 1 and 60 h at R15. The solid line with closed circles represents the left-hand side, while the dotted line with open circles, dash-dotted line with triangles, and dashed line with squares indicate the first term ($-\pi v_r \frac{\partial M}{\partial r}$), the second term ($-\pi \sigma \frac{\partial M}{\partial \sigma}$), and the sum of the fourth and fifth terms (diffusion term), respectively, on the right-hand side. The third term on the right-hand side is omitted because its value is negligible.

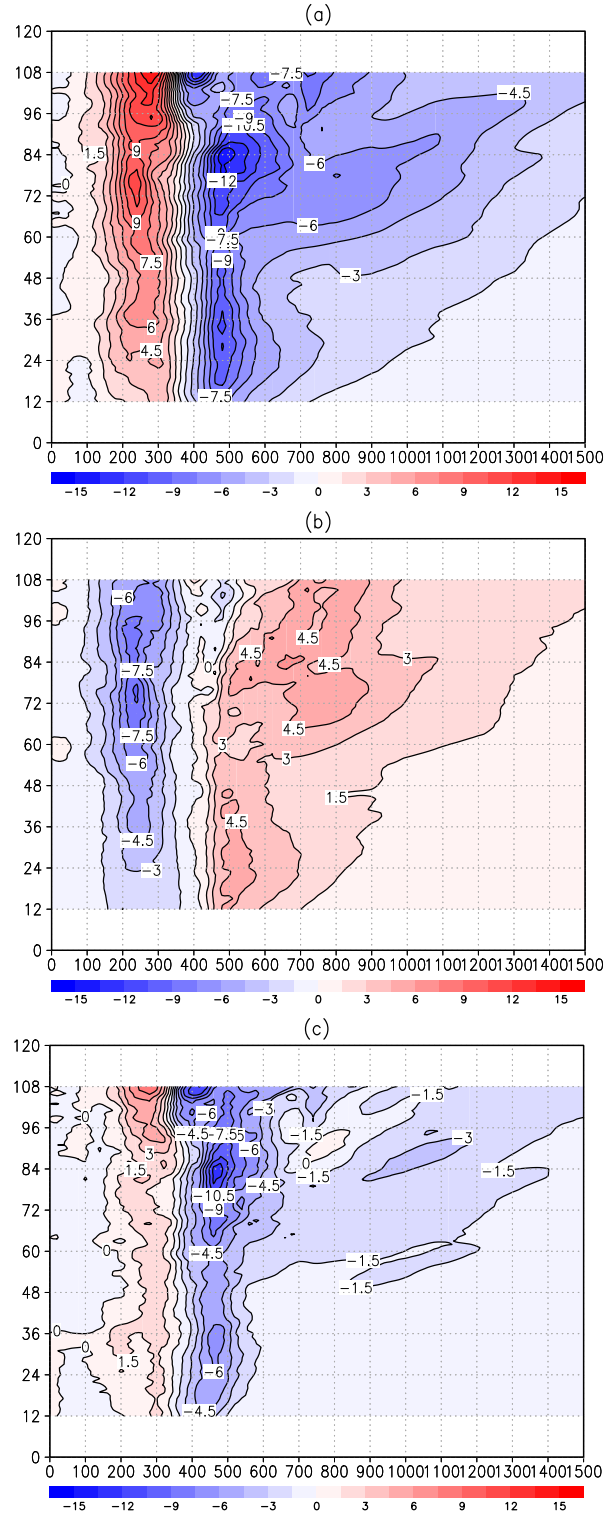


Figure 2.36: Time-radius view of 25-hours moving averaged magnitudes of (a) the asymmetric components of radial advection term, (b) the asymmetric components of vertical advection term, and (c) the sum of the asymmetric components of radial and vertical advection terms at the lowest level in the experiment in which the strength of forcing is set to 1.0Q in parameter experiments Q-L400. The ordinate and abscissa represents time (h) after forcing application and radial distance from the center (km), respectively.

6 Sensitivity of vortex size change to the structure of initial vortex

In section 4 and section 5, the effects of forcing on the size change of vortices are investigated employing common initial vortex. However, the change of R15 also depends on the radial gradient of tangential wind, i.e., the structure of the initial vortex as follows. Because of the definition of R15 and the fact that $|v_\phi| \gg |v_r|$ near R15 (see Fig. 2.10), the rate of change of v_ϕ experienced by an observer who follows the motion of R15 should almost vanish. This implies that, with the aid of the chain rule,

$$0 \sim \frac{d}{dt} \overline{v_\phi}|_{r=R15(t)} = \frac{\partial \overline{v_\phi}}{\partial t} + \frac{dR15(t)}{dt} \frac{\partial \overline{v_\phi}}{\partial r}, \quad (2.20)$$

where $R15(t)$ and d/dt designate R15 as a function of time and a simple time derivative, respectively.

Thus, we yield

$$\frac{dR15(t)}{dt} \approx -\frac{\partial \overline{v_\phi}/\partial t}{\partial \overline{v_\phi}/\partial r}. \quad (2.21)$$

This relationship can be applied to the radius of any certain wind speed as long as the relation, $|v_\phi| \ll |v_r|$, is completed. From this equation, it is clear that the increase of tangential wind and radial gradient of tangential wind contribute to the change of R15.

In this section, we perform the parameter experiment using three initial vortices which have almost the same initial R15 (Series V) but different radial gradient of tangential wind near R15 to examine the effects of the structure of the initial vortex on the size change of vortices.

6.1 Specifications of the experiments

In Series V, we perform the parameter experiments in which strength and scales of forcing are set to the standard values (1.0Q, 100 km) and location of forcing is changed between 100–550 km by using three types of vortices (Gentle, Moderate, and Steep). Initial sizes of each vortex are 675 km, 670 km, and 655 km, respectively. The distributions of tangential wind at the model lowest level are designated in Fig. 2.1b. The radial-vertical distributions of tangential wind and inertial stability are shown in Figs. 2.2 and 2.3, respectively.

6.2 Temporal evolution of vortex size

Figure 2.37 illustrates the time evolutions of R15 in the experiments in which forcing is applied to 500 km from the center of each vortex (Gentle, Moderate, and Steep). Although the locations of forcing and initial sizes of vortices in the three experiments are the same, the change of R15 is different; Initial vortex Gentle becomes the largest and initial vortex Steep becomes the smallest. In the experiments in which forcing is applied to initial vortex Gentle and initial vortex Moderate, R15 rapidly increases with time in the first 24 hours. Even if the contributions of these rapid increase of R15 are excluded, the change of R15 in the three vortices are different. In fact, comparing the time-averaged increase of R15 between 84 and 108 h with that between 48 and 72 h, initial vortex Gentle, whose difference between them is 55.4 km, is larger than initial vortices Moderate and Steep, whose differences between them are 38.9 km and 31.2 km. These results can also be seen in the other experiments in which forcing is applied besides 500 km (not shown).

These results indicate that the vortex having the small gradient of tangential wind tends to become larger, supporting the relationship of Eq. (2.21). Thus, we quantitatively examine the difference in the increase of R15 in the cases in Series V separating the factors related to the AAM budget and those related to the structure of initial vortices.

6.3 Effects of the time evolution of tangential wind

First, the AAM budget and the associated temporal evolution of tangential wind are analyzed. Figure 2.38 shows the results of the budget analyses of AAM at R15 in all the experiments in Series V. The change of the left-hand side is mostly explained by the radial advection of AAM and the contributions of vertical advection term and diffusion terms are small. These features are similar to those for Series L described in section 4. Comparing the experiments with the same forcing location, the radial advection of AAM in initial vortex Gentle is the largest and that in initial vortex Steep is the smallest for all forcing locations.

In the following, we consider the origin of the dependence of R15 change on the structure of initial

vortex. Figure 2.39 shows the relationship between the radial wind at R15 and the increase of R15. In Series V, when comparing the cases with different heating location but with common initial vortex, the inflow at R15 becomes stronger in the cases with larger increase of R15. In contrast, when comparing the cases with the same location of heating but with different initial vortices, the inflow at R15 is weaker in the cases with smaller increase of R15. The inflow is stronger in order of Steep, Moderate, and Gentle not only at R15 but also at the outside of forcing location (not shown).

The reason why the strength of inflow is different even though the experimental conditions except for the initial vortex is the same is that the inertial stability near the forcing location and the outside of there is different. Figure 2.40 shows the radial distribution of time-averaged inertial stability at the lowest level outside the forcing location in the experiments in which forcing is applied to the 500 km from the center of each initial vortex. The inertial stability of initial vortex Steep is the smallest and that of initial vortex Gentle is the largest, reflecting the difference in the radial gradient of tangential velocity in the three vortices. As mentioned in subsection 4.6, the radial movement is prohibited and thus the inflow becomes weak when the inertial stability is large.

Comparing the experiments in which forcing is applied to the same distance from the center, we can see that the largest increase of R15 appear in the case when the forcing is applied to initial vortex Gentle, whose inflow at R15 is the weakest. This indicates that the parcels having large AAM can be transported into the inside of R15 by the small movement due to the large radial gradient of the AAM in initial vortex Gentle.

The results of the trajectory analyses to investigate the AAM which parcels coming into R15 have in experiments in which forcing is applied to 500 km from the center of each vortex is shown in Fig. 2.41. In the experiment in which forcing is applied to initial vortex Steep, which the inertial stability near R15 is small and the inflow at R15 is the strongest, the parcels are transported from the farthest. However, because the radial gradient of the AAM in initial vortex Steep is smaller than the other vortices and the AAM in a distant place is smaller than the other vortices, the AAM that parcels coming to R15 have in initial vortex Steep is smaller than those of initial vortices Gentle and

Moderate. In contrast, in the experiment in which forcing is applied to initial vortex Gentle, in which the inertial stability near R15 is large and the inflow at R15 is the weakest, the distance of movement of parcels is the shortest. However, because the radial gradient of the AAM in initial vortex Gentle is larger than the other vortices and the AAM even near R15 is larger than the other vortices, the AAM that parcels coming to R15 have in initial vortex Gentle is larger than those of the other initial vortices. As discussed above, the vortex size grows the largest in the experiments in which forcing is applied to initial vortex Gentle, which the inflow at R15 is weak, but the AAM which parcels coming to R15 have is the largest.

The above results represent that the tangential wind at R15 increases the most and the size of vortices grows the largest in the experiments in which forcing is applied to initial vortex Gentle because the transport of AAM to R15 is the largest. However, the relationship between the increases of the tangential wind and R15 is different in every initial vortices (Fig. 2.42). When the experiments using different vortices are compared, the increase of R15 is different even though the increase of AAM is the same. To interpret this results, the consideration of the contribution of the radial gradient of tangential wind is necessary in addition to the consideration of the contribution of the time evolution of tangential wind.

6.4 Effects of the radial gradient of tangential wind

In the previous subsection, we demonstrated that the increase of R15 cannot be explained quantitatively by only the consideration of the contribution of the increase of tangential wind from the comparison of the results of experiments using different initial vortices. In this subsection, we represent that the increase of R15 can explain quantitatively by adding the consideration of the contribution of the radial gradient of tangential wind.

Table 2.3 shows the change of AAM, radial gradient of tangential wind multiplied by πr , increase of R15 calculated from both values by using Eq. (2.21), and actual increase of R15, respectively in three combinations of experiments in which the increase of AAM is the same in Fig. 2.42. From this

table, it is clear that the increase of R15 calculated by using Eq. (2.21) is consistent with the actual increase of R15. Unlike Fig. 2.42, the relationship between the actual increases of R15 and calculated increase of R15 by using Eq. (2.21) is finely one-to-one correspondence regardless of the difference of initial vortices (Fig. 2.43).

As described above, it is revealed that the efficiency of the increase of R15 is different when the radial gradient of tangential wind is different, even though the increase of tangential wind is the same. This indicates that the vortex grows in size depending on the structure of the vortex even if the radial wind is weak and the time evolution of the tangential wind is small.

6.5 Summary

From the results of experiments in which the effects of the structure of the initial vortex on the size change of vortices are investigated by using three initial vortices having almost the same initial R15 and different radial gradient of tangential wind (Series V), we clarified that R15 increases more when the radial gradient of tangential wind is small because of the largeness of AAM outside R15. Moreover, we also clarified from comparing experiments in which the increase of AAM is the same that the increase of R15 becomes large when the radial gradient of tangential wind is small because the efficiency of the increase of R15 is high.

Table 2.3: $\pi r \frac{\partial v_\varphi}{\partial t}$, $\pi r \frac{\partial v_\varphi}{\partial r}$, $-\pi r \frac{\partial v_\varphi}{\partial t} / \pi r \frac{\partial v_\varphi}{\partial r} \times 96$ h, and time-averaged increase in R15 between 84 and 108 h in three combinations of experiments in which the values of left-hand side in Eq. (2.18) are the same (L150 in Gentle, L250 in Moderate, and L350 in Steep; L250 in Gentle, L325 in Moderate, and L475 in Steep; L325 in Gentle, L375 in Moderate, and L500 in Steep).

Initial vortex	Forcing location (km)	$\pi r \frac{\partial v_\varphi}{\partial t}$	$\pi r \frac{\partial v_\varphi}{\partial r}$	$-\pi r \frac{\partial v_\varphi}{\partial t} / \pi r \frac{\partial v_\varphi}{\partial r} \times 96$ h	Time-averaged increase in R15 between 84 and 108 h
Gentle	150	4.11	-13.5	105.2	103.8
Moderate	250	4.02	-20.2	68.8	71.3
Steep	350	4.12	-30.0	47.5	49.7
Gentle	250	5.98	-14.4	143.5	129.2
Moderate	325	6.01	-21.0	98.9	100.7
Steep	475	6.09	-30.1	69.9	72.7
Gentle	325	6.58	-15.1	150.6	175.2
Moderate	375	6.63	-21.5	106.6	115.0
Steep	500	6.51	-30.1	74.7	74.9

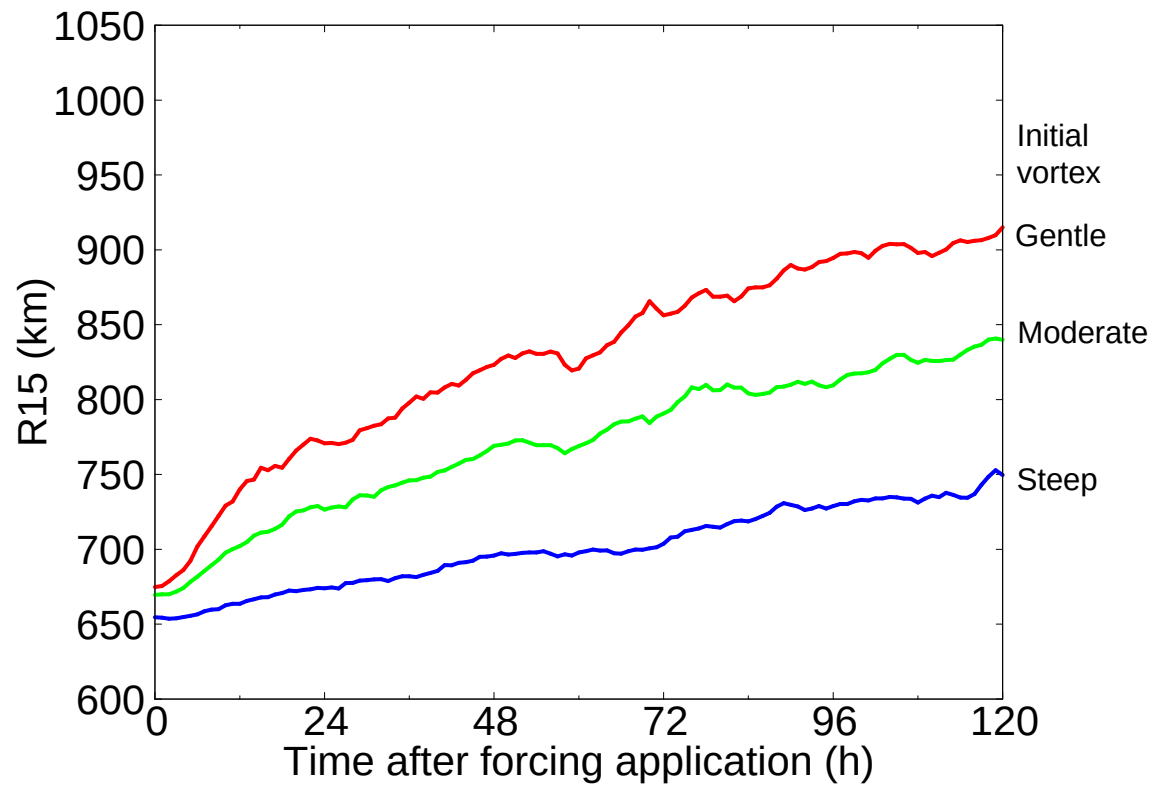


Figure 2.37: Time evolution of R15 in the experiments in which forcing having scales of 100 km and strength of 1.0Q is applied to 500 km from the center of each vortex (Gentle, Moderate, and Steep). The ordinate and the abscissa represent R15 (km) and time (hour) after forcing application, respectively.

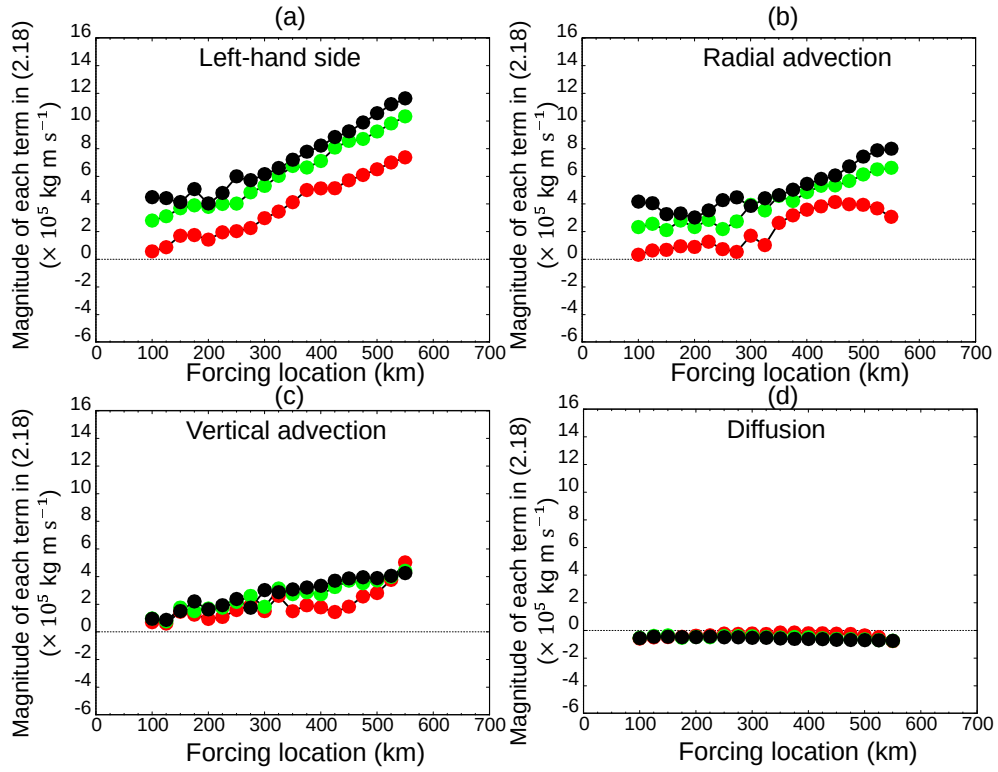


Figure 2.38: Magnitudes of (a) left-hand side, (b) radial advection term, (c) vertical advection term, and (d) diffusion term in Eq. (2.18) of each experiment in Series V (ordinate, unit: 10^5 kg m s^{-1}). Black line, green line, and red line represent the experiments in which forcing is applied to initial vortices Gentle, Moderate, and Steep, respectively. The abscissas show the forcing location. These values are averaged between 1 and 96 h at R15.

