Characteristics of convectively forced gravity waves are investigated through ensemble numerical simulations for various ideal and real convective storms. For ideal storm cases, single-cell-, multicell-, and supercell-type storms are considered, and for real cases, convection events observed during the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) and in Indonesia are used. For each storm case, wave perturbations and the momentum flux spectrum of convective gravity waves in a control simulation with nonlinearity and cloud microphysical processes are compared with those in quasi-linear dry simulations forced by either diabatic forcing or nonlinear forcing obtained from the control simulation. In any case, gravity waves in the control simulation cannot be represented well by wave perturbations induced by a single forcing. However, when both diabatic and nonlinear forcing terms are considered, the gravity waves and their momentum flux spectrum become comparable to those in the control simulation, because of cancellation between wave perturbations by two forcing terms. These results confirm that the two forcing mechanisms of convective gravity waves proposed by previous studies based on a single convective event can be applied generally to various types of convective storms. This suggests that nonlinear forcing, as well as diabatic forcing, should be considered appropriately in parameterizations of convectively forced gravity waves.

1. Introduction

It has been recognized that vertically propagating gravity waves generated by various tropospheric sources (orography, convection, fronts, geostrophic adjustment, and shear instability) can deposit their momentum to the large-scale flow in the middle atmosphere through critical-level filtering and wave breaking (Lindzen 1981). Among those various sources, convection is believed to be a dominant source for nonstationary gravity waves (Taylor and Hapgood 1988; Dewan et al. 1998) in the middle atmosphere. Convectively forced gravity waves are known to play crucial roles in providing the momentum forcing required to drive the quasi-biennial oscillation (QBO) and the mesospheric semiannual oscillation (SAO) in the Tropics (Alexander and Holton 1997; Piani et al. 2000).

As interest increases in understanding convective gravity waves, there have been many numerical modeling studies of convective gravity waves and their generation mechanisms (e.g., Pandya and Alexander 1999; Lane et al. 2001; Song et al. 2003). Pandya and Alexander (1999) showed that spectral characteristics of stratospheric gravity waves generated by convective sources in a fully nonlinear simulation and a quasi-linear simulation forced by diabatic forcing alone are similar, although the amplitude of waves by diabatic forcing alone is much larger than that in the fully nonlinear simulation. Lane et al. (2001) demonstrated that convective gravity waves are generated by two forcings, diabatic forcing and nonlinear forcing, and the magnitude of the nonlinear forcing is 2–3 times larger than that in the diabatic forcing in the mature stage of convective storms. Song et al. (2003, hereafter SCL) extended Pandya and Alexander’s and Lane et al.’s works by separately simulating gravity waves generated by diabatic forcing and nonlinear forcing, and showed that the (i) effective forcing that satisfies the vertical propagation
condition of internal gravity waves in the spectral domain can generate gravity waves that reach to the stratosphere, and (ii) effective diabatic forcing and effective nonlinear forcing have comparable magnitude, but are largely out of phase with each other. Therefore, the magnitude of waves induced by two forcings is smaller than that induced by a single forcing.

Recently, Chun et al. (2005, hereafter CSH) calculated the momentum flux spectrum of convective gravity waves that were simulated in SCL. CSH demonstrated that the momentum flux induced by either diabatic or nonlinear forcing is significantly different from the other, as well as from the momentum flux induced by both forcings. Based on these results, CSH suggested that parameterizations of convectively forced gravity waves must consider nonlinear forcing as well as diabatic forcing to represent properly a reference-level momentum flux spectrum.

Although SCL and CSH have demonstrated clearly the importance of the two forcing mechanisms for convective gravity waves, they are based on a single convection event. Therefore, it is necessary to confirm that their conclusions can be generalized to convective storms of various types. In this study we move toward that confirmation by conducting systematic numerical simulations for various ideal and real storm cases observed in the Tropics. For each storm case, we conducted a control simulation with nonlinearity and cloud microphysics, plus quasi-linear dry simulations forced by either diabatic or nonlinear forcing obtained from the control simulation, as in SCL. To understand the characteristics of waves induced by individual forcing terms, wave perturbations and the momentum flux spectrum in control simulation are compared with those in two quasi-linear dry simulations in each storm case.

