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The Effect of Water Vapor on Tropical Cyclone Genesis:

A Numerical Experiment of a Non-developing

Disturbance Observed in PALAU2010

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Abstract

The environmental conditions for tropical cyclone genesis is examined by numerical experiment. We focus on the case of a non-developing disturbance that had features for tropical cyclone genesis in the Pacific Area Long-term Atmospheric observation for Understanding climate change in 2010 (PALAU2010) observation campaign over the western North Pacific. We clarify the importance of abundant moisture around the disturbance for continuous convection and demonstrate that the collocation of a mid-level vortex and a low-level vortex, i.e., the persistence of an upright structure of vortices, is important in tropical cyclone genesis. We conduct two numerical experiments by using the Weather Research and Forecasting Model-Advanced Research model in the double nested domains with the horizontal grid space 27 km and 9 km for the outer domain and the inner domain, respectively. The first is based on reanalysis data (a control experiment), and the second includes increased water vapor content over the northwestern dry area of the disturbance. In the control experiment, the disturbance did not develop into a tropical cyclone in spite of the existence of the mid-level and low-level vortices. In contrast, the sensitivity experiment shows that a tropical cyclone was formed from the disturbance with increased water vapor content. The presence of persistent upright vortices was supported by continuous convection until genesis of tropical cyclone.

Keywords: tropical cyclone genesis; genesis environmental condition; water vapor; mesoscale vortex; non-developing disturbance; numerical experiment
1. Introduction

Tropical cyclones (TC) are one of the most hazardous phenomena; and many studies have been conducted regarding their structures, development, and decay (Anthes 1982; Chan and Kepert 2010; Emanuel 2003). TC genesis (TCG) is one of the most challenging issues in TC studies because of its complicated processes. A TC is developed from a convective coupled disturbance over the tropical oceans (Anthes 1982; Gray 1968, 1975, 1998). The disturbances are large-scale phenomena with easterly waves and convective systems organized inside the disturbances. Gray (1975) listed favorable environmental conditions for TCG. The environmental conditions are: 1) a large Coriolis parameter, 2) the existence of cyclonic relative vorticity at low-level troposphere, 3) weak vertical shear of horizontal winds, 4) a high sea surface temperature, 5) a vertical gradient of equivalent potential temperature between the low-level and the mid-level troposphere, and 6) abundant moisture from the low-level to the mid-level troposphere.

The detailed process of TCG has become gradually understood through remote-sensing observations and numerical experiments. A mesoscale convective system (MCS) is organized in a convective coupled disturbance, and long lasting MCSs sometimes organize mesoscale vortices in their clouds at low-level or mid-level. The mesoscale convective vortex at mid-level is suggested as an important environment for the organization of a TC vortex by observational and numerical studies (Houze et al. 2009; Kieu and Zhang 2008; Ritchie and Holland 1997; Simpson et al. 1997). The vortical hot-tower is a convective scale vortex at mainly low-level, and is suggested as a possible embryo for the organization of a TC vortex (Hendricks et al. 2004; Houze et al. 2009; Montgomery et al. 2006). However, such mesoscale vortices are also found in disturbances that do not develop into a TC (a non-developing disturbance) (Fu et al. 2012;
It is important to understand the differences between developing disturbances and non-developing disturbances. Fu et al. (2012) showed the differences in environmental conditions between developing disturbances and non-developing disturbances over the western North Pacific. Larger meridional gradients of zonal wind and low-level convergences are found in developing disturbances. In contrast, the differences in sea surface temperature, the vertical shear of the horizontal wind, and the relative vorticity are not significant.

Considering the TCG process, Erickson (1977) found less differences in the convective cloudiness between the developing disturbances and the non-developing disturbances. Meanwhile, Zehr (1992) revealed that the developing disturbances have convective maximums before they become TCs, and the convections in the non-developing disturbances are not persistent. McBride and Zehr (1981) revealed the similarities and differences between the developing disturbance and the non-developing disturbance over the western North Pacific. The common characteristics are a cyclonic vortex, an upper-level warm core, and an axisymmetric structure for the vortex center. The developing disturbances have a clearer warm core, a stronger vorticity, and a lower location of peak vorticity compared to the non-developing disturbances. Bessho et al. (2010) also pointed out that the warm core is well organized in developing disturbances, but the technique to determine the warm core from satellites is still difficult (Stern and Nolan 2012; Ohno and Satoh 2015).

