# A Study of the Effects of the Ice-Microphysics, Surface Friction, and Surface Heat Flux on Tropical Cyclone Formation[§]

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**Abstract:** This paper describes results from numerical experiments which have been performed to understand the effects of the ice microphysics, surface friction, and surface heat flux on tropical cyclone (TC) formation. This study uses the author's non-hydrostatic model that intends to resolve cumulus convection. However, the horizontal grid size is taken to be somewhat large; 2 km in an area of 600 km x 600 km. A non-uniform coarse grid is used in the surrounding area with 4,000-km square. Several buoyancy perturbations arranged in the west-east direction, and a weak vortex with the maximum wind speed of 5 $m\ s^{-1}$ are given at the initial time of the numerical time integrations.

It is confirmed from two numerical experiments with and without ice microphysics that the development of a vortex is slower, and TC formation is delayed, in the presence of ice microphysics. It is also confirmed that a vortex can develop even without surface friction. It is shown that a strong vortex with the maximum wind speed of 20~25 $m\ s^{-1}$ can be obtained. As expected, however, no eye forms, and further development does not occur. That is, it is confirmed that surface friction is indispensable to eye formation and a very strong TC having an eye. As for the third concern of this study, it is shown that a vortex with the maximum wind speed of about 5 $m\ s^{-1}$ does not develop in the absence of the surface heat flux. That is, the surface heat flux plays an important role even in a weak vortex. Important backgrounds and understandings that are concerned with these results are described, based on studies on TCs in the past 50 years.

**Keywords:** Cloud resolving model, cumulus-convection-resolving model, frictional flow CISK, ice microphysics, nonhydrostatic model, surface friction, surface heat flux, tropical cyclone formation.

## 1. INTRODUCTION

In the author's previous paper [1], results from numerical experiments which were performed toward a better understanding of tropical cyclone (TC)[1] formation were presented. Since the process of TC formation has a wide variety in nature, studies on this problem will have to be extensively made by many researchers in the coming years. This study is only one of such studies, and it intends to understand the effects on TC formation, of the ice microphysical processes, surface friction (friction between the atmosphere and the sea surface), and the sensible and latent heat fluxes at the sea surface. Numerical experiments are performed under some restricted (idealized) initial condition that is used for a better understanding of the problem.

As mentioned in the previous paper, TC researchers have, more or less, different views on TC formation. The author's view, which is different from views of some (probably many) of TC researchers, was described in that paper [1] as well as in a review paper [2]. It is an important basis for understanding of the results from numerical experiments presented in this paper. Part of it will be mentioned later.

Among many different processes of TC formation, a case in which a TC forms from convective clouds (mesoscale convective systems, MCSs) embedded in a synoptic-scale vortex (with a horizontal scale of about 2,000 km) was treated in the previous study [1]. Since a large domain had to be used, a mesoscale-convection-resolving model (with a horizontal grid size of 20 km) was used. In this study, we treat another case in which a somewhat small TC forms from convective clouds caused by some buoyancy perturbations embedded in a weak mesoscale vortex. We use a cumulus-convection-resolving model, which has been referred to as 'cloud resolving model' by most of researchers.

The effect of the ice microphysics on the development of TCs that are not very strong was studied by Willoughby *et al*. [3] and Sawada and Iwasaki [4]. It was shown that the TC development is slower when the ice phase is taken into account. A study to understand the mechanism of the slower development has been made by the author [5]. Although these studies did not intend to explain the ice-phase effect on TC formation, the result can be applied to this problem. This study intends to examine the ice-phase effect on TC

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[1]In this paper, the term TC is defined as a tropical vortex in which the maximum wind speed is larger than about 17 $m\ s^{-1}$.

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formation by performing an additional numerical experiment.

The effect of surface friction on TC formation, which is the second topic of this study, was suggested by past studies with two-dimensional models (e.g., Yamasaki [6, 7]; Nasuno and Yamasaki [8]). In this paper, results from a three-dimensional model are presented because the effect of surface friction on TC formation was not intentionally discussed in the author's studies with a three-dimensional model ([9-12]) because the essence of its effect had been understood. At this point, it is important to make some comments concerning past studies. In the 1960s, Ooyama [13] and Charney and Eliassen [14] proposed a TC model in which frictional convergence plays an essential role. The concept of the conditional instability of the second kind (CISK) proposed by these studies has been accepted to explain not only development but also formation (genesis) of TCs by many researchers (e.g., [15]). It was shown later [6, 7] that the CISK proposed in the 1960s, which can be referred to as frictional convergence CISK, is applied primarily only to eyewall circulation. It was also shown [6] that surface friction does not play any significant role in a weak vortex. In the TC formation (genesis) stage when a vortex is strong to some extent, frictional flow CISK (not frictional convergence CISK) plays a primary role [6, 7, 9, 10]. Another result was that a weak vortex can develop even without surface friction [6]. In other words, a vortex can develop by a CISK mechanism (cooperative interaction with convective clouds) even at the stage (weak vortex stage) when surface friction does not play an important role. In addition, it was suggested [7] that the cooling due to rainwater evaporation is important in the two stages of vortex intensification.

The third concern of this study is the effect of the (sensible and latent) heat flux from the sea surface on TC formation. The important role of the surface heat flux on TCs has been widely recognized since the 1950s through observational and diagnostic studies. Ooyama [16] clarified its importance in TC development by numerical experiments. The author [9-12] did not discuss its importance in TC formation because he considered that its importance was well known through many past studies. On the other hand, Rotunno and Emanuel [17] emphasized its importance in terms of the wind-induced surface heat exchange (later, called WISHE). The author's view on WISHE was described in [1, 2]. Some researchers have mentioned that the WISHE is important to vortex intensification at the stage when a vortex is strong to some extent. In this study, it is shown that the surface heat flux is important even at the stage when the maximum wind speed of a vortex is only about 5 $m\ s^{-1}$.

