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A CASE STUDY ON THE DETAILED PROCESS OF THE IONOSPHERIC RESPONSES TO THE TYPHOON

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Abstract A case study is presented to reveal the detailed process of the ionospheric responses to disturbances in the lower atmosphere when a strong typhoon lands or approaches the mainland. The ionospheric HF Doppler shift data during the periods of two strong typhoons which occurred in 1988 and 1990 respectively are analyzed in detail. The results show that except the appearance of significant wave-like disturbances (in general, medium-scale acoustic-gravity waves AGWs) in the ionosphere there are some new phenomena worth noticing: the temporal evolution of these waves in the two cases show clearly the change of both the main frequency and amplitude, the frequency was getting lower and lower as time elapses, and the amplitude enhanced gradually. After sunset, Spread-F phenomena appeared, showing the role of seeding of the AGWs for exciting of ionospheric irregularities. A comparison is made of the above phenomena with the linear theory of TIDs propagation and also with a non-linear numerical simulation of the dynamic features of AGWs propagation in the atmosphere. All these results are in good agreement and the main features of ionospheric response to typhoon were thus explained.

Key words Coupling between lower atmosphere and ionosphere, Acoustic-gravity waves in the ionosphere, Ionospheric disturbances, Ionospheric irregularities

1 INTRODUCTION

The earlier research[1,2] shows that there is a close correlation between severe weather activities appearing in the troposphere and acoustic-gravity waves (AGWs) observed in the ionosphere, and this indicates that AGWs play a very important role in the couplings of lower atmosphere with the ionosphere. Theoretically, people paid much attention to the study of the AGWs and comparison with observational data since Hines[3] attributed the TIDs in the ionosphere to AGWs in 1960s, and the propagation features of AGWs have been studied extensively and a complete linear theory has thus been introduced. The AGWs are also accepted to be one of seeding factors in exciting ionospheric Spread-F[4]. In addition to above-mentioned works, Huang Y N et al.[5] and Shen C S[6] concluded statistically that there is a correlation between ionospheric disturbances and tropospheric meteorological activities such as typhoon and cold front. The recent research on the coupling of lithosphere and ionosphere has revealed more deeply that AGWs is an important channel of possible coupling ionosphere with seismological activity and other lower atmospheric disturbances[7,8].

As a case study, this paper is concentrated on analysis of the detailed process of the ionospheric responses to the strong typhoons and a non-linear numerical simulation of the temporal evolution process of these disturbances. Two strong typhoons occurred on July 13∼20, 1988 and June 16∼26, 1990 respectively and both appeared in the quiet geomagnetic conditions and landed the mainland are chosen as special cases to analyze the ionospheric effect. The full records of ionospheric HF Doppler shift observation at Peking University during the same period are selected to investigate the correlation. The record of the HF Doppler frequency shift is continuous in time, so it is very suitable to reveal the whole evolution process of the corresponding ionospheric disturbances.

The results of analysis and numerical simulation show that the influences of these two typhoons not only generated AGWs but also accompanied with some new significant phenomena in the ionosphere, and the simulation is mainly in agreement with those observations. In Section 2 of the paper, the corresponding typhoons and the observational result of the HF Doppler shift are described and the comparison among them is

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made. Some morphological features of the ionospheric responses are given. In Section 3, result of a numerical simulation of the characteristics of AGWs evolution is introduced. Finally Section 4 is a brief conclusions and discussions.

2 ANALYSIS OF DATA

The HF Doppler shift is a typical technique of probing ionosphere, the records of which is continuous in time, so it is effective and give directly the picture of the temporal evolution of ionospheric disturbances. Wan W X et al.[9], Ning B Q et al.[10] discussed the application of the HF Doppler technology in probing ionospheric disturbances at mid-latitude in China. Peking University HF Doppler Observation Station established in 1987 to receive a 10MHz standard frequency electromagnetic wave signals transmitted by the National Time Service Center (located at Shaanxi Astronomical Observatory) and the frequency shifts were recorded and data accumulated since then[11].

