Climatology Analysis of the Daytime Topside Ionospheric Diffusive $O^+$ Flux Based on Incoherent Scatter Radar Observations at Millstone Hill

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Abstract This paper reports the characteristics of the topside ionospheric $O^+$ diffusive flux ($\Phi_{O^+}$) during both geomagnetically quiet (0 ≤ Kp ≤ 2) and moderate (2 < Kp ≤ 4) times using incoherent scatter radar observations at Millstone Hill (42.6°N, 288.5°E) for solar minimum from 1970 to 2018. $\Phi_{O^+}$ partially characterizes plasma mass exchange between the upper and lower part of the topside ionosphere through diffusion and sometimes serves as upper boundary conditions for ionosphere-thermosphere models. The altitude where the flux sign changes (mainly during daytime) is termed the transition height and the time when the flux sign changes (mainly at dawn and dusk) is termed the transition time. At quiet times, the daytime transition height is ~100 km above the $F_2$ peak height ($h_mF_2$) in summer, and it is about 50 km above $h_mF_2$ in other seasons; the transition time is before 18 solar local time (SLT) in spring and winter, but after 18 SLT in summer and autumn. The daytime average upward $\Phi_{O^+}$, above the transition height shows a significant seasonal variation with a minimum of $2.2 \times 10^8 \text{cm}^{-2} \text{s}^{-1}$ in summer and a maximum of $3.7 \times 10^8 \text{cm}^{-2} \text{s}^{-1}$ in autumn. Under geomagnetically moderate conditions, the transition height increases by ~20 km in spring, winter, and autumn, but moves up by about 20–50 km in summer. The transition time occurs later by ~1 hr in summer but ~1 hr earlier in other seasons. The mean upward $\Phi_{O^+}$ peaks in summer and minimizes in spring.

Plain Language Summary The topside ionospheric $O^+$ diffusive flux ($\Phi_{O^+}$) is a part of the total plasma flux that is a critical parameter to characterize the plasma exchange between the upper and lower part of the topside ionosphere, but has been poorly known due to lack of direct measurements. Using long-term incoherent scatter radar (ISR) data observed at Millstone Hill for nearly five decades, this study investigates $\Phi_{O^+}$ variations as a function of the altitude above the $F_2$ peak height ($h_mF_2$), local time, and season in both geomagnetically quiet and moderate times, and further explores the physical mechanism causing these variations. During quiet times, the summer daytime transition height where $\Phi_{O^+}$ changes from downward to upward along magnetic field lines occurs at ~$h_mF_2 + 100$ km. However, it is usually near $h_mF_2 + 50$ km in other seasons. In addition, the transition time when $\Phi_{O^+}$ changes from upward to downward at a fixed height is earlier than 18 SLT in spring and winter, but later than 18 SLT in summer and autumn. We also found that an increase in geomagnetic activity decreases the vertical gradient of plasma density during the daytime in all seasons, resulting in a ~20 km increase in the transition height and an earlier transition time near dusk in spring, autumn, and winter, but a larger transition height change of about 20–50 km and a later transition time in summer. The change in the seasonal variations of the upward $\Phi_{O^+}$ results from the competition between the variations of plasma diffusive velocity and density when the geomagnetic activity increases, as well as the changes in plasma vertical density profiles.
1. Introduction

Ionospheric O+ diffusive flux is an important parameter to characterize the plasma exchange and coupling between the ionosphere and the plasmasphere. In particular, understanding its variations, for example, local time and seasonal dependency, helps to gain insight into the important roles of the topside flux contribution to some ionospheric F-region phenomena, such as the abnormal electron density enhancements at dusk in summer often observed at Millstone Hill (Evans, 1965; Holt et al., 2002) and elsewhere. Also, it provides convenient upper boundary conditions for many ionosphere-thermosphere coupled models to solve for the O+ mass continuity equation, such as the National Center for Atmospheric Research–thermosphere ionosphere electrodynamics general circulation model (NCAR-TIEGCM) (Qian et al., 2014) and Thermo-Ionosphere Nested Grid model (TING) (Wang et al., 1999). Historically, these numerical models have used simple empirical values (Qian et al., 2014) largely due to limited availability of O+ diffusive flux information. Thus, another important motivation of this research is to provide a more realistic specification for these numerical models.