## 2. MODEL AND EXPERIMENTAL DESIGN

The model used in this study is a cumulus-convection-resolving model which the author developed to apply to tropical squall-lines first [18] and to TCs [2]. As for the cloud microphysical process, a one-moment bulk model is used. It is based on Lin *et al*. [19], but several important modifications were made by Sato and Yamasaki [20], which are described in [5, 18]. Although two-moment bulk models and bin models have been developed in recent years, it seems to the author that clear superiority in using these models for studies on TC dynamics and ice-phase effect on TCs has not been necessarily demonstrated yet. The results presented in this study would not be essentially modified by use of these models. Studies in this direction remain to be made.

In this study, a horizontal grid size is taken to be 2 km (not 1 km) to save computer time, as in the previous studies [4, 5]. Although this grid size is somewhat too coarse to describe cumulus convection properly, the results obtained in this study would be qualitatively similar to those for a 1-km grid size. As in [5], this grid size is used for a 600-km square domain, and a non-uniform, coarse grid is used outside this domain. The whole domain covers the 4,000-km square. A cyclic condition is used in the west-east direction, and rigid boundaries are placed at the northern and southern boundaries. As for the vertical, a 30-layer model is used. The levels where the vertical velocity is predicted are shown in Table **1**, which is slightly different from that used in [1] and the same as that in [5].

The environmental flow and other disturbances such as a subtropical high are not included, as in [5]. The basic-state (environmental) temperature used in this study is the same as that in [5], which is reproduced in Table **1**. It nearly corresponds to that of the tropical atmosphere in northwestern Pacific in summer. The initial relative humidity is also taken to be the same as that in [5]. A non-uniform relative humidity field is used. The relative humidity is taken to be 80 % of the value at the moist center (Table **1**) in areas of x > 800 km, x < -800 km, y > 200 km and y < -900 km. The horizontal profile in the inner domain is the square of

**Table 1. The Heights of the Levels where the Vertical Velocity is Predicted for a 30-Layer Model, the Environmental Temperature $T_B$, and the Initial Relative Humidity $R_{H0}$ at the Center of the Moist Area (x = 0, y = -100 km) are Also Shown**

| z (km) | $T_B$ (K) | $R_{H0}$ (%) | z (km) | $T_B$ (K) | $R_{H0}$ (%) |
|---|---|---|---|---|---|
| 24.0 | 199.2 | 30 | 6.5 | 262.4 | 80 |
| 21.4 | 199.2 | 30 | 6.0 | 265.5 | 82 |
| 19.1 | 199.2 | 33 | 5.5 | 268.4 | 83 |
| 17.2 | 199.2 | 36 | 5.0 | 271.3 | 84 |
| 15.6 | 200.5 | 40 | 4.5 | 274.3 | 85 |
| 14.2 | 205.5 | 44 | 4.0 | 277.2 | 86 |
| 13.0 | 213.0 | 48 | 3.5 | 280.1 | 87 |
| 12.0 | 221.2 | 52 | 3.0 | 282.7 | 88 |
| 11.1 | 229.0 | 56 | 2.5 | 285.5 | 89 |
| 10.3 | 235.4 | 60 | 2.0 | 288.2 | 90 |
| 9.6 | 240.9 | 63 | 1.5 | 290.9 | 92 |
| 9.0 | 245.3 | 66 | 1.0 | 293.6 | 92 |
| 8.5 | 249.1 | 69 | 0.6 | 296.0 | 90 |
| 8.0 | 252.5 | 72 | 0.3 | 298.0 | 88 |
| 7.5 | 256.1 | 75 | 0.0 | 300.0 | 85 |
| 7.0 | 259.4 | 78 | | | |

cosine in the x- and y-directions, respectively. The latitude of the coordinate origin (y = 0) is taken to be 15N. Although the numerical experiments have been made for the non-uniform field, it has been confirmed that essentially similar results are obtained for a uniform field (with the values in Table **1**), with slightly different intensities of computed TCs. The sea surface temperature used in this study is also the same as that in [5]. It is taken to be 302 K between 10N and 20N.

Although an axisymmetric vortex is given at the initial time, as in [5], the maximum wind speed is taken to be 5 $m\ s^{-1}$ in this study (10 $m\ s^{-1}$ in [5]). Its radius (distance from the vortex center) is taken to be 200 km, as in [5]. The vortex center is placed at (x = 0, y = - 150 km). In addition to the weak vortex, five buoyancy perturbations are placed on a west-east oriented line (x = 250, 150, 0, -150, and -250 km; y = -150 km) in this study. The radius of each temperature perturbation area is taken to be 80 km and its maximum anomaly is 2 K. The perturbations are given in the lower layer (0 < z < 2.5 km), with the maximum anomaly at 1.25 km. These specifications of a weaker vortex and buoyancy perturbations are made with an intention of simulating TC formation process more realistically than in [5]. Under this initial condition, convection is initiated by the five buoyancy perturbations. The effect of frictional convergence, which played a primary role in [5], is not important to the initiation of convection (because of weaker low-level winds and larger buoyancy anomaly), although the surface wind associated with the vortex (as well as the cooling due to rainwater evaporation in the subcloud layer) plays an important role to successive formation of convective clouds through the surface heat flux. As mentioned in Section 1, the frictional flow CISK plays a primary role during the stage before the formation of an eyewall [2, 7].

Results from four numerical experiments are presented in this paper. In case (ICE), which is a control case, the ice microphysical process is taken into account. In case (NOICE), it is excluded. In case (NOF), surface friction is excluded, other conditions being the same as those in case (ICE). In case (NOSHF), the surface heat flux is excluded. A bulk formula is used for the momentum and heat fluxes at the sea surface. The value of the drag coefficient (assumed to be independent on the surface wind speed) is taken to be 0.0025 except in case (NOF), and the coefficient as to the surface heat flux is 0.0025 except in case (NOSHF).