Data of typhoon were taken from the Yearbooks published by the China Meteorological Administration, the violent typhoon Warren occurred during the time period of July 13 to 20, 1988, which initiated near 11.6°N, 144.1°E on July 13, and reached the typhoon level on July 14, then proceeded to north-west and finally landed the mainland near Huilei (23.0°N, 116.2°E), Guangdong at 16:00∼17:00 LT on July 19 1988, and the wind force reached up to 12 when it landed. Fig. 1 is the records of the ionospheric HF Doppler frequency shift observed during the typhoon Warren, in which the horizontal coordinate is Beijing local time (LT), the positions of top and bottom line denote positive and negative 1Hz frequency shift respectively, the echo trace should locate just in the middle of two lines without frequency shift, because the 10MHz standard frequency shift caused by ionosphere is usually in the range of positive and negative 1Hz. From Fig. 1, it can be found that the echo traces located steadily at the position of no frequency shift before about 18:00 LT; and the obvious wave-like disturbances started to appear about 3 hours later since the typhoon landed the mainland, i.e. around 19:20 LT July 19, which almost appeared as a quasi-sinusoidal mode. However, from 19:30 LT to 21:00 LT, the period was changing clearly with time, and the frequency immigrated from high to low, the magnitude enhanced gradually; especially at about 20:30 LT the amplitude of the shift came to about negative 1Hz, at this time, the Spread-F appeared and lasted until about 01:00 LT next day (i.e. July 20, 1988). The echo signal blacked out several times from 03:00 LT to 06:50 LT before sunrise.

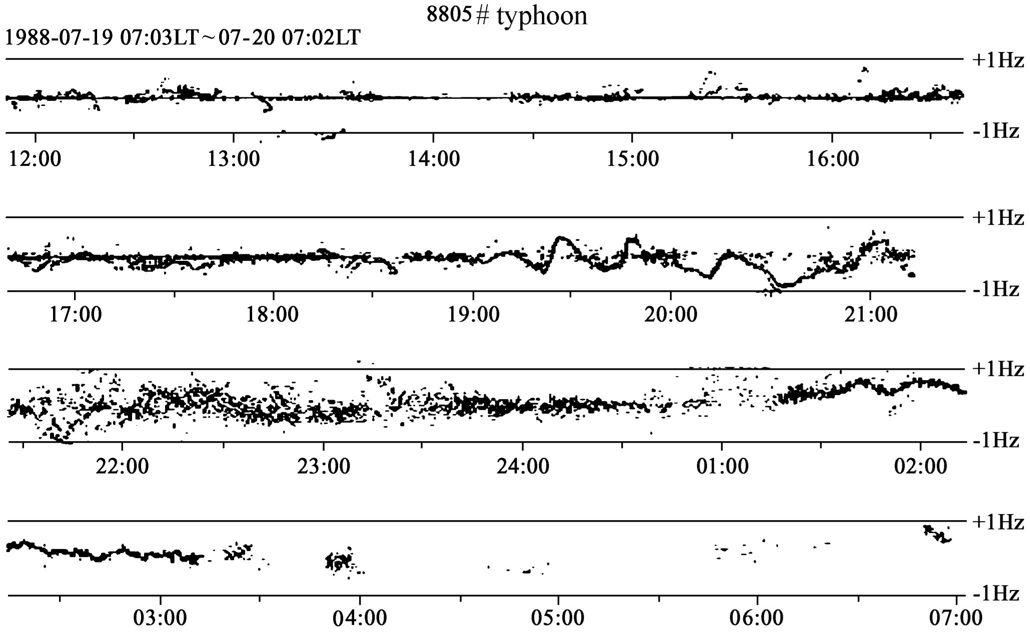

Fig. 1 Doppler frequency shift records observed for typhoon Warren around its landing on July 19 and 20, 1988

There are some new phenomena worth noticing in the complete Doppler frequency shift records during pro- and post- landing of the typhoon Warren: the wave-like disturbances with large amplitude happened especially after the typhoon's landing; their amplitude and period evolved with time, and the nighttime spread-F appeared in the ionosphere. To exclude influence from non-typhoon factors, we investigated the variation of the Kp index during typhoon and this is shown in Fig. 2. The Figs. 2a and 2b are the sum of Kp index everyday (from 13 to 20 July, 1988) during the whole period influenced by typhoon and the average 3-hourly Kp index on that landing day, respectively. The Fig. 2a shows that the effect of the geomagnetic activities seems weak, and the sum of Kp index is 16 on that landing day (July 19). The maximum average 3-hourly Kp index is 3 on the same day shown in the Fig. 2b. Titheridge[12] pointed out that the requirement of generating the large-scale TIDs for geomagnetic activity is that the average 3-hourly Kp should be more than 5 ($Kp > 5$). Therefore the recorded ionospheric disturbances are unlikely associated with geomagnetic activities.