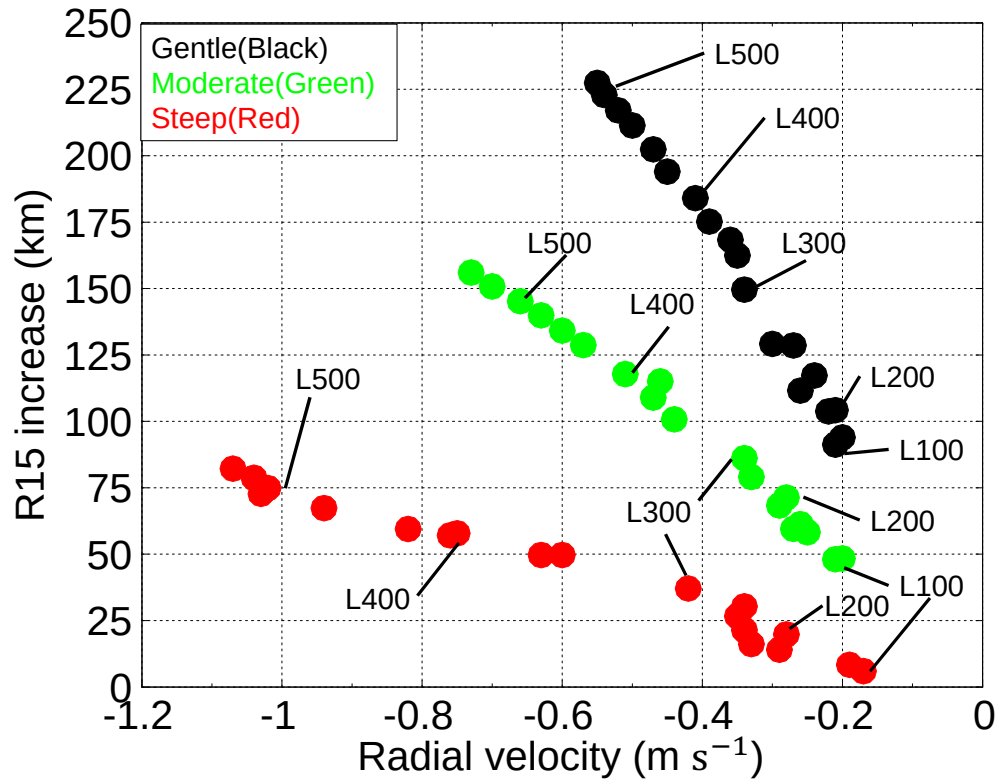


Figure 2.39: Relation between the increase in R15 (ordinate) and time-averaged v_r at R15 (abscissa) in each experiment in Series V. Plots designate each experiment. The increase in R15 is calculated as the difference between the 85 to 108-h average and initial R15, and v_r is averaged between 1 and 96 h.

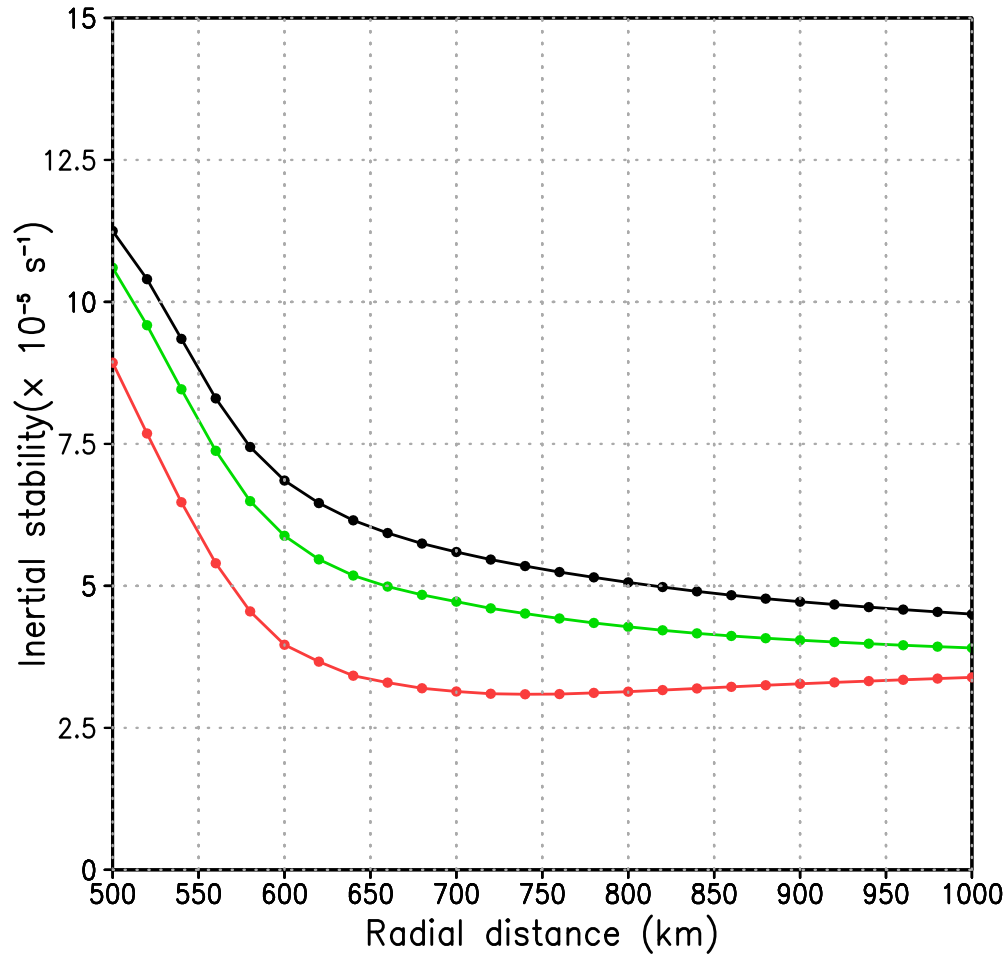


Figure 2.40: Time-averaged inertial stability (I) between 1 and 96 h at the outside of forcing location at the lowest level in experiments in which forcing is applied to 500 km from the center of each vortex. The ordinate and the abscissa represent inertial stability ($\times 10^{-5} \text{ s}^{-1}$) and radial distance from the center (km), respectively.

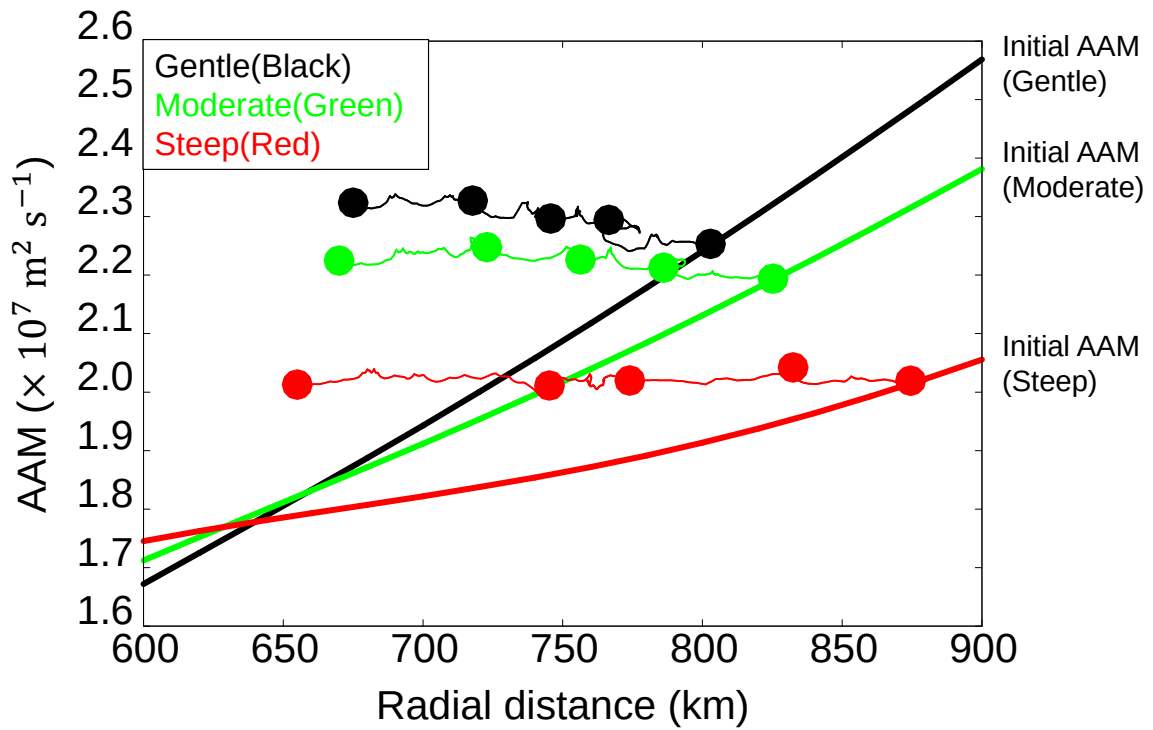


Figure 2.41: Average positions of the 360 parcels from $t = 96$ to $t = 0$ and AAM in the experiments in which forcing is applied to 500 km from the center of initial vortices Gentle (black), Moderate (green), and Steep (red). Solid and thin lines represent the azimuthally averaged initial AAM and the averaged parcel positions, respectively. The closed circles on the thin lines designate the positions at each 24 h.

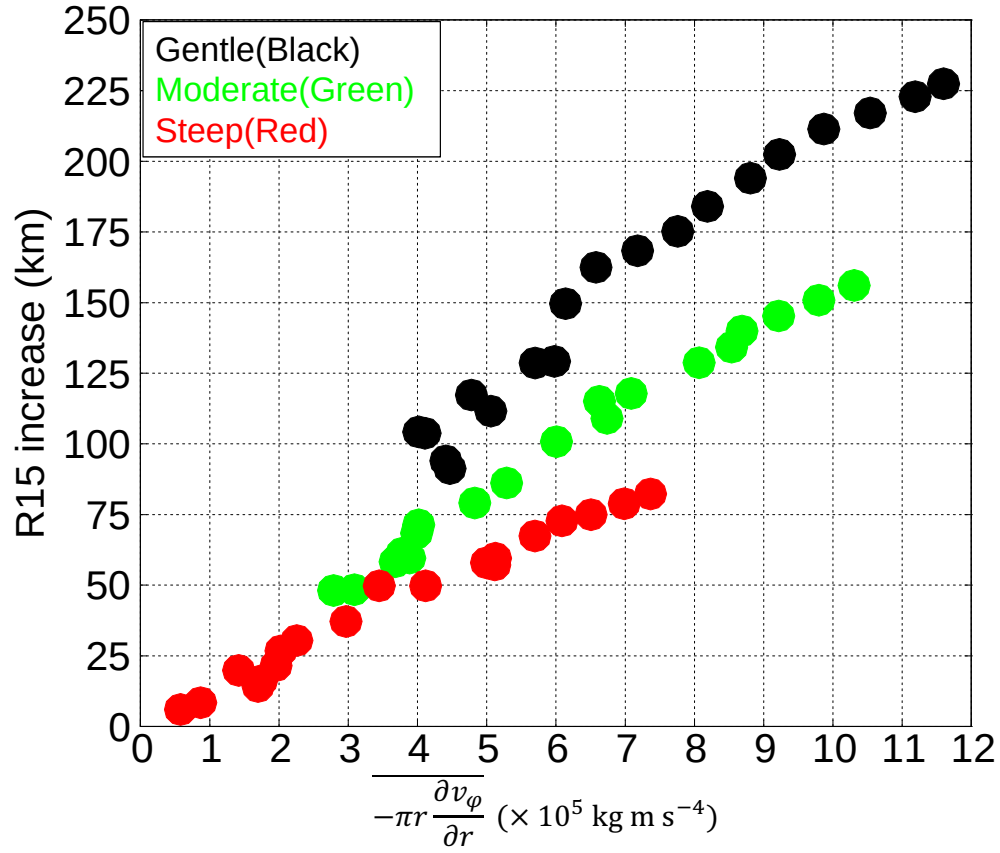


Figure 2.42: Relationship between time-averaged left-hand side in Eq. (2.18) between 1 and 96 h (abscissa) and time-averaged increase in R15 between 84 and 108 h (ordinate). Plots designate each experiment in the experiments in which forcing is applied to initial vortices Gentle (black), Moderate (green), and Steep (red).

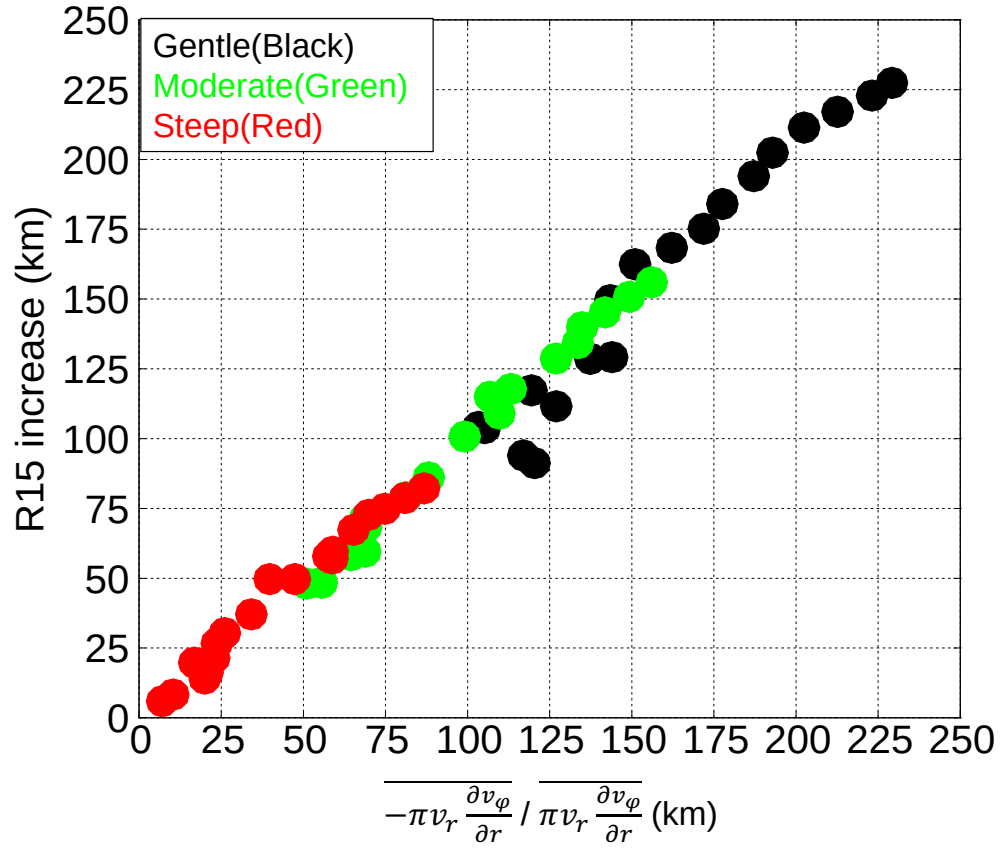


Figure 2.43: Relationship between the increase in R15 calculated by using time-averaged left-hand side in Eq. (2.18) and radial gradient of tangential wind between 1 and 96 h (abscissa) and time-averaged increase in R15 between 84 and 108 h (ordinate). Plots designate each experiment in the experiments in which forcing is applied to initial vortices Gentle (black), Moderate (green), and Steep (red).

7 Experiments in which forcing is applied to two regions

In the experiments shown before this section, forcing was applied to only one region and we discussed the effects of it on the size change of vortices. However, in real TCs, cumulus heatings are located not only at a certain radius, but also at various radii from the inside to the outside of R15, simultaneously. Thus, the discussion about the effects of forcing on the size change of vortices in the case when more than one forcing region exist is needed. In this section, we perform the experiments in which forcing is applied to two regions (Series D) and clarify the response of forcing to the change of R15.

7.1 Specifications of the experiments

In series D, the parameter experiments in which the location and strength of forcing, which have a sensitivity to the size change of vortices as shown in section 4 and section 5, are changed in both inner and outer forcing are performed. The strength of forcing is changed between $0.1Q$ and $1.0Q$. In the experiments in which both inner and outer forcings are applied to the inside of R15 (subsection 7.2), the location of the inner forcing is set to 100km, 200 km, or 300 km and that of the outer forcing is changed between 150 km and 400 km. In the experiments in which forcing is applied to the inside and outside of R15 (subsection 7.3), the location of the inner forcing is set to 100 km, 200 km, 300 km, or 400 km and that of the outer forcing is changed between 700 km and 900 km. The scales of forcing is set to the standard value (100 km) and the initial vortex Nominal, whose initial R15 is 535 km is used.

In the consideration of the results of Series D, we focus on whether the response of forcing to the change of R15 and tangential wind is linear, i.e., how consistent are the results of experiments in which forcing is applied to two regions with the sum of the results of experiments in which only the inner forcing is applied and only the outer forcing is applied in addition to focus on the characteristics of the change of R15 by the two forcings. This verification is performed as follows. The tangential winds of the experiments in which forcing is applied to two regions (V_D), in which only the inner

forcing is applied (V_{IN}), and in which only the outer forcing is applied (V_{OUT}) are defined as

$$V_D = V_i + V'_D \quad (2.22)$$

$$V_{IN} = V_i + V'_{IN} \quad (2.23)$$

$$V_{OUT} = V_i + V'_{OUT}, \quad (2.24)$$

where V_i is the tangential wind at the initial and V'_D , V'_{IN} , and V'_{OUT} represent the increases of the tangential wind from the initial in each experiment, respectively. Supposing that the increase of tangential wind is linearly related to the forcing, the relationship of

$$V_i + V'_D = V_i + V'_{IN} + V'_{OUT} \quad (2.25)$$

is completed. In contrast, the simple sum of the tangential winds in the experiments in which only the inner forcing is applied and only the outer forcing is applied (V_{SUM}) is,

$$V_{SUM} = V_i + V'_{IN} + V_i + V'_{OUT}. \quad (2.26)$$

This means that if Eq. (2.25) is completed, the sum of the tangential wind in the experiments in which only the inner forcing is applied and only the outer forcing is applied does not correspond to the tangential wind in the experiment in which forcing is applied to two regions due to the existence of the initial wind. Therefore, when the results of experiments in which forcing is applied to two regions are compared with the sum of the results of experiments in which only the inner forcing is applied and only the outer forcing is applied in the following analyses, the contribution of the initial tangential wind is removed by subtracting the result of experiment in which forcing does not applied from the latter, i.e., we compare V_D with $V_{IN} + V_{OUT} - V_i$. In the rest of this section, when the sum of the results of experiments in which only the inner forcing is applied and only the outer forcing is applied is represented, we do not repeatedly mention that the result of experiment in which forcing does not

applied is subtracted from the results.

7.2 Experiments in which forcing is applied to two regions inside R15

In this subsection, we designate the results and considerations of the experiments in which both inner and outer forcings are applied to the inside of R15.

a) Temporal evolution of vortex size

First, the sensitivity of vortex size change to the location of forcing is investigated by fixing the strength of forcing and changing the combination of inner and outer forcing location. Figure 2.44 illustrates the time evolution of R15 in the parameter experiments in which the strength of forcing in both inner and outer forcings is set to $0.5Q$, the inner forcing location is fixed to 100 km from the center and the outer forcing location is changed (Fig. 2.44a), and the outer forcing location is fixed to 400 km from the center and the inner forcing location is changed (Fig. 2.44b). R15 increases with time with a constant rate and the vortex size becomes larger as the inner and outer forcings are both located at a further distance from the center. These results are consistent with those in Series L shown in section 4. The same results are obtained when the combination of forcing locations are changed (see also Fig. 2.45).

Next, the linearity of the increase of R15 in each experiment is examined. Figure 2.45 represents the increase of R15 in each experiment in parameter experiment in which the strength of both inner and outer forcings is set to $0.5Q$ and the location of forcing is changed. Figure 2.45 also represents the sum of the increase of R15 in experiments in which only the inner forcing is applied and only the outer forcing is applied. The difference between the increase of R15 in the experiments in which forcing is applied to two regions and the sum of the increase of R15 in the experiments in which only the outer forcing is applied and only the inner forcing is applied is small in any combination of the location of forcings, i.e., the increase of R15 in the experiments in which forcing is applied to two regions is almost the same as the sum of the increase of R15 in experiments in which only the inner forcing is applied and only the outer forcing is applied.

Next, the sensitivity of vortex size change to the strength of forcing is investigated by fixing the location of forcing and changing the combination of inner and outer forcing strength. Figure 2.46 represents the increase of R15 in each experiment in the parameter experiment in which the inner and outer forcing locations are fixed to 100 km and 400 km, respectively, the strength of one forcing out of two is set to $0.5Q$, and the strength of the other forcing is changed from $0.1Q$ to $1.0Q$. The vortex size becomes larger as the strength of forcing is larger even if either forcing is fixed. These results are consistent with those in Series Q shown in section 5. The increase of R15 resulting from changing the strength of forcing in the experiments in which the outer forcing strength is changed is larger than that in which the inner forcing strength is changed. Moreover, the increase of R15 in the experiments in which forcing is applied to two regions is almost the same as the sum of the increase of R15 in experiments in which only the inner forcing is applied and only the outer forcing is applied. The same results are obtained when the combination of forcing locations are changed (not shown).

In summary, the characteristics of the tendency of the change of R15 in the experiments in which forcing is applied to two regions inside R15 are the same as those in the experiments in which forcing is applied to a region, i.e., the vortex size becomes larger as the location of forcing is closer to the initial R15 and the forcing is stronger. Additionally, the increase of R15 in the experiments in which forcing is applied to two regions is almost the same as the sum of the increase of R15 in experiments in which only the inner forcing is applied and only the outer forcing is applied.

b) Mechanism of the linearity of the change of R15

In the previous subsection, we showed that the increase of R15 in the experiments in which forcing is applied to two regions is close to the sum of the increase of R15 in experiments in which only the inner forcing is applied and only the outer forcing is applied. These results indicate that the increase of R15 by heat forcing can be understood by the sum of the contribution of each heating to the increase of R15. In this subsection, the budget analyses of AAM at R15 are performed to clarify the reason. As a representative of all the experiments in which forcing is applied to two regions inside R15, the analyses are performed to each experiments in the parameter experiments in which the inner

forcing strength and location are set to $0.5Q$ and 100 km, respectively, the outer forcing location is fixed to 400 km, and the strength of outer forcing is changed from $0.1Q$ to $1.0Q$.

