Magnetic declination and zonal wind effects on longitudinal differences of ionospheric electron density at midlatitudes

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A prominent ionospheric longitudinal variation at midlatitudes, in particular, over the continental US, was found recently. This variation is characterized as a higher east-side electron density in the evening and a higher west-side electron density in the morning, and with clear seasonal and solar activity dependencies. A combined effect of geomagnetic declination and changing zonal winds was proposed to explain it. This paper represents a comprehensive investigation of this effect by examining climatology for both electron density longitudinal differences and the nighttime zonal winds in the eastern US. Electron density is from incoherent scatter radar extra-wide coverage experiments during 1978–2011 over Millstone Hill for which the spatial separation of the data can be up to 50° in longitude. The thermospheric zonal wind is from the on-site Fabry-Perot interferometer measurements during 1989–2001. The observed zonal wind climatology is found to be perfectly consistent with the expectation based on the east-west electron density differences in terms of local time, seasonal, and solar cycle dependencies. The correlation between the zonal wind and the east-west differential ratio is extremely high with an overall correlation coefficient of 0.93. The observed time delay of ~3 hours in the response of electron density differences to zonal winds is a marked feature. Thus these results confirm positively the declination-zonal wind mechanism and provide new insight into longitudinal variations at midlatitudes for other geographic sectors.


1. Introduction

Some recent studies revealed a prominent ionospheric longitudinal variation at midlatitudes. Over the US continent, substantial east-west coast ionospheric differences in the GPS TEC were found by Zhang et al. [2011]. These differences exhibit a clear local time variation, with the evening TEC higher on the US east coast than on the west, and vice versa for the morning TEC. It was also found, based on the TEC observation made by a dense network of GPS receivers, that the morning-evening variability in the east-west TEC difference minimizes at ~−90°E longitudes of zero geomagnetic declination in the central US.

Further evidence of this type of ionospheric longitudinal variation was provided for the eastern US in a climatology study of long-term incoherent scatter radar (ISR) observations at Millstone Hill by Zhang et al. [2012]. The radar can measure electron density (Ne) on both east and west sides of the site which are separated by 40° in longitude. They found that the east-west difference over the eastern US, up to 60%, varies with local time in a similar fashion as in the GPS TEC results over the continental US [Zhang et al., 2011]. The east-west difference was found to be persistent throughout the year but with season and solar cycle dependencies.

It was suggested that this marked longitudinal differences in ionospheric TEC over the continent US and Ne in the F-region heights over the eastern US at midlatitudes was caused by a combined effect of the varying declination and thermospheric zonal winds [Zhang et al., 2011, 2012]. The longitudinal variation of magnetic declination (including its reversal in the central US) and the climatology in the zonal winds (which vary with local time, season and solar activity) could explain the observations. This mechanism involving magnetic declination and zonal winds was demonstrated in general in some early modeling work [Challinora and Ecclesa, 1971].

At midlatitudes, the fact that the America sectors are more close to the auroral zone than the Asian sectors due to the separation of geographic and geomagnetic poles is often used to explain some ionospheric differences between different longitudinal sectors including annual and semiannual variations [Rishbeth, 1998]. The Weddell Sea anomaly...
(WSA), characterized as an evening enhancement in electron density in summer, is another phenomenon of longitudinal variations at midlatitudes that are associated primarily with meridional winds, partially magnetic declination [e.g., Evans, 1965; Holt et al., 2002; Luan et al., 2008; Lin et al., 2010; Chen et al., 2011; de Larquier et al., 2011], and maybe polarization electric fields [Burns et al., 2011]. Sojka et al. [2012] modeled the longitudinal dependence of storm time midlatitude dayside TEC enhancements, and suggested that the thermospheric wind has potentially an equally large effect as the electric fields. Given the global configuration of geomagnetic fields, the marked longitudinal differences in electron density given by Zhang et al. [2011, 2012] seems to be a more general type of midlatitude feature, however, this has yet to be confirmed and the need for a more detailed climatology for ionospheric longitudinal variations is indicated. Zonal winds are considered to be crucial in explaining observed electron density differences, a direct comparison and quantified correlation study between the density difference and the observed winds is fundamental and needed.

