# Giant ionospheric disturbances excited by the M9.3 Sumatra earthquake of 26 December 2004

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[1] An Mw 9.3 earthquake originated in the Indian Ocean off the western coast of northern Sumatra at 00:58:53 Universal Time (UT) on 26 December 2004. Two giant ionospheric disturbances at 01:19 and 04:10 UT are observed by a network of digital Doppler sounders in Taiwan. The first disturbance excited mainly by Rayleigh waves, which consists of a packet of short-period Doppler shift variations, results in vertical ionospheric fluctuations with a maximum velocity of about 70 m/s and displacement of about 200 m. The second disturbance, in a W-shaped pulse propagating at a horizontal speed of 360 ± 70 m/s, is attributable to coupling of the atmospheric gravity waves (AGW) excited by broad crustal uplift together with the following big tsunami waves around the earthquake source zone. The accompanying ionosonde data suggest that the AGW in the atmosphere may have caused the ionosphere to move up and down by about 40 km. **Citation:** Liu, J. Y., Y. B. Tsai, S. W. Chen, C. P. Lee, Y. C. Chen, H. Y. Yen, W. Y. Chang, and C. Liu (2006), Giant ionospheric disturbances excited by the M9.3 Sumatra earthquake of 26 December 2004, *Geophys. Res. Lett.*, *33*, L02103, doi:10.1029/2005GL023963.

## 1. Introduction

[2] Earthquakes can excite atmospheric and ionospheric disturbances by dynamic coupling: vertical vibrations of the Earth's surface launch pressure waves in the neutral atmosphere that grow in amplitude by several orders of magnitude as they attain ionospheric heights. The first published observations of such disturbances were obtained after the great Alaskan earthquake in 1964. *Bolt* [1964] observed air pressure waves on a Berkeley barogram arriving in two distinct packets of signals: the first one was excited by propagating seismic waves and the second one by big ground upheavals in the earthquake source zone. *Leonard and Barnes* [1965] observed ionospheric disturbances due to the Alaskan earthquake using data at four sites of ionosondes in Alaska and California. Considerable evidence has been accumulated over the years to suggest that transient disturbances can occur in the ionosphere as a result of big earthquakes [*Bolt*, 1964; *Leonard and Barnes*, 1965; *Davies and Baker*, 1965; *Row*, 1966, 1967; *Yuen et al.*, 1969; *Tanaka et al.*, 1984; *Calais and Minster*, 1995; *Afraimovich et al.*, 2001, 2002a, 2002b; *Artru et al.*, 2001, 2004]. In this paper we report observations of giant disturbances in the ionosphere over Taiwan following the M9.3 Sumatra earthquake of December 26, 2004 [*Stein and Okal*, 2005].

## 2. Observations and Interpretation

[3] A preliminary earthquake report by the U.S. Geological Survey gives its origin time at 00:58:53 UT; the epicenter is located at 3.30°N, 95.95°E off the west coast of northern Sumatra. Its moment magnitude of 9.3 ranks it as the second largest earthquake since the 1952 Kamchatka earthquake. Displacements of the adjacent seabed generated damaging tsunami waves that killed more than 280,000 people at countless coastal communities around the Indian Ocean. The land surface uplift is estimated to be up to 10 m on the Nicobar islands by *Bilham et al.* [2005] (Figure 1). This severe earthquake occurred about 3,600 km away from Taiwan. We shall use three kinds of records obtained in Taiwan to show giant disturbances of the ground surface and ionosphere that were excited by the earthquake. Figure 1 shows the locations of our observational sites. They include a broadband seismographic station NACB, and a network of high-frequency Doppler sounders consisting of three receiving stations NCNU, NCU, and DHIT, with a transmitting station, as well as an ionosonde station at HSS, all being located in northern Taiwan. Meanwhile, ionograms concurrently recorded at YAM and KOK ionosonde stations in Japan are also examined.

