Research on the Observation, Simulation and Mechanism of Typhoon-induced Inertial Gravity Waves

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Abstract Typhoons, as strong convective systems, can excite multi-scale atmospheric gravity waves that travel long distances, and play an important role in momentum and energy transmission between the middle and upper atmosphere. In this paper, the research progress in the observation techniques, generation mechanism and propagation characteristics of typhoon-induced gravity waves were systematically reviewed. These studies show that based on the combined application of ground-based and space-based observation (sounding balloons, airglow imaging, and satellite remote sensing) and reanalysis data (such as ERA5), with the aid of ray tracing theory and numerical simulation technology, the mechanism of typhoon induced gravity waves and its dynamic characteristics in the middle and upper atmosphere have been better revealed. At present, there are still some insufficiencies in the fields of propagation path tracking of gravity waves, terrain multi-scale effect modeling and parameterization of inertial gravity waves, which need to be further studied in the future.
Key words Typhoon; Gravity waves; Ray tracing; Terrain effect
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The middle and upper atmosphere is a general term for the middle atmosphere (10 - 100 km) and the upper atmosphere (> 100 km). Atmospheric gravity waves, which are buoyancy oscillations widely existing in stable stratified fluids, play an important role in the middle and upper atmosphere. As a weather system organizing strong convection, typhoon brings strong winds and rainstorm to the ground, and the excites atmospheric gravity wave which propagates vertically and horizontally along the typhoon path, and has an important influence on the evolution of the typhoon itself and the dynamics of the middle and upper atmosphere. In recent years, ground-to-space observation (such as sounding balloons, all-sky airglow imagers, satellite remote sensing, *etc.*) and numerical simulation technology have gradually matured, which provides the possibility for in-depth research on the principle, propagation characteristics and influence of typhoon-induced gravity waves. In this paper, the research progress of typhoon-induced gravity waves was systematically reviewed, and the excitation mechanism of typhoon gravity waves and the current situation of observation methods were analyzed. Besides, the possible research development direction in the future was discussed.

1 Methods of observation and simulation analysis of gravity waves

So far, there are two methods to study atmospheric gravity waves: one is to extract gravity wave signals directly from ground-based and space-based observation data, and the other is to simulate gravity waves through numerical models such as WRF and WACCM. With the continuous iteration and updating of ground-based and space-based observation equipment, it is possible to analyze most gravity spectra by high-resolution numerical simulation. The main instruments used to detect gravity waves are sounding balloons, lidar, TIMED/SABER satellites, *etc.*

1.1 Ground-based and space-based observation techniques

1.1.1 Sounding balloon observation. Sounding balloon observation can obtain high-resolution vertical atmospheric structure below the lower stratosphere, including physical quantities such as temperature, wind, and air pressure, which is an important source for extracting characteristic information of gravity waves[1]. Generally, disturbance data are obtained by subtracting the background field fitted by a polynomial from profile data[2]. Low-frequency inertial gravity waves can be captured by Lomb - Scargle spectral analysis and vector terminal curve method[3]. This method of extracting gravity waves has been widely verified and applied. For instance, the vertical wavelength and other parameters of inertial gravity waves are extracted in Alaska[4] and very low stratosphere[5]. Gravity fluctuation flux phase velocity spectrum in Wuhan was analyzed[6]. In the tropical region, the background atmosphere fitting method was improved, and gravity waves were extracted by the extended empirical orthogonal function (EEOF)[7]. However, the extraction of gravity wave parameters based on sounding balloons has its own limitations. Firstly, the spatial distribution is limited by the location of stations, and the spatial sampling of data is not uniform. Secondly, the sounding station releases sounding balloons twice a day, and the time continuity of the data is poor.

1.1.2 All-sky airglow imager. An all-sky airglow imager is a space atmosphere detection equipment supporting China's meridian

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project, with the advantages of large field of view, multiple bands, high temporal and horizontal resolution[8]. Since atmospheric gravity waves in the mesosphere and low thermosphere are one of the main factors affecting the intensity of airglow radiation[9], the characteristic parameters of inertial gravity waves can be identified through two-dimensional images of the horizontal distribution of the radiation[10]. Therefore, it has been rapidly applied in the observation of gravity waves in the middle and upper atmosphere[11]. It was improved in ongoing research. For example, the two-dimensional cross-period spectrum method was used to identify gravity waves in OH airglow images[10]. The seasonal characteristics of gravity waves observed in airglow images were analyzed in middle and low latitudes in China[8], and the momentum flux of gravity waves was calculated[12]. The machine learning method was adopted to identify the occurrence events of atmospheric gravity waves in the Plateau region and obtain propagation parameters[13], and the influence of atmospheric gravity wave propagation on the distribution of airglow was further studied[14].

