Climatology and latitudinal gradients of quiet-time thermospheric neutral winds over Millstone Hill from Fabry-Perot interferometer measurements

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[1] Midlatitude nighttime thermospheric neutral winds are strongly dependent on season, solar activity, and latitude. We use an extensive database of wind measurements made during 1989–2001 by the Millstone Hill Fabry-Perot interferometer to study the detailed climatology of quiet time neutral winds near an altitude of 250 km. To facilitate the analysis of these data, we develop a local time, day-of-year, solar flux, and latitude-dependent empirical model, with the latitude dependence obtained by considering north looking and south looking observations separately. Our results show that the zonal winds are predominantly eastward after dusk and westward before dawn, with the strongest eastward winds occurring in the winter and with an east-to-west transition that occurs earliest in the summer. The zonal winds exhibit weak-to-moderate latitudinal gradients, with more westward values to the north. The zonal wind magnitudes decrease with increasing solar flux; the strongest trends occur during winter. The meridional winds are predominantly equatorward in all cases and exhibit strong latitudinal gradients, with larger values to the north. The maximum nighttime equatorward winds decrease with increasing solar flux, except during summer, when there is no significant solar activity variation. They are largest during the summer, except at solar minimum when a semiannual variation is observed and the peak winds occur during the equinoxes. Earlier studies of midlatitude wind measurements are generally consistent with our data, with our results providing a considerably more detailed description of the nighttime wind climatology at midlatitudes.

INDEX TERMS: 3369 Meteorology and Atmospheric Dynamics: Thermospheric dynamics (0358); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 2427 Ionosphere: Ionosphere/atmosphere interactions (0335); 3319 Meteorology and Atmospheric Dynamics: General circulation; KEYWORDS: midlatitude thermosphere, Fabry-Perot winds, climatology


1. Introduction

[2] The climatology of quiet time midlatitude neutral winds in the ionospheric F region has been studied extensively over the past three decades using measurements from ground-based Fabry-Perot interferometers (FPIs), incoherent scatter radars (ISR), and ionosondes and from space-based in situ and remote sensing probes. Hernandez and Roble [1984] presented a climatology of FPI winds measured from 1973 to 1979 over Fritz Peak, Colorado (40°N, 106°W), and Sipler et al. [1982] described FPI measurements made over Laurel Ridge, Pennsylvania (40°N, 79°W), from 1975 to 1979. Hagan [1993] performed a climatological analysis of radar-derived meridional winds over Millstone Hill (43°N, 72°W), which was updated by Buonsanto and Witasie [1999]. Other midlatitude ISR climatological studies were presented by Duboin and Laboulle [1992] (St. Santin, France, 45°N, 2°E) and Kawamura et al. [2000] (Shigaraki, Japan, 35°N, 136°E). Miller et al. [1997] studied the climatology of meridional winds inferred from the height of the peak electron density in the ionosphere (hmF2), as measured by ionosondes. Hedlin et al. [1988, 1991] used a variety of ground- and
space-based measurements to develop the horizontal wind model (HWM), an empirical global model of horizontal winds, and Hedin et al. [1994] studied the solar cycle variation of midlatitude meridional winds, using a variety of measurements and models.

[1] The general characteristics of midlatitude winds are thus fairly well established. The winds are primarily generated by pressure gradients caused by dayside solar heating, which results in largely poleward-westward winds during the day and equatorward-eastward winds at night. Diurnal amplitudes are typically on the order of 50–150 m/s and tend to decrease with increasing solar activity as a result of increased ion drag. The diurnal mean winds are typically more equatorward in the summer than in the winter, and nighttime zonal winds are more eastward in the winter. In addition to solar-induced pressure gradients, high-latitude magnetospheric convection can influence midlatitude winds even during quiet conditions. In particular, an antisunward jet that extends across the geomagnetic polar cap results in large midnight equatorward winds at latitudes below the auroral zone [Hernandez and Roble, 1984; Smith et al., 1998]. Strong latitudinal gradients are usually present in FPI meridional winds measured to the north and south of midlatitude observing stations [Spilker et al., 1982; Hernandez and Roble, 1984], and these have been attributed to the deceleration of the midnight wind surge associated with magnetospheric convection.