In the daytime, ionospheric plasma flows upward into the plasmasphere along the magnetic field lines, whereas at night plasma flows downward from the plasmasphere to replenish the ionosphere. Previous studies investigated this type of plasma exchange between the ionosphere and plasmasphere (Evans, 1971a, 1971b, 1975; Evans & Holt, 1971; Greenspan et al., 1994; Ho & Moorcroft, 1975; Skoblin & Förster, 1996). They focused mainly on the total plasma flows determined by the combined effects of neutral winds, electric fields, and ambipolar diffusion. The ambipolar diffusive flux becomes increasingly significant with increasing altitude, as compared to wind and electric field effects, but has rarely been studied partially because it cannot be measured directly. Evans (1971a) reviewed the theory of the F region ion drift and suggested using the ion continuity equation to calculate the ion diffusive velocity in the topside ionosphere under the assumption that external electric fields and neutral winds can be ignored. Then the diffusive flux can be calculated from the diffusive velocity. Lockwood (1983) obtained the diffusive flux of O+ in the topside mid-latitude ionosphere based on satellite soundings under geomagnetically quiet conditions, and investigated its diurnal variations, which were upward during the day and downward at night. This diurnal variation can be explained by solar EUV radiation produced ionization of the neutral constituents to create greater plasma density and high temperatures in the ionosphere that leads to a strong upward pressure gradient in the topside during the daytime (Evans, 1971b). At night, the decrease in temperature and recombination of the electrons and ions induce downward transport of plasmaspheric plasma to help maintain the ionospheric layer (Chen et al., 2014). Many previous studies have investigated the mass and thermal coupling between the ionosphere and the plasmasphere (Bailey et al., 1977a, 1977b; Richards & Torr, 1985, 1986; Richards et al., 1983). Chen et al. (2009, 2010) studied the seasonal and latitudinal variations of O+ diffusive fluxes under different solar activity conditions using electron density profiles retrieved from radio occultation measurements of CHAMP (German CHAllenging Minisatellite Payload) and COSMIC (Constellation Observing System for Meteorology Ionosphere and Climate) satellites. Chen et al. (2014) fitted Millstone Hill incoherent scatter radar (ISR) data using the Chapman–α layer function (Lei et al., 2005) to investigate the response of ionospheric diffusive fluxes to two geomagnetic storms in October 2002. They found that the variations in the vertical gradient of plasma density during storms dominated the diffusive flux, rather than the variations in the plasma density. Nevertheless, the understanding of the variations of the O+ diffusive flux in the topside ionosphere is still limited, but these studies provided a reliable method to explore the diffusive flux which will be applied to the present study.

The Millstone Hill ISR observations have accumulated abundant ionospheric data (e.g., electron density, electron and ion temperatures, and ion drift), which makes it possible to characterize the O+ diffusive flux in the topside ionosphere. This paper focuses on the variations of topside O+ diffusive flux with altitude, local time, and season, and during geomagnetic quiet and moderate periods at solar minimum.

2. Data and Method

2.1. Data Source and Distribution

The Millstone Hill (42.6°N, 288.5°E, invariant latitude 53.4°) ISR is a powerful ground-based instrument for monitoring the ionospheric ion temperature $T_i$, electron temperature $T_e$, electron number density $N_e$, and
ion drift over a broad height range (Holt & Zhang, 2008). The data used in this study are available from the Madrigal Database (http://millstonehill.haystack.mit.edu/). The Millstone Hill UHF zenith-directed, 68-m diameter, fixed parabolic antenna radar system commenced operation in 1963, and the-steerable 46-m antenna commenced operation in 1978 (Holt et al., 2002). This study analyzed the zenith measurements with pulse length <640 microsecond above 250 km. Below 250 km, the Alternating Code (A/C) pulse scheme data after its introduction in the 1990s and short pulses data before were used in this study. The O\textsuperscript{+} diffusive flux in the topside ionosphere was calculated from the ISR \( N_e, T_e, \) and \( T_F \) at solar minimum (\( F_{\alpha,7} \leq 100 \)) spanning four and a half solar cycles between 1970 and 2018. A similar data set was used previously for a long-term trend study (Zhang et al., 2016).

First, the data was excluded if there is daily Kp \( \geq 5 \) within five days before the considered days because strong storms occurred prior the considered days could affect the diffusive flux through emptying the plasmasphere. Subsequently, the remaining data was grouped according to solar local time (SLT), height, season, and geomagnetic activity. This results in 24 local time bins (each containing data from two hours), 4 seasonal bins (each containing 91-day centered at equinox and solstice), two geomagnetic levels with 0 \( \leq 3\)-hourly Kp \( \leq 2 \) for quiet and 2 \( < 3\)-hourly Kp \( \leq 4 \) for moderate conditions, and 23 altitude bins between 100 and 550 km (each 20 km wide). The altitude spacing is short compared to Zhang et al. (2016), which is necessary for proper height gradient calculations.

The top panels of Figure 1 show the distribution of the number of \( N_e \) data points as a function of altitude and SLT in four seasons at solar minimum under geomagnetically quiet conditions. The number of data points above 250 km for the four seasons is mostly between 1,500 and 3,000 during the day (06–18 SLT) in each-altitude bin, but usually less than 1,500 at night (18–24–06 SLT). Altitude bins below 250 km have more data points (3,000–6,000) because of the finer resolution (−5 km) A/C data. The bottom panels of Figure 1 show the data distribution during geomagnetically moderate times at solar minimum. For moderate times, there are fewer observations (<1,000) during both the daytime and nighttime. The data distributions of \( T_i \) and \( T_F \) are similar to \( N_e \). There are enough high-quality data for the daytime analysis but not for nighttime. This paper focuses on the daytime and uses the nighttime results only for reference purposes. The NRLMSISE00 model (Picone et al., 2002) was used to specify neutral parameters for the calculation of the collision frequency between the ions and neutral species.