The paper is organized as follows. Experiment design is described in section 2. Results from control and quasi-linear dry simulations for various storm cases are presented in section 3. Characteristics of momentum flux spectra of stratosphere gravity waves induced by various storm are analyzed in section 4. Summary and discussion are given in the last section.

2. Experiment design

The numerical model used in this study is a two-dimensional $(x-z)$ version of the Advanced Regional Prediction System (ARPS; Xue et al. 2000, 2001), which is a nonhydrostatic and compressible model. Most of the model configurations are identical to those used in SCL. For ideal (real) storm cases, the model domain is 1200 km (600 km) wide by 51 km (50 km) deep with a horizontal and vertical grid spacing of 1 km (1 km) and 300 m (100 m), respectively. In the domain above $z = 35$ km, a sponge layer is included. At lateral boundaries, radiation and periodic conditions are used for ideal and real storm cases, respectively. For ideal storm cases, a sponge layer with a width of 100 km is included at the right boundary to prevent artificial reflection detected in long-term simulations.

In this study, we conduct numerical simulations for eight ideal and two real storm cases. For ideal cases, each simulation is performed under different vertical basic-state wind shear environments. The basic-state wind profiles are assumed to linearly increase with height from the ground to $z = 6$ km with different surface winds ($U_s = -27, -24, -21, -18, -15, -12$, and $-9$ m s$^{-1}$) and to be uniform ($2$ m s$^{-1}$) above $z = 6$ km (Fig. 1a). The $U_s = -18$ m s$^{-1}$ case is identical to the SCL case. In addition, a nonshear case with zero basic-state wind is conducted. As in SCL, the analytic sounding of Weisman and Klemp (1982) is used for the thermodynamic basic-state profile for all the ideal cases. This sounding has a convective available potential energy (CAPE) of 2436 J kg$^{-1}$, and the Brunt–Väisälä frequency is about 0.01 and 0.021 s$^{-1}$ in the troposphere and stratosphere, respectively (Fig. 1b).

Weisman and Klemp (1982) showed that storms can be classified into single-cell, multicell, or supercell storms according to bulk Richardson number:

$$R = \frac{B}{\frac{1}{2} (\Delta \bar{u})^2},$$

where $B$ is the CAPE and $\Delta \bar{u}$ is the difference between density-weighted wind speed averaged over the lowest 6 km and surface wind speed averaged over the lowest 500 m. Following the above criterion, simulated storms are classified as single-cell ($U_s = 0$ m s$^{-1}$ case), multicell ($U_s = -9$ to $-21$ m s$^{-1}$ cases), and supercell ($U_s = -24$ and $-27$ m s$^{-1}$ cases) storms.

For real storm cases, we consider two observed tropical storms. The first, called the TOGA COARE case, is a squall-line case observed during the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) on 22 February 1993 reported by Trier et al. (1996). In this case, the basic-state profile below $z = 19$ km is obtained from a blend of aircraft observations and rawinsonde soundings at 1800 and 2400 UTC 22 February, following Trier et al. (1996). The basic-state wind has a strong low-level westerly jet with a speed of 12 m s$^{-1}$ at $z = 2$ km, and the modeled storms propagate eastward at this speed. To keep simulated storms near the center of model domain, a constant propagation speed of 12 m s$^{-1}$ is
subtracted from the observed wind profile (Fig. 1a). The CAPE of the basic-state thermodynamic profile is 2210 J kg\(^{-1}\). Above \(z = 19\) km, the Brunt–Väisälä frequency is set to the constant value of 0.023 s\(^{-1}\). For the second real case, called the Indonesia case, we use an event in the Indonesian convective storm experiment in Koto Tabang (0.2°S, 100.3°E) on 11 April 2004, which is one of the two events used for the analysis of convectively forced gravity waves in Dhaka et al. (2005). In this case, the basic-state profile below \(z = 19.2\) km is obtained from radiosonde sounding at 1200 local standard time (LST), about 30 min before the strongest convection was detected at the observing site. The basic-state zonal wind is mostly easterly and has a strong positive shear over \(z = 13.5–16\) km and a strong negative shear over \(z = 16–19.2\) km (Fig. 1a). The CAPE of the sounding is 3312 J kg\(^{-1}\), and the basic-state wind and stability above \(z = 19.2\) km is assumed to be uniform (\(-13.8\) m s\(^{-1}\) and 0.022 s\(^{-1}\)).

