Effects of geomagnetic storms on the middle atmosphere and troposphere by ground-based GPS observations

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Abstract

Among Solar activities' events, the geomagnetic storms are believed to cause the largest atmospheric effects. The geomagnetic storm is a complex process of solar wind/magnetospheric origin. It is well known to affect severely on the ionosphere. However, this effect of this complex process will maybe act at various altitudes in the atmosphere, even including the lower layer and the neutral middle atmosphere, particularly the stratosphere. Nowadays, the GPS-derived ZTD (zenith tropospheric delay) can be transformed into the precipitable water vapor (PWV) through a function relation, and further has been widely used in meteorology, especially in improving the precision of Numerical Weather Prediction (NWP) models. However, such geomagnetic effects on the atmosphere are ignored in GPS meteorology applications. In this paper, we will investigate the geomagnetic storms' effects on the middle atmosphere and troposphere (0-100km) by GPS observations and other data. It has found that geomagnetic storms' effect on the atmosphere also appears in the troposphere, but the mechanism to interpret correlations in the troposphere need be further studied.

Keywords: GPS; geomagnetic storm; troposphere.

1. Introduction

The changes in the atmosphere with height are results of specific physical conditions that exist on the earth and in its atmosphere. The atmosphere can be divided into four regions (Figure 1). The bottom layer, where temperature decreases with altitude, is known as the troposphere. The troposphere is approximately 12 kilometers thick, but there are slight variations. All the weather that we are primarily interested occurs in the troposphere. The top of the troposphere is marked by the tropopause. Above the tropopause lies the stratosphere. The layer is stratified with the denser, cooler air below the warmer, lighter air, which leads to an increase in temperature with height. The temperature increases with height until it reaches about 10°C at an altitude of 48 km. The primary reason that there is a temperature increase with altitude is that most of the ozone is contained in the stratosphere. Ultraviolet light interacting with the ozone causes the temperature increase. The boundary between the stratosphere and the next layer is called the stratopause. Above the stratopause, the temperature again decreases with altitude. This layer is called the mesosphere, or "middle layer." The temperature drops to ~-90°C near the top of the mesosphere. Above the mesopause is the thermosphere, or "warm layer." In the thermosphere the temperature does increase with height (to >1000°C), but as we have already seen, the number of molecules present are so few that even thought they are very energetic, they have such a low density, that temperature as we call it means very little. Above the thermosphere lies the exosphere ("outer layer"). The boundary between the two is very diffuse. Molecules in the exosphere have enough kinetic energy to escape the earth's gravity and thus fly off into space. The outer part of the mesosphere and the thermosphere are sometimes called the ionosphere (from 60-1000 km) as most of the molecules and atoms are ionized by the ultraviolet light and other high energy particles at this height.