2.2. Method

Our data analysis procedure began with the calculation of the median values of \( N_e, T_e, \) and \( T_F \) in each-altitude-SLT-season bin. The \( T_e \) and \( T_F \) altitude profiles are smoothed using five point averaging, and linearly interpolated between the 23 altitude grid points. However, altitude profiles of \( N_e \) were determined by fitting the bin medians between 200 and 500 km to a Chapman–\( \alpha \) layer function (Lei et al., 2005; Rishbeth & Garriott, 1969),

\[
N_e(h) = N_m F_2 \exp \left[ -0.5 \left( 1 - e^{-z} \right) \right],
\]

where \( N_m F_2 \) is the peak electron density of the \( F_2 \) layer, \( h_m F_2 \) is the peak height of the \( F_2 \) layer, and \( H(h) \) is the Chapman scale height that can be taken as \( H(h) = A(h - h_m F_2) + H_m \). The adjustable variables \( N_m F_2, h_m F_2, A, \) and \( H_m \) are determined using least-squares fitting.

The red lines in the top row of Figure 2 show a sample of fitted topside \( N_e \) and plasma temperature (\( T_p = T_i + T_e \)) profiles while the solid dots show the observed bin medians. The error bar represents the standard deviation of the observations. Note that the standard deviation increases significantly with altitude, which is why the fitting range is limited to less than 500 km. The fitted \( h m F_2 \) (bottom left panel of Figure 2) displays diurnal and seasonal variations consistent with that of Lei et al. (2005) at solar minimum, even though the quiet time data used in the study are restricted to Kp \( \leq 2 \) (i.e., Ap \( \leq 7 \)) rather than Ap \( < 20 \) used by Lei et al. (2005). Also there are a lot more data in our analysis.
Equations 2 and 3 (Chen et al., 2009, 2014; Rishbeth & Garriott, 1969) were used to calculate the ambipolar diffusive velocity and flux,

$$V_d = \frac{k(T_e + T_i)}{m_i n_i} \left[ \frac{1}{N_i} \frac{\partial N_i}{\partial h} + \frac{1}{T_i + T_e} \frac{\partial (T_i + T_e)}{\partial h} + \frac{m_i g}{k(T_i + T_e)} \right]$$

$$\Phi_d = N_i V_d$$  

where $V_d$ and $\Phi_d$ are the diffusive velocity and flux. $N_i$ is the number density of $O^+$, which is assumed to be equal to the measured $N_i$ in the daytime topside ionosphere below 500 km at solar minimum. Previous studies have suggested that the transition of $O^+ / H^+$ at both low- and mid-latitudes is above 500 km during the daytime (Aponte et al., 2013; Kotov et al., 2015, 2016, 2018; Vaishnav et al., 2020). $m_i$ is the mass of $O^+$; $k$ is the Boltzmann constant; $I$ is the inclination of the geomagnetic field line; $g$ is the acceleration due to gravity and attenuates with height; $h$ is the altitude. $\nu_{cm}$ is the collision frequency between $O^+$ and neutral species.

Figure 1. Millstone Hill electron density ($N_e$) data distribution as a function of altitude and solar local time in different seasons under geomagnetically quiet (top panel) and moderate (bottom panel) times at solar minimum.
\[ n_w = \frac{3.67 \times 10^{-11}}{2} \sqrt{\frac{T_e + T_i}{2}} \left( 1 - 0.064 \log_{10} \left( \frac{T_e + T_i}{2} \right) \right) N(O) f_{cor} + 6.64 \times 10^{-10} N(O_2) + 6.82 \times 10^{-10} N(N_2) \]

(Schunk & Nagy, 2009), where the Burnside factor \( f_{cor} = 1.26 \) (Nicolls et al., 2006). \( N(O) \), \( N(O_2) \) and \( N(N_2) \) are the number densities of the major neutral species, which are from the NRLMSISE00 model (Picone et al., 2002). The geomagnetic inclination \( I \) from the International Geomagnetic Reference Field 12 model (Thebault et al., 2015) changed from \( \sim 71^\circ \) in 1970 to \( \sim 67^\circ \) in 2018. The assumption that \( I = 69^\circ \) which can cause \( \sim \pm 1\% \) uncertainty for calculating the diffusive velocity/flux.

3. Results

\( h_mF_2 \) was chosen as the reference height to display the analysis results of the diffusive flux, because the mid-latitude \( h_mF_2 \) tends to lie at a fixed atmospheric pressure level regardless of the latitude, season, and solar activity (Rishbeth & Edwards, 1990). In addition, the use of height above \( h_mF_2 \) reduces any complication due to the movement of \( h_mF_2 \) in the interpretation of data (Chen et al., 2009).

Figure 3 shows a comparison between the total ion flux (\( \Phi_i \)) from the observed vertical ion velocity and electron density with the vertical projection of the calculated \( O^+ \) diffusive flux component (\( \Phi_{o+,i} = \Phi_{o+} \sin I \)). The gray line is \( h_mF_2 \). In the daytime, \( \Phi_i \) is mostly downward below approximately \( h_mF_2 + 100 \) km while \( \Phi_{o+,i} \) is upward between 20 and 100 km above \( h_mF_2 \), which reveals that the wind and electric field induced ion drift in the region is stronger than the upward ambipolar diffusion velocity. At higher altitudes where the diffusive velocity increases rapidly and becomes larger than the wind-induced drift, \( \Phi_i \) becomes upward above approximately \( h_mF_2 + 100 \) km during the daytime. Figure 3 demonstrates that the ambipolar diffusive...
flux can be substantially different from the total vertical plasma velocity measured by the ISR which includes plasma transport by winds and electric fields.