1.1.3 Satellite data observation. TIMED satellite was launched by the National Aeronautics and Space Administration (NASA) on December 7, 2001. The satellite updates data slowly at a specific observation point, and runs for about 60 d to achieve global 24-hour data coverage. 15 orbits of data can be measured every day, and one orbit contains 96 detection profiles. There are more than 1 000 detection profiles of the upper-middle vertical structure of the Earth's atmosphere everyday[15], which can cover most areas of the world in the range of about 83° N – 52° S. TIMED carries four observation instruments, one of which is the broadband radiometer for atmospheric exploration (SABER)[16]. SABER, a multi-channel radiometer[17], completes a horizon scan within 58 s to measure atmospheric thermal radiation in ten selected bands (wavelength 1.27 – 17 um) and then obtain effective vertical profile data of atmospheric temperature, density, water vapor and carbon dioxide at altitudes from 180 km to the Earth's surface. The temperature data measured by this method is very accurate, and the temperature accuracy is less than 0.3 K at an altitude of 10 – 70 km and 0.7 K at 70 – 80 km[16]. SABER satellite data are generally region-average grid profile data formed through horizontal and vertical interpolation, and their processing method is similar to that of radiosonde data. A brief flow of the method for extracting atmospheric gravity waves from sounding and satellite observation is showed in Fig. 1.