[6] In the present study, we attempt to connect the FPI zonal wind observation to the observed east-west electron density difference as shown in Zhang et al. [2012]. To do so, we will summarize their results and provide a more complete climatology for the east-west electron density differences that can be directly compared to the FPI wind results and used for the correlation study. This climatology, derived from the long-term (1978–2011) ISR database, allows for determination of local time, season and solar cycle dependencies. The zonal wind climatology was discussed for Millstone Hill by Fejer et al. [2002] and Emmert et al. [2003]. Here we present the same Fabry-Perot interferometer (FPI) dataset over the same 1989–2001 period as presented in these earlier studies, but with an immediate context to the Ne results and quantify correlation analyses between them. In the following sections, we start with reviewing the Zhang et al. [2012] work, including the dataset, modeling method and climatology results. This is followed by a subsection to describe the magnetic declination and zonal wind mechanism, and to discuss the expected zonal wind climatology based on the electron density results. In the next section, we present the observed FPI zonal wind climatology, and discuss quantitative analyses of the correlation between the zonal winds and the Ne longitudinal differences. In the discussion section, we address other influences on the observed electron density differences, and the applicability of the mechanism to understanding the WSA as well as longitudinal variations in the Asia sector where a similar magnetic declination configuration exists. The final section provides a summary of our main findings.

2. East-West Ne Differences and The Expected Zonal Winds

[7] First, in section 2.1, we present the observed climatology for the east-west electron density differences from the ISR at Millstone Hill (42.5°N, 288.6°E). We will summarize the dataset, modeling method, and the east-west Ne differences as reported in Zhang et al. [2012]. We will also provide a complete set of summary plot for the Ne differences and remark some features that were not noticed previously. This will enable a quantified correlation analysis between these Ne results and the zonal winds as shown in section 3. Then, in section 2.2, we describe the declination-zonal wind mechanism and the expected zonal wind variations based on the Ne difference climatology and the mechanism. These expectations on the winds will be compared to the observation in section 3.

2.1. East-West Ne Difference in The Eastern U.S.

[8] The east-west differences in electron density Ne at various F region heights were derived based on the Millstone Hill ISR observations during 1978–2011. This was possible since the radar, with a fully steerable antenna, can provide an extra wide coverage with a longitude span from approximately –45 to –95°E depending on the antenna’s elevation and the height of interest. This covers nearly the entire eastern US and a height span of a few hundreds of kilometers. Data of interest was from the east and the west sides of the site obtained with a typical radar elevation angle of 5° when the antenna was performing the azimuth scanning. Empirical models were then created for each of the two sides using a bin-fit method [Zhang and Holt, 2007]. On each side, the data was binned according to height, with nodes at 150, 200, 250, 300, 350, 400 and 450 km, respectively. For the bin of 450 km, most data points were from (–51 ± 3°E, 47 ± 6°N) on the east side, and (–92 ± 2°E, 48 ± 6°N) on the west side, while for ~150 km, most data points were from (–61 ± 1°E, 45 ± 3°N) on the east side and (–82 ± 1°E, 45 ± 3°N) on the west side. Here for the 450 km bin, for instance, ±3° and ±2° indicate the spread of the data in longitude in a standard deviation sense; the data spread in latitude is ±6°, and any latitudinal variations within 12° are smoothed out. Then for each of these bins, observational data are fitted to a model with terms of solar activity, magnetic activity, season, and local time. It should be noted that in this very large dataset, 70% of the observations was from ap index <10, and therefore results obtained in this way will represent only magnetic quiet conditions. The spread of all NEL, log10(Ne, 1/m³), data for a given bin is ~30% (standard deviation / mean), while the spread of model regression is ~25%. Approximately 85% of observational NEL is represented by the regression model with errors ≤2%.

[9] The east-west density differential ratio \( R \) is then derived based on the models. \( R \) is defined as

\[
R = 2(\text{Ne}_E - \text{Ne}_W)/(\text{Ne}_E + \text{Ne}_W),
\]

where \( \text{Ne}_E \) and \( \text{Ne}_W \) are Ne for the east and west sides, respectively. Zhang et al. [2012] concluded that (1) the east-west difference, up to 60%, varies with local time, being positive (\( \text{Ne}_E \geq \text{Ne}_W \)) in the evening, and vice versa before noon; (2) the east-west difference is persist throughout the year, with the nighttime positive \( R \) the largest in winter and the daytime negative one the largest in early spring and later summer; (3) the difference tends to increase with decreasing solar activity; (4) the local times of the largest positive and negative differences in Ne are separated by 12–13 hours, and each of these local times occurs earlier in summer and later in winter.