Figure 4 shows the calculated O\(^+\) diffusive flux \(\Phi_{oE}\) as a function of altitude relative to \(h_mF_2\) and local time at solar minimum in different seasons under geomagnetically quiet and moderate times. The solar zenith angle (SZA) corresponding to local time is marked above the X-axis. The corresponding analysis is summarized in Table 1 and Table 2. The diffusive flux is generally upward during the day and downward after night, in agreement with the expected behavior of ionosphere-plasmasphere plasma exchange process (Evans, 1971b). Note that there is low reliability of the results at the shadow areas in Figure 4.

The transition height in Table 1 is the altitude where \(\Phi_{oE}\) in the topside ionosphere switches from downward to upward (mainly during the day). During daytime the switch usually occurs above \(h_mF_2\). In general, there is a large downward \(\Phi_{oE}\) below \(h_mF_2\) due to gravity and the greater loss rate. \(\Phi_{oE}\) changes to upward just above \(h_mF_2\), as shown in Figures 3 and 4. The transition time in Table 1 is the time at dawn and dusk when \(\Phi_{oE}\) at some height in the topside ionosphere switches between upward (primarily during the daytime) and downward (primarily at night).

During geomagnetically quiet times (0 ≤ Kp ≤ 2), the transition height in spring and winter is near \(h_mF_2+50 \text{ km}\) in both the morning and afternoon, but in summer and autumn, the transition height in the morning is closer to the \(F_2\) peak height, at least 20 km lower than that in the afternoon. Furthermore, the average transition height during daytime shows apparent seasonal variations with a higher altitude (~\(h_mF_2+100 \text{ km}\)) in summer, a lower altitude (~\(h_mF_2+50 \text{ km}\)) in both spring and autumn, and the lowest altitude (~\(h_mF_2+30 \text{ km}\)) in winter. The transition time at dawn is generally between 07 and 08 SLT. The transition time at dusk is later than 18 SLT in the summer and autumn but earlier than 18 SLT in the spring and winter. Furthermore, the transition time is earliest at dusk in winter by at least 1 hr. It is interesting that the transition time at dusk is around SZA = 120° in autumn, while it is close to SZA = 90° in other seasons. In addition, the mean daytime upward \(\Phi_{oE}\) below \(h_mF_2+200 \text{ km}\) in summer is about \(2.2 \times 10^8 \text{ cm}^{-2} \text{s}^{-1}\), which is relatively smaller than that in other seasons, and the largest mean of the upward \(\Phi_{oE}\) occurs in autumn \((3.7 \times 10^8 \text{ cm}^{-2} \text{s}^{-1})\). The daytime upward \(\Phi_{oE}\) generally increases with altitude, so the maximum of \(\Phi_{oE}\) always occurs above \(h_mF_2+200 \text{ km}\) in all four seasons. These maxima usually appear in the afternoon and are larger than \(6 \times 10^8 \text{ cm}^{-2} \text{s}^{-1}\).
As geomagnetic activity increases from quiet \((0 \leq Kp \leq 2)\) to moderate \((2 < Kp \leq 4)\), the transition height generally increases by \(\sim 20\) km in spring, autumn, and winter, but by \(\sim 20–50\) km in summer. Thus the transition height is still the highest in summer \((\sim h_mF_2+120\) km\) compared to other seasons \((50–100\) km above \(h_mF_2\)). The transition height does not change much with local time during the day in all four seasons. This seasonal variation is different from quiet times. In addition, the transition time at dawn in all seasons is similar to the quiet times. However, the transition time at dusk in spring, autumn, and winter is about one hour earlier for higher geomagnetic activity. The transition time at dusk in summer occurs one hour later than for quiet activity. Furthermore, the seasonal variations of the daytime upward \(\Phi_o\) changes significantly with the increase of geomagnetic activity. The largest mean upward \(\Phi_o\) below \(h_mF_2+200\) km moves from autumn to summer \((3.9 \times 10^8\) \(cm^{-2} s^{-1}\)), the lowest mean flux moves from summer to spring \((1.5 \times 10^8\) \(cm^{-2} s^{-1}\)).

**Figure 4.** \(O^+\) diffusive flux as a function of altitude above \(h_mF_2\) and local time in different seasons at solar minimum under geomagnetically quiet (top) and moderate (bottom) times. The dot-dashed and dashed lines denote 06 LT and 18 LT, respectively. The shadow areas indicate low reliability of the results. The red text above the X-axis gives the solar zenith angle corresponding to the local time.
The diffusive flux in the topside ionosphere switches its sign from downward to upward. The transition time is the solar local time (SLT) when the diffusive flux at a particular height in the topside ionosphere switches between upward and downward. The transition height is the altitude where the O\textsuperscript{+} diffusive flux in the topside ionosphere switches its sign from downward to upward. The transition time is the solar local time (SLT) when O\textsuperscript{+} diffusive flux at a particular height in the topside ionosphere switches between upward and downward.

