Convective Bursts With Gravity Waves in Tropical Cyclones: Case Study With the Himawari-8 Satellite and Idealized Numerical Study

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Abstract Convective bursts occur frequently in tropical cyclones and help their intensification by diabatic heating, but their quantitative importance has not been established. By using the high-frequency observation of infrared brightness temperature with Himawari-8, a latest-generation geostationary meteorological satellite, convective bursts in Typhoon Lan (2017) were studied. Aided with a series of numerical simulations, it was revealed that the anvil edges of many bursts are associated with finite-amplitude gravity waves consistent with internal bores, creating warm anomalies by subsidence ahead of the edges. As the edges spread, they are thinned, and their propagation speeds are often decreased. In many such instances, gravity waves, now linear, are separated from the edges to propagate away, spreading convective heating. It is proposed that by quantifying these processes with geostationary satellites, diabatic heating by convective bursts can be estimated to diagnose their impacts on tropical-cyclone intensification.

Plain Language Summary Convective bursts (CBs) are intense long-lasting cumulonimbus that occur frequently in tropical cyclones (TCs). Many studies suggested that condensation heating associated with CBs is an important factor in TC intensification but to what extent they are important has not been established. The latest-generation (also known as the third-generation) geostationary meteorological satellites such as Himawari-8 provided opportunities to observe TCs at frequencies much higher than before. We studied the anvil clouds (outflow clouds near the tropopause) of CBs in Typhoon Lan (2017) by using infrared images from Himawari-8. We also conducted numerical simulations to help interpretation. It was found that the anvil of a CB frequently spreads as an internal gravity wave in such a way that the anvil edge is preceded by the subsidence and temperature increase due to an internal bore (finite-amplitude gravity wave similar to tidal bore). Since the anvil spreads circularly, its edge is thinned gradually. It was found that its expansion speed is often slowed down, and the gravity wave is separated to propagate further ahead, disseminating convective heating. It is proposed that geostationary-satellite observations can be used to estimate convective heating associated with each CB. It will help establish the impacts of CBs in TC intensification.

1. Introduction

Spacecraft and satellite observations revealed that outbreak of intense deep convection occurs frequently in intensifying tropical cyclones (TCs; e.g., Gentry et al., 1970; Steranka et al., 1986; Zehr, 1992). Such intense convection is called with a variety of terms such as a “circular exhaust cloud” (Gentry et al., 1970), “hot tower” (Malkus & Riehl, 1960), and “convective burst” (Steranka et al., 1986). Here we use the term convective burst (CB). A number of studies have suggested that diabatic heating associated with CBs is important in the intensification of TCs (e.g., Chen & Zhang, 2013; Hazelton et al., 2017; Heymsfield et al., 2001; Kelley & Halverson, 2011; Montgomery et al., 2006; Rodgers et al., 1998; Rogers et al., 2015; Shimada & Horinouchi, 2018; Steranka et al., 1986; Zehr, 1992), but some observational studies suggest that this effect is limited (e.g., Zagrodnik & Jiang, 2014; Tao & Jiang, 2015), so further studies are needed. Penetrative cumulus convection occurs in the environment stable to dry convection, so the convection excites gravity waves. Convectively generated gravity waves not only propagate into and influence the middle atmosphere (e.g., Alexander et al., 1995; Fovell et al., 1992; Horinouchi et al., 2002; Lane et al., 2001), but also propagate horizontally in the troposphere to transfer condensation heating (Bretherton &
Smolarkiewicz, 1989; hereinafter BS) and interact with cumulus convection (Liu & Moncrieff, 2004; Mapes et al., 2003). Even though some studies investigated gravity waves associated with TCs (e.g., Kim et al., 2005; Nolan & Zhang, 2017), to the authors’ knowledge, gravity waves associated with CBs have not been studied, except by Chen and Zhang (2013) who argued that gravity-wave radiation can limit in situ heating.

