A case study of typhoon-induced gravity waves and the orographic impacts related to Typhoon Mindulle (2004) over Taiwan

J. F. Wu1,2, X. H. Xue1,2, L. Hoffmann3, X. K. Dou1,2, H. M. Li4, and T. D. Chen1,2

1CAS Key Laboratory of Geospace Environment, Department of Geophysics and Planetary Sciences, University of Science and Technology of China, Hefei, China, 2Mengcheng National Geophysical Observatory, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, China, 3Forschungszentrum Jülich, Jülich Supercomputing Centre, Wilhelm-Johnen-Straße, Jülich, Germany, 4Network and Information Center, University of Science and Technology of China, Hefei, China

Abstract

Atmospheric gravity waves (GWs) significantly influence global circulation. Deep convection, particularly that associated with typhoons, is believed to be an important source of gravity waves. Stratospheric gravity waves generated by Typhoon Mindulle were investigated using the Weather Research and Forecasting (WRF) model. The initial and boundary data were determined by the high-resolution European Center for Medium-Range Weather Forecasts reanalysis data. The WRF simulation reproduces the main features of Typhoon Mindulle and the significant GWs. The simulated GWs with horizontal wavelengths of 100–400 km match the AIRS observations: they propagate upward and eastward, and the westward components are mostly filtered in the stratosphere. By comparing the measured waves with a WRF simulation in the absence of orography (WRF-FLAT), we find that the orographic gravity waves (OGWs) generated by the flow of Typhoon Mindulle over the Central Mountain Range (CMR) in Taiwan account for approximately 50% of the total wave momentum flux in the troposphere. The dominant orientation of the OGW wave fronts is parallel to the CMR rideline. When entering into the stratosphere, OGW propagation is determined by the position of the typhoon center relative to the CMR.

1. Introduction

Atmospheric gravity waves (GWs) in the lower and middle atmosphere have attracted research attention due to their significant impacts on global atmospheric circulation and midatmospheric features [Lindzen, 1981; Matsuno, 1982; Garcia and Solomon, 1985; Andrews et al., 1987; Dunkerton, 1997; Fritts and Alexander, 2003; Ern and Preusse, 2009; Kawatani et al., 2010; Xue et al., 2012].

Deep convection is one of the most important sources of GWs, particularly in the tropics. Recent research has indicated that diabatic forcing and overshooting within a deep convective system can excite a broad spectrum of GWs on large temporal and spatial scales [Lane et al., 2001]. In the northwestern region of the Pacific Ocean, a typhoon (equivalent to a hurricane in the eastern North Pacific and western North Atlantic) is a well-organized, large-scale severe convective system that can induce a series of GWs with horizontal wavelengths of several hundred kilometers long and durations that last for multiple hours [Kim et al., 2009]. Typhoon-induced GWs (TGWs) are generated in the troposphere along the typhoon track and propagate horizontally and vertically. TGWs play an important role in the momentum budget of the middle atmosphere and affect global atmospheric circulation [Kim et al., 2013]. Significant progress toward understanding GWs has been achieved recently as a result of improvements in observational and modeling capabilities. Many studies have been conducted on the characteristics of GWs using in situ, ground-based, and space-based observations, as have studies using numerical simulations and addressing theoretical concerns [Alexander et al., 2009; Zhang et al., 2012, 2013; Hoffmann et al., 2013; Yue et al., 2013; Lu et al., 2015]. Because typhoons develop over the sea, in situ and ground-based observational instruments (e.g., lidar and radiosonde) are limited in their ability to monitor TGWs. In the past, TGWs were observed using aircraft, middle and upper
Figure 1. The track of Typhoon Mindulle obtained from JTWC (pink), JMA (yellow), and STI (green). The WRF-simulated track is shown in purple. The red triangle, diamond, and star mark the typhoon center at 0530 UTC 1 July (before landing), 1430 UTC 1 July (during landing), and 0530 UTC 3 July (after landing), respectively. Topography of Taiwan is also underlayed in gray.

Each parameterization scheme requires the input of a set of gravity wave properties at the launch altitude or at the model’s lower boundary. A comprehensive understanding of GW parameters, including source and spectrum properties and the momentum flux carried by waves, can clarify the impacts of GWs on global circulation.

