Dependence of the high-latitude lower thermospheric wind vertical vorticity and horizontal divergence on the interplanetary magnetic field

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Abstract We analyze the vertical component of vorticity and the horizontal divergence of the high-latitude neutral wind field in the lower thermosphere during the southern summer time for different interplanetary magnetic field (IMF) conditions with the aid of the National Center for Atmospheric Research thermosphere ionosphere electrodynamics general circulation model, with the following results. (1) The mean neutral wind pattern in the high-latitude lower thermosphere is dominated by rotational flow, imparted primarily through the ion drag force rather than by horizontally divergent flow. (2) The vertical vorticity depends on the IMF. (3) The difference vertical vorticity, obtained by subtracting values with zero IMF from those with nonzero IMF, is much larger than the difference horizontal divergence for all IMF conditions. (4) The effects of IMF penetrate down to 106 km altitude. To determine the processes forcing strong rotational flow in the high-latitude lower thermospheric wind fields, a term analysis of the vorticity equation is also performed, with the following results. (1) The primary forcing term that determines variations of the vertical vorticity is ion drag. This forcing is closely related to the flow of field-aligned current between the ionosphere and magnetosphere. Significant contributions to variations of the vorticity, however, can be made by the horizontal advection term. (2) The effects of the IMF on the ion drag forcing are seen down to around 106 km altitude. (3) The continual forcing of magnetic zonal mean B_y-dependent vertical vorticity by ion drag can lead to strong polar vortices.

1. Introduction

High-latitude thermospheric winds are forced mainly by solar EUV and UV radiation, atmospheric tides, waves propagating from below, and energy and momentum sources associated with magnetospheric-ionosphere coupling, such as the magnetospheric convective electric field and the precipitation of energetic electrons and ions into the auroral regions. The magnetospheric electric field and auroral precipitation are strongly influenced by the solar wind and interplanetary magnetic field (IMF). One useful way to examine the winds is in terms of their vorticity (curl) and horizontal divergence, because different physical processes drive these two diagnostics of the wind. In the absence of momentum forcing, drag forces, and vertical winds, the vertical component of absolute vorticity (the sum of relative and planetary vorticity) is conserved following fluid motions. Changes in vertical absolute vorticity can therefore be related to vorticity sources like ion convection, to sinks like drag forces, to transport, and to vertical motions. Divergence of the horizontal wind, on the other hand, has no such conservative property and tends to be closely related to vertical motions induced by heating and cooling.

Several previous theoretical and experimental studies of vorticity and divergence in the high-latitude thermosphere have led to a better understanding of the momentum and energy sources involved in driving the high-latitude thermospheric winds. Mayr and Harris [1978] and Volland [1979] used linear models to show that while ion drifts induce horizontal winds that are predominantly divergence free and give rise to small pressure variations, Joule heating is mainly responsible for the horizontally divergent wind field. Roble et al. [1982] calculated the vorticity and horizontal divergence fields from a simulated wind field forced by magnetospheric convection and concluded that the generated neutral wind field at F layer altitudes from a nondivergent momentum source was mostly nondivergent. Larsen and Mikkelsen [1983] and Mikkelsen and Larsen [1983] also illustrated that the nondivergent component of the F region horizontal neutral wind was an order of magnitude greater than the divergent component. Larsen and Mikkelsen [1987] used a two-dimensional, linear version of
the shallow water equations along with a vertical structure equation, excluding the effects of Joule heating, and determined that horizontal winds driven by steady state ion drag tend to have much larger rotational than divergent components at all heights above about 110 km and that the pattern of the rotational wind component rotates toward increasingly later local times as one descends in altitude below 125 km, while the amplitude decreases. Clark et al. [1988] found that time-varying ion drag can generate significantly larger horizontally divergent winds, which, however, are not steady. Thayer and Killeen [1991] carried out an experimental determination of the large-scale vorticity and horizontal divergence patterns in the polar upper thermosphere for periods of both quiet and enhanced geomagnetic activity using observations made from the Dynamics Explorer 2 satellite during December solstice periods in 1982–1983. They found that the mean horizontal neutral wind pattern is dominated by rotational flow rather than divergent flow and that the divergent component of the horizontal neutral flow intensifies more significantly with increasing geomagnetic activity than does the rotational component. Förster et al. [2011] analyzed the dependence of high-latitude vertical vorticity on the interplanetary magnetic field (IMF), determined from a statistical analysis of cross-track winds from the CHAMP satellite around 400 km altitude. They showed how the pattern of vertical vorticity is closely related to that of field-aligned current flow into and out of the ionosphere. To date, however, no study of the high-latitude vorticity and divergence of the horizontal wind associated with the interplanetary magnetic field (IMF) effect has been made for the lower thermosphere, 100–200 km.