More specifically, BS studied the linear response of a hydrostatic atmosphere at rest with a rigid lid at the altitude $D$ to a horizontally pointwise heating with a vertical ($z$) profile of $\cos(\frac{\pi z}{D})$. In the two-dimensional case (with $x$ representing the horizontal coordinate), if the heating is turned on at $t = 0$, the solution for buoyancy and horizontal wind are proportional to $\cos(\frac{\pi z}{D})H(ct-|x|)$ and $-\text{sgn}(x)\sin(\frac{\pi z}{D})H(ct-|x|)$, respectively, where $H()$ is the Heaviside step function, $\text{sgn}(x)$ is the sign of $x$, $N$ is buoyancy frequency, and $c \equiv \frac{H}{D}$ is the horizontal phase speed of hydrostatic gravity waves; $m$ is the vertical wavenumber ($m = \frac{\pi}{D}$). This solution, which we shall call the BS solution, can be described as a square wave consisting of continuous Fourier components. The abrupt buoyancy change at $|x| = ct$ is accompanied by a delta-functional subsidence. The three-dimensional solution is similar but is proportional to $\frac{H(ct-d)}{r^2 \sqrt{1-(d/c)^2}}$ for the horizontal distance $d$ from the heat source, so the buoyancy anomaly is peaked at $d = ct$. These solutions demonstrate that the warming by compensating subsidence to deep convective heating spreads as gravity waves. Note that the horizontal wind response is inflow and outflow at the lower and the upper, respectively, part of the atmosphere. In other words, if the heating starts abruptly, the associated inflow and outflow behave as gravity wave.

In this study, we investigate gravity waves associated with CBs by using a latest-generation geostationary meteorological satellite, Himawari-8, which is operational since 2015 (Bessho et al., 2016). With the aid of numerical simulations, we show that CBs are frequently accompanied by gravity waves. We also propose its possible application to diagnose the effect of CBs on TC intensification.

2. Data and Methods

We used infrared (IR) brightness temperature at 10.4 μm (Band 13) from the target observation of Typhoon Lan (2017) with Himawari-8. The target observation captures a TC over a ~1000 km × 1000-km region every 2.5 min. The resolution of IR data is 2 km at the subsatellite point. Visible-light (0.64 μm) images were also used in supplemental Movie S1.

The satellite data were mapped onto equally spaced grid points on the azimuthal equidistant projection with respect to the TC center obtained by interpolating the best track compiled by the Regional Specialized Meteorological Center Tokyo by using the cubic spline interpolation with time. Figures 1a and 1b show the track and the estimated intensity. On this projection, $x$ (zonal) and $y$ (meridional) coordinates are defined relative to the TC center. Figure 1c shows the environmental stability ($N$). The environmental shear obtained by the same averaging in Figure 1c is weak; the absolute values of the zonal and meridional winds were smaller than 4 ms$^{-1}$ between 1000 and 125 hPa, and the zonal wind at 100 hPa was approximately $-7$ ms$^{-1}$.

A simple two-dimensional model was developed using the anelastic and Boussinesq approximations, as detailed in Appendix A. The anelastic version of the model is based on the following equations:

$$\frac{Du}{Dt} = -\frac{\partial P'}{\partial x} + X_u, \quad (1)$$

$$\frac{Dw}{Dt} = -\frac{\partial P'}{\partial z} + b + X_w, \quad (2)$$

$$\frac{Db}{Dt} + N^2 w = Q + X_b, \quad (3)$$

$$\frac{\partial u}{\partial x} + c^2/H \frac{\partial}{\partial z} \left( e^{-z/H} w \right) = 0, \quad (4)$$

where $u$ and $w$ are horizontal and vertical velocities, respectively, $\frac{\partial P'}{\partial x}$ and $\frac{\partial P'}{\partial z}$ are pressure-gradient terms to be eliminated (as in Equation (A1)), $H$ is a constant scale height, $b$ is buoyancy, $Q$ is diabatic heating, and $X_u$, $X_w$, and $X_b$ are the numerical dissipation as hyperdiffusion plus (when the model has the stratosphere) a
sponge near the model top. The equations are nondimensionalized and discretized by the Fourier transforms with \(x\) (horizontal; cyclic) and \(z\) (vertical; bounded); \(t\) is time.