[10] To provide a more comprehensive view of these results for the next-step examination of the zonal wind effect, Figure 1 is now generated based on the models to demonstrate the local time and day number of the year variation in \( R \) for three typical heights 350, 400, 450 km under low, medium, and high solar activity conditions, respectively. The overall diurnal and seasonal variation patterns do
not change much with solar activity: $R$ is always positive in the evening and negative in the morning; $R$ is always the largest (positive) in winter and the smallest (negative) in the February-March period. The amplitude of the diurnal and seasonal variations, however, does change with solar activity. Specifically, in winter the positive $R$ value (nighttime) increases with decreasing solar activity; the negative $R$ (daytime) appears to behave similarly, and the daytime $|R|$ increases, almost regardless of season, with decreasing solar activity as well. There is one exception for the summer and later spring period (May-June) when the positive $R$ value (nighttime) is enhanced with increasing solar activity so that a secondary maximum $|R|$ is developed. This secondary maximum gets intensified at low altitudes.

Figure 1. Variations in the east-west density differential ratio $R$, defined as $R = 2(N_{eE} - N_{eW})/(N_{eE} + N_{eW})$, where $N_{eE}$ and $N_{eW}$ are $N_{e}$ for the east and west sides, respectively. These variations are for altitudes of 350, 400 and 450 km at solar activity levels of low ($F_{10.7} = 85$), medium ($F_{10.7} = 135$), and high ($F_{10.7} = 185$), as a function of day number and local time. The seasonal versus local time variation in $R$ can be seen in each frame of the plot. Variations in $R$ with solar activity and with height/longitude can be observed by examining frames from the left to the right, and from the bottom to the top, respectively. Notice the local time-season variation pattern remains essentially stable, while the magnitude of $R$ as indicated by the color scales decreases with increasing solar activity and with decreasing height/longitude. See text for details.

2.2. The Expected Zonal Wind Climatology

[12] We intend to use the declination-zonal wind mechanism to explain these variations in $R$. Figure 2 illustrates this mechanism. The magnetic declination is westward (negative) on the east side of the US continent and eastward (positive) on the west side; along $\sim-90^\circ$E longitude, the declination is zero. The parallel ion drift $V_{zonal}^\parallel$ (positive for upward drifts along the field lines) induced by thermospheric zonal winds $U_e$ (positive for geographic eastward winds), $V_{zonal}^\parallel = -U_e \sin D \cos I$, is either upward or downward depending on the sign of declination angle $D$ and
the sign of zonal winds $U_e$ ($I$ is the dip angle). Figure 2 shows an eastward wind scenario: $V_{\text{zonal}}^\parallel$ is downward on the west side of the zero declination longitude, and upward on the east side. The downward field-aligned drift $V_{\text{zonal}}^\perp$ causes a lower Ne, because the ions are moved to lower altitudes where their recombination rate, exponentially increasing toward lower altitudes, is enhanced so that they are lost more quickly. The upward drift $V_{\text{zonal}}^\perp$ produces an opposite effect for the same eastward wind. As a result, an east-west electron density difference is developed: the eastward wind causes higher Ne on the east side where $D$ is negative than on the westside where $D$ is positive, and the westward wind causes lower Ne on the east side than on the westside. This mechanism can explain the GPS TEC results over the continental US [Zhang et al., 2011]. In our case here for the eastern US, the longitude spans from $-90^\circ$E (geomagnetic declination $\sim 0^\circ$) to $-50^\circ$ to $-60^\circ$E (geomagnetic declination $\sim 20^\circ$). Therefore electron density difference between these two ends of the radar’s field of view can be explained in a similar manner although the expected magnitude of difference is less than that for the west-east coasts of the continental US which involve a direction reversal in geomagnetic declination.

