First U.S.-China joint ground-based Fabry-Perot interferometer observations of longitudinal variations in the thermospheric winds

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Abstract For the first time, three Fabry-Perot interferometers from the U.S. (Boulder, 40°N, 105°W, 49°N magnetic latitude (MLAT)) and China (Xinglong: 40°N,115°E, 34°N, MLAT; Kelan: 39°N, 112°E, 33°N MLAT) were used to examine the longitudinal variations in the thermospheric winds due to the geomagnetic latitude differences between the American and Asian sectors. During a case of quiet geomagnetic condition, the meridional winds were very similar at the U.S. and Chinese stations. The meridional winds at Boulder reached most equatorward winds after midnight, whereas in China, the largest equatorward winds were found near midnight. The Boulder zonal winds turned westward earlier in the morning hours and had larger diurnal variations because of its higher magnetic latitude. During the case of low geomagnetic activity (Kp~2), the meridional winds were still similar in the U.S. and in China. Boulder zonal winds had much larger diurnal variation compared to the quiet condition (Kp~1). Thermosphere-ionosphere-electrodynamics general circulation model simulations show a very good agreement with observation for the meridional winds. The simulated zonal winds exhibit noticeable differences with observations, but the general tendencies in longitudinal variations with a larger diurnal variation near the auroral oval are correct. Simulations showed that the ion drift is not directly responsible for the longitudinal variations in the winds. The pressure gradient had more direct effect on the longitudinal changes in the winds. The simulation results also showed larger diurnal variations at higher geomagnetic latitudes due to the auroral oval heating. Nonmigrating tides were not observed in the two cases in October 2012.

1. Introduction

There are several possible sources for the longitudinal variations in the thermosphere: geomagnetic latitudinal variations and nonmigrating tide. If there were no ionosphere, the longitudinal variations would mainly be caused by nonmigrating tides. Because of the strong influence from the ionosphere, the longitudinal variation in the thermosphere is more complicated. A good longitudinal coverage is needed to study the longitudinal variations, and spaceborne instruments should be more suitable to study these phenomena. There were past thermospheric wind observations from DE-2, UARS, and CHAMP satellites [Wu et al., 1994; Killeen et al., 1982; Shepherd et al., 1993; Lühr et al., 2007]. Wu et al. [1994] particularly used the DE-2 data to examine the longitudinal variations in the thermospheric winds in the equatorial region and reported larger zonal wind variations than meridional. The longitudinal variations were clearer under geomagnetic quiet conditions. A difficulty with satellite observations is the limited local time coverage, and the analysis needs to be based on long data sets.

Thermospheric wind observations from ground-based instruments are generally based on Fabry-Perot interferometer (FPI) Doppler airglow remote sensing observations. FPI instruments however were not evenly distributed longitudinally in the past, with most of them in the American sector. Hernandez et al. [1978] used a pair of FPIs near Boulder (105°W) and Laurel Ridge (79°W) with a 26° longitudinal separation to study longitudinal variations. The thermospheric winds were found to be mostly consistent with each other if arranged in the local times. That is not totally surprising because Boulder and Laurel Ridge are located at a similar magnetic latitude.

More FPIs have recently been deployed in the Asian sector. FPIs in China and in the U.S. at the same geographic latitude are available for joint observations. In this study, thermospheric winds from three FPIs at
Boulder, U.S. (BD: 40°N, 105°W, 49°N magnetic latitude (MLAT)), Xinglong, China (XL: 40°N, 115°E, 34°N MLAT), and Kelan, China (KL: 39°N, 112°E, 33°N MLAT) are examined. The FPIs in China and in the U.S. are separated in longitude by more than 100°, which creates an opportunity to examine the longitudinal variations in the thermospheric winds. The two Chinese stations are close together and therefore can give validation to each other and can help avoid the possibility of small-scale variations being interpreted as longitudinal changes.

In addition to observations, the National Center for Atmospheric Research (NCAR) thermosphere-ionosphere-electrodynamics general circulation model (TIEGCM) is available to simulate the thermospheric winds for comparison with observations in order to understand longitudinal variations. In this paper, the focus is on the geomagnetic latitude difference between China and the U.S. and its effect on thermospheric winds. TIEGCM simulations with and without geomagnetic dipole tilt from the geographic pole were also performed and compared with the observations. The paper is organized as follows: first, the FPI observations and TIEGCM model simulations are presented; next, the observational results are discussed in detail with more output from the TIEGCM; finally, the findings are summarized.