Diabatic heating \(Q\) is either prescribed or parameterized. The parameterization crudely represents condensation heating in conditionally unstable atmosphere as

\[
Q = \gamma N^2 w
\]  

(5)

only where \(w > 0\) in a limited designated region; \(Q = 0\) elsewhere. The constant \(\gamma\) is greater or equal to 1; \(\gamma = 1\) corresponds to the conditionally neutral stratification.

We used two environmental and domain settings. One, called setting B, is Boussinesq with a uniform \(N\) of 0.01 s\(^{-1}\), topped with a rigid lid at 15 km, having the horizontal domain size of 600 km. The vertical and horizontal resolutions are 0.5 and 0.781 km, respectively. The other, setting A, is anelastic with \(N\) mimicking the actual one (Figure 1c) by using an analytic function (Appendix A; Figure 1d). The domain sizes and the resolutions are vertically 32 km and 0.5 km, respectively, and horizontally 1000 km and 0.651 km.

With the setting B, we conducted experiments with prescribed heating: B1 with \(Q = q_1 \cos\left(\frac{\pi z}{D}\right) \cos\left(\frac{\pi x}{W}\right)\) for \(|x| \leq W\), where \(D\) is the domain height, \(W\) is the half width of the heating and set to 7.81 km, \(q_1 = 8\) (non-dimensional amplitude in Appendix A), B1-Linear: as B1 but is linearized (Appendix A), and B1-LinearHydro: as B1 but is linear and hydrostatic; B2, B2-Linear, and B2-LinearHydro: as the B1 series but with a top-heavy heating \(Q = \left[q_1 \cos\left(\frac{\pi z}{D}\right) - q_2 \cos\left(\frac{2\pi z}{D}\right)\right] \cos\left(\frac{\pi x}{W}\right)\), where \(q_1 = 6\) and \(q_2 = 2\).

With setting A, we conducted experiments with parameterized heating: A1 with \(\gamma = 1.01\) and nonzero \(Q\) is limited to \(|x| \leq 9.77\) km and up to where \(N\) is minimized \((z < 12.5\) km\), and A2 as A1 but for \(\gamma = 1.1\). Convection was initiated by prescribed heating over a short time.

Figure 1. (a) Maximum 10-min surface wind (red circles) and central pressure (black crosses) based on the best track data; time is in UTC. (b) TC center track. (c) Buoyancy frequency profile derived from the Japanese 55-Year Reanalysis (Kobayashi et al., 2015), averaged over 130–135°E, 7.5–12.5°N, and 12 UTC, 16 October, to 12 UTC, 17 October. (d) Background buoyancy frequency used in the simulations with stratosphere, specified by Equation (A4).
3. Case Study of Convective Bursts in Typhoon Lan (2017)

The target observation of Lan started at around 7 UTC, 16 October. We studied CBs from 8 UTC, 16 October, to 12 UTC, 18 October. From subjective visual inspection using all of the Band-13 images over this period, we identified 20 CBs whose anvils spread more-or-less circularly with radii reaching 50 km or greater, as summarized in Table S1 (in the online supporting information file). The initial positions of the CBs, \( (x_0, y_0) \), are frequently situated at distances further than 100 km from the nominal TC center where \( (x, y) = (0, 0) \). However, the interpolated best track TC center can be away from the actual circulation center by more than a few tens of kilometers. From visual inspection, a majority of the CB centers appeared to be situated within 100 km from actual centers.