The characteristics of the high-latitude lower thermospheric horizontal wind field for different IMF conditions have been reasonably well documented by observations made from the Wind Imaging Interferometer (WINDII) on the Upper Atmosphere Research Satellite [Richmond et al., 2003] and by simulation with the aid of the National Center for Atmospheric Research (NCAR) thermosphere ionosphere electrodynamics general circulation model (TIE-GCM) [Kwak and Richmond, 2007; Kwak et al., 2007]. Moreover, Kwak et al. [2007] have shown that ionosphere-thermosphere coupling processes profoundly affect the high-latitude lower thermospheric neutral wind system depending on the IMF. Especially, because of ion drag, the lower thermospheric neutral winds at high latitudes tend to be influenced by the IMF-dependent high-latitude ionospheric convection and thereby develop similar vortex structures down to 105 km, although the strength of the vortices rapidly weakens with descending altitude below about 130 km.

In this paper, we have extended these previous works [Kwak and Richmond, 2007; Kwak et al., 2007] and have carried out a systematic analysis of the IMF dependence of the vertical component of vorticity and the horizontal divergence of the high-latitude lower thermospheric neutral wind field for Southern Hemisphere summer conditions, on the basis of numerical simulations using the NCAR TIE-GCM. We have also performed a term analysis of the vorticity equation that describes the forces that drive the rotational component of horizontal wind, in order to determine the processes that are mainly responsible for causing strong rotational flow in the high-latitude lower thermospheric wind fields.

2. Model Description

The NCAR TIE-GCM used in this study is an extension of the NCAR TIGCM (thermosphere-ionosphere general circulation model) described by Roble et al. [1988] and computes self-consistently the coupled thermospheric/ionospheric dynamics, the associated dynamo electric fields and currents, and the electrodynamic feedback on the neutral and plasma motions and thermodynamics [Richmond et al., 1992].

The nonlinear primitive equations for momentum, energy, continuity, and the equations of state are solved for the neutrals and the ions. The model calculates global distributions of neutral gas temperature, wind, mass mixing ratios of the major constituents \( \text{O}_2, \text{N}_2 \), and \( \text{O} \), and of the minor constituents \( \text{N}^+(\text{O}), \text{N}^+(\text{S}) \), and \( \text{NO} \). The Eulerian model of the ionosphere solves for global distributions of electron and ion temperatures and number densities of \( \text{O}^+, \text{O}_2^+, \text{NO}^+, \text{N}_2^+, \) and \( \text{N}^+ \). The TIE-GCM has a 5° latitude-by-longitude grid. The vertical coordinate of the model consists of 29 constant pressure levels ranging from approximately 97 km to 500 km in altitude, with a vertical resolution of two grid points per scale height. In this study we focus on altitudes up to about 200 km. The external inputs to the TIE-GCM are the solar EUV and UV spectral irradiance, auroral particle precipitation, the ion convection pattern (electric field) at high latitudes, and the upward propagating tides from the middle atmosphere.
We analyze the vorticity and divergence of the high-latitude lower thermospheric horizontal wind for different IMF directions, for seasonal and solar conditions representative of 23 January 1993. This period is characteristic of conditions for UARS-WINDII wind observations analyzed by Richmond et al. [2003] and previous analyses of forcing [Kwak and Richmond, 2007; Kwak et al., 2007]. On this date, the daily F10.7 index was recorded as $102.7 \times 10^{-22}$ W/m$^2$/Hz. The total hemispheric power (HP) was used to specify the high-latitude auroral particle precipitation pattern. The $Kp$ index was used to represent the HP (in gigawatts) as $HP = -2.78 + 9.33 \times Kp$; this formula is from Maeda et al. [1989]. The mean $Kp$ index on 23 January 1993 was 1, although the actual time-varying values for this date were used. The empirical electric potential model by Weimer [2001] was adopted to specify the pattern of the ionospheric convection. The prescriptions of the upward propagating diurnal and semi-diurnal tides are taken from the global scale wave model [Hagan and Forbes, 2002].

To investigate the response of the model fields to varying IMF, five TIE-GCM simulations are made, for steady IMF ($B_y, B_z$) values of $(-3.2, 0.0), (+3.2, 0.0), (0.0, -2.0), (0.0, +2.0)$, and $(0.0, 0.0)$ nT. The magnitudes of the nonzero reference values of $B_y$ and $B_z$ that is, 3.2 nT and 2.0 nT, are their respective root-mean-square values for the temporally smoothed data set analyzed by Richmond et al. [2003]. Each simulation is made with time-varying F10.7 and $Kp$ indices for 20–23 January 1993, but with steady IMF. A 2 min time step is used for the entire simulation, and linear interpolations of input values are made at a given time step. The TIE-GCM history is recorded hourly for the period that we studied, but only the results for 23 January are analyzed here. Simulations we performed for other Southern Hemisphere summer periods with steady IMF showed very similar dependencies on the IMF as in the current study, and so we can consider our results representative of Southern Hemisphere summer conditions for relatively steady IMF and low geomagnetic activity. However, our results are probably not representative of magnetic storm conditions.