2. FPI Thermospheric Wind Observations

The three FPI instruments are similar in design to the FPI deployed in Resolute, Canada [Wu et al., 2004]. Yuan et al. [2010] provides more details about the XL FPI. The FPI measures the thermospheric winds by observing wind-induced Doppler shift in the O 630 nm emission. The O 630 nm is a forbidden line, which peaks at ~250 km. At low altitude, the emission is quenched by collisions. The three instruments have a 10 cm clear aperture with a 2 cm gap. The instrument samples the four cardinal directions with a 45° elevation angle and the zenith, all with a 5 min integration time. The wind error is a few meters per second, which varies with the airglow intensity. All instruments operate nightly on a routine basis.

One of the issues for selecting nighttime data from two longitudinal sectors is the lack of overlap in coverage. The nighttime in the American sector usually starts near 0 UT and ends near 12 UT, when the nighttime in Asia begins, which ends near 24 UT. Because the thermospheric winds are affected by the geomagnetic activities, it is important to select data intervals when the geomagnetic activity levels are comparable at the two locations during their nighttime hours. Otherwise, the temporal change in geomagnetic activity could be misinterpreted as longitudinal variations. Data from two time intervals (11 and 22 October 2012) were selected when the weather conditions at all locations were favorable. On 11 October 2012, the Kp index varied from 2 to 1, which represents low geomagnetic activity (Figure 1). In another case (22 October 2012), Kp was mostly below 1, which is a geomagnetically quiet condition. On both days, the Kp indices for the first half of the day (nighttime in the U.S.) and the second (nighttime in China) were similar.

The thermospheric winds from the three stations on 11 October 2012 (day 285) are plotted in Figure 2 in the same local times for comparison. The meridional winds from the three stations were very similar. The zonal winds showed noticeable differences between the American and the Asian sectors. The winds in the American sector had larger diurnal variations. The zonal winds from China, on the other hand, mostly stayed close to zero. The zonal winds from BD were more westward near dawn than that at XL and KL. The XL and KL data were very consistent to each other. It should be noted that there were some geomagnetic activities 1 day earlier on 10 October, when the Kp index reached above 3 and below 4 near 18 UT. The implication of this will be discussed later in this paper.
The thermospheric winds on 22 October 2012 (day 296) are shown in Figure 3. The Kp values for 21 October 2012 were all around 1, with very quiet geomagnetic conditions. The meridional winds were very close from all the three stations. However, some subtle differences do exist. Winds at BD were slightly less southward than that at the other two stations and reached a minimum after midnight. The zonal winds were also very close. Only near dawn did the BD data deviate from that of the other two stations. The BD data showed stronger westward winds near dawn similar to the case of 11 October 2012.

Figure 2. Nighttime FPI thermospheric winds from Xinglong (green), Kelan (red), and Boulder (blue) in local time for 11 October 2012 (11–23 UT for Xinglong and Kelan and 1–13 UT for Boulder). (top) Meridional and (bottom) zonal winds. The data from Boulder and Kelan are plotted with separate viewing directions (north, triangle and south, square, for the meridional winds; west, triangle and east, square, for the zonal winds). The Xinglong data were combined for the meridional and zonal wind components, respectively.

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Figure 3. Same as Figure 2 but for 22 October 2012. The last data point from Xinglong (green) at 5 LT has a large error bar due to the strong atmospheric scattering caused by the twilight.
3. NCAR TIEGCM Model Simulation Results

The NCAR TIEGCM is a coupled thermosphere and ionosphere model, which solves coupled, nonlinear, hydrodynamic, thermospheric, and continuity equations of the neutrals with ion energy, ion momentum, and ion continuity equations. The model calculates neutral winds, ion drift, compositions, and temperature. The resolution of the model can be set at 5 × 5° or 2.5 × 2.5°. In this study, the 5 × 5° resolution was used. The TIEGCM covers from 97 to roughly 500 km, with 60 or 30 levels depending on the resolution [Roble et al., 1988; Richmond et al., 1992]. The solar EUV and UV spectral fluxes are parameterized with the solar $F_{10.7}$ index. The high-latitude convection is described by the Heelis model, which is driven by the $Kp$ index [Heelis et al., 1982]. The TIEGCM used the apex geomagnetic coordinate system with the International Geomagnetic Reference Field (IGRF) model configuration [Richmond, 1995].