A large number of observational and modeling studies have reported that the occurrence of orographic gravity waves varies significantly with season and latitude. Hoffmann et al. (2013) found that most of the orographic gravity wave hot spots are distributed in the middle and high latitudes during the autumn to the spring seasons using the high horizontal resolution of Atmospheric Infrared Sounder (AIRS) observations. Alexander and Grimsdell (2013) have shown that the small island mountain waves in the southern oceans commonly occur during the May–September season. Because prevailing wind patterns prevent orographic gravity wave (OGW) propagation, a limited number of OGWs are detected and investigated at low latitudes during the summer. However, a surface wind field reconstruction occurs when a typhoon passes, which provides the conditions for OGW propagation. We focus on the summer period from 1 July 2004 to 3 July 2004, when Typhoon Mindulle (2004) passed over the island of Taiwan. As expected, constant OGW propagation occurred before and after typhoon landfall. Because dozens of cyclones and typhoons form in the Pacific every year, it is important to examine the OGWs associated with these cyclones.

In this study, we investigate the GWs generated by Typhoon Mindulle (2004), which formed in June 2004 near Guam (13°N, 144°E), using Atmospheric Infrared Sounder (AIRS) observations and the Weather Research and Forecasting (WRF) model. The paper is organized as follows: section 2 provides a description of the observational data, section 3 introduces the model. section 4 describes the characteristics of the GWs, section 5 presents the orographic influence on GWs, and section 6 gives a summary of the research.

2. Observations of Typhoon Mindulle and Deep Convection

2.1. Typhoon Mindulle

In this study, we focus on GWs that are induced by Typhoon Mindulle (the tenth tropical cyclone issued by the Joint Typhoon Warning Center (JTWC) in 2004). Mindulle developed near Guam at 0600 UTC 23 June and then moved west-northwestward. It turned northward on 30 June 2004 and landed on the east coast of Taiwan at approximately 1500 UTC 1 July. After that, Mindulle moved north-northeastward toward the East China

atmosphere (MU) radar, and Global Positioning System (GPS) wind soundings from the troposphere and stratosphere [e.g., Sato, 1993; Dhaka et al., 2003; Chun et al., 2007a]. However, further investigations into TGW source spectrum characteristics are essential to the appropriate parameterization of GWs in global circulation models (GCMs).

Convective GWs play an important role in the vertical momentum transport in GCMs, and their forcing likely drives long-term oscillations such as the quasi-biennial oscillation (QBO) in the middle atmosphere [Alexander et al., 2010; Baldwin et al., 2001; Beres et al., 2005; Ricciardulli and Garcia, 2000]. However, TGWs generally remain unresolved or underresolved in GCMs; to improve the accuracy of such models, the effects of TGWs must be parameterized. Currently, several parameterization schemes have been proposed and implemented in global models [Fritts and Alexander, 2003].
The Central Mountain Range (CMR) in Taiwan has an average elevation of over 3000 m, runs a north-south distance of 300 km, and has an east-west width of 100 km. The CMR was expected to impact the propagation of GWs after Mindulle made landfall. Reports verified this effect; specifically, the shape of Mindulle became irregular, and its track disappeared overnight (http://agora.ex.nii.ac.jp/digital-typhoon/news/2004/TC0407/index.html.en) [Lee et al., 2008]. This effect was also investigated by comparing the observations from the JMA, JTWC, and STI (Figure 1). The typhoon tracks observed by the three organizations correlate well at all of the typhoon stages, except for the relatively large deviations when Mindulle was over Taiwan. This case study provides a good opportunity to study the orographic influence on GWs, as a convective system (the source of the waves) that passed over the CMR.

2.2. Deep Convection Observed by AIRS

The AIRS instrument [Aumann et al., 2003] is mounted onboard the Aqua satellite and was launched by the National Aeronautics and Space Administration (NASA) on 4 May 2002. AIRS provides recordings from an altitude of 705 km in a Sun-synchronous polar orbit with a 98° inclination and a 99 min period (14.5 orbits per day). AIRS measures atmospheric CO₂ thermal emissions in the nadir and off-nadir geometry, and it provides an across-track scan angle of ±48.95°, a spatial resolution of 13.5 km at nadir, and a 41 km × 21.4 km area at the scan extremes [Hoffmann et al., 2013].

