Thermospheric Wind Variation in the Low Latitude using CHAMP Satellite Data

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Abstract
Using cross-track wind data from the accelerometer on board CHAMP, wind variation in the low latitude have been studied during the high and low solar fluxes. The data set covered the 2002 and 2004 March and September equinox periods. Analysis of the average results from this study found peak eastward speeds of about 220m/s and 120m/s for the low and high fluxes respectively, occurring at about 01.00SLT. Westward peak speeds occurred at about 13.00SLT with low flux and high flux values of about 250m/s and 140m/s respectively. The geomagnetic effect at each of the fluxes did not reveal significant changes. The changes in wind direction occurred 3 hours earlier than those from observations in previous studies. Interestingly when solar flux is low, wind speeds are heavily enhanced, both at high and low geomagnetic conditions. Some of the observed signatures of the thermospheric wind variation were attributed to both extraterrestrial phenomena, like cosmic rays and solar activity.

Keywords: solar flux; geomagnetic activity, cross-track winds, thermosphere, variation

INTRODUCTION
Atmosphere layers are characterized by variations in temperature resulting primarily from the absorption of solar radiation. The sun radiates particles out into space as well as electromagnetic waves. The structure and variability of the ionosphere is controlled in large part by the dynamics of the thermosphere in which it is imbedded. The dynamics of the thermosphere is mainly driven by extreme ultra-violet radiation (EUV). At middle and low latitudes, winds in the ionospheric dynamo region tend to be dominated by global oscillations. Variability of the thermospheric winds on a day to day, seasonal and solar –cycle basis caused about by; variations in the sources of the winds, and variations in the propagation conditions of tides and planetary waves through the middle atmosphere.

Vila et al.(1998), presented some nighttime observations of neutral wind variations at F2 layer levels near the dip equator. The wind data presented were the first observations in Africa. The nighttime equatorial F2 layer showed a complex behaviour during the period of regular measurements from 1994-1995.

Martinis et al. (2001) sampled simultaneously the thermospheric winds at two locations, Arequipa, Peru (17°S, 69°W,-2.7° dip latitude) and Carmen Alto, Chile (23°S, 69°W,-10° dip latitude), during times when Peak F- region densities at the two sites differed by nearly an order of magnitude. Thermospheric neutral wind data was collected during the solar minimum periods of September-October 1996 and 1997. Analysis of the averaged results, found the peak evening zonal wind speed of 127±15m/s eastward for the Arequipa observatory (located near dip equator) to occur between 21:30 and 22:30 LT. The peak evening zonal winds of about 100±10m/s eastwards was observed from Carmen Alto, which is located near the crest of the equatorial ionization anomaly.

Liu et al. (2006), used wind data for 3years (2002-2004) to evaluate the horizontal wind model (HWM). They carried their studies within a band of 5°N and 5°S geomagnetic latitudes. Around equinoxes, increasing geomagnetic activity enhanced the night time wind by over 50ms⁻¹ at low solar flux levels but produced little effect at high solar flux level. Around June solstice, the wind appeared rather unresponsive to geomagnetic activities except for slight enhancement around 1800 MLT at low F10.7 level. Around December solstice, increasing geomagnetic activity weakened the wind in the post mid-night sector by about 40ms⁻¹ regardless of solar flux levels. An improved understanding of the thermospheric dynamics can have a direct impact on studies of ionospheric perturbations and interruptions in communication systems. It is evident from literature, and from results of work carried out in the area of thermospheric wind, that several issues are yet to be resolved .For example, the prediction of onset of irregularities at low latitudes that cause scintillations in radio signals has not been possible (Buonsanto and
Fuller-Rowell, 1997). Again, the effects of the variation of thermospheric wind and distribution of plasma in the low latitude upper atmosphere have not been fully resolved. The cause of the apparent long-term decrease in thermosphere density spanning four decades has not been determined (Forbes, 2007). Similarly, the climatology of the thermospheric wind at equatorial and low latitudes has not been fully established. Furthermore, it has not been possible to carry out separate studies on the response of thermospheric wind to geomagnetic and solar activities due to non-availability of data. With the very current thermospheric wind data, derived from STAR accelerometer on board, the Challenging Mini-satellite Payload (CHAMP), it is now possible to analyze wind variations in the thermosphere on a global scale.

