Morphological features of ionospheric response to typhoon

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[1] Couplings between the ionosphere and meteorological events have been studied widely. However, most of them are individual case studies or correlation analyses, and few are aiming at the full morphological features of the ionospheric response processes. In this paper, complete records of 24 strong typhoons from 1987 to 1992 were collected, and comparison was made with corresponding ionospheric HF Doppler shift data. The main purpose of the present work is to find the temporal evolution of these responses and their common features by the merit of the continuities of HF Doppler shift observation in time. On the basis of the statistical analyses, this paper reveals the common features of ionospheric responses to typhoon. A summary of these characteristics is as follows: (1) During the existing time of a typhoon, there are almost always medium-scale traveling ionospheric disturbances (TIDs) in the ionosphere, especially when a strong typhoon is landing or near the coast of a mainland. (2) These TIDs show quite clear periodicity and their periods vary with time and gradually grow longer. (3) After sunset, the wavelike disturbances with large magnitudes often excite the midlatitude spread-*F*. (4) The intense typhoon can cause the wavelike records of the Doppler shift to show the S-shaped echo tracing, which means that the amplitudes of those waves are sufficiently large, and (5) the sunrise-like phenomena often appear in nonsunrise time during the period the typhoon exists. The phenomena mentioned above are generally in agreement with the linear propagation theories of the acoustic-gravity waves (AGWs) in the atmosphere. A typhoon is surely one of the important ground sources of the wavelike disturbances in troposphere; this source is very effective especially when a typhoon is landing on or near a mainland coast. Of course, the morphological details of the ionospheric response to typhoon can by no means be completely identical every time. In this study, except for TIDs that almost always appear during all the typhoon events, the other common features are not seen every time. However, we are certain that the phenomena summarized above are statistically the manifestation of the ionospheric response to typhoon since they appear much more frequently during periods influenced by typhoon.

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1. Introduction

[2] The propagation features of acoustic-gravity waves (AGWs) have been studied extensively since Hines began to discuss during the 1960s [*Yeh and Liu*, 1974]. By ignoring all source and loss processes, *Hines* [1960] introduced a dispersion relation of AGWs in an isothermal atmosphere. The main conclusions of this linear theory are as follows: (1) When AGWs propagate upwards, the amplitude enhances gradually so to satisfy the requirements of energy conservation. (2) Group velocity enhances gradually along with increasing frequency and the direction of energy flux tends to become horizontal as frequency decreases, and (3) the vertical component of AGW's phase velocity is opposite that of the group velocity. Since in most cases the observed phase velocity has a downward component, the conclusion is that most of the AGWs observed in the ionosphere known as traveling ionospheric disturbances (TIDs) come from the lower atmosphere and that some severe meteorological activities play roles of generating such waves. Lots of earlier investigations show that there is a close correlation between ionospheric wavelike disturbances and severe weather activities such as thunderstorms, typhoons, tornadoes, hurricanes, and cold fronts, etc. *Baker and Davies* [1969] pointed out that the wavelike ionospheric disturbances, characterized by periods in the range 2–5 min, are apparently closely associated with severe local

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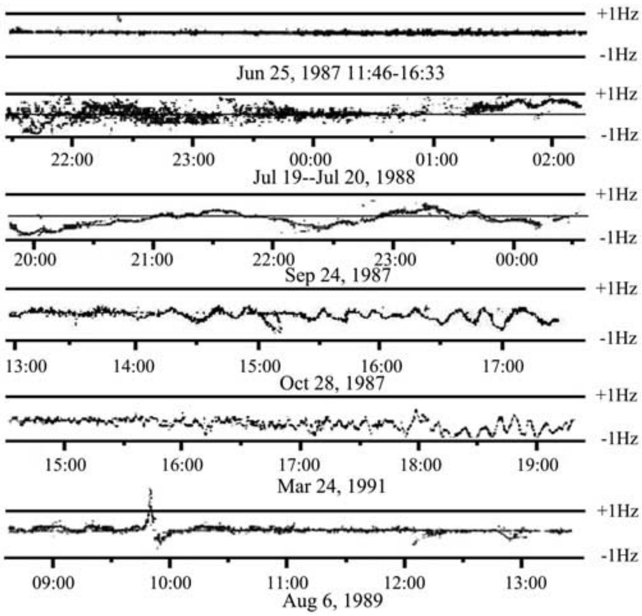