The characteristics of the environments and structures in developing disturbances have been gradually revealed by previous studies. To address the TCG process, we should identify the environmental conditions and processes that are found in developing
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disturbances. Tuleya (1991) conducted numerical simulations for two disturbance cases, a developing case and a non-developing case. The environmental condition of the developing case had more moisture and a weaker vertical shear of the horizontal wind than did the non-developing case. In addition, the upper-level warming occurred continuously only in the developing case. In the non-developing case, a drying at mid-level resulted in the interruption of the convections and led to insufficient upper-level warming. The collocation of an upper-level warming over the low-level vortex was also an important feature in the developing case. In contrast, the upper-level warming was located to the east of the low-level vortex in the non-developing case. Although Tuleya (1991) conducted a sensitivity experiment by increasing water vapor content with 10% relative humidity, a TC did not develop in the non-developing case.

Even with these previous studies and the understanding of these differences, it is still not clear if non-developing disturbances have the potential to develop into a TC. The non-developing disturbances might lack a crucial feature to develop into a TC. Another issue is the process necessary for TCG. If the non-developing disturbances can develop into a TC with sufficient environmental conditions, understanding which process is necessary for the development process of TCG is crucial. Therefore, we conduct two numerical experiments in this study to determine: (1) the potential for non-developing disturbance to develop into a TC, and (2) a necessary process for the development.

We describe a target case and the simulation settings in Section 2. We explain the control experiment based on reanalysis data in Section 3 and the experiment with increasing water vapor content in Section 4. Finally, we provide a summary of the paper in Section 5. In this paper, a tropical cyclone is defined as the convective disturbance with the clear eye of the vortex for convenience sake.
2. A target case and simulation settings

We focus on a convective coupled disturbance observed during the observation campaign of the Pacific Area Long-term Atmospheric observation for Understanding climate change in 2010 (PALAU2010) operated by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). In the PALAU2010 observation campaign, the disturbance was a candidate for developing into a TC and observed by dropsonde in the observation period from June 18-22. We use the observation data for verification of the numerical simulation. The disturbance is the low of an easterly wave. Easterly waves are well known as precursors of TCs (Gray 1968, 1975, 1998; Heta 1990, 1991; Yanai 1961), and TCGs with an easterly wave comprise approximately 20% of the TCG events over the western North Pacific (Lee et al. 2008; Ritchie and Holland 1999; Yoshida and Ishikawa 2013).

Figure 1 shows the infrared images observed by the geostationary satellite of MTSAT-1R. The disturbance moves westward from 150°E along 7°N during the observation period. At 12Z on June 18, 2010, in the disturbance highlighted by the red circle, an MCS is found with a blackbody temperature (TBB) lower than 208 K with several kilometers of horizontal scale. The MCS did not continue for a long period and dissipated by 12Z on June 19. The disturbance is also represented by the NCEP final analysis data (NCEP-FNL; NCEP 2000). The disturbance can be found in the vertical vorticity field at 850 hPa around 8°N/160°E at 00Z June 16, and develops gradually moving westward. Figure 2 shows a relative vorticity at 12Z June 18, 2010, and the red circles show the same location indicated in Fig. 1 (i.e., the area of the concentrated convection). Positive relative
vorticities are present both at the 500- and 850-hPa levels, indicating that the disturbance has vortices at mid-level and low-level. Although these vortices can be identified by June 23 in the NCEP-FNL, the disturbance did not develop to a TC and dissipated after June 23. From the dropsonde data, the low-level temperature in the cloudy area in the disturbance is approximately 1 K lower than the clear sky area (not shown). The clear sky area is located at the north-western side of the cloudy area. The low temperature implies an existence of a cold pool at the location and supports the identification of the MCS from the satellite data.