For each ideal and real storm case, we conduct a control (CTL) simulation with nonlinearity and cloud microphysics (without ice process) and two quasi-linear dry simulations forced by either diabatic forcing (DRYQ) or nonlinear forcing (DRYMH) obtained from the control simulation. In each quasi-linear simulation, cloud microphysical processes are turned off and nonlinear and diabatic forcings calculated from the CTL simulation are reduced by factor of 10,000. These reduced forcing terms are included in the governing equation to elicit a quasi-linear response in the nonlinear numerical model. For details, refer to SCL.

### 3. Control and quasi-linear dry simulations

In this section, we describe the structure and evolution of convective storms in the CTL simulations and their relationship with the stratosphere gravity waves forced by the simulated storms. In the CTL simulation, an ellipsoidal warm bubble with a maximum potential temperature perturbation of 2 K is introduced to initiate convection. For ideal storm cases, time integration is carried out for 30, 24, 12, and 10 h for \(U_s = -27, -24, -21\) through \(-9\) (5 cases) and 0 m s\(^{-1}\) cases, respectively. For stronger wind shear, a longer time integration is needed to reach the mature stage. For real storm cases, storms decay rapidly compared with ideal cases, and shorter time integrations (6 h) are conducted.

Figure 2 shows the time series of domain-maximum perturbation vertical velocity (\(w'_{\text{max}}\)) in the CTL simulations for ideal and real storm cases. Dashed lines de-
note a time at which most convective cells are tilted westward (upshear) in association with a mature cold pool for cases with a positive basic-state wind shear. The time is defined at which the domain-averaged perturbation zonal velocity in the troposphere becomes negative. For ideal cases, $w_{\text{max}}$ oscillates rapidly from the beginning until the cold pool develops sufficiently.

For ideal supercell storm cases (Figs. 2a,b), the rapid fluctuation of $w_{\text{max}}$ lasts much longer than for the other cases, that is, before convective cells tilt upshear. This is because it takes much longer for the negative vorticity associated with cold pool to overcome the positive vorticity associated with strong positive wind shear. For real storm cases, a cold pool develops soon after the

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**Fig. 2.** Time series of domain-maximum vertical velocity in the CTL simulation for all ideal and real storm cases. The time at which most of the convective cells are tilted westward due to a sufficiently mature cold pool is indicated by a dashed line for each case, except for (h) and (j).
initiation of convection, and convective cells are severely tilted westward after $t = 3$ h. Consequently, latent heating required to maintain convective system and vertical displacement to excite gravity waves become quite weak after $t = 6$ h.

Figure 3 shows the contours of perturbation vertical velocity of $2 \text{ m s}^{-1}$, total potential temperature, cloud region ($q_c > 0.1 \text{ g kg}^{-1}$), and cold pool boundary ($\theta' = -1 \text{ K}$) at $t = 5$ h in the CTL simulations for all the ideal storm cases, and for real storm cases with contours of vertical velocity of $1 \text{ m s}^{-1}$ at $t = 3$ h. Here, $q_c$ and $\theta'$ are the cloud water mixing ratio and perturbation potential temperature, respectively. For the ideal supercell storm with strong vertical wind shear (Figs. 3a,b), cloud regions are mostly tilted in the downshear (eastward) direction. The feature is similar to the initial stage of storm evolution demonstrated by Rotunno et al. (1988), where the negative vorticity induced by the cold pool is much weaker than the positive vorticity associated with basic-state wind shear, and consequently convective cells move toward the downshear side. In this situation, storm-relative midlevel inflow associated with the premature cold pool (Lin et al. 1998) becomes small. Predominance of eastward-propagating gravity waves in the stratosphere is due to the eastward-moving convective cells, as shown by Fovell et al. (1992) and SCL. The relationship between cell motion and wave propagation in the stratosphere also has been demonstrated analytically by Song and Chun (2005), who showed that the momentum flux above convection is determined by the spectral combination of wave source and a wave filter-resonance factor (WFRF). Depending on cell motion, spectral peaks of the wave source change, and consequently, spectral characteristics of waves above convection change.

