The Contribution of N⁺ Ions to Earth’s Polar Wind

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Abstract The escape of heavy ions from the Earth atmosphere is a consequence of energization and transport mechanisms, including photoionization, electron precipitation, ion-electron-neutral chemistry, and collisions. Numerous studies considered the outflow of O⁺ ions only, but ignored the observational record of outflowing N⁺. In spite of 12% mass difference, N⁺ and O⁺ ions have different ionization potentials, ionospheric chemistry, and scale heights. We expanded the Polar Wind Outflow Model (PWOM) to include N⁺ and key molecular ions in the polar wind. We refer to this model expansion as the Seven Ion Polar Wind Outflow Model (7iPWOM), which involves expanded schemes for suprathermal electron production and ion-electron-neutral chemistry and collisions. Numerical experiments, designed to probe the influence of season, as well as that of solar conditions, suggest that N⁺ is a significant ion species in the polar ionosphere and its presence largely improves the polar wind solution, as compared to observations.

Plain Language Summary Nitrogen is the most abundant element in the Earth’s atmosphere. Around 78% N₂ and 21% O₂ form the air we breathe and expand into high-altitude atmosphere, the thermosphere, and eventually the ionosphere. The neutral molecules in the ionosphere are ionized by solar radiation, and some of them break up into atoms, and others become charged particles. The ionospheric ions with sufficient energy can flow out into space, and the abundances of these outflowing ionospheric ions highly impact the near-Earth plasma properties. Studies focused on outflowing O⁺ ions have been conducted for several years. However, the contribution of N⁺ ions to the outflow solution is still largely unknown due to the instrumental limitations. This letter addresses the transport and energization of ionospheric N⁺ ions based on theoretical predictions, and examines the role of N⁺ ions to the collision and chemistry in the topside ionosphere. This study shows that N⁺ ions are important components in the high-altitude polar ionosphere and their abundances can be affected by the sunlight and seasonal variations.

1. Introduction

While the magnetospheric H⁺ ions are sourced both in the solar wind and the ionosphere, the low charge state heavier ions, such as N⁺ and O⁺, can only come from the Earth’s ionosphere through the process of ionospheric escape. The polar wind, first suggested by Axford (1968), represents an ambipolar outflow of thermal plasma from the high-latitude ionosphere to the low pressure magnetosphere. As it flows out, the polar wind undergoes several processes, from chemical to diffusion dominance, from subsonic to supersonic flow, and from collision dominated to collisionless, and the composition is changing from heavy to light ion dominance (Ganguli, 1996). The acceleration of ionospheric H⁺ has been well explained by the “classical polar wind theory” (Banks, 1969; Banks & Holzer, 1968), where the ambipolar electric field continuously accelerates the ions and electrons upward, providing sufficient acceleration to allow them to overcome gravity. However, this theory does not include the necessary acceleration mechanisms, such as centrifugal acceleration (Delcourt et al., 1993), required to explain the acceleration of heavy ions and their subsequent escape from the ionosphere.

Since the discovery of O⁺ ions in the magnetosphere (Shelley et al., 1972), the impact and contribution of O⁺ ions in the Earth’s magnetosphere-ionosphere system has been the subject of numerous studies (e.g., Glocer et al., 2009; Ilie et al., 2013, 2015; Kronberg et al., 2014; Schunk & Raitt, 1980; Schunk & Sojka, 1997). Heavy ions, which most studies considered to be O⁺ only, control the mass and energy flow in the Earth’s magnetosphere (Daglis et al., 1999; Hamilton et al., 1988; Wingler et al., 2002). The presence of the heavy ions in the Earth’s magnetosphere can alter the wave propagation (Bashir & Ilie, 2018; Keika et al., 2011; Summers & Thorne, 2003; Summers et al., 2007), the mass loading of the magnetospheric plasma (Garcia et al., 2010; Nosé et al., 2005; Wingler et al., 2002; Wiltberger et al., 2010), the ring current formation and decay.
It is well established that O+ is dominant ion up to 4,000 km altitude, and manifest different behaviors (Ilie & Liemohn, 2016). While the density of N+ ions is determined from chemical equilibrium because they are considered a minor ion species and, therefore, their dynamics are less important (Varney et al., 2014). In spite of only 12% mass difference between N+ (m = 14) and O+ (m = 16), as well as the same electric charge, N+ and O+ have different properties and manifest different behaviors (Ilie & Liemohn, 2016).