In this study, the Weather Research and Forecasting Model (WRF)-Advanced Research WRF (WRF-ARW) model version 3.4.1 (Skamarock et al. 2008) is used for the numerical simulation. The computational domains are double nested as shown in Fig. 3, and the horizontal grid space is set as 27 km and 9 km for the outer domain and the inner domain, respectively. The number of vertical levels is 36 layers for both domains. The one-way online domain nesting system is used for better preparation of the lateral boundary condition for the inner domain. The experimental settings are listed in Table 1. The time integration period is from 00Z June 16, 2010 to 00Z June 23, 2010. To allow adequate spin-up of the atmospheric field and simulate the genesis process in the model, the initial time is set as two days before the development of the disturbance at 00Z June 18, 2010.

3. Control experiment and time evolution of non-developing disturbance

The simulated horizontal distribution of the cloudy area is shown in Fig. 4. Deep convections associated with the simulated disturbance spreads over an area wider than the observation in Fig. 1. The simulated disturbance develops as a circular shaped cloud
cluster by June 20, 2010. The disturbance did not develop into a TC by the end of the
time integration. The temperature in the clear sky is approximately 0.5 K higher than in
the cloudy area of the disturbance (not shown), consistent with the dropsonde
observations.

Figure 5 shows the relative vorticity field to confirm the simulated vortex structure.
Positive vorticities are found both at 500- and 850-hPa levels, which is the same as in the
observations. The positive vorticity areas at 500 hPa level collocate over the positive
vorticity at 850 hPa level at 00Z on June 19. That is, the vortices have an upright structure
in the convective coupled disturbance. According to previous studies on TCG (Ritchie
and Holland 1997; Simpson et al. 1997), the upright structure of the vortices is found in
developing disturbances and is attributed to TCG. However, in this simulation, the
positive vorticity area at 500 hPa level moves away toward the west of the positive
vorticity at 850 hPa by 00Z on June 20. The upright structure of the vortices tilts westward
gradually for 24 hours. In this simulation, since the vertical shear of the horizontal wind
is approximately 10 m s$^{-1}$ with almost easterly shear, the vortices structure lean out toward
down-shear. The simulated disturbance fails to maintain the upright structure of the
vortices and, consequently, dissipates. A similar tilted structure has been found in non-
developing disturbances. According to Tuleya (1991), the upper-level warming is located
just above the low-level vortex in developing disturbances, while it is located to the east
of the low-level vortex in non-developing disturbances.

One of the possible reasons for the tilting of the vortices is the vertical shear of the
horizontal wind. However, from the view point of storm scale, the magnitude of the
easterly wind shear between the 850- and 400-hPa levels is approximately 10 m s$^{-1}$ in the
simulation, which is calculated by area averaging over the rectangle area of one degree
by one degree centering the disturbance. The magnitude of vertical wind shear is moderate compared to the average value of the vertical shear in TCG (Yoshida and Ishikawa 2013). McBride and Zehr (1981) concluded that vertical shear is substantially strong even in developing cases over the western North Pacific. Fu et al. (2012) also found that a difference in strength of the vertical shear was small between developing cases and non-developing cases over the western North Pacific. Therefore, the vertical shear would not be a crucial environmental condition for the TCG over the western North Pacific.

Fu et al. (2012) emphasized that moisture content at mid-level and low-level are very different between developing disturbances and non-developing disturbances. Compared with developing disturbances, the relative humidity is quite low in non-developing disturbances at the west of the disturbance both at low-level and mid-level. The moisture field in the simulated disturbance is shown in Fig. 6 with horizontal distribution of convective available potential energy (CAPE) and relative humidity. The yellow rectangle area indicates the area around the moisture convergence of the disturbance, which is found in Fig. 6b. The northeastern area of the low has much lower CAPE compared with the southern area of the moisture convergence. Therefore, the convection tends to be suppressed over the low CAPE region. It is also clear that dry air exists over the northwestern area of the disturbance.