If the above mechanism is valid, the statistics shown for Ne should provide some insight into the zonal wind climatology, including diurnal and seasonal variations and solar cycle dependency. Now based upon Ne results, we can expect the following climatology for the zonal wind: (1) The sign change in $R$ between negative and positive in the diurnal variation is an indication of sign change in the zonal wind direction. The sign change in $R$ once a day indicates the same frequency of sign change in zonal winds. More specifically, zonal winds are very strongly eastward in the late evening when $R$ is maximum, and westward before noon when $R$ is minimum (and negative). (2) In the seasonal variation, the eastward wind is stronger in winter than in summer because $R$ is larger in winter than in summer at night. Since the time of maximum and minimum $R$ occurs earlier in summer than in winter by about 2 hours, the zonal wind directional reversal should take place earlier in summer than in winter. (3) For solar activity dependency, a larger $|R|$ for lower solar activity implies a stronger zonal wind. The midlatitude Ne decreases with decreasing solar activity, and therefore the resultant weaker ion drag is a favoring factor for a stronger neutral wind. In the next section, we are examining the above expectations against the zonal wind observations.

3. Observed Zonal Wind Climatology and Correlation With $R$

3.1. Zonal Wind Climatology

Both Fejer et al. [2002] and Emmert et al. [2003] have published zonal wind climatology over Millstone Hill based on FPI measurements for a full solar cycle (1989–2001). Technical details of the long-term FPI wind measurements at Millstone Hill were described in these two and other prior publications. Here in order to make direct comparison between $R$ results and zonal wind results, we repeat the data binning procedure of Fejer et al. [2002] and create an empirical zonal wind model similar to Emmert et al. [2003]. The wind data during 1989–2001 within $\pm 600$ m/s from the FPI’s measurements in all directions under magnetic quiet conditions are considered. The quiet conditions are defined as when the current-time kp as well as kp for the previous 6 hours are all less than 3. Three solar activity levels are selected based on daily F10.7 flux: F10.7 < 100; F10.7 = [100 200]; F10.7 = [185 300]. The three seasonal
bins are winter for November through February, summer for May through August, and equinox for other months. Hourly medians in a running two-hour bin are then found and shown in Figure 3, which compares, not surprisingly, perfectly well to Figure 2 in Fejer et al. [2002]. A further modeling on these binned data is performed to represent local time and seasonal variations using piecewise cubic interpolation. For this purpose, however, now we use monthly medians (rather than 3 seasonal medians as in Figure 3) calculated in a running three-month bin. The models for three solar activity levels are shown in Figure 4.

These binned averages shown in Figures 3 and 4 and prior studies for Millstone Hill all indicate that zonal winds are indeed eastward in the evening and predominantly before midnight (except for summer); the eastward wind speed in the evening is highest in winter when it reaches maximum before but close to midnight; the directional reversal of the zonal wind from eastward to westward takes place earlier in summer and later in winter; the eastward wind speed tends to be enhanced toward low solar activity, in particular, in winter. All these results are consistent with the expectations based on the east-west Ne difference $R$, and confirm in general the validity of the declination-zonal wind mechanism being responsible for the east-west density difference. Further comparisons, however, do not show a one-to-one correspondence between the zonal wind and $R$. For instance, the zonal wind reversal time at night (0000–0400LT, depending on season) is well ahead of the time of sign change in $R$ (0400–0900LT). This is an indication that there is a time delay in the Ne response to zonal wind changes. We further examine this time delay in the next subsection.

### 3.2. Correlation Between $R$ and Zonal Winds

To quantify the relationship between the east-west differential ratio $R$ and zonal winds, we may calculate the correlation coefficient between them. The FPI zonal wind (as given in the model of Figure 4) and corresponding $R$ (as given in Figure 1) for three seasons of winter, summer and equinox under low, medium and high solar activity conditions are selected. For a given height, season and solar activity, there are 11 pairs of hourly nighttime data for 1900–0500LT and a simple binary correlation coefficient is calculated. Figure 5 provides a scatterplot of $R$ and zonal wind data at 400 km, and the calculated correlation coefficient $r$ is given. $r$ varies between 0.88 and 0.98 depending on season and solar activity, however, the overall correlation for the 99 pairs of $R$-wind nighttime data for the whole selected seasons and solar activities is 0.93. This is indeed a very high correlation, given the fact that these two datasets were