In this study we will try to analyze thermospheric wind variation in the low latitudes during geomagnetically active and quiet conditions for 2 solar flux levels, using the same data set for each of the levels. The same data set is employed for the equinox periods under consideration. In this study the geodetic latitude (9°N), falls within the magnetic equator.

**DATA SOURCES**

Solar flux data used, originated from the Dominion Radio Astrophysical Observatory near Peticon, British Colombia. The 10.7cm solar flux is measured using two fully automated radio telescopes (called ‘flux monitors’). These measurements constitute the 10.7cm solar flux index. Fluxes are given in units of 10^{-22}Js m^{-2}Hz^{-1} or solar flux units (s.f.u.). Often used names for this index are F10.7 and Covington index. The observed values are adjusted for the changing sun-earth distance (adjusted values) and for uncertainties in antenna gain (absolute values). The data are tabulated in two forms: the “observed flux” (F), and the “adjusted flux” (F_a). The “adjusted fluxes” are more purely descriptive of the sun’s behaviour.

**Geomagnetic Activity Index (Ap).**

The Ap index is the occurring maximum 24-hour value obtained by computing an 8-point running average of successive 3-hour ap indices during a geomagnetic storm event and is uniquely associated with the storm event. The 3-hourly ap index is derived from the planetary 3-hour-range index (kp) as follows

\[ Kp = 0, \quad 1, 1, 1, 2, 2, 3, 3, 4, 4, 4 \]
\[ ap = 0, 2, 3, 4, 5, 6, 7, 9, 12, 15, 18, 22, 27, 32 \]
\[ Kp = 5, 6, 6, 6, 6, 7, 7, 7, 8, 8, 9, 9 \]
\[ ap = 39, 48, 56, 67, 80, 94, 111, 132, 154, 179, 207, 236, 300, 400 \]

**Thermospheric wind speed**

Thermospheric wind is obtained from the STAR accelerometer on board the CHAMP satellite.

**CHAMP Satellite and STAR Accelerometer**

The German satellite CHAMP (challenging mini-satellite payload) was launched in July 2000 in a near polar and near-circular orbit at an initial altitude of 460km. The mission objectives are to map the magnetic and gravity fields of the earth and to monitor the ionosphere and troposphere (Bruitisma et al., 2002). Values of thermospheric density and cross track speed can be retrieved from the accelerometer data. These objectives are achieved by the following instruments, which constitute the scientific payload: two fluxgate magnetometers, and overhauser magnetometer, a digital ion-drift meter, a GPS receiver for orbit determination and limb sounding of the atmosphere, a laser retro reflector array, star sensors, and the STAR accelerometer (Spatial Triaxial Accelerometer for Research).

The STAR accelerometer measures the non-gravitational accelerations acting on the satellite. The non-gravitational perturbations include air drag, solar and earth radiation pressure and the atmospheric lift. The accelerometer measures rotational and linear accelerations in the range of ±10^{-4} ms^{-2} with a resolution of ±10^{-5} ms^{-2}. Two independent star camera systems are flown on the CHAMP satellite; one is mounted on the spacecraft body and one on the boom. Readings of the former are for instruments on the body and the latter for the interpretation of the magnetometer readings. Each of the systems operates two camera heads. The readings from the camera heads on the body system are transformed into the spacecraft system by processing on the ground.

**THEORY**

**Derivation of the neutral wind from accelerometer measurement.**

When a spacecraft travels through the atmosphere, it experiences a drag force. If the CHAMP satellite is broken down into a macro model of 13 individual plates (Luhr, 2002) the acceleration caused by the drag and lift forces imparted to each plate according to Sutton et al. (2007) is given by equations (1a) and (1b) respectively.

\[ a_d = \frac{1}{2} \left( C_P A/m \right) \rho \left| \mathbf{F} \right|^2 \]

(1a)

\[ a_l = \frac{-1}{2} \left( C_L A/m \right) \rho \left| \mathbf{L} \right|^2 \]

(1b)

Where \( a_d \) is the acceleration caused by the drag acting in the direction of \( \mathbf{F} \), \( a_l \) is the acceleration caused by the lift acting in the direction of \( (\mathbf{F} \times \mathbf{L}) \times \mathbf{F} \).