Two different simulations were performed with the TIEGCM to examine the effect on the geomagnetic and geographic latitude offset. In both cases, the model is driven at the lower boundary (97 km) with the global scale wave model with migrating tidal variations [Hagan et al., 1995, 1997, 2007, 2009; Hagan and Forbes, 2002]. Consequently, the thermosphere should not contain nonmigrating tides from the lower thermosphere. In the first case, the geomagnetic field with standard IGRF configuration was used (referred to as "with tilt"). In the second simulation, the nondipole field components and tilt of the geomagnetic dipole were removed so that the dipole is aligned with the Earth’s rotation axis (referred to as "without tilt"). Hence, in the second simulation, the geomagnetic latitudes coincide with the geographic latitudes. By comparing these two simulations, the effects of the longitude variations of the geomagnetic field on the wind were examined.

Figure 4 shows the FPI observations from China and U.S. and the TIEGCM simulations of the winds at these locations on 11 October 2012. For easy comparison with model, the data are plotted in UT. Since the XL and KL locations are close in distance, they are near the same TIEGCM grid point. Therefore, only the XL location is used to select the TIEGCM output for comparison. The meridional winds from the FPIs and TIEGCM agree very well both at Boulder and at the two stations in China. The TIEGCM slightly overestimates the southward wind before midnight. The simulations with and without tilt do not show large differences. The zonal winds, on the other hand, show large discrepancies between the model and observations at Boulder. The observed winds had a stronger eastward component for most of the night. The winds at the two Chinese stations agree with the model very well. The tilted and without tilt TIEGCM simulations show small differences for the two Chinese stations and a large separation at BD. The simulation with tilt shows a larger diurnal variation at BD than that without tilt. In this case, the simulation with tilt is more consistent with observed data. However, the model
underestimates the eastward wind by about 100 m/s. The TIEGCM with tilt also gives a slightly smaller diurnal variation in the zonal winds near the Chinese stations, making it more consistent with the observations.

Figure 5 shows the FPI observations and TIEGCM simulations for 22 October 2012. There is good agreement between the observed data and the simulation results in the meridional winds. Changing the magnetic field makes no difference for the meridional winds at XL and KL. The TIEGCM with tilt gives slightly more southward wind at BD after midnight, which is closer to the observations. The modeled zonal winds are slightly more westward at XL and KL. The TIEGCM simulation with tilt gives large diurnal variations in zonal winds at BD, which is more consistent with the observed data. Near dawn (10–12 UT), the simulation with tilt shows a stronger westward wind than that without tilt.

4. Discussions

Overall, both the observations and the TIEGCM simulations show more longitudinal variation in the zonal winds than in the meridional winds. As a result, the zonal winds are the focus of this study. To examine the source of the large longitudinal variations in the zonal winds, the TIEGCM ion drift data and geopotential height gradient in the zonal direction were examined. The ion velocity affects the ion drag force on the wind. The zonal gradient of geopotential height is proportional, by a factor of $1/g$, to the zonal wind acceleration due to the pressure gradient.

The TIEGCM zonal ion drift and zonal geopotential height gradient for 11 October 2012 are plotted in Figure 6. In the case without tilt, the ion drifts are similar at BD and XL. The geomagnetic dipole tilt makes a large difference in the ion drift in the TIEGCM. The ion drift at BD is more westward in the TIEGCM with tilt. The ion drift at XL went the other way and became less westward. Hence, based on the ion drift alone, neutral winds at BD should be more westward compared to XL and KL. That is opposite of the observational data. BD actually had stronger eastward winds. The TIEGCM gives a longer and stronger negative (westward) geopotential height gradient before midnight at BD compared to XL and KL. Having a westward geopotential height gradient just after sunset is understandable, because the Sun is above the western horizon, heating the thermosphere and pushing the wind eastward. After midnight, the geopotential height gradient at BD turned to eastward earlier than at XL and KL.