Figure 1. Doppler shift echo traces illustrating some typical morphological features of ionospheric disturbances (from top to bottom, half-transparent Es, irregularities, large-scale acoustic-gravity waves, medium-scale acoustic-gravity waves, high-frequency wave, and flare response).

storms in the troposphere and are interpreted as manifestations of acoustic waves generated by the storms. *Davies and Jones* [1971, 1973] and *Prasad et al.* [1975] indicated that ionospheric disturbances could be produced by severe thunderstorms. *Hung et al.* [1978] presented the notion that gravity waves or medium-scale TIDs with a wave period of 13–15 min and 27–30 min were observed at *F*-region ionospheric height during the time period of the extreme tornado outbreak of 3 April 1974, and large-scale TIDs with a wave period of 36 min were also detected. *Huang et al.* [1985] analyzed the correlation between all typhoons occurring near Taiwan Island in 1982 and 1983 and ionospheric disturbances detected by the HF Doppler frequency sounding array and concluded that the AGWs generated by a typhoon can sometimes be detected since the response to typhoon mainly displayed a wave period of 11–13 min. They pointed, at the same time, that the detectability was not very high; for instance, 2 out of 12 showed significant wavelike variations in the ionosphere. *Shen* [1982] and *Shen and Zi* [1986] discovered, based on statistical analysis, that there is a certain correlation between the critical frequency of the F_2 region in the ionosphere, typhoon, and cold front.

[3] By all accounts, the above-mentioned works intended to show the ionospheric response to an individual event or statistical correlations between them. Little work has been done so far to reveal the common features of the corresponding disturbances, and in particular, no more observational evidence to show the characteristics of the temporal evolution of these disturbances. This is highly necessary for any further study, especially the nonlinear computer simulation of AGWs in the real atmosphere.

[4] The purpose of this paper is to show the morphologic features of the ionospheric response to typhoon, emphasizing the temporal evolution of the response. Data of ionospheric HF Doppler shift observations at Peking University from 1987 to 1992 are used to make comparison with corresponding typhoon records during the same period. All the strong typhoon events with their paths near the continental coast or that landed were selected, except those accompanied by geomagnetic disturbances. In section 2 the source of the data used in statistical analysis and the criteria of the data selection are described in some detail, and section 3 presents the results of the morphologic features of the ionospheric response to AGWs related to typhoon, especially the common feature. Finally, conclusions and discussions are presented in section 4.

2. Data

[5] The data of typhoon records are quoted from the typhoon yearbook (1987–1988) and the tropical cyclone yearbook (1989–1992) published by the China Meteorological Administration. Although the definition of typhoon is somewhat different in the different yearbooks, strong typhoons in 1987 and 1988 and typhoons from 1989 to 1992 are both selected by the same criteria of maximal wind speed near the center of tropical cyclone in excess of 32.6 m/s, equivalent to class 12. At the same time, the total number of 36 typhoon events used in these statistics are all those that landed or were near the mainland from 1987 to 1992 documented in the yearbooks.

[6] The data concerning the ionospheric disturbances in the statistical analysis come from the records of the HF Doppler frequency observation station at Peking University, using the Peking University HF Doppler frequency ionospheric sounder developed in 1986. The sounding system receives a 10 MHz standard frequency electromagnetic wave, which is transmitted by the National Time Service Center (located at Shanxi Astronomical Observatory) [*Xiao et al.*, 1987] in order to monitor continuously the Doppler frequency shifts caused by the ionosphere. The distance between the transmitting station (35.0°N, 109.5°E) and the receiving station (39.4°N, 116.2°E) at Peking University is about 700 km and as oblique incidence, reflection height is in the ionospheric F_2 region. Frequency shift records during the above-mentioned 36 typhoon events were used for this study.