[2] FPIs provide the most direct ground-based measurements of nighttime winds in the F region, and the only ground-based measurements of the zonal wind component. Recently, Fejer et al. [2002] used 11 years of Millstone Hill FPI wind data to study the climatology of quiet time and storm time nighttime winds. The focus of that paper was on storm-induced disturbance winds, and the results presented were latitudinally averaged (i.e., north looking and south looking measurements were combined). In this paper, we describe and quantify the quiet time patterns in much more detail and present the first local time, day-of-year, solar flux, and latitude-dependent climatology derived from the extensive Millstone Hill FPI observations. In the following sections we first describe the wind measurements and our empirical model of their climatology. Then, we discuss the general characteristics of the average winds as well as their seasonal, latitudinal, and solar cycle dependence. Finally, we relate these results to other data and published climatologies, particularly the FPI measurements made at Fritz Peak.

2. Data and Methodology

[3] The Millstone Hill (42.6°N, 71.5°W) Fabry-Perot interferometer (FPI) has been routinely observing the 630.0-nm nightglow emission (which typically peaks near 250 km) since 1989. This instrument and its operation were described by Spilker et al. [1991] and Buonsanto et al. [1992]. Line-of-sight (LOS) winds are derived from the Doppler shift of the observed fringes in the FPI. Since the FPI is pressure scanned, the basic measurement is intensity as a function of pressure. The pressure measurements are translated into wavelength measurements by use of a frequency-stabilized laser, which is observed at regular intervals (20–30 min) throughout the observing period. Since the signal-to-noise ratio of the laser measurements is very high, these measurements are used to define the instrumental parameters, including the free spectral range of the FPI and the position (pressure) of the laser peaks. Consequently, we have a time history of the instrumental parameters, which can be used to compensate for any instrumental drifts. Nightglow fringe positions are referred to the interpolated laser peak position, which compensates for any drift in the plate spacing or (more likely) the pressure transducer characteristics.

[4] Drifts in the peak positions are observed regularly and have been traced to a temperature dependence of the pressure transducer electronics. In order to minimize the drift, we place the transducer electronics as well as the FPI in an active thermal enclosure, which stabilizes the temperature within ~0.1°C. This reduces the drift to <3% of the free spectral range. Using the position of the stabilized laser fringe to monitor the drift further reduces the effect of the drift to <10 m/s on the LOS wind measurement.

[5] This technique has been used to derive winds from the FPI measurements since the beginning of the data set. Although the programs have been updated through the years to accommodate new computers and provide more convenience to the analyst, the basic algorithm has not changed. Also, as significant changes are made to the analysis program, random previous observations are reanalyzed and checked against the original analyses to ensure that no significant changes in the results result from the recoding.

[6] In the standard operating mode, four measurements are made at an elevation of 30° and azimuths of (315°, 45°) and (135°, 225°). A fifth measurement is made in the vertical direction and is used to generate a zero-velocity reference. In this mode the LOS wind measurements are used to derive horizontal vector winds to the north and south of the observatory, assuming negligible longitudinal gradients and vertical winds. Tepley et al. [1984] and Cogger et al. [1985] present a detailed description of this technique. Other elevation and azimuth modes, including direct measurements in the cardinal directions, are used less frequently. Hernandez et al. [1978] and Tepley et al. [1984] showed that the assumption of negligible longitudinal gradients is reasonable; the assumption of negligible vertical winds is examined in section 4.1.

[7] The FPI wind database consists of ~30,000 observations made on 1300 nights between January 1989 and October 2001. These measurements have an average cycle time of 20 min and an average uncertainty of ~25 m/s. Figure 1 shows the geographical distribution of the combined and direct zonal wind data, assuming an emission height of 250 km; the distribution of the meridional wind data is very similar (the only differences are due to relatively small numbers of direct measurements made along the cardinal directions).