Figure 2 shows examples of circular anvil clouds of the CBs. Initially, the anvil of CB1 had a sharp edge fringed by a relatively dark belt over a width of 10 to 20 km, as pointed by the pink outlined arrow in Figure 2a. From the time sequence of the IR images, one can confirm that the cloud-top temperature of pre-existing upper clouds was increased (darkened in the grayscale images) as the CB edge approached (see supplementary Movie S1). Thus, the anvil edge was preceded with downward motion. Later, the anvil edge became obscure (white outlined arrow in Figure 2b), and the front of the “darkening” (brightness temperature increase of preexisting upper clouds) was separated to move at a faster speed than the anvil edge (black arrows in Figure 2b). At this stage, it is obvious that the darkening is associated with internal gravity wave, since the darkening passed through upper clouds without affecting their morphology (see the supplemental Movie S1), indicating propagation at \( O(10) \text{ ms}^{-1} \). The propagating darkening is qualitatively consistent with the buoyancy change in the BS solution (section 1).

Figures 2c–2f visualize several CBs, and here we focus on CB7. Initially, its anvil had a sharp edge with conspicuous darkening (Figure 2c). Later, the optical thickness of the edge became thicker (Figure 2d; pink outlines arrows), and the darkening front was separated to travel as gravity wave (Figures 2e and 2f) as in CB1. Nearly a half of the CBs exhibited similar time evolutions (column “GE” in Table S1). The initial sharp edge fringed with darkening is also interpreted in terms of gravity wave, as explored in the next section.

Figure 3 shows the time evolutions of cross sections of CB1 and CB7; the same plots of the other CBs are provided as supplementary figures (Figures S1–S18). The expansion speed is typically \( 20 \text{ ms}^{-1} \), but it varies. In some cases, it was initially \( \sim 30 \text{ ms}^{-1} \) (the arrow marked with “x” in Figure 3c) and decelerated later. The initial fast expansion tended to occur in the CBs having overshooting convection, as visualized in Figure 3 as white (cold) strips. In some CBs, the propagation speeds are much lower than \( 20 \text{ ms}^{-1} \) (supplementary figures S1–S18).

4. Numerical Results and Their Implication

We first examine the Boussinesq simulations. Figure 4a shows buoyancy \( b \), stream function \( \psi \) (where \( w = -\frac{\partial \psi}{\partial x} \)), and an outline of the nondimensional heat-induced passive scalar \( r \) [Equation (A3)] at \( t = 3000 \text{ s} \) in experiment B1. Since the scalar is produced by diabatic heating, it is like a density-free cloud that never precipitates. The \( b \) and \( \psi \) fields are similar to the linear case (Figure 4b), but at close look, they are more like the B2-Linear (top-heavy) case (Figure 4d) over \( |x| < 80 \text{ km} \) with regard to the concentration to the upper troposphere. This is because the positive buoyancy induced by heating is advected upward, as is evident in the top-heavy buoyancy around \( x = 0 \) in Figure 4a. Some local maxima exist in \( b \) and \( \psi \) except in the hydrostatic cases. This wobbling is thus due to the nonhydrostatic dispersion; hydrostatic gravity waves sharing a fixed vertical wavenumber \( (m) \) do not disperse horizontally, since \( \omega = \frac{c}{m} \). Note that \( c = 48 \text{ ms}^{-1} \) for the half-cosine wave \( (\frac{\omega}{m} = 15 \text{ km}) \); called the first mode hereinafter) and \( c = 24 \text{ ms}^{-1} \) for its second harmonics (second mode), which is consistent with Figures 4c and 4e; Figure 4c visualizes the BS solution for a case in which the heating has a finite width. Note also that the buoyancy changes associated with the nonhydrostatic first mode are not as sharp as in the hydrostatic cases.

If the background absolute vorticity \( f \) were nonzero, some portion of heating would remain as in the geostrophic adjustment (Liu & Moncrieff, 2004). However, the gravity wave response is similar while the horizontal extent of the warmed region is limited (more specifically, since the anelastic dispersion relation is
Figure 2. Snapshots of infrared brightness temperature. Pink outlined arrows indicate relatively sharp anvil edges following the “darkening.” White outlined arrows indicate relatively obscure anvil edges from which gravity waves have radiated away; black straight arrows suggest the warming front of the radiated gravity wave. Black curly arrows point overshooting cumulus tops. CB = convective burst.
\( \omega^2 = \frac{N^2 k^2 f^2 m^2}{k^2 + m^2 + |2H|}, \) where \( \omega \) is angular frequency and \( k \) is horizontal wavenumber, the contribution of the Fourier components with \( k \) being smaller than or comparable to \( N^{-1} f m \) is minor as long as the extent is smaller than \( ND/f \).

