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A statistical investigation of pre-earthquake ionospheric TEC anomalies

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Abstract: Previous researches show that the total electron content (TEC) in the ionospheric exhibits anomalous disturbances a few days or hours prior to earthquakes. The paper used TEC data from Internet GPS Service (IGS), and examined 50 earthquakes of magnitude $Ms \geqslant 7.0$ during 2007 - 2009 worldwide. The result shows significant anomalous increases and decreases about 7 days prior to 94% of the earthquakes.

Key words: earthquake; Total Electron Content(TEC); statistical investigation; anomaly

1 Introduction

In the search of new methods for earthquake prediction, the study of ionospheric disturbances before earthquakes has become a hot topic. One of the parameters studied since the 1990s is ionosphere's total electron content (TEC). Recent application of the Global Positioning System (GPS) to monitor the ionosphere TEC has shown great advantages over conventional methods: low - cost, high accuracy, near real-time and continuity. Many studies[1-21] both in China and abroad showed that ionospheric TEC anomalies occurred within a few days or hours before some earthquakes of magnitude greater than 5.0.

In order to better delineate the relationship between ionospheric TEC anomalies and earthquakes, we did a statistical study on the ionospheric TEC disturbances before earthquakes of magnitude $Ms \geqslant 7.0$ during 2007 to 2009 worldwide. We used the TEC data of Internet GPS Service(IGS) with a time interval of 2 hours.

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2 Data sources and anomaly-recognition method

The worldwide Global Positioning System has provided a new and effective technique for global monitoring of ionospheric TEC, and high-precision values can be obtained by using dual-frequency GPS observations[22-29]. The Jet Propulsion Laboratory (JPL) in the U.S, the Centre for Orbit Determination (CODE) in European, the Energy, Mines and Resources Center (EMR) in Canada, the European Space Agency (ESA), and the Universitat Politècnica de Catalunya in Spain (UPC) have completed algorithm for making global ionospheric maps (GIM) and provide worldwide GIM products through the IGS service center.

In the present study, we used the final ionospheric TEC data of IGS, which has nearly one thousand global GPS stations in operation. The time interval is 2 hours; the spatial resolutions in latitude and longitude are $2.5° \times 5°$. In order to study the large-scale global changes of the ionospheric TEC structure more effectively, we made data interpolation and smoothing, and filtered out some of the small-scale ionospheric disturbances in space and time.

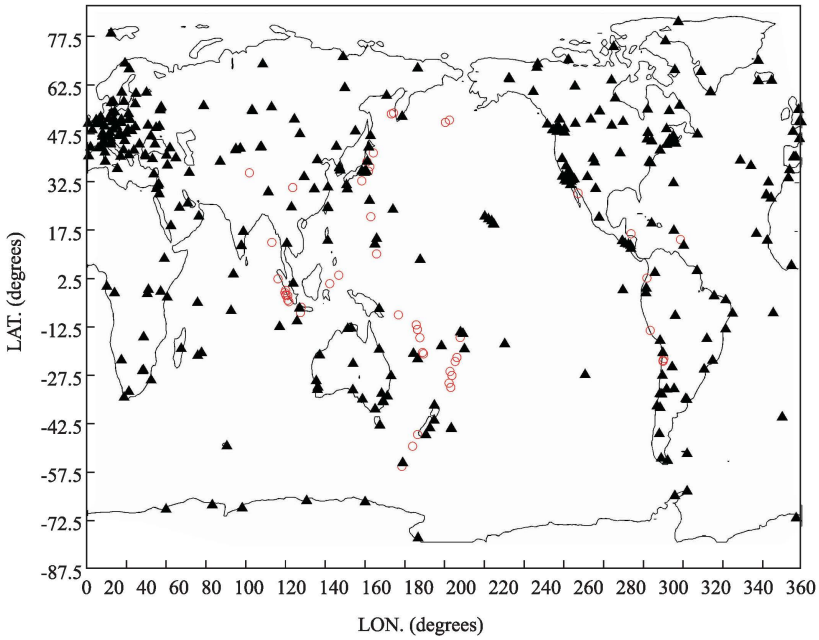

Figure 1 Location of the GPS observation stations (triangles) and the epicenters (circles) of the 50 $Ms \geqslant 7.0$ earthquakes all over the world during 2007 – 2009.