For the multicell storms with weak to moderate vertical wind shears (Figs. 3c–g), convective cells are tilted westward rather quickly in association with a mature cold pool. This feature is similar to the final stage of storm evolution described in Rotunno et al. (1988), where the negative vorticity induced by the cold pool dominates the positive vorticity from the basic-state wind shear. Thus, most convective cells propagate in the upshear direction with an enhanced midlevel inflow. These westward-moving cells induce predominantly westward-propagating waves in the stratosphere.

For the single-cell storm under the environment with zero wind (Fig. 3h), gravity waves in the stratosphere propagate westward and eastward symmetrically. As the cold pool spreads from the center, convective cells generated near the western (eastern) edge of the cold pool are tilted eastward (westward), due to positive (negative) vorticity induced by the cold pool. The eastward (westward) tilted cells also move eastward (westward), and thus generate predominantly eastward (westward) propagating waves in the stratosphere.

For the real storm cases (Figs. 3i,j), convective cells are also tilted westward and move mainly westward. For the TOGA COARE case, convective storms simulated in the present study are much more tilted compared with observation. This discrepancy is likely due to neglecting the ice microphysics and surface fluxes, which can weaken cold pool strength (Trier et al. 1996). Although the convective cells move westward for the two real cases, in the stratosphere eastward-propagating gravity waves are comparable to the westward-propagating waves in their magnitude for the TOGA COARE case and are dominant for Indononesia case. This is because large portions of the westward-propagating components of waves are filtered out by the easterly basic-state wind in the mid-to-upper troposphere for both cases. Compared with the TOGA COARE case, westward-propagating waves are very weak for the Indonesia case at $t = 3$ h because these convective cells move westward relatively slowly (indicated by location of convective cells in Figs. 3i,j), and waves generated by those convective cells with relatively small magnitude of negative phase speed are filtered out significantly below about $z = 13 \text{ km}$. Although waves with large magnitude of negative phase speeds can propagate up to $z = 18 \text{ km}$, the amplitude of waves with those phase speeds might be relatively small due to the weak power of the source spectrum at those phase speeds. On the other hand, for the TOGA COARE case, convective cells move westward fast, and large amplitude of waves generated by fast moving convective cells with phase speeds of less than $-17 \text{ m s}^{-1}$ can reach above $z = 15 \text{ km}$ without critical-level filtering process.

Figure 4 shows perturbation vertical velocities in the CTL, DRYQ, and DRYMH simulations and the sum of the perturbations in the DRYQ and DRYMH simulations (DRYQ + DRYMH) for selected ideal cases ($U_* = -27, -21, -12,$ and $0 \text{ m s}^{-1}$ cases) at $t = 5$ h and for two real storm cases at $t = 3$ h. Note that the perturbation vertical velocities in the quasi-linear simulations are multiplied by factor of 10 000 for comparison with the CTL simulation. For each case, the structure of perturbation vertical velocities in the DRYQ and DRYMH simulations are different from each other as well as from that in the CTL simulation. Also, the magnitude of perturbations in the DRYQ and DRYMH simulations is about 1.5–3 times larger than that in the CTL simulation. Especially for ideal multicell storm cases (Figs. 4b,c), the magnitude of gravity waves in the two quasi-linear dry simulations is about 3–4 times
FIG. 3. Contours of vertical velocity of 2 m s$^{-1}$ (thick lines) superimposed on total potential temperature (thin lines) at $t = 5$ h for the ideal storm cases [$U_s = (a) -27$, (b) $-24$, (c) $-21$, (d) $-18$, (e) $-15$, (f) $-12$, (g) $-9$, and (h) 0 m s$^{-1}$] and real storm cases [(i) TOGA COARE case and (j) Indonesia case] with contours of vertical velocity of 1 m s$^{-1}$ at $t = 3$ h. The contour interval for total potential temperature is 10 K. Gray shadings denote cloud regions where cloud water mixing ratios are larger than 0.1 g kg$^{-1}$, and gray dashed lines denote cold pool boundaries with a perturbation potential temperature of $-1$ K.
larger than that in the CTL simulation. In addition, perturbations in the DRYQ and DRYMH simulations are out of phase with each other in both the troposphere and stratosphere, while the sum of perturbations in the DRYQ and DRYMH simulations (DRYQ + DRYMH) compares well with perturbations in the CTL simulations.