### 3. High-Latitude Lower Thermospheric Wind Vorticity and Divergence

#### 3.1. Vorticity and Divergence

Vorticity is the curl of velocity and gives a measure of wind shear. We focus on the vertical (or upward) component of vorticity, for which positive values represent cyclonic (anticyclonic) rotation and negative values represent anticyclonic (cyclonic) rotation in the Northern (Southern) Hemisphere from perspective looking from outside Earth onto the atmospheric layers. Divergence of the horizontal wind, which we call “horizontal divergence,” is related to horizontal outflow, which is typically closed by outflow from the denser lower regions of the thermosphere associated with heating. In spherical coordinates the vertical component of the relative vorticity ($\zeta$), the absolute vorticity ($\omega_a$), and the horizontal divergence ($D$) are given, respectively, as,

$$
\zeta = \mathbf{k} \cdot (\nabla_z \times \mathbf{V}) = \frac{1}{r \cos \phi} \left( \frac{\partial v}{\partial \lambda} - \frac{\partial u}{\partial \phi} (u \cos \phi) \right)
$$

(1)

$$
\omega_a = \zeta + f = \zeta + 2 \Omega \sin \phi
$$

(2)

$$
D = \nabla_z \cdot \mathbf{V} = \frac{1}{r \cos \phi} \left( \frac{\partial u}{\partial \lambda} + \frac{\partial v}{\partial \phi} (v \cos \phi) \right)
$$

(3)

where $\mathbf{k}$ is a unit upward vertical vector, $\mathbf{V}$ is the neutral wind velocity, $\nabla_z$ is the two-dimensional horizontal Del operator for fixed pressure, $r$ is radial distance from center of earth, $u$ is the zonal wind, $v$ is the meridional wind, $\phi$ is latitude, $\lambda$ is longitude, $f = 2 \Omega \sin \phi$ is the Coriolis parameter, which equals the vertical component of planetary vorticity, and $\Omega$ is the angular rotation rate of the Earth; it has a value of $7.29 \times 10^{-5}$ s$^{-1}$. The vorticity equation that we analyze in section 4 is expressed most conveniently in terms of absolute rather than relative vorticity, and so we concentrate on absolute vorticity in this paper. We will often refer to the vertical component of absolute vorticity as simply “vorticity” or “vertical vorticity”.

The vertical component of the vorticity and the horizontal divergence in units of inverse seconds at all model grid points for each hour of universal time are obtained by using equations (1), (2), and (3) with outputs of TIE-GCM, where finite differencing is performed to calculate the vorticity and the divergence at a given pressure for each universal time. We bin each quantity for each universal time in magnetic coordinates for different orientations of the IMF; we analyze the quantities in quasi-dipole (QD) coordinates (QD-latitude and magnetic local time (MLT)) [Richmond, 1995]. For analysis of neutral winds, the QD-latitude/MLT region poleward of 47.5°S is divided into 145 subregions of approximately equal size, each having 5° width in latitude, and a
variable, latitude-dependent, width in MLT. The number of MLT subregions at a given latitude decreases from 32 at 50°S to 4 at 85°S, plus one at the pole. We then carry out an averaging for 24 UT hours of each quantity in each bin for each of the different IMF conditions. The resultant terms with respect to different pressure levels can be then mapped out over magnetic latitude and magnetic local time.

3.2. Dependence of Vorticity and Divergence on the IMF Orientation

To examine how the lower thermospheric winds from the TIE-GCM agree with the observations, the results of the TIE-GCM are compared with measurements by the Wind Imaging Interferometer (WINDII) on the Upper Atmospheric Research Satellite (UARS) as analyzed by Richmond et al. [2003].

Figures 1a and 1b show the average neutral wind circulations around 140 km over the Southern Hemisphere for IMF (By, Bz) values of (−3.2, 0.0), (+3.2, 0.0), (0.0, −2.0), and (0.0, +2.0) nT from WINDII data and the TIE-GCM runs, respectively. As for all other figures in this paper, these projections are as if one were looking up on the thermosphere from below or looking from the Northern Hemisphere through a transparent Earth. As shown in Figure 1, the wind patterns in the high-latitude lower thermosphere depend on the orientation of the IMF. Around 140 km altitude, the TIE-GCM wind patterns show agreements with the WINDII observations as follows, although the latter have a data gap around MLT midnight. The winds for negative By show a strong anticyclonic (clockwise) vortex on the duskside with enhanced antisunward flow inside the polar cap and a return sunward flow at lower latitudes in the vicinity of the auroral oval. The morning cell virtually disappears in the neutral wind field, and there is an equatorward flow in the early morning hours. The winds for positive By around 140 km have a two-cell pattern. The winds poleward of −70° on the duskside tend to show weaker anticyclonic motion than when By is negative, while the cyclonic (counterclockwise) circulation on the dawnside is more fully developed than for negative By, and the equatorward flow in the postmidnight sector is enhanced. For negative Bz, the two-cell wind pattern is also evident, with a larger and stronger anticyclonic vortex on the duskside and with relatively stronger equatorward flow in the early morning sector than for other IMF conditions. The winds poleward of −70° around 140 km tend to be the weakest when Bz is positive. Around 140 km altitude, the modeled maximum wind speeds for negative and positive Bz and negative and positive By are 268, 250, 271, and 158 m s⁻¹, respectively. The TIE-GCM wind patterns show disagreements with the WINDII observations in the following aspects. In all four patterns around 140 km, the modeled wind