**4. Discussion**

In this section, the physical mechanisms that cause the variations of O\textsuperscript{+} diffusive flux with geomagnetic activity are explored. To simplify the discussion, the three terms in Equation 2, \(-1/H_{\text{pet}} \times \partial N_\text{i}/\partial h\), 1/(1 + T\textsubscript{i}) × \partial (T\textsubscript{i} + T\textsubscript{a})/\partial h, and m\textsubscript{i}g/(k(1 + T\textsubscript{i} + T\textsubscript{a})) are defined as T\textsubscript{gradNi}, T\textsubscript{gradT}, and T\textsubscript{Hscale}, respectively. This definition is similar to Chen et al. (2014), but with plasma temperature normalization. T\textsubscript{gradNi} represents the effects of the density gradient term and is the reciprocal of plasma scale height (H\textsubscript{scale}) is also smaller than H\textsubscript{pet}, the gravity term and is the reciprocal of plasma scale height. 1/H\textsubscript{pet} (H\textsubscript{pet} = kT\textsubscript{pet}/m\textsubscript{i}g). The combined effects (\Delta = T\textsubscript{gradNi} - T\textsubscript{gradT} - T\textsubscript{Hscale}) of the three terms determine the magnitude and direction of the diffusive flux \Phi_{O+}.

In general, the magnitude of T\textsubscript{gradNi} is larger than T\textsubscript{gradT} and T\textsubscript{Hscale} in the F\textsubscript{2} layer during the daytime, as shown in Figure 5 where terms T\textsubscript{gradNi}, T\textsubscript{gradT}, and T\textsubscript{Hscale} are given along with N\textsubscript{i} as a function of altitude (above h\textsubscript{o}F\textsubscript{2}) and local time in different seasons for quiet times at solar minimum. It is clear that the spring and autumn N\textsubscript{i} is larger than that in summer and winter, which is consistent with the well-known semiannual variation of the climatological behavior of the ionosphere locally at Millstone Hill. There is a clear evening enhancement of N\textsubscript{i} in summer with the greatest post-sunset N\textsubscript{i} values throughout a year. This evening enhancement was noted by Evans (1965) and was consistent with the mid-latitude summer night anomaly (MSNA) (Chen et al., 2016; Liu et al., 2010; Richards et al., 2017). Furthermore, during the day, T\textsubscript{gradT} and T\textsubscript{Hscale} (mainly controlled by the plasma temperature) do not change much with season, but T\textsubscript{gradNi} has a clear seasonal variation. Moreover, T\textsubscript{gradT} is very small (<3 \times 10\textsuperscript{7}/km) compared to T\textsubscript{gradNi} and T\textsubscript{Hscale} at all local times and altitudes. Accordingly, the contribution of its variability to the variation of the diffusive velocity and flux can be ignored. In addition, T\textsubscript{Hscale} is also smaller than T\textsubscript{gradNi} during the daytime. Therefore, the variation of the diffusive velocity is primarily determined by T\textsubscript{gradNi}. In other words, the direction of \Phi_{O+} is mainly determined by the vertical gradient of O\textsuperscript{+} number density (Chen et al., 2014).

### Table 1

**Summary of the Analysis Results of O\textsuperscript{+} Diffusive Flux During Geomagnetically Quiet Times at Solar Minimum**

| Geomagnetic conditions | Season     | Transition height (km) | Transition time (SLT) | Daytime upward \(\Phi_{O+}\left(\text{cm}^2\text{s}^{-1}\right)\) |
|-----------------------|------------|------------------------|-----------------------|-------------------------------------------------|
| Quiet (0 \leq Kp \leq 2) | Spring     | 50 (50)                | 6.5–08 (07)          | 17–18 (17.5)                                     |
|                       | Summer     | 60–120 (75)            | 07–08 (7.5)          | 18–21 (20)                                       |
|                       | Autumn     | 50 (50)                | 07–08 (07)          | 18–21 (20.5)                                     |
|                       | Winter     | 30 (30)                | 08 (08)             | 15–17 (16.5)                                     |
|                       |            |                        |                      | Mean (\leq 200 km)\textsuperscript{a}          |
|                       |            |                        |                      | Maximum (its height, SLT)                       |
|                       |            |                        |                      | 2.6 \times 10\textsuperscript{8}               |
|                       |            |                        |                      | 6.6 \times 10\textsuperscript{8}               |

\(\text{Note}\): The reference height is \(h_0F_2\). The transition height is the altitude where the O\textsuperscript{+} diffusive flux in the topside ionosphere switches its sign from downward to upward. The transition time is the solar local time (SLT) when O\textsuperscript{+} diffusive flux at a particular height in the topside ionosphere switches between upward and downward.

\(\text{aThe mean is calculated by using the positive diffusive flux below } h_0F_2 + 200 \text{ km, which eliminates the influence of some outstanding values above } h_0F_2 + 200 \text{ km.}\)

### Table 2

**Same as Table 1, but for Geomagnetically Moderate Times**

| Geomagnetic conditions | Season     | Transition height (km) | Transition time (SLT) | Daytime upward \(\Phi_{O+}\left(\text{cm}^2\text{s}^{-1}\right)\) |
|-----------------------|------------|------------------------|-----------------------|-------------------------------------------------|
| Moderate (2 < Kp \leq 4) | Spring     | 50–70 (65)            | 06–08 (07)          | 16–18 (16.5)                                     |
|                       | Summer     | 110 (110)             | 07–08 (7.5)          | 18–21.5 (21)                                     |
|                       | Autumn     | 70 (70)               | 07–08 (7.5)          | 18–20.5 (19.5)                                    |
|                       | Winter     | 50 (50)               | 08 (08)             | 15–16.5 (15.5)                                    |
|                       |            |                        |                      | Mean (\leq 200 km)\textsuperscript{a}          |
|                       |            |                        |                      | Maximum (its height, SLT)                       |
|                       |            |                        |                      | 1.5 \times 10\textsuperscript{8}               |
|                       |            |                        |                      | 2.7 \times 10\textsuperscript{8}               |