It is well established that O+ is dominant ion up to 4,000–7,000 km (Yau et al., 2007, 2012). Albeit limited, several early NASA space missions reported on the presence and the importance of N+ ions, in addition to that of O+, in the terrestrial ionosphere. During undisturbed time, Polar Orbiting Geophysical Observatory (OGO2) and Explorer 31 observed significant amounts of N+ ions in the ionosphere between 500 and 1,400 km above 60° latitude, and the number density of N+ ions is generally 5% to 30% of O+ ions (Brinton et al., 1968, 1971; Hoffman, 1967). Moreover, Ion Mass Spectrometer (IMS) on board NASA International Satellite for Ionospheric Studies (ISIS-2) (Hoffman, 1970) indicated that abundances of N+ ions consistently varied together with those of O+ ions at roughly 1 order of magnitude lower (Hoffman et al., 1974). In addition, N+ seems to be a constant companion of outflowing O+ during the storm time (Chappell et al., 1981), and its concentration varied with geomagnetic conditions (Craven et al., 1995). The abundance of N+ ions in the ionosphere was reported to increase dramatically during the geomagnetic storm time (Hoffman et al., 1974). Ion flux measurements from the suprathermal mass spectrometer (SMS) on board the Akebono satellite (Whalen et al., 1990; Yau & Whalen, 1992) also showed that the ratio of N+ / O+ ~ 1 in the dayside high-altitude (>1,000 km) polar (>70°) ionosphere during the main phase of a large storm.

Although several other observations have shown the importance of ionospheric N+ ions in the ionosphere and magnetosphere, the mechanisms responsible for accelerating the ionospheric N+ ions from eV to keV energies, as well as the relative abundance of N+ ions in the high-altitude ionosphere, are still largely unknown. In the topside ionosphere, three possible mechanisms are known to produce and energize N+ ions in the polar wind: photoionization, Suprathermal Electron (SE) impact, ion-neutral-electron collisions, and chemistry. The presence of SE can increase the electric potential drop and alter the ambipolar electric field (Glocer et al., 2012, 2017; Khazanov et al., 1997). Moreover, the reflected photoelectrons are considered to be a significant source of heat for the topside polar ionosphere (Varney et al., 2014). Ion-neutral-electron collision and chemistry also play a fundamental role in the dynamics and energetics of the polar wind (Schunk & Nagy, 2009). Ion-neutral-electron chemistry acts as a source of ions in the polar wind, while collisions are the main energy and momentum source for heavy ions upflow, as they can acquire sufficient energy from various collision mechanisms, including Coulomb collisions (ion-ion), nonresonant ion-neutral interactions, resonant charge exchange, and electron-neutral interactions (Yau et al., 1993). This letter presents the first study that addresses the role of N+ ions in the overall polar wind outflow solution, based on a first principle numerical model, which is the Seven Ion Polar Wind Outflow Model (7iPWOM), developed from the Polar Wind Outflow Model (PWOM) (Glocer et al., 2009, 2012, 2017, 2018).

