Numerical Investigation of Development Processes of Baiu Frontal Depressions

Part I: Case Studies

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Abstract

This work investigates the development processes of Baiu frontal depressions (BFDs) using a numerical model. To investigate the effects of upper-level disturbances, latent heating, and baroclinicity on the development of BFDs, case-study numerical simulations are performed. In the present study, two typical cases were selected from BFDs that appeared in June and July, 2000–2007—a BFD that developed in the western part of the Baiu frontal zone (W-BFD) from 26 to 27 June, 2003, and a BFD that had formed in the eastern part of the Baiu frontal zone (E-BFD) from 1 to 3 July, 2003. An available potential energy diagnosis shows that the effect of latent heating is dominant during the W-BFD development, while baroclinicity as well as latent heating is important to the E-BFD development. A sensitivity experiment excluding upper-level potential vorticity (PV) anomalies shows that upper-level disturbances are important contributors to the development of E-BFDs.

The low-level PV and its production associated with latent heating suggest that the W-BFD has a development mechanism driven by latent heating. In the early developmental stage, PV near the W-BFD center is enhanced. This feature is consistent with the nonlinear conditional instability of the second kind mechanism. In the later developmental stage, PV is produced in front of the W-BFD center, in which low-level baroclinicity is large. This process is consistent with a diabatic Rossby vortex. In contrast, the E-BFD develops through a baroclinic instability-like mechanism in the moist atmosphere.

Keywords Baiu; depression; extratropical depression
development (e.g., Montgomery and Farrel 1991, 1992; Takayabu 1991; Davis and Emanuel 1991; Davis 1992; Davis et al. 1996; Huo et al. 1999; Wernli et al. 2002). Takayabu (1991), for instance, investigated the rapid deepening of EDs using a channel primitive model on a beta plane and showed that coupling development occurs when a low-level vortex is initially located at the latitude of the jet axis, and an upper vortex exists to the northwest of the low-level vortex. The result of his model is consistent with the coupling development of EDs observed in the real atmosphere. Davis and Emanuel (1991) applied a piecewise potential vorticity (PV) inversion technique to a case of cyclogenesis and showed that low-level potential temperature (PT) anomaly intensification by upper-level PV anomalies is important for cyclogenesis.

The effect of latent heating caused by the condensation of water vapor also enhances the ED development. Reed et al. (1998) examined the effects of latent heating on the development of EDs in the north Atlantic with a sensitivity experiment, in which latent heating was excluded. They showed that the intensity of the EDs in the sensitivity experiment is reduced to approximately 50–60% of the intensity of the full-physics simulation. Davis (1992) investigated two EDs that developed near the East Coast of the United States. He pointed out that latent heating contributes to the development of depressions, although the magnitude of this contribution differs from case to case.

The importance of coupling between lower- and upper-level disturbances and the effects of latent heating on the development of BFDs has also been pointed out (e.g., Akiyama 1984, 1990a, b; Ninomiya and Kurihara 1987; Chang et al. 1998; Ninomiya and Shibagaki 2003; Shibagaki and Ninomiya 2005). Akiyama (1984) showed that a weak low-level vortex associated with a cloud cluster grew into a BFD coupled with an upper-level trough. Shibagaki and Ninomiya (2005) investigated the structures and development processes of four BFDs that had formed in July 1992 and showed that vertical coupling of disturbances was responsible for the development of the BFDs. Ninomiya and Kurihara (1987) performed a numerical case study for a BFD that appeared in July 1979 and suggested that condensational heating is important for the formation and development of the BFD. Chang et al. (1998) examined the development processes of several strongly developed depressions that had formed in the Baiu front in June 1992 using a PV inversion technique. They showed that latent heating plays an important role in the development of the BFDs during the early stage and upper-level disturbances contribute to the BFD development in the later stage of development.