The difference between the linear and nonlinear cases are conspicuous in the region where “clouds” exist in the nonlinear case (Figure 4a). This is taken for granted since this fact indicates that gravity waves there are at finite amplitude [e.g., by using the BS solution, one can easily show that the advection term in the thermodynamic Equation (3) is comparable to the \( N^2 \omega \) term, when the magnitude of \( u \) is comparable to \( c \)].

We now turn to the setting A, which are more realistic anelastic simulations with the stratosphere and parameterized heating. Figures 4f–4i shows the time evolution of \( b \) and \( r \) in the experiment A1 in which conditional instability is weak \( (\gamma = 1.01) \). Figure 5a shows the \( x-t \) cross section at \( z = 13 \) km. Despite the existence of the stratosphere and the nonuniform \( N \) in the troposphere, the first and second modes travel similarly to the Boussinesq cases at \( \sim 50 \) and \( \sim 25 \) ms\(^{-1} \), respectively (as in the Boussinesq case, the second mode is excited by advection in nonlinear simulations). However, these waves are weak and decoupled from the “cloud” that spreads at a speed around \( 13 \) ms\(^{-1} \) together with shallower \( b \) anomalies near the tropopause, consistent with higher-mode gravity waves if linear. Figures 4j–4m and 5b show the results of A2, the more unstable case \( (\gamma = 1.1) \). The cloud edge spreads at \( \sim 25 \) ms\(^{-1} \), which is preceded by an increase of \( b \) over 10–20 km, as in the observed anvil tip of CBs.

Figure 3. \( x'-t \) (left) and \( y'-t \) (right) cross sections of the anvils of CB1 (upper) and CB7 (lower). Here, \( x' = x - x_c(t) \) and \( y' = y - y_c(t) \), where \([x_c(t), y_c(t)]\) is the linearly interpolated approximate CB center at the beginning and the end of the time covered as shown on the bottom of each panel. The ordinate is time in UTC. Lines indicate movement at \( \pm 20 \) ms\(^{-1} \). Arrows are as in Figure 2. CB = convective burst; IR = infrared.
Figure 4. Snapshots of the simulation results. Black contours: stream function $\psi$ (m$^2$ s$^{-1}$) except at 0; color shading: buoyancy $b$ (m s$^{-2}$), grayscale shading (f–m) or gray contours (a–e): nondimensional heat-induced passive scalar $r$ [Equation (A3); contours are drawn at 0.05]. (a–e) results at $t = 3000$ s from setting B results: (a) B1, (b) B1-Linear, (c) B1-LinearHydro (d) B2-Linear, and (e) B2-LinearHydro. (f–i) Time evolution of the experiment A1 at $t = 1500, 3000, 4500, 6000$ s. (j–m) As in (e–h) but for the experiment A2.
These results suggest that the observed IR-image darkening (downward displacement of preexisting cloud-top) can be interpreted as the buoyancy increase due to finite-amplitude gravity wave. This gravity wave is essentially an internal bore, which is buoyancy-driven flow penetrating into quiescent flow (Klemp et al., 1997). Normally, bore is dense flow on bottom, but in the present case, it is buoyant and topped by the tropopause. In case of two-layer stratified fluid, an internal bore is a linear gravity wave when the depths ahead and behind are close, and it is a gravity current when the depth ahead is infinitely thin (Klemp et al., 1997).

The CB anvil edges are circular, so as they spread, the mass flux per unit edge length decreases. The slow-down of the edge and the gravity-wave separation described in section 3 is explained as its consequence; it is like A2 initially and is more like A1 later.