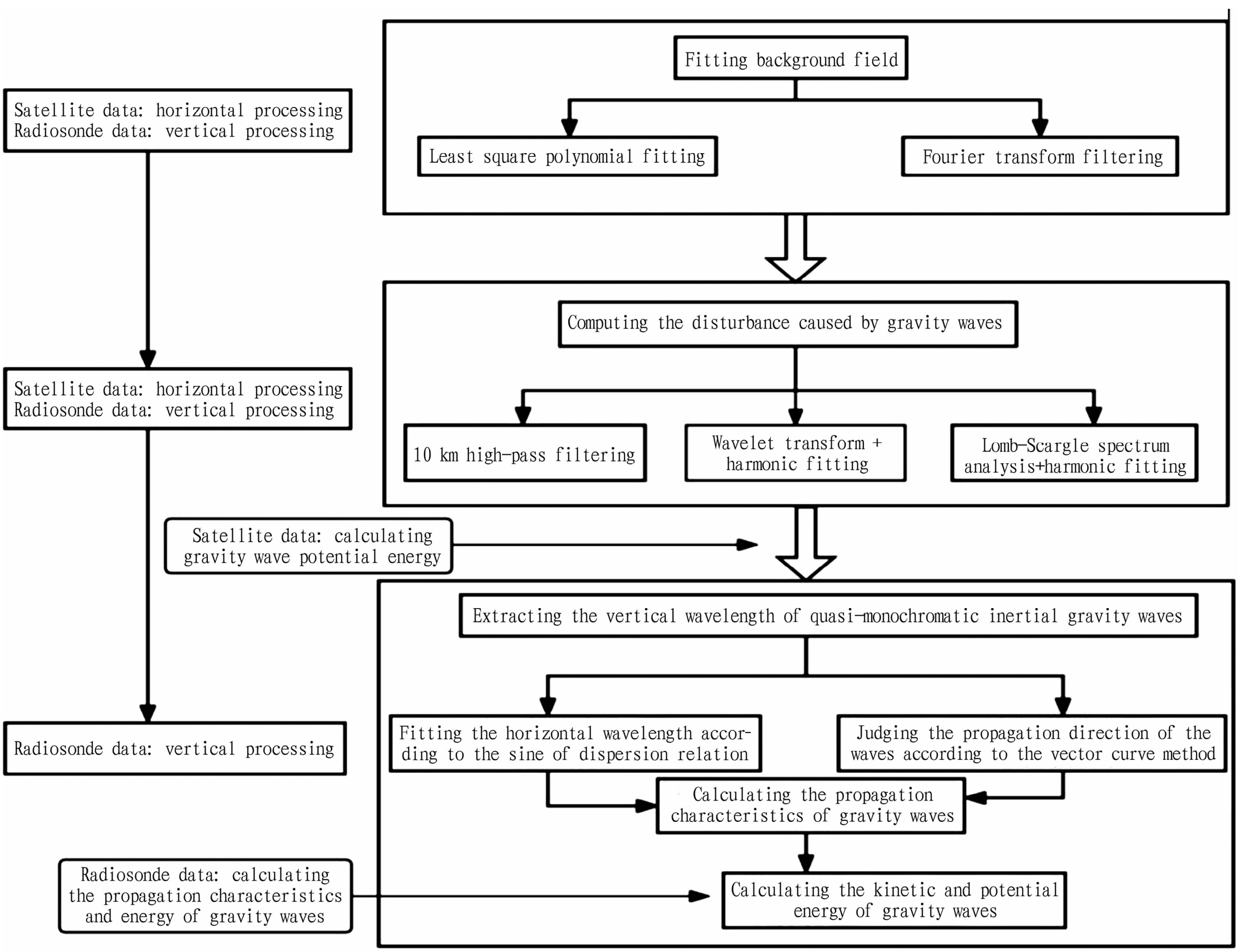

Fig. 1 Brief flow of the method for extracting atmospheric gravity waves

1.1.4 ERA5 reanalysis data. ERA5 reanalysis data is the fifth generation of atmospheric reanalysis data set produced by the European Centre for Medium – Range Weather Forecasts (ECMWF), formerly known as ERA – Interim reanalysis data. ERA5 is a global reanalysis data since January 1950, which consist of hour-by-hour data of the atmosphere, land and oceans. The data have a resolution of about 0.125 latitude and longitude degrees horizontally, and 137 layers vertically (from the surface to 80 km). ERA5 has been widely used in studying the excitation sources of gravity waves in the middle and upper atmosphere, such as gravity waves stimulated by deep convection[18], topography over the Tibetan Plateau[19], and the influence on rainfall of gravity waves stimulated by both convection and topography[20]. The vertical coverage of gravity wave detection instruments/sources together with the vertical structure of atmosphere are showed in Fig. 2.

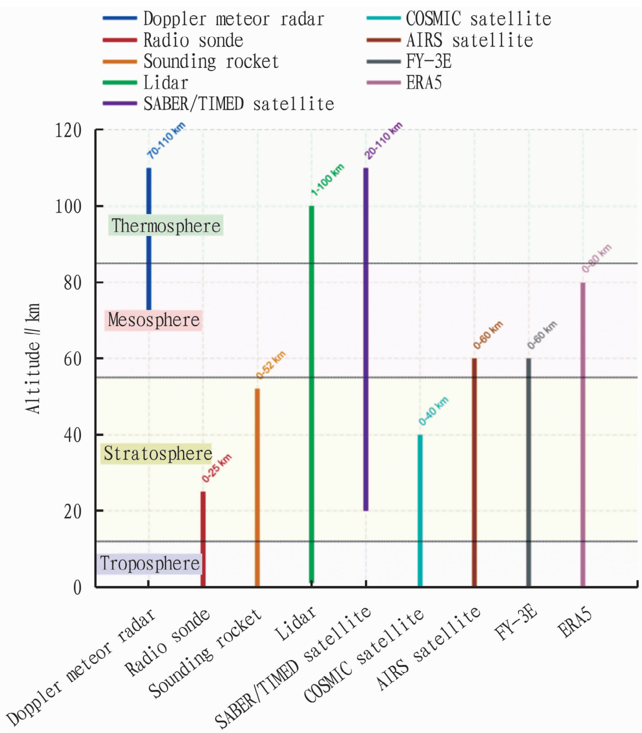

Fig. 2 The vertical coverage of gravity wave detection instruments/sources and structure of the atmosphere (0 – 120 km)