The detection of deep convective clouds in AIRS observations was discussed in detail by Aumann et al. [2006], Hoffmann and Alexander [2010], and Hoffmann et al. [2013]. Based on the measurements of the 8.1 μm AIRS radiance channel (1231.3 cm⁻¹, AIRS channel number 1291), high cold clouds are identified by low brightness temperature, whereas clear air conditions are associated with high brightness temperature. The AIRS radiances at 8.1 μm at 0530 UTC 3 July are presented in Figure 3a. The regions of low brightness temperature, which indicate the existence of deep convection, correlated well with satellite images of Typhoon Mindulle’s cloud cover (not shown). The cold brightness temperatures (i.e., < 210 K) in the southwest region of Taiwan suggest significant deep convection associated with Mindulle.

The typhoon center, which is marked by a red star in Figure 3a, does not match the center of deep convection located southwest of Taiwan (marked by a black star in Figure 3a) at 0530 UTC 3 July. This disagreement was also reported in previous case studies. For example, Kuester et al. [2008] found that the direction of convective forcing did not match the direction of Hurricane Humberto’s path.

2.3. TGWs Observed by AIRS

Previous studies have indicated that stratospheric gravity waves can be directly detected from AIRS radiance measurements [e.g., Hoffmann and Alexander, 2010; Hoffmann et al., 2013]. In this study, we selected the same channels that were used by Hoffmann and Alexander [2010] and Hoffmann et al. [2013], i.e., 42 AIRS
Figure 3. The AIRS observations and WRF simulation at 0530 UTC 3 July for the Taiwan region. (a) The 8.1 μm brightness temperature. (b) The 4.3 μm brightness temperature perturbation. (c) The variances of the 4.3 μm brightness temperature perturbation. (d) The WRF simulated 4.3 μm BT perturbation maps with an applied AIRS mean weighting function. (e) The 2-D FFT spectrum of the 4.3 μm brightness temperature perturbation (as shown in Figure 3b). (f) The 2-D FFT spectrum of the WRF-simulated 4.3 μm BT perturbation (as shown in Figure 3d). The red star in Figures 3a and 3b marks the typhoon center at the observation time derived from the WRF simulation; the red dash lines in Figure 3b and black star in Figures 3a and 3b are the rough fitting circles and center of GWs, respectively.
channels (2322.6 to 2366.9 cm$^{-1}$) from the 4.3 μm CO$_2$ fundamental band, which are sensitive to temperature disturbances at altitudes from 20 to 65 km. Maximum sensitivity was identified at 30–40 km. The brightness temperature perturbations were calculated as the differences from a fourth-order polynomial fit for each scan [Hoffmann and Alexander, 2010]. The result of the AIRS observation over Taiwan at 0530 UTC 3 July is illustrated in Figure 3b. Semicircular GW patterns are easily identified, and the mean perturbation in the illustrated example is 0.5 K. To determine the center of these semicircular GWs, efforts were made to fit circles and retrieve the center of the ring circle as outlined in Yue et al. [2014] and Gong et al. [2015]. The center of the semicircular GWs is located west of Taiwan (22°N, 117°E, denoted by the black stars in Figures 3a and 3b). The fact that the location of the semicircular GW center is consistent with the deep convection center, as shown in Figure 3a, strongly suggests that the semicircular GWs are generated by the deep convection of Mindulle’s arms. The concentric waves are mainly distributed in a sector area with a radius of approximately 1000 km and have a dominant horizontal wavelength of approximately 200 km, as calculated from the fitted circles. The local variance in the brightness temperature perturbations identified through the AIRS data can be used to determine whether the perturbations in Figure 3b are statistically significant [Hoffmann and Alexander, 2010] and related to the GWs. In general, the radiance variance ($\sigma^2$) has two main components: the contributions from the gravity waves ($\sigma_{GW}^2$) and instrument noise ($\sigma_{n}^2$). The variance filter is a direct and simple way to distinguish gravity wave disturbances from instrument noise for a large amount of AIRS data. When the local variance exceeds a threshold of 0.05 K² (50 times greater than the instrument noise or approximately 0.001 K²), we assume that the GW event is significant [Hoffmann and Alexander, 2010]. Figure 3c displays the brightness temperature variance for the perturbations provided in Figure 3b. The maximum variance exceeds 0.1 K² near Taiwan at a horizontal scale of 600 km × 600 km; this matches the area of the GW perturbations. A 2-D fast Fourier transformation (FFT) analysis of the temperature perturbations is shown in Figure 3e. The significant spectral components are oriented in a zonal direction with dominant wavelengths of 100–400 km.