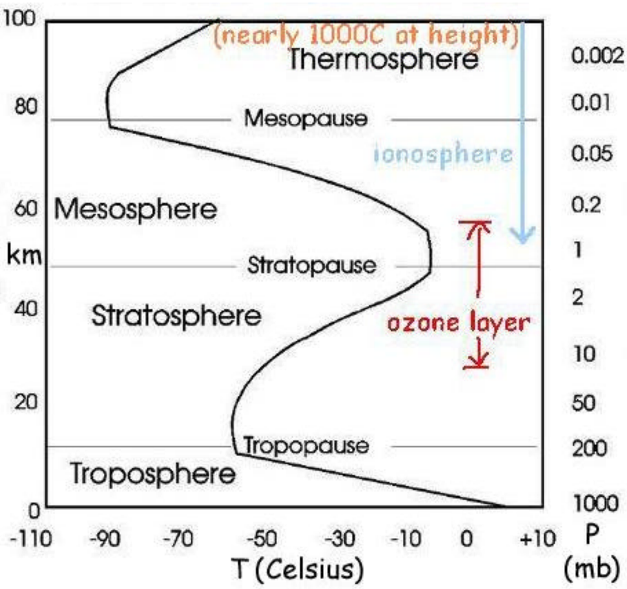

Figure 1 Structure of the atmosphere

Because of the solar wind originating from the Sun, Earth is hit by hot, magnetized, supersonic collisionless plasma carrying a large amount of kinetic and electrical energy. Some of this energy finds its way into our magnetosphere creating, e.g., geomagnetic activity that consists of geomagnetic storms, substorms, and aurora. Geomagnetic storms are probably the most important phenomenon among those related to solar wind and high-energy particles. They produce large and global disturbances in the ionosphere, but they probably affect also the neutral atmosphere, including the middle atmosphere and troposphere [e.g., Lastovicka, 1996]. However, such effects on the troposphere are ignored in meteorology and troposphere research. Nowadays, GPS has been widely used to monitor the zenith tropospheric delay (ZTD) and further transformed into the precipitable water vapor (PWV) for meteorology applications, especially in improving the precision of Numerical Weather Prediction (NWP) models. However, some factors affecting the atmosphere are ignored in GPS meteorology applications, such as solar activities' events. Among them, the geomagnetic storms are believed to cause the largest atmospheric effects. It is well known that this effect on the lower ionosphere is well understood, but not understood in the lower layer and in the neutral middle atmosphere, particularly in the stratosphere. In this paper, we will first investigate the geomagnetic storms' effects on the middle atmosphere and troposphere (0-100km) by GPS observations.

2. Methods and analysis

2.1 Observation methods

When the GPS signal propagates through the atmosphere, it is delayed by variation of the refraction index and results in lengthening of the ray-path, usually referred to as the "atmospheric delay", including tropospheric and ionospheric delays. These delays are one of important error sources for GPS positioning. The followings are the observation equations of carrier phase (L) and code observations (pseudorange P) of double frequency GPS:

$$L_{kj}^{i} = l_k f_{1,j}^{i} = r_{0,j}^{i} - d_{ion,k,j}^{i} + d_{trop,j}^{i} + c(t^{i} - t_{j}) - l_k (b_{k,j}^{i} + N_{k,j}^{i})$$
$$P_{k,j}^{i} = r_{0,j}^{i} + d_{ion,k,j}^{i} + d_{trop,j}^{i} + c(t^{i} - t_{j}) + d_{q,k}^{i} + d_{q,k,j} + e_{j}^{i} \quad (1)$$

where superscript i and subscript j represent the satellite and ground-based GPS receiver, respectively; superscript k is the frequency number (k=1, 2); r_0 is the true distance between the GPS receiver and satellite; d_{ion} and d_{trop} are the ionospheric and tropospheric delays, respectively; c is the speed of light in vacuum space; t is the satellite or receiver clock offset; b is the phase delay of satellite and receiver instrument bias; d_q is the code delay of satellite and receiver instrumental bias; l is the carrier wavelength; f is the total carrier phase between the satellite and receiver; N is the ambiguity of carrier phase; and e is other residuals.

These unknown parameters can be resolved by dual-frequency GPS observation data. Therefore, GPS nowadays has widely been used to determine the tropospheric and ionospheric delays. And the ZTD (Zenith Tropospheric Delay) and TEC (Total Electron Content) can be further obtained and widely applied in meteorology and space environments.

2.2 Ionospheric disturbances during geomagnetic storms

The geomagnetic storms usually cause electrical disruption to satellites and spacecraft and may temporarily affect satellite positioning and HF communications. Here we will investigate the GPS-derived TEC variations during the great geomagnetic storm commenced on 20 Nov 2003. The time series of the Dst index, and geomagnetic activity index Kp by multiplying –30 times are shown in Figure 2. The Dst profile is the solid line and Kp indexes are the dash line. The Dst index is used to define the occurrence, duration and magnitude of a storm, whose unit is nT, nanotesla. And the Kp index is a disturbed level of geomagnetic field. The Kp indexes reach a value of –9 (close to its maximum, from 20:00 on 20 Nov and 4:00 UT on 21 Nov 2003, indicating a severely disturbed geomagnetic condition during these time. The Dst index also reach the summit at 20:00 on 20 Nov, indicating a stronger geomagnetic activity.