The vertical cross section of equivalent potential temperature and vertical mass flux through the AB path in Fig. 6b is shown in Fig. 7. In Fig. 7, the red arrow indicates the disturbance location at 450 km from point A. The large upward mass flux is found at the disturbance location, and the upward mass flux corresponds to the convection at the disturbance. The low equivalent potential temperature air is found in the northwestern area of the disturbance (from 150 – 300 km) at the mid-level of the troposphere. In the
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... dry air area, downward mass flux is observed, but upward mass flux is found in the upper level of the dry air area. In addition, quite high equivalent potential temperatures are found from the surface to 1 km height. Therefore, this dry air might not result from the large-scale subsidence but could be created by advection. A similar feature regarding the existence of dry air was suggested by Tuleya (1991) in the non-developing case.

Therefore, we focus on the water vapor content as the required environmental condition for TCG and verify a hypothesis that the upright structure of the vortices in the disturbance can be maintained with the continuous convection against the vertical shear of the horizontal wind. We evaluate the effect of the water vapor content on continuing the convection and processes toward TC with an additional numerical experiment by increasing water vapor content artificially in the next section.

4. Water vapor increasing experiment

4.1 case with developed TC

To evaluate the effect of the water vapor content to continue convection and allow the disturbance to progress toward a TC, we carry out a restart calculation from 12Z June 18, 2010 when the disturbance shows remarkable convection. Although Tuleya (1991) increased moisture over the whole computational domain, we increase the mixing ratio of water vapor (Qv) only in the area indicated by the yellow rectangle in Fig. 6 in order to increase the low-level moisture convergence around the disturbance. Lu et al. (2012) used the data assimilation system to modify Qv in the sensitivity test of a TC genesis case, but we modified Qv by adding directly for the simple instruction. We assume that the intense convection will lead to an intensified upward mass flux and that the intensified...
mass flux will strengthen the low-level convergence. The upper limit of Qv is set as the average value of the computational domain at each level, and the Qv is increased up to this upper limit. The rest of the experimental setting was completely the same as the control experiment (CTL). In this study, we increased water vapor content at all the model layers. The difference of the relative humidity between the CTL and the Qv increasing experiment (QVplus) is shown in Fig. 6c. The difference is found only in the yellow rectangle area of the Fig. 6b. The maximum difference is 30 % in relative humidity, which is located at the northwestern area of the disturbance. The increasing amount is larger than Tuleya (1991), which was 10 % in relative humidity. The horizontal wind field is not affected significantly by this modification at one hour after the restart of the time integration (at 13Z on June 18), but the low-level convergence is intensified as was the aim of the experimental setting. The horizontally averaged wind around the disturbance is easterly wind from 1000 hPa to 300 hPa, and weak westerly wind aloft 200 hPa. From the view point of environment scale, the magnitude of the vertical shear of zonal wind is 6 ms\(^{-1}\) approximately, which is calculated by area averaging over the rectangle area of six degrees by six degrees centering the disturbance. The magnitude of vertical shear in QVplus is not significantly different from that in CTL during several hours after the restart calculation.

Figure 8 shows the time evolution of the disturbance in QVplus. At 00Z on June 19, a more intense convection can be found in QVplus than in the CTL (Fig. 4), and the cloudy area decreases rapidly in the first 24 hours. The disturbance in QVplus has a larger area of deep convection as indicated by a TBB lower than 208 K. Especially, the convections are intensified over the eastward of the moisture convergence (12°N-13°N, 144°E-150°E), and the vertical profile of temperature difference from the area averaged value at the
intensified convection is similar with that in CTL. Although the disturbance in CTL starts to dissipate after 12Z on June 20, the disturbance in QVplus continues to develop into a TC by 12Z on June 21 with a clear eye forming. The disturbance that dissipates in reality develops into a TC by increasing the water vapor content. Therefore, non-developing disturbances have the potential to develop into a TC if the appropriate environment is present.

The temporal evolution of the relative vorticity is shown both for 500- and 850-hPa levels in Fig. 9. Although the low-level vortex is located to the east of the location of the mid-level vortex in CTL (Fig. 5) at 00Z on June 20, the low-level vortex is collocated under the mid-level vortex during the whole time period in QVplus. Therefore, the vortices persist in the upright structure in QVplus. At 00Z on June 19, the high positive vorticity area ($< 3 \times 10^{-4} \text{ s}^{-1}$) is larger in QVplus than that in CTL. This suggests that the low-level vortex in QVplus is more intense.