\(\text{aThe mean is calculated by using the positive diffusive flux below } h_0F_2 + 200 \text{ km, which eliminates the influence of some outstanding values above } h_0F_2 + 200 \text{ km.}\)
4.1. Variations During Geomagnetically Quiet Times

As shown in Figure 5, term $T_{\text{grad}N_i}$ in summer is significantly smaller than that in other seasons during the daytime because the $F_2$ peak is broader in summer, and the magnitude of $T_{\text{grad}N_i} (<8 \times 10^{-3} / \text{km})$ is less than the sum of $T_{\text{grad}T} + T_{\text{Hscale}}$ ($\approx 3 \times 10^{-3} / \text{km}$) in most regions below $h_{mF_2} + 100 \text{ km}$. Namely, the direction of the diffusive flux is mainly downward ($\Delta < 0$) below $h_{mF_2} + 100 \text{ km}$ in summer, but upward ($\Delta > 0$) in other seasons. As a result, the transition height in summer is higher than that in other seasons. $T_{\text{grad}N_i}$ at dusk (around 18 SLT) in winter is smaller than that in other seasons, which causes an earlier transition time of $\Phi_{O_\alpha}$, from upward to downward. In other words, the transition time at dusk in winter is earlier than in other seasons.

Now we further explore the contribution of $T_{\text{grad}N_i}$ to the seasonal variation of the diffusive flux at quiet times at two altitudes of 100 and 200 km above the $F_2$ peak. Figure 6 shows the local time variations of $\Phi_{O_\alpha}$, $V_{d}$, $N_{e}$, and $T_{\text{grad}N_i}$ in different seasons under geomagnetically quiet conditions at $h_{mF_2} + 100 \text{ km}$ (top panels, a–d), and $h_{mF_2} + 200 \text{ km}$ (bottom panels, e–h). The local time variation of $V_d$ is controlled by $T_{\text{grad}N_i}$, $T_{\text{grad}T}$, and $T_{\text{Hscale}}$, which can be understood from Equation 2. Daytime $N_e$ in winter (solid line) is the smallest compared to those in other seasons at $h_{mF_2} + 100 \text{ km}$, but the daytime upward $\Phi_{O_\alpha}$ is not the smallest because $V_d$ in winter is larger than those in the other seasons due to the fact that $T_{\text{grad}N_i}$ has the largest values during the daytime in winter. On the other hand, $N_e$ in summer (dotted line) is greater than $N_e$ at winter at $h_{mF_2} + 100 \text{ km}$, but $V_d$ in summer is the lowest as $T_{\text{grad}N_i}$ is the smallest during the daytime, resulting in the lowest $\Phi_{O_\alpha}$ in summer compared to other seasons. The situation at $h_{mF_2} + 200 \text{ km}$ is similar to that at $h_{mF_2} + 100 \text{ km}$. Therefore, the lowest $V_d$ resulting from the smallest $T_{\text{grad}N_i}$ leads to the daytime upward $\Phi_{O_\alpha}$ in summer being generally smaller than those in other seasons. On the other hand, it is evident that the $N_e$ in the equinoxes (dot-dashed and dashed lines) is generally larger than that in winter (solid lines) during the daytime at both $h_{mF_2} + 100$ and $h_{mF_2} + 200 \text{ km}$. However, the daytime upward $\Phi_{O_\alpha}$ in the equinoxes is not necessarily greater than that in winter at some local times, especially at low altitudes. These indicate that the magnitude of $V_d$ plays a very important role in modulating the seasonal variation of $\Phi_{O_\alpha}$, but $V_d$ is dominated by $T_{\text{grad}N_i}$.

As mentioned in Section 3, the daytime upward diffusive flux usually increases with altitude. This is because the diffusive velocity increases much faster than the plasma density decrease, which can be clearly seen in Figure 7. As the altitude increases from $h_{mF_2} + 100$ to $h_{mF_2} + 250 \text{ km}$ at 14 SLT in spring under...
geomagnetically quiet conditions at solar minimum, the electron number density (black line) reduces by a factor of \(3\times10^{10}\ cm^{-3}\) to \(3\times10^{8}\ cm^{-3}\). However, the diffusive velocity (red line) increases by a factor of \(12\) from \(12\ m/s\) to \(140\ m/s\). This also illustrates the importance of diffusive velocity to the variation of diffusive flux.

4.2. The Geomagnetic Activity Effects

Terms \(T_{\text{grad}N_e}\) and \(T_{\text{Hscale}}\) change very little as the geomagnetic condition changes from quiet to moderate (not shown). Figure 8 demonstrates the physical mechanisms of \(O^+\) diffusive flux variations during geomagnetically moderate time. Like the quiet times, \(N_e\) in spring and autumn is generally greater than that in summer and winter, especially near the \(F_2\) peak (Zhang et al., 2005). However, the enhancement of \(N_e\) in summer near sunset is stronger than at quiet times. This is consistent with the expected behavior of the
ionosphere at dusk for any season of the year during the main phase of a geomagnetic disturbance (Buonsanto, 1999). The relative contributions of different terms to the variations of $\Delta \Phi_{OE}$ in the moderate times are similar to those during quiet times. The values of $\Delta$ in summer below $h_m F_2 + 120$ km are in general negative due to the relatively smaller $T_{\text{grad} N_i}$ results from a larger plasma density scale height, which directly leads to a downward diffusive velocity at and below that height as well as the higher transition height (purple lines in the middle column in Figure 8) in summer than in other seasons. In addition, the value of $\Delta$ around 18 SLT in summer and autumn is larger than zero, but it is less than zero in spring and winter, resulting in a later transition time in summer and autumn compared to spring and winter during geomagnetically moderate time.