For the ideal single-cell storm case (Fig. 4d), perturbations in the DRYQ and DRYMH simulations are significantly different from those in the CTL simulation, especially above \( z = 10 \text{ km} \). The horizontal and vertical wavelengths of stratospheric perturbations in the DRYQ and DRYMH simulations are very small, within the area where the eastward-propagating waves generated from the western edge of convective source and westward-propagating waves from the eastern edge of convective source are overlapped. It is amazing to see that the sum (DRYQ + DRYMH) of the perturbations in the DRYQ and DRYMH simulations is comparable to the perturbations in the CTL simulation in their magnitude and structure. Cancellation between the wave perturbations in the DRYQ and DRYMH simulations is responsible for the result. This is perhaps the best case to demonstrate clearly the importance of the two forcing mechanisms of convective gravity waves.

For the real storm cases, results of wave perturbations in the CTL, DRYQ, and DRYMH simulations are basically similar to those for the ideal storm cases mentioned above. For the TOGA COARE (Indonesia) case, westward (eastward) propagating waves are dominant in the DRYQ and DRYMH simulations, as explained before with Fig. 3. However, again perturbations in the DRYQ and DRYMH simulations are largely out of phase with each other, and perturbations in DRYQ + DRYMH only can reproduce those in the CTL simulations in these real storm cases. The results of the ensemble numerical simulations confirm that the two forcing mechanisms demonstrated by SCL based on a single convection case can be applied generally to various types of convective storms.

4. Wave momentum flux spectrum

In this section, the wave momentum flux spectrum is calculated. As shown in the previous section, simulated storms undergo changes in storm development stages during their evolution. To avoid a dependency of the calculated spectra on a particular stage of storm development, momentum flux spectra are calculated using the data over the whole period of time integration for each of the storm cases. Figure 5 shows the momentum flux spectrum in the CTL, DRYQ, and DRYMH simulations, and in DRYQ + DRYMH at \( z = 18 \text{ km} \) for all ideal and real storm cases. Cross-correlation momentum flux terms between the waves induced by DRYQ and DRYMH simulations are also shown in Fig. 5. According to CSH, the momentum flux induced by two forcings can be written as

\[
\rho u'_{\text{DRYQ}} w_{\text{DRYQ}} + \rho u'_{\text{DRYMH}} w_{\text{DRYMH}} + \rho u'_{\text{DRYQ}} w_{\text{DRYQ}} + \rho u'_{\text{DRYMH}} w_{\text{DRYMH}},
\]

where \( u'_{\text{DRYQ}} \) and \( w_{\text{DRYQ}} \) are the perturbation horizontal and vertical velocities induced by diabatic (nonlinear) forcing, respectively. The term on the left-hand side and the first two terms on the right-hand side of (2) are momentum fluxes in the DRYQ + DRYMH, DRYQ, and DRYMH simulations, respectively. The third and fourth terms on the right-hand side are cross-correlation terms. The two cross-correlation momentum fluxes are almost identical for all cases, and also as in CSH, because the vertical wavelengths (6–9 km) of gravity waves in various storm cases considered in this study are generally much less than \( 4\pi H \), where \( H (\sim 7 \text{ km}) \) is the density scale height (i.e., satisfying the Boussinesq approximation).

For supercell storm cases (Figs. 5a,b), the magnitude of the positive momentum flux is much larger than that of the negative momentum flux, and it decreases as wind shear decreases. This is because for strong shear cases waves propagate eastward for a longer period of time (Figs. 2a,b) associated with eastward (downshear) tilted convective cells, and consequently, positive momentum flux dominates negative momentum flux. For multicell storm cases (Figs. 5c–g) negative momentum flux dominates positive momentum flux, because the convective cells tilt upshear rather quickly (Figs. 2c–g), and consequently, the westward-propagating waves are dominant in the stratosphere. Proportional to the period for upshear tilt of convective cells, the magnitude of negative (positive) momentum flux increases (decreases). That is, as wind shear decreases the magnitude of negative momentum flux increases, while that of positive momentum flux decreases. For the single-cell storm case (Fig. 5h), positive and negative momentum fluxes are symmetric, since convective clouds propagate westward and eastward symmetrically.