\( \mathbf{F} \) is the unit normal vector to the satellite plate, \( C_P \) is the coefficient of drag, \( C_L \) is the coefficient of lift,
A is the total plate area, m is the mass of the satellite, ρ the atmospheric density and \( \vec{v} \) is the velocity of the satellite relative to the surrounding atmosphere. Equation (1a) and (1b) are combined into a new vector (2) equation relating the total acceleration to the summation of the effect of density and wind speed on each plate of the satellites.

\[
\mathbf{a} = -\frac{\rho}{2m} \mathbf{v} + \sum_{t=1}^{12} \left[ A_t \cos \Theta_t \left( \frac{C_{D_t}}{|\vec{v}|} \mathbf{v} + \frac{C_{L_t}}{|\vec{v}|} \frac{\vec{v}}{|\vec{v}|} \right) \right] 
\]

Where \( \mathbf{a} \) is the acceleration caused by drag and lift, the subscript \( t \) is the index for each flat plate in the macro-model, the \( A_t \)'s are the total areas of each plate, the \( \Theta_t \)'s are the angles of incidence of atmospheric particles on each plate, and the \( \mathbf{n} \) are the unit normal vectors for each plate. The largest component of the acceleration not caused by gravity which is measured by the accelerometer on board the CHAMP satellite is atmospheric drag. According to the model by Sutton et al. (2007), up to 10% of the acceleration comes from other sources, these sources include the solar radiation pressure (SRP), followed by albedo and infrared radiation from the earth. These forces are subtracted from the original accelerometer measurements in order to accurately derive the unit speed.

Sutton et al. (2007) adapted the method used by Liu et al. (2006) to obtain the neutral wind vector. If \( \mathbf{a} \) is the measured satellite acceleration with the lift acceleration\( (\mathbf{a}_L) \), solar radiation pressure\( (\mathbf{a}_\text{SRP}) \) and earth radiation pressure\( (\mathbf{a}_\text{ER}) \) removed (i.e. \( \mathbf{a} = \mathbf{a}_\text{SRP} - \mathbf{a}_\text{ER} - \mathbf{a}_\text{L} \)), the equation relating the acceleration caused by drag to the wind speed from equation (3.2) is given by:

\[
\mathbf{a} = -\frac{\rho}{2m} \mathbf{v} + \sum_{t=1}^{12} \left[ A_t \cos \Theta_t \left( \frac{C_{D_t}}{|\mathbf{v}|} \mathbf{v} + \frac{C_{L_t}}{|\mathbf{v}|} \frac{\mathbf{v}}{|\mathbf{v}|} \right) \right] 
\]

Where \( \mathbf{v} = \mathbf{v}_r - \mathbf{v}_o \); \( \mathbf{v}_r \) is the velocity of the satellite with respect to the co-rotating atmosphere; and \( \mathbf{v}_o \) is the wind velocity with respect to the co-rotating atmosphere. Only the cross-track is studied for the following two reasons: neutral density and wind speed cannot be separated from each other in calculations using the along track acceleration axis, and the radial accelerometer axis does not provide measurements of sufficient accuracy. Thus when solving equation (3) for wind speed, components of \( \mathbf{v}_o \) in the along track and radial directions are assumed to be zero.

Equation (3.5) is broken down into three scalar equations when solving for the cross track wind speed.

\[
\alpha_x = -\frac{\rho}{2m} \mathbf{v}_x \mathbf{v}_y \sum_{t=1}^{12} \left[ A_t \cos \Theta_t \left( \frac{C_{D_t}}{|\mathbf{v}|} \mathbf{v} + \frac{C_{L_t}}{|\mathbf{v}|} \frac{\mathbf{v}}{|\mathbf{v}|} \right) \right] \]

\[
\alpha_y = -\frac{\rho}{2m} \mathbf{v}_x \mathbf{v}_y \sum_{t=1}^{12} \left[ A_t \cos \Theta_t \left( \frac{C_{D_t}}{|\mathbf{v}|} \mathbf{v} + \frac{C_{L_t}}{|\mathbf{v}|} \frac{\mathbf{v}}{|\mathbf{v}|} \right) \right] \]

\[
\alpha_z = -\frac{\rho}{2m} \mathbf{v}_x \mathbf{v}_y \sum_{t=1}^{12} \left[ A_t \cos \Theta_t \left( \frac{C_{D_t}}{|\mathbf{v}|} \mathbf{v} + \frac{C_{L_t}}{|\mathbf{v}|} \frac{\mathbf{v}}{|\mathbf{v}|} \right) \right] 
\]

Where the subscripts \( x, y, \) and \( z \) refer to the along track, cross track, and radial axes respectively.