Figure 1. The neutral winds in the Southern Hemisphere, as viewed from the Northern Hemisphere through a transparent Earth in magnetic-latitude/MLT coordinates poleward of −50°, for IMF (By, Bz) values of (−3.2, 0.0), (+3.2, 0.0), (0.0, −2.0), and (0.0, +2.0) nT from (a) WINDII data and (b) the TIE-GCM run, respectively. A vector length of 200 m s⁻¹ is shown at the bottom right.
magnitudes are usually weaker than the WINDII observations. The cyclonic dawn cell, weak or absent in the WINDII observations, is stronger in the TIE-GCM wind patterns except for negative $B_y$. The differences between the observed and modeled winds may be associated with differences in the IMF variations and averaging periods for the data and model, inaccuracy in estimating the model ion drag forcing, inaccuracy in the tidal boundary conditions for the TIE-GCM, or possibly with numerical smoothing features of the model.

The general agreement between wind observations and model results indicates that we can use the model to analyze in more detail the forces that maintain the wind system in the summertime lower thermosphere. Since the behavior of high-latitude winds in the lower thermosphere varies strongly with the IMF direction, one can expect that the wind vortices should also vary strongly with the IMF direction.

In order to address the dependence of the wind vortices on the IMF direction, we analyze vorticity in the high-latitude lower thermosphere over the Southern Hemisphere for the different IMF orientations. Figure 2a shows the derived vertical component of the absolute vorticity at 142 km for IMF $(B_x, B_y)$ values of $(3.2, 0.0), (0.0, -2.0)$, and $(0.0, 2.0)$ nT for the TIE-GCM winds shown in Figure 1b. Positive (negative) vorticity, shown by solid (dotted) lines, denotes clockwise (counterclockwise) rotation in an inertial frame from this perspective, looking from the Northern Hemisphere through the transparent Earth (i.e., looking up on the thermosphere from below in the Southern Hemisphere). The minimum and maximum values of vertical absolute vorticity are indicated at the lower right side of each plot. Note that vertical planetary vorticity is negative in the Southern Hemisphere, with a value of $-14.1 \times 10^{-5} \text{s}^{-1}$ at the magnetic pole and an average value of $-11.1 \times 10^{-5} \text{s}^{-1}$ around $-50^\circ$ magnetic latitude. Although it contributes significantly to the absolute vorticity, the main variations of absolute vorticity over the region shown come primarily from the large variations of relative vorticity rather than planetary vorticity. The strong antisunward flow over the magnetic pole bordered by sunward flow in the dawn and dusk sectors creates two regions of counter-rotating flow. In all four patterns of Figure 2a, positive vertical vorticity or clockwise rotation occurs primarily in the dusk sector, while negative vertical vorticity or counterclockwise rotation occurs in the dawn sector. These features are most pronounced when the IMF $B_y$ is negative. As the IMF $B_y$ becomes increasingly positive, the areas of strongest vertical vorticity contract toward higher magnetic latitudes, and the vorticity magnitudes are significantly reduced. Regarding IMF $B_y$, as $B_y$ changes sign from positive to negative, the region of negative vertical vorticity moves away from the pole, while the region of positive vertical vorticity...
extends across the pole and its magnitude intensifies. These features are similar to those seen in the IMF-dependent Southern Hemisphere vertical vorticity maps of Förster et al. [2011] at 400 km, but the simulation amplitudes at 142 km are only about half as large as the observed amplitudes at 400 km, owing to the smaller ion drag coefficients at 142 km. Equatorward of $-60^\circ$ magnetic latitude, the magnitude of vertical vorticity is significantly reduced, illustrating the strong influence of the high-latitude ion convection in creating rotational motion in the neutral flow.