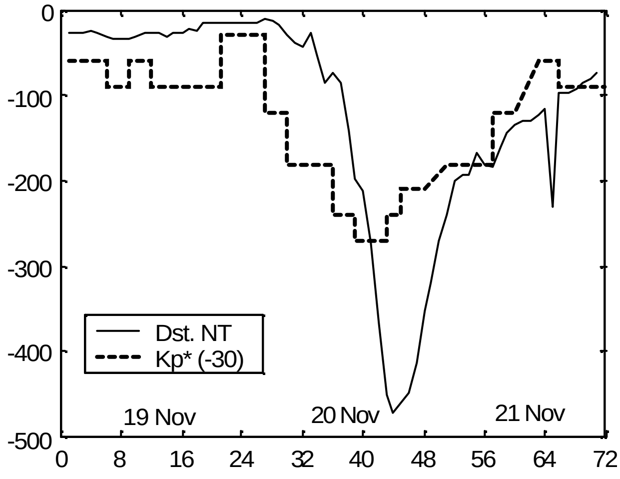

Figure 2 The time series of Dst index and Kp index on 19-21 Nov 2003.

During this time, the variation of TEC is studied by continuous GPS observations in Australia. First, we have developed a Regional Grid Ionospheric Model (RGIM) with a spatial resolution of 5ox5o using the Multiquadric function fitting method. This model can estimate the vertical total ionospheric electron content (VTEC) at the any specified ionospheric grid points with continuous GPS network (Jin et al. 2004). Here, we established an Australian Regional Grid Ionospheric Model with the IGS GPS station data in Australia, which can provide the VTEC at specific grid point to investigate the TEC anomalous variations to the magnetic storms. Figure 3 shows the VTEC time series during the geomagnetic storms on day 29-20 Nov., 2003. The VTEC series from 19 to 21 Nov 2003 are at the grid points of different latitudes, (-15S, 145E), (-30S, 145E) and (-45S, 145E), respectively.

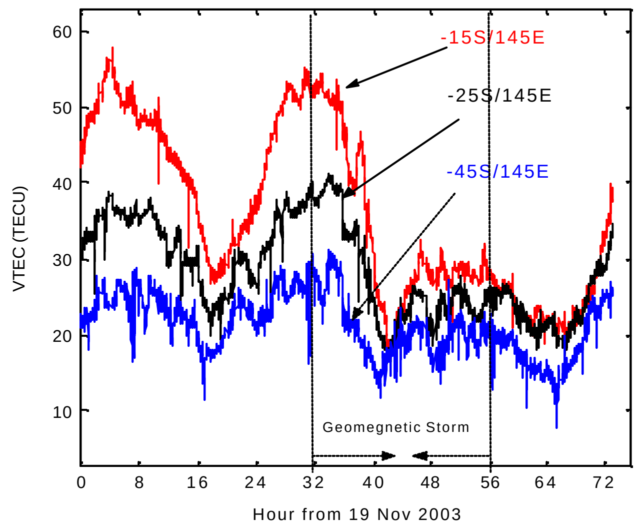

Figure 3 VTEC series at three grid points from 19 to 21 Nov 2003.

The TECs normally vary from day to night on 19 Nov 2003. But it suddenly reduces from 8:00 to 16:00 20 Nov 2003, and rarely varies from day to night on 21 Nov 2003. The distributions that the TEC doesn't normally vary smoothly from day to night on this day are the severe effects due to suffering a great geomagnetic storm. Furthermore, from the low latitude to high latitude, this effect is gradually reducing. The biggest effect induced a 30 TEC degrade in the ionospheric delay. Totally, TEC observations at different latitudes show a clear correlation with Kp and Dst indices, respectively, which indicate a close correction of GPS-derived VTEC with the geomagnetic storms and geomagnetic activities. Therefore, this variation is perhaps caused due to the coupling and interactions of solar activities and ionosphere/ thermosphere.

2.3 Tropospheric disturbances during geomagnetic storms

The geomagnetic storm is a complex process of solar wind/magnetospheric origin. It is obvious to affect severely on the ionosphere. However, this effect of this complex process will maybe act at various altitudes in the atmosphere, even including the troposphere. In the following, we will investigate the strong geomagnetic storm effect on the troposphere.