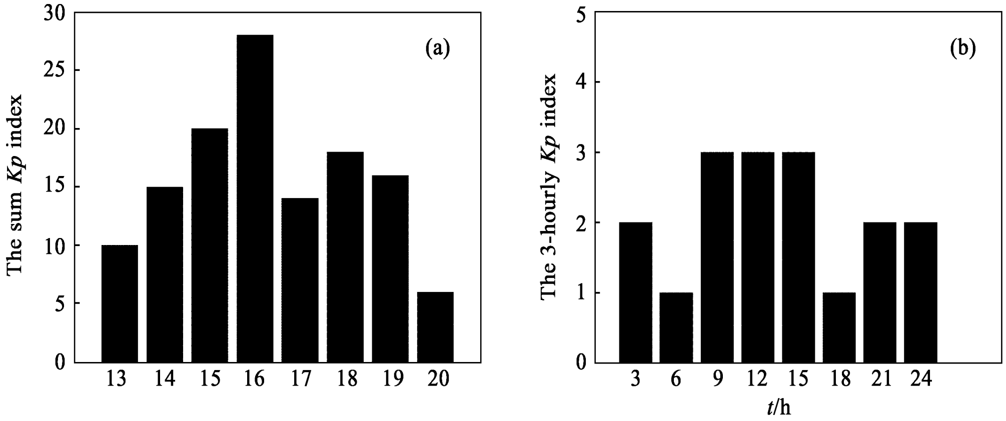

Fig. 2 Kp index during the times period of typhoon Warren influenced (a) and the day when the typhoon landed (b)

The second example is the ionospheric response to the typhoon Ofelia on June 16∼26, 1990, which has almost entirely similar features showing in Fig. 3.

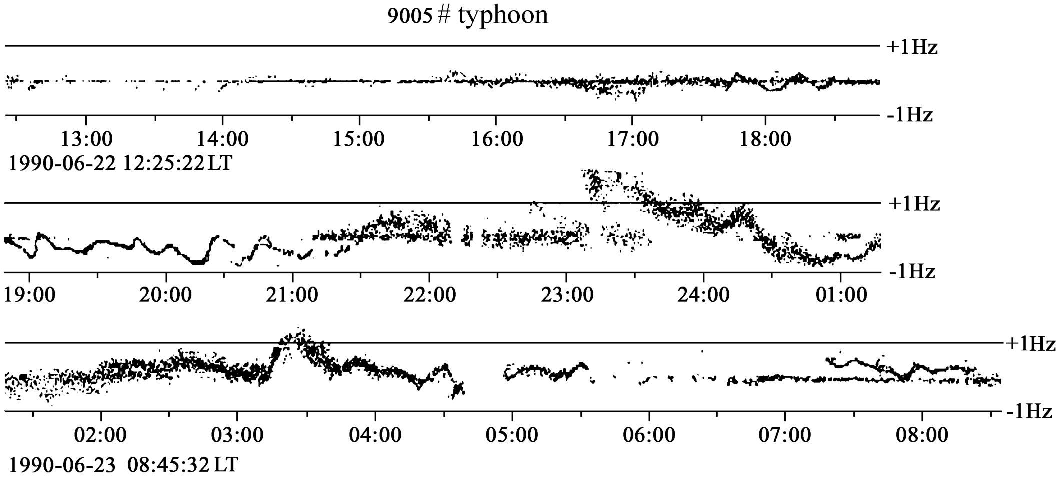

Fig. 3 Doppler frequency shift records on June 22 and 23, 1990, the influence time of the typhoon Ofelia

According to the record of the tropical cyclone yearbook, the typhoon Ofelia originated near 8.5°N, 139.0°E on June 16,1990, and reached the strength of tropical storm on June 18, then proceeded to north-west. The records of satellite image analysis revealed that the 24h strength variation of tropical cyclone center enhanced obviously in the afternoon and evening of June 21, and became very severe at 18:00 LT June 18 and 02:00 LT, 08:00 LT on June 21, but weakened clearly in early morning of June 22, and enhanced again at 02:00 LT, 08:00

LT and 14:00 LT on June 23, then it began to weaken once more on June 24. The typhoon Ofelia landed at Hualien Kang-Hsinkang (24.0°N, 121.5°E) Taiwan, China at around 13:00 LT on June 23, 1990, at this time it reached up to a wind force of 12. Then it turned to north, and landed again in Fuding (27.2°N, 120.3°E), Fujian at 04:00 on June 24, 1990.