[7] Among all 36 typhoons, four typhoons were without Doppler records due to equipment problems, seven typhoons from the other 32 records might be affected by geomagnetic activities ($Kp > 5$, Kp is the 3-hour average magnetic index), and one typhoon occurred during the period of solar flares. These eight typhoons were ignored and the 24 typhoons were used for the comparison. The results showed that 22 events out of 24 were accompanied with significant AGWs in the ionosphere. The description of these observations and results of the analysis will be given in detail in the following section.

3. Results of the Data Analysis

[8] The ground-based ionospheric Doppler frequency shift measurement is continuous in time, so it is more suitable for revealing the evolution process of the ionospheric disturbances than ionosondes are. Figure 1 shows

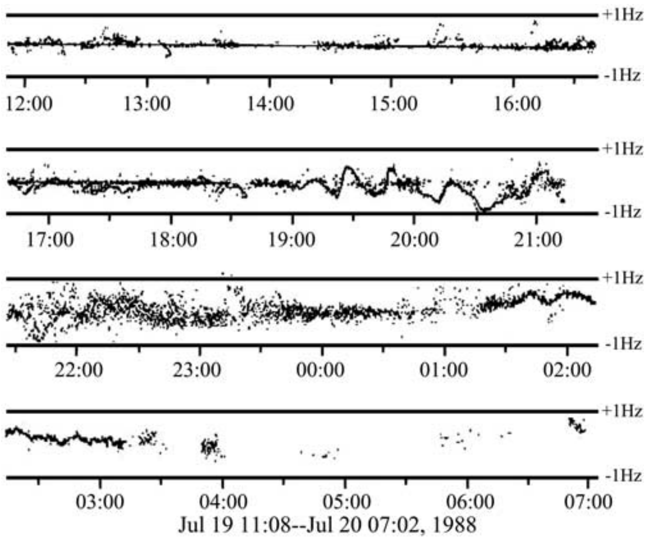

Figure 2. HF Doppler shift records during Typhoon Warren near coast in Huilei, Guangdong province at 1600–1700 LT, 19 July 1988.

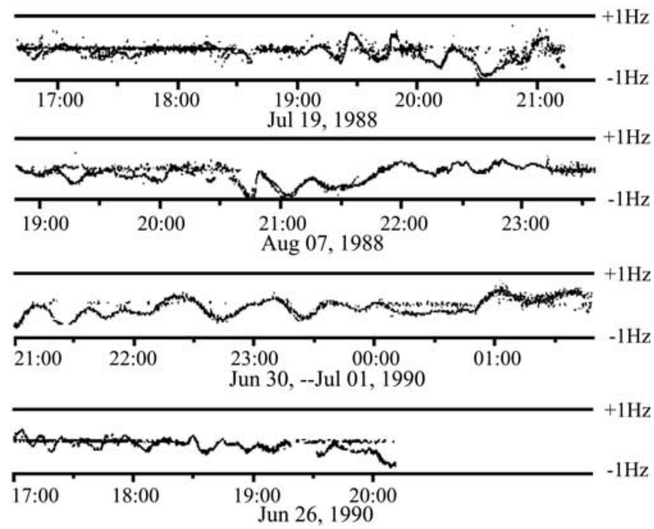

Figure 4. The results of a part of ionospheric Doppler shift observation during four typhoons, noticing the variation of period with time.

some records of the HF Doppler shift at Peking University, illustrating the traces of morphological features for some typical ionospheric disturbances.

[9] Figure 2 shows one of the wavelike disturbances during Typhoon Warren. Apparently this disturbance is a medium-scale TID caused by the typhoon. The period of the wave is around 20 min and changes with time. The temporal evolution of the wave shows clearly the changes of both the wave main period and amplitude, the period growing longer and longer as time elapses. At the same time, the amplitude enhanced gradually reaching more than 1 Hz, and then spread-*F* phenomena appeared after sunset.

[10] This wavelike phenomenon is very popular in the time influenced by typhoon. Figure 3 shows other two examples, in which the wave and change of its periods and amplitudes can also be seen. Figure 4 shows the records of more examples, indicating clearly the gradual changes of periods and amplitudes. The main characteristics in Figure 5 are the excitation of nighttime spread-*F*. Spread-*F* was generated when the periods and amplitudes changed with time and after sunset,when amplitudes were large enough.