For the TOGA COARE case, negative momentum flux dominates positive momentum flux in the DRYQ and DRYMH simulations, as expected from the predominance of westward-propagating waves in the stratosphere (Fig. 4e). The maximum magnitude of negative momentum flux occurs at \( c = -30 \text{ m s}^{-1} \) in the
DRYQ and DRYMH simulations, and this confirms the previous statements related to Fig. 3i that the westward-propagating waves with large magnitude of negative phase speeds, generated by convective cells moving fast to the west, can propagate into the stratosphere. For the Indonesia case, eastward-propagating waves are dominant, as expected from the predominance of eastward-propagating waves shown in Fig. 3j. However, the magnitude of the negative momentum flux with phase speeds less than $-20$ m s$^{-1}$ is not small, especially in DRYQ simulation. This is similar to the TOGA COARE case, because the source spectrum has strong westward-propagating components associated with westward-moving convective cells in the tropo-

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**Fig. 4.** Perturbation vertical velocity in the CTL, DRYQ, and DRYMH simulations and DRYQ + DRYMH at $t = 5$ h for the ideal cases [(a) $U_s = -27$, (b) $-21$, (c) $-12$, and (d) $0$ m s$^{-1}$] and at $t = 3$ h for the real storm cases [(e) TOGA COARE and (f) Indonesia]. Negative values are shaded. Contour intervals are 2 (1) m s$^{-1}$ for the ideal (real) cases.
sphere, and waves presumably generated by the source spectrum with phase speeds less than $-20 \text{ m s}^{-1}$ can propagate above about $z = 13 \text{ km}$ without critical-level filtering process under the given basic-state wind profile (Fig. 1).

Comparison of momentum flux spectra in the quasi-linear dry simulations with those in the CTL simulation demonstrates the following characteristics in common for all convection cases: First, the maximum magnitude of momentum flux in either the DRYQ or DRYMH simulation is larger than that from CTL simulation. Especially for ideal single-cell and multicell storm cases, the momentum flux induced by a single forcing is 10 times larger than that in the CTL simulation. Second, cross-correlation momentum fluxes are out of phase with spectra in the DRYQ and DRYMH simulations. Third, momentum flux spectra in DRYQ + DRYMH are comparable to the CTL simulation, because of the

Fig. 4. (Continued)
cancellation of the momentum flux by the cross-correlation terms. The cross-correlation momentum flux terms always have opposite sign to those of momentum flux spectra in the two quasi-linear dry simulations, and thus this negative correlation leads to the cancellation between wave perturbations in the DRYQ and DRYMH simulations.

The above findings are basically the same as those obtained from the single convection case by SCL and CSH, with one exception. In contrast to results in CSH, the shapes of wave momentum flux spectra in the DRYQ and DRYMH simulations are not significantly different from each other and from that in the CTL simulation in many cases, although the magnitude of the momentum flux spectra differs more or less. In the case considered in CSH (i.e., $U_s = -18 \text{ m s}^{-1}$ case in this study), the primary peak in the DRYMH simulation appears at $c = -24 \text{ m s}^{-1}$, while it is at $c = -12 \text{ m s}^{-1}$.
in the DRYQ simulation. Owing to this difference, the wave spectrum in the CTL simulation becomes significantly different from that in the DRYQ and DRYMH simulations. Although it is less pronounced, a similar feature also is found for the $U_s = -21 \text{ m s}^{-1}$ case, where the magnitude of the secondary peak appears only in the DRYMH simulation at $c = -26 \text{ m s}^{-1}$. In most cases except for these two, the spectral shapes of wave momentum flux in the DRYQ and DRYMH simulations are, to the first approximation, similar to each other and to that in the CTL simulation, although with different magnitudes. Pandya and Alexander (1999) also showed that spectral characteristics of stratospheric gravity waves generated by diabatic forcing alone are similar to those in a fully nonlinear simulation, and that the amplitude of these waves is much larger than that in the nonlinear simulation. Although Pandya and Alexander (1999) did not consider explicitly the nonlinear forcing mechanism, which is responsible for reducing the wave amplitude in the nonlinear simulation, their work justifies the use of diabatic forcing alone to derive wave spectral properties in convective gravity wave drag (GWD) parameterization by Beres (2004).