## 3. RESULTS

The mixing ratios of rainwater at the lowest level (0.15 km height) of the model (or surface rainfall intensity) in cases (NOICE) and (ICE) at several selected times are shown in Fig. (**1**). As mentioned in Section 2, five buoyancy perturbations are given in the west-east direction in a non-uniform relative humidity field at the initial time. It is seen from the figures for 10 hours that two of the five convective

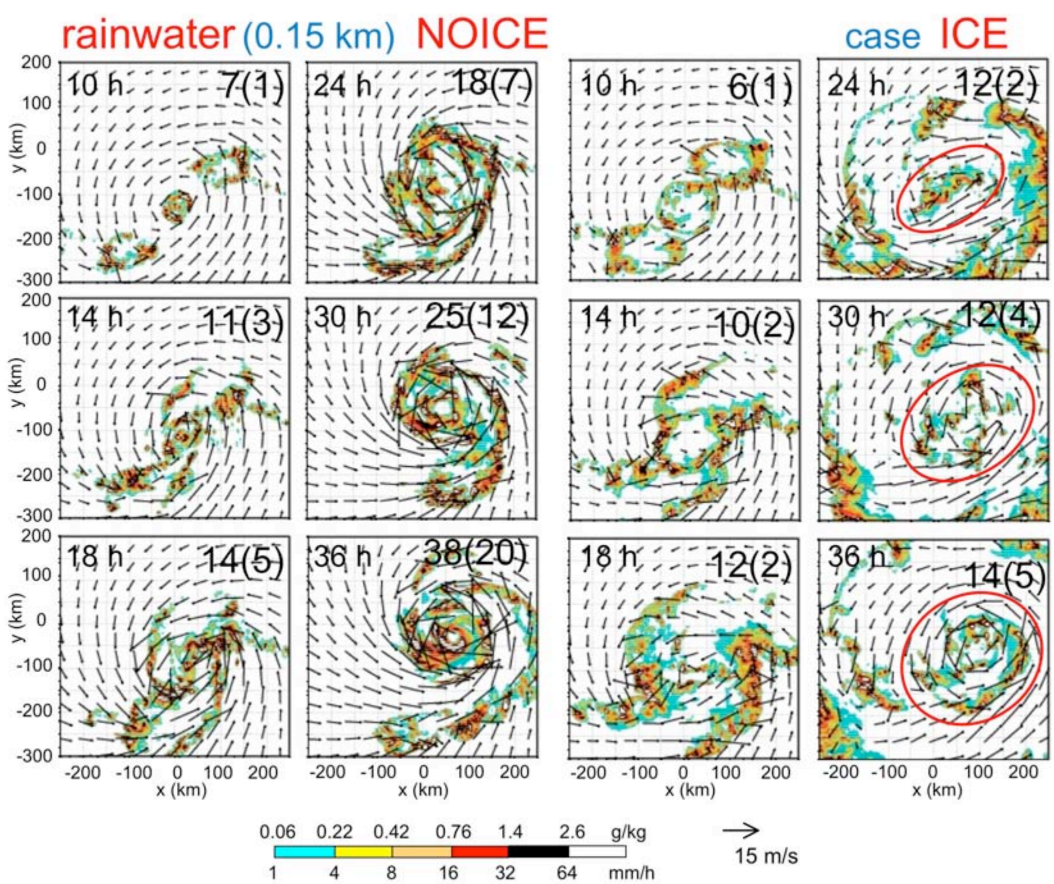


**Fig. (1).** Mixing ratios of rainwater at a height of 0.15 km and wind vectors at 0.8 km at six selected times in case (NOICE) and case (ICE). The length of the wind vector at 24 h, 30 h, and 36 h in (NOICE) is taken to be 75% of that in other panels. The maximum of the low-level wind speed (m/s) and the central surface pressure anomaly (hPa, negative sign: omitted) are also shown by numerals on the upper-right of each panel.

clouds are weak because of the lower humidity and that a convective line rotates cyclonically owing to the horizontal advection caused by the initial vortex flow. In a period of 14~18 h, convective clouds are separated into two bands, which are oriented in the northnortheast-southsouthwest direction. These bands propagate in the opposite directions. This feature can be compared with that obtained in the previous study [5] in which a ring-shaped convective cloud propagates outward from the vortex center.

It is important to note that the propagation speed of the two convective bands is larger in case (ICE) than in case (NOICE). This feature corresponds to the different speeds of ring-shaped convection that propagates outward in [5]. The faster speed in case (ICE) is attributed to stronger cold pool in the subcloud layer, which is due to more amount of precipitating water substance in the mid-troposphere. The latter reasoning was emphasized in [5]. As also mentioned in [5], the faster propagation in (ICE) makes development of the vortex slower. The low-level maximum wind speed and the surface pressure anomaly from the environment (negative sign: omitted) are shown by numerals on the upper-right in each panel. It can be clearly seen that the vortex development is much slower after 18 h in (ICE) than in (NOICE). This is primarily due to the faster propagation of the convective bands and resulting smaller pressure gradient at low-levels in (ICE), as discussed in [5]. In (NOICE), some of slow-propagating bands contribute to the formation of inner cloud bands and an eyewall, and some become spiral bands. The convective activity that is rather concentrated in the inner portion of the vortex is responsible for the faster development through larger pressure gradient. The vortex attains TC intensity after 24 h, and an eye can be seen at 30 h. On the contrary, in (ICE), the two propagating band-shaped convections become a nearly ring-shaped convection that is located far from the vortex center, as in [5]. At this stage, convective clouds (indicated by red ellipse) form in the central area of the vortex, and these play a primary role in further intensification of the vortex and TC formation, as in [5]. Results after 36 h are shown later (Fig. **4**).

The distributions of the wind speed at 1.25 km in case (ICE) are shown in the lower panels of Figs. (**2**, **3**). The mixing ratios of rainwater at 0.15 km are shown in the upper panels. The mixing ratios at 18 h, 24 h, 30 h, and 36 h (Fig. **1**) are reproduced for convenience of comparison with the wind field. The rainwater field at 12 h is nearly symmetric with respect to the red line. On the contrary, the wind field is quite asymmetric, which is a well-known feature due to the latitudinal variation of the Coriolis parameter. The wind is stronger in an area to the southeast of the vortex center during the period shown in Fig. (**2**). The maximum wind is located around the outer (southeastern) edge of the southeastern rainband, which is also a well-known feature.