Note that features of the Baiu frontal zone differ between its western and eastern parts (e.g., Matsumoto et al. 1971; Ninomiya and Akiyama 1992). In the western part (west of approximately 140°E), the frontal zone is characterized by weak baroclinicity and a strong south–north gradient of water vapor. However, in the eastern part (east of approximately 140°E), the zone is characterized by relatively strong baroclinicity. These differences must influence the development of BFDs. Recently, Tochimoto and Kawano (2012) categorized BFDs into two groups on the basis of the region—BFDs that developed in the western (west of 140°E) and eastern (east of 140°E) parts of the Baiu frontal zone were referred to as W-BFDs and E-BFDs, respectively. They performed composite analyses and a number of case studies investigating the development processes by using the piecewise PV inversion technique developed by Davis and Emanuel (1991). They presented the results for a W-BFD that had formed on 26–27 June, 2003 and an E-BFD that formed on 1–3 July, 2003, which are typical cases. The results indicated that upper-level PV anomalies inducing low-level southerly winds intensified both the W-BFD and E-BFD through warm PT advection. They also suggested that positive high PV associated with latent heating contributed to the development of both BFDs. The effect of latent heating is larger in the W-BFD; however, it was suggested that the effect of low-level baroclinicity is more important to the E-BFD development.

In the present study, to investigate more quantitative contributions of latent heating, baroclinicity, and upper-level disturbances, numerical experiments are conducted using the Weather Research and Forecasting (WRF) model. Several sensitivity experiments and available potential energy diagnosis are performed to examine the evolution of those contributions.

This paper is organized as follows. In Section 2, model and experimental designs are presented. Case study overviews are illustrated in Section 3. In Section 4, results from numerical simulations are presented. The development processes of BFDs are discussed in Section 5. Finally, a summary is presented in Section 6.

2. Model and experimental design

A three-dimensional nonhydrostatic fully compressible numerical model, the Advanced Research Weather WRF (ARW) version 3.3 (Skamarock et al. 2008), is used in this study. The model domains are shown
in Fig. 1. The number of horizontal grid points with a spacing of 20 km for the W-BFD and E-BFD are 257 × 194 and 251 × 164, respectively. Both domains have 40 vertical levels from the surface to 50 hPa. The Noah land surface model (Chen and Dudhia 2001), the Yonsei University planetary boundary layer scheme (Noh et al. 2003), the WRF single-moment 6-class (Hong and Lim 2006) microphysics scheme, and the Kain–Fritsch cumulus parameterization scheme (Kain 2004) are applied to both simulations.

The W-BFD and E-BFD simulations start at 12 UTC 26 June 2003 and 06 UTC 2 July 2003, respectively. The initial and boundary conditions are calculated from the six-hourly available Japanese 25-year Re-Analysis (JRA-25) / Japan Meteorological Agency (JMA) Climate Data Assimilation System (JCDAS) (Onogi et al. 2007), which has a horizontal resolution of 1.25° × 1.25°, except for the skin temperature, which was obtained from available six-hourly National Centers for Environmental Prediction Final Analysis data (NCEP-FNL) with a horizontal grid spacing of 1.0°. Sea surface temperature is estimated by using surface temperature in NCEP-FNL.

To investigate the effects of latent heating and upper-level disturbances on the BFD development, three types of experiments were performed: control (CNTL), no latent heating (NOLH), and no upper-level disturbances (NOUL) simulations. The CNTL is a simulation including full physical processes. In NOLH, surface heat, moisture, and momentum fluxes remain on, but there is neither latent heating nor cooling with microphysics and cumulus schemes. The NOUL is a simulation without upper-level disturbances. According to Moore et al. (2008), upper-level PV anomalies from 500 hPa to the top of the model, which are defined as deviations from the 15-day mean, are excluded from initial and boundary conditions in NOUL using the piecewise PV inversion technique (Davis and Emanuel 1991).

3. Results

3.1 The W-BFD case

a. Case overview

During the early developing stage (06 UTC 26 to 18 UTC 26 June 2003), it appears that low- to mid-level processes such as moisture dynamics associated with convection along the Baiu front rather than upper-level process may lead to the development of the W-BFD. Figures 2a–d show the evolution of 850-hPa Ertel’s PV (Ertel 1942) and sea level pressure (SLP) obtained from JRA-25. The W-BFD was detected at 06 UTC 26 June 2003 in the JMA surface weather chart (117°E, 32°N; not shown); however, it was not clearly identified in Fig. 2a because of the coarse resolution of JRA-25. The region of positive PV with a maximum value exceeding 1.0 potential vorticity unit (PVU) was located around 110°E and 30°N. It seems that the positive PV was produced by convection around the Baiu (Meiyu) front over the mainland of China. It is suggested that a large-scale trough above China (100–120°E, 20–50°N) provided warm and moist air, leading to the formation of the W-BFD. As shown in Fig. 2e, an upper-level high PV at 300 hPa was located far northwest of the low-level depression at 06 UTC 26 June (90–100°E, 45°N). Subsequently, the W-BFD was clearly detected and a low-level PV of approximately 1.0 PVU is located around 115–120°E and 30–35°N at 12 UTC 26 June (Fig. 2b). It seems that upper-level disturbances had little influence on the W-BFD development in the early developing stage.
Fig. 2. (a)–(d) SLP (contour lines; hPa) and 850-hPa PV (shading; PVU), and (e)–(h) 300-hPa geopotential height (contour lines; m) and PV (shading) at (a, e) 06 UTC 26, (b, f) 18 UTC 26, (c, g) 00 UTC 27, and (d, h) 06 UTC 27 June 2003. (i) Vertical cross-section of PV along the A–A′ line.
since the upper-level trough was still located far from the W-BFD (Fig. 2f).