First, the results of the budget analyses of AAM at R15 are shown. Figure 2.47 represents the values of each term in Eq. (2.18) at R15 in the experiments in which forcing is applied to two regions and the sum of those in the experiments in which only the inner forcing is applied and only the outer forcing is applied. As in the results of the analyses shown previously, the evolution of the left-hand side of Eq. (2.18) is mainly controlled by the radial advection of AAM and the contribution of the vertical advection of AAM and diffusion terms are small. Moreover, in all terms, both values are additive regardless of the strength of forcing. These results are the same as those in the parameter experiments in which the strength of outer forcing is fixed and that of inner forcing is changed (not shown).

Next, to examine the reason why the radial advection of AAM, which controls the increase of AAM, in both experiments in which forcing is applied to two regions and the sum of experiments in which only the inner forcing is applied and only the outer forcing is applied is overlapped, we examine the distributions of the radial flow and radial gradient of AAM. Figure 2.48 represents the radial gradients of AAM in the experiments in which inner forcing location and strength are set to 100 km and $0.5Q$, respectively and outer ones are set to 400 km and $0.5Q$, respectively, only the inner forcing whose forcing location and strength are set to 100 km and $0.5Q$, respectively is applied, and only the outer forcing whose forcing location and strength are set to 400 km and $0.5Q$, respectively is applied. Around the outer forcing location (400–500 km), the radial gradients of AAM in the experiments are different, whereas those around R15 (500–600 km) are the same. On the other hand, the distribution of the radial wind is almost overlapped besides around R15 (Fig. 2.49).

Above results represent that if the radial wind induced by forcing is linearly related to heating and the radial gradient of AAM around R15 are the same, the increase of R15 by forcing can be understood by the sum of the contribution of each heating to the increase of R15. Supposing that the Sawyer-Eliassen equation (e.g., Shapiro and Willoughby 1982) is applies, the response of heat forcing

to the radial wind induced by heat forcing is linear. Thus, it is natural that the distribution of radial wind in the experiments in which forcing is applied to two region overlaps with the sum of that in which only the inner forcing is applied and only the outer forcing is applied. Therefore, the reason why the effects of forcing on the size change of vortices are equal to the sum of the effects of each forcing on the size change of vortices is that the radial gradient of AAM around R15 is almost the same.

7.3 Experiments in which forcing is applied to the inside and outside of R15

In this subsection, the results and considerations of the experiments in which two forcings are applied to the inside and outside of R15.

a) Temporal evolution of vortex size

First, the sensitivity of vortex size change to the location of forcing is investigated by fixing the strength of forcing and changing the combination of inner and outer forcing location. Figure 2.50 shows the increase of R15 in each experiments in the parameter experiment in which the strength of forcing in both inner and outer forcing is set to $0.5Q$ and the combination of inner and outer forcings is changed. Vortices with the inner forcing applied near the initial R15 becomes larger. Interestingly, the increase of R15 when the outer forcing is applied to 700 km or 750 km from the center is larger than that when the outer forcing is applied to 800–900 km.

Next, the linearity of the increase of R15 in each experiment is examined. Figure 2.50 also represents the sum of the increase of R15 in experiments in which only the inner forcing is applied and in which only the outer forcing is applied. The difference between the increase of R15 in the experiments in which forcing is applied to two regions and the sum of the increase of R15 in the experiments in which only the inner forcing is applied and only the outer forcing is applied becomes larger as the location of the outer forcing is near the initial R15. These results are different from those of experiments in which both inner and outer forcings are applied to the inside of R15 (Fig. 2.45).

Focusing on the sign of the increase of R15 from the initial R15, the only cases that the increase

of R15 becomes negative and vortex size becomes smaller than the initial is when the inner forcing is applied to 100 km from the center. Except for this case, the sign of the increase of R15 from the initial R15 becomes positive and vortex size becomes larger than the initial wherever the location of the outer forcing is. Considering the fact that when forcing is applied to the inside of R15, the contribution of forcing on the increase of R15 is smaller as the forcing is applied more nearer the center of the vortex (Series L, section 4). These results suggests that the positive effect of the inner forcing on the size of vortices are more intense than negative effects of the outer forcing on the size of vortices. As mentioned in section 4.7, this is because the strength of heat-induced circulation located at the outer side of the forcing location is stronger than that located at the inner side of the forcing location.

Next, the sensitivity of vortex size change to the strength of forcing is investigated by fixing the location of forcing and changing the combination of inner and outer forcing strength. In the rest of this subsection, we show the results of two parameter experiments as representatives. One is the parameter experiment in which the inner and outer forcings are applied to 100 km and 900 km from the center, respectively, whose location of outer forcing is far from the initial R15 and whose increase of R15 is compared with the sum of the increase of R15 in the experiments in which only the inner forcing is applied and only the outer forcing is applied. The other is the parameter experiment in which the inner and outer forcings are applied to 300 km and 700 km from the center, respectively, whose location of outer forcing is near the initial R15 and whose increase of R15 is different from the sum of the increase of R15 in the experiments in which only the inner forcing is applied and only the outer forcing is applied.

First, we examine the results of experiments in which the outer location of forcing is far from the initial R15. Figure 2.51 represents the increase of R15 in each experiment in the parameter experiment in which the inner and outer forcing locations are fixed to 100 km and 900 km, respectively, the strength of one forcing out of two is set to $0.5Q$, and the strength of the other forcing is changed from $0.1Q$ to $1.0Q$. Vortices with stronger outer forcing becomes small and those with stronger inner forcing becomes large. Moreover, in any strength of forcing, the increase of R15 in the experiments

in which forcing is applied to two regions is almost the same as the sum of the increase of R15 in the experiments in which only the inner forcing is applied and only the outer forcing is applied, which is the same as the results shown in Fig. 2.46.

In contrast, when the outer forcing is located near R15, the tendency of time evolution of R15 is different from the other experiments whose results are shown previously. Figure 2.52 shows the time evolutions of R15 in each experiments in the parameter experiment in which the strength and location of the inner forcing are set to 300 km and 0.5Q, respectively, location of the outer forcing are set to 700 km, and the strength of the outer forcing is changed. Differing from the results of experiments shown previously, the increase of R15 becomes larger after about 60–72 hours. Additionally, vortex size becomes larger as the strength of the outer forcing, whose contribution to the R15 change has been negative in the previous sections, is stronger.

b) The reason of varying the increase rate of R15 in the middle of experiments

In this subsection, we perform the budget analyses of AAM and examine the time evolution of each term in Eq. (2.18) to consider the reason why the increase rate of R15 varies in the middle of experiments.

Figure 2.53 shows the time evolution of the left-hand side of Eq. (2.18), radial advection term, vertical advection term, and diffusion term at R15 in the experiments in which the location and strength of forcing are set to 300 km and 0.5Q, respectively, in the inner forcing and 700 km and 1.0Q, respectively, in the outer forcing, and those in which only the inner forcing whose location and strength of forcing are set to 300 km and 0.5Q, respectively is applied. In the experiment in which only the inner forcing is applied, the time variation of each term is small. In contrast, in the experiment in which forcing is applied to 300 km and 700 km from the center, the left-hand side and radial advection term becomes larger after about 60–72 hours. The timing when these terms become large is the same as that when the tendency of the change of R15 varies (see also Fig. 2.52). In the experiment in which forcing is applied to 300 km and 700 km from the center, the diffusion term also increases with time, but the magnitude of the term is less than the half of the magnitude of the left-hand side and radial

advection term. Thus, the effect of the diffusion terms on the change of R15 is smaller than that of the radial advection term on the change of R15.

Next, the time variation of each term is investigated not only at R15 but also near R15. Figure 2.54 illustrates the time-radius views of the left-hand side, horizontal advection term, vertical advection term, and diffusion term in Eq. (2.18). Around R15 (500–600 km), the vertical advection term and diffusion term scarcely change with time, whereas the radial advection term becomes large after about 60 hours, when the left-hand side of Eq. (2.18) at R15 becomes large (Fig. 2.53). The appearance of the region where the radial advection of AAM is large around R15 causes the variation of the left-hand side and thus the increase of R15 in the later period of integration.

Next we analyse the radial advection term $(-\pi v_r \frac{\partial M}{\partial r})$ by separating axisymmetric component $(-\pi \overline{v_r} \frac{\partial \overline{M}}{\partial r})$ and asymmetric component $(-\pi (\overline{v_r})' \frac{\partial M'}{\partial r})$. Figure 2.55 shows the time-radius view of the axisymmetric and asymmetric component of the radial advection term. Focusing on around R15 (500–600 km), the axisymmetric component hardly changes with time, whereas the asymmetric component increases with time.

As described above, we can conclude that the increase rate of R15 changes in the middle of experiments due to the contribution of AAM increase caused by the asymmetric component of radial advection of AAM.

7.4 Summary

From the results of the parameter experiments in which forcing is applied to two regions (Series D), we obtained the following results. When both inner and outer forcings are applied to the inside of R15, the vortex size becomes larger as the forcing is located at closer to the initial R15 and as the forcing is stronger. This characteristic is consistent with the linear superposition of the experiments in which forcing is applied to one location. We also showed that the increase of R15 is linearly related to the heat forcing, i.e., the increase of R15 in the experiments in which forcing is applied to two regions is corresponded to the sum of the increase of R15 in experiments in which only the inner forcing

is applied and only the outer forcing is applied. The condition which the relationship between the increase of R15 and heat forcing is linear is that the radial gradient of AAM near R15 is the same.

It is revealed that when the forcing is applied to the inside and outside of R15, the vortex size becomes larger as the inner forcing is located at closer to the initial R15 and stronger, and as the strength of outer forcing is weaker except for the case that the outer forcing is located near R15. In the experiments in which the outer forcing is located near R15, the tendency of the change of R15 varies during the course of time integration due to the effect of asymmetric component of radial advection of AAM. In this case, the vortex size becomes larger as the outer forcing is stronger. This can be attributed to the fact that the effects of the inner forcing on the increase in size of vortices are larger than those of the outer forcing on the decrease in size of vortices.

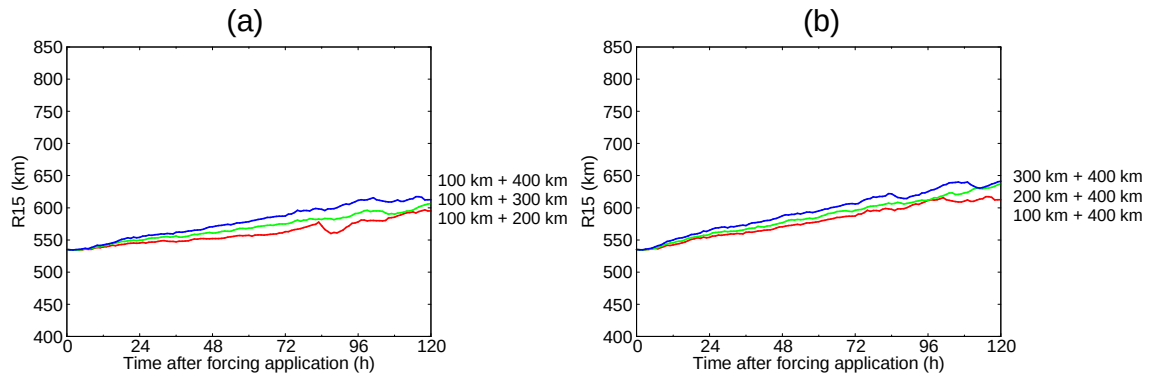


Figure 2.44: Time evolution of R_{15} in the experiments in which (a) the strength of both inner and outer forcings are set to $0.5Q$, the inner forcing location is fixed to 100 km from the center and the outer forcing location is set to 200 km, 300 km, and 400 km, and (b) the strength of both inner and outer forcings are set to $0.5Q$, the outer forcing location is fixed to 400 km from the center, and the inner forcing location is set to 100 km, 200 km, and 300 km. The ordinate and the abscissa represent R_{15} (km) and time (h) after forcing application, respectively.

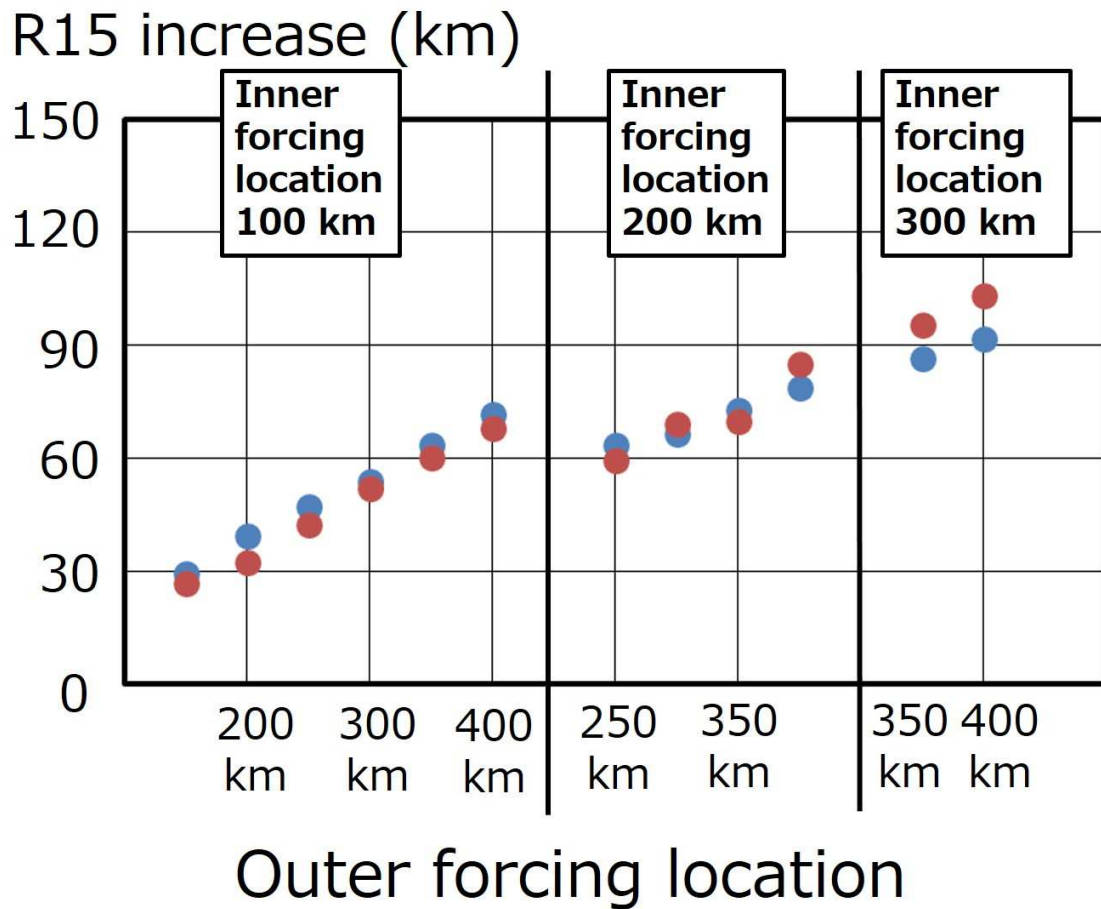


Figure 2.45: Time-averaged increase in R15 between 84 and 108 h in each experiment in the parameter experiment in which two forcings having strength of $0.5Q$ are applied to the inside of R15 (blue closed circle). In addition, the sum of the time-averaged increase in R15 between 84 and 108 h in experiments in which only the inner forcing is applied and only the outer forcing is applied is shown as red closed circles. The ordinate and the abscissa represent the increase in R15 (km) and the location of outer forcing, respectively.

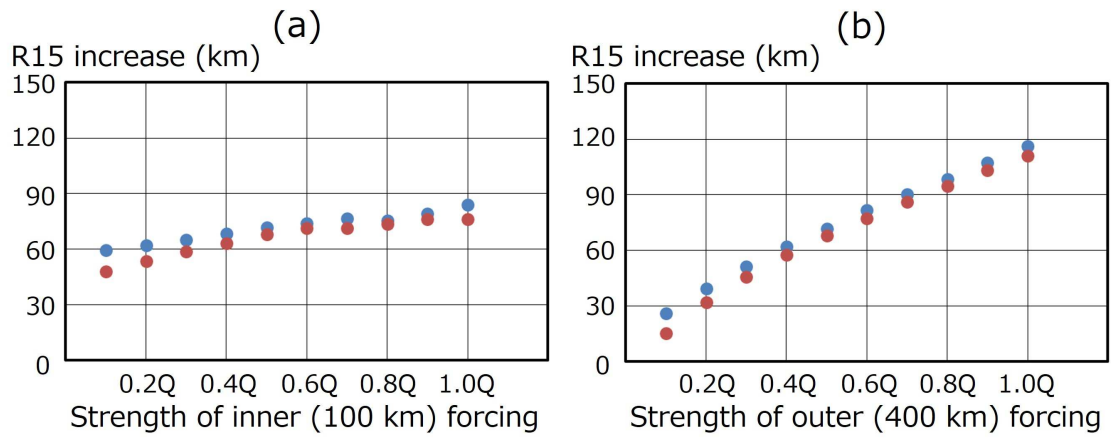


Figure 2.46: Time-averaged increase in R15 between 84 and 108 h in each experiment in the parameter experiment in which the locations of inner and outer forcings are set to 100 km and 400 km, respectively, and (a) the strength of inner forcing is fixed to $0.5Q$ and that of outer forcing is changed from $0.1Q$ to $1.0Q$ and (b) the strength of outer forcing is fixed to $0.5Q$ and that of inner forcing is changed from $0.1Q$ to $1.0Q$ (blue closed circle). In addition, the sum of the time-averaged increase in R15 between 84 and 108 h in the experiments in which only the inner forcing is applied and only the outer forcing is applied is shown as red closed circles. The ordinate and the abscissa represent the increase in R15 (km) and the strength of outer forcing (400 km) in (a) and inner forcing (100 km) in (b), respectively.

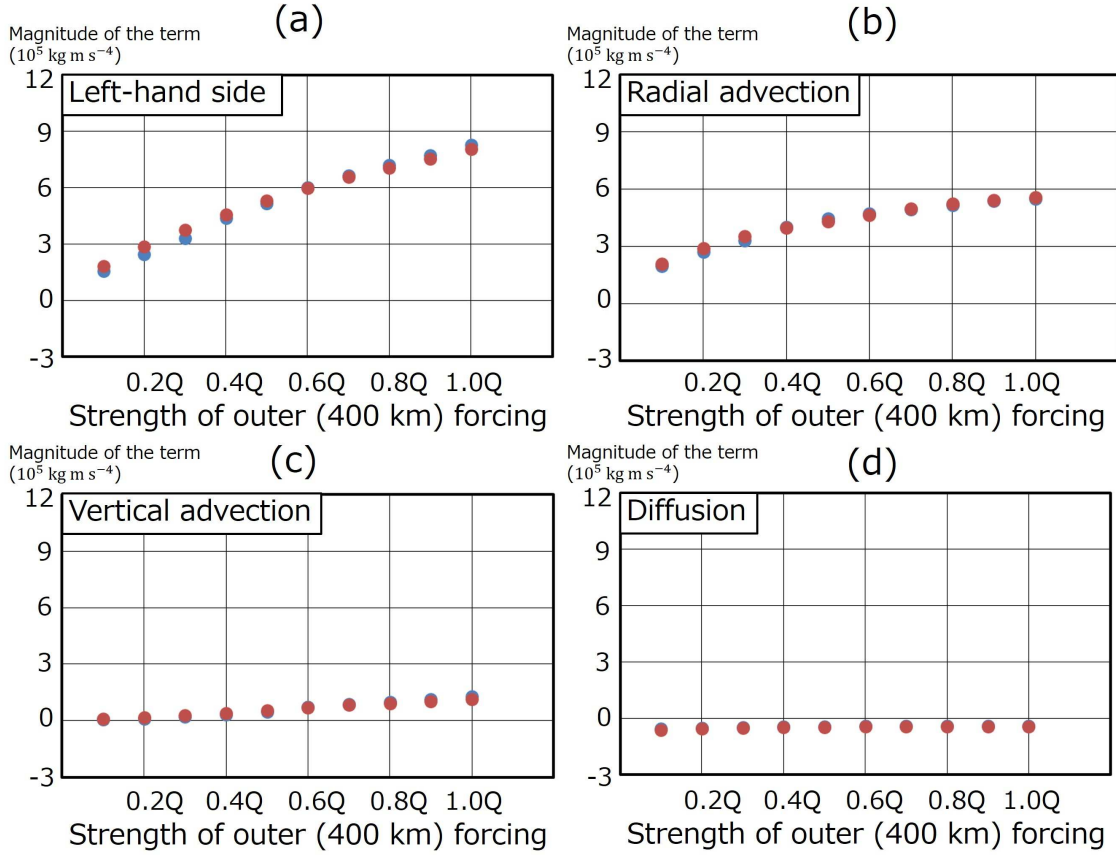


Figure 2.47: Magnitudes of (a) left-hand side, (b) radial advection term, (c) vertical advection term, and (d) diffusion term in Eq. (2.18) of experiments in which the inner forcing strength and location are set to $0.5Q$ and 100 km , respectively, the outer forcing location is fixed to 400 km , and the strength of outer forcing is changed from $0.1Q$ to $1.0Q$ (blue closed circle). In addition, the sum of the time-averaged magnitudes of each term in Eq. (2.18) in the experiments in which only the inner forcing is applied and only the outer forcing is applied is shown as red closed circles. These values are averaged between 1 and 96 h at R15. The ordinate and the abscissa represent the magnitudes of each term ($\times 10^5 \text{ kg m s}^{-4}$) and strength of outer forcing, respectively.