Given that the difference in the spectral shape of momentum flux between the DRYQ and DRYMH simulations is one of the key issues in CSH, the present result is an interesting finding, which could be drawn from the ensemble simulations. This result has an important implication for development of convective GWD parameterization. Further discussion about this issue will be presented in the last part of the paper.

5. Summary and conclusions

In this study, characteristics of convectively forced gravity waves are investigated through ensemble numerical simulations for various convective storms. As members of ensemble simulations, eight ideal and two real (TOGA COARE and Indonesia) storm cases are considered. In ideal cases, storms are classified into supercell, multicell, and single-cell storms according to the bulk Richardson number. For each storm case, a control (CTL) simulation with nonlinearity and cloud microphysics is carried out, and two quasi-linear dry simulations are conducted. The two dry simulations (DRYQ and DRYMH) are forced by nonlinear and diabatic forcings in the CTL simulation, respectively.

Results in the CTL simulations for each storm case are summarized as follows. For ideal supercell storm cases with strong basic-state wind shear, convective clouds move mainly in the eastward (downshear) direction, and thus eastward-propagating waves are dominant in the stratosphere. For ideal multicell storm cases where a low-level cold pool develops quickly, convective cells move predominantly in the westward (upshear) direction, and these cells induce strong westward propagating gravity waves in the stratosphere. For the ideal single-cell storm case, gravity waves in the stratosphere propagate symmetrically in the horizontal direction as convective cells spread out along the boundaries of the cold pool. For two real storm cases, convective cells move mainly in the westward direction. However, the eastward-propagating waves are dominant for the Indonesia case, while they are comparable to the westward-propagating waves for the TOGA COARE case, under similar easterly basic-state wind conditions in the mid-to-upper troposphere. The different characteristics of stratosphere gravity waves in the two real cases result mainly from the different spectral structure of the convective sources.

By comparing gravity wave momentum flux spectra in the CTL and two quasi-linear dry simulations for various convective storms, we found the following characteristics:

(i) The magnitude of momentum flux in either DRYQ or DRYMH simulation is much larger than that from CTL simulation for all ideal and real cases.

(ii) The cross-correlation momentum flux spectra are out of phase with spectra in the DRYQ and DRYMH simulations for all ideal and real cases.

(iii) For all cases, the momentum flux spectra in DRYQ + DRYMH are comparable to the CTL simulation, because of the cancellation between wave perturbations in the DRYQ and DRYMH simulations and cross-correlation momentum flux terms.

(iv) Except for the two cases ($U_s = -21$ and $-18 \text{ m s}^{-1}$ cases), the shape of momentum flux spectra by diabatic and nonlinear forcings is roughly similar to each other and to that in the CTL simulation, although with different magnitudes.

The results of (i)–(iii) are consistent with those found in CSH, and this implies that the out-of-phase relationship between gravity waves induced by diabatic and nonlinear forcing terms can be applied to convective storms of various types, and both forcing mechanisms are important in generating spectra of convectively forced gravity waves. The result of (iv) has important implications for development of convective GWD parameterization. When the shape of wave momentum flux spectra by diabatic and nonlinear forcings is significantly different from that in the CTL simulation, it would be required to take into account diabatic and nonlinear forcings separately in parameterizations of
convective gravity waves. In this case, recent parameterizations (Beres 2004; Song and Chun 2005) based on diabatic forcing alone might need significant modifications, as suggested by CSH. However, the similarity in spectral shape between wave momentum flux induced by DRYQ and CTL simulations found in most storm cases (except for the two multicell-storm cases) and in the previous study by Pandya and Alexander (1999) may suggest the possibility of simple ways of including nonlinear forcing effects in parameterizations of convective gravity waves. One possible way is to correct the magnitude of the cloud-top momentum flux induced by diabatic forcing alone, using a scale factor that represents the degree of nonlinear forcing effects on convective gravity waves, as proposed by Chun et al. (2007). Further investigations on this topic are needed.

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