For comparing with vorticity, the derived average horizontal divergence patterns at 142 km are shown in Figure 2b, with a smaller contour interval. In order to reduce numerical noise in the calculation of the horizontal divergence, the values have been smoothed over 2 h of MLT. The minimum and maximum values are indicated at the lower right side of each plot. As with the vertical vorticity pattern, the regions of horizontal divergence occur primarily at high latitudes. Regions of strong horizontal divergence that occur primarily around $-65^\circ$ and $-75^\circ$ latitudes in the dawn sector coincide with areas of typically strong Joule heating, although Joule heating patterns are not shown in this paper. The horizontal divergence field is much more complex and significantly smaller in magnitude than the corresponding vertical vorticity field. Overall, the ratio of the peak values of horizontal divergence to vertical vorticity at 142 km altitude is about 1:6 for the level of forcing used in these simulations. Since the Joule heating that contributes to horizontally divergent motion increases more strongly with increasing electric field intensity than does ion drag forcing that contributes to vertical vorticity, the relative importance of horizontally divergent motion is likely to increase during magnetic storms, when the electric field increases. From Figure 2, it is evident not only that the high-latitude lower thermospheric vertical vorticity and horizontal divergence depend on the IMF but also that the mean horizontal neutral wind pattern in the high-latitude lower thermosphere is dominated by rotational flow rather than by divergent flow, consistent with studies cited in the introduction.

The derived vertical component of the vorticity at 169, 142, 123, and 111 km altitudes for referenced to zero IMF.

In order to examine more closely how the vertical vorticity, which dominates the mean high-latitude neutral wind pattern, is influenced by the IMF, we take the difference vertical vorticity, obtained by subtracting values with zero IMF from those with nonzero IMF. Figure 4 shows the difference vertical vorticities at 169, 142, 123, and 111 km for IMF $(B_y, B_z)$ values of $(0.0, 0.0)$ nT, referenced to zero IMF, are illustrated in Figure 3. These altitudes are one scale height apart. At all altitudes negative vertical vorticity on the dawnside is stronger than positive vertical vorticity on the duskside. Although not shown here, above 169 km, the vertical vorticity is found to change considerably less with altitude than below. Vertical vorticity gets weaker rapidly with descending altitude below 142 km. The transition regions of vertical vorticity between positive and negative values with respect to MLT poleward of $-70^\circ$ magnetic latitude lie toward later MLTs with descending altitude.

In order to examine more closely how the vertical vorticity, which dominates the mean high-latitude neutral wind pattern, is influenced by the IMF, we take the difference vertical vorticity, obtained by subtracting values with zero IMF from those with nonzero IMF. Figure 4 shows the difference vertical vorticities at 169, 142, 123, and 111 km for IMF $(B_y, B_z)$ values of $(3.2, 0.0), (0.0, 2.0)$, and $(3.2, 0.0)$ nT. The difference vertical vorticities for negative and positive $B_y$ show significantly strong simple positive (clockwise rotation) and negative (counterclockwise rotation) values, respectively, at magnetic latitudes poleward of $-70^\circ$. The apparent centers lie nearly at the pole. Although not shown here, such a tendency can be seen down to 106 km. Regarding IMF $B_z$, the difference vertical vorticity extends to subauroral latitudes. For negative and positive $B_z$, the difference vertical vorticities have opposite signs at the same place. Negative IMF $B_z$
has a stronger effect on the vertical vorticity than does positive $B_z$. For negative $B_z$ the difference vertical vorticity is asymmetric, with a strong minimum in the dawn sector on the order of $12.6 \times 10^{-5} \text{ s}^{-1}$ at 142 km and a weak maximum in the dusk sector on the order of $8.0 \times 10^{-5} \text{ s}^{-1}$ at 142 km. Negative and positive difference vertical vorticities for negative $B_z$ are weaker than those in the polar cap region for positive and negative $B_y$ by a factor of about 0.5 and about 0.35, respectively, partly due to the fact that the IMF strength we use for the $B_z$ cases is only 0.625 as large as that for the $B_y$ cases. Although not shown here, the difference horizontal divergence is much smaller than the difference vertical vorticity for all IMF conditions. Overall, the difference horizontal divergence: difference vertical vorticity ratio at 142 km altitude is about 1:6. The relative changes of vertical vorticity and horizontal divergence with IMF changes are comparable, indicating that IMF effects on the rotation in the wind field are much stronger than those on the horizontal divergence.

To see the influence of IMF $B_y$ on the summertime high-latitude lower thermospheric vorticity over the Southern Hemisphere, we examine the $B_y$-dependent component of the geomagnetic zonal mean (or MLT averaged) vertical component of the vorticity in Figure 5. This is simply the zonal average of the difference vertical vorticity for $B_y = 3.2 \text{ nT}$ shown in Figure 4 (second column). Poleward of $-73^\circ$ magnetic latitude, the difference vertical vorticity is negative and its minimum lies at the pole. The $B_y$-dependent vertical vorticity has a significant amplitude down to about 106 km in the negative vertical vorticity region. Negative vertical vorticity above 125 km is nearly constant with altitude. Below 125 km, negative vertical vorticity decreases

![Figure 4](image-url)
In this section, we quantify the forces that maintain such wind pattern in the high-latitude lower thermosphere is dominated by rotational flow rather than by divergent flow. In this section, we quantify the forces that maintain such rotational flow in the high-latitude lower thermospheric wind fields. A term analysis of the vorticity equation is required to resolve the relative contributions of the various sources to rotational flow, because this equation describes the forces that drive the nondivergent component of the horizontal wind.