2. Seven Ion Polar Wind Outflow Model

To assess the role of N+ ions to the overall outflow solution, the PWOM of Glocer et al. (2018) has been further developed to include N+ ions in the ionospheric plasma. The PWOM solves for the supersonic ionospheric outflow solution, along high-latitude magnetic field lines, ranging from 250 km to a few Earth radii, and 65° latitude or above. The gyroscopic transport equations, including continuity, momentum, and energy equations, as well as the ambipolar electric field, derived from generalized Ohm’s equation, are solved for electrons and three ion species, namely, H+, He+, and O+. The number density of the neutral species, including O, H, O2, N2, and He, are derived from NRLMSISE-00 empirical model (Picone et al., 2002). The equation set (Gombosi & Nagy, 1989) is shown in the Equations 1–4:
The subscripts \( i \) and \( e \) refer to the ion and electron species, respectively. The parameter \( r \) represents the distance from the footpoint of the magnetic field line; \( m \) is the particle mass; \( \rho \) represents the mass density; \( A \) is the cross-sectional area of a magnetic flux tube, which varies inversely with the magnetic field strength; \( A' \) is the gradient of \( A \); \( \gamma \) represents the specific heat ratio; \( \kappa \) denotes the heat conductivity; \( k \) is Boltzmann's constant; and \( g \) is the local gravitational acceleration. The following three terms will be further discussed: \( S \), represents the production or loss rates of a particular species; \( \frac{\delta M}{\delta t} \) is the momentum exchange rate, and \( \frac{\delta E}{\delta t} \) represents the energy exchange rate. Note that Equation 4 in Gombosi and Nagy (1989) was incorrect and the correct version is presented here. Since the PWOM assumes that the plasma is quasi-neutral, electrons are solved from the charge neutrality condition, and a steady state of electron velocity and energy assumption with the limitation of current conservation, as shown in the Equations 5–8:

\[
\begin{align*}
\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial r} (\rho u_i^2) &= A S_i, \\
\frac{\partial}{\partial t} (\rho u_e) + \frac{\partial}{\partial r} (\rho u_e^2) &= \frac{\partial}{\partial r} (\rho E_t) - \rho u_e \frac{\partial T_e}{\partial r} + \frac{\partial}{\partial r} (\rho E_i) - \rho u_i \frac{\partial T_i}{\partial r} \tag{1}
\end{align*}
\]

\[
\begin{align*}
\frac{\partial}{\partial t} (\rho u_i^2) &= \frac{\partial}{\partial r} (\rho u_i^2) + \frac{1}{\gamma_i - 1} \frac{\partial}{\partial r} (\rho p_i) = \frac{\partial}{\partial r} (\rho u_i^2) + \frac{1}{\gamma_i - 1} \frac{\partial}{\partial r} (\rho p_i) = \rho u_i \left( \frac{\partial E_t}{\partial r} - \rho u_e \frac{\partial T_e}{\partial r} \right) + \frac{\partial}{\partial r} (\rho E_i) - \rho u_i \frac{\partial T_i}{\partial r} \tag{2}
\end{align*}
\]

\[
\begin{align*}
E_i &= -\frac{1}{en_e} \left[ \frac{\partial}{\partial r} \left( \rho E_t + \rho u_e u_i^2 \right) - \frac{A'}{A} \rho u_e u_i^2 \right] + \frac{1}{en_e} \left( \sum_i \frac{m_e}{m_i} [(u_e - u_i) S_i - \frac{\delta M_{ei}}{\delta t} + \frac{\delta M_{ei}}{\delta t}] \right). \tag{3}
\end{align*}
\]

Note that \( j \) represents the electric current density and the subscript 0 denotes the value for certain reference altitude, at which we assume that the cross-sectional area \( A \) is 1 cm\(^2\) and corresponds to the lower boundary of the magnetic flux tube.

For the rest of the letter, we will refer to the PWOM of Glocer et al. (2018) as the three ion PWOM (3iPWOM), since it only solved for three ion species. The inclusion of N\(^+\) as an additional ion species required the expansion of the PWOM from three to seven ions. The 7iPWOM, developed from the 3iPWOM, solves the same transport equations for electron and accounts for the contributions of seven ions, H\(^+\), He\(^+\), N\(^+\), O\(^+\), N\(_2\)^+, NO\(^+\), and O\(_2\)^+. The inclusion of the molecular ion species, such as N\(_2\)^+, NO\(^+\), and O\(_2\)^+, is required in the 7iPWOM due to their significant abundances in the topside ionosphere, as well as their importance in the ionospheric photochemistry (Richards & Voglozin, 2011; Solomon, 2010). At this stage, the model does not track the field aligned transport of molecular ion species, and they are assumed to be stationary and having the same fixed temperature as the neutral species; however, the molecular ion densities are determined via chemical equilibrium. This assumption is established only in the quiet time when the molecular ion outflow is negligible, as there is no sufficient energization (Craven et al., 1985; Peterson et al., 1994; Yau et al., 1993). The neutrals number density are also obtained from NRLMSISE-00
depends on the chemical source. In order to describe possible mechanisms that produce and energize N+ species, meaning that there is no upward collision, as well as suprathermal electron production. In the following sections, we present a detailed description of the 7iPWOM, and the impact of these changes on the 3iPWOM.