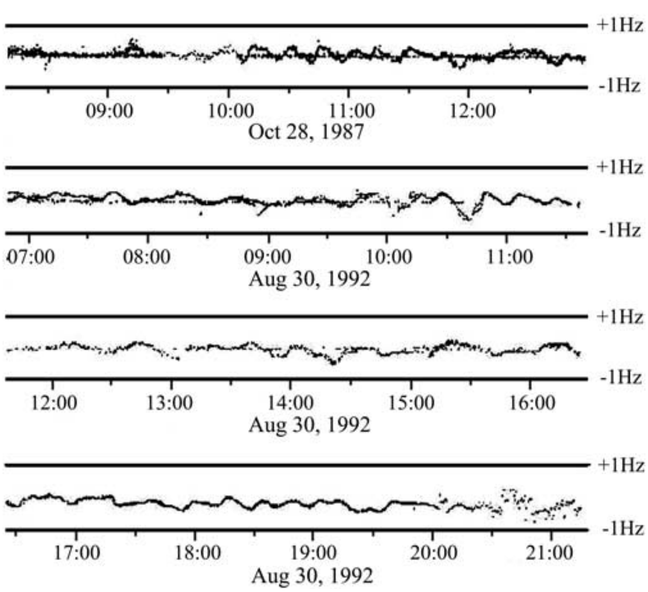

Figure 3. Other two examples of AGWs caused by Typhoons Lynn and Polly near the coast.

[11] Among the 22 typhoons, there are altogether 11 nighttime spread-*F* generated. Examples in Figure 5 show that very large amplitudes of the AGWs had developed by sunset, and nighttime spread-*F* appeared after sunset. The known studies indicated that the nighttime F_2 region irregularities in midlatitude could be excited by the large-amplitude AGWs [*Zhang et al.*, 1999]. This result showed that typhoon-generated AGWs can play the seeding roles.

[12] Figure 6 shows more S-shaped traces. *Davies and Baker* [1966], early in 1960s for vertical Doppler sounding, and *Xiao et al.* [2002], for oblique incident, attributed the phenomena to the large amplitudes of AGWs. This indicates that AGWs caused by typhoon generally have large amplitude.

[13] We found a very interesting phenomenon in the records of the ionosphere response to the AGWs generated by typhoon, and we termed it the "sunrise-like effect." Generally, at sunrise/sunset, sharp increasing/decreasing of the ionosphere electron density leads to positive/negative Doppler frequency shift quickly, as shown in Figure 7, which is the sunrise effect in quiet ionosphere. The records during typhoon events in this study showed some sudden positive Doppler shifts similar to the sunrise effect, but all of them took place in the nonsunrise period; instead, they occurred in the afternoon and evening, which is what we call the "sunrise-like effect."

[14] There were six sunrise-like effects that appeared during all 22 typhoons, and some of them are shown in Figure 8. By the data, which are dated the start and end time of the typhoons in Figure 8, it is obvious that these six occurrences of sunrise-like effect all appeared at the end of the period affected by typhoon, at which time there were

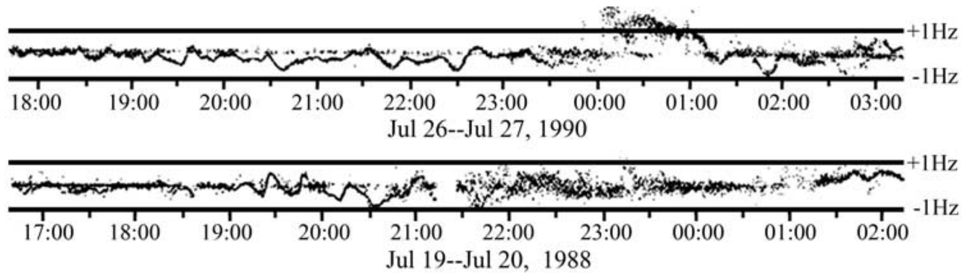

Figure 5. The ionospheric HF Doppler shift records during two typhoons, showing the excitation of irregularities.

already no wavelike disturbances in the ionosphere generally. Taking Typhoon Gerald (8712) for example, which took place from 2 to 11 September 1987, a sudden positive Doppler shift appeared at about 1300 LT on 11 September, indicating that the electron density was increasing quickly around this time.