As was mentioned, new convective clouds form in the central area of the vortex at 24 h when the propagating bands are located at some distance from the vortex center. Corresponding to this, another maximum of the wind speed appears to the northwest of the old maximum (closer to the vortex center). The new maximum rotates cyclonically. It is located to the east, and north-northeast of the vortex center at 36 h and 42 h, respectively. Some of convective clouds take a spiral-shape at and after 36 h. The vortex center does not move westward but eastward (as well as northward) owing

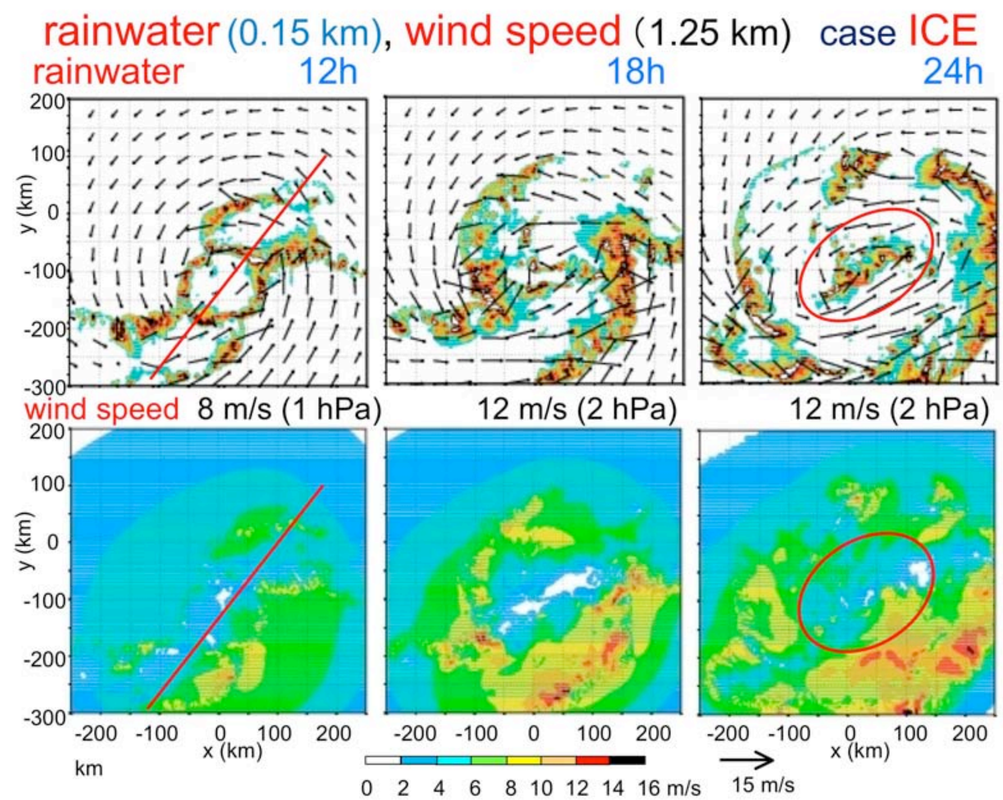


**Fig. (2).** Rainwater mixing ratio (upper panels) and the wind speed at 1.25 km (lower panels) at 12 h, 18 h, and 24 h in case (ICE). The maximum wind speed and the central surface pressure anomaly are also shown by numerals.