1.2 Numerical simulation and theoretical models

1.2.1 Ray tracing technology. Ray tracing technology has been widely used to study the source of atmospheric gravity waves in the middle and upper atmosphere[21]. This algorithm is based on wave propagation theory, and the propagation and characteristics of gravity waves in the atmosphere are analyzed by simulating the propagation trajectory of waves. The algorithm can not only help us understand the propagation mechanism of gravity waves, but also reveal the location and characteristics of wave sources. The ray tracing program first needs to input the initial data of ray tracing (longitude, latitude, height, vertical wave number, longitudinal vertical wave number, and zonal vertical wave number) and set the program cutoff conditions (WKB approximation), and then integrate through RK4 or Matsuno iterative format, fix the integral step size, and set the integral direction to achieve "forward" and "backward" tracking. Finally, a complete ray path is calculated, and the position of wave sources (longitude, latitude, height, vertical wave number, longitudinal vertical wave number, and zonal vertical wave number) is recorded and output. This technique has been widely applied in the research on the temporal and spatial variation of atmospheric gravity waves[22]. A ray tracing model for atmospheric gravity wave tracing was constructed[16]. Combined with lidar observation data, the source of gravity waves in the upper atmosphere was traced[23], and the characteristics of gravity waves over the Tibetan Plateau were studied[13].

1.2.2 Numerical models. Three-dimensional mesoscale model (MM5) and mesoscale numerical prediction model (WRF) were used to study the characteristics of gravity waves excited by tropical cyclones, including their effects on the background flow and the tropical cyclone itself[24]. MM5 is the representative of the early mesoscale numerical model with old parameterization schemes. WRF is a mesoscale model that replaces MM5 and improves the ability to simulate cloud-scale to synoptic-scale systems. In addition, a global atmospheric climate model (WACCM6), which contains a simple gravity wave parameterization scheme, can reproduce the data of temperature, wind and trace component in the global middle atmosphere[25]. It can simulate the stratospheric explosive warming[26]. The simulation level of the aligned quasi-biennial oscillation (QBO)[27] and the long-term trend of the middle atmosphere is high, and it has been applied to the analysis of the high-precision simulation of gravity waves excited by tropical cyclones[28]. However, WACCM6 has difficulty to diagnose small-scale gravity waves in the vertical direction. In contrast, regional WRF model can better simulate gravity wave signals[29]. Through numerical simulation, some scholars had studied the influence of gravity waves on sea fog[30] and gravity waves stimulated by the Southwest Vortex[31].

2 Generation and propagation mechanism of gravity waves induced by typhoons

2.1 Excitation sources of gravity waves Atmospheric gravity waves can be divided into high-frequency, medium-frequency and low-frequency gravity waves according to their frequency. Atmospheric gravity waves exist widely in the disturbance of the atmosphere, and are closely related to many phenomena in the atmosphere[32]. Atmospheric gravity waves are often generated by terrain[33], typhoons[29,34], fronts[35], and thunderstorms[36]. Among them, topographic forcing[33] often occurs when the horizontal movement of surface wind speed is hindered by mountains to stimulate topographic gravity waves, and topographic gravity waves propagate vertically upward[2], causing changes in the middle and upper atmosphere. Typhoons[34] and fronts[37] belong to background circulation excitation, wherein the gravity wave is mainly caused by the evolution, geostrophic adjustment and base loss stability. Under a stable stratified atmospheric background, convection and vorticity disturbance regions interact with the background atmosphere[28], thus generating gravity waves. These gravity waves can propagate to the height of mesosphere, even low thermosphere[2]. Among the type of gravity waves induced by background circulation, the most intense one is usually stimulated by the typhoon. As an important excitation source of background circulation, the excited gravity waves not only significantly affect the material exchange in the stratosphere[29], but also have an important impact on the total electron content of the ionosphere[38]. Under the influence of the excitation sources of gravity waves, the lower gravity waves propagate upward. When gravity waves become saturated then breaks, the kinetic energy and monmentum are released to the middle and upper background atmosphere, which stimulates secondary waves and thus generates gravity waves in the middle and upper atmosphere. Therefore, gravity waves in the middle and upper atmosphere generally originate from the lower atmosphere.