Assuming that the along track wind speed is zero and noticing the common terms in the three equations, cross track wind speed is given by

\[
\mathbf{V}_{xy} = \mathbf{V}_{xy} - \left[ \frac{\rho}{2m} \mathbf{v}_x \mathbf{v}_y \sum_{t=1}^{12} \left[ A_t \cos \Theta_t \left( \frac{C_{D_t}}{|\mathbf{v}|} \mathbf{v} + \frac{C_{L_t}}{|\mathbf{v}|} \frac{\mathbf{v}}{|\mathbf{v}|} \right) \right] \right] 
\]

**Data selection and processing**

Two solar flux levels have been considered; F10.7>145 for high solar flux and F10.7<140 for the low flux. The high flux covers the March and September equinoxes of 2002 while the low flux covers the March and September equinoxes of 2004. Each equinox season covers three months; February, March, April for the March equinox and August, September, October for the September equinox. Each of the solar flux levels is further split into geomagnetically quiet (Ap > 7) and disturbed (Ap ≤ 7) conditions as shown in figure 2. The variation of the F10.7 Ap index with the days of the equinox periods is shown in figures 3a, 3b, 4a, and 4b respectively.

The solar flux level and geomagnetic activity levels are fixed simultaneously for each data group. The wind speeds centered at latitude 9°N of the 3-degree bin are binned and averaged over the satellite local time to get the 24 hour coverage. Figures 5a, 5b and 5c show the number of data points in each local time bin during different levels of solar flux for each geomagnetic condition.

The satellite orbit height ranged from about 372 to 430km during the periods under consideration.

![Fig. 2. Wind data processing at two different geomagnetic activity levels.](image)

**RESULTS AND DISCUSSION**

The time interval of 2002-2004 is characterized by major changes of the solar flux level associated with the declining phase of the solar cycle (Liu et al., 2006). During this period, the F10.7 value dropped from 250 to 78. Zonal winds at the two different solar flux levels and all geomagnetic activity levels are shown in figure 6 below. The derived cross-track wind was found to be blowing eastwards from 01.00hours. A significant difference is observed for
the two flux levels from 01.00 SLT to 07.00 SLT with the low flux value larger by an average value of about 50 m/s. The solar effect from 13.00 hours to 19.00 hours is significant with the low flux westward winds, leading high flux westward winds by an average value of about 80 m/s. Increasing the solar flux level introduced little effect to change in wind speed from 20.00 - 23.00 SLT. Peak westward and eastward wind speeds occur at about 13.00 hours and 1.00 hours respectively for all the flux levels.

The daytime upward $E\times B$ Plasma drift produces crests on either side of the magnetic equator, about 15°-18° dip latitude (N and S), in the afternoon period, in which is termed the ‘equatorial ionization anomaly’ (EIA). An electron density trough is seen near the magnetic equator in the afternoon. The trough at the geomagnetic equator particularly pronounced in the evening to midnight sector is attributed to the ionosphere being raised to higher altitudes by the evening pre-reversal enhancement of the eastward electric field (Maruyama et al., 2003). The peak westward wind speeds occurring from 12.00 - 14.00 hours can be attributed to the less ion drag within the trough. Increasing solar flux level lead to a rapid increase in the pressure gradient force on the dayside (Cho and Yeh, 1970). This partly explain the wind variation from 11.30 - 19.00 hours in figure 6. At the dip equator, electron density exhibits minimum values and so is neutral temperature, maxima of zonal wind speed, eastward at 19 LT, westward at 11 LT (Rishbeth, 2000). Analysis of averaged results during some selected nights of September 1996/97 equinox period found the peak evening zonal neutral wind speed of ~127 ± 15 ms⁻¹ eastward for the Arequipa observatory, which is located near the magnetic equator, that occurred between 21.30 and 22.30 LT (Martinis et al., 2001). In this study, peak westward winds occur between 12.00 and 14.00 SLT while peak night eastward winds occurred between 23.00 and 02.00 SLT. The geomagnetic effect as is not clearly defined at high flux is as seen in figure 8a. From figure 8b, increasing geomagnetic activity at low solar flux slightly enhances the wind speed from 17.00 SLT to 23.00 SLT. Quiet time winds at low flux are slightly more eastwards from 6.00 - 12.30 SLT. The wind speeds are greatly enhanced during high and low geomagnetic conditions when solar flux is low is evident from figures 8a and 8b.