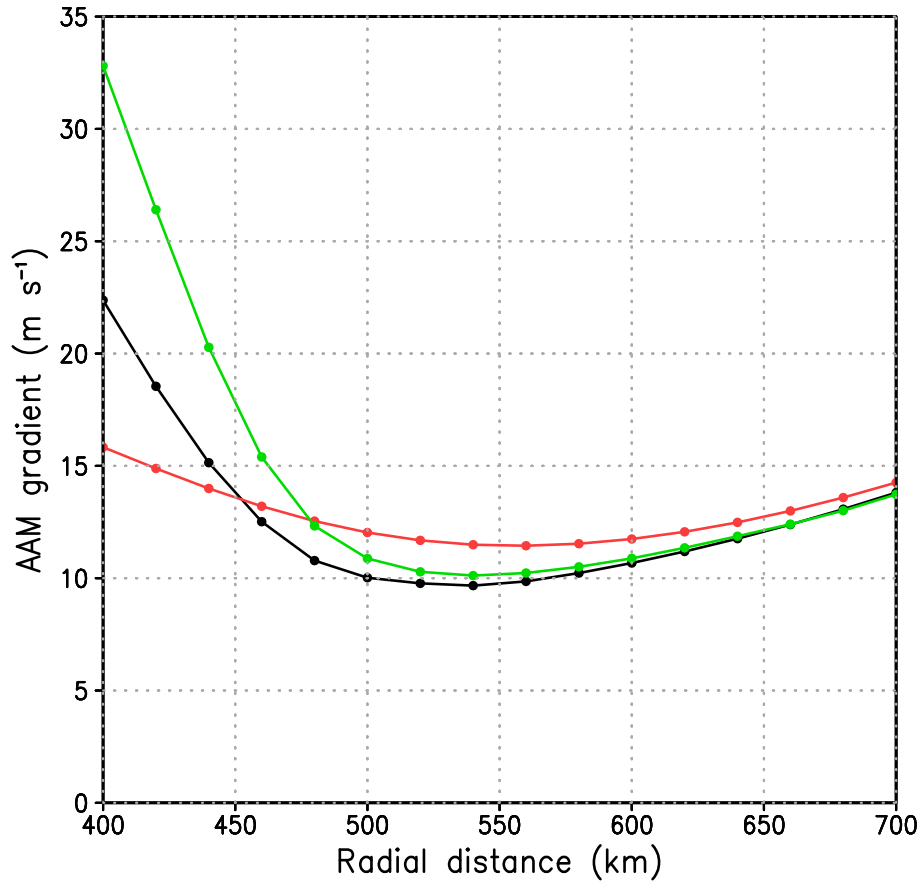


Figure 2.48: Radial distribution of time-averaged AAM gradient between 1 and 96 h in the experiment in which location and strength of inner forcing are set to 100 km and 0.5Q, respectively, and location and strength of outer forcing are set to 400 km and 1.0Q, respectively (black line). In addition, the radial distribution of time-averaged AAM gradient between 1 and 96 h in the experiments in which only the inner forcing is applied (red line) and only the outer forcing is applied (green line) are illustrated. The ordinate and the abscissa represent the radial gradient of AAM (m s^{-1}) and radial distance from the center (km), respectively.

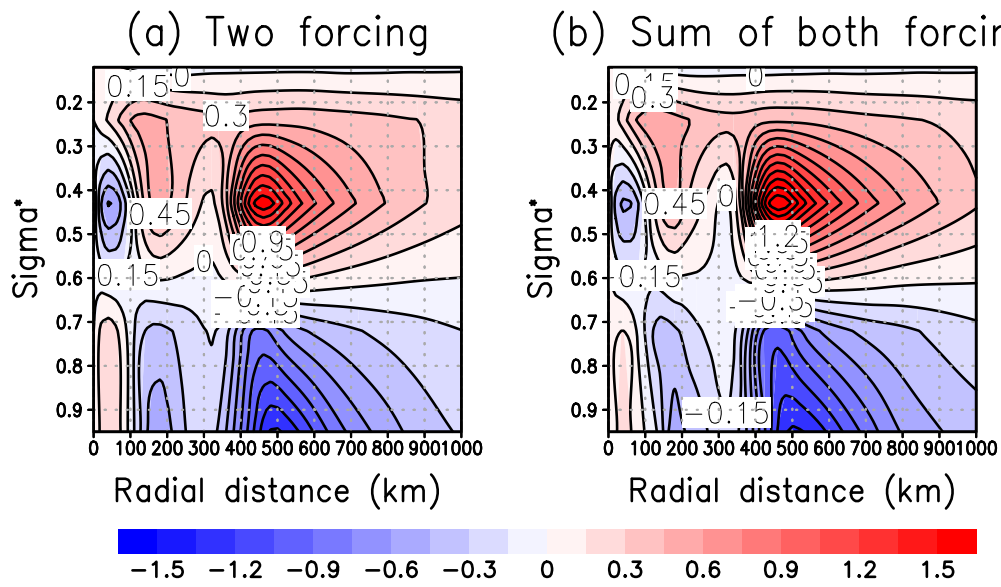


Figure 2.49: Distribution of (a) time-averaged radial wind between 1 and 96 hours in the experiment in which location and strength of inner forcing are set to 100 km and 0.5Q, respectively, and location and strength of outer forcing are set to 400 km and 1.0Q, respectively, and (b) the sum of time-averaged radial wind between 1 and 96 hours in the experiments in which only the inner forcing is applied (red line) and only the outer forcing is applied. The ordinate and the abscissa represent σ^* and radial distance from the center (km), respectively.

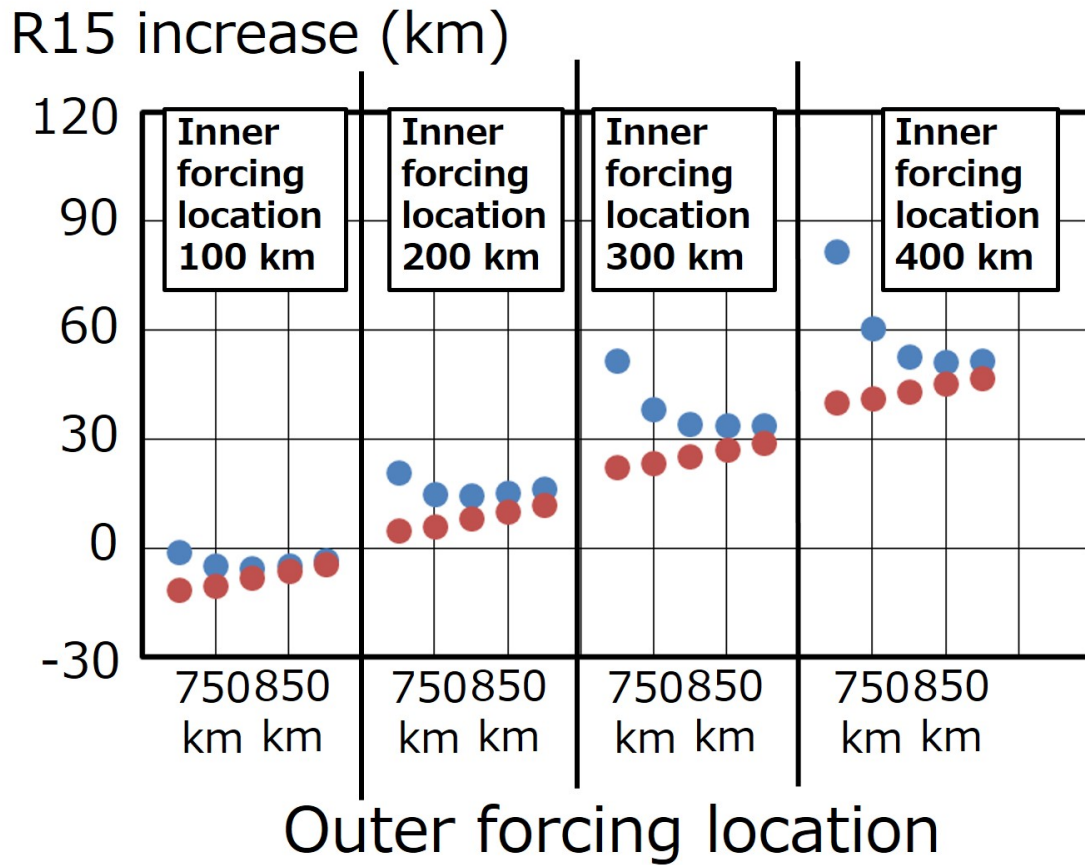


Figure 2.50: Time-averaged increase in R15 between 84 and 108 h in each experiment in the parameter experiment in which two forcings having strength of $0.5Q$ are applied to the inside and outside of R15 (blue closed circle). In addition, the sum of the time-averaged increase in R15 between 84 and 108 h in experiments in which only the inner forcing is applied and only the outer forcing is applied is shown as red closed circles. The ordinate and the abscissa represent the increase in R15 (km) and the location of outer forcing, respectively.

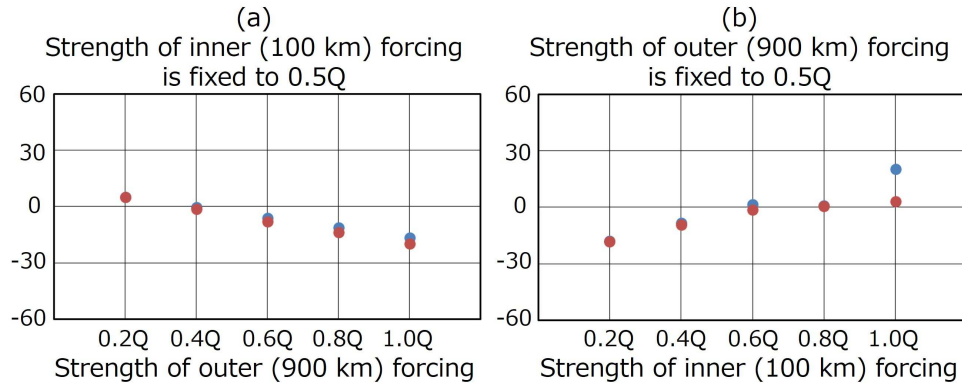


Figure 2.51: Time-averaged increase in R15 between 84 and 108 h in each experiment in the parameter experiment in which the locations of inner and outer forcings are set to 100 km and 900 km, respectively, and (a) the strength of inner forcing is fixed to 0.5Q and that of outer forcing is changed from 0.2Q to 1.0Q and (b) the strength of outer forcing is fixed to 0.5Q and that of inner forcing is changed from 0.2Q to 1.0Q (blue closed circle). In addition, the sum of the time-averaged increase in R15 between 84 and 108 h in the experiments in which only the inner forcing is applied and only the outer forcing is applied is shown as red closed circles. The ordinate and the abscissa represent the increase in R15 (km) and the strength of outer forcing (900 km) in (a) and inner forcing (100 km) in (b), respectively.

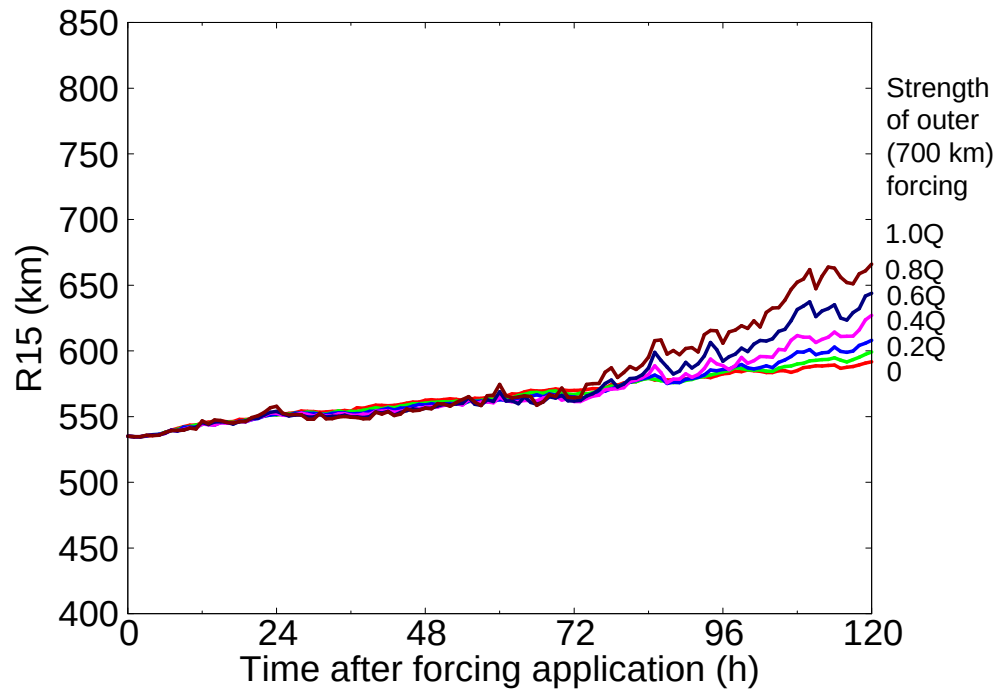


Figure 2.52: Time evolution of R15 in each experiment in the parameter experiment in which the strength and location of the inner forcing are set to 300 km and 0.5Q, respectively, location of the outer forcing are set to 700 km, and the strength of the outer forcing is changed. The ordinate and the abscissa represent R15 (km) and time (h) after forcing application, respectively.

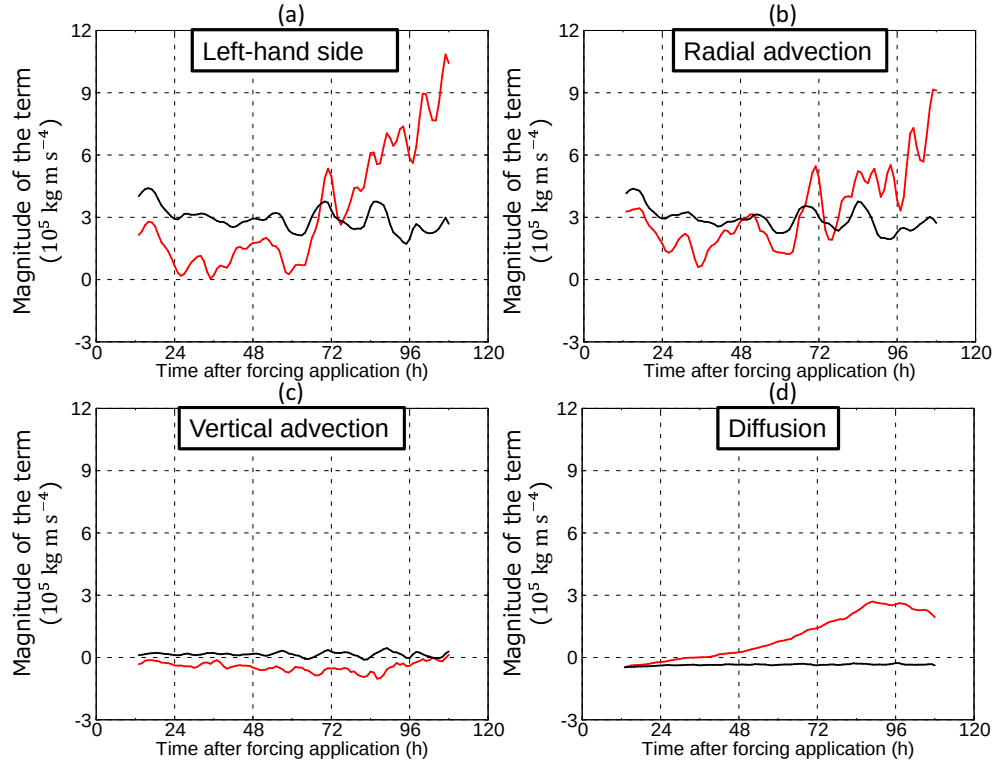


Figure 2.53: Time evolution of 25-hours moving averaged magnitudes of (a) left-hand side, (b) radial advection term, (c) vertical advection term, and (d) diffusion term in Eq. (2.18) of experiment in which the location and strength of forcing are set to 300 km and 0.5Q, respectively, in the inner forcing and 700 km and 1.0Q, respectively, in the outer forcing (red line), and those of experiment in which only the inner forcing whose location and strength of forcing are set to 300 km and 0.5Q, respectively is applied (black line). The ordinate and the abscissa represent the magnitude of each term ($\times 10^5 \text{ kg m s}^{-4}$) and time (h) after forcing application, respectively.

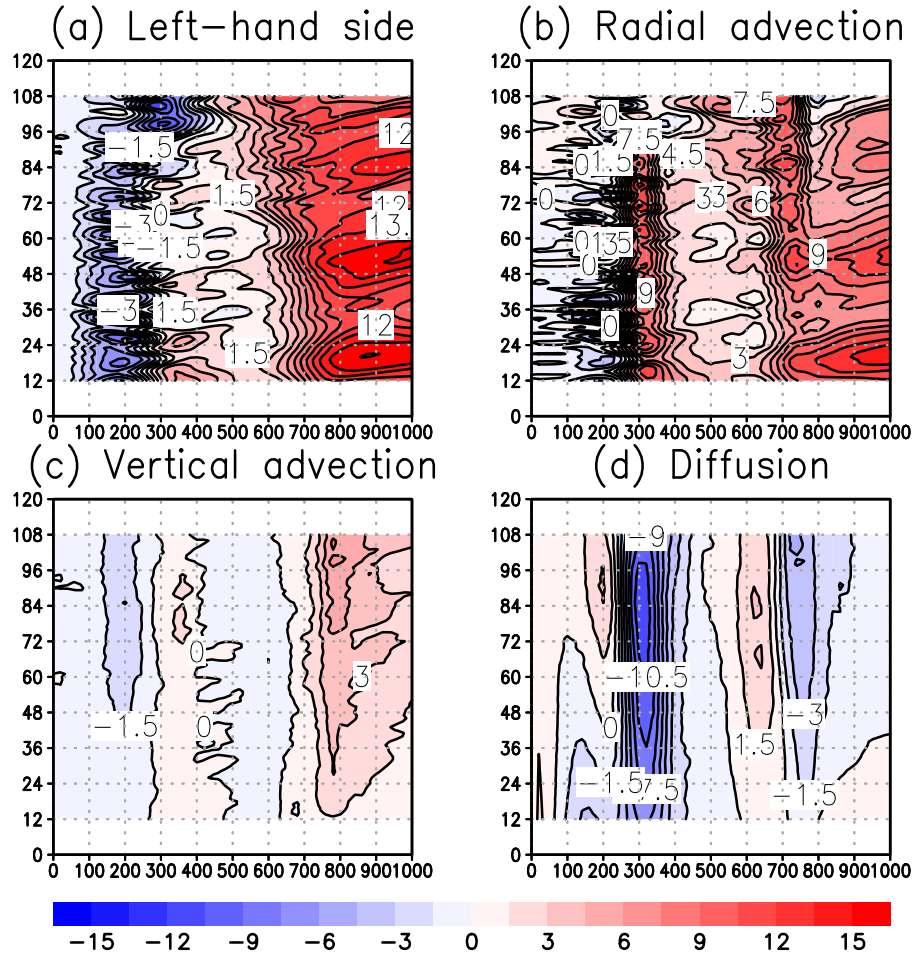


Figure 2.54: Time-radius views of 25-hours moving averaged magnitudes of (a) left-hand side, (b) radial advection term, (c) vertical advection term, and (d) diffusion term in Eq. (2.18) of experiment in which the location and strength of forcing are set to 300 km and 0.5Q, respectively, in the inner forcing and 700 km and 1.0Q, respectively, in the outer forcing. Color indicates the magnitudes of each term ($\times 10^5 \text{ kg m s}^{-4}$). The ordinate and the abscissa represent time (h) after forcing application and radial distance from the center (km), respectively.

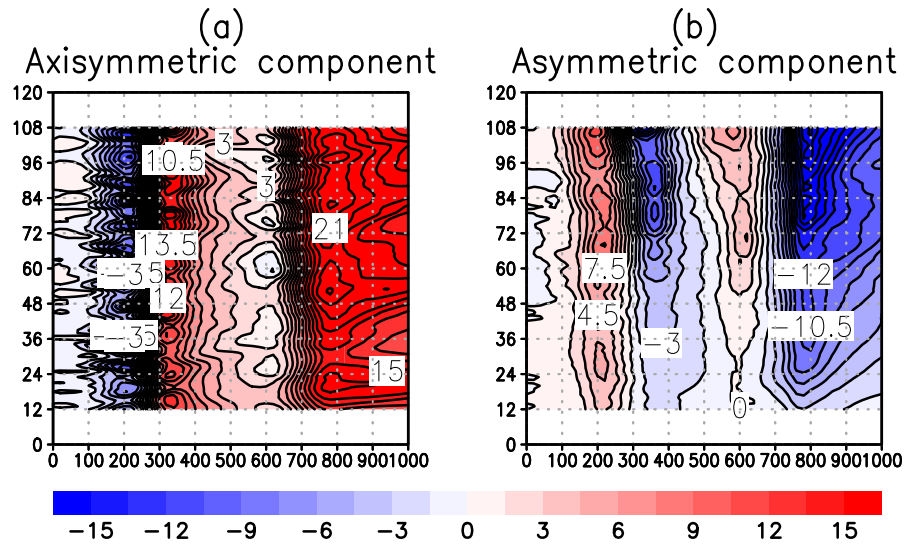


Figure 2.55: Time-radius views of 25-hours moving averaged magnitudes of (a) axisymmetric and (b) asymmetric components of radial advection term in Eq. (2.18) of experiment in which the location and strength of forcing are set to 300 km and 0.5Q, respectively, in the inner forcing and 700 km and 1.0Q, respectively, in the outer forcing. Color indicates the magnitudes of each component ($\times 10^5 \text{ kg m s}^{-4}$). The ordinate and the abscissa represent time (h) after forcing application and radial distance from the center (km), respectively.