3. Numerical Experiment
3.1. WRF Experimental Design
The numerical simulation of Typhoon Mindulle was performed using the Advanced Research Weather Research and Forecasting modeling system version 3.6.1 [Skamarock et al., 2008]. The model was set up with a horizontal domain of 100 × 100 grid cells with a grid spacing of 21 km centered on Taiwan (23.8°N, 120.9°E), a nested domain with 7 km grid spacing fixed over Taiwan and a vertical domain with 130 unevenly spaced sigma levels from the surface to 0.5 hPa (53 km); the topmost 10 km was established as a damping layer. The vertical grid spacing was less than 500 m in the troposphere and the lower and middle stratosphere and less than 1000 m in the upper stratosphere. The simulation was integrated for 132 h from 0000 UTC 1 July to 1200 UTC 6 July. Initial and boundary conditions were established using the European Center for Medium-Range Weather Forecasts (ECMWF) interim reanalysis data, which had a N128 Gaussian grid (0.7° × 0.7°) resolution.

The model physics schemes applied are the Kain-Fritsch scheme for cumulus parameterization [Kain and Fritsch, 1993], the WRF single-moment three-class scheme for microphysics [Hong et al., 2004], the Rapid Radiative Transfer Model scheme for longwave radiation [Mlawer et al., 1997], the Dudhia scheme for shortwave radiation [Dudhia, 1989], and the Yonsei University planetary boundary layer for vertical diffusion process [Hong et al., 2006].

![Figure 4](image-url)
Figure 3d displays the simulated 4.3 μm brightness temperature perturbations based on the WRF output, to which an AIRS mean weighting function was applied at 0530 UTC 3 July for the same region scanned by AIRS. Figure 3b and the WRF BT perturbation maps (Figure 3d) are relatively similar, although some details are lost in Figure 3d as a result of the vertical smoothing of the weighting functions for the 4.3 μm channels and the fact that the WRF wave amplitudes are slightly smaller than the AIRS observations. The semicircular GWs identified from the AIRS BT perturbations are reproduced well in the WRF simulation, both in terms of wave morphology and horizontal wavelength. The 2-D FFT spectrum of the WRF BT perturbation shown in Figure 3f correlates well with the AIRS data shown in Figure 3e, both in terms of horizontal wavelength and wave orientation. Given that the 2-D AIRS 4.3 μm snapshot cannot provide a specific phase velocity direction, phase velocity direction will be assessed in more detail using a 3-D FFT spectrum method later.

4. TGW Characteristics

To further analyze the TGW characteristics, we used $\frac{dw}{dz}$ to measure the gravity waves; this ratio corresponds to the opposite of horizontal wind divergence. The horizontal distributions of $\frac{dw}{dz}$ at two selected altitudes (12 and 33 km) for 0530 UTC 1 July (before landing), 1430 UTC 1 July (during landing), and 0530 UTC 3 July...
Figure 6. The angular spectra of the PSDs of the vertical gradients for the vertical wind components $d w/dz$ at (a and d) 0530 UTC 1 July, (b and e) 1430 UTC 1 July, and (c and f) 0530 UTC 3 July as a function of the ground-based phase speed and propagation direction at (Figures 6a–6c) $z = 12$ km and (Figures 6d–6f) $z = 33$ km. The angle is the propagation direction counterclockwise from the east. The radius of the circle (dashed lines) indicates the horizontal phase speeds of 20 m/s, 40 m/s, and 60 m/s.

(after landing) are depicted in Figure 5. These distributions illustrate the temporal and vertical development of the horizontal GW structure. The two selected altitudes, 12 km and 33 km, represent the tropopause and the most sensitive altitude for the AIRS 4.3 μm channels, respectively. Following Kim et al. [2009], the corresponding 3-D power spectral densities (PSDs) of $d w/dz$ as a function of the horizontal phase speed and the horizontal direction are shown in Figure 6.