Figure 7 shows the ion drift and the geopotential gradient for 22 October 2012. This was a geomagnetically quiet day. The ion drifts in the two simulations were quite different from the 11 October 2012 case. The zonal ion drift was overall more eastward. The tilted simulation produced the same effect on the ion drift that is more westward at BD and eastward at XL, as compared to the simulation without tilt. These ion drift changes
were not reflected in the neutral winds, indicating that the ion drift was not a major factor. In the tilted TIEGCM case, the geopotential height gradient was more westward before midnight and turned eastward after midnight at BD. It is opposite at XL. That is more consistent with the wind direction from the observation than was the case of 11 October 2012.

**Figure 6.** TIEGCM zonal ion drift and geopotential height zonal gradient for 11 October 2012. (top) The zonal ion drifts at Boulder (blue) and Kelan (red). The dashed line (dash-dotted line) is for simulation with (without) dipole tilt. (bottom) The geopotential zonal gradient with same color and line style coding. Positive (eastward) means that the geopotential height is higher on the east than on the west. The wind generated by the gradient should always have the opposite sign. The negative (westward) gradient before midnight pushes the wind eastward.

**Figure 7.** Same as Figure 6 but for 22 October 2012. The tilted TIEGCM (dash-dotted) geopotential height gradient is less eastward (positive) near dawn at Boulder. Consequently, it pushes wind more westward at Boulder near that time.
The TIEGCM ion drift and geopotential gradient can provide some insights into the cause of the longitudinal variations in the thermospheric zonal winds from BD to XL and KL. The geomagnetic latitude difference is the underlying cause. The larger diurnal variation near BD is due to its proximity to the auroral oval. However, the mechanism for the longitudinal change in the winds is not the ion neutral interaction through ion drift. The main driving force is the pressure gradient. It is possible that there is more Joule heating, producing more pressure gradient diurnal variation near the auroral oval, which in turn causes large diurnal variations in the zonal winds.

Close to the auroral oval may also be the reason Lieberman et al. [2013] saw a stronger diurnal tide in the thermospheric zonal winds from CHAMP satellite around 50° geographic latitude compared to other latitudes. Lieberman et al. [2013] showed that the phase of the diurnal variation in the zonal winds shifts to earlier local time from low to midlatitudes. That is consistent with observations from BD, XL, and KL, since the stations are at different geomagnetic latitude (BD being higher). The earlier turning of the zonal wind from eastward to westward will result in a phase shift for the diurnal variations. Because CHAMP satellite could only provide zonal winds, there were no results shown for the meridional winds. If the meridional wind data were available, it should be expected that the meridional diurnal variation phase would shift toward later hours from low to midlatitudes, because the largest equatorward winds occurred after midnight at BD.

The TIEGCM performed very well under quiet conditions (22 October 2012). The meridional wind from the model was in better agreement with the observations. The tilted TIEGCM shows the tendency for larger equatorward wind after midnight at BD, which was consistent with the observations. Under low geomagnetic activity (11 October 2012, Kp=−2), the zonal wind from the model departed from observations at BD, when BD was even closer to the auroral oval due to its expansion with the low geomagnetic activity. The auroral input for the TIEGCM is an empirical model based on statistical results [Roble and Ridley, 1987]. So it should not be a surprise that the size of the auroral oval and the forcing in the model did not match the real conditions. Consequently, the modeled thermospheric wind near the auroral oval may differ from observations. During quiet conditions, BD is farther from the auroral oval, and the simulation results agree with observations better, because the influence of the auroral oval is weaker. Since XL and KL are at 34°N MLAT farther from the auroral oval, the TIEGCM results are more consistent with observations even under the low-activity condition (11 October 2012). Overall, the TIEGCM performs better farther from the auroral oval, where the influence of the auroral oval is less significant. It should be noted that the BD data were taken closer to 10 October 2012 (0 to 12 UT on 11 October 2012), when the Kp index was near 3 around 18 UT. It is known that the midlatitude thermospheric zonal winds are affected hours after geomagnetic activities with stronger westward winds [Fejer et al., 2002; Wu et al., 2014]. However, the BD zonal wind showed an increase in the eastward direction, which suggests that the BD zonal wind did not have the same lingering geomagnetic effect reported by Fejer et al. [2002] and Wu et al. [2014].