[8] We selected data corresponding to geomagnetically quiet conditions, defining quiet conditions as when the current and two preceding 3-hour Kp indices were all <3, which for our database gives an average Kp ~ 1.4. A more stringent criterion does not significantly affect the average wind patterns, but the zonal wind results change substantially when less stringent criteria are used. We sorted the quiet time data into north looking and south looking winds, using azimuth bins of 345°–45° and 135°–225°, respectively, as shown in Figure 1. The average latitudes of the...
data in these bins are \( \sim 45^\circ \) and \( 40^\circ \). We also used four decimetric solar flux \( (F_{10.7}) \) bins; these bins and the number of nights in each bin are shown in Table 1. The greater number of north looking data is due to the fact that measurements are only made to the north during full moon periods. Table 1 also shows the average latitude and \( F_{10.7} \) for each bin. We have verified that the average flux values shown in Table 1 do not vary significantly with the sampled season and local time.

[11] Note that the peak emission height of the 630.0-nm nightglow is very broad and varies significantly with season and solar cycle. The average latitudes shown in Table 1 are based on an emission height of 250 km; if instead a height of 300 km were assumed, the derived average latitudinal difference between the north looking and south looking observations would increase from 5.5° to \( \sim 6.6^\circ \).

[12] For each bin we performed a least squares fit of the data to normalized periodic cubic splines in local time and day of year, with nodes at \( \{1.0, 3.5, 6, 18, 20.5, 23\ \text{hours}\} \) and \( \{0, 91.5, 183, 274.5\} \), respectively. These functions are shown in Figure 2, and the model formulation may be written as follows:

\[
U(t,d) = \sum_{i=1}^{6} \sum_{j=1}^{4} a_{ij} N_i(t) M_j(d),
\]

where \( U \) is the neutral wind, \( t \) is the local solar time, \( d \) is the day of the year, \( a_{ij} \) are coefficients, and \( N_i \) and \( M_j \) are the cubic spline functions. We also experimented with harmonic functions (up to terdiurnal and semiannual terms), which gave similar results but were not as well behaved near the fringes of the data. The cubic spline representation is also more compact (24 terms versus 35 terms), so this purely empirical representation is preferred over the harmonic coefficients, which, owing to the lack of daytime data, lose their advantage of providing physical information.

[13] To evaluate the model for intermediate solar flux values, we interpolate the model results from the four solar flux bins. The model coefficients and the Interactive Data Language code for evaluating the model are available from the authors upon request.

[14] The quiet time FPI results presented in our earlier paper, Fejer et al. [2002], are largely an average of the north looking and south looking results described here, but tend slightly toward the north looking case because of the greater number of observations in this direction (see Table 1). The present results include additional data from 2000 to 2001,

| Table 1. Statistical Properties of the Quiet Time Data in the Solar Flux and Azimuth Bins Used in This Study |
|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
|                                                   | \( F_{10.7} \leq 100 \)                          | \( 90 \leq F_{10.7} \leq 160 \)                 | \( 150 \leq F_{10.7} \leq 200 \)                |
|                                                   | North   | South  | North   | South  | North   | South  | North   | South  |
| Number of nights                                  | 342     | 281    | 350     | 273    | 243     | 190    | 195     | 159    |
| Average \( F_{10.7} \)                           | 82      | 82     | 125     | 124    | 177     | 177    | 227     | 228    |
| Average latitude, deg                            | 45.3    | 40.0   | 45.3    | 39.9   | 45.4    | 39.8   | 45.4    | 39.8   |

Figure 1. Geographical distribution of Fabry-Perot interferometer (FPI) zonal wind observations used in this study, assuming an emission height of 250 km for the 630.0-nm nightglow. The dashed lines indicate the bins used to select north looking and south looking observations.

Figure 2. Cubic B splines used to represent the (top) local time and (bottom) day-of-year dependence of the quiet time winds.
but omit the small number of west looking and east looking data included in the previous study.

3. Results

3.1. General Characteristics and Latitudinal Gradients

Figure 3 shows binned averages of the data as a function of local time along with corresponding results from our empirical model. North looking and south looking conditions are superimposed, and the results are stacked by seasonal bins: December solstice (November–February), combined equinoxes (March, April, September, and October), and June solstice (May–August). The two left-hand panels of Figure 3 show the zonal winds during solar minimum and maximum, and the right-hand panels of Figure 3 show the meridional winds.

