Analysis of the characteristics of gravity waves during a local rainstorm event in Foshan, China

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ABSTRACT
A detailed analysis of the dynamic frequency spectrum characteristics of gravity waves (GWs) during a local heavy rainfall event on 20–21 November 2016 in Foshan, China, is presented. The results of this analysis, which were based on high-precision microbarograph data, indicate that GWs played a key role in generating the rainstorm. The GWs experienced two intermittent periods of amplitude enhancement and period widening. The largest amplitudes of the GWs were 80–160 Pa, with a corresponding period range of 140–270 min, which were approximately 4 h ahead of the rainstorm. The severe storms appeared to affect the GWs by augmenting the wave amplitudes with center amplitudes of approximately 80–100 Pa and periods ranging between 210 and 270 min; in particular, the amplitudes increased to approximately 10 Pa for GWs with shorter periods (less than 36 min). The pre-existing large-amplitude GWs may be precursors to severe storms; that is, these GWs occurred approximately 4 h earlier than the time radars and satellites identified convective. Thus, these results indicate that large-amplitude GWs constitute a possible mechanism for severe-storm warning.

1. Introduction

In the troposphere, gravity waves (GWs) play an important role in adjusting the circulation of nearby clouds, releasing unstable energy, and initiating severe weather systems (Bosart and Sanders 1986; Koch and Dorian 1988; Plougonven and Zhang 2014). Convection systems are thought to be another source of GWs, exerting positive feedback upon the periods, amplitudes, and velocities of GWs (Curry and Murty 1974; Balachandran 1980). Therefore, studying the characteristics of GWs during convective activities is meaningful for forecasting severe storms as well as for understanding the interactions between GWs and severe storms.

Studies of GW characteristics during severe storms mainly focus on theories and observations. Li (1978) noted that GWs could trigger torrential rain and estimated the mesoscale pressure disturbance fields, potential temperature disturbance fields, and distributions of vorticity and divergence in GW structures by calculating the Boussinesq approximation equation. Chao (1980) revealed that the propagation of GW energy profoundly affects the area of heavy rainfall. Ran and Chen (2016) calculated the nonhydrostatic wave equation set in Cartesian coordinates and found that the generation of GWs is closely associated with the release of condensational latent heat in a mesoscale convection system.

In terms of GW observations, in the past, mean features of long-period GWs (one hour to several hours) have been obtained from observations of surface pressure fluctuations by ground-based instruments such as conventional surface barometers. These features have

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been reported in a series of papers (Koch and Golus 1988; Ruppert and Bosart 2014; Stobie, Einaudi, and Uccellini 1983; Uccellini 1975). These studies showed that long-period GWs (0.5–4 h) with large amplitudes of 50–1500 Pa and wavelengths of 50–500 km can induce zonal precipitation and lead to the generation of hail or a rainstorm.

In recent years, many researchers have observed the mean characteristics of short-period GWs (several to dozens of minutes) by using microbarographs, which provide high-precision pressure data (Hauf et al. 1996). Curry and Murty (1974), Balachandran (1980), and Rees et al. (2000) utilized a microbarograph network to emphasize the GWs of 1–20-min periods, calculating wave properties such as amplitudes and wavelengths.

However, previous studies have mostly focused on the mean features of long-period or short-period GWs associated with convective systems, while studies on the temporal evolution of GW frequency spectra during convection systems are relatively rare. Li, Xie, and Yang (1993), providing a GW dynamic spectrum using microbarograph data, noted that GWs of large amplitudes (>30 Pa) with short periods ranging from 30–70 min precede hailstorms by 1–4 h. Nevertheless, the dynamic properties of the frequency spectra of long-period (≥70 min) GWs were not considered in their study.

In this paper, the dynamic characteristics of both long-period (80–270 min) and short-period (≤80 min) GWs during a rainstorm event in Foshan, China, on 20–21 November 2016 are presented. High-resolution spatial and temporal pressure data from a microbarograph were used to obtain temporal evolutions of the amplitudes and periods of the GWs and to investigate the effects of pre-existing GWs upon convections, as well as the feedback effects of convections upon the waves.

2. Data and methods

The 20–21 November 2016 GWs were documented using microbarograph data, data from 192 Foshan surface automatic meteorological stations, radar data from Guangzhou, and Feng-Yun-2G (FY2G) satellite black body temperature (TBB) data downloaded from http://data.cma.cn/.