At the tropopause ($z = 12$ km), GWs at the launch level exhibited quasi-isotropic but preferential horizontal propagation to the northwest, northeast, and southeast at three stages, respectively (Figures 5 and 6). In their simulation of Typhoon Ewiniar, Kim et al. [2009] found that convective forcing was the strongest in the direction of the typhoon’s movement. In the case of Mindulle, this was not the case. At $z = 33$ km, the stratospheric GWs were oriented quite differently than they were at the launch level, and only eastward propagating GWs were significant. Most of the westward propagating GWs were filtered by an easterly background wind (background wind shown in Figure 7a), and only the remaining eastward propagating GWs existed when they reached the middle and upper stratosphere [Fritts and Alexander, 2003; Baldwin et al., 2001]. The upward propagation of GWs in the simulation is consistent with results found in previous studies [Chun et al., 2007b; Kim et al., 2005; Lu et al., 2009; Zhang and Yi, 2004, 2008].

Although previous case studies have illustrated various characteristics of TGWs, this case appears to be quite unique in several ways. First, the structure of the TGWs in this study, both before and after landing, was quite different from structures identified in previous studies, which primarily focused on pretyphoon landfall. Second, the distance between the typhoon center and the convective rainbands that formed over the Taiwan Strait reached approximately a thousand kilometers on 3 July (distance between the red and black stars in Figure 3). Third, the structure of the TGWs underwent significant changes after Mindulle made landfall on Taiwan, as shown in the stratospheric fitting results (Figures 5d–5f). The red stars in Figure 5 denote the typhoon center at three stages. At 0530 UTC 1 July, prior to landfall, the typhoon center coincided with the TGW source (Figures 5a and 5d). At 1430 UTC 1 July, when the typhoon landed, the structure of the wave was complicated but still coalesced around the typhoon center (Figures 5b and 5e). At 0530 UTC 3 July, after the typhoon has passed over Taiwan, the plotting area was filled with TGWs; there was an obvious dislocation between the typhoon center and the center of the semicircular GWs (Figures 5c and 5f). The TGW structures derived from the simulation were consistent with the AIRS observations taken on 3 July.
Figure 7. (a) The mean zonal wind over Taiwan as a function of time and height from 0000 UTC 1 July. (Black dotted line is the typhoon landing time, the first red dotted line is 0530 UTC 1 July, prior to typhoon landing, and the second red dotted line is 0530 UTC July 3.) (b) The vertical cross sections of the mountain gravity wave on 1 July (calculated by averaging the 12 h $dw/dz$ 0000–1200 UTC) corresponding to the first red dotted line in Figure 7a. (c) The vertical cross sections of the mountain gravity wave on 3 July (calculated by averaging the 12 h $dw/dz$ 0000–1200 UTC) corresponding to the second red dotted line in Figure 7a.

The GW spectrum was calculated using the method outlined in Kim et al. [2009], and the horizontal wavelength, period, and vertical wavelength are listed in Table 1. The dominant horizontal wavelength was confined to the 100–400 km range and peaked at ~200 km, which correlates very closely with measurements from AIRS shown in Figure 3e. The GW period peaked at ~8 h at 33 km. The vertical wave number was derived using the dispersion relation of inertia gravity waves [Fritts and Alexander, 2003], and the vertical wavelength spectrum covered approximately 6 km to 12 km (the peak occurred at 8 km in the lower stratosphere and at 10 km in middle and upper stratosphere).

The regionally averaged zonal ($\rho_0 u' w'$) and meridional ($\rho_0 v' w'$) momentum fluxes were estimated on the basis of the WRF simulation for the region indicated in Figure 1, where $\rho_0$ is the basic state density and $u'$, $v'$, and $w'$ are the zonal, meridional, and vertical wind perturbations, respectively, and overbar indicates area average over multiple wavelengths [Kim and Chun, 2010; Lane et al., 2001; Plougonven et al., 2008]. Table 2 lists the mean zonal and meridional momentum fluxes at the two selected altitudes (12 km and 33 km) for the three sample times (0530 UTC 1 July, 1430 UTC 1 July, and 0530 UTC 3 July). The zonal momentum flux is always positive (eastward), while the meridional momentum flux shifts from positive (northward) to negative at 0530 UTC 3 July. The magnitude of the momentum flux decreases with height and becomes weak in the upper stratosphere, as illustrated in Table 2. This indicates that most of the momentum flux within the GWs is transferred to the mean flow in the lower stratosphere. At the tropopause ($z = 12$ km), the zonal momentum flux induced by the GWs is positive during the entire simulation, and the mean magnitude is ~5 mPa. This value is comparable with that of Typhoon Ewiniar (2006) [Kim and Chun, 2010] and has the same order of magnitude as the radar observations of Typhoon Kelly (1987) [Sato, 1993]. The rather dramatic change in the meridional momentum flux from northward to southward coincides with a shift in the meridional wind direction.