During December solstice months the quiet time zonal winds are eastward for most of the night and shift to westward at 0400 LT. The zonal wind magnitudes decrease with increasing solar flux, with the eastward winds peaking at 2200 LT with values of 130 m/s during solar minimum and values of 60–80 m/s during solar maximum. During June solstice months the zonal wind magnitudes are much smaller and shift to westward values at earlier local times: 0000 LT for the south looking winds and 2100 LT for the north looking winds. The solar flux dependence is weak during June solstice and equinox months, and the equinox winds are largely an average of the solstice cases.

The latitudinal gradients of the quiet time zonal winds are very weak during December solar minimum conditions and are strongest for June solstice in the 2100–0000 LT sector, when the north looking winds are 50 m/s more westward than the south looking winds. Slightly smaller gradients are observed in the same local time sector during equinox and during the December solar maximum.

The quiet time meridional winds are equatorward in all cases except near dusk and dawn during December solstice and equinox months. They generally peak around 0100–0200 LT and are stronger in June than in December. The solar flux dependence is very weak during the June solstice, but in the other seasons the wind magnitudes decrease with increasing solar flux.

The latitudinal gradients of the quiet time meridional winds are very strong for all cases. The north looking
equatorward winds are as much as 100 m/s stronger than the corresponding south looking winds; the differences are larger during solar minimum. The largest equatorward winds occur to the north of Millstone Hill during equinox solar minimum conditions, with a peak value of 180 m/s. In general, however, the June solstice values are larger than the equinox values. The north looking (south looking) June winds have peak values of \(~150\) m/s (\(~80\) m/s). The weakest peak magnitudes occur to the south of Millstone Hill during December solar maximum conditions, with a value of \(~20\) m/s.

3.2. Model Results

Figure 4 shows a summary of model results for the zonal winds as a function of local time and day of year; the unshaded portions of the figure are (mostly daytime) regions where the model is not valid owing to the lack of data. The model shows an annual variation for the north looking and south looking cases and at all levels of solar activity. The seasonal dependence is generally characterized by rapid transitions between eastward December winds to westward (or less eastward, in some cases) June winds, with a relatively flat variation during June solstice months. The seasonal variation is fairly weak during solar maximum and is strongest during solar minimum. The westward winds observed in June appear at earlier local times in the north looking case. During solar minimum the south looking winds show a sharp eastward peak around midnight during both equinoxes; this feature can also be seen in Figure 3.

Figure 5 shows a summary of model results for the meridional winds, in the same format as Figure 4. The model generally shows an annual variation in the meridional winds, with peak equatorward winds occurring at the June solstice. However, in the case of north looking solar minimum, there is a semiannual variation, with the peak equatorward winds in excess of 180 m/s occurring at the equinoxes, and there is no noticeable difference between spring and fall. The large difference between meridional winds to the north and south of Millstone Hill is readily apparent from Figure 5. In addition, the south looking winds appear to be more variable, especially during solar minimum, although this could be due to decreased airglow intensities.

Figure 6 shows the model vector winds as a function of local time and latitude for two solar flux levels and three seasons. The strong reduction in the meridional winds with decreasing latitude can be clearly seen in the plots, particularly for equinox solar minimum conditions, but there is little or no rotation of the wind vectors as the latitude changes. In the premidnight sector a clockwise rotation of the wind direction is observed as the season changes from December to June for both solar minimum and solar maximum conditions. The wind magnitudes decrease with increasing solar flux, but the direction of the wind field remains largely unchanged.

3.3. Solar Cycle Dependence

Figure 7 shows the zonal and meridional winds as a function of solar flux, for the respective local time periods when the winds are at a maximum. The model results are shown as a solid line and are averaged over the local time periods and seasons indicated. The symbols with error bars are binned averages, with bins 30–60 flux units wide (larger bins for solar maximum conditions); note the different vertical scales for the zonal and meridional components. The strongest solar flux variations are observed during December in the case of the zonal winds and for north looking equinox conditions in the case of the meridional winds. In both cases the wind magnitudes decrease (becoming less eastward/equatorward) with increasing \(F_{10.7}\); this effect tends to saturate for \(F_{10.7} > 180\). Weaker flux variations can be seen in other cases. Overall, the winds become consistently weaker with increasing flux, except for the south looking June solstice zonal winds (which are eastward), where a positive (more eastward) trend is observed, similar to that of the north looking winds (which are westward). The meridional wind trends during June are probably insignificant, as are the equinoctial zonal wind trends (which are a mixture of the opposing December and June trends).