5. Discussion: Possible Application

Our results open a new way to estimate diabatic heating associated with actual CBs. That can be done by diagnosing CB properties from satellite images and comparing them with a database of CBs in realistic three-dimensional cloud-resolving simulations. The required observational properties will be like the ones in Table 1 and the amount of temperature increase associated with the preceding darkening as well as the altitude of the cloud-top at which the darkening occurred. Once the heating is estimated, its effect on the TC-intensity change can be estimated following Hack and Schubert (1986).

6. Conclusions

We have studied CBs in Typhoon Lan (2017). It was revealed that the anvils of CBs frequently follow the downward displacement of preexisting upper clouds. This phenomenon is explained by the propagation of finite-amplitude gravity wave in the form of an internal bore. As the edge spreads, it is thinned, and the buoyant region associated with gravity wave is separated to propagate at a faster speed. It was proposed that the satellite IR observations of CBs can be applied to diagnose the intensity change of TCs. If this approach is established, one can apply it to all TCs seamlessly.

Appendix A: Model

We used a two-dimensional model nondimensionalized by the time scale $T = N_0^{-1}$, the vertical scale $Z$, and the horizontal scale $\alpha^{-1}Z$, where $N_0$ is a constant reference buoyancy frequency, $Z$ is the model’s vertical extent divided by $\pi$, and $\alpha$ is a scaling constant to make the nondimensional horizontal domain width $2\pi$. In this section, we express dimensional variables and coordinates with asterisks and their nondimensional forms without it, so $t = Tt$, $z = Zz$ ($0 \leq z \leq \pi$), $x = \alpha^{-1}Zx$ ($0 \leq x \leq 2\pi$).

The anelastic model solves the following nondimensional equations:

$$\alpha^{-1} \frac{\partial \zeta}{\partial t} = -e^{C\zeta} \left[ \frac{\partial \zeta}{\partial x} + w \left( \frac{\partial \zeta}{\partial z} + 2C \zeta \right) \right] - \frac{\partial b}{\partial x} + X_b,$$

$$\alpha^{-1} \frac{\partial b}{\partial t} = -e^{C\zeta} \left( u \frac{\partial b}{\partial x} + w \frac{\partial b}{\partial z} \right) - N^2w + Q + X_b,$$

where $C \equiv Z/(2H)$, $u^* = ZT^{-1}C^2u$, $w^* = aZT^{-1}C^2w$, $\zeta^* = \frac{\partial \zeta}{\partial z}$ (horizontal vorticity), $b^* = ZT^{-2}C^2b$, $Q^* = aZT^{-3}C^2Q$, $N^* = N_0N$. A stream function $\psi$ is introduced so that $u = \frac{\partial \psi}{\partial z} - C\psi$, $w = -\frac{\partial \psi}{\partial x}$, and $\zeta^*$. 

Figure 5. $x$-$t$ cross sections at $z = 13$ km of the experiments A1 (a) and A2 (b). Color shading shows $b$ (m s$^{-1}$) and dots show where $r > 0.03$ (a) or $r > 0.09$ (b). Lines indicate movement at 25 m s$^{-1}$. 

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The Boussinesq formulation is obtained by setting $C = 0$. A heat-induced passive scalar $r$ is introduced as

$$\alpha^{-1} \frac{\partial r}{\partial t} = -e^C \left( \frac{w}{\partial x} + \frac{\partial r}{\partial z} \right) + Q + X_r.$$

Equations (A1) and (A2) are discretized by the spectral transform method by expressing $\psi$ and $b$ with the cyclic Fourier transform with $x$ and the sine transform with $z$. The maximum wavenumbers are set to the halves of the grid-point numbers. The hyper diffusion is $X_f = -v\left(\frac{\alpha^2}{\partial x^2} + \frac{\alpha^2}{\partial z^2}\right)^2 f (f = \zeta, \phi, r)$; $v$ was set to make the greatest of the wavenumber-dependent e-folding times equal to 0.1. A sponge was introduced in the simulations with the stratosphere, adding $-sf r$ to $X_f (f = \zeta$ or $b)$, where the constant $s$ was set to nonzero over the topmost six layers, increased linearly with height to 5 at the top.