Table 1. TGW Characteristics Obtained From WRF Simulation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range of Values</th>
<th>Peak Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>100–400 km</td>
<td>~200 km</td>
</tr>
<tr>
<td>Period</td>
<td>7–12 h</td>
<td>~8 h</td>
</tr>
<tr>
<td>Vertical</td>
<td>6–12 km</td>
<td>8 km (lower stratosphere)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 km (middle and upper stratosphere)</td>
</tr>
</tbody>
</table>
Table 2. The Three Representative Times of Mean Zonal and Meridional Momentum Flux at the Two Selected Altitudes

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>0530 UT 1 July</th>
<th>1430 UT 1 July</th>
<th>0530 UT 3 July</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zonal Momentum Flux (mPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>9.54</td>
<td>3.56</td>
<td>3.81</td>
</tr>
<tr>
<td>33</td>
<td>0.58</td>
<td>0.83</td>
<td>1.26</td>
</tr>
<tr>
<td>Meridional Momentum Flux (mPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>2.80</td>
<td>3.83</td>
<td>-0.02</td>
</tr>
<tr>
<td>33</td>
<td>0.22</td>
<td>0.55</td>
<td>-0.08</td>
</tr>
</tbody>
</table>

Further analysis indicates that the GWs with horizontal wavelengths of 100–400 km were the main contributors to the total momentum flux in both the zonal and meridional directions, which agrees with the AIRS observation illustrated in Figure 3d. GWs with periods of less than 10 h dominated the zonal stratospheric momentum flux and the positive (northward) meridional momentum flux, while those with periods greater than 10 h contributed to the zonal momentum flux in the lower stratosphere (<18 km) and the negative (southward) meridional momentum flux (not shown).

Figure 8. OGWs retrieved from the vertical gradients for the vertical wind components \( \frac{dw}{dz} \) averaged over a 12 h window and centered approximately at 0530 UTC 1 July in the troposphere \( (z = 8 \text{ km}) \) and stratosphere \( (z = 33 \text{ km}) \), as obtained from the 7 km WRF and WRF-FLAT nested domain. (a) The standard WRF run at 8 km. (b) The standard WRF run at 33 km. (c) The WRF-FLAT run at 8 km. (d) The WRF-FLAT run at 33 km.
Orography is a well-known source of GWs in the atmosphere [Durran, 1995; Chen et al., 2007; Fritts and Alexander, 2003]. After Typhoon Mindulle encountered the CMR, the propagation of the GWs changed. OGW generation and wave propagation are closely related to surface winds. Here we examined the OGWs for different surface wind directions before and after Typhoon Mindulle landed. Because terrain-generated waves are stationary relative to the ground surface [Nappo, 2002], they are not easily distinguished from propagating TGWs using current observational techniques and under the weather conditions that existed during the study period. Thus, an average vertical gradient of vertical wind components \( dw/dz \) over a 12 h window (approximately centered at 0600 UTC 1 July and 0600 UTC 3 July 2004, respectively) was calculated to separate the OGWs from the TGWs as OGWs are stationary with respect to the ground [Smith et al., 2009]. To demonstrate the method, we use a nested domain with 7 km horizontal spacing fixed over Taiwan. Because the CMR extends from north to south (\( \sim 300 \) km), the zonal wind significantly contributes to the generation of OGWs. The mean zonal wind over the island from 0000 UTC 1 July is shown in Figure 7a as a function of time and height. The black dotted line is the typhoon landing time, and the red dotted lines represent 0530 UTC 1 July and 0530 UTC 3 July, which correspond to the periods before and after the typhoon landing, respectively. An examination of the mean zonal wind shows that the low-level wind shifted from easterly to westerly after the typhoon landed. Vertical cross sections of the OGWs before and after the typhoon landed were derived using the method described above and are plotted in Figures 7b and 7c. Figure 7b shows that the OGWs were able to propagate upward when the background wind remains easterly from the surface to higher altitudes without the existence of a critical level of zero wind. Conversely, the change in wind direction on 3 July resulted in a critical level that halted OGW propagation at a lower altitude (Figure 7c), and OGWs generated by the westerly surface wind were filtered in the troposphere. However, it is worth noting that a stationary, wave-like structure formed at approximately 20 km altitude; this wave is shown in Figure 7c, and its source remains a mystery. If this is the OGW, the upward phase propagation cannot be explained, and its existence cannot be resolved by the model at the lower altitudes. If the wave is generated by the wind shear or a secondary wave, its quasi-static characteristics over the mountain become difficult to explain. A similar wave structure was also found by the DEEPWAVE over New Zealand in the Southern Hemisphere [Mixa et al., 2014], and further exploration of this phenomenon is needed.
The horizontal structures of the OGWs at selected tropospheric and stratospheric altitudes at 0530 UTC 1 July are shown in Figures 8a and 8b, respectively. OGWs are extremely prominent at 8 km over the CMR of Taiwan (Figure 8a); however, they weaken as they propagate upward to an altitude of 33 km (Figure 8b).