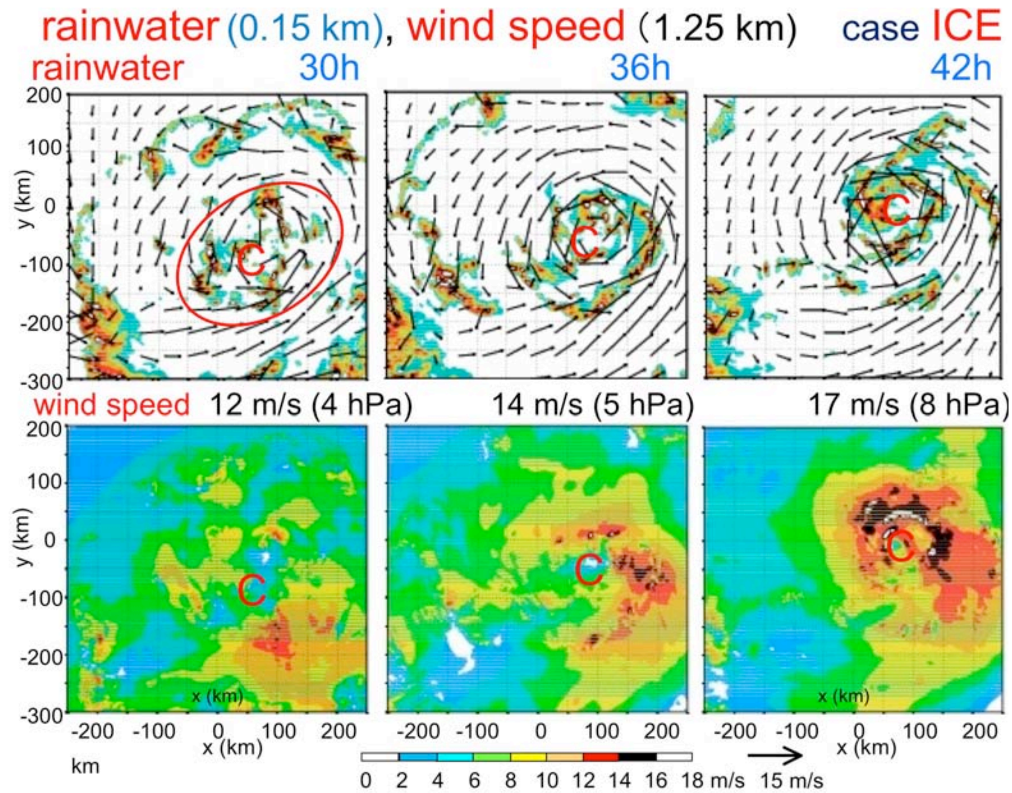


**Fig. (3).** Same as Fig. (**2**) except at 30 h, 36 h, and 42 h.

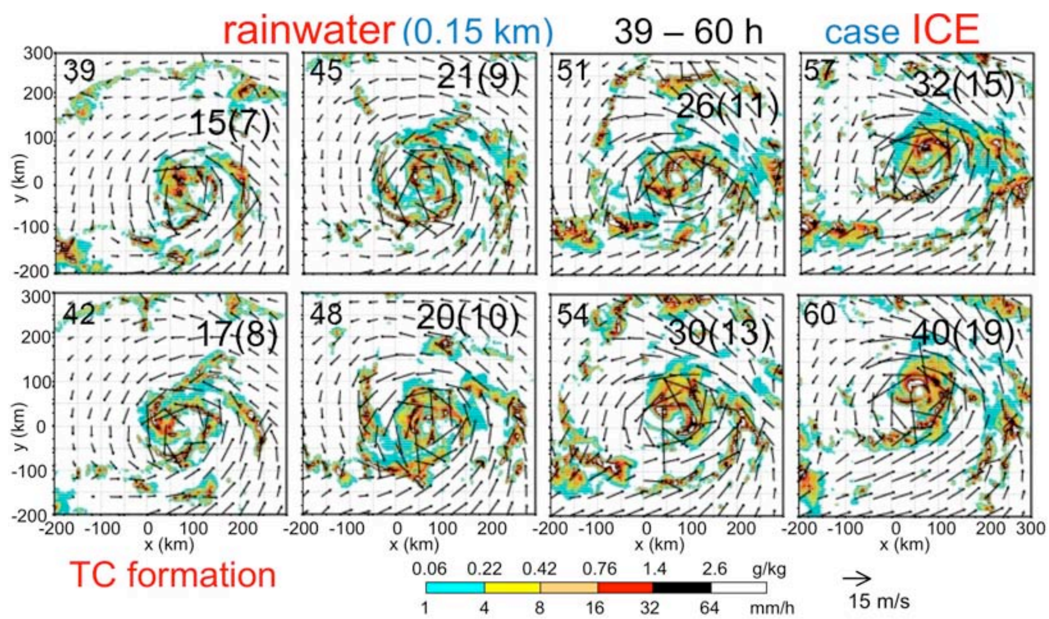


**Fig. (4).** Mixing ratios of rainwater at a height of 0.15 km and wind vectors at 0.8 km at a time interval of 3 hours from 39 h to 60 h in case (ICE). The length of the wind vector is taken to be shorter than that in case ICE in Fig. (**1**). The maximum of the low-level wind speed (m/s) and the central surface pressure anomaly (hPa, negative sign: omitted) are also shown by numerals on the upper-right of each panel.

to stronger southwesterly flow to the south of the vortex center. This feature is due to the non-uniform Coriolis parameter. In the real atmosphere, vortices at the pre-TC and TC stages usually move westward (as well as northward) in the presence of the environmental easterly flow such as the trade easterlies.

Fig. (**4**) shows the low-level rainwater fields at a time interval of 3 hours from 39 h to 60 h. The maximum wind speed and the surface pressure anomaly (negative sign: omitted) are also shown, as in Fig. (**1**). The area shown is different from that of Figs. (**1-3**). The vortex attains TC intensity after 42 h. That is, TC formation is delayed in the presence of the ice phase. However, the gross features of the structure are essentially similar to those in the case without the ice phase. Although the stage after TC formation is not the main concern of this study, some further remarks are made. The results obtained from the model for this stage should be a better measure to estimate model validity because the TC stage is relatively known well compared with the TC formation stage. The patterns of the rainwater distributions shown in Fig. (**4**) are essentially similar to some of various patterns of observed radar reflectivity. It is also seen from Fig. (**4**) that the TC is still at the developing stage at 60 h. A somewhat small TC is realized in this experiment. The initial condition used is one of the primary causes. It is known since the 1960s that the horizontal scale of well-developed (matured) TC depends on its initial state. It should also be remarked that the structures of spiral rainbands were described in [2], which showed three types of spiral rainbands. The structures of spiral rainbands with four types were studied with a mesoscale-convection-resolving model [21]. This problem will be extensively described in a paper based on future studies, including estimation of model validity.

The author has been interested in the latent instability field as one of the very important physical quantities to discuss TCs (and other phenomena), and presented the distribution of buoyancy of the air rising from the boundary layer. Although most of researchers have used the term CAPE (convective available potential energy), it means a vertically integrated value of the energy. The author has considered that the vertical distribution of buoyancy is much more important, and has been most interested in the buoyancy which the rising air acquires in the lower troposphere (in a layer of 2~3 km height). Fig. (**5**) shows a measure of buoyancy at 2.75-km height (defined as the difference between the equivalent potential temperature of the boundary layer air at 0.8-km height, and its saturation value of the rising air at that level) at nine selected time in case (ICE). Although the buoyancy is affected by some factors such as entrainment and drag force of precipitating water substance, the essence of discussions here is not modified. The left, middle, and right panels correspond to Figs. (**2-4**), respectively. It is seen from the figure that the latent instability fields around the two propagating band-shaped convections at 12 h and 18 h (Fig. **2**) are similar to those around squall-lines that propagate against low-level flow, although dynamical fields such as the environmental wind are quite different. The central area of the vortex becomes latently stable, but it becomes unstable after 24 h. Corresponding to this, convection occurs in the central area, as indicated by the red ellipse in Figs. (**2**, **5**). After 30 h, latent instability is stronger around and at the outer (convex) side of (spiral) rainbands located at some distance from the vortex center (indicated by C). Since latent instability (as well as ascending motion) is one of necessary conditions for convection, it suggests where convection forms or becomes active. Under a condition that a subtropical high is present, an area to the north of a vortex is usually latently stable. In this case the air with low equivalent potential temperature tends to enter the central area of the vortex (TC), and latently stable areas can be seen much more than in the present case.