[4] Figure 2 illustrates, in the upper panel, the Doppler shifts observed at three Doppler sounder stations, and in the bottom panel ionograms recorded at the ionosode station HSS. From the Doppler shifts we can see two distinct types of signals: a compact packet of short-period signals arriving at about 01:19 UT. From the ionograms recorded between 01:00 and 01:30 UT we can estimate that the reflection height of the 5.26 MHz Doppler sounding signals was at about 200 km altitude. This is followed by a big W-shaped pulse with a long duration of about 30 minutes arriving at approximately 04:10 UT at the three Doppler sounder receiving stations. The W-shaped Doppler shift and the two ionograms at 04:00 to 04:15 UT, in the lower panel, show that the ionosphere has moved up and down by about 40 km. This big pulse is followed by a series of long-period signals. From the delay times of the big pulse and the following long-period signals among the three stations we can find that they are propagating signals possibly arriving from the earthquake source areas at a velocity of about 314 m/s, which agrees with the speed of atmospheric gravity waves (AGW) observed after the great Alaskan earthquake [*Bolt*, 1964]. Thus the big pulse was probably

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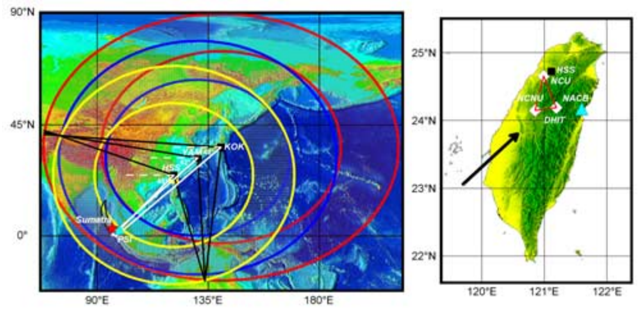


**Figure 1.** (left) Locations of the epicenter (red star) and fault rupture area (black box) of the M9.3 Sumatra earthquake, the broadband seismic station PSI, and the ionosonde stations HSS (24.7°N, 121.0°E; 3580 km to the epicenter), YAM (31.7°N; 130.6°E, 4810 km), and KOK (35.9°N; 140.1°E, 5800 km). The possible distance to the source from HSS (yellow rings), YAM (blue rings) and KOK (red rings). (right) Observational sites in Taiwan, including the ionospheric reflection points of the digital Doppler sounder receiving stations NCNU (24.1°N; 120.8°E), DHIT (24.2°N; 121.2°E), and NCU (24.7°N; 121.0°E), digital ionosonde station HSS, and broadband seismic station NACB.

coupled to the ionosphere by the AGW excited by the slow and permanent uplift of northern Sumatra, as revealed by the vertical broadband seismogram in Figure 3, as recorded at an Ocean Hemisphere Project Network station PSI at about 352 km east of the earthquake epicenter [*Ocean Hemisphere Project Data Management Center*, 2005]. As for the long-period signals following the big pulse, they were probably