To further estimate the orographic influence on typhoon-induced GWs, a modified WRF simulation of Typhoon Mindulle was conducted using the same settings from the first run with the orography removed (resp. WRF and WRF-FLAT). We set the altitude and slopes to zero for all geographical data, similar to the method used by Réchou et al. [2013]. When we compared the mean meridional/zonal winds derived from the WRF and WRF-FLAT models, we found that only minor differences existed (not shown). The WRF-FLAT vertical gradients of the vertical wind components (dw/dz) for the same altitudes and times used in the standard WRF run (Figure 5) are shown in Figure 9. The semicircular concentric GWs generated by the typhoon were reproduced in the WRF-FLAT run. It should be noted that the waves over Taiwan, which are distinct in Figures 5a and 5d, disappear in Figures 9a and 9d on 1 July. By averaging dw/dz of WRF-FLAT at the same altitudes and within the same timeframe as denoted in Figures 8a and 8b, we found that no evident OGWs appear (Figures 8c and 8d).

Furthermore, we calculated the vertical profiles of the regional mean zonal momentum fluxes for total GWs and OGWs, as well as the ratio of the OGW component to the total zonal momentum fluxes in the stratosphere (12–30 km) over Taiwan at 0530 UTC 1 July and 0530 UTC 3 July, respectively. The results are shown in Figure 10. At 0530 UTC 1 July, the zonal momentum flux is positive at all altitudes, while at 0530 UTC 3 July, the zonal momentum flux changes from negative to positive at 10 km altitude. The momentum fluxes carried by the OGWs are similar to the total GW momentum flux, especially in the troposphere, and the momentum flux of OGWs in the troposphere contributes approximately 60% and 50% of the total momentum flux on 1 July and 3 July, respectively. By comparing the zonal momentum flux values from the troposphere on these 2 days, we see that the amplitude of momentum flux is much larger on 1 July (Figures 10a and 10b). As shown in Figure 7a, the low-level zonal wind directions changed during these 2 days. Differences between the OGW generation and propagation and the tropospheric zonal momentum flux directions on these 2 days are likely due to different surface wind patterns. These differences may also be confirmed by the contribution of OGW to the total momentum flux, as shown in Figure 10c. In the stratosphere, OGWs accounted for ~10–20% of the total momentum flux on 1 July, while the portion was <5% on 3 July (Figure 10c).

Figure 11 shows PSDs for the vertical gradients of the vertical wind components dw/dz with respect to the horizontal wavelengths at the troposphere (8 km), tropopause (12 km), and stratosphere (33 km) for TGWs derived from the standard WRF (solid line) and WRF-FLAT (dotted line), as well as the OGWs (red line), during (1 July).
and after the typhoon landing (3 July). The TGWs were calculated using \( \frac{d w}{d z} \) in standard WRF and WRF-FLAT models for 0530 UTC 1 July and 0530 UTC 3 July (before landing and after the typhoon landed, respectively), while the OGWs were reconstructed from 12 h averaged \( \frac{d w}{d z} \) in the standard WRF. The TGWs in the WRF-FLAT model were deemed “pure” TGWs, i.e., without the orographic influence. In the troposphere \((z = 8 \text{ km})\), the OGWs exhibited considerable amplitude and accounted for approximately 50% of the total values both on 1 July and 3 July (Figures 11a and 11d). Meanwhile, the OGW PSDs in the troposphere were much larger on 1 July than on 3 July, which is consistent with the results of zonal momentum fluxes shown in Figure 10. At the tropopause, the magnitude of the OGWs was significantly reduced; the pure TGWs accounted for 80% of the total GW magnitude on 1 July without the existence of the critical level (Figure 11a) but accounted for approximately 90% of the total GW spectrum on 3 July because most of the OGWs were filtered at the critical level (Figure 11d). In the stratosphere, the pure TGWs were responsible for more than 90% of the total GW magnitude. The sum of magnitudes of the OGWs and the pure TGWs roughly equals that of the total GWs derived in the standard WRF. The PSD method is a feasible and effective way to determine the relative importance of orographic waves and convective waves by altitude. However, the method only isolates the orographic and convective gravity waves linearly and ignores interactions between them. Furthermore, the WRF-FLAT run may have altered local flow patterns near Taiwan because the orography was removed, which may have affected the convective activity as well as the GWs.