We use the GAMIT software (King and Bock 1999) to resolve the 2-hour resolution ZTD parameters on Nov. 19-21, 2003 with the newly recommended strategies (Byun et al. 2005). The GAMIT software parameterizes ZTD as a stochastic variation from the Saastamoinen model (Saastamoinen 1972), with piecewise linear interpolation in between solution epochs. GAMIT is very flexible in that it allows *a priori* constraints of varying degrees of uncertainty. The variation from the hydrostatic delay is constrained to be a Gauss-Markov process with a specified power density of 2 cm/$\sqrt{hour}$, referred to below as the "zenith tropospheric parameter constraint". We designed a 12-hour sliding window strategy in order to process the shortest data segment possible without degrading the accuracy of ZTD estimates. The Gauss-Markov process provides an implicit constraint on the ZTD estimate at a given epoch from observations at proceeding and following epochs, which means that the accuracy is expected to be lower at the beginning and end of each window. We therefore extract ZTD estimates from the middle 4 hours of the window and then move the window forward by 4 hours. Finally, the ZPD time series are obtained per site with a temporal resolution of 2 hours.

Figure 4 shows the ZTD time series at Tow2, Darw and Mobs stations of Australia in the Southern Hemisphere from 19-21 Nov, 2003. It has been seen that on 20-21 Nov 2003 of the great geomagnetic storm (seeing Figure 2), the ZTD also degrades, indicating great effects on the ZTD, especially at the higher latitude Mobs station (37.5°S) where the ZTD reduction is up to 150 mm. This geomagnetic storm occurred from 8:00 UT on 20 Nov., 2003, and the ZTD at stations of the middle-high latitude has a large decrease, but few variations at the station of low latitude, such as Darw (12.8°S). Meanwhile, we further calculate the ZTD time series of IGS GPS stations in the Northern Hemisphere on these days. Figure 5 shows the ZTD time series at Wuhn (China), Suwn and Daej (Korea) and Tskb (Japan) stations. It has seen that there are more systematic and consistent ZTD variations at these GPS stations in the Northern Hemisphere during this great geomagnetic storm (20-21 Nov, 2003) that the ZTD largely decreases with great geomagnetic storm occurrence, up to 150 mm.

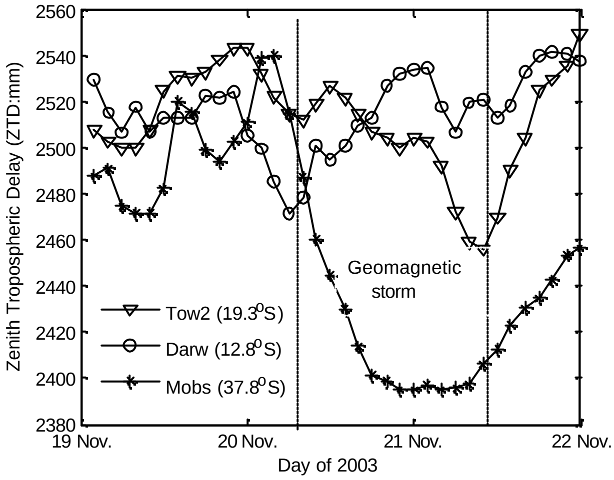

Figure 4 ZTD time series from 19 to 21 Nov 2003 in Australia.

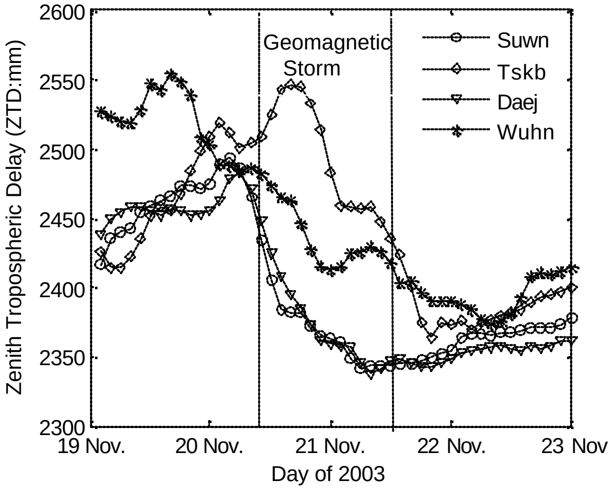

Figure 5 ZTD time series from 19 to 21 Nov 2003 in NE Asia.