### Table 1

**Updated Chemical Scheme in the 7iPWOM**

| Chemistry process                                      | Reaction rate (cm$^3$ s$^{-1}$) | Reference       |
|--------------------------------------------------------|---------------------------------|-----------------|
| O + hv$\rightarrow$ O$^+$ + e$^-$                     | see text                        |                 |
| O$^+$ + O$\rightarrow$ O$^+$ + O + e$^-$               | see text                        |                 |
| He + hv$\rightarrow$ He$^+$ + e$^-$                   | see text                        |                 |
| H + hv$\rightarrow$ H$^+$ + e$^-$                      | see text                        |                 |
| O + e$^-$ $\rightarrow$ O$^+$ + 2e$^-$                | see text                        |                 |
| O$^+$ + e$^-$ $\rightarrow$ O$^+$ + O + 2e$^-$        | see text                        |                 |
| He + e$^-$ $\rightarrow$ He$^+$ + 2e$^-$              | see text                        |                 |
| H + e$^-$ $\rightarrow$ H$^+$ + 2e$^-$                | see text                        |                 |
| O$^+$ + N$\rightarrow$ N + NO$^+$                      | 1.2 $\times$ 10$^{-12}$         | Schunk and Nagy (2009) |
| O$^+$ + O$\rightarrow$ O$_2$ + O                       | 2.1 $\times$ 10$^{-11}$         | Schunk and Nagy (2009) |
| He$^+$ + O$\rightarrow$ O$^+$ + O + He                | 9.7 $\times$ 10$^{-10}$         | Schunk and Nagy (2009) |
| He$^+$ + N$\rightarrow$ N$_2$ + He                    | 5.2 $\times$ 10$^{-10}$         | Schunk and Nagy (2009) |
| He$^+$ + N$_2$ $\rightarrow$ N$_2$ + N + He           | 7.8 $\times$ 10$^{-10}$         | Schunk and Nagy (2009) |
| H$^+$ + O $\rightarrow$ H + O$^+$                      | 2.2 $\times$ 10$^{-11}$ $\times$ T$^{0.5}$ | Schunk and Nagy (2009) |
| N + hv$\rightarrow$ N$^+$ + e$^-$                     | see text                        |                 |
| N$^+$ + O$\rightarrow$ O$^+$ + N + e$^-$              | see text                        |                 |
| O$_2$ + hv$\rightarrow$ O$_2$ + e$^-$                 | see text                        |                 |
| NO + hv$\rightarrow$ NO$^+$ + O + e$^-$               | see text                        |                 |
| NO + hv$\rightarrow$ NO$^+$ + e$^-$                   | see text                        |                 |
| N$_2$ + e$^-$ $\rightarrow$ N$_2$ + 2e$^-$            | see text                        |                 |
| O$^+$ + e$^-$ $\rightarrow$ O$_2$ + 2e$^-$            | see text                        |                 |
| N$_2$ + e$^-$ $\rightarrow$ 2N$^+$ + 3e$^-$           | see text                        |                 |
| N$_2$ + e$^-$ $\rightarrow$ N$^+$ + N + 2e$^-$        | see text                        |                 |
| N$^+$ + O$_2$ $\rightarrow$ NO$^+$ + O                | 3.07 $\times$ 10$^{-10}$        | Schunk and Nagy (2009) |
| N$^+$ + O$_2$ $\rightarrow$ O$_2$ + N + N             | 2.32 $\times$ 10$^{-10}$        | Schunk and Nagy (2009) |
| N$^+$ + O$_2$ $\rightarrow$ O$^+$ + NO                | 4.6 $\times$ 10$^{-11}$         | Schunk and Nagy (2009) |
| N$^+$ + NO $\rightarrow$ NO$^+$ + N                    | 2 $\times$ 10$^{-11}$           | Lindinger et al. (1974) |
| N$^+$ + O $\rightarrow$ N + O$^+$                      | 2.2 $\times$ 10$^{-12}$         | Richards and Voglozin (2011) |
| N$^+$ + H $\rightarrow$ N + H$^+$                      | 3.6 $\times$ 10$^{-12}$         | Harada et al. (2010) |
| N$_2$ + N $\rightarrow$ N$^+$ + N$_2$                 | 10$^{-11}$                      | Richards and Voglozin (2011) |
| N$_2$ + NO $\rightarrow$ NO$^+$ + N$_2$               | 4.1 $\times$ 10$^{-10}$         | Schunk and Nagy (2009) |
| N$_2$ + O $\rightarrow$ NO$^+$ + N                    | 1.3 $\times$ 10$^{-10}$         | Schunk and Nagy (2009) |
| N$_2$ + O$^+$ $\rightarrow$ O$^+$ + N$_2$             | 1.0 $\times$ 10$^{-11}$         | Schunk and Nagy (2009) |
| N$_2$ + O$_2$ $\rightarrow$ O$_2$ + N$_2$             | 5.0 $\times$ 10$^{-11}$         | Schunk and Nagy (2009) |
| O$^+$ + NO $\rightarrow$ NO$^+$ + O                    | 8.0 $\times$ 10$^{-13}$         | Schunk and Nagy (2009) |
| N$^+$ + e$^-$ $\rightarrow$ N                           | 3.6 $\times$ 10$^{-12}$ $\times$ ($\frac{M_{H}T_{e}}{M_eT_{e}}$)$^{0.7}$ | Schunk and Nagy (2009) |
| N$_2$ + e$^-$ $\rightarrow$ N + N                      | 2.2 $\times$ 10$^{-7}$ $\times$ ($\frac{M_{H}T_{e}}{M_eT_{e}}$)$^{0.39}$ | Schunk and Nagy (2009) |
| NO$^+$ + e$^-$ $\rightarrow$ N + O                      | 4.0 $\times$ 10$^{-7}$ $\times$ ($\frac{M_{H}T_{e}}{M_eT_{e}}$)$^{0.5}$ | Schunk and Nagy (2009) |
| O$_2$ + e$^-$ $\rightarrow$ O + O                       | 2.4 $\times$ 10$^{-7}$ $\times$ ($\frac{M_{H}T_{e}}{M_eT_{e}}$)$^{0.7}$ | Schunk and Nagy (2009) |