8 Summary and discussion

In this chapter, we performed numerical experiments using the primitive equation system on an f -plane to understand the correspondence of the thermal forcing mimicking cumulus heating to the size change of TC-like vortices, as a first step to clarify the mechanism governing the size change of TCs. In the numerical experiments, we investigated the sensitivity of vortex size change to the location, strength, and horizontal scale of forcing, the effect of the structure of initial vortices on the size change of vortices, and the vortex size change when forcing is applied to two regions. The vortex size is defined as the radius of 15 m s^{-1} lowest model level wind speed (R15).

From the parameter experiment in which the location of forcing is varied, we found that the change of vortex size is small when forcing is applied near the center, vortex size becomes large when forcing is located on the outer part of vortex but still inside R15, and vortex size decreases when forcing is applied to the outside of R15. The dependence of the forcing location on the size change of vortices can be understood by considering radial transport of the AAM at R15 by the heat-induced SC, whose structure is governed by the distribution of inertial stability. Specifically, when forcing is applied near the center of the vortex, the structure of the SC becomes horizontally narrow because inertial stability in the forcing region is high, so that the inflow consisting the SC is weak near R15 and, hence, the radial advection of AAM becomes small. Thus, R15 hardly changes. When forcing is located on the outer part of vortex but still inside R15, the horizontal extent of the SC becomes wide because inertial stability near the forcing region is low. Therefore, the inflow resulted from the SC is strong near R15, which causes strong radial AAM advection. Thus, the vortex size becomes large. When the forcing location is outside R15, the flow direction of the SC induced by the forcing near R15 is outward. Thus, the sign of the radial advection of AAM at R15 is negative and the vortex size decreases.

From the parameter experiments in which the strength and horizontal scale of forcing is varied, we found that vortex size becomes larger in proportion to the strength of forcing, whereas that does not depend on the scales of forcing. When the location of forcing is the same, the largeness of the radial advection of AAM is proportional to the strength of the heat-induced SC, i.e., the strength of

the radial flow at the lower level. Therefore, the increase of R15 is proportional to the strength of forcing. Moreover, when the amount of heating is the same, the scales of forcing does not affect the size change of vortices.

The effects of the structure of the initial vortices on the size change of vortices can be understood by the difference of the efficiency of the increase of R15 resulting from the difference of the radial gradient of tangential wind. When the radial gradient of tangential wind is small, vortex size becomes larger even if the increase of AAM at R15 is the same, because the efficiency of the increase of R15 is higher in the case that the radial gradient of tangential wind is small.

From the experiments in which forcing is applied to two regions, we found that the change of vortex size can be understood by the sum of the each effect of forcing on the size change except for the cases in which the outer forcing is applied outside the initial R15 but near the initial R15. Because the response of heat forcing to the strength of the heat-induced radial wind is linear supposing that the Sawyer-Eliassen equation is completed, the strength of radial wind at R15 can be understood by the sum of the strength of the radial wind induced by each forcing. Therefore, if the difference of the radial gradient of AAM is small, the change of R15 when the forcing is applied to two regions can be understood by the sum of the contribution of each forcing to the size change of vortices. In contrast, when the outer forcing is applied to the outside of R15, the changing rate of R15 increases in the middle of experiment if the outer forcing is applied near R15. In this case, the outer forcing contributes to the increase of vortex size even though the outer forcing is located outside R15. This is because the increase rate of the tangential wind near R15 increases in the middle of experiment by the contribution of the asymmetric component of the radial advection of AAM.

Some of the findings in this chapter summarized above are consistent with those obtained from recent modeling studies about TC size. First, Hill and Lackmann (2009) indicated the importance of humidity to TC size, finding that under a more humid environment, rainbands extend to the outer region of TCs, as do the potential vorticity field induced by diabatic heating and its associated wind field. Thus, TC size increases. In the context of our results, the extension of the rainbands corresponds

to the existence of thermal forcing in the region of low inertial stability far away from the vortex center. This forcing can induce SC extending outside of the TC, thus increasing TC size.

Fudeyasu and Wang (2011) indicated that diabatic heating in the outer rainband (about 40–150 km from the center) contributes to the increase in tangential wind in the middle layer in the outer core region (about 60–200 km from the center) whereas that in the inner core region does not. Our results can interpret the different sensitivity of tangential wind to the heating in the inner and outer core regions as resulting from the difference of inertial stability at the forcing locations. In addition, the present results also indicate that an analogous process operates also in the lower layer and over the region much more isolated from the TC center than in the case of Fudeyasu and Wang (2011). The results of Musgrave et al. (2012), indicating that thermal forcing outside the RMW (outer edge of the vorticity skirt) affects the vortex size whereas forcing inside the RMW does not, can also be interpreted similarly.

The results of previous observations and realistic numerical experiments have also indicated that the inertial stability near the TC center is too large for the extent of the SC to reach outside of R15. For example, I^2 near the TC center was shown to reach 1000 times that of f^2 (Holland and Merrill 1984). The ratio is comparable to that observed in the experiment L100 (Fig. 2.20a). Ito et al. (2011) showed from idealized numerical experiments that the period of the inertial oscillation for mature TCs is often shorter than 20 min. This result corresponds to I of approximately $5 \times 10^{-3} \text{ s}^{-1}$, which is larger than that observed in L100. Thus, the contribution of heating in the inner core region to the size of real TCs is expected to be small.

The dependence of the change of vortex size on the inertial stability around the forcing location exemplified in the present study can reasonably explain the weak correlation between TC size and intensity having been investigated by Merrill (1984) and other studies. The spatial separation between the locations of heating affecting intensity and size, i.e., the neighborhood of the TC center where heating affects intensity and the outer region where heating affects size, indicates that the intensity and size of TCs can evolve independently if the clouds near the center and outer region of TCs develop

independently.

As described above, the obtained results from the numerical experiments shown in this chapter can explain some characteristics of actual TC size change investigated by previous studies even though TCs are investigated in the point of view of the simplified TC-like vortices, which strongly indicate that the framework of the idealized numerical experiment performed in this chapter has a possibility to be applied to the size change of TCs in a realistic situation. Therefore, it is worthy to investigate that how much the size change of real TCs can be understood based on the results of the idealized numerical experiments shown in this chapter. In the next chapter, we investigate the relationship between the size change of real TCs and distribution of heating by using observation data.

Chapter 3

Relationship between the size change of tropical cyclones and heating distribution observed in the tropical cyclones in the real atmosphere

1 Introduction

In the previous chapter, we have examined the relationship between the thermal forcing mimicking cumulus heating and size change of TC-like vortices by the idealized numerical experiments. In this chapter, based on the results of the idealized experiments shown previous chapter, we investigate the relationship between the size change of TCs and the distribution of cumulus heating (precipitation) by using observation data.

1.1 Correspondence between the results of idealized experiments and mechanism of size change of real tropical cyclones

In the idealized experiments shown in chapter 2, a number of physical processes in actual TCs are excluded to simplify the consideration. Thus, the relationship between heating and size change of vortices obtained from the experiments does not consider the effects of these excluded processes. Therefore, the direct applicability of the mechanism obtained from the idealized experiments to actual TCs is unclear. Still, however, there are two reasons to expect that the mechanism obtained in the previous chapter has a possibility to explain the change of actual TC size change. One is that as discussed in section 1 of chapter 2, cumulus heating is unquestionably important as a factor governing TC size change. The other is that as discussed in section 8 of chapter 2, the results of the idealized experiments can explain the TC size change examined in many previous studies in which more realistic numerical experiments were performed.

Based on the discussion above, it is worthy to investigate whether the relationship between the size change of actual TCs and the distribution of cumulus heating, i.e., distribution of precipitation is consistent with the results of the idealized numerical experiments. In this chapter, we statistically examine the relationship between the change of TC size, which we define by R15 again, and precipitation distribution by using satellite observation data.

1.2 Review of researches on tropical cyclones by using satellite observation data

In this subsection, before performing satellite data analyses, we review the previous studies considering the size of TCs and the rainfall distribution of TCs by using satellite observation data.

There have been several studies about TC size by using satellite observation data. Liu and Chan (1999) investigated the TC size, which is defined by the distance from the center of TCs to the location where azimuthally averaged vorticity becomes less than $1 \times 10^{-5} \text{ s}^{-1}$, by using observation data obtained by European Remote-Sensing Satellites 1 and 2. They concluded that TCs over the western North Pacific is larger than those over the Atlantic. They also showed that TCs over the western North

Pacific in late seasons (October and November) are large and those in midsummer (July and August) are small. Chan and Chan (2012) also investigated the size of TCs, which is defined as the average radial extent of gale-force surface winds (17 m s^{-1} ; R17), by using observation data obtained from Quick Scatterometer (QuikSCAT). They found that TCs over the western North Pacific are larger than those over the North Atlantic and the size of TCs depends on seasons. Additionally, they showed that the interannual variation of TC size in the western North Pacific is related to El Niño-Southern Oscillation, with larger size in El Niño and smaller size in La Niña. Using QuikSCAT data, Chavas and Emanuel (2010) examined the distribution of TC size for which they employed two different definitions, i.e., the azimuthally averaged radius of 12 m s^{-1} wind speed (R12) and the radius of vanishing winds (R0) calculated adopting the outer wind structure model of Dean et al. (2009). They pointed out that the distribution of TC size is qualitatively log-normal, and that TC size defined by R0 or R12 tend to expand very slowly with time early in the storm lifecycle and remains nearly constant after the expansion. Lee et al. (2010), defining TC size by the radius of 15 m s^{-1} wind speed (R15) calculated by using QuikSCAT data, compared TC size at the first observation time during tropical storm stage (over 34 kt or 17.5 m s^{-1}) with those at the first observation time during typhoon stage, finding that TCs initially larger (smaller) than others remain larger (smaller) after development, even though size increases with development.

As reviewed above, there are a number of papers using satellite observation data focusing on climatological characteristics of TC size. In contrast, except for Lee et al. (2010), few studies have examined the temporal evolution of TC size, and research investigating the relationship between TC size and precipitation distribution does not exist.

There are also a number of papers considering precipitation distributions in TC using satellite data. Lonfat et al. (2004) examined relationship between precipitation distribution in TCs and TC intensity by using Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TRMM/TMI), and found that the amount of azimuthally averaged precipitation inside 250–300 km from the center is greater and found that, as TCs intensify, the location of the peak of azimuthally averaged rain rate

shifts to a smaller radius. Additionally, they investigated the relationship between the geographical location of TCs and the rainfall distribution, finding that the characteristics of the rainfall distribution vary depending on oceanic basins. Jiang et al. (2013) investigated the characteristics of convection and precipitation in TCs by using TRMM data including TRMM Precipitation Radar (TRMM/PR). They analyzed the rainfall regions in TCs by dividing into inner core region, inner rainband region, and outer rainband region (beyond 150–200 km from the center), finding that the signature of strong convection is found more frequently in the order of inner core region, inner rainband region, and outer rainband region. Zagrodnik and Jiang (2014) examined the distribution of precipitation, convection, and latent heating in rapidly intensifying TCs by using TRMM data including TRMM/PR, finding that the frequency of TRMM/PR pixels with a near surface reflectivity exceeding 20 dBZ, which is analogous to the raining area, is strongly correlated with future intensity change. They also showed that the radius of maximum frequency of pixels of near surface reflectivity exceeding 20 dBZ shifts to a smaller radius as TCs intensify more rapidly. Additionally, they showed that moderate-to-deep convection and latent heating significantly increase in the inside of 50 km from the center when the rapid intensification continues over 12 hours. Tao and Jiang (2015) also investigated the distribution of rainfall and convection in rapidly intensifying TCs by using TRMM data including TRMM/PR, finding that the shallow precipitation in rapidly intensifying TCs extends wider than that in TCs not rapidly intensifying.

As reviewed above, researches about precipitation distribution in TCs are actively executed by using TRMM data. However, almost all of the previous studies focus on the precipitation near the center of TCs and discuss the relationship between precipitation distribution and TC intensity, or TC intensity change. Studies focusing on the precipitation distribution at far from the center such as around R15 or the relationship between precipitation distribution and TC size change have not been carried out yet.

In the previous observational studies, climatological studies such as the relationship between TC size and environmental condition are carried out for TC size, and studies about the relationship between TC intensity or its intensity change and precipitation distribution are performed about the dis-

tribution of rainfall. However, few studies were carried out about TC size change and precipitation distribution at far from TC center. Therefore, analyses about the relationship between TC size change and precipitation distribution by using satellite observation data are definitely required.

This chapter consists of six sections as follows. In section 2 and section 3, we explain about the data used in the analyses and method of the analyses. We show the results of analyses in section 4. In section 5, we discuss the results of analyses with those of idealized experiments in chapter 2. The contents of this chapter are summarized in section 6.

2 Data

2.1 Data used in the analyses

a) Tracks and maximum wind speed

The six-hourly besttrack data of Japan Meteorological Agency are used to obtain the maximum wind speed of TCs, which is used to calculate the estimation of radial profile of wind speed and to classify intensity and intensity change of TCs shown later, and the location of TC center.

b) Wind speed

To calculate TC size, which we define by the radius of 15 m s^{-1} wind speed (R15), we use wind speed data over the ocean surface obtained from SeaWinds microwave scatterometer on the QuikSCAT satellite (hereafter, referred to as “QuikSCAT data”). The QuikSCAT satellite was a sun-synchronous satellite launched in June 1999 and its mission ended in November 2009. The advantages of QuikSCAT data are the width of swath (1800 km), which fits to correct estimate of TC size by R15, and the long duration of observation period, in which a large number of TCs are captured. Although newer satellites observing ocean surface wind were launched after SeaWinds, no one is superior to SeaWinds in the width of swath and the duration of observation period.

In this study, we use the postprocessed $0.25^\circ \times 0.25^\circ$ gridded QuikSCAT data from the Remote Sensing Systems (RSS) database (RSS version4). This dataset is produced by reprocessing QuikSCAT

L2A data produced by the Jet Propulsion Laboratory by using Ku-band Geophysical Model Function (Ku-2011). The data are available at <http://www.remss.com>.

c) Precipitation

We use two types of precipitation data to calculate rainfall distribution. One is the version 7 of TRMM/TMI 2A12 precipitation data. TRMM was a non-sun-synchronous satellite launched in November 1997 and its mission ended in April 2015 after changing its average operating altitude in August 2001. The horizontal resolution and swath width of TRMM/TMI are 7–58 km and about 870 km, respectively, after changing operating altitude. Although TRMM/TMI cannot observe vertical structures unlike TRMM/PR, it has an advantage of having an about three times more wider range of observation area than TRMM/PR. The long duration of observation period is also an advantage of TRMM/TMI data. Additionally, because TRMM/TMI data contains the estimate of convective precipitation in addition to surface precipitation, we can analyze rainfall discriminating convective and stratiform precipitation.

The other data we use is Global Satellite Mapping of Precipitation (GSMaP) data, which is a precipitation product estimated by combining various data such as satellite data including TRMM and the objective analysis data made by Japan Meteorological Agency. The GSMaP project was promoted for a study “Production of a high-precision, high-resolution global precipitation map using satellite data,” sponsored by Core Research for Evolutional Science and Technology (CREST) of the Japan Science and Technology Agency (JST) during 2002–2007. After that, GSMaP project activities are continued by the promotion by the JAXA Precipitation Measuring Mission (PMM) Science Team. The temporal and spatial resolution of GSMaP data is 1 hour and 0.1×0.1 degree in longitude and latitude. This high resolutions are an advantage of GSMaP data. Additionally, because there are no restrictions related to the swath of instrument differing from satellite data, whole of TCs can be covered at each observational time.

The reason why we use two precipitation data is to make up for the disadvantages of each dataset. As mentioned above, the GSMaP data have the advantages of the temporal and spatial resolution and

coverage, whereas factitious features of precipitation sometimes appears in the joint of different data (Fig. 3.1). In contrast, TRMM/TMI 2A12 data do not include such factitious features, whereas the observation width, which is about 870 km after changing operating altitude, is not wide enough to observe whole of TCs. Moreover, the frequency of the observation by TRMM is not constant because TRMM is a non-sun-synchronous satellite.

In the following, we first analyze a representative case of TC by using TRMM/TMI data. Then, the generality and data dependence of the results obtained from the analysis of the representative case are examined by performing statistical analyses comparing TRMM/TMI data and GSMaP data. Thereafter, the dependence of the results on the intensity and intensity change of TCs is investigated by using GSMaP data.

In the analyses of this study, we use precipitation distribution instead of latent heat distribution. The reason why we use precipitation distribution although it is more reasonable for comparing with the idealized experiments to analyze the relationship between TC size change and latent heat distribution is that TRMM/TMI cannot observe latent heat distribution. The latent heat data are included in TRMM/PR data, but the width of observation in TRMM/PR is too narrow to obtain enough data to analyze. The correspondence between precipitation observed by TRMM/TMI or TRMM/PR and latent heating in TCs is investigated, for example, by researches as below. Park and Elsberry (2013) pointed out that the heating rate in lower level in strong convective raining areas is overestimated. However, Zagrodnik and Jiang (2014) mentioned that “latent heating obtained by TRMM 2H25 is closely correlated with PR 2A25 rain rates, as the linear correlation coefficient in this study is 0.89 overall and 0.74 for rain rates above 20 mm h^{-1} ”. Moreover, Cecil and Wingo (2009) compared four precipitation products including version 6 TRMM/TMI 2A12 and TRMM/PR 2A25, finding that the mean rain rate of 2A25 data in the inner core region (0–100 km) in hurricanes is high biased, but TRMM/PR 2A25 and TRMM/TMI 2A12 tend to agree on the average amount of rain in tropical storms, tropical depressions and further away from the center of hurricanes. Considering above, the precipitation distribution of TRMM/TMI data can be regarded as the proxy for the latent heating distribution around the outer

part of TCs including around R15, where the results of the idealized experiments indicate the strong relationship between TC size change and latent heating.

2.2 Period and region for analysis

Because we need both precipitation and wind data, we analyze data between August 2001, when the operating altitude of TRMM was changed, and November 2009, when the observation of QuikSCAT ended. The analyses region is set to the area from 0°N to 30°N and 125°E to 180°E to avoid the effect of land and the low observation precision of TRMM at poleward than 30° .

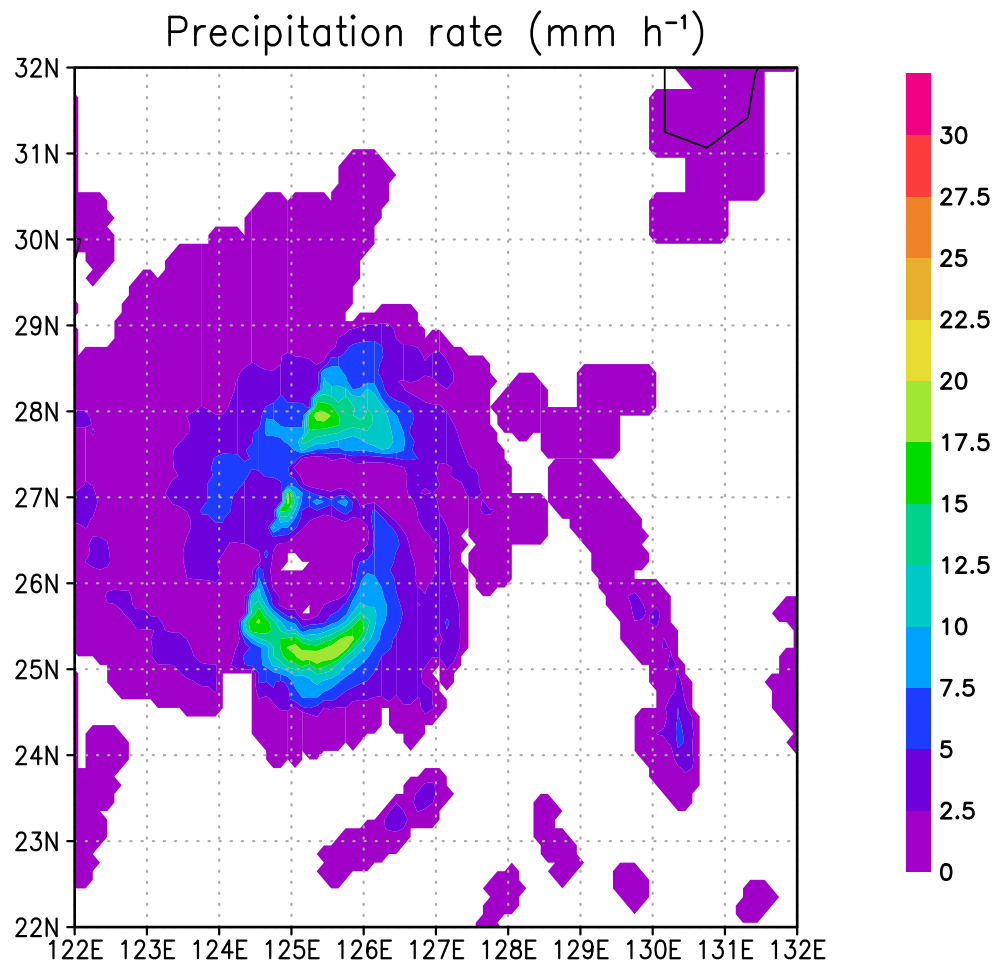


Figure 3.1: Distribution of precipitation rate at 1800 UTC 15 September 2002 in TC Sinlaku (2002) obtained from GSMaP data. Color represents hourly precipitation rate (mm h^{-1}). The ordinate and the abscissa represent latitude and longitude, respectively.