To investigate the difference in temporal evolution between CTL and QVplus, we track the low-level vortex for each experiment and calculate the area averaged vorticity, the potential temperature, and the sea level pressure in a rectangle area of 90 km by 90 km centering on the low-level vortex location (Fig. 10). The low-level vorticity in QVplus is always higher than that in the CTL after 12Z on June 18, which is the start time of QVplus. It is confirmed that the disturbance in QVplus has a more intense low-level vortex than did CTL. The mid-level vorticity above the low-level vortex in CTL has a negative value occasionally. In contrast, the mid-level vorticity in QVplus is a positive value continuously after 12Z June 18. Therefore, it is suggested that the upright structure of the vortices persists in QVplus, but not in CTL. In addition, the potential temperature averaged from the 400- to 200-hPa level in QVplus is higher than that in CTL, and the
sea level pressure in QVplus decreases more than in CTL. These characteristics would result in the more intense convection and its persistence in QVplus as compared to CTL. Therefore, the increase of water vapor intensifies the convection around the disturbance, and the intensified convection induces a stronger updraft and horizontal convergence at the low-level. The stronger low-level and mid-level vortices would be organized by continuous convections through tilting, stretching and convergence mechanisms, and the upright structure of the vortices persists against the vertical shear of the horizontal wind. Although Tuleya (1991) concluded that the vertical shear of horizontal wind was stronger in the non-developing case than in the developing case, the disturbance developed into a TC under the similar condition of the magnitude of vertical shear in this study.

In addition, the continuous convection intensifies and sustains the mid- to upper-level warming. The mid- to upper-level warming results in decreasing pressure at the low-level below the warming area, and the low pressure at the low-level would intensify the low-level vortex. The mid- to upper-level warm core is stable with the intensification of the low-level vortex considering the thermal wind balance. This process would work efficiently with collocation of the upper-level warming and the low-level vortex, which is attributed to the continuous convection. Although a more detailed analysis is needed for complete understanding of the temporal evolution of vorticity and the relationship between vorticity and convective activity, QVplus experiment supports the hypothesis that abundant moisture leads to continuous convection, the continuous convection allows the persistence of the upright structure of vortices, and the non-developing disturbance can develop into a TC. Therefore, sufficient water vapor content is one of the crucial environmental conditions for continuous convection and the intensification of low-level vortices.
4.2 sensitivity to the increasing Qv

In QVplus in Section 4.1, the Qv is increased up to the upper limit as the average value of the computational domain at each level. To evaluate the sensitivity to the increasing Qv, we carried out further three experiments changing the amount and area of the increasing Qv; (1) the QV is the upper limit to 66% of QVplus (QVp-66), (2) the QV is reduced the upper limit to 83% of QVplus, but the increasing area is extended northward to cover the whole area of dry air (QVp-83ext), and (3) the QV is same with QVp-83ext, but the upper limit is increased to 125% of QVplus (QVp-125ext). QVp-125ext is conducted to investigate the impact of extension of the increasing area. Figure 11 shows the difference of the relative humidity between the CTL and each experiment. The other experimental settings are completely same with QVplus.

The horizontal distribution of clouds and the track of the simulated disturbance in three experiments are similar to these in the CTL, but the track in QVp-125ext tends to be shifted northward comparing with the CTL. The temporal evolution of mid-level vorticity is shown in Fig. 12, which is calculated by the same way with Section 4.1. The disturbance in QVp-66 and QVp-83ext does not develop into a TC. The mid-level vorticity is not significant in both cases, and the low-level vorticity is also not intensified (not shown). In comparison to QVplus, the Qv in both the QVp-66 and QVp-83ext are insufficient to intensify convection to maintain the upright structure of the vortices. Although the increasing area was extended in QVp-83ext, the disturbance still does not develop to a TC. The mid-level vorticity in QVp-83ext is similar amount to CTL. Therefore, the extension of the increasing area does not have significant impact to intensify convection. By tracking each vortex at mid- and low-levels, the upright structure of the vortices is not
maintained in both QVp-66 and QVp-83ext. On the other hand, the disturbance in QVp-125ext develops into a TC, but the vorticity is not intense than that in QVplus at the first 24 hours. At the first 12 hours after the restart at 12Z June 18, convections are initiated over the larger area in QVp-125ext than in QVplus. As a result, the concentrated low-level convergence is not organized near the low of easterly wave, and the weak broad convergence would not be appropriate to intensify vorticity rapidly. However, the convective activity is enough to maintain the upright structure of vortices, and the disturbance can become the TC.