Figure 8 shows the zonal and meridional winds, at the times of their respective maximums, as a function of day of year and solar flux. Note the different color scales for the zonal and meridional components. The seasonal and solar cycle dependence of the zonal winds is seen to be generally the same for the north looking and south looking cases, except that in the former the June winds are more westward. In both cases, the solar flux dependence is very weak during June solstice months.

The solar flux dependence of the meridional winds is fairly consistent with the results from FPIs, ISRs, ionosondes, and theoretical models summarized by Hedin et al. [1994]. These results suggested that the midnight equatorward winds weaken with increasing flux except during summer and that this trend is strongest in the winter. Our results confirm the lack of a solar flux trend in the summer, but we find that the winter and equinox trends are similar to each other and that the trends are considerably stronger for the higher-latitude north looking observations.

Hedin et al. [1994] attributed the solar activity dependence of the meridional winds to a shift in the balance of pressure gradient and ion drag forces, with the latter showing a stronger dependence on solar activity than the former. This also explains the reduction of the zonal wind magnitudes with increasing solar activity. The fact that the solar flux dependence is strongest during winter can be explained by the stronger solar flux dependence of the plasma density in this season, which is a consequence of the absence of the winter anomaly during solar minimum [e.g., Forbes and Garrett, 1978].

4. Discussion

4.1. Effects of Vertical Winds on the Inferred Latitudinal Gradients

The assumption of zero vertical winds in the calibration and processing of the FPI measurements is not always valid, but in a study of eight geomagnetically quiet nights at midlatitudes, Sipler et al. [1995] found that the average vertical velocities are probably only on the order of 10 m/s downward. In the standard operating mode of the Millstone Hill FPI a uniform vertical wind field would not
Figure 4. Empirical model of quiet time zonal winds, as a function of local time and day of year. North looking results are shown on the left and south looking results on the right. Results at different solar flux values are shown in each row. The contour interval is 20 m/s.
Figure 5. Empirical model of quiet time meridional winds, as a function of local time and day of year. The format is the same as for Figure 4.
affect the zonal wind determination but would generate the following error in the inferred meridional wind:

\[ V_{\text{true}} - V_{\text{inferred}} = \frac{W(1 - \sin \theta)}{\cos \theta \cos \varphi}, \]  

where \( V_{\text{true}} \) is the true meridional wind (positive toward the observatory), \( V_{\text{inferred}} \) is the inferred meridional wind, \( W \) is the vertical wind (positive downward), \( \theta = 30^\circ \) is the elevation angle, and \( \varphi = 45^\circ \) is the half angle between the two LOS measurements used to calculate the meridional wind. For \( W = +10 \) m/s this difference amounts to \(+8\) m/s, with the true meridional wind being more toward the observatory than the inferred wind. Note that when the meridional wind is expressed as positive northward, the difference is negative for north looking observations and positive for south looking observations. Consequently, the following error would be generated in the inferred latitudinal gradients:

\[ (V_N - V_S)_{\text{true}} - (V_N - V_S)_{\text{inferred}} \approx -16 \text{ m/s}, \]

where \( V_N \) and \( V_S \) are the meridional winds (positive northward) to the north and south of the observatory, respectively. Therefore the peak latitudinal gradients reported in section 3.1, which are \( \sim -20 \) to \(-100\) m/s, could actually be as much as \(-36 \) to \(-116\) m/s.

4.2. Comparison With Earlier Fabry-Perot Interferometer Results

[Hernandez and Roble 1984] analyzed FPI wind measurements made at Fritz Peak Observatory (39.9°N, 105.5°W) from 1973 to 1979. This location is only \( \sim 30^\circ \) west and \( \sim 2.5^\circ \) south of Millstone Hill, so one would expect these observations to give similar results. The Fritz Peak measurements were made in the cardinal directions, so a comparison of latitudinal gradients is only possible for the meridional component.