The vertical component of the vorticity equation can be derived by taking the vertical component of curl $(\mathbf{k} \cdot \nabla x)$ of the horizontal momentum equation given by Kwak and Richmond [2007], yielding

\[
\frac{\partial \omega_z}{\partial t} = -\mathbf{V} \cdot \nabla \omega_a - \omega_a \mathbf{V} \cdot \mathbf{V} - \frac{W \partial \omega_a}{\partial Z} + \mathbf{k} \times \nabla \mathbf{V} \cdot \mathbf{W} + \mathbf{k} \cdot \nabla \times \left[ \frac{\sigma_F B^2}{\rho} \mathbf{U} - \nabla \mathbf{V} \right] \tag{4}
\]

where $W = \partial Z/\partial t$ is vertical velocity in scale heights per unit time; $Z = \log_{10}(P_0/P)$, where $P_0$ is reference pressure ($=50 \mu\text{Pa}$); $\rho$ is gas density; $\mu$ is the sum of the molecular and turbulent viscosity coefficients; $\sigma_P$ and $\sigma_H$ are the Pedersen and Hall conductivities, respectively; $\mathbf{E}$ is the electromagnetic convection velocity $\mathbf{E} \times \mathbf{B}/B^2$; $\mathbf{E}$ is the electric field; $\mathbf{B}$ is the geomagnetic field; and $\mathbf{V}_\perp$ is the component of $\mathbf{V}$ perpendicular to $\mathbf{B}$. The left-hand side is the time-rate-of-change in the vertical component of the absolute (and relative) vorticity. The terms, reading from left to right on the right-hand side in the vorticity equation (4), refer to, respectively, the horizontal advection, stretching, vertical advection, tilting (or twisting), viscosity, and ion drag terms. The stretching term represents modification of vertical absolute vorticity by horizontal divergence. The tilting term represents generation of vertical vorticity by the tilting of horizontally oriented components of vorticity into the vertical by a nonuniform vertical motion field. The various terms in (4) are the result of performing the curl operation on the force terms in the momentum equation. The horizontal advection and stretching terms are determined from the horizontal advection of momentum and the Coriolis force. The vertical advection and tilting terms are determined from the vertical advection of momentum. The viscosity term is determined from the viscous force, while the ion drag term is determined from the ion drag force. The pressure gradient force is curl free and does not contribute in the generation of vorticity. Thus, the significant forces involved in generating nondivergent motion are the Coriolis force, the advection of momentum, the viscous force, and the ion drag force.

The individual vorticity forcing terms in units of square second at all model grid points for each hour of universal time are obtained by using equation (4), where vertical and horizontal finite differencing is performed to calculate forces at a given altitude for each universal time. The processes to obtain the distributions of the vorticity forcing terms with respect to different altitudes are the same as those to obtain the vorticity patterns in section 3.

### 4.2. Vorticity Forcing

In this section, forces at different altitudes in the high-latitude lower thermosphere over the southern summer hemisphere for negative IMF $B_y$ are analyzed. Figure 6 illustrates the calculated distributions of various forces forcing the vorticity at 169, 142, 123, and 111 km over the Southern Hemisphere for IMF $(B_y, B_z)$ values of $(0.0, -2.0)$ nT: ion drag (Figure 6a), horizontal advection (Figure 6b), and stretching terms(Figure 6c).
The vertical vorticity tendency, or time derivative, is the sum of all the forcing terms and is shown in Figure 6d. The minimum and maximum values are indicated at the lower right side of each plot. Positive and negative values denote clockwise and counterclockwise forcing, respectively.