![Figure 3. Binned zonal wind averages over Millstone Hill as a function of local time for equinox, summer and winter at three solar activity levels of low (F10.7 < 100; with circles), medium (F10.7 = [100 200], with dots) and high (F10.7 > 185, with triangles).](image)

![Figure 4. Empirical model of eastward winds derived from the Millstone Hill FPI zonal wind data as a function of month and local time for three solar activity levels of low (F10.7 < 100), medium (F10.7 = [100 200]) and high (F10.7 > 185). The white curves are for the zero wind speed. The model result is compared to corresponding east-west electron density differential ratio $R$. The model is also used for the $R$-wind correlation calculation under a variety of local time, season and solar activity conditions.](image)
obtained from independent instruments and with very different modeling approaches.

[17] We have already considered a time delay of 3 hours when calculating these coefficients $\rho$, so that each $R$ value considered corresponds to the zonal wind at 3 hours ago. This 3-hour time delay is an optimal result to give the highest correlation coefficient among other delay times. Figure 6 shows how the correlation coefficient varies with the delay time. Without considering a time delay, the overall correlation is relatively lower. The overall correlation grows as the delay time increases till it reaches 3 hours, then it is reduced slowly toward longer delay times. The time of the highest correlation varies slightly with the level of solar activity; at high solar activity, the optimal delay time corresponding to the highest correlation is 2 hours, shorter than under other solar activity conditions.

[18] Figure 5 also shows the offset $R_0$, defined as the $R$ value for zero zonal wind speed on the fitted line. Here $R_0$ is found to be 0.2 for the delay time of 3 hours. $R_0$ values for other delay times are also determined: without the time delay, $R_0$ is 0.3; with a 5 hour time delay, $R_0$ decreases to <0.1; the longer the delay time is, the smaller the offset is.

[19] Some time delay between the wind change and Ne response is reasonable, because of the drift speed of the ions, as well as chemical recombination and diffusion processes. The recombination rate and the plasma diffusion velocity depend on the neutral densities and temperature, as well as plasma temperatures, which are all season dependent and strongly height and solar cycle dependent. When the zonal wind remains in the same direction, its effect on the Ne difference accumulates; when it changes the direction, its effect can be canceled. Therefore the observed Ne difference.

Figure 5. Correlation between the east-west differential ratio $R$ at 400 km and the FPI eastward winds over Millstone Hill during the nighttime for three seasons of the year and three solar activity levels. Therefore 9 groups of 11-paired nighttime (1900–0500 LT) hourly values for $R$ and the eastward wind are generated with different solar activity and season combinations. These groups of data are shown by various symbols, and the correlation coefficient for each group is also given in the plot. Delay times of 3 hours for $R$ values to respond to zonal winds are considered. The correlation is generally very high and varies with season and solar activity. An overall correlation coefficient, derived from combining the 9 groups of 11-paired data, is found to be 0.93.

Figure 6. Correlation between $R$ and eastward zonal winds as a function of delay time. The correlation coefficients are calculated with paired zonal wind and $R$ data at night for low (dashed line), medium (solid line), and high (dashed line with dots) solar activity, respectively. The $R$ data are delayed by various hours from 0 to 5.
represents an accumulated effect over time. The complicity involved in the time delay feature may be better addressed by theoretical models.

[20] The high correlation between $R$ and zonal winds suggests that it might be feasible to derive zonal wind information based on electron density differences $R$ across the east-west sides of the site. This idea is similar to the servo model that reveals a relationship between $h_m F_2$ and the applied winds, and makes it possible to infer the equivalent winds from $h_m F_2$ (see some early papers: Rishbeth et al. [1978]; Buonsanto [1986]; Zhang et al. [1992]). We will explore this technique in details in a future work.

4. Discussion

[21] The consistency of the observed climatology in zonal winds and the expectations based on the Ne difference as well as the high correlation between the zonal wind and $R$ strongly suggest a combined magnetic declination-zonal wind mechanism in action. So far, our discussion has focused on zonal wind effects. Other influences may present as well on the $R$ variation.