The average zonal winds measured at Fritz Peak are very similar to the Millstone Hill results described in section 3. During solar minimum (\( F_{10.7} \sim 82 \) in the July 1973 to December 1977 Fritz Peak study), maximum eastward winds occur in the premidnight sector during the winter solstice. However, the peak eastward magnitudes at Millstone Hill are consistently \( \sim 130 - 140 \) m/s, whereas the Fritz Peak values are at most \( 100 \) m/s. In both cases the December solstice winds shift from eastward to westward at \( \sim 0400 \) LT, and progressively earlier toward summer solstice, when they are westward throughout the night. The Fritz Peak summer solar minimum winds are largest near 2200 LT with values of \( \sim 100 \) m/s. The Millstone Hill westward winds are weaker (40–60 m/s) and show no clear maximum, instead leveling off around 2300 LT in the case of the north looking winds and around 0100 LT in the case of the south looking winds. Note that the Millstone Hill south looking zonal winds are at the same geographic latitude as the Fritz Peak zonal winds.

Figure 6. Vector winds from our empirical model as a function of local time and latitude. Solar minimum conditions are shown on the left and solar maximum conditions on the right. Results from (top) December solstice, (middle) equinox, and (bottom) June solstice months are shown.

Figure 7. Maximum nighttime winds as a function of solar flux. The left hand column shows zonal winds in the 2030–2330 LT range, and the right-hand column shows meridional winds in the 0000–0300 LT range. The symbols show average winds in overlapping \( F_{10.7} \) bins; error bars indicate the estimated uncertainty of the mean. The solid curves show corresponding results from our empirical model. Note the different vertical scales for the meridional and zonal components.

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The Fritz Peak solar maximum zonal winds ($<F_{10.7}>_{10.7}$) for the January 1978 to December 1979 period) during winter are similar to the solar minimum case but with smaller peak eastward values of 60 m/s compared with 100 m/s in the solar minimum case. The corresponding Millstone Hill south looking winds (the $<F_{10.7}>_{10.7} = 175$ case of Figure 4) also show a reduction in the winter eastward winds: 80 m/s versus 140 m/s during solar minimum. The Fritz Peak solar maximum winds during summer are eastward until ~2200–2300 LT, and then become increasingly westward, reaching 75–100 m/s near dawn. The Millstone Hill south looking summer winds are also eastward in the premidnight sector, but the shift to westward winds occurs later, around 0100 LT. Also, the Millstone Hill westward values are <40 m/s, which is much smaller than those reported in the Fritz Peak study.

Overall, the local time, seasonal, and solar cycle dependences of the Millstone Hill zonal winds are consistent with those of the earlier Fritz Peak study, except that the average winds indicated in the latter are 30–50 m/s more westward overall. This is partly a result of the different quiet time criteria used to obtain the Fritz Peak results: daily $Ap \leq 20$, which corresponds to daily $Kp \leq 3.5$. Fejer et al. [2002] showed that strong westward disturbance winds begin to develop over Millstone Hill for 3-hour $Kp > 3.0$. We find that the use of Fritz Peak quiet time criterion with the Millstone Hill data produces results that are 0–20 m/s more westward, with the largest differences occurring during winter and equinox (the meridional component is unaffected).

The Fritz Peak observations were made at an elevation of 20° in the cardinal directions, so the north looking and south looking meridional winds are ~45° apart in latitude, in contrast to the 5.5° spread of the Millstone Hill observations (30° elevation at 45° to the cardinal directions). Therefore the north looking latitudes of Millstone Hill and Fritz Peak are ~45° and 46°, respectively, and the south looking latitudes are ~40° and 34°, assuming an emission height of 250 km.