From these additional experiments, it is suggested that the increasing Qv has some threshold to develop into a TC, and the increasing Qv around the low of easterly wave is appropriate rather than over the larger area. In Tuleya (1991), the increasing amount of moisture would not be enough to develop. In addition, the moisture was increased over the whole computational domain in Tuleya (1991), hence, this setting would not be appropriate to develop the disturbance because of preventing to organize concentrated convergence. On the other hand, Lu et al. (2012) examined the sensitivity for moisture by reducing relative humidity to 60% of original amount in the disturbance that develop into a TC in reality, and the disturbance still developed into the TC. Therefore, the threshold of moisture required to develop can be different on a case by case basis.

5. Summary

We investigated the potential for non-developing disturbances to develop into a TC and demonstrated that simulated disturbances that dissipated in nature had the potential for developing into TCs with abundant moisture. We also suggested that the persistence of
the upright structure of vortices in the disturbance is a necessary process for this
development. A numerical simulation for a convective coupled disturbance
accompanying a mesoscale vortex observed in the PALAU2010 was carried out using the
WRF-ARW model. The convective coupled disturbance selected in this study did not
develop into a TC in spite of the existence of vortices. The numerical simulation provided
a similar structure and temporal evolution compared to the observations. The simulated
disturbance had both a low-level vortex and a mid-level vortex, and the vortices had an
upright structure. These features are similar to those in the developing disturbances
reported by previous studies. However, the upright structure gradually leaned out toward
the down-shear direction; and the disturbance did not develop into a TC since the
convection was not continued, likely because of a low moisture condition.

To examine the effect of the moisture field, we conducted an additional experiment
(QVplus) that increased the water vapor content only near the disturbance. In QVplus
experiment, the convection in the higher moisture area became more intense and persisted
longer period than in the control experiment. As a result, the upright structure of the
vortices persisted for a longer period than in the control experiment. In the experiment
conducted by Tuleya (1991), a non-developing disturbance in the observation did not
developed into a TC under an increased moisture environment. However, with the
environment in this study, a non-developing disturbance from the observation data did
develop into a TC.

We have found that a non-developing disturbance has a potential to develop into a TC
if adequate environment conditions were satisfied. As summarized in the illustration in
Fig. 13a, one of the possible obstructions for development of a TC was a break in
convection due to the low water vapor content. If the convection did not continue, mid-
to upper-level warming and the intensification of the low-level convergence and vortex were lost. Therefore, the upright structure did not persist. However, as depicted in Fig. 13b, a mid- to upper-level warming occurred just above the low-level vortex when the upright structure persisted. When the surface pressure decreased, the low-level vortex again intensified. A continuing upright structure was a key process found in developing disturbances.

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Fig. 2. Vertical component of relative vorticity at 12Z June 18, 2010 at 500 hPa level and 850 hPa level. Red circles show the same area with the same size as in Fig. 1. The relative vorticity was calculated by using NCAP-FNL 1° data.

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Fig. 13. Schematic illustration of the necessary environment condition and the process to develop a TC compared with a dissipation case. In the developing disturbance, the abundant environmental moisture leads to continuous convection, and the continuous convection allows persistence of the upright structure of the vortices.

Fig. 1. Blackbody temperature (TBB) distribution observed by MTSAT-1R (IR1 channel) from 12Z June 18, 2010 to 00Z June 20, 2010. Red circles show the location of the disturbance, and the radius of the circle is 10°.