During the later stage (from 00 UTC 27 to 06 UTC 27 June 2003), the upper-level disturbance approaching the low-level disturbance may have affected the W-BFD. By 00 UTC on 27 June, the 300-hPa-high PV associated with the upper-level trough, which has a value of approximately 3.0 PVU, reached 100–110°E and 40–45°N (Fig. 2g). In addition, the 850-hPa PV developed to a maximum of 1.5 PVU (Fig. 2c). At 06 UTC 27 June, the central surface pressure of the W-BFD was approximately 993 hPa, which is the minimum pressure attained during its lifecycle. Although the upper-level trough was still located to the west of the cyclone center at this time, the development of W-BFD ended. Figure 2i shows a vertical cross-section along line A–A′ in Fig. 2c. The low-level disturbance is coupled with an upper-level high PV, exhibiting a structure tilted westward with height.

b. Control simulation

Before analyzing the results of the CNTL for the W-BFD (hereafter, W-CNTL), we verified whether the characteristics of the simulated W-BFD agree with those detected by JRA-25. The track of the simulated W-BFD in the CNTL agrees with that in JRA-25 (not shown). The W-CNTL reasonably reproduces the SLP distribution associated with the W-BFD (Figs. 3a, b), except that the simulated fields have a delay of approximately two hours and the maximum strength (approximately 990 hPa) is somewhat stronger than that in JRA-25 (approximately 993 hPa). The simulated lower central pressure could be attributed to the finer horizontal resolution in the present numerical

![Fig. 3](image-url)
experiment. In addition, the evolution of the simulated precipitation systems is two hours behind the radar observation of JMA (not shown).

At the lower and upper levels, the W-CNTL also adequately captures the structure and evolution of the PV detected in JRA-25 (Fig. 3). A high-PV region, exceeding 3 PVU, extends from mainland China to the Yellow Sea at 20 UTC 26 June 2003 (Fig. 3a). The maximum value of PV at this time is approximately 4 PVU. The high-PV region propagates eastward over the Yellow Sea and is elongated zonally by 08 UTC 27 June (Fig. 3b). The maximum PV of 4 PVU is maintained. After this time, the low-level PV gradually decreases because of the weakening of PV production due to latent heating. The simulation represents the upper-level high-PV region, which gradually approaches from the northwest of the cyclone center. This result is consistent with that in JRA-25 (Figs. 3c, d).

In order to quantitatively investigate the contributions of latent heating and baroclinicity to the BFD development, each term in the tendency equation of the available potential energy (APE) is estimated according to Parker and Thorpe (1995), Moore and Montgomery (2004; 2005), and Moore et al. (2008). The tendency equation of the APE is expressed as

\[
\frac{\partial A_E}{\partial t} = C_A - C_E + G_E + R,
\]

where \(A_E\) is the APE of the disturbance, \(C_A\) is the conversion from the APE in its basic state to \(A_E\), \(C_E\) is the conversion from \(A_E\) to the eddy kinetic energy, \(G_E\) is the conversion from the diabatic source to \(A_E\), and \(R\) is the residual term. These terms are defined as

\[
A_E = \int_{p_1}^{p_2} \frac{[T]}{2\sigma} dp,
\]

\[
C_A = -\int_{p_1}^{p_2} \frac{[\omega T']}{\sigma} \frac{\partial [T]}{\partial y} dp - \int_{p_1}^{p_2} \frac{[\omega T']}{\sigma} \frac{\partial [T]}{\partial p} dp,
\]

\[
C_E = \int_{p_1}^{p_2} \frac{[Q T']}{c_p \sigma} dp,
\]