We considered 60 earthquakes of magnitude $Ms \geqslant 7.0$ during 2007 to 2009 worldwide, with detailed seismic parameters given by the China Earthquake Networks Center. By eliminating smaller earthquakes that occurred on the same day we selected 50 of these earthquakes for study. Figure 1 shows the locations of the global GPS stations and the epicenters of the studied earthquakes.

We treated the data as in reference[11], by first removing the apparent periodic term by fitting for the time series with some periodic functions, and then processing the residuals by the moving-average method. We obtained the initial average and the variance from data between the 30th day and the 20th day before the earthquake. Assuming X to be the value of the time series at a grid point in the two-dimensional ionospheric TEC field and using a time window of 10 days, we calculated the mean and the associated standard deviation. We set the error limit to 2σ at 95% confidence level. If a value was lower than the lower boundary ($\bar{X} - 2\sigma$) or larger than the upper boundary ($\bar{X} + 2\sigma$), we defined it as an anomalous disturbance.

3 Data analysis and interpretation

We processed the pre-earthquake ionospheric TEC data for each earthquake and selected local time 14: 00 as the reference time. To exclude the interference caused by magnetic storms and geomagnetic activity, we considered concurrently the geomagnetic Kp index data provided by the International geomagnetic data center. Kp index was designed to describe the physical strength of the geomagnetic activity; it is updated every 3 hours. If there was a moment on any day when the Kp value was larger than 4, then the ionospheric TEC anomaly on that day was excluded from our consideration. Table 1 lists the date, time, epicenter, depth, and magnitude of the earthquakes and the corresponding ionospheric TEC anomalies.

As shown in Table 1, among the 50 earthquakes, 47 were preceeded by aparent anomalous increases and/or decreases within 10 days before the eaqrthquakes. In order to better show the characteristics of these changes, we plotted in Figure 2 the ratio between earthquakes that showed anomalies and the total number of earthquakes as a function of time. It can be seen in Figure 2(a) that the highest ratio for increase is 34%, and the next highest is within one day before earthquake occurrence. The temporal variation is not a simple function of time. As shown in Figure 2(b), negative anomalies also occurred before these earthquakes and 86.2% of them occurred within a week before the earthquakes, which is consistent with a previous study[13]

Table 1 The statistics of the ionospheric TEC anomalies prior to the $Ms \geqslant 7.0$ earthquakes all over the world from January 1, 2007 to October 1, 2009