Fig. 2. Vertical component of relative vorticity at 12Z June 18, 2010 at 500 hPa level and 850 hPa level. Red circles show the same area with the same size as in Fig. 1. The relative vorticity was calculated by using NCAP-FNL 1° data.
Fig. 3. A computational domain setting. Dark rectangles show the domain areas for domain 1 and domain 2, respectively.

Fig. 4. TBB distribution of the simulated disturbance in domain 2 (9 km) from 12Z June 18, 2010 to 00Z June 20. The TBB is estimated from outgoing longwave radiation based on the Stefan-Boltzmann law. Red circles show the location of the disturbance, and the radius of the circle is 10°.

Fig. 5. Vertical component of relative vorticity in domain 2 from 00Z June 19, 2010 to 00Z June 20. The color shading shows the relative vorticity at 850 hPa level, and the blue contours show that of $1.0 \times 10^{-4}$ [s$^{-1}$] at 500 hPa level.
Fig. 6. Horizontal distributions of environmental factors. (a) Convective available potential energy (CAPE), (b) relative humidity at 850 hPa level, and (c) the difference in relative humidity (QVplus - CTL) at 850 hPa level. CAPE was calculated by lift-up of the parcel at 100 m height. Yellow rectangles are the modification region for QV increasing. The path A-B shows the path of the vertical cross section.

Fig. 7. Vertical cross-section of equivalent potential temperature (color shade). The contour shows the vertical mass flux [kg s\(^{-1}\) m\(^{-2}\)] (contour) in the A-B path in Fig. 6. For the vertical mass flux, the upward flux is positive value. A red arrow shows the location of the disturbance.
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Fig. 8. TBB distribution of QVplus experiment in domain 2 (9 km) from 00Z June 19, 2010 to 12Z June 21. The TBB is estimated from outgoing longwave radiation based on the Stefan-Boltzmann law.

Fig. 9. Vertical component of relative vorticity for QVplus experiment in domain 2 (9 km) from 00Z June 19, 2010 to 00Z June 20. The color shading shows the relative vorticity at 850 hPa level, and the blue contours show that of $1.0 \times 10^{-4}$ [s$^{-1}$] at 500 hPa level.
Fig. 10. Temporal evolution of (a) vertical vorticity (VR) at 500- and 850-hPa levels and (b) potential temperature (TH) and sea level pressure (SLP). Each is a horizontally averaged value in a rectangular area of 90 km by 90 km centering on the low-level vortex location. The low-level vortex location was tracked for CTL and QVplus experiments, respectively. Theta is also vertically averaged between 400- and 200-hPa levels.

Fig. 11. Horizontal distributions of the difference in the relative humidity; (a) between CTL and QVp-66, (b) between CTL and QVp-83ext, and (c) between CTL and QVp-125ext. Yellow rectangles are the modification region for QV increasing.
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Fig. 12. Temporal evolution of vertical vorticity at 850-hPa levels. This is a horizontally averaged value in a rectangular area of 90 km by 90 km centering on the low-level vortex location. The low-level vortex location was tracked for each experiments, respectively.

Fig. 13. Schematic illustration of the necessary environment condition and the process to develop a TC compared with a dissipation case. In the developing disturbance, the abundant environmental moisture leads to continuous convection, and the continuous convection allows persistence of the upright structure of the vortices.
Table 1. The experimental settings for performance assessment with triple-nested domains.

<table>
<thead>
<tr>
<th>settings</th>
<th>domain 1</th>
<th>domain 2</th>
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<tr>
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<td>time integration period</td>
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<td>initial/boundary data</td>
<td>NCEP-FNL</td>
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<td>model top level</td>
<td>50 hPa level</td>
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<td>cloud microphysics scheme</td>
<td>WSM6</td>
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<td>cloud parameterization</td>
<td>Kain-Fritsch (5 minutes interval)</td>
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<td>boundary layer scheme</td>
<td>Yonsei University scheme</td>
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<td>radiation scheme</td>
<td>RRTM and Dudhia scheme</td>
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