3 Method of analyses

3.1 Method of calculating R15

R15 is calculated by using the QuikSCAT data. Because the accuracy of wind speed data in raining region is not good due to the characteristics of scatterometers, the rain-flagged data are excluded.

To calculate R15 by using the QuikSCAT data, we first consider polar coordinate whose center is set to that of the TC to be examined and calculate the radial profile of azimuthally averaged wind speed. The location of TC center on the QuikSCAT observation time is estimated by linear interpolation from the besttrack data. The center of the circulation on the QuikSCAT data sometimes misaligned to that of TCs estimated from the besttrack data¹. However, we do not consider the misalignment because our focus is on the evolutions and structures of the wind and precipitation at further from the center.

Next, the data without rain-flag in 25 km wide annuli around the TC center are averaged. The averaged wind speed is estimated as the azimuthally averaged wind speed at the radial grids beginning from 12.5 km separated by 25 km. All data within 12.5 km from the radial grid is combined. When rain flagged or missing data in each annulus is greater than five or 50%, the radial grid is regarded as missing and we do not use the data, which is the same as the criteria of Chan and Chan (2012) for reference.

By using the estimated radial profile of wind speed, R15 is estimated by the linear interpolation between the closest not-missing radial grid to the center, where the wind speed is less than 15 m s^{-1} outside the radius of maximum wind (RMW), and the one closer radial grid to the center. When the wind speed of the closest not-missing radial grid to the center is less than 10 m s^{-1} or the not-missing radial grid whose wind speed is greater than 15 m s^{-1} does not exist, R15 is not defined. In this case, the observation is not used in the analyses.

¹According to Chan and Chan (2012), the cases in which the estimated TC center is deviated over 1° latitude from the center of circulation in the QuikSCAT data are less than 1% in all QuikSCAT observation.

3.2 Extraction of size increase period and size stationary period

To discuss the change of TC size, the size increase period and size stationary period are extracted by using R15 calculated by the QuikSCAT data. For such periods to be identified, R15 must be defined for some interval of time. However, the observation by QuikSCAT is performed no more than once every 12 hours. Additionally, QuikSCAT cannot observe TCs in some case because the satellite does not always pass over TCs. Bearing the limited availability of QuikSCAT observations in mind, for each of the TCs, we first extract 48 hour periods that includes more than four observation with which R15 is obtained for the TC, or 72 hour periods that includes more than five observation with R15.

Among the extracted time periods, period is judged as “size increase period” if it meets the following requirements.

1. R15 monotonically increases with time in the period
2. The period must include more than 50% observations whose R15 deviates from the period-averaged R15 more than 30% of the average R15

The second criterion is set to exclude the case in which the increase of R15 is very small.

The size stationary period is defined by the time period in which the following requirements are met. Similarly, period is judged to be “size stationary period ” if it meets the following requirements.

1. R15 does not monotonically change with time in the period
2. No R15 deviates from the period-averaged R15 by more than 20% of the average R15

The specific terms of each period are shown in Tables 3.1 and 3.2. The number of TCs with which one or more size increase periods are found is 31; the number of TCs with which one or more size stationary periods are found is 31. In 11 TCs, both size stationary and size increase period can be identified. The period in which both periods are overlapped is regarded as size stationary period.

3.3 Method of calculating inertial stability

Inertial stability is defined by Eq. (2.15). It is required to calculate $\partial v_\varphi / \partial r$, but the radial profile of the wind speed estimated from the QuikSCAT data is often discontinuous, making the calculation of the gradient of tangential wind continuously difficult. Thus, we fit the wind structure of modified Rankine vortex to the observed radial profile of tangential wind in TCs and determine the radial profile of tangential wind.

Following Mueller et al. (2006), modified Rankine vortex is defined by

$$v_\varphi(r) = \begin{cases} V_m \left(\frac{r}{R_m} \right) & (r < R_m) \\ V_m \left(\frac{R_m}{r} \right)^x & (r > R_m), \end{cases} \quad (3.1)$$

where V_m , R_m , and x designate the maximum wind speed, the RMW, and size parameter, respectively. These are estimated as below. First, x is estimated by supposing V_m and R_m as the maximum value of the azimuthally averaged wind speed and RMW obtained from QuikSCAT data, respectively. Then, the data in which the azimuthally averaged wind speed is greater than 20 m s^{-1} are excluded because the accuracy of the wind speed greater than 20 m s^{-1} is not good due to the characteristic of the instrument (RSS homepage, URL: www.remss.com). The estimated value of x is calculated by using all data located between R_m and the radius of 10 m s^{-1} wind speed, and averaging them. At this time, if the number of valid (not missing) data between R_m and the radius of 10 m s^{-1} wind speed is less than five, the data are excluded. If there are no valid wind speed data greater than 20 m s^{-1} and the maximum wind speed in the besttrack data at the observation time, which is estimated from the linear interpolation according to time, is greater than that obtained from the QuikSCAT data, x is estimated by supposing V_m and R_m as the maximum wind speed in the besttrack data and the RMW obtained from the QuikSCAT data, respectively.

When the maximum wind speed in the besttrack data is used to estimate x , the radial profile of tangential wind is estimated by V_m in the besttrack data, R_m obtained from the QuikSCAT data, and the estimated x . In contrast, when the maximum wind obtained from the QuikSCAT data is used to

estimate x , R_m is estimated by using V_m in the besttrack data at the observation time, which is estimated from the interpolation according to time, and the estimated x . If the besttrack data just before or after the observation time do not have the information of the maximum wind speed, the data do not use. The estimated value of R_m is calculated by using all data located between the radii of 20 m s^{-1} and 10 m s^{-1} wind speed and averaging them. From the above processes, V_m , R_m , and x are determined and the radial profile of tangential wind also determined. Therefore, inertial stability is calculated by using this tangential wind profile.

The radial distribution of tangential wind estimated by modified Rankine vortex almost corresponds to that obtained from QuikSCAT data (Fig. 3.2a). However, in the observation of about 10%, these are quite different (Fig. 3.2b). Such cases are excluded from the analyses by a subjective judgment.

3.4 Method of estimating the radial distribution of precipitation

The estimation of the radial distribution of precipitation from TRMM/TMI data is performed by using the similar method of calculating R15. First, the location of TC center on TRMM observation time is estimated by the linear interpolation from the besttrack data. If the TC center is located outside the observation area of TRMM/TMI, the data are excluded from the analyses. Next, the precipitation at pixels without quality-flag in 15 km wide annuli around the TC center are averaged, which is regarded as the azimuthally averaged precipitation at the center of each ring belt (radial grid). When the quality-flagged pixels in each annulus is more than five or 50%, the radial grid data at the radius are regarded as missing data. The estimation of the radial distribution of precipitation from GSMaP data is also performed in the same way.

The idealized experiments shown in Chapter 2 are performed with fixing the amount of heating in a certain annuli region. To compare the results of the idealized experiments with those of the analyses by using observation data, the azimuthally averaged precipitation must be converted to the azimuthally integrated amount, which is obtained by being multiplied by the distance from the center of TCs to

each radial grid. We refer the azimuthally averaged precipitation multiplied by the distance from the center of TCs to each radial grid as precipitation amount at the radius.

To compare the distribution of precipitation amount among different observation times or different TCs is difficult because R15 is different depending on the observation times and cases. In this study, therefore, the radial distance from the center of TCs is normalized by R15 when the radial distribution of precipitation amount is discussed. Because the TRMM or GSMaP observation times are needed to exist near the QuikSCAT observation time to perform the radial normalization, the criterion that the observation of TRMM or GSMaP exist within ± 12 hours from that of QuikSCAT is set for the analysis. If there are more than two QuikSCAT observations within ± 12 hours from the observations of TRMM or GSMaP, the temporally closer observation of QuikSCAT is used for the radial normalization.

3.5 Classifications of intensity and intensity change of tropical cyclones

In the latter part of this chapter, the precipitation distribution in size increase period and size stationary period will be compared separating the periods in which TCs are intense and weak, or those in which TCs are intensifying and the intensity of TCs does not change. Each period is defined as below by using the besttrack data.

The periods in which TCs are intense or weak are determined by whether the maximum wind speed in the besttrack data is greater than 85 kt, or not. The reason why the threshold is set to 85 kt is that all of the data in the size increase period and size stationary period can be divided almost in half. In fact, the ratio of the maximum wind speed greater than 85 kt and less than 85 kt is 33:67 in size increase period and 49:51 in size stationary period.

The period in which the intensity of TCs does not change is defined by the periods in which the maximum wind speed in the six-hourly besttrack data is the same for more than 18 hours and that is within ± 5 kt from the maximum wind speed before and after the period. However, the period in which the maximum wind speed changes more than 5 kt within 12 hours is excluded. The period in which TCs are intensifying is defined as the period in which the difference of the maximum wind speed in the

six-hourly besttrack data before and after 12 hours is more than 10 kt and which does not overlap the period in which the intensity of TCs does not change. The threshold at the increase of the maximum wind speed of 10 kt within 24 hours is set based on Jiang (2012) and Jiang and Ramirez (2013).

Table 3.1: List of TCs including size increase period and size stationary period (from 2001 to 2004). Time is expressed in Coordinated Universal Time.

Name of TC	Size increase period	Size stationary period
Danas(2001)	9/3 1942 – 9/7 0830	
Krosa(2001)		10/6 0936 – 10/8 0842
Haiyan(2001)	10/21 1918 – 10/24 1948 10/25 0812 – 10/26 1900	
Mitag(2002)	3/1 2018 – 3/4 0936	3/3 2106 – 3/5 0912
Rammasun(2002)		6/30 2018 – 7/3 0930
Halong(2002)	7/8 0730 – 7/12 0906	
Fengshen(2002)	7/18 1912 – 7/21 1942	7/21 1942 – 7/24 2006
Phanfone(2002)		8/15 2036 – 8/17 0836
Rusa(2002)	8/24 0718 – 8/26 0806	8/25 1942 – 8/29 2118
Sinlaku(2002)		8/29 1936 – 9/3 0942
Pongsona(2002)	12/4 0700 – 12/6 0748	
Kujira(2003)		4/14 2006 – 4/20 0948
Chan-Hom(2003)	5/24 0830 – 5/25 1912	
Etau(2003)	8/4 0912 – 8/7 2042	
Dujuan(2003)	8/29 2112 – 8/31 0912	
Maemi(2003)	9/7 2042 – 9/11 0930	
Ketsana(2003)		10/18 2124 – 10/20 0924
Parma(2003)	10/29 0848 – 10/30 1936	
Lupit(2003)		11/26 2112 – 11/29 0848
Sudal(2004)		4/10 2100 – 4/13 2124
Dianmu(2004)		6/15 2054 – 6/17 0854
Tingting(2004)	6/26 1924 – 6/29 0842	6/28 2018 – 7/1 0930
Namtheun(2004)	7/25 2018 – 7/27 0818	
Chaba(2004)	8/20 1906 – 8/22 1954	8/22 1954 – 8/28 2042
Songda(2004)		9/1 2036 – 9/6 1036
Meari(2004)		9/26 2130 – 9/28 0930
Tokage(2004)	10/12 1936 – 10/15 0854	10/15 0854 – 10/17 0936
Noru(2004)	12/20 0842 – 12/21 1924	

Table 3.2: List of TCs including size increase period and size stationary period (from 2005 to 2009). Time is expressed in Coordinated Universal Time.

Sonca(2005)		4/24 2054 – 4/26 2006
Nesat(2005)	6/4 2130 – 6/6 2042	6/6 0930 – 6/7 2018
Haitang(2005)	7/14 0806 – 7/16 2148	
Banyan(2005)		7/23 0918 – 7/25 0824
Talim(2005)	8/27 0912 – 8/30 0930	
Nabi(2005)	8/29 0818 – 9/1 1948	9/1 1948 – 9/5 1012
Saola(2005)	9/21 1930 – 9/3 2018	
Kirogi(2005)	10/10 2118 – 10/12 2024	10/11 2052 – 10/17 0848
Ewiniar(2006)		7/3 2124 – 7/8 2054
Saomai(2006)		8/7 0830 – 8/8 2048
Yagi(2006)	9/18 1948 – 9/21 2012	
Soulik(2006)	10/13 2042 – 10/15 0836	10/10 2018 – 10/13 2042
Durian(2006)	11/27 2106 – 11/29 0912	
Yutu(2007)		5/19 2124 – 5/22 0854
Man-Yi(2007)		7/12 1012 – 7/13 2100
Nakri(2008)		5/29 0918 – 6/1 2048
Sepat(2007)	8/12 2118 – 8/16 1006	
Fitow(2007)	8/29 0748 – 8/31 0836	8/30 0724 – 9/3 0900
Wipha(2007)	9/15 2136 – 9/17 0936	
Krosa(2007)	10/1 2118 – 10/4 2142	
Choi-Wan(2009)	9/13 0818 – 9/16 0842	
Melor(2009)		10/4 0918 – 10/6 1000
Lupit(2009)		10/18 2100 – 10/21 2118

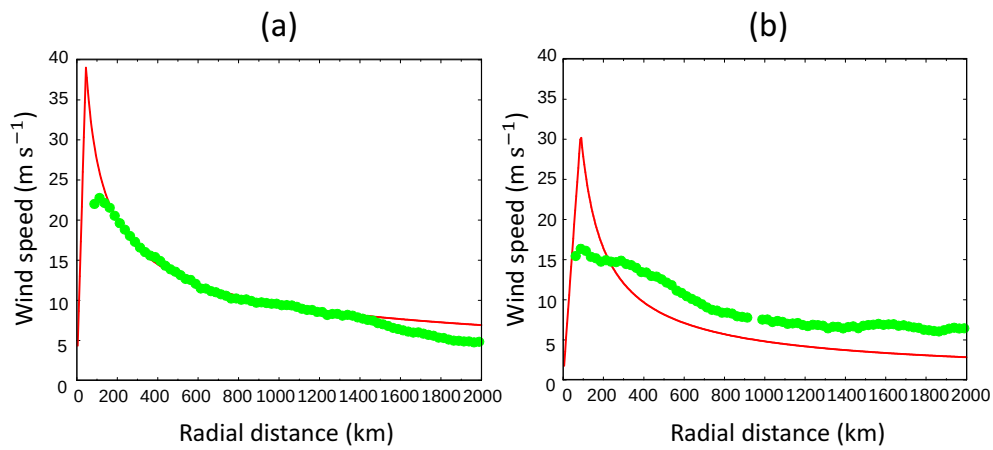


Figure 3.2: Azimuthally averaged observation values of wind speed obtained from QuikSCAT data (green closed circle) and radial profile of tangential wind estimated as modified Rankine vortex (red line) at (a) 0806 UTC 26 August 2002 and (b) 0830 UTC 25 August 2002 in TC Rusa (2002). The ordinate and the abscissa represent wind speed (m s^{-1}) and radial distance from the center (km), respectively.

4 Results

4.1 Representative case

As a first example, we show the precipitation distribution in TC Rusa (2002) which has both size increase period and size stationary period. Figure 3.3 shows the time-radius view of precipitation distribution and temporal evolution of R15 in TC Rusa (2002). The size increase period is from 0718 UTC 24 August to 0806 UTC 26 August and the size stationary period is from 1942 UTC 25 August to 2118 UTC 29 August.

First, we focus on the characteristics of the precipitation distribution in size increase period. Precipitation areas are located from inside to outside R15 in this period (Fig. 3.3). Spiral precipitation areas like rainband is observed from inside to outside R15 in the plane view of precipitation in size increase period (Fig. 3.4).

Next, we focus on the characteristics of the precipitation distribution in size stationary period. The precipitation areas in size stationary period are concentrated near the TC center and not distributed near R15 (Fig. 3.3). The intense and axisymmetric precipitation area corresponding to eyewall is confirmed in the plane view of precipitation in size stationary period (Fig. 3.5). Unlike in the size increase period, the precipitation area located from inside to outside R15 is absent.

From the above, we concluded that the precipitation distribution in TC Rusa (2002) is different between size increase period and size stationary period.

4.2 Composite analyses

In the previous subsection, we showed that the precipitation distribution in TC Rusa (2002) is different between size increase period and size stationary period. To examine the generality of the difference, we perform the composite analyses for the precipitation distribution in size increase period and size stationary period and examine the results. The procedure of making composite is as follows. First, all observations within each period in a TC are averaged. Then, the averaged data of each period in all TCs including each period is averaged.

a) Composite analyses for all cases

First, we perform composite analyses for all the cases being able to analyze (size increase period: 31 cases, size stationary period: 31 cases) and examine the general characteristics of the difference of precipitation distribution between size increase period and size stationary period.

Figure 3.6 represents the composites of the radial distribution of the precipitation amount in size increase period (31 cases) and size stationary period (31 cases). The precipitation amount in size stationary period is greater than that in size stationary period near the center ($R^* = r/R15 < 0.6$), although the difference between them is small. In contrast, the precipitation amount in size increase period is significantly greater than that in size stationary period in the outer region of TCs and the outside of R15 ($R^* > 0.6$). In particular, the difference between them is statistically significant in $R^* > 0.8$. These results are consistent with those noted in the case of TC Rusa (2002) in section 4.1.

In Fig. 3.6, the results of composite analyses by using GSMaP data are also shown (Fig. 3.6b) in addition to those by using TRMM/TMI data (Fig. 3.6a). We find the different characteristics of precipitation distributions in size increase and size stationary period in both of the figures based on the two different data products.

Next, the analyses with dividing precipitation into convective precipitation and the stratiform precipitation are performed to examine the difference of the precipitation distribution by the characteristics of precipitation. Figure 3.7 shows the results of composite analyses of the radial distribution of the precipitation amount in size increase period and size stationary period by dividing precipitation into convective precipitation and stratiform precipitation. The results of both convective and stratiform precipitation have the same characteristics as in Fig. 3.6, indicating that there are differences in the precipitation distribution in size increase period and size stationary period regardless of the convective precipitation or the stratiform precipitation.

b) Sensitivity to intensity and intensity change of tropical cyclones

Because the precipitation distribution in TCs differs depending on the intensity of TCs (e.g., Lonfat et al. 2004; Jiang et al. 2008) and the intensity change of TCs (e.g., Tao and Jiang 2015), the

relationship between precipitation distribution and TC size change may vary depending on the intensity or intensity change of TCs. In this subsection, therefore, we examine the characteristics of precipitation distribution in size increase period and size stationary period by separating the periods in which TCs are intense and weak, or separating the periods in which TCs are intensifying and the intensity of TCs does not change.

From Fig. 3.6, we clarified that the results of analyses by using the TRMM/TMI data are qualitatively the same as those by using GSMaP data. Thus, in the analyses of this subsection, GSMaP data are used to assure the number of observations.

First, to examine the effects of TC intensity on the relationship between precipitation distribution and TC size change, the relationship is investigated by separating the periods in which the maximum wind speed is greater than 85 kt and less than 85 kt. Figure 3.8 represents the results of composite analyses of the distribution of the precipitation amount in the period in which the maximum wind speed is greater than 85 kt and those in the period in which the maximum wind speed is less than 85 kt. In the period in which the maximum wind speed is less than 85 kt, the results similar to those in Fig. 3.6 are obtained. In contrast, in the period in which the maximum wind speed is greater than 85 kt, the precipitation in the size increase period is greater than that in the size stationary period in $R^* > 0.8$, but the difference between them is smaller compared with Fig. 3.6.

The reason why the difference of precipitation distribution between size increase period and size stationary period within the period of the maximum wind speed over 85 kt is small is that the size increase rate is small in the large portion of the size increase period with the maximum wind speed over 85 kt. There are 19 cases of size increase period within the maximum wind speed over 85 kt. Comparing the increase rate of R15 in each of the 19 cases ($\dot{R15}^{85kt}$) with that of all cases ($\dot{R15}^{all}$), which is calculated regardless of the maximum wind speed, the number of cases in which the increase rate of R15 in $\dot{R15}^{85kt}$ is greater than the minimum value of $\dot{R15}^{all}$ is only eight (Fig. 3.9). Additionally, three cases out of eight seems to be affected by the structure change associated with extratropical transition because the size increases in these cases occur in the latter part of the lifecycle of TCs. In

the remaining cases, the precipitation amount in size increase period and size stationary period within the period of the maximum wind speed over 85 kt of TC Fengshen (2002), TC Chaba (2004), and TC Nabi (2005), which have both size increase period and size stationary period in a case, is shown in Fig. 3.10. The precipitation amount in size increase period is greater than that in size stationary period in $R^* > 0.6$, which is the same characteristic as in Fig. 3.6, although the relationship is reversed in the region of $R^* > 1.7$ in TC Chaba (2004). This result indicates that TC intensity does not affect the relationship between TC size change and precipitation distribution.