Note. The complete chemical scheme adopted in the 7iPWOM (blue and black) versus in 3iPWOM (black only). Note that e$^+$ represents the suprathermal electrons.

empirical model. However, the 7iPWOM includes two additional neutral species, NO and N. While the neutral N density is available from NRLMSISE-00 model, the neutral NO density is not, so it is approximated based on the chemical equilibrium value in the upper thermosphere (Bailey et al., 2002; Siskind et al., 2004). This is a reasonable assumption since the polar wind neutrals are considered as static species, meaning that there is no upward flux above 200 km. Therefore, the density of neutral NO only depends on the chemical source. In order to describe possible mechanisms that produce and energize N$^+$ ions in the polar wind, the 7iPWOM developed expanded schemes, including ionospheric chemistry and collision, as well as suprathermal electron production. In the following sections, we present a detailed description of the 7iPWOM, and the impact of these changes on the 3iPWOM.
2.1. Updated Chemical Scheme

In 7iPWOM, the production and loss of all ionospheric ion species contribute to the source term $S_i$ in the Equations 1–3, implying that the change of the chemical scheme significantly impacts the outflow solution. The expanded chemical scheme includes 20 chemical reactions in 7iPWOM and is presented in Table 1. The SE production rate of outflowing ions are described in the following section. Other than the production of $N^+$ ions from the SE production, $N^+$ ions can be produced via dissociative charge transfer between $He^+$ and $N_2$ and between $N_2^+$ and $N$. Conversely, $N^+$ ions can be lost through charge exchange with neutral atmosphere, such as with $H$, $O_2$, NO, and O, and the recombination with thermal electrons. The 7iPWOM expanded chemical scheme provides not only how $N^+$ and molecular ions are produced and lost, but also the additional ion production and loss sources for $O^+$ and $H^+$. For instance, $O^+$ ions can be produced via charge exchange between $N^+$ with neutral $O_2$ and O, and between $N_2^+$ and O, while $O^+$ ions are lost via charge exchange between $O^+$ and neutral NO.