4.1. Other Influences on $R$

[22] Ideally, the offset $R_0$ should be close to zero, i.e., when the zonal wind is zero, there should be no significant east-west density differences (with some time delay effect considered), however, Figure 5 shows a positive $R_0$, implying influences other than the zonal wind cannot be totally ignored. They might come from differences in the magnetic latitudes, neutral composition, and meridional winds. At 400 km the location of the data points on the east side is ($-52^\circ$E, $48^\circ$N), and on the west side ($-91^\circ$E, $48^\circ$N). The corresponding declination, dip and magnetic latitude are $-20^\circ$, $69^\circ$, $54^\circ$N, respectively, on the east side and $0.3^\circ$, $74^\circ$, $58^\circ$N on the west side. The west side is slightly higher in magnetic latitude and the dip angle. We expect that this small magnetic latitude difference can cause some small differences in the neutral composition and winds, contributing to a positive $R_0$.

[23] Meridional winds in the magnetic meridian contribute to the vertical ion drift, however, meridional winds in the geographic coordinate are unlikely critical for our primary emphasis here on longitudinal differences within $\sim 40^\circ$ in longitude; due to limit observations and a lack of study, there seems no indication of a clear longitudinal change (or a east-west difference) in geographic meridional winds that happen to vary systematically with local time, season and solar activity at midlatitudes during non-storm conditions. The TIE-GCM simulation indicates that magnetic meridional winds do show some dependency, mostly around midnight, on longitude, which is caused by the combined declination and zonal wind effect as mentioned here; longitudinal gradients in geographic meridional winds are much smaller than in magnetic meridional winds [Luan and Solomon, 2008].

[24] The high correlation of 0.93 between $R$ and zonal winds is based on datasets from statistical models, therefore the noise in the Ne and wind data including possible minor disturbances due to electric fields and the spatial variation in meridional winds are essentially smeared out. But any residual effect, such as from the spatial variation in the meridional wind, can contribute to the non-zero $R_0$. In fact, the $R$ values concern measurements for two locations, the east and west sides of the Millstone Hill ISR, while the FPI zonal winds were measured over the radar at approximately the middle point of the two locations. Ideally, we should use both zonal and meridional winds from the two locations. These midpoint measurements, however, may be a valid approximation to the averages between the two locations if the longitudinal variation in the winds over the $40^\circ$ longitude span is either uniform or linear in a statistics sense. The linear assumption perhaps can be satisfied more easily than the uniform assumption, but actual measurements and further investigations on the longitudinal variation in the winds are needed.

[25] Our discussion has been limited to the nighttime when the optical FPI data is available. Due to the absence of photoionization, the nighttime data provides a better opportunity to examine this relationship of the thermospheric dynamics cause and the ionospheric electron density effect. During the day, strong photochemical processes can mask to some degree the declination-zonal wind effect, and the time delay we have observed may be reduced. Therefore when sufficient daytime zonal wind data are available, the current study should be extended.

[26] In the following discussions, we examine two other possible implications of the declination-zonal wind effect.

4.2. WSA Phenomena

[27] This effect can explain the type of longitudinal ionospheric differences in GPS TEC over the US continent as well as in the F2 region Ne in the eastern US. The declination - zonal wind effect is also a favoring factor for the Weddell Sea anomaly (WSA) development, because this is the area where declination is positive and the zonal wind direction reverses generally from westward during the day to eastward in the evening. The WSA-like summer evening behavior in Ne over Millstone Hill has long been pursued (Evans [1965]; Holt et al. [2002]; and more recently de Larquier et al. [2011]). Figure 7 provides comparisons of Ne and $R$ at 400 km between the two sides among summer, winter and spring seasons with medium solar activity. These Ne and $R$ are from the ISR models mentioned earlier. We can see the WSA-like variations in summer above both sides, however, they are much more prominent on the east side. On the east site, the evening enhancement that elevates Ne above its daytime level is most pronounced in summer and least in winter, although the declination - zonal wind effect can always, throughout the year, lead to the daytime density decrease and the nighttime density increase. The east-west difference $R$ for the evening hours is up to 60% in winter, 40% in equinox, and 30% in summer. All these imply that the zonal wind-declination effect is a favoring factor for the WSA-like variations, although not a dominant one to cause the WSA. This conclusion is consistent with earlier results [Luan et al., 2008; Lin et al., 2010].