Date (year-month-day)	Time (UT)	Lat. (°)	Lon. (°)	Depth (km)	Mag. (*Ms*)	The day distribution occured	The state of distribution
2009-10-08	06:03:13	-13.0	166.3	33	7.7	-8, -6, -5, -3, -2, -1,0	-, -, -, -, -, +, +, +
2009-09-30	18:16:08	-0.8	99.8	60	7.7	-10, -9, -6, -5,0	+, -, +, +, +
2009-09-30	01:48:15	-15.5	-172.2	33	8.0	-7, -5, -1,0	-, +, -, -
2009-09-02	15:55:02	-7.8	107.3	60	7.3	-10	+
2009-08-16	15:38:25	-1.5	99.5	50	7.0	-10, -9, -5, -1	+, +, +, +
2009-08-11	03:55:41	14.1	92.9	33	7.5	-5,0	+, +
2009-08-09	18:56:00	33.1	138.2	320	7.2	-9, -1	+, +, +
2009-08-04	02:00:00	29.3	-112.9	10	7.1	-8, -6, -5,0	+, +, +, +
2009-07-15	17:22:32	-45.7	166.4	33	7.8	-4	-
2009-05-28	16:24:41	16.8	-86.2	15	7.0	-6, -5, -2, -1	+, +, +, -
2009-03-20	02:17:37	-23.0	-174.7	10	7.9	-8, -4, -3	+, +, -
2009-02-19	05:53:46	-27.3	-176.3	33	7.3	-5, -4	+, +
2009-02-12	01:34:48	3.9	126.6	30	7.2	-8, -7, -5, -3	+, +, +, -
2008-12-09	14:24:00	-31.0	-176.9	30	7.0	-4	+
2008-11-24	17:02:57	54.2	154.3	520	7.2	-8	+
2008-11-17	01:02:32	1.3	122.1	33	7.1	-8, -7, -5, -1,0	+, +, -, +, +
2008-10-19	13:10:33	-21.7	-173.8	33	7.1	-4, -2,0	+, -, +
2008-09-29	23:19:35	-29.7	-177.8	33	7.2		
2008-09-11	08:20:51	41.8	144	30	7.1	-5	+
2008-07-19	10:39:27	37.5	142.3	33	7.3	-6	+
2008-07-05	10:12:05	53.9	153.1	610	7.6	-10, -7	-, -
2008-06-14	07:43:42	39.1	140.8	10	7.0		
2008-05-12	14:28:04	31.0	103.4	14	8.0	-6, -5, -4, -3	-, -, -, +
2008-05-08	00:45:07	36.1	141.6	33	7.1	-8, -3	+, -
2008-05-02	09:33:36	52.0	-177.6	33	7.0	-10, -5, -2, -1	+, +, +, +
2008-04-12	08:30:12	-55.6	158.4	15	7.1	-9, -5,0	+, +, +
2008-04-09	20:46:20	-20.2	168.9	96	7.3	-9, -4	-, +
2008-03-21	06:33:03	35.6	81.6	33	7.3	-10, -9, -6, -1	+, +, -, +
2008-02-26	05:02:18	-2.2	99.8	33	7.0	-6, -4, -3	-, +, -
2008-02-25	16:36:35	-2.4	100	33	7.6	-5, -4, -3, -2	-, +, -, -
2008-02-20	16:08:33	2.8	96	33	7.7	-6	-
2007-12-19	17:30:28	51.3	-179.6	33	7.0	-9, -4, -1	+, -, +
2007-12-16	16:09:18	-22.6	-70.1	33	7.0	-10, -5, -2	+, +, -
2007-12-09	15:28:23	-26.1	-177.3	160	7.7	-8	-
2007-11-30	03:00:21	15.0	-61.3	150	7.3	-7, -6, -3, -2, -1	-, -, +, +, +
2007-11-15	23:06:01	-22.9	-70.1	33	7.1	-10, -7 -6, -2	+, -, -, +
2007-11-14	23:40:50	-22.1	-69.7	33	7.9	-8, -6, -5, -1	+, -, -, +
2007-10-25	05:02:44	-3.9	100.9	33	7.0	-9, -5, -1,0	-, +, -, -
2007-09-30	13:23:38	-49.3	163.9	33	7.4		
2007-09-30	10:08:31	10.5	145.7	15	7.0	-10, -9, -8, -7, -6, -5, -3, -2, -1,0	-, +, +, +, +, -, -, +, +, +
2007-09-28	21:38:53	22.1	142.8	223	7.0	-8, -7, -4, -2, -1	-, +, +, -, +
2007-09-13	07:49:06	-2.5	100.9	15	8.3	-10, -6, -4, -1	+, +, -, +
2007-09-12	19:10:24	-4.4	101.5	15	8.5	-10, -9, -5, -3,0	+, +, +, -, +
2007-09-10	09:49:15	3.0	-78.2	33	7.0	-10, -9, -7, -6, -5, -4, -3, -2, -1,0	-, +, +, +, +, -, -, -, +, +, +
2007-09-02	09:05:16	-11.6	165.7	33	7.1	-7, -6, -4	+, +, -
2007-08-16	07:40:58	-13.3	-76.5	33	7.8	-10, -7, -6, -5, -4, -3, -2, -1,0	+, -, +, +, +, -, -, -, +
2007-08-09	01:04:58	-6.1	107.7	300	7.8	-9, -8, -7, -6, -3	+, +, -, +, +
2007-08-02	01:08:55	-15.6	167.5	160	7.1	-9, -6, -5, -3	+, +, -, +
2007-04-02	04:39:55	-8.5	156.7	15	7.8	-9, -6	+, +
2007-03-25	08:40:01	-20.6	169.4	33	7.1	-3, -1,0	+, +, +

In order to view the temporal distribution of the anomalies in more detail, we show in Figure 3, the same result at two-hour interval during one week before earthquake occurrence. Anomalous increases mostly occurred at about 04:00 and 12:00 – 18:00 LT, while anomalous decrease occurred without any clear pattern. This conclusion is similar to that of a previous study by Liu[14] for earthquakes of magnitude $Ms \geq 5.0$ in Taiwan area during 1997 – 1999.