The linear experiments were made by dropping the advection terms in Equations (A1) and (A2) but not in (A3). In the Boussinesq hydrostatic cases, $\zeta$ was expressed as $\alpha^2 \frac{\partial^2 \psi}{\partial r^2}$.

In the setting $A$, $N_b$ was set to 0.01 s$^{-1}$, and the nondimensional stability was set to

$$N = (N_a - N_b) \left( \left\{ \frac{N_a - N_b}{N_a - N_b} + 1 \right\} x^4 - 1 \right)^2 + N_b,$$

where $N_a = 1.2$, $N_b = 0.5$, $N_c = 2.5$, $x \equiv \left(\frac{z}{\tau}\right)^2$ for $0 \leq z \leq \frac{\tau}{2}$, and $N = N_c$ for $\frac{\tau}{2} \leq z \leq \pi$. Its dimensional profile is shown in Figure 1d.

Time integration was conducted with the fourth-order Runge-Kutta scheme. The time step used was 0.05.

References

Alexander, M. J., Holton, J. R., & Durran, D. R. (1995). The gravity wave response above deep convection in a squall line simulation. *Journal of the Atmospheric Sciences*, 52(12), 2212–2226.

Besio, K., Date, K., Hayashi, M., Ikeda, A., Imai, T., Inoue, H., et al. (2016). An introduction to Himawari-8/9—Japan’s new-generation geostationary meteorological satellites. *Journal of the Meteorological Society of Japan, 94*(2), 151–183. https://doi.org/10.2151/jmsj.2016-009

Bretherton, C. S., & Smolarkiewicz, P. K. (1989). Gravity waves, compensating subsidence, and detrainment around cumulus clouds. *Journal of the Atmospheric Sciences*, 46, 740–759.

Chen, H., & Zhang, D.-L. (2013). On the rapid intensification of Hurricane Wilma (2005). Part II: Convective bursts and the upper-level warm core. *Journal of the Atmospheric Sciences*, 70, 146–162.

Fovell, R., Durran, D., & Holton, J. R. (1992). Numerical simulations of convectively generated stratospheric gravity waves. *Journal of the Atmospheric Sciences*, 49(16), 1427–1442.

Gentry, R. C., Fujita, T. T., & Sheets, R. C. (1970). Aircraft, spacecraft, satellite, and radar observations of Hurricane Gladys, 1968. *Journal of Applied Meteorology*, 9, 837–850.

Hack, J. J., & Schubert, W. H. (1986). Nonlinear response of atmospheric vortices to heating by organized cumulus convection. *Journal of the Atmospheric Sciences*, 43(15), 1559–1573.

Hazelton, A. T., Hart, R. E., & Rogers, R. F. (2017). Analyzing simulated convective bursts in two Atlantic hurricanes. Part II: Intensity change due to bursts. *Monthly Weather Review*, 145(8), 3095–3117.

Heymsfield, G. M., Halverson, J. B., Simpson, J., Tian, L., & Bui, T. P. (2001). ER-2 Doppler radar investigations of the eyewall of Hurricane Bonnie during the Convection and Moisture Experiment-3. *Journal of Applied Meteorology*, 40, 1310–1330.

Horinouchi, T., Nakamura, T., & Kosaka, J. (2002). Convectively generated mesoscale gravity waves simulated throughout the middle atmosphere. *Geophysical Research Letters*, 29(21), 2007. https://doi.org/10.1029/2002GL104669

Kelley, O. A., & Halverson, J. B. (2011). How much tropical cyclone intensification can result from the energy released inside of a convective burst? *Journal of Geophysical Research*, 116, D20118. https://doi.org/10.1029/2011JD015954

Kim, S. Y., Chun, H. Y., & Baik, J. J. (2005). A numerical study of gravity waves induced by convection associated with Typhoon Rusu. *Geophysical Research Letters*, 32, L24816. https://doi.org/10.1029/2005GL024662

Klep, J. B., Rotunno, R., & Skamarock, W. C. (1997). On the propagation of internal bores. *Journal of Fluid Mechanics*, 331, 81–106.

Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., Onoda, H., et al. (2015). The JRA-55 reanalysis: General specifications and basic characteristics. *Journal of the Meteorological Society of Japan, 93*(1), 5–48. https://doi.org/10.2151/jmsj.2015-001

Lane, T. P., Reeder, M. J., &Clark, T. L. (2001). Numerical modeling of gravity wave generation by deep tropical convection. *Journal of the Atmospheric Sciences*, 58(10), 1249–1274.

Liu, C., & Moncrieff, M. W. (2004). Effects of convectively generated gravity waves and rotation on the organization of convection. *Journal of the Atmospheric Sciences*, 61(17), 2218–2227.

Malkus, J. S., & Riehl, H. (1960). On the dynamics and energy transformations in steady-state hurricanes. *Tellus*, 12(1), 1–20. https://doi.org/10.3402/tellusa.v12i1.9351

Mapes, B. E., Warner, T. T., & Xu, M. (2003). Diurnal patterns of rainfall in northwestern South America. Part III: Diurnal gravity waves and nocturnal convection offshore. *Monthly Weather Review*, 131(5), 830–844.

Acknowledgments

The Himawari-8 data we used are downloaded from the NICT Science Cloud. The data are publicly available upon registration through the contact address shown (https://sc-web.nict.go.jp/sc_staff.html). The typhoon best track data by the Regional Specialized Meteorological Center Tokyo is available online (https://www.jma.go.jp/jp/sc_staff.html). The typhoon best track data by the Regional Specialized Meteorological Center Tokyo is available online (https://sc-web.nict.go.jp/sc_staff.html). The typhoon best track data by the Regional Specialized Meteorological Center Tokyo is available online (https://sc-web.nict.go.jp/sc_staff.html). The typhoon best track data by the Regional Specialized Meteorological Center Tokyo is available online (https://sc-web.nict.go.jp/sc_staff.html).
Montgomery, M. T., Nicholls, M. E., Cram, T. A., & Saunders, A. B. (2006). A vortical hot tower route to tropical cyclogenesis. *Journal of the Atmospheric Sciences*, 63, 355–386. https://doi.org/10.1175/JAS3604.1

Nolan, D. S., & Zhang, J. A. (2017). Spiral gravity waves radiating from tropical cyclones. *Geophysical Research Letters*, 44, 3924–3931. https://doi.org/10.1002/2017GL073572

Rodgers, E. B., Olson, W. S., Karyampudi, V. M., & Pierce, H. F. (1998). Satellite-derived latent heating distribution and environmental influences in Hurricane Opal (1995). *Monthly Weather Review*, 126, 1229–1247.

Rogers, R. F., Reasor, P. D., & Zhang, J. A. (2015). Multiscale structure and evolution of Hurricane Earl (2010) during rapid intensification. *Monthly Weather Review*, 143(2), 536–562.

Shimada, U., & Horinouchi, T. (2018). Reintensification and eyewall formation in strong shear: A case study of Typhoon Noul (2015). *Monthly Weather Review*, 146(9), 2799–2817.

Steranka, J., Rodgers, E. B., & Gentry, R. C. (1986). The relationship between satellite measured convective bursts and tropical cyclone intensification. *Monthly Weather Review*, 114(8), 1539–1546.

Tao, C., & Jiang, H. (2015). Distributions of shallow to very deep precipitation-convection in rapidly intensifying tropical cyclones. *Journal of Climate*, 28(22), 8791–8824.

Zagrebnik, J. P., & Jiang, H. (2014). Rainfall, convection, and latent heating distributions in rapidly intensifying tropical cyclones. *Journal of the Atmospheric Sciences*, 71(8), 2789–2809.

Zehr, R. (1992). Tropical cyclogenesis in the western North Pacific. NOAA Tech. Rep. NESDIS 61, 181 pp.