Figure 7. The altitude variations of electron number density (black line) and diffusive velocity (red line) between 100 and 250 km above $h_m F_2$ at 14 LT in spring under geomagnetically quiet conditions at solar minimum.

Figure 8. (from left to right) Electron number density in log10, diffusive velocity, and $T_{\text{grad} N_i} - T_{\text{grad} T} - T_{\text{Hscale}}$ as a function of altitude above $h_m F_2$ and local time in spring (top row), summer (second row), autumn (third row), and winter (bottom row) at solar minimum and geomagnetically moderate time.
To evaluate the geomagnetic activity impact, we calculated the relative differences of geomagnetic activity-induced variations with respect to quiet time, \( \frac{f_{\text{ff}}(\text{moderate}) - f_{\text{ff}}(\text{quiet})}{f_{\text{ff}}(\text{quiet})} \), where \( f \) represents the value of a relevant variable under a given geomagnetic condition. Figure 9 shows the geomagnetic activity-induced variations in \( \Phi_{\text{OE}} \), \( \Phi_{\text{E}} \), \( e_{\text{EN}} \), and \( T_{\text{grad}N_i} \) as a function of altitude above \( h_{\text{mF}2} \) and local time. As shown in Figure 9d, as geomagnetic activity increases, \( T_{\text{grad}N_i} \) in all four seasons generally decreases below \( h_{\text{mF}2} + 150 \) km during the daytime, which causes the value of \( \Delta \) positive at higher altitudes. As a result, the directional change of \( \Phi_{\text{OE}} \) from downward to upward occurs at a higher altitude. Furthermore, the decrease of \( T_{\text{grad}N_i} \) is greater in the morning of summer and autumn, which produces a higher transition height. Note that \( T_{\text{grad}N_i} \) has a significant decrease above \( h_{\text{mF}2} + 200 \) km in the afternoon in autumn, which causes an abnormal downward diffusive flux, as shown in Figure 4.

In addition, the transition time near dusk in spring and autumn becomes earlier due to the decrease of \( T_{\text{grad}N_i} \) as the geomagnetic activity increases. Although \( T_{\text{grad}N_i} \) in winter after 18 SLT increases by \( \sim 5\% \), it is too small to reverse the direction of \( \Phi_{\text{OE}} \). Instead, the transition time at dusk in winter has also been advanced due to the reduction of \( T_{\text{grad}N_i} \) before 18 SLT. Moreover, \( T_{\text{grad}N_i} \) above \( h_{\text{mF}2} + 150 \) km in summer increases by \( \sim 15\% \) during 18–22 SLT, which results in \( \sim 1 \) hr delay in transition time. The transition time at dusk has remarkable importance for improving the upper boundary conditions of some theoretical models, such as the TIEGCM, because after this time the ion flux flows from the plasmasphere to the ionosphere.

Figure 9a shows that the daytime upward \( \Phi_{\text{OE}} (= V_{\text{J}} N_{\text{e}}) \) in spring decreases by \( \sim 30\% \) although \( N_{\text{e}} \) increases by \( \sim 10\% \) during the daytime as geomagnetic activity increases from quiet to moderate. This is because \( N_{\text{e}} \) increases are usually greater at high altitudes than at low altitudes during the daytime (Figure 9c). This directly leads to a decrease of \( T_{\text{grad}N_i} \) which further results in a significant reduction of \( V_{\text{J}} \) by approximately 40% (decreases from \( \sim 50 \) m/s to \( \sim 30 \) m/s). Therefore, the decrease of \( V_{\text{J}} \) is much greater than the increase of \( N_{\text{e}} \), which results in a significant decrease of \( \Phi_{\text{OE}} \) in spring. Similarly, the daytime upward \( \Phi_{\text{OE}} \) in autumn and winter also generally decreases. However, \( \Phi_{\text{OE}} \) in summer generally increases with the increase
of geomagnetic activity, especially near dusk. This is because the increment of \(N_e\) in summer occurs with a maximum at \(h_m F_2 + 120 \text{ km}\) at dusk, which directly creates an increase of \(T_{grad N_e}\) above \(h_m F_2 + 120 \text{ km}\) and further enhances \(V_d\). Therefore, the simultaneous increases of \(N_e\) and \(V_d\) produce the largest \(\Phi_O\), in summer compared to other seasons.

Therefore, geomagnetic activity alters the vertical structure of the plasma density profile, and thus directly controls the variations in the transition height and time. Furthermore, the changes in plasma density vertical structure can also influence the altitudinal and local time variations of the \(O^+\) diffusive velocity in the topside ionosphere. Eventually, the competition between the plasma density and the diffusive velocity at Millstone Hill dominates the changes of the seasonal variations of the \(O^+\) diffusive flux with geomagnetic activity.