The ion drag term (Figure 6a) has a major contribution to vertical vorticity tendency. The region of strong positive tendency in the afternoon and the region of strong negative tendency in the morning lie mostly within the two cells of high-latitude ion convection (which are shown, for example, in Kwak et al. [2007, Figure 3]). At 169 km altitude, there is strong positive (with maximum value of $5.2 \times 10^{-8}$ s$^{-2}$) and negative (with minimum value of $-5.6 \times 10^{-8}$ s$^{-2}$) ion drag forcings of the vertical vorticity in the dusk and dawn sectors at higher magnetic latitudes of 70° to 80°, respectively. At lower magnetic latitude of 60° to 70°, positive and negative ion drag forcing occurs in the dawn and dusk sectors, respectively. Because of the Earth’s rotation and also because of horizontal advection of absolute vorticity, the positive and negative forcings have a tendency to cancel at a given geographic location when averaged over 24 h. The magnitude of forcing is significantly reduced equatorward of 60° magnetic latitude, illustrating the strong influence of the high-latitude ion convection in forcing vertical vorticity in the high-latitude thermosphere. Below 123 km only weak ion drag forcing is seen. At these lower altitudes, where the ion-neutral collision frequency is comparable with or larger than the ion gyrofrequency, the ion drift is strongly influenced by collisions with the neutral atmosphere [Kwak and Richmond, 2007].
The ion drag force represents the $\mathbf{J} \times \mathbf{B}$ force on the medium, where $\mathbf{J}$ is electric current density. At high latitudes, where $\mathbf{B}$ is nearly vertical, the vertical component of the curl of $\mathbf{J} \times \mathbf{B}$ is approximately proportional to the horizontal divergence of $\mathbf{J}$ in the ionosphere, which in turn is connected to the flow of geomagnetic-field-aligned current (FAC) from the magnetosphere. Thus, it is expected that the contribution of the ion drag force to vertical vorticity generation will be closely related to the FAC, as noted by Förster et al. [2011]. If weighted by the mass density and integrated in altitude, the ion drag contribution to vertical vorticity generation should be nearly proportional to the FAC density, with upward (downward) FAC generating positive (negative) vertical vorticity in the Southern Hemisphere. Indeed, the patterns of ion drag vertical vorticity generation in Figure 6a are similar to the region 1/region 2 pattern of FAC seen in empirical models like that of Weimer [2005].

Figure 6b illustrates the horizontal advection of vertical absolute vorticity. At 169 km altitude, there are positive regions with a maximum value of $5.2 \times 10^{-8} \text{ s}^{-2}$ around midnight and in the early morning and in the later evening hours at higher magnetic latitudes of $70^\circ$ to $80^\circ$, while broad negative regions with a minimum value of $-3.6 \times 10^{-8} \text{ s}^{-2}$ are located around noon and in the dawn and dusk sectors in the auroral
Although not shown here, the vertical advection, the tilting, and the viscous terms of the vertical absolute vorticity (Figure 7f) are small, indicating that their contributions to the establishment of the rotational flow are low. This is particularly true for the region of strong downward gradient of zonal mean vertical vorticity. The mean tilting (Figure 7e) and viscous advection forcing (Figure 7d) to the generation of the mean vorticity is relatively small, although it has weaker than that of $\zeta$. Unlike the case for horizontal advection of vertical absolute vorticity, the contribution of planetary vorticity to the stretching term is often important, because the magnitude of $f$ is often comparable with that of $\zeta$, while the gradient of $f$ is relatively weaker than that of $\zeta$.

Figure 6c shows the distribution of the stretching term. Localized islands of the stretching occur primarily in the high-latitude region above $-65^\circ$ magnetic latitude, and somewhat strong stretching forcing with maximum value of $3.4 \times 10^{-8} \text{ s}^{-2}$ at 169 km occur in the dawn sector. This forcing weakens with decreasing altitude. This stretching represents the modulation of vertical absolute vorticity associated with horizontal divergence. A reduction of the amplitude of the vertical absolute vorticity occurs where the horizontal divergence is positive, as often occurs in regions of strong Joule heating. Unlike the case for horizontal advection of vertical absolute vorticity, the contribution of planetary vorticity to the stretching term is often important, because the magnitude of $f$ is often comparable with that of $\zeta$, while the gradient of $f$ is relatively weaker than that of $\zeta$.

Although not shown here, the vertical advection, the tilting, and the viscous terms of the vertical absolute vorticity have maximum values of $0.2 \times 10^{-8} \text{ s}^{-2}$, $0.2 \times 10^{-8} \text{ s}^{-2}$, and $1.1 \times 10^{-8} \text{ s}^{-2}$, respectively, at 169 km altitude. These forcing terms are less important compared to other forcing terms (i.e., the ion drag forcing, the horizontal advection term, and the stretching term) because of their relatively small magnitude.

In order to investigate the influence of IMF $B_y$ on the forcing of the vertical absolute vorticity in the summertime high-latitude lower thermosphere over the Southern Hemisphere, we examine the $B_y$-dependent geomagnetic zonal mean (or MLT averaged) vorticity forcing terms in Figure 7, for a $B_y$ value of 3.2 nT. The mean ion drag term is shown in Figure 7a. Poleward of $-77^\circ$ magnetic latitude, it is strongly negative and minimizes at the pole. At $-77^\circ$ to $-65^\circ$ magnetic latitude, it is positive, with a maximum around $-75^\circ$ latitude. The $B_y$-dependent ion drag forcing on the vorticity has a significant amplitude down to about 105 km in the negative region and about 110 km in the positive region. Other forcing terms in the vorticity equation tend to counteract the $B_y$-dependent geomagnetic zonal mean ion drag term. The mean horizontal advection forcing on the vorticity shown in Figure 7b is generally negative and has significant amplitude down to about 120 km poleward of $-70^\circ$. It has a minimum around 135 km at $-85^\circ$ latitude and a secondary minimum around 135 km at $-75^\circ$ latitude. The mean stretching term (Figure 7c) is generally positive and has significant amplitude poleward of $-75^\circ$ latitude and down to 120 km altitude. The contribution of the mean vertical advection forcing (Figure 7d) to the generation of the mean vorticity is relatively small, although it has significant amplitude around 120 km altitude poleward of $-80^\circ$ latitude, owing to upward motion in a region of strong downward gradient of zonal mean vertical vorticity. The mean tilting (Figure 7e) and viscous (Figure 7f) terms are small, indicating that their contributions to the establishment of the rotational flow are low.