Microbarographs can detect surface pressure disturbances. A microbarograph was independently developed by the Key Laboratory of Cloud-Precipitation and Severe Storms, Institute of Atmospheric Physics, Chinese Academy of Sciences, and has been continuously operated since 1 May 2016 in the Sanshu district of Foshan (Figure 1).

Microbarographs have three obvious advantages over conventional barometers. First, microbarograph data have higher sensitivity and detection accuracy, and the detection precision is 0.1 Pa with a sampling frequency of 1 Hz and a minimum probing frequency of $10^{-5}$ Hz. Second, a constant temperature technique is applied to ensure that the environmental temperature is stable to within 0.5°C. Third, noise filtering is applied to the pressure data to avoid noise interference.

To analyze the dynamic spectrum of these GWs, fast Fourier transform (FFT), a signal processing technique that converts a signal from the time domain to the frequency domain, was performed on the microbarograph data. The sampling points were selected as 16384, and the sampling frequency was set as 1 Hz. The microbarograph data were calculated with the FFT method every second to obtain the wave amplitudes and periods up to the current time. Then, after gathering data to visualize the FFT results at each time step, the evolution of the GW periods and amplitudes with time were obtained.

3. Overview of heavy rainfall

A heavy rainfall event occurred from 1800 Beijing Time (BJT) 20 November to 0100 BJT 21 November 2016 in Foshan, China. Almost all heavy rainfall stations (Figure 1) were distributed in the Sanshu district of Foshan, China.

Measurements from station G6953 were selected to demonstrate the rainfall event (Figure 2). This figure shows the 5-min accumulated rainfall, perturbation pressure ($\rho'$) with the 24-h mean removed, dewpoint temperature, and temperature. The data illustrate that the main rainfall occurred from 2200 BJT 20 November to 0100 BJT 21 November 2016. The accumulated precipitation was 107.3 mm. There was obvious pressure fluctuation at 2300 BJT; and at the same time, a burst of intense rainfall
coincided with the ridge of $\rho'$. It can be seen that the pressure fluctuation coincided with a burst of precipitation, and such a close relationship is a fundamental feature of GWs (Li 1978).

A sequence of radar echoes revealed that several scattered radar echoes appeared and soon dissipated from 1500 to 1800 BJT over Foshan (figure omitted). Strong echoes began to develop after 1800 BJT (Figure 3), accompanying precipitation from 1800 BJT 20 November to 0100 BJT 21 November (Figure 2). Afterwards, strong echoes quickly moved north and weakened at 0100 BJT on 21 November (figure omitted).

4. GW dynamic characteristics

FFT was applied to the microbarograph data to obtain the dynamic spectrum of the GWs (Figure 4). To analyze the dynamic characteristics of these GWs in more detail, the periods of the GWs were divided into two parts: long-period GWs (80–270 min) with amplitudes smaller than 20 Pa omitted (Figure 4(a)) and short-period GWs (< 80 min) (Figure 4(b)). Both Figure 4(a,b) were obtained by applying FFT.

4.1. Long-period GW dynamic characteristics

Figure 4(a) shows that the GWs with long periods (80–270 min) had amplitudes of between 20 and 160 Pa. As the periods of the GWs increased, their amplitudes became larger. Three evolutionary stages were observed: 0630–1130 BJT 20 November, 1130–1800 BJT 20 November, and between 1800 BJT 20 November and 0100 BJT 21 November. The amplitudes of the GWs first increased and then decreased in every stage. To gain insight into the relationship between GWs and heavy rainfall, two phases were distinguished:

(1) Before the rainstorm (0630–1800 BJT 20 November): GWs with periods of 220–270 min appeared at 0630 BJT, and then the amplitudes of the GWs increased continuously. During 0800–1030 BJT, the amplitudes of the GWs increased rapidly to 60–80 Pa, and the periods ranged from 200 to 270 min. Then, the amplitudes of the waves decreased quickly.

The amplitudes of the GWs started to increase for a second time at 1130 BJT. In particular, the amplitudes of the GWs increased dramatically at 1400–1500 BJT. For example, the waves had amplitudes of less than 60 Pa with periods of 80–270 min at 1130 BJT, and their amplitudes increased to 40–160 Pa with periods of 80–270 min at 1400–1500 BJT. In particular, the central amplitude of GWs reached 80–160 Pa with periods ranging from 140 to 270 min. Furthermore, the central amplitudes of the GWs during this second increasing stage were apparently greater than those during the first stage. The amplitudes of the GWs began to decrease quickly after 1500 BJT, and strong radar echoes (Figure 3) suggest that severe storms appeared at 1800 BJT. Therefore, the second amplitude enlargement was approximately 4 h before the storm.