2.2 Excitation mechanism of gravity waves by typhoons The internal structure of a typhoon is complex, and its influence range is large in space and time[39]. It is generally believed that the eye wall and spiral rain band of a typhoon are the main excitation sources of gravity waves. Tepper[40] first proposed that tropical cyclones generate gravity waves near the eye wall and propagate outward to become spiral rain zones. In the subsequent studies on the generation of gravity waves near the eye wall of a typhoon[41-44], the reasons for the excitation of gravity waves include convection[41], mesoscale vorticity[42] and updraft[43] or deep convection[44]. Some scholars also believed that the excitation source of typhoon gravity waves is located in the core region of typhoons, and the evidences supporting this theory mainly confirm that the excitation of typhoon gravity waves is due to the vorticity disturbance in the core region[45] and potential vorticity disturbance[46] or unstable vortex motion[47]. In addition, some scholars have proposed that typhoon gravity waves are stimulated by convective movement in the spiral rain band of typhoons[48].

2.3 Characteristics of gravity waves induced by typhoons As early as more than 30 years ago, gravity waves over typhoons and even ionospheric disturbances in the ionosphere over typhoons have been observed[49]. Matsumoto *et al.* [50] detected for the first time that the structure of pressure drop caused by a typhoon was consistent with gravity internal waves, but they failed to directly reveal the relationship between the typhoon and gravity waves. With the continuous refinement of observation equipment and the maturity of observation conditions, the applying of mu radar observation data has made a breakthrough in the study of the characteristics of typhoon-induced gravity waves. For example, Sato[51] used mu radar data to qualitatively show for the first time that typhoon Kelly was one of the important sources of gravity waves in the middle atmosphere, and the gravity waves were inertial gravity waves; the propagation direction was far away from the direction of the typhoon, propagating upward and southwestwards, with a period of 6 h, a vertical wavelength of 6 km, and a horizontal scale of 1 000 km. In 2003, Dhake *et al.* [52] further revealed the characteristics of high-frequency gravity waves stimulated by a typhoon on the basis of Sato's method. It was found that the period of high-frequency gravity waves stimulated by typhoon 9426 was less than 1 h, and the vertical wavelength was 3 km.

Typhoon-induced gravity waves have a wide spectrum range, while different observation data are inherently limited by equipment, and only a single observation equipment can capture only part of the spectral information of gravity waves[2], which is also known as the "observation filtering" effect[53]. In 2002, Chane-Ming *et al.* [54] pointed out that gravity waves could be extracted with daily resolution radiation data, and significant release of gravity wave energy was observed during the landing of typhoon Hudah. In 2010, Chane-Ming *et al.* [55] further used radiosonde to extract the characteristic parameters of gravity waves stimulated by typhoons Dina and Faxai, and pointed out that the horizontal wavelength of gravity waves stimulated by the typhoons in the upper troposphere was less than 2 000 km, while the horizontal wavelength of gravity waves stimulated by typhoons in the lower stratosphere was greater than 2 200 km; the location of the excitation source is in the tropopause, and the vertical wavelength was 1-3 km; the period was 6 h-2.5 d, and the direction of propagation was east. In 2015, Hong Jun *et al.* [29] analyzed the stratospheric gravity waves induced by typhoon "Muifa" using the observation data of high-resolution satellite AIRS. The horizontal wavelength also reached 1 000 km, and the period was 15-25 h, while the vertical wavelength was about 8-12 km. However, Wu *et al.* [56] studied the stratospheric gravity waves generated by typhoon Mindulle using the satellite infrared sounder AIRS, and the horizontal wavelength of the waves was only 100-400 km.