The meridional winds to the north of Fritz Peak and Millstone Hill during solar minimum are very similar, with the maximum equatorward values occurring between 0000 and 0200 LT. The summer Fritz Peak values are ~150 m/s compared with 140 m/s for Millstone Hill, and in the winter these values are reduced to 75 m/s and 90 m/s, respectively. However, the local time-month contours shown in Figure 4 of Hernandez and Roble [1984] do not exhibit the semianual trends seen in the Millstone Hill observations. Furthermore, the Fritz Peak winds do not show the latitudinal gradients observed in the Millstone Hill winds, although Hernandez and Roble [1976] found significant latitudinal gradients in earlier (1973–1975) solar minimum measurements and Hernandez et al. [1978] reported large gradients on May 17, 1977.
The agreement between the Fritz Peak and Millstone Hill meridional winds is better during solar maximum. Table 2 summarizes the maximum equatorward winds from Fritz Peak and Millstone Hill, along with the local time of the occurrence. The Millstone Hill values were obtained from the $F_{10.7} = 175$ case of Figure 5. The north looking values, at roughly the same latitude, are very similar, whereas the south looking Millstone Hill winds are stronger than the south looking Fritz Peak winds, probably because of the higher latitude (40° versus 34°). Both stations show stronger latitudinal gradients in summer than in winter, and in both cases the winds peak at earlier local times at lower latitudes.

The strong latitudinal gradients observed over Fritz Peak and Millstone Hill are attributed to the deceleration of convection-driven antisunward winds that flow over the polar cap and are consistent with the predictions of global circulation models [Hernandez and Roble, 1984; Smith et al., 1998]. This midnight wind surge and the resulting latitudinal gradients have also been observed by Antarctic FPI stations [Smith et al., 1998]. The maximum midnight equatorward wind over Halley, Antarctica (76°S, 27°W), during winter was observed to decrease from 130 m/s at a magnetic latitude of 65° to 50 m/s at 57°. Over Millstone Hill (magnetic latitude 54°), for the same seasonal and solar flux conditions (winter, $F_{10.7} = 140$), the maximum equatorward winds similarly decrease from 100 m/s at 56° to 30 m/s at 51° magnetic latitude. The fact that the latitudinal gradients of the Fritz Peak meridional winds are apparently strongest during solar maximum, whereas those at Millstone Hill are strongest during solar minimum, is possibly due to the geomagnetic location of the two sites (Millstone Hill has a magnetic latitude of 54° versus 49° for Fritz Peak) and may be an indication of how the equatorward boundary of the cross-polar cap jet changes with solar flux.

### 4.3. Comparison With Other Data

Figure 9 shows a comparison of the model with corresponding zonal wind results from the Wind and Temperature Spectrometer (WATS) [Spencer et al., 1981] on board the Dynamics Explorer 2 (DE-2) spacecraft. We selected WATS zonal wind measurements in the 200- to 600-km height range and in a 90° longitude bin centered on Millstone Hill, and sorted and averaged the data in 5° latitude bins.

![Figure 9](image-url)
latitude bins and 3-hour local time bins. We treated ascending and descending orbital passes separately in order to get a one-to-one correspondence between the local time and season (the day of the year and local time are locked together by virtue of the DE-2’s polar orbit). To compare with the FPI results, we evaluated our empirical model using the average conditions (local time, day-of-year, solar flux, and latitude) of the DE-2 data. The average height of the DE-2 observations is \(350\) km, versus \(250\) km for the FPI results.

[37] The left-hand panel of Figure 9 shows results for the ascending DE-2 passes, which cover the March equinox and December solstice periods. The local time dependences of the zonal winds from the two instruments are in good agreement, but in the postmidnight (December–February) sector, the DE-2 winds are \(50\) m/s more westward. Both the FPI and DE-2 results show latitudinal gradients of \(10\) m/s, with more westward winds to the north of Millstone Hill. The right-hand panel shows results for descending passes, which cover the September equinox and June solstice periods. Both instruments show an overall westward trend with increasing local time, but the DE-2 winds have a sharp peak around \(2200\) LT (September), whereas the FPI winds have a much smoother trend. The DE-2 winds show no difference between latitudes to the north and to the south of Millstone Hill, but the FPI results are more westward in the north looking case. The other DE-2 longitude sectors give similar local time trends but show latitudinal gradients that are in better agreement with the FPI gradients. It should be remembered that there are large longitudinal variations in the thermosphere and ionosphere in the American sector, so the broad longitudinal bin used for the satellite data is not optimal for comparing with the ground-based data.