Alexander et al. [2009] observed that small island gravity waves may be an important missing or grossly underestimated source of GWs and drag in climate models. Alexander and Grimsdell [2013] examined AIRS observations to detect gravity waves in the stratosphere above 14 islands in the Southern Hemisphere. In their study, surface winds and peak altitude played a significant role in the occurrence of orographic waves. Generally speaking, stationary OGWs tend to be filtered in the summer over Taiwan because easterly wind patterns prevail in the stratosphere. However, typhoons may change the surface flow, as shown in Figure 7, which provides favorable conditions for the vertical propagation of OGWs, especially during the typhoon landing. The portion of landfalling typhoons to formed typhoons is large; for example, of the 29 typhoons formed during the 2004 Pacific typhoon season, 19 landed (http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/bstve_2004_m.html). Thus, the orographic impact during typhoon landings could propagate OGWs into the upper atmosphere, particularly when typhoon-induced changes to prevailing summer wind patterns occur, and contribute to atmospheric momentum and energy transport at higher altitudes.
6. Summary and Conclusions

The 8.1 μm and 4.3 μm AIRS channels were used to detect the convective source and corresponding GWs related to Typhoon Mindulle (2004), respectively. The center of the semicircular GWs identified in the stratosphere using the 4.3 μm AIRS brightness temperature was correlated with the deep convection center. The GWs observed through the AIRS data generally propagated eastward; they had a mean brightness temperature perturbation of 0.5 K and a horizontal wavelength of 100 to 400 km in the altitude range 30–40 km.

The WRF model was used to investigate the GWs generated by Typhoon Mindulle in detail. The typhoon-induced GWs simulated by the WRF model correlated well with the AIRS observations in the stratosphere, and a similar semicircular GW structure was reproduced at the same location by the WRF simulation. The GWs at the tropopause (TGW launch level) exhibited a variable distribution, with the prevailing orientations being northwest, northeast, and southeast. The westward propagating GWs were filtered by an easterly background wind as they propagated upward, and the eastward GWs dominated when they entered the stratosphere. The structures of TGWs at three stages (before landing, during landing, and after landing) were also compared using the WRF simulation.

We calculated regionally (16–31°N, 114–128°E) averaged momentum flux and the corresponding body force carried by the GWs. During the simulation, the zonal momentum flux and body force were always positive (eastward), with mean magnitudes of 2.0 mPa and 1.2 ms⁻¹day⁻¹, respectively, in the stratosphere, as determined by the dominant eastward propagating GWs. However, the meridional momentum flux and body force shifted from northward to southward, and the mean magnitudes were weaker than those in the zonal direction. The meridional direction variations may be associated with meridional wind reversals in the area to the north of Taiwan in lower stratosphere.

By comparing the WRF-FLAT results to the standard WRF results, we found that orography does not play a significant role in the generation or propagation of stratospheric TGWs in this case. Regardless of the TGWs, large-amplitude OGWs with horizontal wavelengths of approximately the same scale as the CMR in the troposphere were generated parallel to the mountain ridge under the influence of the typhoon. OGW propagation was determined by the position relative to the typhoon center and the orography because typhoons strongly influence surface winds. We found that the OGWs propagated upward prior to the typhoon landing, when the background wind was easterly from the surface to high altitudes without the existence of the critical level, but were filtered by the critical level in the troposphere after typhoon landing. Because OGWs account for a large portion of the total GWs in the troposphere and dozens of cyclones and typhoons are formed in the Pacific every year, they are an essential contribution to the momentum and energy budgets of global circulation and should not be ignored.

References