To confirm the geomagnetic storm's effect on the troposphere, we calculate the ZTD time series at global IGS stations during the great geomagnetic storm on days 18-22 Nov., 2003. Now the fourth Global IGS Data Center in Asia area was established in 2006 at Korea Astronomy and Space Science Institute (KASI) (http://gdc.kasi.re.kr). It archives all available near-real-time global IGS observation data (ftp://nfs.kasi.re.kr), including collecting more regional permanent GPS stations in Asia-Pacific area. It will contribute to geodesy and atmosphere research activities in global scale. This study selects the global well-distributed 150 IGS sites with better continuous observations. The raw GPS data on days 18-22 Nov. 2003 are processed by GAMIT with above methods. The ZTD time series are obtained per site with a temporal resolution of 2 hours. ZTD has a daily and subdaily variation, but the mean daily ZTD values should be generally almost the same if have no effects, such as rains. But such rain effect on the troposphere will result in ZTD increase, not decrease. Here we investigate the average ZTD response to the geomagnetic storms. Figure 6 shows the mean daily ZTD distributions at global well-distributed GPS stations on day 18, 19, 20, 21 Nov. 2003. We can see that the ZTD distributions are almost the same in the quiet days (18-29 Nov., 2003) as well as the day 22 Nov. 2003, but have differences on the geomagnetic storm days of 20 Nov. 2003. For example, the most obvious difference is the area of middle Asia (about 40°N, 50°E), and there is a significant decrease in this area due to this geomagnetic storm.

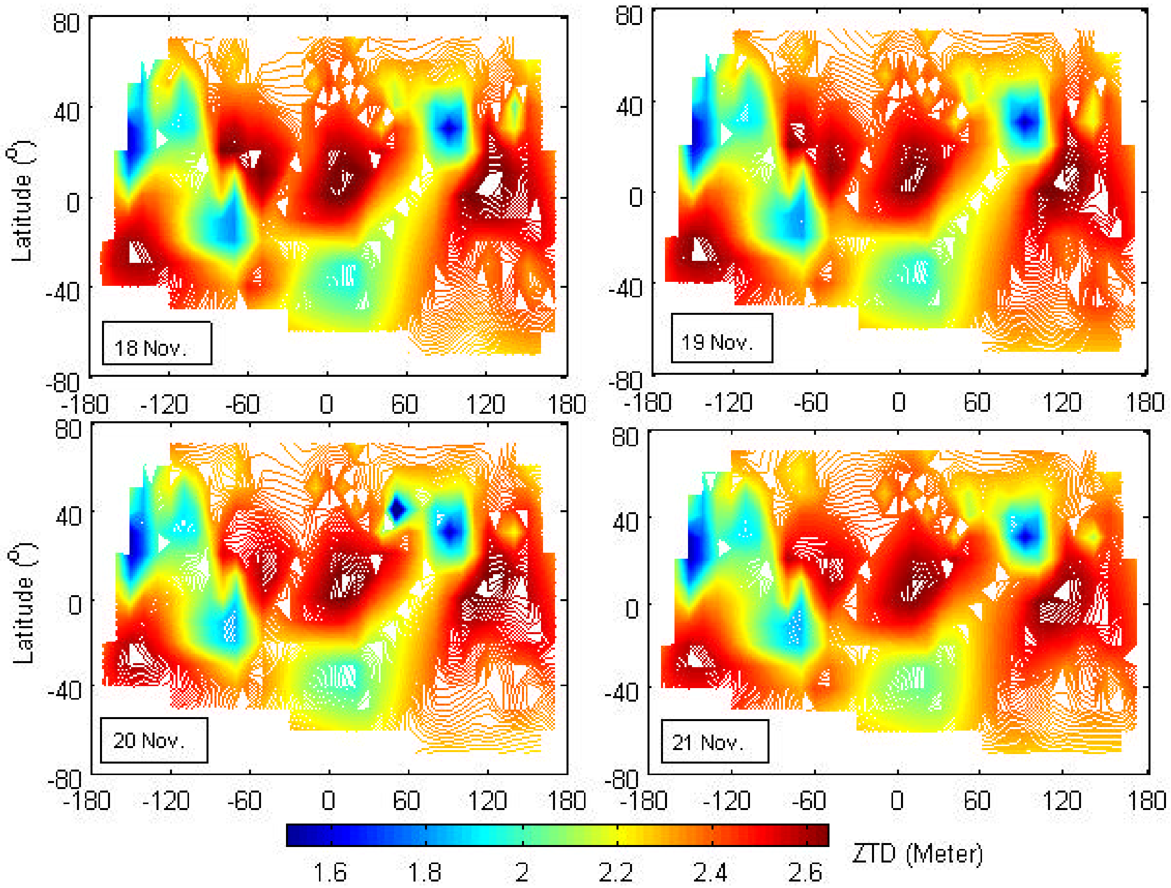

Figure 6 ZTD distributions at global GPS stations on day 18, 19, 20, 21 Nov. 2003