[38] Figure 10 shows a comparison of the model with corresponding meridional wind results from the Millstone Hill ISR climatology of Buonsanto and Witasse [1999]. We evaluated our FPI model for the average solar flux conditions of the ISR climatology, averaged the results over the same seasonal bins, and computed the component along the magnetic meridian (magnetic declination \(15^\circ\)). Note that Buonsanto and Witasse defined quiet conditions as \(K_p\) \((t-0\) hours\) <3.3 and \(K_p\) \((t-3\) hours\) <3.0, whereas we used a slightly more stringent criterion of \(K_p\) \((t-0, 3, 6\) hours\) all <3.0. We find that our meridional wind results change by \(<10\) m/s when the weaker criterion is employed.

[39] The ISR winds generally fall between the north looking and south looking FPI results but tend more toward the north looking case. This tendency is probably consistent with the fact that most of the ISR measurements were made to the north and west of Millstone Hill, at an elevation of \(60^\circ\) [Hagan, 1993].

[40] The ISR equatorward winds during summer solar minimum conditions are much stronger than the north looking FPI results. This difference could be due to a relative lack of nighttime ISR data for this case; Figure 5 of Buonsanto and Witasse [1999] suggests that the uncertainty of the nighttime ISR averages is larger for the summer solar minimum case than for the other bins. Also, two thirds of the ISR data used in this case were from 1986, which could have been an anomalous year. Another difference in the results is that the solar minimum ISR winds tend to reach their maximum values 1–2 hours earlier than the FPI winds. A reexamination of the ISR wind data might help to resolve these issues.

[41] Fejer et al. [2002] reported generally good agreement between the quiet time FPI meridional winds and corresponding HWM 93 results, particularly at solar minimum, but did not examine the latitudinal gradients. We find that the HWM zonal winds have the same latitudinal gradients (not shown) as the FPI results, with the north looking winds being \(10–40\) m/s more westward in the premidnight sector, although there are some differences in the seasonal dependence of these gradients. The HWM meridional wind gradients are in the same direction as those observed by the FPI, but the former are much smaller \((<20\) m/s). The HWM winds over Millstone Hill are more
representative of the north looking FPI winds, especially during solar maximum. This is partly because of the weaker solar flux dependence of the HWM meridional winds noted by Fejer et al. [2002].

[42] Fejer et al. [2002] presented the climatology of latitudinally averaged storm-induced disturbance winds over Millstone Hill. We have repeated that analysis, treating the north looking and south looking observations separately, and found that the latitudinal gradients of the meridional disturbance winds are weak (i.e., the strong north-south difference does not change much with magnetic activity), whereas the zonal perturbation winds are much stronger to the north of Millstone Hill. These results will be presented in a future paper.

5. Summary

[43] We have used 13 years of FPI wind measurements from Millstone Hill to study the climatology of nighttime quiet time F region winds at this location, and we have developed a local time, day-of-year, solar flux, and latitude-dependent empirical model of these data. The latitude dependence was obtained by separately analyzing north looking and south looking observations, which are ~5° apart. Earlier studies of nighttime thermospheric winds are generally consistent with our results, which describe the wind climatology in much more detail.

[44] The zonal winds are eastward for most of the night during winter and change to westward at 0400 LT. The reversal occurs much earlier in the summer, so the winds are then predominantly westward with smaller values than in the winter. The day-of-year dependence consists of an annual variation that is strongest during solar minimum and contains rapid equinoctial transitions. In the premidnight sector, the north looking winds are 20–50 m/s more westward than the south looking winds, except during solar minimum winter, when the latitudinal gradients are very weak. The solar activity dependence of the zonal winds is strongest during winter, becoming less eastward with increasing solar flux. Weaker trends of less westward/more eastward winds are observed in the summer data. For both the meridional and zonal wind components, the solar activity dependence tends to saturate for $F_{10.7} > 180$.

[45] The meridional winds are equatorward except near dawn and dusk during winter, with the maximum winds usually occurring at 0100–0200 LT. The north looking winds are as much as 100 m/s stronger than the south looking winds; the strongest latitudinal gradients occur during equinox solar minimum conditions, and the weakest occur during winter solar maximum. The meridional winds generally have an annual variation with the strongest equatorward values occurring in the summer, but during solar minimum the north looking winds display a semiannual variation, with the largest values occurring during equinox. The nighttime peak equatorward values decrease with increasing solar flux except during summer, when there is no significant trend.

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