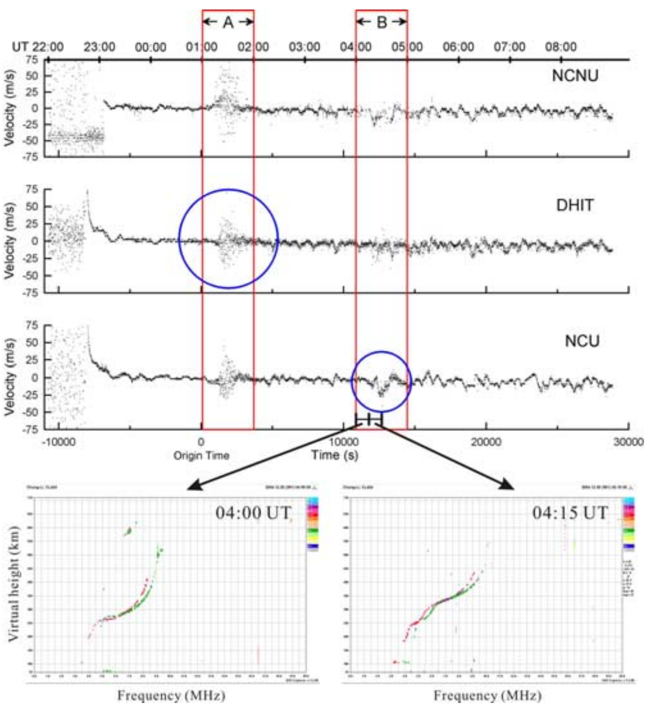


**Figure 2.** (top) Digital Doppler sounder records of the ionospheric disturbance obtained at stations NCNU, DHIT, and NCU. The circled portions of NCU and DHIT are enlarged in Figures 3 and 4, respectively. (bottom) Ionosode records obtained at station HSS at 04:00 UT and 04:15 UT.

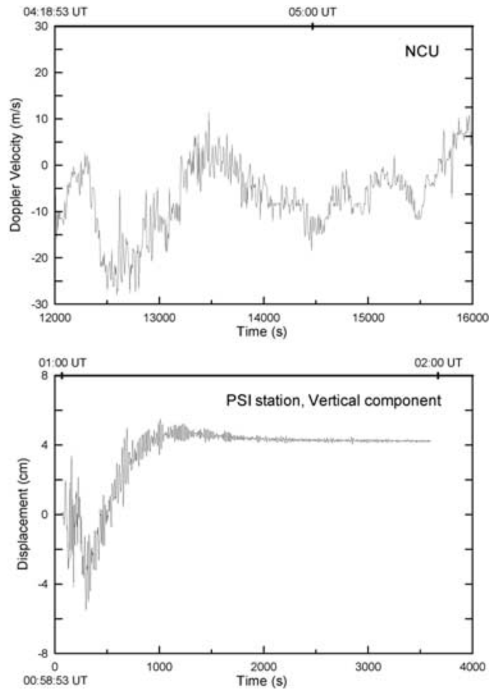


**Figure 3.** (top) Enlarged portion of the Doppler sounder record obtained at NCU, showing a big pulse of 30-minute duration. (bottom) Vertical ground displacement record obtained at the broadband seismic station PSI, showing a big transient followed by a permanent uplift of about 4 cm.

coupled to the ionosphere by the AGW excited by big tsunami waves along the coast of Indian Ocean.

[5] Figure 4 illustrates, in enlarged plots, the compact packets of short-period signals of the Doppler sounder data at DHIT and the signals on a broadband vertical seismogram at nearby NACB station, arriving in northern Taiwan at about 01:19 and 01:15 UT, respectively. The time delays of about 1000 seconds (00:58 UT to 01:15 UT) at NACB gives an approximate horizontal speed of 3.6 km/s for these packets (or Rayleigh waves). The trace in the upper panel of Figure 4 displays the packet received by the Doppler sounder at DHIT. The maximum vertical Doppler shift (velocity) in the packet at 1810 sec is 2.5 Hz (70 m/sec). The integration of the velocity packet shows the ionosphere was fluctuating with a maximum vertical displacement of about 200 m. The Doppler sounding signals begin at about 01:19 UT which is delayed by about 4 minutes after the S wave arrival marked on the vertical seismic waveforms that

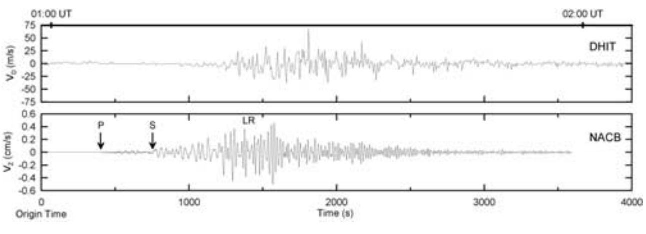


**Figure 4.** (top) Enlarged portion of the Doppler sounder record obtained at DHIT, showing oscillatory ionospheric disturbances. (bottom) Time histories of the vertical ground velocity obtained at NACB. The arrival times of P, S, and LR (Rayleigh) waves are marked on the trace.