Next, to examine the effects of the intensity change of TCs on the relationship between precipitation distribution and TC size change, the relationship is investigated by dividing into the periods in which TCs are intensifying and the intensity of TCs does not change. Figure 3.11 shows the results of composite analyses of the distribution of the precipitation amount in the size increase period and size stationary period by using data in the periods in which TCs are intensifying and the intensity of TCs does not change. In both periods in which TCs are intensifying and the intensity of TCs does not change, the precipitation distribution in size increase period and size stationary period has the similar characteristics to Fig. 3.6, i.e., the difference of precipitation distribution between size increase period and size stationary period is small near the center, whereas that is significantly large near R15 to outside R15. These results indicate that the intensity change of TCs does also not affect the relationship between precipitation distribution and TC size change.

From above results, we can conclude that the relationship between precipitation distribution and TC size change is independent from TC intensity and the existence of intensity change of TCs.

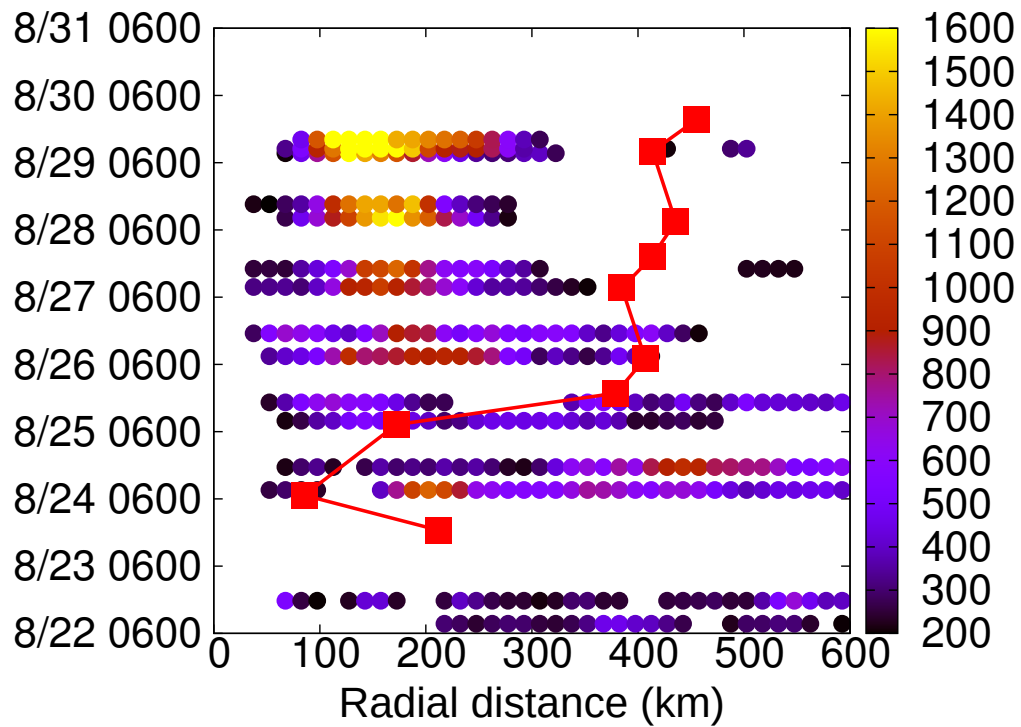


Figure 3.3: Time-radius view of the distribution of the precipitation amount and time evolution of R15 in the case of TC Rusa (2002). Color closed circles designate precipitation amount (km mm h^{-1}) calculated by using TRMM/TMI data. Red line with closed squares designate R15 calculated by using QuikSCAT data. The ordinate and the abscissa represent time (UTC) and radial distance from the center (km), respectively.

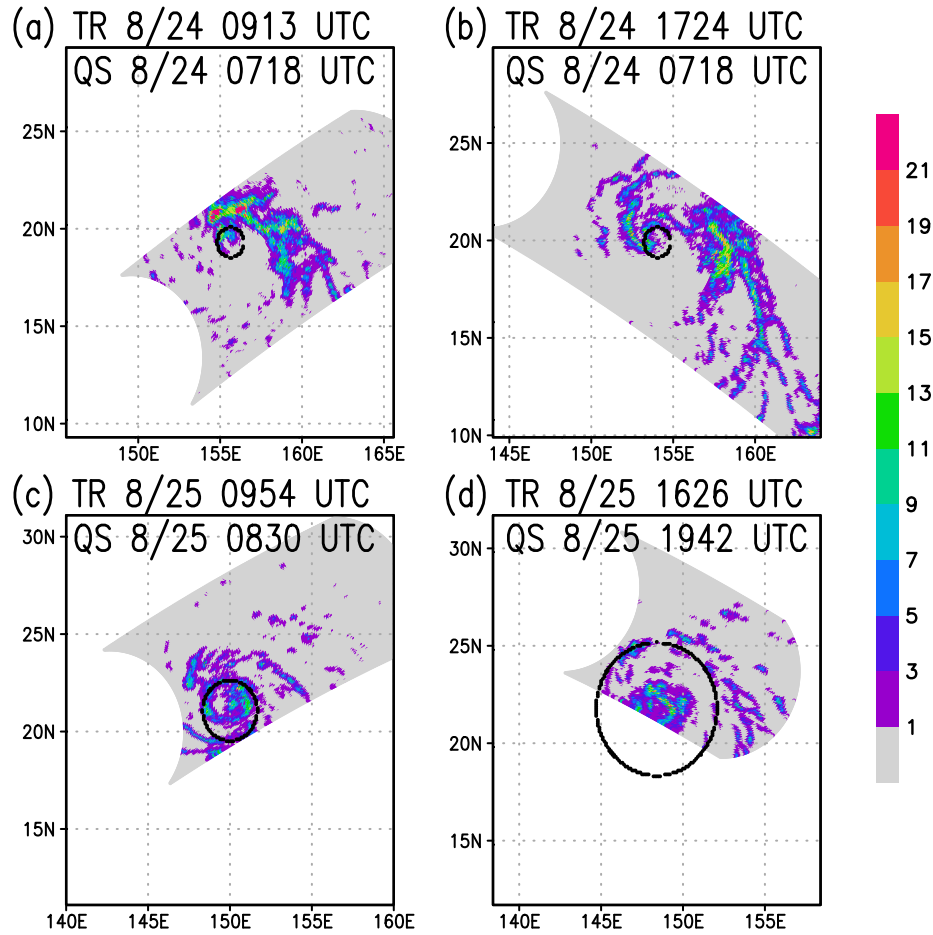


Figure 3.4: Precipitation rates obtained from the TRMM/TMI data in the increase period in TC Rusa (2002). Color indicates precipitation rate (mm h^{-1}). Black circles indicate R15 calculated by using the QuikSCAT data at the nearest observation time from the observation time of TRMM. The observation times of TRMM (TM) and QuikSCAT (QS) are shown above each figure. The ordinate and the abscissa represent latitude and longitude, respectively.

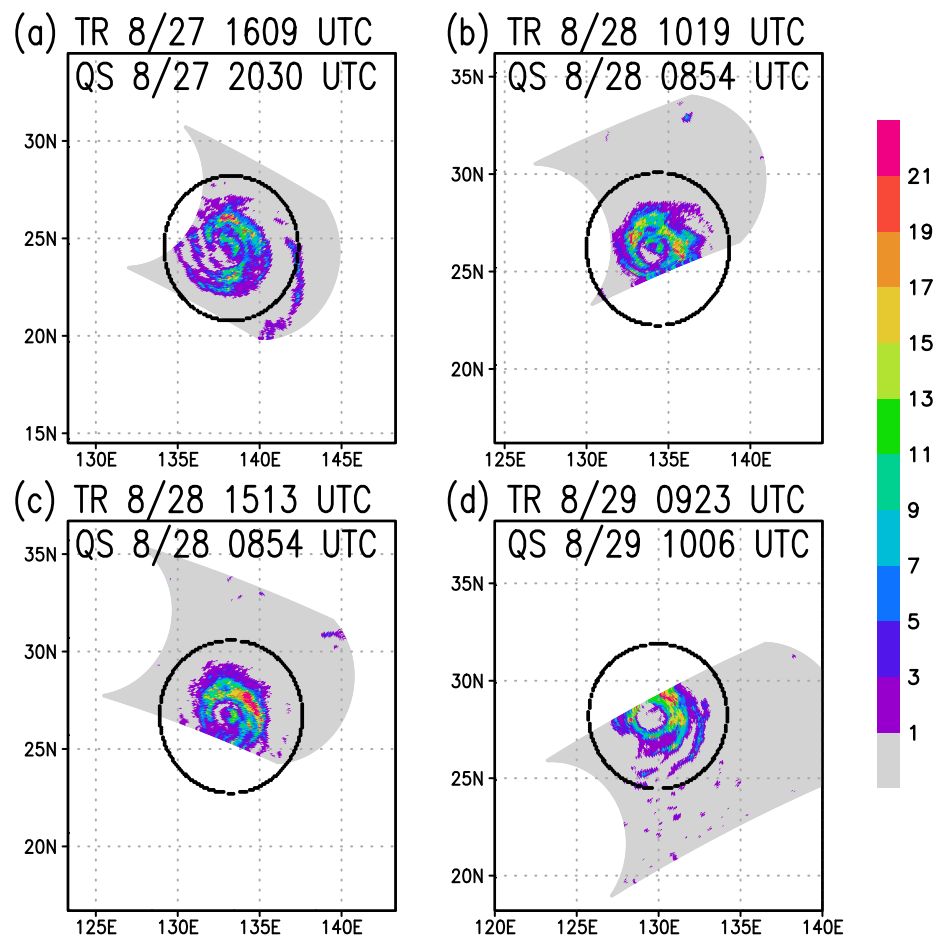


Figure 3.5: As in Fig. 3.4, but for the size stationary period in TC Rusa (2002).

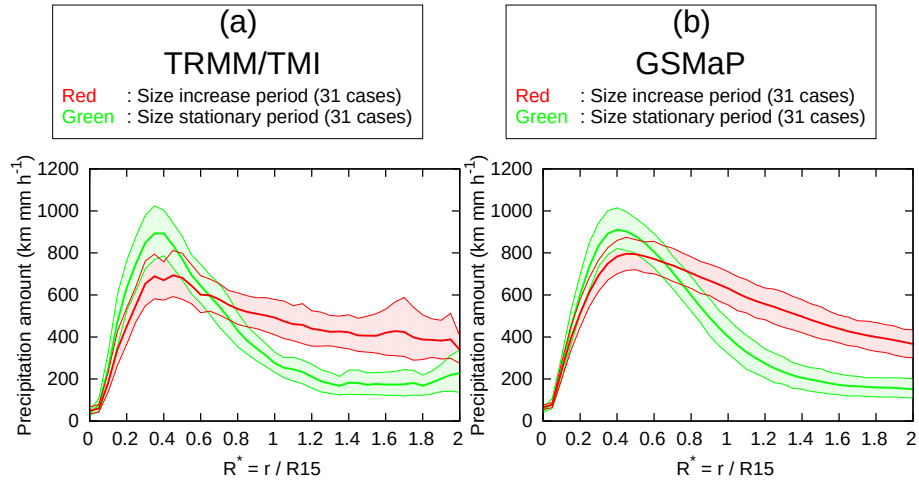


Figure 3.6: Composite of horizontally normalized distribution of precipitation amount calculated by using (a) TRMM/TMI data and (b) GSMaP data. Red and green lines represent composite of 31 cases of size increase period and composite of 31 cases of size stationary period, respectively. Shade area shows 95% confidence interval. The ordinate and the abscissa represent precipitation amount (km mm h^{-1}) and radial distance from the center normalized by R15, respectively.

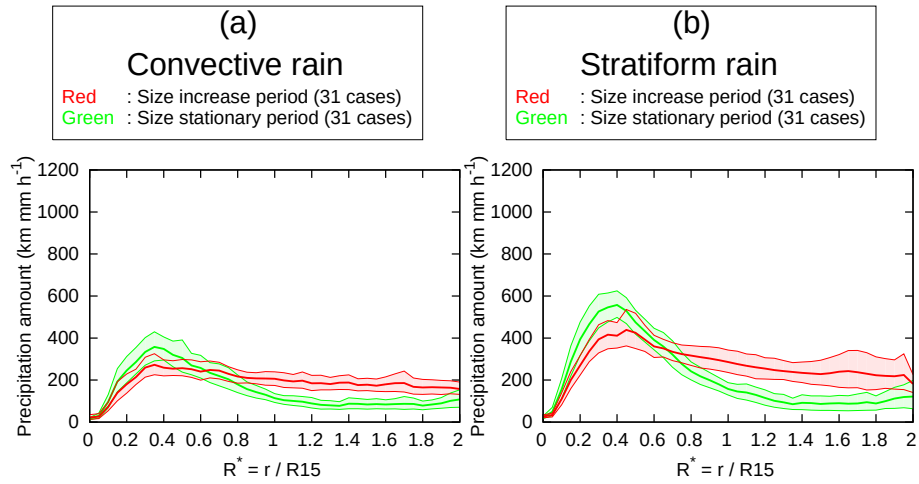


Figure 3.7: Composite of horizontally normalized distribution of (a) convective precipitation amount and (b) stratiform precipitation amount calculated by using TRMM/TMI data. Red and green lines represent composite of 31 cases of size increase period and composite of 31 cases of size stationary period, respectively. Shade area shows 95% confidence interval. The ordinate and the abscissa represent precipitation amount (km mm h^{-1}) and radial distance from the center normalized by R15, respectively.

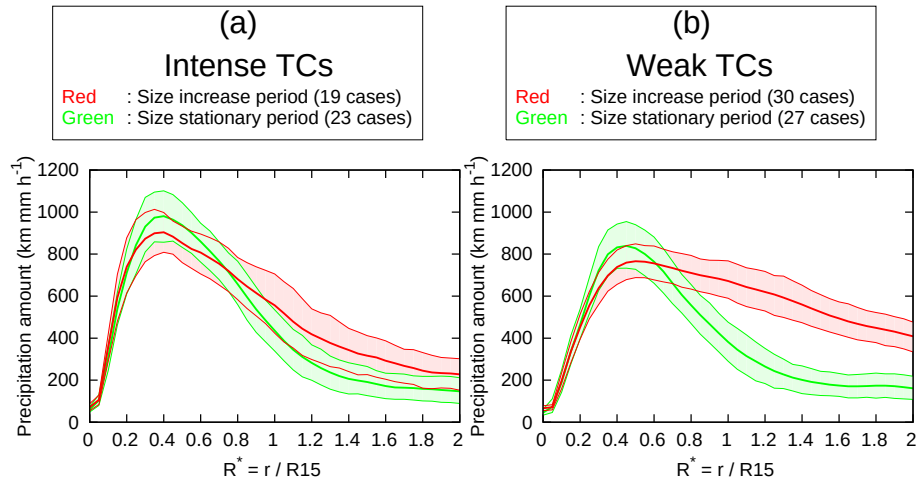


Figure 3.8: Composite of horizontally normalized distribution of precipitation amount calculated by using GSMaP data. Red and green lines in (a) represent composite of 19 cases of size increase period and composite of 23 cases of size stationary period, respectively, in which the maximum wind speed is greater than 85 kt. Red and green lines in (b) represent composite of 30 cases of size increase period and composite of 27 cases of size stationary period, respectively, in which the maximum wind speed is less than 85 kt. Shade area shows 95% confidence interval. The ordinate and the abscissa represent precipitation amount (km mm h⁻¹) and radial distance from the center normalized by R15, respectively.

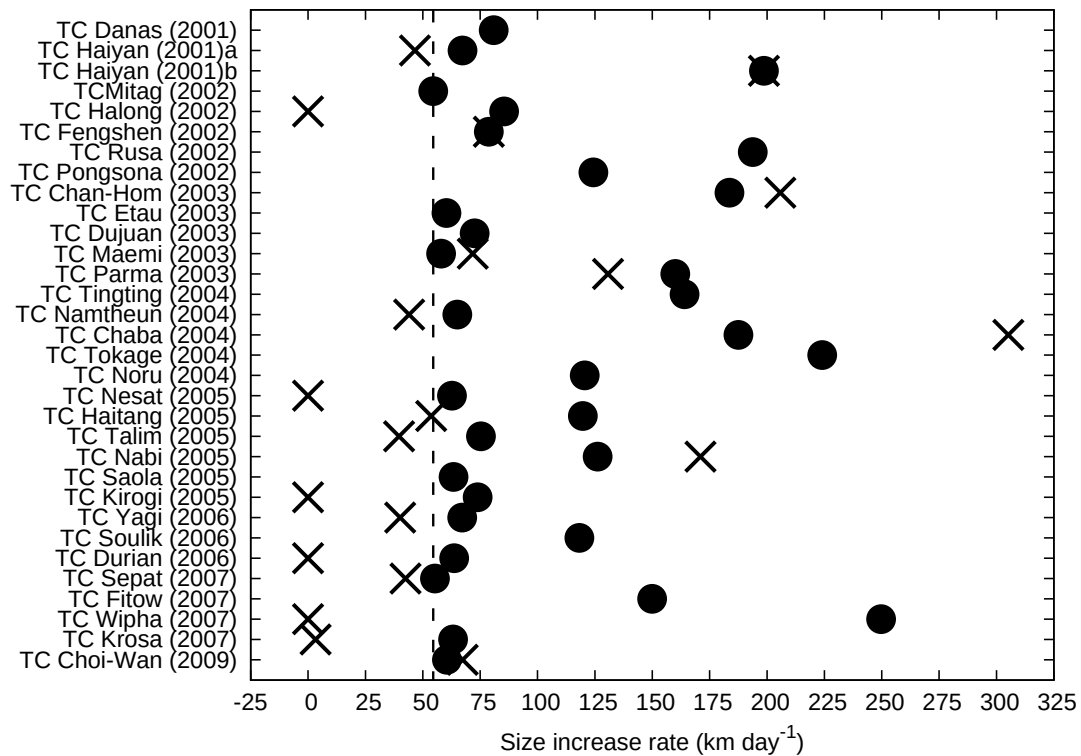


Figure 3.9: Scatter diagram of size increase rate in each TC in size increase period. Closed circles and crosses represent size increase rate calculated by using all data in size increase period and that calculated by using the data in the period in which the maximum wind speed is greater than 85 kt, respectively. Dashed line represent the minimum increase rate in size increase rate calculated by using all data in size increase period.

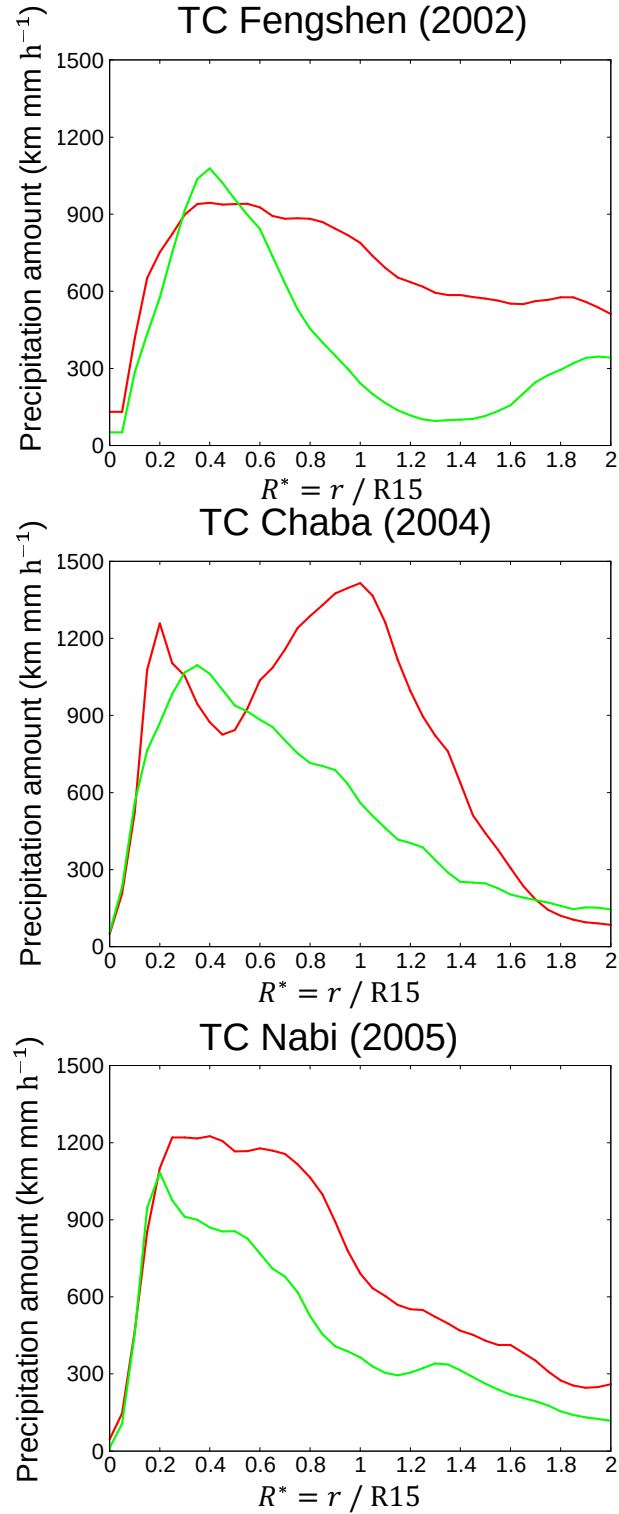


Figure 3.10: Composites of horizontally normalized distribution of precipitation amount in the period in which the maximum wind speed is greater than 85 kt in TC Fengshen (2002), TC Chaba (2004), and TC Nabi (2005) calculated by using GSMP data. Red and green lines represent size increase period and size stationary period, respectively. The ordinate and the abscissa represent precipitation amount (km mm h⁻¹) and radial distance from the center normalized by R15, respectively.