2.2. Updated Collision Scheme

Collision processes are responsible for the change in momentum and energy (via the $\Delta M/\Delta t$ and $\Delta E/\Delta t$ terms in Equations 2 and 3). The momentum and energy exchange due to collision processes are approximated using the momentum transfer collision frequencies as the Chapman-Cowling collision integrals (Schunk & Nagy, 2009). That is, any velocity and temperature difference of between ion, neutral, or electron can cause the change of the momentum and energy transport equations. The 7iPWOM includes all the relevant collision parameters between ion-neutral-electron collisions, including Coulomb collisions, and resonant and nonresonant ion-neutral interactions. Therefore, since the 7iPWOM accounts for four additional ion species, namely, $N^+$, $N_2^+$, NO+, and $O_2^+$, and two additional neutral species, NO and N, the contributions of collisions to the momentum and energy transport equations from all ions and neutrals in the 7iPWOM are expected to change.

2.3. Suprathermal Electron Production Rate

The SE production rates in the 7iPWOM are calculated based on the GLObal airglow (GLOW) model (Solomon et al., 1988) solution, a two-stream electron transport model, which provides the photoelectron and secondary electron fluxes at various energies. The details of the suprathermal electron transport equation, and coupling with 3iPWOM are presented in Glocer et al. (2018). The 3iPWOM assumes that the SE impacts mostly the production of $O^+$. However, with the cross-sectional area of the neutral-electron collision provided (Gronoff, Simon Wedlund, Mertens, & Lillis, 2012; Gronoff, Simon Wedlund, Mertens, Barthlemy, et al., 2012), and the density of the relevant neutral species from NRLMSISE-00 model, the 7iPWOM has the capability to derive the production rate of each ion species. This expanded scheme can also quantify the SE production on the heavy ions, under different geomagnetic activity conditions.

3. Data

The observational data set used here comes from the Atmosphere Explorer (AE-C) and OGO-6 satellites, which covered from $\sim$120–1,200 km altitude. The ion mass spectrometers on board the OGO-6 and AE-C were nearly identical (Hoegy et al., 1991), and all ion densities were either measured by a Bennet radio frequency ion mass spectrometer (Brinton et al., 1973; Taylor 1973) or a magnetic ion mass spectrometer (Hoffman et al., 1973). The AE-C, launched in December 1973, aimed to study the structure of thermosphere, especially how the photochemical processes govern the region (Richards & Voglozin, 2011). During the first year of operation, the latitude of perigee moved from about $68^\circ$ north down to about $60^\circ$ south, and the orbit became circular at $\sim$390 km altitude. The OGO-6 was launched in June 1969 as one of the large observatory to study the interrelation of high-altitude atmospheric parameters during increased solar activity (Jackson & Vette, 1975). Although inclination of OGO-6 orbit was $82^\circ$ north, the tilt of the dipole axis results in a wide range of latitude coverage (Taylor 1971).

The ion density data used in this letter are retrieved from Craven et al. (1995) and have been digitized to use. Each AE data point was averaged over 40 km altitude, all activity levels, and over 6 hr local time centered on noon or midnight. The data were divided into two ranges based on the invariant latitudes, as $60^\circ$–$70^\circ$ and $70^\circ$–$90^\circ$, and averaged. The OGO-6 data was organized similarly as AE-C, and included all events for
which the F10.7 flux was larger than $120 \times 10^{-22}$ WHz/m$^2$ during the peak solar activity of cycle 20, which was representative of solar maximum. The F10.7 index during the AE-C mission was generally $\sim 70$ to $100 \times 10^{-22}$ WHz/m$^2$, and these data provide ion densities during solar minimum (Craven et al., 1995; Grebowski et al., 1993).

4. Results

This letter presents an analysis of the relative contribution of the nitrogen ions to the overall outflow solutions based on eight different sets of numerical experiments, designed to probe the influence of season, as well as that of solar conditions. The 7iPWOM model results are validated using the data sets described in section 3.