In the following, we examine the second concern of this study; the role of surface friction in TC formation. As

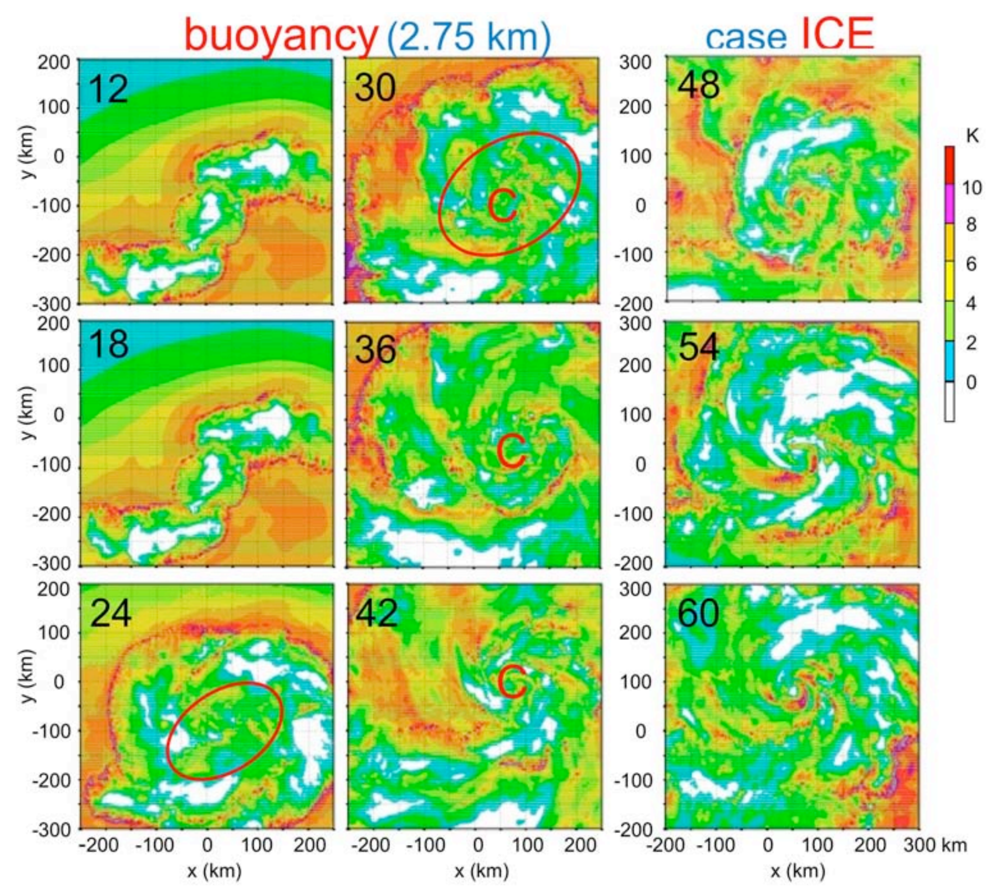


**Fig. (5).** A measure of buoyancy which the rising air acquires at 2.75- km height at nine selected time in case (ICE). For details, see text.

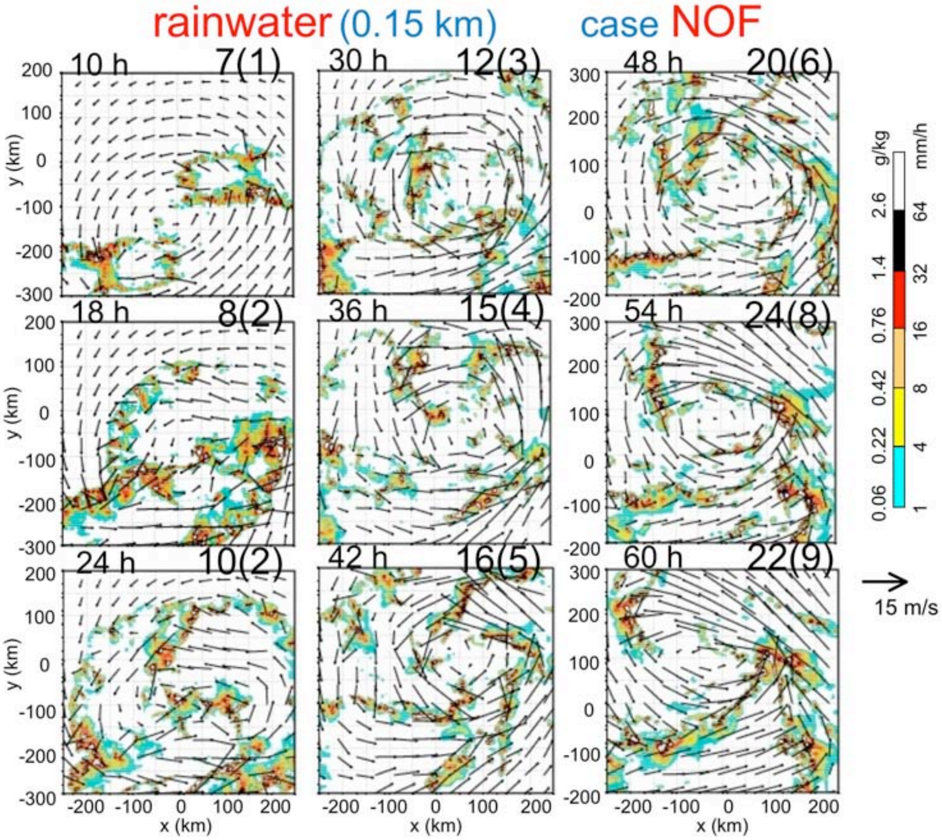


**Fig. (6).** Rainwater mixing ratio at 0.15 km and wind vector at 0.8 km at selected times in case (NOF). The length of the wind vector at 48 h, 54 h, and 60 h is taken to be 75% of that in other panels.

mentioned in Section 1, the author has understood that surface friction does not play any significant role in a weak vortex, and (not frictional convergence but) frictionally controlled flow plays a primary role in vortex development at the stage when the vortex becomes strong to some extent [7, 2]. In addition, a vortex can develop even without surface friction [6]. The author's concerns in this study are to what extent a vortex can develop without surface friction and how surface friction contributes to the structure of a vortex (TC) and the distribution of convective clouds. The author's understanding of this problem from a two-dimensional model [7] was that one of the important roles of surface friction is to act to confine convective activity to some restricted area by preventing its outward propagation. Although the author has considered that this role of surface friction is also valid for a three-dimensional model and that it is one of the important aspects of the frictional flow CISK, he has not confirmed it with the use of a three-dimensional model. Fig. (**6**) shows the low-level rainwater field in case (NOF) in which surface friction is not taken into account. This figure should be compared with Figs. (**1**, **4**) for case (ICE). This figure clearly shows that a vortex can develop without surface friction and acquire wind speeds of about 20~25 $m\ s^{-1}$, which corresponds to TC intensity. Convective activity is maintained in the inner area of the vortex for a long period of time. On the other hand, the distribution of convective clouds in case (NOF) is quite different from that in the control case (ICE), except at the early stage when the vortex is weak. The most important difference, which has probably been known by some researchers, and has been the author's belief, is that no eyewall forms in the case without surface friction. The numerical experiment has shown (or confirmed) that, without an eyewall, the vortex (TC) cannot develop further, without exceeding the maximum wind speeds of 20~25 $m\ s^{-1}$.