Ion drag and day-night are produced by direct heating from solar EUV radiation. The geomagnetic activity index (Ap) used in this work is a summation of Kp index values which are related to the solar wind intensity and the orientation of the interplanetary magnetic field (IMF) embedded in it. Geomagnetic effects originating from high latitudes suffer attenuation before reaching the equatorial latitudes, thus its influence on zonal winds is small as compared to the solar flux.

Figures 9a and 9b are contour maps showing diurnal wind variation across all longitudes at high and low solar fluxes respectively. At high flux, winds are generally westwards from ~ 10.00 to 20.00 SLT with peak values up to 200 m/s between 12.00 and 18.00 SLT. Westward winds are slowest in the South American sector (~50°- 100°W). From about 23.00 to 09.00 SLT in the morning winds are generally eastwards with peak values reaching 180 m/s. During the low flux, winds were westwards from 10.00 to midnight with speeds above 350 m/s experienced at some longitudes.

**CONCLUSION**

We used wind speeds from the new technique by Sutton to study wind variation in the low latitude at high and low solar flux levels. We also used the same data set to study variation for two geomagnetic conditions in each of the flux levels. Some of the observed features showed similarities to previous studies but there were some significant departures. Points of switching wind direction and maximum values depicted a lag of about 1-3 hours, when compared with results of previous workers. Surprisingly, the extreme high values of low solar flux levels from about midnight to early morning hours. The general high values observed for the low flux variation and other signatures of wind variations may be attributed to also both extraterrestrial phenomena; like the cosmic rays and solar activity. There exists a very strong dependence of cosmic ray flux on solar activity. Geomagnetic activity influences recorded were relatively minimal for each of the solar flux levels, this could be explained with reference to non-environmental condition influence, of which geomagnetic fields and geomagnetic latitudes are inclusive.

Errors arising from longitudinal averaging of the winds may not lead to significant departures from previous observed diurnal patterns, as wind variation across the longitudes is almost uniform as can be seen from figures 9a and 9b. Notably, some of our findings are in agreement with that of some other work (e.g. wind direction is eastward most of the night and westward most of the day, increasing the geomagnetic activity level did not lead to corresponding large increases in the wind speed), it is equally observed that there are some discrepancies with some authors previous findings (e.g. enhancement of wind speed at low flux). Therefore, there still exists controversy which still needs to be resolved. Also the use of very low solar flux intensity values will yield a good comparison with the 2002 high flux values. As suggested by Sutton et al. (2007) other thermospheric wind instruments can be used as instrument calibration for the accelerometer on CHAMP satellite.
ACKNOWLEDGEMENT
The authors thank Dr. Eric Sutton of the Department of Aerospace Engineering sciences, university of Colorado, Boulder, U.S.A, whose data base used was for the study. We equally acknowledge the centre for Basic Space Science for providing the necessary facilities used in this work.

REFERENCES


Fig. 4 (a) distribution of the Ap geomagnetic index versus days of March and September 2002 equinoxes

Fig. 5 (a). Number of data points in each local time bin at high and low fluxes

Fig. 5 (b). Number of data points in each local time bin during disturbed times at high and low fluxes.

Fig. 5 (c). Number of data points in each local time bin during quiet times at high and low fluxes.

Fig. 6. Cross-Track wind variation during high and low fluxes at all geomagnetic conditions

Fig. 7. Uncertainty in cross-track wind speed at high and low fluxes (m/s).
Fig. 8a. Cross-Track wind variation during quiet and disturbed times at high flux.

Fig. 8b. Cross-track wind variation during quiet and disturbed times at low flux.

Fig. 9 (a). Diurnal variation of cross-track wind speed at latitude 9°N across all longitudes for high solar flux.

Fig. 9 (b). Diurnal variation of cross-track wind speed at latitude 9°N across all longitudes for low solar flux.