In Fig. 3, influenced by the typhoon Ofelia, it is so obvious that wave-like disturbances appeared in the ionosphere after the strength of tropical cyclone center enhanced severely at about 18:00 LT June 22, and lasted till around 21:00 LT on June 22; furthermore, the period of waves from 20:00 LT to 21:00 LT was longer than the one from 18:00 LT to 19:00 LT, and the amplitude of shifts became larger and larger, the spread-F appeared in the ionosphere after sunset and lasted until at about 04:00LT next day. The complete absence of echo signal occurred several times from 04:30 LT to 07:20 LT near sunrise on July 23, which showed again that there was no reflection signal of 10MHz shortwave communication between Shaanxi and Beijing because of penetration of the signal resulting from electric density decreasing in the ionosphere.

During the period of typhoon Ofelia influencing, the Kp index was rather low all the time. In the period of the HF Doppler records in Fig. 3, the maximum average 3-hourly Kp index was 3, the sum of Kp index on June 22 and 23 were 12 and 13 respectively. Hence these results of the observations are hardly influenced by solar and geomagnetic activities, so we are certain that these ionospheric features shown in Fig. 3 were really caused by the typhoon Ofelia.

3 THE RESULTS OF NUMERICAL SIMULATION

The linear theory of AGWs confirms that the phase velocity of the TIDs in the ionosphere generally has the vertical downward component. It proves that most of ionospheric TIDs originate from the lower atmosphere and propagate in the ionosphere. The theoretical investigations on the characteristics of the upper atmosphere response to a pulsed point source indicated that the remote response to the source is that the higher frequency arrives earlier[13]. In this paper, starting from hydrodynamic equations, a numerical simulation of two-dimensional nonlinear propagation of AGWs in compressible atmosphere is performed to explain some of the observed features during the typhoon Warren and Ofelia. The method used in the simulation is the same as reported by Yi F and Zhang S D[14] and the full-implicit-continuous-Eulerian (FICE) scheme is adopted. It may also refer to Ref.[15].

Considering the generalization of the case[14], the horizontal velocity is selected from the four variables (density, pressure, horizontal velocity and vertical velocity) as the initial disturbance. In an isothermal and hydrostatic equilibrium atmosphere at initial moment, a Gaussian disturbance packet is added on the horizontal velocity to simulate the disturbance excited by typhoon, the center of the disturbed wave packet is located 50km from the surface and this position is about 3 scale heights above the tropopause level. The disturbed horizontal velocity is in the form[14]:

$$u(x,z,0) = u_{\mathrm{c}}\mathrm{e}^{\frac{(x-x_{\mathrm{c}})^2}{2\sigma_x^2}}\,\mathrm{e}^{\frac{(z-z_{\mathrm{c}})^2}{2\sigma_z^2}}\sin(k_x(x-x_{\mathrm{c}})+k_z(z-z_{\mathrm{c}})), \tag{1}$$

where u_{c}, x_{c}, z_{c} are all constants, $u_{\mathrm{c}} = 1\mathrm{m/s}$, k_x, k_z are the horizontal and vertical components of the wave-number vector, respectively; σ_x and σ_z are the half widths of the wave packet in the horizontal and vertical direction, respectively.

To be in accordance with the characteristics of the observed TIDs in the ionosphere during the period influenced by typhoon, two periods are used in the simulation, namely, 15min and 30min respectively. The main results are shown in Fig. 4.

The solid line and small circles, the dashed line and small squares refer to the propagation path of the center of AGWs packet with the period of 15min and 30min, respectively, in Fig. 4. The intervals of every circle or every square are 15 or 60 minutes respectively. It is seen that first, the AGWs with the period of 15min and 30min, can both propagate up to the ionospheric level. Second, to reach the same height, it takes them different time, and the time for 15min-period AGWs to arrive ionosphere (for instance 180km) is much shorter than the 30min-period AGWs. In addition, for the AGWs of different frequencies their packets propagate with different elevation angles, the lower frequency of AGWs, the less elevation angle. In other words, AGWs with lower frequencies can propagate farther distance along the horizontal direction while it propagates upwards.