With the continuous development of mesoscale numerical simulation, Kuester *et al.* [57] used MM5 to study gravity waves stimulated by hurricane Humberto. Gravity waves generated by convection were observed in the lower stratosphere, with a horizontal scale of 15-300 km, a vertical scale of 4-8 km, and an internal period of about 20-100 min. In 2005, Chen *et al.* [58] studied the gravity waves induced by typhoon Winnie through a mesoscale model, with a horizontal wavelength of 500-1 000 km and a period of 10-15 h. In the same year, Kim *et al.* [59] also used MM5 to simulate the gravity waves stimulated by typhoon Rusa. At a height of 17-26 km, the gravity waves reaching the upper layer propagated eastwards, with a horizontal wavelength of 300-600 km, a vertical wavelength of 3-11 km, and a period of 6-11 h. It is further pointed out that the convection activities such as typhoons are one of the important sources of gravity waves in summer in the Northern Hemisphere. Based on AIRS satellite temperature disturbance data and WRF numerical simulation of vertical wind/temperature field, Kim *et al.* [48] revealed the characteristics of gravity waves stimulated by typhoon Ewiniar. It is proposed that horizontal wavelength was 50-500 km, and the period was 1 h-1.6 d; gravity waves propagating eastwards dominated in the stratosphere. Chen *et al.* [60] used the mesoscale model WRF-ARW to carry out a case study on the numerical simulation of stratospheric gravity waves excited by typhoon "Matsa". The horizontal wavelength of the excited stratospheric gravity waves was about 1 000 km, and the time period was about 12-18 h, while the vertical wavelength was about 7-9 km. It is also pointed out that the net zonal momentum generated by fluctuations at a height of 20 km had a significant contribution to driving the QBO (accounting for about 26%)[61]. In 2013, Liu[62] used WRF to study the gravity waves induced by typhoon Meranti, and found that the gravity waves had more obvious characteristics on the left side of the typhoon moving direction. In 2018, Yao *et al.* [34] studied the gravity wave stimulated by strong typhoon Soulik. The horizontal wavelength was about 500 km, and the time period was about 3 – 5 h. The vertical wavelength was different at different heights. It was about 10 – 14 km at 20 km, about 14 – 18 km at 30 km, and around 22 – 26 km at 40 km. The fluctuation center of typhoon-induced gravity waves was mainly located on the east side of the typhoon center, namely on the side of positive horizontal wave number. It is worth noting that the area was also the spiral rain belt zone of the typhoon. The characteristics of gravity waves induced by the above-mentioned typhoons are shown in Table 1.

Table 1 Characteristics of gravity waves induced by different typhoons

Typhoon	Vertical wavelength//km	Horizontal wavelength//km	Period//h	Propagation direction
Kelly	6	About 1 000	6	Upside, and southwest
9426	3		<1	
DINA and Faxai	1 – 3	<2 000 (upper troposphere), and >2 200 (lower stratosphere)	6 – 60	East
Muifa	8 – 12	1 000	15 – 25	
Mindulle		100 – 400		
Humberto	4 – 8	15 – 300	0.33 – 1.67	
Winnie		500 – 1 000	10 – 15	
RUSA	3 – 11	300 – 600	6 – 11	East
Ewiniar		50 – 500	1 – 38.4	East
Matsa	7 – 9	Around 1 000	12 – 18	
Soulik	10 – 26	500	3 – 5	

The observational and research methods of gravity waves excited by different typhoons have their own limitations. For example, high-resolution satellite AIRS can only detect stratospheric gravity waves with a vertical wavelength of more than 20 km, while middle-level gravity waves with a vertical wavelength of more than 10 km can be seen based on VIIRS/DNB data[63], and it can be used to observe gravity waves generated by tropical cyclones that travel to an altitude of 80 – 90 km[64]. Mesoscale models can only simulate gravity waves at an altitude of below 45 km[65]. As early as Sato[51] observed the gravity waves induced by a typhoon, it was proposed that the gravity waves induced by the typhoon might affect the disturbance of the upper atmosphere. However, due to the insufficient observation height at that time, further clear data proof could not be obtained. With the development of satellite remote sensing technology, the study of typhoon-induced gravity waves has made more progress. The combination of observation data at different altitudes can indeed confirm the characteristics of the same kind of gravity waves at different altitudes, but there is no observation or simulation data that can comprehensively monitor the origin, development and extinction of gravity waves. In order to further reveal the propagation of gravity waves in the middle and upper atmosphere, the reflection ray tracing technique makes up for the gap of observation data and provides a new research algorithm besides observation.

Ray tracing technology has long been applied to the study of mid-upper atmosphere fluctuations. For instance, some scholars used reverse ray tracing technology to identify possible tropical cyclones in the ionosphere[66–67]. Ray tracing technology has also been widely used in the study of gravity waves in the middle and upper atmosphere. In the study of gravity waves stimulated by super typhoon Chaba[68], ray tracing technology was used to reveal the fact that the gravity waves stimulated by typhoon Chaba were transmitted all the way to the mesosphere (about 87 km), and the secondary waves generated were then transmitted to the thermosphere (about 250 km). The wave had a horizontal wavelength of about 265 and 290 km in the stratosphere, about 156 km in the mesosphere, and around 120 km in the thermosphere.