were recorded at the NACB broadband seismographic station, as shown in the lower panel of Figure 4. The maximum ground velocity was about 0.5 cm/sec during the passage of a group of surface waves with a period of about 22 sec. The integrations of the two traces in Figure 4 reveal that the vertical displacements in the ionosphere and on the ground are about 200 m and 0.4 cm, respectively. This would give an amplification factor of 50,000 in vertical displacement of the ionosphere relative to the ground surface. The time delays of 4–5 minutes indicate that this packet of ionospheric disturbances was excited by the AGW propagating upward at an apparent velocity of about 800 m/s after having been excited by seismic ground vibrations [*Leonard and Barnes*, 1965; *Artru et al.*, 2001, 2004].

## 3. Discussion and Conclusion

[6] It can be seen in Figure 2 that the short-period signals start at about 01:19 UT (01:18.2 UT at ionospheric reflection point of NCNU; 01:18.6 UT at DHIT; 01:19.2 UT at NCU) in Taiwan. A cross correlation study [*Liu et al.*, 1993] of the three arrival times suggests that the short-period signals, which are triggered by seismic surface waves, have an average horizontal speed of 1.6 ± 0.5 km/s coming from the southwest direction within a range of about ±30° in azimuth. Although the derived mean speed is somewhat less than the Rayleigh waves 3.6 km/s, the average propagation direction mainly is from the epicenter. The discrepancy in the speeds might be due to the distance between the two ionospheric reflection points, at about 40–60 km, being too short in comparison with the horizontal scale of the signals. Nevertheless, the general similarity in waveforms between the Doppler shift fluctuations and seismic motions suggests that the short-period ionospheric signals are triggered by Rayleigh waves traveling at 3.6 km/s from the M9.3 Sumatra earthquake [*Artru et al.*, 2004].

[7] For a longer wavelength disturbance, such as the big W-shaped pulse, it is even more difficult to derive the associated propagation speed via small phase (or arrival time) differences observed by a small receiving array, such as the Doppler sounding system in Taiwan. Alternatively, we employ ionosonde stations at HSS, YAM, and KOK (http://wdc.nict.go.jp/ISDJ/index-E.html) to evaluate the propagation speed and to locate the source of the pulse (see Figure 1). The recorded ionograms show that the ionosphere is disturbed when the big W-shaped pulse arrives at HSS, YAM, and KOK at about 04:15, 04:30, and 05:15 UT, respectively. Taking the ionogram sampling interval of 15 minutes into consideration, we find the travel times are 187(=04:15–00:58 UT) ± 15 minutes at HSS, 192(=04:30–00:58 UT) ± 15 minutes at YAM, and 255(=05:15–00:58 UT) ± 15 minutes at KOK. We further divide the distances from the earthquake by the travel times for all three stations and obtain the big W-shaped pulse coming from the earthquake area with an average horizontal speed of about 360 ± 70 m/s. Based on the method of intersecting circles [*Lay and Wallace*, 1995], which is traditionally employed for locating the hypocenter of an earthquake, we calculate the possible distance (zone) to the source from each ionosonde station. For an ionosonde station, the outer (inner) ring of its propagation zone equals to the product of the maximum speed 430(=360 + 70) m/s and the maximum travel time (the minimum speed 290(=360–70) m/s and the minimum travel time). The overlapped area of the three zones shown in Figure 1 confirms that the big W-shaped pulse, attributable to the AGW excited by broad crustal uplift together with the following big tsunami waves around the earthquake source zone and traveling in the atmosphere at 360 ± 70 m/s, comes from the M9.3 Sumatra earthquake to Taiwan within a range of about ±45° in azimuth.

[8] **Acknowledgments.** We thank the Institute of Earth Science, Academia Sinica of Taiwan for providing the NACB broadband seismograms. This research was supported by the Ministry of Education under grant 91-N-FA07-7-4.

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