4 Summary and discussion

By using ionospheric TEC data offered by IGS, we examined 50 earthquakes of magnitude $Ms \geq 7.0$ during 2007 – 2009 all over the world. The preliminary results showed that, after eliminating the interference caused by geomagnetic activity, within 10 days before the earthquakes, there were significant ionospheric TEC anomalous disturbances prior to 94% of all the earthquakes. The disturbances included anomalous increases and decreases. The decreases mostly appeared within about one week before earthquakes while the increases were irregular. The increases mostly appeared at about 12:00 LT – 18:00 LT, while the decrease times were irregular.

Ionospheric TEC is affected not only by earthquake occurrence but also by other variables, including thunderstorms and lightning impact of human activities which are difficult to exclude presently. Furthermore, the mechanism of seismo-ionospheric coupling is not well understood and the accuracy of observation is limited, because of uneven distribution of the GPS stations. To improve the study of seismo-ionospheric signatures, it is desirable to explore new space observation technology and establish a three-dimensional ionospheric observation system.

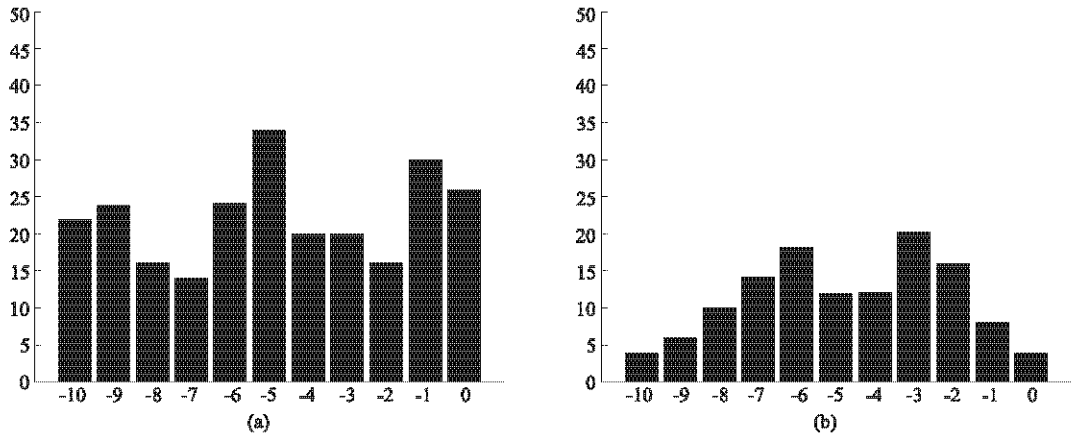

Figure 2 The percentage of earthquakes that showed positive (a) and negative (b) anomalies each day within 10 days before the earthquakes

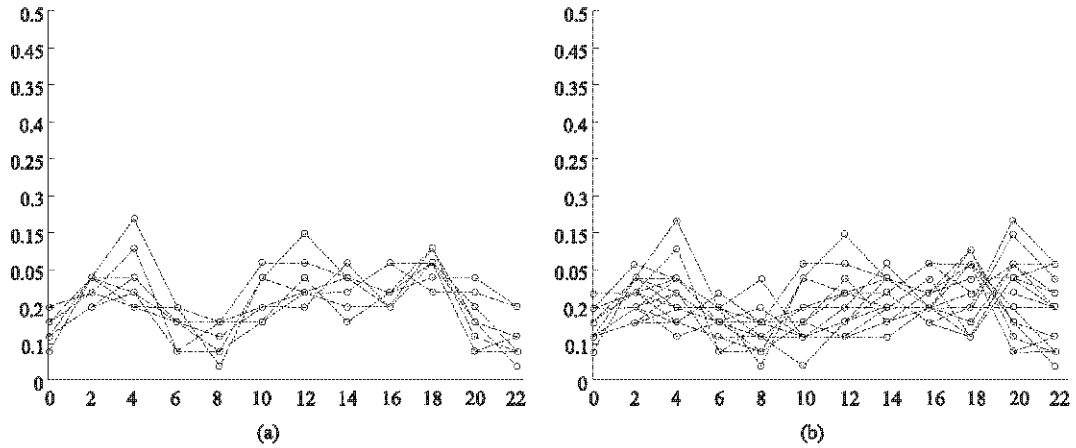

Figure 3 The percentage of positive (a) and negative (b) anomalies that appeared every hour during the week before earthquakes

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