The third concern of this study is to understand the effect of the surface heat flux on TC formation more clearly than what has been understood. As mentioned in Section 1, some researchers have argued that the WISHE is important to vortex intensification at the stage when a vortex is strong to some extent. For example, Molinari *et al*. [22] referred to tropical depression and early tropical storm periods as pre-WISHE period. However, it is probably not appropriate to distinguish TC formation (vortex intensification) process into two stages, using the term pre-WISHE. The pre-WISHE stage, if any, may be very restricted in the real atmosphere.

Results from a case which excludes the surface heat flux in case (ICE) are shown in the left portion of Fig. (**7**). This case is referred to as case (NOSHF1). Another numerical experiment, case (NOSHF2) is performed, with the use of the data of 10 h in case (ICE). The results are shown in the right portion. These results should be compared with the right panels of Fig. (**1**). It is clearly seen that the initially given vortex does not develop without the surface heat flux in case (NOSHF1). Although convective activity is maintained for a long period of time, a somewhat ring-shaped convection merely expands (propagates outward), and it does not show any sign that stronger convection forms. The vortex itself does not show any sign of its

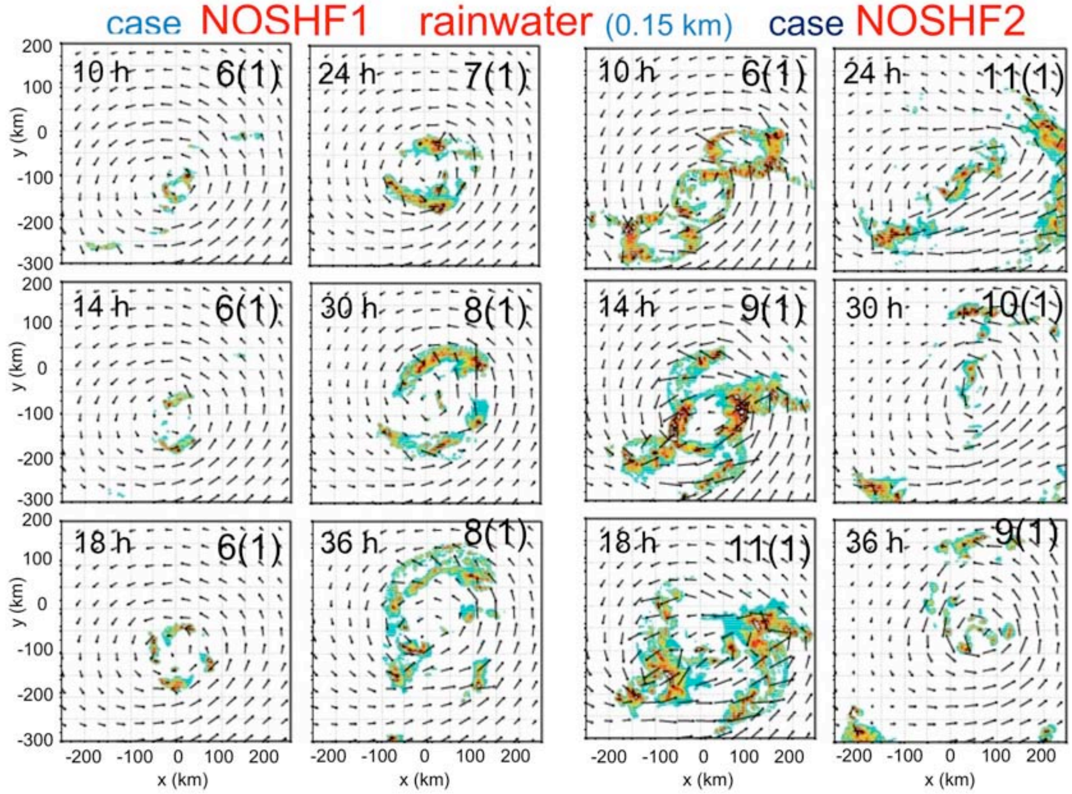


**Fig. (7).** Rainwater mixing ratio at 0.15 km and wind vector at 0.8 km at six selected times in cases (NOSHF1) and (NOSHF2).

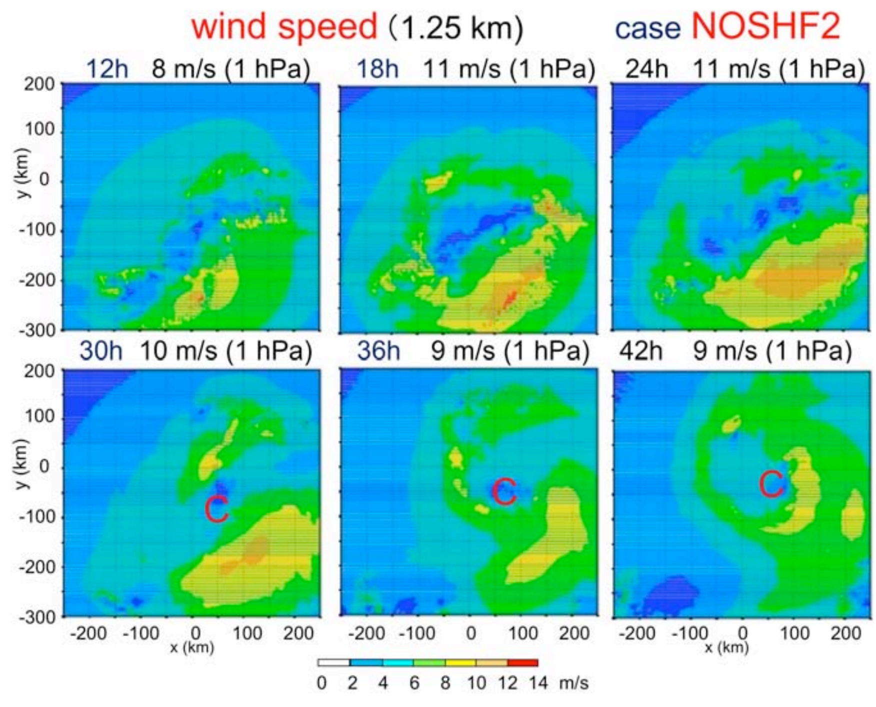


**Fig. (8).** The wind speed at 1.25 km in a period of 12 h-42 h at a time interval of 6 hours in case (NOSHF2). The maximum wind speed and the central surface pressure anomaly are also shown by numerals.

development. In case (NOSHF2), convective activity becomes weaker after 18 h, and the vortex does not develop. Fig. (**8**) shows the wind speed at 1.25 km in case (NOSHF2). This figure can be compared with the lower panels of Figs. (**2**, **3**). It can be confirmed from these results that any CISK does not work without the surface heat flux.