\[
G_E = \frac{1}{g} \left( \frac{\bar{T}}{c_p} - \frac{p}{R} \frac{\bar{T}}{\partial p} \right),
\]

where \([\cdot]\) means a zonal average of \((\cdot)\) and \([\bar{\cdot}]\) a regional average of \((\cdot)\). A prime and an asterisk indicate a deviation from the zonal average and a deviation of the zonal average from the area mean, respectively. All variables have their usual meteorological meaning, and \(\bar{\sigma}\) represents the mean static stability in pressure coordinates. The calculation domain in the W-BFD (E-BFD) is a 1000 (2000) km × 1000 (2000) km square around the center of the W-BFD (E-BFD). The calculation domain for E-BFD is larger than that for W-BFD because the horizontal scale of E-BFD is larger. All terms are integrated from 950 to 250 hPa.

The evolution of each term in the tendency equation (Eq. 1) for the W-BFD is shown in Fig. 4. In the W-BFD, the diabatic term (GE) is dominant (maximum of 8 W m\(^{-2}\)) during the entire period. However, the contribution of baroclinicity (CA), which is gradually increasing with time, is quite small (maximum of 1 W m\(^{-2}\)) compared to the diabatic process. These results indicate that the diabatic process plays a cen-
central role in the development of the W-BFD. The conversion term (CE), which is negative throughout the entire period, indicates that the eddy APE is converted to eddy kinetic energy.

The evolution of the low-level PV and its production provide additional insight into the effects of latent heating on the BFD development. Following Hoskins et al. (1985), the diabatic generation of PV can be approximated as

$$\frac{dPV}{dt} \approx -g\eta \frac{\partial Q}{\partial p},$$  \hspace{1cm} (7)

where $Q$ is the diabatic heating rate, $\eta$ the absolute vorticity, and $g$ the gravitational acceleration rate. In the W-CNTL, low-level PV is produced near the W-BFD center, where a 850-hPa high-PV region is located at the early stage of the BFD evolution (18 UTC 26 June; Fig. 5a). At the later developing stage

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Fig. 5. (a, b) 850-hPa PV production rate due to latent heating (color shading; PVU h$^{-1}$) and (c, d) 850-hPa PV for the W-CNTL at (a) 18 UTC 26 and (b) 02 UTC 27. Contour lines in (a) and (b) show SLP (hPa), and those in (c) and (d) show PT at 850 hPa. Vectors indicate wind fields at 850 hPa.
(02 UTC 27 June), the region of high PV production is found in front of the W-BFD center (around 125°E, 36°N), in which the low-level horizontal PT gradient is large (Figs. 5b, d). These features suggest that the development mechanism of the W-BFD may vary between the early and later development stages as will be discussed in section 5. A band-shaped PV and its production (Fig. 5) could be associated with linearly aligned convections in the frontal region (not shown). These features were also found in other studies of extratropical cyclones (e.g., Hirata et al. 2015). Moreover, a region of negative PV production also exists around the cyclone center in the later stage (Fig. 5b) because the vertical gradient of latent heating is negative ($-\partial Q/\partial P < 0$) but absolute vorticity is positive ($\eta > 0$). In this region, the depth of convection is shallow and the maximum of latent heating is located below 850 hPa, resulting in a negative vertical gradient of latent heating at 850 hPa.

c. Simulation without latent heating

The depression structure cannot be maintained in the NOLH for the W-BFD (hereafter, W-NOLH). The SLP and 850-hPa PV fields simulated in the W-NOLH are shown in Figs. 6a, b. At 02 UTC 27 June 2003, a central SLP weakens from the initial time in the W-NOLH (Fig. 6a). Subsequently, no closed isobar associated with the W-BFD is found at 08 UTC 27 June (Fig. 6b).

Unlike in the W-CNTL (Figs. 3a, b), no high-PV region associated with the depression is predicted at 850 hPa in the W-NOLH (Figs. 6a, b), which indicates that the weakening of the disturbance in the W-NOLH is due to a lack of PV production by diabatic heating associated with cloud systems. Thus, diabatic heating is needed for the development of the W-BFD.