2.4 Coupling effect of terrain and typhoons Convection activity within a typhoon excites gravity waves. When a typhoon passes through complex terrain (such as mountains, coast, *etc.*), the coupling effect of terrain and a typhoon may also generate a large number of terrain gravity waves in addition to the convective gravity waves generated by the circulation situation[69]. Alexander *et al.* [70] proposed that gravity waves generated by a small island may be an important driving force in climate models. Gravity waves triggered by typhoon Mindulle[28] which landed on Taiwan Island in 2016 only propagated eastwards in the stratosphere, with a horizontal wavelength of about 100 – 400 km, a vertical wavelength of about 6 – 12 km, and a period of 7 – 12 h.

At present, there are few studies on the coupling mechanism of terrain and typhoons. Some scholars have found that the lift effect of topographic gravity waves will cause the typhoon path to deviate, that is, the landing typhoon path is more likely to deviate to the direction indicated by the lift force of topographic gravity waves[71]. In addition to the influence on typhoon paths, in terms of the influence on typhoon intensity, the research results of model simulation provide an effective supplement to the effect of gravity waves on typhoons. Taking gravity wave drag into account in the model can also significantly improve the intensity prediction of landing typhoons and better reduce systematic errors[72]. At present, the research on the coupling effect of terrain and typhoon on gravity waves is still in the preliminary stage, and the related characteristics and mechanism of the induced gravity waves need further research.

3 Controversies, unanswered questions and future research directions

Although remarkable progress has been made in the observation and numerical simulation of typhoon-induced gravity waves, the following three problems still need to be further studied.

3.1 Complexity of the propagation path of gravity waves The spectrum range of gravity wave is wide, and the excitation sources of gravity waves are distributed widely. A typhoon process also brings difficulty to the acquisition of ground-based observation data. The incompleteness of the observational data limits the verification of the vertical propagation theory of gravity waves. Therefore, the three-dimensional propagation model of ray tracing of gravity waves is constructed by integrating ground and space-based observation data, which is helpful for further detailed study of gravity wave parameters and propagation characteristics.

3.2 Multiscale effects of topographic effects The fluctuation characteristics of typhoon-induced gravity waves show an obvious wide spectrum, and with the change of the underlying surface such as typhoon landing, the dragging and lifting effects of topographic gravity waves make the excitation of typhoon gravity waves more complicated. At present, the mechanism of typhoon-induced gravity waves is not fully clear, and more studies are needed to reveal or verify the specific process of excitation of gravity waves by typhoons. Alexander *et al.* [70] pointed out that an island may be an overlooked or seriously underestimated source of gravity waves. Compared with previous studies on gravity waves induced by island topography and typhoons, the typhoon landing area along the southeast coast of China is large, and when the landing typhoon is located along the southeast coast, the gravity waves triggered by the typhoon are of theoretical value for further study of the coupling effect of typhoons and terrain on gravity waves. At the same time, using the stratospheric typhoon gravity wave signal to indicate or forecast the change of typhoon intensity in advance, and improving the understanding of the change of typhoon gravity wave sign during the change of typhoon intensity can provide more reference and support for the improvement of the corresponding observation, inversion, simulation and other capabilities in the future, and also have practical significance for the anti-typhoon disaster reduction in the landing area.

3.3 Calculation of inertial gravity waves The calculation of the characteristic parameters and propagation trajectory of inertial gravity waves are mainly derived from the equations of atmospheric motion. In the rotating, stratified and compressible atmosphere[16], WKB approximation and non-static dispersion relation are used to solve the characteristic values of the low-frequency gravity waves, so as to describe the propagation law of inertial gravity waves. However, the approximate constraint method ignores the nonlinear term relationship in the equations of atmospheric motion[73], and the calculation results are idealized, which is not suitable for describing the propagation law of high-frequency gravity waves but also idealized for describing inertial gravity waves. In the future, it is necessary to further solve the primitive or less-simplified equations of atmospheric motion for gravity waves, so as to better reveal the whole activity law of gravity waves.

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