5. Summary and Conclusions

The vertical component of vorticity and the horizontal divergence of the high-latitude neutral wind field in the lower thermosphere during the southern summer time for different interplanetary magnetic field (IMF) conditions have been analyzed using the NCAR TIE-GCM. This analysis provides the determination of the large-scale vertical vorticity and horizontal divergence patterns in the lower polar thermosphere and provides insight into the relative strengths of the different physical processes that affect the vertical vorticity. This investigation leads to the following principal conclusions:

1. Consistent with previous studies, we find that the mean horizontal neutral wind pattern in the high-latitude lower thermosphere, between 100 km and 200 km altitude, is dominated by rotational flow, which is imparted primarily through the ion drag force, rather than by horizontally divergent flow, which is driven more through Joule and solar heating. Poleward of $-60^\circ$ magnetic latitude the magnitude of the relative vertical vorticity $\zeta$ generated by ion convection often exceeds the magnitude of planetary vertical vorticity $f$, and horizontal gradients of absolute vorticity tend to be dominated by gradients of $\zeta$ rather than gradients of $f$ above 120 km. Overall, the vorticity: divergence ratio at 142 km altitude is about 6:1 for the level of forcing used in these simulations. This ratio is expected to decrease when the strength of the high-latitude electric fields increases, owing to a stronger dependence of Joule heating than ion drag on the electric field strength.
2. The vertical vorticity in the high-latitude lower thermosphere depends on the direction of the IMF. For negative and positive $B_z$ conditions the difference vertical vorticity, obtained by subtracting values with zero IMF from those with nonzero IMF, is positive (clockwise vortex as viewed from the north through a transparent Earth) and negative (counterclockwise vortex), respectively, at magnetic latitudes higher than $-70^\circ$. For negative $B_z$, the sign of the difference vertical vorticity is positive in the dusk sector and negative in the dawn sector. The difference vertical vorticity for positive $B_z$ has the opposite sign. Negative IMF $B_z$ has a stronger effect on the vertical vorticity than does positive $B_z$.

3. The difference vertical vorticity is much larger, by a factor of about 6, than the difference horizontal divergence for all IMF conditions considered here, indicating a larger response of the high-latitude thermospheric wind system to IMF-related changes in the momentum input generating the rotational motion than to the corresponding changes in energy input generating the divergent motion.

4. The effects of the IMF on the vertical vorticity in the high-latitude lower thermospheric neutral wind fields are seen down to around 106 km altitude. The effects likely extend even lower with reduced amplitudes but cannot be adequately analyzed with the TIE-GCM because altitudes below 106 km are too close to its lower boundary. Whether the effects might be large enough to perceptibly influence mesospheric dynamics is an unresolved question.

Since this analysis was limited to the summer hemisphere, where the WINDII observations were available for comparison, we cannot directly draw conclusions about conditions in the winter hemisphere, other than to say that we expect the vorticity forcing to be weaker there owing to the smaller ion densities in the winter lower thermosphere.

Since it is evident that the mean neutral wind pattern in the high-latitude lower thermosphere is dominated by rotational flow rather than by divergent flow, we examined the processes contributing to changes in vertical vorticity through a term analysis of the vertical vorticity equation. This investigation leads to the following principal conclusions:

1. It is evident that the magnitude of forcing terms on vorticity is significant poleward of $-60^\circ$ magnetic latitude, illustrating the generation of the rotational flow or vertical vorticity at the high-latitude regions.

2. The primary force that determines variations of the vertical vorticity is the ion drag forcing term, indicating strong effect of the ionospheric convection on creating rotational motion in the neutral flow. This forcing is closely related to the flow of FAC between the ionosphere and the magnetosphere, with upward (downward) FAC generally contributing to positive (negative) vertical vorticity generation in the Southern Hemisphere. Significant contributions to variations of the vertical vorticity, however, can be made by the horizontal advection term.

3. The effects of the IMF on the ion drag forcing are seen down to around 106 km altitude.

4. The continual forcing of magnetic zonal mean $B_y$-dependent vertical vorticity by ion drag can lead to strong polar vortices. Stretching and horizontal advection are the main terms tending to counteract the magnetic zonal mean $B_y$-dependent ion drag vertical vorticity forcing, with a lesser contribution from vertical advection around 120 km altitude.

References