In contrast, the upper-level high-PV region exceeding 3.0 PVU is well reproduced (Figs. 6c, d). Thus, it is suggested that upper-level forcing without moist

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**Fig. 6.** Same as Fig. 3 except for the presence of W-NOLH instead of W-CNTL.
processes has little impact on the W-BFD development.

d. Simulation without upper-level disturbances

We investigated the impacts of upper-level disturbances on the W-BFD development by comparing the CNTL and NOUL simulations. First, the initial vorticity fields at 300 hPa for the W-BFD in CNTL and NOUL are compared. In the W-CNTL (Fig. 7a), a strong vorticity (up to $1.0 \times 10^{-4}$ s$^{-1}$) region associated with an upper-level disturbance is located around 100–120°E and 40–45°N. In contrast, as shown in Fig. 7b, the strong vorticity is significantly reduced in the NOUL for the W-BFD (hereafter, W-NOUL).

Figure 7c shows the SLP and 850-hPa PV in the W-NOUL at 08 UTC 27 June 2003. Although the central SLP in the W-NOUL (992 hPa) is weaker than that in the W-CNTL (approximately 990 hPa; Fig. 3b), it reaches considerable strength. The evolution of the 850-hPa vorticity averaged over a 600 km × 600 km square around the W-BFD center is shown in Fig. 7d. Note that the vorticity is suitable to compare the strength of depressions between CNTL and NOUL since PV depends on not only the relative vorticity.

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Fig. 7. (a, b) Vorticity (shading; s$^{-1}$) and wind fields (vectors; m s$^{-1}$) at 300 hPa in the (a) W-CNTL and (b) W-NOUL at 12 UTC 26 June 2003. (c) SLP (contour lines; hPa) and PV (shading; PVU) for the W-NOUL at 08 UTC 27 June 2003. (d) Time series of 850-hPa vorticity (s$^{-1}$) averaged over an area of 600 km × 600 km around the W-BFD center. Black and gray lines show the evolution of vorticity for the W-CNTL and W-NOUL, respectively.
but also the latitude and static stability. At the early
developing stage, the low-level vorticity evolution in
the W-NOUL is quite similar to that in the W-CNTL.
A difference arises at the later stage, when the upper-
level trough approaches from the northwest. The
maximum of the averaged vorticity in the W-NOUL
develops to 75% of that in the W-CNTL. These re-
results indicate that the W-BFD can reach considerable
intensity even without upper-level forcing.

We now focus on the influence of the upper-level
disturbance on low-level PT advection. Figure 8 shows
the 900-hPa PT advection fields in the W-CNTL and
W-NOUL. In the W-CNTL, a positive PT advection,
exceeding 3 K h\(^{-1}\), extends from 120–130°E and from
35–36°N. In contrast, PT advection notably weakens
in the W-NOUL, which results in the inhibition of the
W-BFD development. This enhancement of low-level
PT advection induced by upper-level disturbances is
consistent with the result from the data analysis men-
tioned in TK12.

3.2 The E-BFD case

a. Case overview

In the E-BFD case, an upper-level trough somewhat
intensified the BFD. At 12 UTC 1 July 2003, an
upper-level trough and its associated high-PV area
were found to the west of the low-level low-pressure
area near the southeast coast of Japan (Figs. 9a, e).
The low-level relatively high-PV band zonally elong-
gated near the Japanese islands and was produced
by convection along the Baiu front. Then, the trough
propagated eastward as it developed, and the SLP
deepened. The E-BFD is detected at 18 UTC 1 July
in the JMA surface weather map (35°N, 145°E; not
shown). At 00 UTC 2 July, the E-BFD had a distinct
structure around 140–155°E and 30–40°N (Fig. 9b).
The distance between the upper-level and low-level
disturbances shrank with time. By 12 UTC 02 July,
the upper-level trough approached near the minimum
SLP (approximately 998 hPa) center (Figs. 9c, g). At
00 UTC 3 July, the central pressure fell to approxi-
mately 995 hPa (Fig. 9d). The vertical cross-section of
PV along B–B’ in Fig. 9c shows the strong coupling
between the upper- and low-level high PVs, exhibiting
a structure that is tilted westward with height (Fig. 9i).
The distance between the upper-level and low-level
disturbances is much smaller than in the W-BFD
throughout the entire period (Fig. 2).

b. Control simulation

The CNTL for the E-BFD (hereafter, E-CNTL)
reasonably reproduces the depression structure and
its evolution detected in the JRA-25, except that the
simulated E-BFD track slightly shifts to the north. The
Fig. 9. Same as Fig. 2 except that the E-BFD is at (a, e) 12 UTC 1, (b, f) 00 UTC 2, (c, g) 12 UTC 2, and (d, h) 00 UTC 3 July 2003.
simulated SLP fields agree with the JRA-25 data (Figs. 10a, b).