To clearly show the geomagnetic storm's effects on the troposp here, we subtract the ZTD difference between the mean daily ZTD on day 19 and 20 Nov 2003. Figure 7 is the ZTD difference distribution on day 19 Nov. 2003 with respect to the day 20 Nov. 2003. It has been clearly seen that the mean ZTDs on the quiet geomagnetic storm day of 19 Nov. 2003 are larger than ones on the geomagnetic storm day of 20 Nov. 2003 at most continent areas, such as North America, Europe, Asia and Australia. This means that the ZTDs degrade on the geomagnetic storm day.

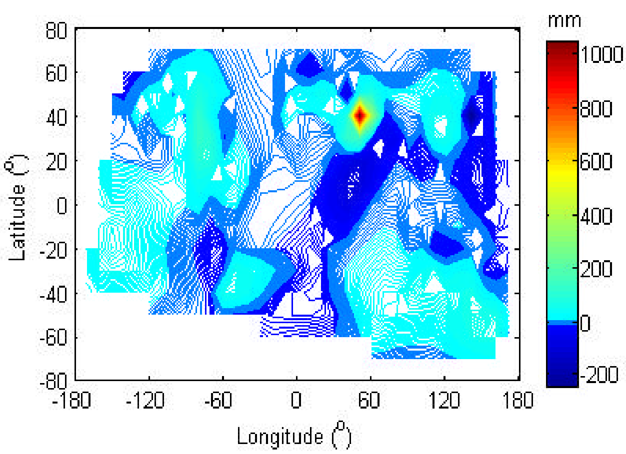

Figure 7 The ZTD difference distributions between the mean daily ZTD on day 19 and 20 Nov 2003.

3. Discussion and Conclusion

Geomagnetic storms are probably the most important phenomenon among those related to solar wind and high-energy particles. They produce large and global disturbances in the ionosphere, but they probably affect also the neutral atmosphere, including possibly the middle atmosphere and troposphere [e.g., Lastovicka, 1996]. In the past time, some cases have shown th e response of basic parameters (e.g. temperature, circulation and pressure) to geomagnetic storms. A decrease of pressure after strong sporadic geomagnetic, particularly developed in the northern Atlantic-European and eastern Siberia-Aleutian sectors, was reported by Mustel et al. (1977). These two regions were confirmed by Smirnove (1984) to be the most sensitive areas of the Northern Hemisphere troposphere to solar/geomagnetic forcing. However, there is a long lived controversy as to geomagnetic storm effects on the troposphere due to lack of observation evidence or adequate mechanisms. Here we addressed other real observation evidence: Global GPS Observations.

In this paper, we will investigate the geomagnetic storms' effects on the middle atmosphere and troposphere (0-100km) by GPS observations. The ZTD time series at global well-distributed GPS stations are calculated during the great geomagnetic storms (18-22 Nov. 2003). It has found that geomagnetic storms' effect on the atmosphere also appears in the troposphere. On the great geomagnetic storm day of 20 Nov 2003, the ZTD has systematically degraded, up to 150, indicating great effects on the ZTD. The global mean-daily ZTD distributions show the mean daily ZTD behaviors are almost the same in the quiet days (18-19 Nov., 2003) as well as the day 22 Nov., 2003, but have differences on the geomagnetic storm day 20 Nov. 2003. There is significant decrease in most continental areas due to this geomagnetic storm. This paper gives the GPS observation evidence of geomagnetic storms effects on the troposphere, but the mechanism to interpret correlations in the troposphere need be further studied.

Acknowledgement

We are grateful to National Geographic Information Institute (NGII), Ministry of Government Administration and Home Affairs (MOGAHA) and other members who made the observation data available. This work was supported by the Korean Meteorological Administration Research and Development Program under grant CATER-2006-3104

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