4.3. Wave-2 Like Longitudinal Variations?

[28] Given the generality of the magnetic declination-zonal wind mechanism for midlatitudes, similar longitudinal variations at a given local time should exist in European and Asian sectors where geomagnetic declination reverses its direction with longitude. Zhang et al. [2012] noted evidence of a similar east-west difference in FoF2 over an east-west paired Chinese ionosonde stations, which was reported in a work by Wu et al. [1998]. In fact, as shown in Figure 4 in Zhang et al. [2011], vertical ion drifts induced by zonal
winds for the Asia sector are different between the two sides with opposite declination. The difference in vertical drifts is significant enough to produce hmF2 differences (as shown in Wu et al. [1998]). With FPI zonal wind observations becoming available for the Chinese subcontinent, it will be possible to understand those observed foF2 and hmF2 differences and compare these differences to the America sectors.

Results from America sectors as well as from the Chinese subcontinent may imply that there exists a wave-2 like structure in the northern hemisphere midlatitude ionospheric electron density, since in the northern hemisphere, magnetic declination changes its sign four times such that there are two zones of negative declination and two zones of positive declination. This structure, caused by the zonal wind and magnetic declination configuration, should exhibit, for instance, in the evening (at given local times) with eastward zonal winds, two zones of electron density enhancement over the east coasts for the US continent as well as for the Chinese subcontinent, and electron density reduction zones for the US west coast and the west part of Europe-Asia continent. The locations of enhancement and reduction zones may switch with local time as the zonal wind direction reverses. The magnitude of these two enhancements, however, can be different due to different magnetic field configurations, including the fact that the distance to the magnetic pole [Rishbeth, 1998], the relationship between magnetic and geographic latitudes, and the magnetic dip angle all vary with longitudes. In the southern hemisphere, there are only one zone of negative declination and one zone of positive declination at midlatitudes. Therefore, longitudinal variations caused by the declination change are relatively simple with only one electron density enhancement zone and one electron density reduction zone for a give local time, but the separation between the magnetic and geographic poles gives rise to additional complicity in explaining the actually observed longitudinal variations. Nevertheless, all these hypothetical structures remain to be confirmed. However, this topic deserves further investigation in the future.

## 5. Summary

A prominent ionospheric longitudinal variation at midlatitudes, in particular, over the continental US, was found recently Zhang et al., 2011, 2012]. This variation is characterized as a higher east-side electron density (or TEC) in the evening and a higher west-side electron density (or TEC) in the morning, and with clear seasonal and solar activity dependencies. A combined effect of changing geomagnetic declination and zonal winds was proposed to explain it. The present study provides a detailed examination of the effect using long-term observations made with the incoherent scatter radar over Millstone Hill during 1978–2011 and the on-site Fabry-Perot interferometer observation during 1989–2001. The extra-wide coverage of the radar allows for a study of the ionospheric differences on east and west sides of the radar, which are 40° apart in longitude at 400 km.

The east-west electron density differences, as initially reported by Zhang et al. [2012], are significant in magnitude, vary with local time, and are persistent throughout the year. In particular, the largest differential ratio $R$ occurs at night in winter, and $|R|$ tends to increase toward low solar activity. The zonal wind climatology over Millstone Hill, derived from FPI measurements, is perfectly consistent with the expectation based on these east-west electron density difference results. The observed nighttime zonal winds are mostly eastward, and the highest occurs in winter. In winter they are enhanced with low solar activity. The correlation between the zonal wind speed and the east-west differential ratio are extremely high with an overall correlation coefficient of 0.93. The observed time delay ($\sim$3 hours) in the response of Ne differences to zonal winds is a significant feature.

This study further points out a possibility of a wave-2 like electron density structure at midlatitudes in the northern hemisphere, where zones of enhanced density for given local times in the evening may be observed in the east coasts of both the US and China. These are the zones where geomagnetic declination are negative/westward. This study implies that longitudinal variations in ionospheric electron density at midlatitudes contain critical information on thermospheric zonal winds.

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