The evolution of the simulated lower- and upper-level PV in the E-CNTL is consistent with that of the PV detected in JRA-25. At 12 UTC 2 July, a low-level high PV elongated zonally is located in the region of 145–155°E and 37–38°N (Fig. 10a). The high-PV region is cyclonically wrapped and broadens as it develops (Fig. 10b). A 300-hPa high-PV region associated with an upper-level trough is also cyclonically wrapped as it develops (Figs. 10c, d). At 00 UTC 3 July, the PV region exceeding 3 PVU is located just above the low-level high-PV area (Fig. 10d).

The result of the APE diagnosis shows that the baroclinic term is comparable to the diabatic term in the developing stage (Fig. 11). This indicates that both baroclinic and diabatic processes are important for the E-BFD development and are consistent with the results of TK12, which showed that baroclinicity is
more important for the development of E-BFDs than for that of W-BFDs. The negative values of the CE term are reflected by the conversion of the eddy APE to the eddy kinetic energy.

In the E-CNTL, the evolution of low-level PV production differs somewhat from that of the W-CNTL. A region of PV production for the E-CNTL extends from the northwest to the east of the depression center, in which the low-level horizontal PT gradient is large (Fig. 12), while the region of low-level PV production is found only east of the cyclone center for the W-CNTL in the later developing stage (Fig. 5b). This feature for E-CNTL is reflected by PV production in a bent-back-like warm front and is maintained during the entire period (Fig. 12). The PV production could be associated with convective precipitation rather than stratiform precipitation for both the W-CTNL and E-CNTL because the precipitation is produced by narrow and strong updrafts (not shown). The convection for the E-CNTL is weaker than that for the
c. Simulation without latent heating

The NOLH for the E-BFD (hereafter, E-NOLH) indicates that the impact of latent heating on the E-BFD development differs from that on the W-BFD development. Although the BFD in the E-NOLH does not develop, the structure of the BFD is maintained (Fig. 13). In addition, northward propagation is weakened in the E-NOLH. In the E-NOLH, simulated low-level PV is also significantly weaker than in the CNTL because of a lack of production of PV due to latent heating (Figs. 13a, b). These results indicate that latent heating is important for the development of the E-BFD.

A difference in features of upper-level PV between the E-CNTL (Figs. 10c, d) and E-NOLH (Figs. 13c, d) suggests that latent heating affects the development of upper-level disturbances. At 00 UTC 03 July, the 300-hPa PV exceeding 3 PVU in the E-NOLH was restricted within a narrower region (around 152°E, 37°N, and 157°E, 39°N).

d. Simulation without upper-level disturbances

Upper-level disturbances in the NOUL for the E-BFD (hereafter, E-NOUL) are excluded from the initial field in the E-CNTL (Figs. 14a, b). A region of strong vorticity (exceeding $1.0 \times 10^{-4}$ s$^{-1}$) associated with an upper-level trough, which is located around 138–148°E and 33–39°N in the E-CNTL, is not found in the E-NOUL.

It is clear that upper-level disturbances are important for the E-BFD development. The central SLP in the E-NOUL is significantly weakened by excluding
upper-level disturbances (Figs. 10b, 14c): the minima of the central SLP in the E-NOUL and E-CNTL are approximately 999 hPa and 995 hPa, respectively. The time series of the 850-hPa vorticity averaged over an area of 600 km × 600 km around the center of the E-BFD also shows the reduced vorticity development in the E-NOUL throughout the simulation period (Fig. 14d). The vorticity is $0.6 - 0.7 \times 10^{-4}$ s$^{-1}$ throughout the developing period in the E-NOUL; however, it increases from $0.6 \times 10^{-4}$ s$^{-1}$ to approximately $1.0 \times 10^{-4}$ s$^{-1}$ in the E-CNTL. Thus, upper-level disturbances are needed for the E-BFD development.

There is a prominent difference in low-level PT advection between the E-CNTL and E-NOUL (Fig. 15): a zonally elongated region of positive PT advection exceeding 1.5 K h$^{-1}$, which is widely found around 155–165°E in the E-CNTL, is limited to a narrow region between 161°E and 163°E in the E-NOUL. This is consistent with the result in TK12, which showed that PT advection is enhanced by southerlies induced by upper-level disturbances.