4. Discussions and Conclusions

[15] The statistical analyses of the whole 22 events show that the ionospheric disturbances accompanying typhoon, or the ionospheric responses to typhoon, are definite and have very clear common features. The time period for comparison is when typhoon were near the coast or landing because it is speculated that when typhoon is landing, the rapid loss of momentum due to viscous interaction could be an additional factor in exciting AGWs with various frequencies, the distance between Doppler receiver and landing sites ranges from about 1200 to 1800 km. The following is a summary of the facts mentioned above:

[16] 1. Around the time when a strong typhoon was near the mainland coast or immediately after its landing, an obvious wavelike disturbance always appears in the ionosphere in the form of medium-scale TIDs (in this case study of 6 years, 22 out of 24 instances).

[17] 2. The periods of typhoon accompanied TIDs are not fixed but vary with time. It can be seen clearly that the period gradually grows longer during each typhoon event.

[18] 3. After sunset, these wavelike disturbances with large magnitude often activate the midlatitude spread-*F*.

[19] 4. The very strong typhoon can cause the wavelike records of the Doppler shift to form the S-shaped echo tracing.

[20] 5. In the echo trace there often appear sunrise-like phenomena in nonsunrise time. They usually occur toward the ending period of some typhoons, seeming to indicate a fast recovery of the electron number density.

[21] The linear theory of gravity waves tells that almost all TIDs in the ionosphere have a downwards component of phase velocity indicating a source in the lower atmosphere, small perturbations in lower atmosphere can be easily detected in the ionosphere because energy conservation must be satisfied, there is frequency dispersion of gravity waves in the ionosphere and waves with higher frequency propagate faster [*Hines*, 1960]. Our observations are in agreement with the linear theory of the AGWs propagation in the atmosphere. We are certain that typhoon is one of the important ground sources of wavelike disturbances in troposphere; this source is very effective especially when a typhoon is landing or near the mainland coast. The AGWs generated by typhoon propagate up into the ionosphere to form the medium-scale TIDs. AGWs in the atmosphere cannot propagate exactly in the vertical direction; the tilt angles and group velocity depend on their frequencies. The AGWs are also accepted as playing the role of seeding factor for exciting of ionospheric spread-*F*. *Whitehead*

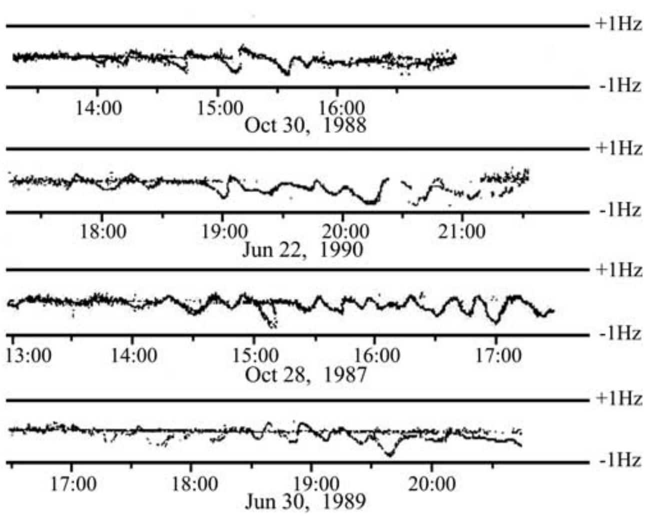

Figure 6. A part of ionospheric Doppler shift records during several typhoons, noticing the "S"-shaped tracing.