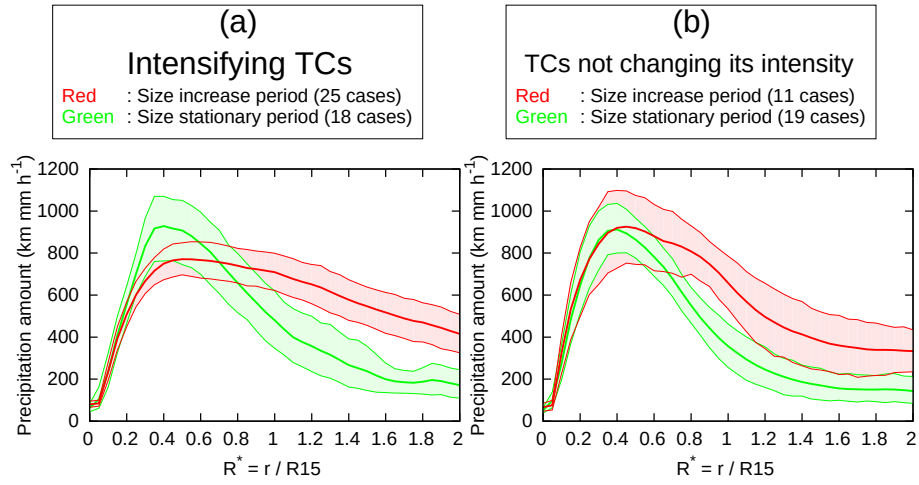


Figure 3.11: Composite of horizontally normalized distribution of precipitation amount calculated by using GSMaP data. Red and green lines in (a) represent composite of 25 cases of size increase period and composite of 18 cases of size stationary period, respectively, in which TCs are intensifying. Red and green lines in (b) represent composite of 11 cases of size increase period and composite of 19 cases of size stationary period, respectively, in which the intensity of TCs does not change. Shade area shows 95% confidence interval. The ordinate and the abscissa represent precipitation amount (km mm h^{-1}) and radial distance from the center normalized by R15, respectively.

5 Correspondence to the results of idealized experiments

5.1 Geometrical comparison

In the previous section, we showed that there is a connection between TC size change and precipitation distribution. In this subsection, we discuss the correspondence between the relationship obtained the previous subsection and the results of the idealized experiments shown in chapter 2.

First, we focus on the precipitation distribution near the center ($R^* < 0.6$). In Fig. 3.6, the precipitation amount in both size increase period and size stationary period is large, but the difference between them is small in $R^* < 0.6$. In the discussion in section 4 in chapter 2, we pointed out that the effects of heat forcing on the size change of vortices are small when the forcing is applied near the center, i.e., the result of the analyses can be interpreted as that the effects of the precipitation located near the center of TCs on the TC size change is small even if the precipitation amount is greater.

Next, we focus on the precipitation distribution in the outer part of TCs inside R15 ($0.6 < R^* < 1.0$). In this region, the precipitation amount in size increase period is greater than that in size stationary period. In particular, the difference is significantly large in $R^* > 0.8$ (Fig. 3.6). In chapter 2, we showed that the forcing located on the outer part of vortex but still inside R15 makes vortex size large. Based on it, the fact that the precipitation amount in size increase period is greater than that in size stationary period in $0.6 < R^* < 1.0$ is consistent with the results of the idealized experiment in chapter 2.

Finally, we focus on the precipitation distribution in the outside of R15 ($1.0 < R^*$). In this region, the precipitation amount in size increase period is significantly greater than that in size stationary period (Fig. 3.6). In chapter 2, the forcing located outside R15 is shown to affect the size decrease of vortices. However, as shown in subsection 7.3 in chapter 2, the effect of the forcing located outside R15 on the size decrease of vortices is smaller than that of the forcing located inside R15 on the size increase of vortices. Additionally, when forcing is applied to the inside and outside of R15 and the outer forcing is located near R15, the outer forcing positively contributes to the size increase of vortices (subsection 7.3 in chapter 2). Concerning the heating distributed both inside and outside of

R15 observed in the composite analyses, the effect of heating inside R15 on the size increase of TCs is probably stronger than that outside R15 on the size decrease of TCs because the precipitation amount becomes small with the distance from the center of TCs. Therefore, the result that the precipitation amount is larger outside of R15 in size increase period than that in size stationary period is probably interpreted by the results of the idealized experiments in which forcing is applied to the inside and outside of R15 (subsection 7.3).

5.2 Comparison with considering inertial stability

Based on the discussion in the previous subsection, the results shown in Fig. 3.6 can be explained by those of the idealized experiments shown in chapter 2. However, the discussion in the previous subsection can describe the geometric correspondence between precipitation distribution and the change of R15, but cannot describe that the relationship between precipitation distribution and TC size change is dynamically consistent with the results of the idealized experiments. In the idealized experiments, the largeness of inertial stability affects the horizontal extent and strength of heat-induced circulation and the largeness of the advection of AAM, resulting in affecting the size change of vortices (sections 4 and 6 in chapter 2). Therefore, we examine the relationship between precipitation distribution and TC size change closely by focusing on the distribution of inertial stability.

Figure 3.12 represents the relationship between the precipitation amount and inertial stability (I^2) in size increase period and size stationary period. From this figure, the inertial stability near the center ($R^* < 0.6$), where the precipitation amount is large, is large in both periods. The value of inertial stability at $R^* = 0.4$, where the precipitation amount is the largest, is about $2 \times 10^{-8} \text{ s}^{-2}$, which is almost the same as the time-averaged inertial stability between 1 and 96 hours at just outside of the forcing region (about 250 km from the center) in the idealized experiment L100 (forcing is applied near the center in Series L) in chapter 2. This fact means that the effects of precipitation near the center on the change of R15 is small because of the large inertial stability.

In contrast, inertial stability in both periods is small near R15 and outside R15 ($R^* > 0.6$). In this

smaller inertial stability region, the precipitation amount in size increase period is greater than that in size stationary period. The difference can be seen prominently in the region of $0.8 < R^* < 2.0$ and $2.5 \times 10^{-9} \text{s}^{-1} < I^2 < 1 \times 10^{-8} \text{s}^{-1}$. The inertial stability in this region is almost the same as the time-averaged inertial stability between 1 and 96 hours in the forcing region (400–500 km from the center) in the idealized experiment L400 (forcing is applied at far from the center inside R15 in series L) in chapter 2. This fact means that the difference of the precipitation amount between size increase period and size stationary period appears at the region where the inertial stability is small enough to permit the extension of the heat-induced SC beyond R15.

As discussed above, we can confirm that the relationship between TC size change and precipitation distribution obtained from the composite analyses is consistent with the results of the idealized experiments shown in chapter 2 not only geometrically, but also dynamically.

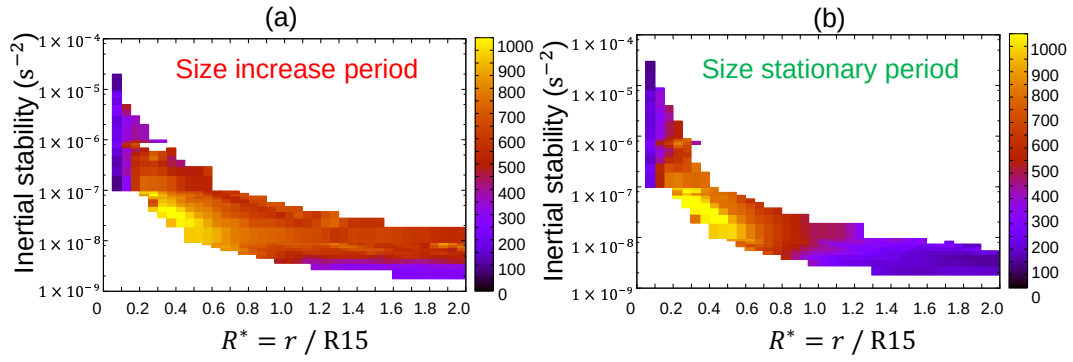


Figure 3.12: Contour plot of precipitation amount in (a) size increase period and (b) size stationary period. Color designates precipitation amount. The ordinate and the abscissa represent inertial stability I^2 (s^{-2}) and normalized radial distance from the center by R15, respectively.

6 Summary

To examine the relationship between TC size change and precipitation distribution in actual TCs, the relationship between them is investigated by using satellite observation data. The TC size is defined by the radius of 15 m s^{-1} wind speed (R15) calculated by using QuikSCAT data and the precipitation distribution is obtained from TRMM/TMI data and GSMaP data. We performed composite analyses of precipitation distribution for size increase period and size stationary, which are defined based on the time evolution of R15, and investigated the difference of the characteristics of precipitation distribution between both periods.

From the results of analyses, we clarified that the precipitation distribution is different between size increase period and size stationary period. The precipitation in the size increase period is greater than that in the size stationary period at the location far from the center inside R15 and outside R15. In contrast, the difference of precipitation between both periods is small near the TC center. Moreover, we also clarified that the above relationship between TC size change and precipitation distribution does not depend on the TC intensity and intensity change of TCs.

We confirmed that the results of the composite analyses are consistent with those of the idealized experiments in chapter 2. The precipitation in size increase period is greater than that in size stationary period at far from the center of TC but inside R15, which is consistent with the results of the idealized experiments. In contrast, the precipitation in size increase period is also greater than that in size stationary period at the outside of R15, where heating contributes to the decrease of vortex size, which is shown in section 4 in chapter 2. This can be explained by considering the results of idealized experiments in which forcing is applied to the inside and outside of vortices shown in section 7 in chapter 2 that the effects of forcing located outside R15 on the decrease of vortex size is smaller than those of forcing located inside R15 on the increase of vortex size, and the outer forcing affects the increase of vortex size when forcing is applied to the inside and outside of R15 and the outer forcing is located near R15. Additionally, the effects of the large precipitation amount near the center of TCs in both periods on the change of TCs are most likely small because of large inertial stability near the

center.

Chapter 4

General conclusion

1 Conclusion

In this study, to clarify the mechanism governing the size change of tropical cyclones (TCs), we firstly perform idealized numerical experiments using the primitive equation system on an f -plane to understand the correspondence of the thermal forcing mimicking cumulus heating to the size change of TC-like vortices. We investigated the sensitivity of vortex size change on the location, strength, and horizontal scales of forcing, the effects of the structure of initial vortices on the size change of vortices, and the vortex size change when forcing is applied to two regions. Then, based on the results obtained from the idealized experiments, we examined the relationship between TC size change and precipitation distribution by using satellite observation data. The vortex size is defined as the radius of 15 m s^{-1} wind speed (R15). R15 is calculated by using the wind speed at the model lowest level in the idealized experiments and the wind speed over the ocean surface obtained from microwave scatterometer on QuikSCAT satellite in the analyses of satellite observation data.

From the results of idealized experiments, we found that the vortex size change depends on the location and strength of forcing and does not depend on the scales of forcing. The size change of vortices is small when the forcing is applied near the center of vortices, the vortex grows in size when the forcing is located at the outer part of vortices but still inside R15, and the vortex size decreases

when the forcing is applied to the outside of R15. The vortex size becomes larger as the forcing is stronger. Moreover, from the results of experiments in which forcing is applied to two regions, we clarified that the size change of vortices can be understood by the sum of the contribution of the effects of each forcing on the size change of vortices except for some cases. When one out of two forcings is applied outside R15, the change rate of R15 varies in the middle of experiments if the forcing applied outside R15 is located near the initial R15. In this case, the outer forcing contributes to the increase of R15 even if the forcing is located outside R15. We also found that the structure of initial vortices affects the size change of vortices. The initial vortex with small radial gradient of tangential wind becomes larger than that with large radial gradient of tangential wind for the same forcing.

The temporal evolution of tangential wind and radial advection of absolute angular momentum (AAM) at R15 contribute to the change of vortex size defined by R15. The former is mainly controlled by the radial advection of AAM at R15. Therefore, the results of the idealized experiments by using the same initial vortex are explained by considering the radial transport of AAM at R15 by the heat-induced secondary circulation (SC).

The amount of the radial advection of AAM at R15 can be divided into three by the location of forcing. When the forcing is located near the center of the vortex, the horizontal extent of the heat-induced SC becomes narrow due to the large inertial stability in the forcing region. Thus, the inflow constituting the SC near R15 becomes weak and the radial advection of AAM also becomes small. As a result, the size change of the vortex is small. When the forcing is located at the outer part of vortices but still inside R15, the horizontal extent of the SC becomes wide because of the small inertial stability in the forcing region. Thus, the inflow constituting the SC near R15 becomes strong and the radial advection of AAM also becomes large. As a result, the vortex size becomes large. When the forcing is applied to the outside of R15, the radial advection of AAM becomes negative because the direction of the heat-induced SC at R15 is outward. Therefore, the vortex size decreases.

When the forcing location is fixed, the amount of the radial advection of AAM is proportional to the strength of the heat-induced SC, i.e., the strength of the inflow at lower level. Therefore, the

increase of R15 is proportional to the strength of forcing. If the amount of heating is the same, the scales of forcing does not affect the size change of vortices. Because the response of heat forcing to the strength of the heat-induced radial wind is linear supposing that the Sawyer-Eliassen equation applies, the strength of the radial flow at R15 can be understood by the sum of the radial flow induced by each forcing. Therefore, the change of R15 in the experiments in which forcing is applied to two regions can be understood by the sum of the contribution of each forcing if the difference of the radial gradient of AAM is small. However, in the experiments in which forcing is applied to the inside and outside of R15 and the outer forcing is located near the initial R15, vortex size becomes larger than the sum of the increase of each forcing because the increase rate of tangential wind increases by the contribution of asymmetric component of the radial advection of AAM in the middle of experiments.

The change of vortex size defined by R15 also depends on the radial gradient of the tangential wind at R15. Therefore, if the amount of the radial advection of AAM is the same, the vortex having smaller gradient of tangential wind becomes larger than that having larger gradient of tangential wind due to the large efficiency of increasing R15.

From the results of the analyses of satellite observation data, we found that there are differences between the precipitation distribution in size increase period and that in size stationary period of TCs, which can be explained by the results of the idealized experiment, i.e., the precipitation in the size increase period is greater than that in the size stationary period at the location far from the center inside R15. The precipitation in the size increase period is also greater than that in the size stationary period at the outside of R15, which is seemingly inconsistent with the results of the idealized experiments that vortex size decreases when the forcing is applied outside R15. This can be explained by considering the results of the idealized experiments in which forcing is applied to two regions, whose results indicate that the effects of the inner forcing on the increase in size of vortices are larger than those of the outer forcing on the decrease in size of vortices and the forcing located at just outside R15 contribute to the increase of R15 when the forcing is applied to the inside and outside R15. We also found that this relationship between TC size change and precipitation distribution does not depend on

the TC intensity and intensity change of TCs.

2 Implications of this study to overall research on tropical cyclones

In this study, we found the relationship between thermal forcing and size change of vortices from the idealized experiments and confirmed that the relationship which can be explained by the results of the idealized experiments can be seen in the relationship between real TC size change and precipitation distribution. In previous studies (e.g., Wang 2009), the effects of precipitation on the structure of TCs near the center have been investigated. By combining our results, in which the effects of precipitation on the outer structure of TCs are discussed, with that of the previous studies, it has a possibility to clarify the relationship between the overall structure of TCs and precipitation distribution.

Precipitation distribution will be observed higher frequency and higher resolution by the development of the Global Precipitation Measurement mission promoted by Japan Aerospace Exploration Agency, National Aeronautics and Space Administration, and other international organizations. By using the relationship between precipitation distribution and TC size change found in the present research and newly available observation data, the evolution of TC size change shall be predicted with higher accuracy. Because TC has significant impacts on society through, for example, its relation to the duration of high winds and heavy precipitation, prediction of the size change of TCs has a significant meaning to broader areas of society beyond scientific interests.

3 Future works

In the idealized experiments in which the location of forcing is varied (section 4 in chapter 2), the importance of horizontal extent of the heat-induced SC is discussed, but the quantitative consideration about the extent of the SC was not completed. The extent of the SC is expected to correspond to Rossby radius of deformation if we follow the case where the spatial distributions of inertial stability and static stability are constant (Shapiro and Willoughby 1982). However, these distributions are not spatially constant even in the present idealized experiments. Moreover, there are inertially unstable

regions in some experiments. Consideration on the correspondence between the extent of the SC and Rossby radius by considering these conditions and more quantitative understanding on the extent of the SC are the foci of future.

In the idealized experiments in which the strength and scales of forcing is varied (section 5 in chapter 2) and forcing is applied to two regions (section 7 in chapter 2), we found that the asymmetric component of the radial advection of AAM plays an important role in the size change of vortices. The asymmetric component possibly consists of the multiplex effects of barotropic instability, inertial instability, inertia-gravity wave, and vortex Rossby wave. Quantitative investigation on the effects of these instabilities on the generation of the asymmetric component remains for a future work. Additionally, also left for future works are clarifying whether the asymmetric component working in the idealized experiments also contributes to the change of R15 in the real TCs and identifying what kind of physical process causes the asymmetric component that affects the change of R15.

We found from the analyses of satellite observation data in chapter 3 that the relationship between TC size change and precipitation distribution is qualitatively consistent with the results of the idealized experiments. However, quantitative investigation has not been performed yet. To investigate the relationship quantitatively, it is useful to use Sawyer-Eliassen equation and diagnose the SC induced by cumulus heating at each radius. To solve Sawyer-Eliassen equation, there are some problems such as the estimation of the radial-vertical distribution of inertial stability and static stability, and the treatment of inertially unstable regions.

In section 5 in chapter 3, we found that inertial stability near the center is large and the contribution of cumulus heating to the change of TC size is small, whereas inertial stability around R15 and outside R15 is small and the contribution of cumulus heating to the change of TC size is large. These results suggest that the relationship between TC size change and precipitation distribution is dynamically consistent with the results of the idealized experiments. To clarify whether the relationship between TC size change and precipitation distribution is governed by the same mechanism of idealized experiments or not, simulations of TCs by using a numerical model with high-resolution and

investigation of the structure of SC and advection of AAM are required, which is also left for a future work. In the analysis of such realistic simulations of TCs, considerable care shall be required in the examination of validity of the conclusion of the present study, because several factors excluded from the idealized experiments possibly affect the change of TC size with their mutual interaction. These remain as foci of future researches.

Acknowledgement

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Appendix A

Method of determining the vertical structure of forcing

The vertical structure of forcing, $\eta(\sigma^*)$, is taken from averaged vertical structure of heating in a TC which is simulated by using the primitive equation system on an f -plane in the σ coordinate. This model is the same as that in Itoh and Ghil (1988) except for the f -plane and cyclic boundary conditions. This model includes surface friction, moist processes including cumulus parameterization, and latent heat flux from the sea surface. The cumulus parameterization represents the moist convective adjustment and is computed every 360 s. The model domain is $6400 \text{ km} \times 6400 \text{ km}$ with a resolution of 20 km, and the number of vertical levels is five ($\sigma^*=0.95, 0.72, 0.43, 0.24$, and 0.12). The horizontal diffusion coefficient and SST are taken as constant values of $2.5 \times 10^5 \text{ m}^2 \text{ s}^{-1}$ and 28°C , respectively. The value of the Coriolis parameter is $3.8 \times 10^{-5} \text{ s}^{-1}$, which corresponds to the value at 15° latitude. The other coefficients and settings are the same as those employed in Itoh and Ghil (1988).

The simulation of the TC to determine the vertical structure of forcing is performed as follows. First, a warm bubble is established at the lowest level at the center of the model domain. The radius and amplitude of the bubble are 250 km and 5 K, respectively. In the initial environment, the potential temperature is horizontally uniform at each level, set at 293.2, 303.2, 316.6, 343.9, and 410.7 K from

the lowest level upward, and the humidity is 50% at all levels. We use time and spatial average of cumulus heating between 24 hours from the time when the maximum wind speed exceeds 17.2 m s^{-1} in each level to determine the vertical structure of forcing. In this 24 hours, the bubble grows into a TC with a strong wind speed (over 40 m s^{-1}) and precipitation areas corresponding to eyewalls and rainbands. The vertical structure of forcing is determined by the ratio of averaged cumulus heating in each level. The specific values are 2.0, 16.870, 23.734, 5.134, and 0 from the lowest level upward.

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