There are some common features can be found through comparing our statistical results at solar minimum with the storm case analysis at solar maximum of Chen et al. (2014). During the autumn day, the increase of geomagnetic conditions decreases the magnitude of \(\Phi_O\), increases the transition height, and slightly advances the transition time at dusk. In addition, the change in the shape of the plasma density profile mainly determines the diffusive flux changes as the increase of geomagnetic conditions, and plasma temperature gradient is less important. These seem to indicate that the geomagnetic activity response of the diffusive flux is not dependent on solar activity. Furthermore, it is reasonable that the magnitude of \(\Phi_O\), in our results is one order smaller than that of Chen et al. (2014), because they have a larger plasma density at solar maximum.

Finally yet importantly, the calculated diffusive velocity is sensitive to plasma temperature and its height gradient, increasing significantly as a function of height. In winter, 1\% plasma temperature increase yields \(\sim 6 \text{ m/s}\) change in diffusive velocity at \(h_m F_2 + 50 \text{ km}\), and \(\sim 130 \text{ m/s}\) change at \(h_m F_2 + 200 \text{ km}\) at 12 SLT during geomagnetically quiet times at solar minimum. Figure S2 shows two temperature sensitivity tests on the diffusive flux. In addition, we also evaluated the effect of ionospheric long-term trends on the diffusive flux, see Figure S3.

5. Conclusions

In this study, a statistical analysis of mid-latitude topside ionosphere \(O^+\) diffusive flux \(\Phi_O\), has been performed based on the Millstone Hill ISR observations of \(N_e\), \(I_n\), and \(I_F\) at solar minimum. The changes of \(\Phi_O\) with elevated geomagnetic activity were also studied. In addition, the physical processes associated with plasma density and temperature gradients in height and plasma scale height that control the transition height and time, and the seasonal variations of \(\Phi_O\), were analyzed in detail. The main conclusions are as follows:

1. During both quiet and moderate times, the gravity and vertical gradient of plasma temperature terms have negligible effect on the topside \(O^+\) diffusive flux during the day. The dominant factor is the vertical gradient of the \(O^+\) number density
2. During geomagnetically quiet times, the transition height is highest in summer (\(\sim h_m F_2 + 100 \text{ km}\)) because the vertical gradient of \(O^+\) density is the smallest below \(h_m F_2 + 100 \text{ km}\) due to a broader \(F_2\) peak. This small vertical density gradient causes a small upward \(V_o\) and therefore a small upward \(\Phi_O\), in summer. The largest upward \(\Phi_O\), occurs in autumn due to the combined effects of a large \(O^+\) number density and a large upward \(V_o\). The transition time (from upward on dayside to downward on nightside) near dusk is 1 hr earlier in winter than in other seasons, because the vertical gradient of the \(O^+\) number density around 18 SLT in winter is the smallest in a year
3. A moderate increase in geomagnetic activity results in an increase of the topside plasma density for all four seasons. As plasma density increases more at higher altitudes its vertical gradient decreases. This leads to an increase in the transition height in all four seasons as well as an earlier transition times except for summer. The enhancement of \(N_e\) near dusk (relative to an earlier time) in summer increases as the geomagnetic activity increases, especially in the region near \(h_m F_2 + 120 \text{ km}\). This results in an increase in the plasma vertical gradient at dusk above \(h_m F_2 + 120 \text{ km}\) and causes a later transition time
4. As geomagnetic activity increases, the contribution to the magnitude of \(\Phi_O\), from the increased plasma density does not offset that from the decrease of \(V_d\) in spring, autumn, and winter. However, the plasma
density increase in spring is ~50% of the increases in other seasons. Therefore, $\Phi_d$, in the spring day-time remains the smallest compared of all seasons. The simultaneous increase of plasma density and $V_p$ produces the largest $\Phi_d$, in summer. Overall, the increase of the geomagnetic activity changes the altitudinal, local time, and seasonal variations of $\Phi_d$, through modulating the vertical structure of the plasma density profile in the topside ionosphere.

In the follow-up work, we will use these statistical results as the upper boundary conditions for global circulation models, such as the TIEGCM, to improve the calculation of topside ionospheric plasma densities. Of particular interest is the dusk/evening enhancement of plasma density in summer at Millstone Hill and more broadly in many mid-latitude regions.

Data Availability Statement
The F10.7 and Kp data were downloaded from the National Oceanic and Atmospheric Administration (NOAA; https://www.ngdc.noaa.gov/geomag/indices/kp_ap.html). The analysis results are available at https://osf.io/rcgkg/.

Acknowledgments
The Authors acknowledge the support by the B-type Strategic Priority Program of the Chinese Academy of Sciences (Grant No. XDB41000000), the Project of Stable Support for Youth Team in Basic Research Field, CAS (YSBR-018), the Open Research Project of Large Research Infrastructures of CAS—Study on the interaction between low/mid-latitude atmosphere and ionosphere based on the Chinese Meridian Project,” and the National Natural Science Foundation of China (41427901). Long-term ISR observations at Millstone Hill have been supported by the US NSF through cooperative agreements with MIT over decades, and the data are distributed through the Madrigal database (http://openmadrigal.org). Work at MIT is funded through NSF grant AGS-952737, US AFSOR MURI award FA9559-16-1-0364, and US ONR Grant N00014-17-1-2186. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

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