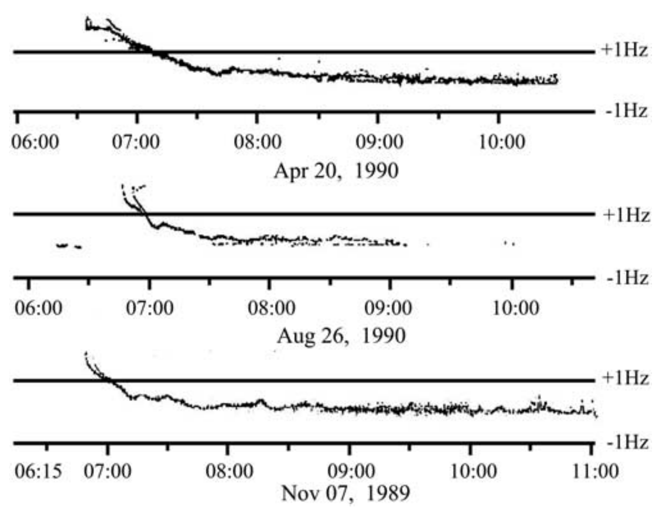

Figure 7. HF Doppler shift records showing the normal ionospheric features at sunrise (sunrise effect).

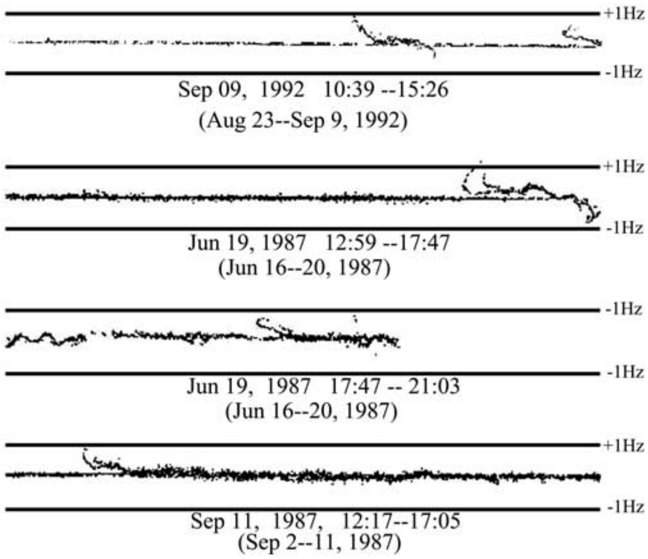

Figure 8. A part of ionospheric Doppler shift records during several typhoons showing the sunrise-like effect.

[1971] first introduced spatial resonance effect. There are more recent studies on the seeding role of AGWs in exciting equatorial and midlatitude spread-*F* [see *Kelley et al.*, 1981; *Xiao and Xie*, 1994; *Huang and Kelley*, 1996; *Zhang et al.*, 1999].

[22] The studies on the typical S-shaped medium-scale disturbance in the ionosphere given by *Davies and Baker* [1966] for vertical incident and *Xiao et al.* [2002] for oblique incident both showed that as the amplitude of the AGWs becomes larger, the distortion of S-shaped disturbance is more obvious and gradually vanishes as the amplitude of the waves decreased. The effect of the AGWs generated by typhoon on the ionosphere shows some typical S-shaped disturbance too: the relationship between the degree of twisting and the wave amplitude is in agreement with the conclusion drawn by *Xiao et al.* [2002].

[23] During the ending stage of several typhoons, the sunrise-like effect appeared in the ionosphere, which indicates that the ionospheric electron number density is possibly less than the normal value during the typhoon effect and that a fast recovery exists during the ending stage of typhoon. Indeed, some authors argued that the electron density decreased during typhoons [*Shen*, 1982], but the mechanism remains unclear.

[24] Of course, the morphological details of the ionospheric response to typhoon can by no means be completely identical every time. In this study, except for TIDs that almost always appear during all the typhoon events, the other common features are not seen every time. However, it is sure that the phenomena summarized above are statistically the manifestation of the ionospheric response to typhoon because they appear much more frequently during the period influenced by typhoon. Here, it is particularly worthy of emphasizing that the detectability of AGWs is very high, up to 22 out of 24, during the time periods referred to in this study. This figure is much higher than the two out of 12 concluded by*Huang et al.* [1985] in their observations. Considering the difference of relative locations of typhoon and Doppler observation sites, this is interesting and needs some further studies.

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