The results of this simulation not only show that the AGWs with period of 15min and 30min, respectively, in non-linear condition, can propagate up to the height of ionosphere from the lower atmosphere, but also provide the evidence for dispersion phenomena. The AGWs with period of 30min reach the ionosphere level about 1.5h later than the one with period of 15min, it is in agreement with the observations shown above. Actually, the above results can be drawn directly from dispersion relation of linear theory[13]. The simulation indicates that under certain non-linear conditions those results are the same. Of course, the non-linear effects of atmosphere on AGW's propagation need more detailed investigations since in our primary simulations the effects of non-isothermal atmosphere and winds are not taken into account, the conditions are not exactly for the real atmosphere.

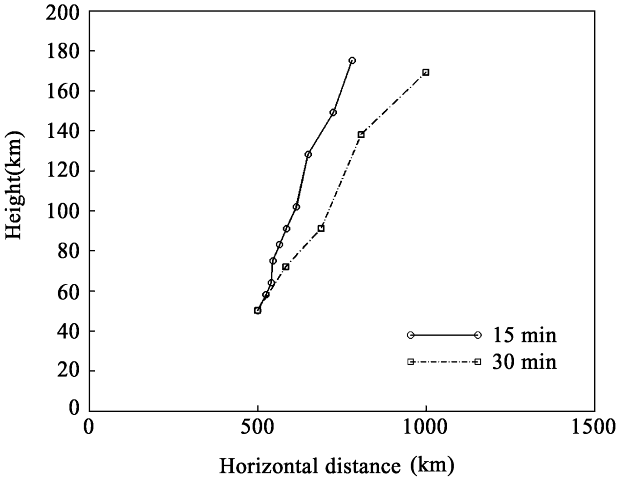

Fig. 4 Propagation path of the AGWs packet with the period of 15min and 30min in an isothermal atmosphere

4 CONCLUSIONS AND DISCUSSIONS

The observational facts in this paper have revealed the detailed process of the ionospheric responses to the strong typhoon through the analysis of the full ionospheric HF Doppler frequency shift records and relevant typhoon data during the periods influenced by these two typhoons. The AGWs generated during the period influenced by typhoon can propagate up to the height of ionosphere and impact the ionosphere, the variation of the HF Doppler frequency shifts is the manifestation of the evolution of these waves in the ionosphere level. The obvious quasi-sinusoidal wave-like disturbances appear firstly in the ionosphere, then as time elapsing, the periods of AGWs getting lower and lower and amplitudes enhanced gradually, showing a distinct dispersion of AGWs in the atmosphere. After sunset, the AGWs with large magnitude can activate the mid-latitude Spread-F phenomena. The main morphological features of ionospheric responses to these two strong typhoons can be explained by both linear theory and a simple non-linear simulation

Theoretically, it is known that AGWs may play an important role of seeding in exciting ionospheric Spread-F. Whitehead[4] first introduced spatial resonance effect: when the plasma drift velocity is close to the phase velocity of AGWs, the waves and the plasma can interact for so long time that there occurs a periodic oscillation in the plasma. Such electron density disturbance can be amplified by the Raleigh-Taylor (R-T) instability, which then leads to the phenomenon of Spread-F. Xiao Z and Xie H[16] reproduced by numerical simulation the process that AGWs in mid-latitude exciting the extensive Spread-F. Huang C S and Kelley M C[17] simulated the ionospheric response to AGWs in equatorial regions. Associating with the factors of the background wind and the electric field, Zhang T H et al.[18] deduced a more perfect formula of linear growth rate of the ionospheric R-T instability in mid-latitude. There were medium-scale AGWs with large magnitude before the Spread-F appeared in the ionosphere during these two typhoons. Apparently, these AGWs with large magnitude could play a significant role in the formation of Spread-F in the ionosphere.

Of course, the ionospheric response to each individual typhoon can not be exactly identical, there must be some differences from each other due to various conditions such as time, place, strength and propagation path of typhoon, the background of thermosphere, ionosphere at that time, and other geophysical environment elements.

The numerical simulation of the present paper is not entirely including the real distribution of background wind and temperature distributions, the consistence of simulation result and observation is basically half-qualitative and half-quantitative. However, there are certain common characteristics in the ionospheric response to typhoon as revealed in this case study.

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