It will be interesting to compare the observation with the simulation by Cnossen and Richmond [2012]. In their analysis of the geomagnetic dipole tilting effect on the magnetosphere-ionosphere-thermosphere system, they examined the thermospheric winds using the TIEGCM with a 0° and a 30° tilt mostly under a negative interplanetary magnetic field $B_z (=−5 \text{ nT})$ condition. Such a condition would create a more active geomagnetic condition, which is more comparable with the 11 October 2012 case. In Figure 6 of their paper, it can be seen that the thermospheric winds under a 30° dipole tilt showed more westward winds (24 h average) over North America than over China, because the polar cap is shifted toward northeast of North America and pushes the winds more westward over the U.S. Since the ground-based observations cover only nighttime, it is not possible to create a 24 h average for comparison. In the 11 October 2012 case, the BD nighttime zonal winds were more eastward and also turned westward earlier near dawn than those in China. The tilted TIEGCM simulations in Figure 5 showed similar large eastward winds and an earlier westward turn and appear to have more westward daily mean wind at BD consistent with Cnossen and Richmond’s [2012] results. Eventually, future thermospheric wind observations can be made during the daytime, so that 24 h average winds can be calculated.

Even though this study is on the longitudinal variations, the focus is on the geomagnetic latitude difference between the two continents. Therefore, it is useful to examine the geomagnetic latitude dependence in one longitudinal sector for comparison. Emmert et al. [2006] examined thermospheric winds from several ground-based stations, which include Millstone Hill (MH: 42.6°N, 71.5°W, 53°N MLAT) and Arecibo (AC: 18.4°N, 67°W, 29°N MLAT). These two stations have geomagnetic latitudes similar to BD (49°N MLAT), XL, and KL (~34°N MLAT).
however, they have a large geographic latitudinal difference as well. Hence, it is hard to separate the geomagnetic and geographic latitudinal dependences. Nevertheless, the results from MH and AC do resemble those from BD, XL, and KL. The zonal winds at MH turned westward earlier than those at AC. As shown earlier, the BD zonal winds turned westward earlier than that of XL and KL. BD, XL, and KL data show that the earlier westward turning in the zonal winds is mostly due to the geomagnetic latitudinal dependence and not to geographic latitudinal dependence. This is a significant result in understanding the latitudinal dependence of neutral wind diurnal variation. The three-station observation also showed no sign of nonmigrating tide in these two cases.

Another point of interest is that the meridional wind did not show much effect of the magnetic latitudinal variations. Emmert et al. (2006) however showed noticeable differences between MH and AC in the meridional winds under quiet conditions. The MH meridional wind tends to reach minimum after midnight, while the AC meridional wind minimizes near or before midnight. That is similar to the BD, XL, and KL meridional wind patterns. The equatorward wind magnitude at MH is larger than that at AC. That is not clear in the case of BD, XL, and KL. Hence, it is possible that the magnetic latitude at MH and BD determines the local time of the minimum in the meridional winds. The magnitude of the equatorward winds is more associated with the geographic latitude of the stations.

5. Summary

The first U.S.-China joint observation of thermospheric wind longitudinal variations provided a good opportunity to examine the effect on the geomagnetic latitude dependence of the thermospheric winds: (1) The observations showed that the large longitudinal variation at 40°N is due to the geomagnetic latitude difference between the U.S. and China. Being at higher geomagnetic latitude, the zonal winds in the U.S. turned westward earlier; (2) the effect is stronger in the zonal winds compared to the meridional winds. The TIEGCM simulations with and without geomagnetic dipole tilt showed a similar effect; (3) the TIEGCM simulations strongly suggest that Joule heating near the auroral oval is the main driving force for the geomagnetic latitude dependence-related longitudinal variations; and (4) the model performs better under geomagnetic quiet conditions and farther from the auroral oval. The simulation and observation agreement are better for the meridional winds. Even though more FPIs are being deployed, the distribution of thermospheric instruments is still very sparse. More wind instruments and studies are needed for improving our understanding of the thermospheric dynamics, which is very important for the ionospheric and space weather researches.

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