4. Discussion

As mentioned in Section 3, it is suggested that the W-BFD is characterized by a development process that is mainly driven by latent heating. During the early stage of development, a low-level PV is produced near the W-BFD center. Because the PV production rate is proportional to vorticity itself (see Eq. 7), the low-level PV is rapidly enhanced in the
region of large vorticity. This process is similar to the nonlinear conditional instability of the second kind mechanism mentioned by Cho and Chen (1995).

During the later development stage, high PV production by latent heating shifts in front of the W-BFD center. The enhanced low-level vortex that had formed during the early development stage advects low-level warm and moist air into the front of the center from the south. In addition, the low-level meridional temperature gradient is intensified there. Figure 16 shows the 900-hPa equivalent potential temperature (EPT) and water vapor flux convergence in the later developing stage. In front of the W-BFD center (around 123–130°E, 36°N), a region with a large EPT, exceeding 340 K, extends from the south and water vapor flux converges there. Consequently, active convection is initiated and maintained in front of the W-BFD. This process is consistent with the diabatic Rossby
However, the structure of the E-BFD is maintained integral to the development of both types of BFDs.

In contrast, baroclinicity as well as latent heating is essential for the development of the W-BFD and E-BFD and the temporal evolutions of latent heating and baroclinicity to the development of BFDs and for revealing the evolution of those contributions. BFDs that develop in the west and east of 140°E were categorized as W-BFDs and E-BFDs, respectively, and a typical case was investigated for each of these types. The typical cases are the same as those analyzed in TK12. Moreover, the W-BFD that formed at 06 UTC 26 June 2003 propagated from mainland China to the Sea of Japan and peaked at 06 UTC 27 June 2003, while the E-BFD occurred near the southeast coast of Japan at 18 UTC 01 July 2003 and reached its maximum intensity in the northwestern Pacific at 00 UTC 03 July 2003. Because the full-physics simulations (CNTLs) with WRF well reproduced both the W-BFD and E-BFD in JRA-25, the development processes of the simulated BFDs were analyzed.

An APE diagnosis revealed quantitative contributions of latent heating and baroclinicity to the development of the W-BFD and E-BFD and the temporal evolution of those contributions. Latent heating is the primary contributor to the development of the W-BFD, while the effect of baroclinicity is small throughout the developing period. In contrast, baroclinicity as well as latent heating is essential for the development of the E-BFD. In addition, simulations without latent heating (NOLHs) illustrate that latent heating is integral to the development of both types of BFDs. However, the structure of the E-BFD is maintained even without latent heating.

Comparisons between CNTLs and simulations without upper-level disturbances (NOULs) reveal that the contributions of upper-level disturbances are different between the W-BFD and E-BFD, although they are needed for the development of both BFDs. Upper-level disturbances are not major contributors to the W-BFD development; however, they are essential for the E-BFD development.

The evolution and distribution of low-level PV and its production suggest that the W-BFD has a development mechanism driven by latent heating: in the early developing stage, a low-level disturbance is enhanced by PV production near the cyclone center. The enhanced low-level disturbance advects warm and moist air to the front of the cyclone center, resulting in the generation of moist convection there. Thus, a low-level disturbance develops through latent heating to the east of the cyclone center during the later development stage, which is similar to the DRV process. In contrast, the development of the E-BFD is explained by baroclinic instability in the moist atmosphere.

The Baiu frontal zone in 125–140°E is characterized by a transitional zone, in which low-level baroclinicity gradually increases from the west to east. Thus, the structures and development processes of BFDs may change with eastward propagation in the transitional zone. However, the present study does not consider this effect.

The horizontal scales of the W-BFD and E-BFD in this study are approximately 1000 and 2000 km, respectively. In the Baiu season, BFDs with smaller horizontal scales from approximately 100–500 km have also been observed (e.g., Yoshizumi 1977; Tagami et al. 2007). Note that the development processes described in this study may not be consistent with those of smaller BFDs. A comparison of development processes between BFDs studied here and smaller-scale disturbances may provide additional insight into the dynamics of BFDs.

Other numerical case studies (two W-BFDs and two E-BFDs) were also performed but are not shown here. The simulated features of these case studies are consistent with those presented in this paper. Although our study has revealed key factors and their relative contributions to the development of each category of BFDs, our findings are confined to case studies. In order to generalize the effect of latent heating and baroclinicity on the BFD development, we conducted idealized numerical simulations in composite environmental fields obtained from TK12. The results of these simulations will be shown in Part II.
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