(2) During the rainstorm (1800 BJT 20 November to 0100 BJT 21 November): Figure 5 displays the evolution of the TBB. Maddox (1980) proposed that $-32^\circ$C and $-52^\circ$C TBBs can be used to identify mesoscale convective systems. Generally, TBB $\leq -32^\circ$C and TBB $\leq -52^\circ$C are the thresholds for identifying convective systems. Figure 5 shows severe storms with TBB $\leq -52^\circ$C at 1800 BJT, after which these mesoscale storms moved eastward. The convectons began to weaken at 1900 BJT, and the TBB quickly decreased to less than $-32^\circ$C at 2100 BJT. However, the storms strengthened again with TBB $\leq -52^\circ$C from 2200 BJT 20 November to 0000 BJT 21 November. Therefore, both the radar data (Figure 3) and the TBBs (Figure 5) demonstrate that deep convections were initiated at 1800 BJT, but the amplitudes of all the GWs sharply decreased to lower than 40 Pa (Figure 4(a)). Li (1978) showed that a stable atmosphere favors GW generation, while a violently unstable atmosphere promotes GW disappearance. The features of the GWs at 1800 BJT were consistent with the above theory. Severe storms continued to develop after 1800 BJT (Figures 3 and 5), accompanying small amounts of precipitation during 1800–2200 BJT (Figure 2). At the same time, the
amplitudes of the GWs increased for a third time. The waves had central amplitudes of 80–100 Pa and periods between 210 and 270 min during 2030–2200 BJT. Soon thereafter, short and intense precipitation occurred from 2200 BJT 20 November to 0100 BJT 21 November, which represented the principal stage of heavy rainfall (Figure 2). Clearly, the growth of convections followed the occurrence of large-amplitude GWs, which in turn contributed to short and intense precipitation from 2200 BJT 20 November to 0100 BJT 21 November.

4.2. Short-period GW dynamic characteristics

Figure 4(b) reveals that the GWs had short periods of 4–80 min with amplitudes ranging from 1 to 45 Pa. Again, three stages were observed: 0700–1100 BJT 20 November, 1200–1800 BJT 20 November, and from 1800 BJT 20 November to 0100 BJT 21 November. The analysis below was also based on two phases:

(1) Before the rainstorm (0700–1800 BJT 20 November): The amplitudes of the short-period GWs started to increase at 0700 BJT. The waves had central amplitudes of 20 Pa and periods ranging from 60 to 80 min during 0800–1030 BJT. In addition, GWs with narrow periodic ranges of 26–32 min and amplitudes of approximately 10 Pa were initiated. Then, the amplitudes of the GWs decreased rapidly to 5 Pa. The amplitudes of the short-period GWs began to clearly increase for a second time at 1200 BJT. The largest amplitudes of the short-period GWs (60–80 min) were approximately 35 Pa during 1400–1600 BJT. At the same time, waves with shorter periods of approximately 28 min and amplitudes of 12 Pa were also initiated. Then, the amplitudes of the GWs sharply decreased again.

These evolution characteristics indicate that the amplitude variations of the short-period GWs were the same as those of the long-period GWs. The GWs also experienced two intermittent amplitude enlargement processes that occurred prior to the arrival of severe storms, and GWs of short periods were initiated during the two enlargement processes.

(2) During the rainstorm (1800 BJT 20 November to 0100 BJT 21 November): The short-period GWs...
(60–80 min) were initiated with amplitudes of approximately 12 Pa during 1800–1900 BJT. Then, intermittent shorter-period (≤ 36 min) wave activities were excited by strong convections, including GWs with central amplitudes of approximately 25 Pa and periods ranging from 52 to 80 min, GWs with central amplitudes of approximately 12 Pa and periods ranging from 34 to 36 min, GWs with amplitudes of approximately 10 Pa and periods of approximately 28 min, GWs with amplitudes of approximately 10 Pa and periods of approximately 25 min, and GWs with amplitudes of approximately 10 Pa and periods of approximately 20 min. Clearly, the development of strong convections was in accordance with the generation of shorter-period GWs (≤ 36 min). Moreover, such GWs were also closely related to the short burst of intense precipitation that occurred between 2200 BJT 20 November and 0100 on 21 November.