## 4. CONCLUDING REMARKS

This paper describes the results from numerical experiments which have been performed for better understanding of TC formation, with the use of a cumulus-convection-resolving model in contrast to a mesoscale-convection-resolving model used in the previous study [1].

The primary objective is to understand the effects of ice microphysics, surface friction, and surface heat flux on TC formation.

The main results are as follows: (1) Development of a vortex is slower, and TC formation is delayed, in the presence of ice microphysics. The role which the ice phase plays in TC formation process is essentially the same as that described in the previous paper [5]. (2) A vortex can develop even without surface friction, up to the stage when the maximum wind speed is 20~25 $m\ s^{-1}$. As expected, however, no eye forms, and further development does not occur. That is, it is confirmed that surface friction is indispensable to eye formation and a very strong TC having an eye. (3) A vortex with the maximum wind speed of about 5 $m\ s^{-1}$ does not develop in the absence of the surface heat flux. That is, the surface heat flux plays an important role even in a weak vortex.

Although most of the results are confirmations of what the author has understood in these many years, this paper describes some important results that are, more or less, different from what many of researchers have understood. As the next step of this study, the author has performed numerical experiments to understand the effect of the vertical shear of environmental flow on TC formation, as studied by Tuleya and Kurihara [23]. The results will be reported in a separate paper.

As mentioned in Section 1, it is strongly hoped that further extensive studies will be made by many researchers in the coming years to better understand TC formation (genesis) which has many different processes in nature.

## CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

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## REFERENCES

[1] Yamasaki M. Toward an understanding of tropical cyclone formation with a nonhydrostatic, mesoscale-convection-resolving model. Open Atmos Sci J 2013; 7: 37-50.

[2] Yamasaki M. A view on tropical cyclones as CISK. J Meteor Soc Japan 2007; 85:145-64.

[3] Willoughby HE. Jin H-L. Lord SJ. Piotrowicz JM. Hurricane structure and evolution as simulated by an axisymmetric, nonhydrostatic numerical model. J Atmos Sci 1984; 41: 1169-86.

[4] Sawada M, Iwasaki T. Impacts of ice phase processes on tropical cyclone development. J Meteor Soc Japan 2007; 85: 479-94.

[5] Yamasaki M. A study on the effects of the ice-microphysics on tropical cyclones. Adv Meteor 2013; vol. 2013: Article ID 573786, Available on: http://dx.doi.org/10.1155/2013/573786

[6] Yamasaki M. The role of surface friction in tropical cyclones. J Meteor Soc Jpn 1977; 55: 559-72.

[7] Yamasaki M. A further study of the tropical cyclone without parameterizing the effects of cumulus convection. Papers Meteor Geophys 1983; 34: 221-60.

[8] Nasuno T. Yamasaki M. The effect of surface friction on the mesoscale organization of cumulus convection in tropical cyclones. J Meteor Soc Jpn 1997; 75: 907-23.

[9] Yamasaki M. Towards an understanding of the interaction between convection and the larger-scale in the tropics. Aust Met Mag 1988; 36: 171-82.

[10] Yamasaki M. Numerical experiment of tropical cyclone formation in the intertropical convergence zone. J Meteor Soc Jpn 1989; 67: 529-40.

[11] Yamasaki M. A study of tropical cyclone formation with a 20-km grid model. SOLA 2006; 2: 9-12.

[12] Yamasaki M. A numerical study of tropical cyclone formation from two mesoscale convective systems in a large-scale convective system. SOLA 2006; 2: 57-60.

[13] Ooyama K. A dynamical model for the study of tropical cyclone development. Geophys Int 1964; 4: 187-98.

[14] Charney JG. Eliassen A. On the growth of the hurricane depression. J Atmos Sci 1964; 21: 68-75.

[15] Gray WM. Global view of the origin of tropical disturbances and storms. Mon Wea Rev 1968; 96: 669-700.

[16] Ooyama K. Numerical simulation of the life cycle of tropical cyclones. J Atmos Sci 1969; 26: 3-40.

[17] Rotunno R. Emanuel KA. An air-sea interaction theory for tropical cyclones. Part II: Evolutionary study using a nonhydrostatic axisymmetric numerical model. J Atmos Sci 1987; 44: 542-61.

[18] Yamasaki M. A study of the 22 February 1993 TOGA COARE squall line: a case used for the GCSS model intercomparison. J Meteor Soc Japan 2004; 82: 1331-63.

[19] Lin Y-L. Farley RD. Orville HD. Bulk parameterization of the snow field in a cloud model. J Climate Appl Meteor 1983; 22: 1065-92.

[20] Sato D. Yamasaki M. A formulation of cloud ice formation and representation of graupel in a model of tropical squall clusters. Presented at a fall meeting of the Meteorological Society of Japan 1998; B152 (Japanese).

[21] Yamasaki M. A study of the mesoscale structure of Typhoon Flo (T9019): a case of COMPARE model intercomparison. J Meteor Soc Jpn 2005; 83: 1057-84.

[22] Molinari J. Vollaro D. Corbosiero KL. Tropical cyclone formation in a sheared environment: a case study. J Atmos Sci 2004; 61: 2493-509.

[23] Tuleya RE. Kurihara Y. A numerical study on the effects of environmental flow on tropical storm genesis. Mon Wea Rev 1981; 109: 2487-506.

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