The above analysis reveals that large-amplitude GWs preceded and initiated deep convections. Before the rainstorm, the wave activities were characterized by intermittently increasing amplitudes and periodic ranges at two times. For instance, the GWs had central amplitudes of 60–80 Pa during 0800–1030 BJT and 80–160 Pa during 1400–1500 BJT with corresponding period ranges of 200–270 min and 140–270 min, respectively. The central amplitudes of the short-period GWs (60–80 min) were approximately 20 Pa and 35 Pa. The largest amplitudes of the GWs preceded the convective storm by approximately 4 h.

During the rainstorm, convections positively impacted the GWs by augmenting the wave amplitudes and greatly increasing the period ranges. For example, the long-period GWs (210–270 min) had large amplitudes of 80–100 Pa during 2030–2200 BJT, and GWs with shorter periods ranges (≤ 80 min) had amplitudes of approximately

Figure 4. GW dynamic frequency spectra (shaded: amplitudes, units: Pa; y-axis: periods, units: min; x-axis: time; denotes the onset time of heavy rainfall; (1) and (2) denote before the rainstorm and during the rainstorm respectively) from 0600 BJT 20 November to 0200 BJT 21 November 2016: (a) the periods below 270 min; (b) the periods below 90 min.
10–25 Pa. Notably, the GWs and convections interacted with each other. Such results are in accordance with those of previous studies (Bosart and Sanders 1986; Curry and Murty 1974; Ruppert and Bosart 2014; Uccellini 1975).

4.3. The possibility of early warnings by large-amplitude GWs

Figure 4 suggests that pre-existing large-amplitude (80–160 Pa) GWs with periods ranging between 140 and 270 min during 1400–1500 BJT preceded convections by approximately 4 h. Such results may be meaningful for providing early warnings for storms.

At present, severe-storm identification and warning systems are often made with radar and satellite data. The warning time for severe storms can range from several to dozens of minutes. Grum, Saffle, and Wilson (1998) determined that storm warnings could occur approximately 20 min prior to heavy rainfall events. The radar and satellite data first identified convections at 1800 BJT (Figures 3 and 5). The large-amplitude GWs (80–160 Pa) appeared during 1400–1500 BJT; that is, 4 h before the radar- and satellite-identified convections. Therefore, in this case, GWs are possibly superior in their ability to provide warnings related to heavy rainfall events compared with radars and satellites. However, whether large-amplitude GWs are suitable to provide warning of convections for other severe storms remains to be investigated.

5. Conclusions

This study documents the 20–21 November 2016 rainstorm event in Foshan, China, in which GWs were closely linked to local heavy rainfall. Based on the high-resolution pressure data collected by a microbarograph, the dynamic characteristics of
the frequency spectra of GWs were obtained to analyze the effects of pre-existing GWs on convections as well as the feedback effects of convections upon GWs. The findings are summarized below.

1. This heavy rainfall event was characterized by a small spatial scale, short life history, and sudden onset. This process was closely related to GWs, in which the ridge of the perturbation pressure corresponded with a short and intense burst of precipitation.

2. Large-amplitude GW precursor activities were observed over several hours. The GWs were characterized by an intermittent increase in amplitudes and two widenings of their period ranges. The largest amplitudes of the long-period GWs (140–270 min) and short-period GWs (60–80 min) were 80–160 Pa and approximately 35 Pa, respectively.

3. When convections developed, the center amplitudes of the long-period GWs (210–270 min) increased to 80–100 Pa, accompanied by short-period GWs (52–80 min) with amplitudes of approximately 25 Pa and GWs with shorter period ranges (34–36 min, 28 min, 25 min, and 20 min) with amplitudes of approximately 10 Pa.

4. Large-amplitude GWs initiated severe storms, and the development of storms promoted increases in the GW amplitudes, especially those of GWs with shorter period ranges (≤36 min). The relationship between them was interactional.

5. The occurrence of intermittent large-amplitude GWs is possibly meaningful for severe-storm warnings; that is, these GWs identified storms approximately 4 h before radar and satellite data were able to identify them.

Several questions remain unanswered. For instance, the enhanced GWs triggered the storms in this case, but what was the direction of the GW source? Where was the GW source? These questions will be answered by installing more microbarographs to locate the GW source.

**Acknowledgments**

The author gratefully acknowledges YU Rui, YU Lefu, and the Foshan Meteorological Bureau for the supporting meteorological data.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**Funding**

This study is sponsored by the National Key R&D Program of China [Grant No. 2018YFC1507900] and the National Natural Science Foundation of China [Grant No. 41530427].

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