4.1. Simulation Configuration

Figure 1 shows the simulation results from eight different sets of numerical experiments, designed to take advantage of data availability. All of the simulations use a time step of $10^{-3}$ s, with a field-aligned grid spacing of 20 km. The lower boundary of the 7iPWOM is at 200 km altitude, where the number density of ions is determined based on the chemical equilibrium assumption. The upper boundary is set around 8,000 km altitude and assumes to be a low-pressure region where the ion pressure decays with the ion scale height.

The 7iPWOM performance is validated using the data from OGO-6 satellites and AE-C satellite. The latitude locations for the footpoint of the field lines used for these eight simulations were selected to allow assessment of the effect of the solar zenith angle. To test the influence of solar conditions, we have run simulations for both solar maximum (top row) and solar minimum (bottom row) conditions. From left to right, each column presents the number density for H$^+$ (green line), He$^+$ (dark green line), O$^+$ (blue line), and N$^+$ (orange line) transported along field lines, which the footpoints are located at noon and midnight during summer conditions and noon and midnight during winter conditions. The upward transport of these ions in the Earth’s polar ionosphere (200–1,200 km) is solved for using both the 7iPWOM (solid line) and the 3iPWOM (dashed line), and comparison with the appropriate data (dotted line) from OGO-6 and AE-C for various solar flux and seasonal conditions is presented. Each simulation is initialized for 10 hours to achieve steady state. The nightside solutions are obtained via a 24 hr simulation, which allows a field line from the noon sector to
convect across the polar cap to the night sector for multiple times, with the convection velocity \( \mathbf{u} = \frac{\mathbf{E} \times \mathbf{B}}{B^2} \). Note that as mentioned in section 3, each data point from AE-C and OGO-6 was averaged over 40 km altitude and over 6 hours local time. Therefore, the results from the 7iPWOM and the 3iPWOM are chosen to be the center of invariant latitude regions for the comparison of dayside solutions, and averaged from multiple simulations of magnetic field lines in neighboring locations to compare nightside solutions. For example, summer noon is represented by the steady-state solution of a single field line located in 80° latitude and 12 MLT, which is centered in the region of 70°–90° latitudes. Summer midnight is averaged by the convection result between one around 60°–65° latitude and 65°–70° latitude for the other, with the longitude close to 0 MLT. Note that the roots of simulated field lines are all located in the Earth’s Northern Hemisphere, meaning that summer is denoted by 20 July and winter is set as 20 December.

### 4.2. The Role of \( N^+ \) in the Outflow Solution

Figure 1 shows that the 7iPWOM provides a reasonable prediction of the polar wind solutions in 200–1,200 km altitude, as compared with observations. For all geomagnetic conditions, the simulated ion number densities based on the 7iPWOM model are similar to the observed averaged OGO-6 or AE-C data. As expected, the \( O^+ \) ion is the most abundant ion species in the polar wind at these altitudes. However, the \( N^+ \) ion is the second most abundant ion for all geomagnetic conditions, confirming that \( N^+ \) ion is an important component of ionospheric outflow. Under most conditions, \( N^+ \) exceeds \( He^+ \) in concentration. Moreover, the abundance of \( N^+ \) ions consistently vary together with that of \( O^+ \) ions, being about 1 order magnitude lower for all seasons and solar conditions. All of these findings are in agreements with measurements from early missions, such as OGO-2 (Brinton et al., 1968), Explorer 31 (Hoffman, 1967, 1970), and ISIS-2 (Hoffman et al., 1974).

Figure 1 also shows that the 3iPWOM generally predicts higher number densities of \( O^+ \), and lower number density of \( He^+ \), as compared to the 7iPWOM solution. For instance, during solar maximum summer noon conditions, the number density of \( He^+ \) ions as predicted by 3iPWOM is 1 order of magnitude lower than the solution provided by the 7iPWOM, and the number density of \( O^+ \) ions predicted by the 7iPWOM is \( \sim 50\% \) of that predicted by the 3iPWOM. This, together with the demonstrated improvement in data-model comparison, shows that the inclusion of \( N^+ \) ions in the polar wind model is important to ionospheric outflow modeling. The roles of ion-neutral-electron chemistry, collision, and SE production in the overall evolution of the polar wind solution when \( N^+ \) ions are present, are examined later in this letter.

### 4.3. Variations due to Seasons and Solar Flux

The variations in the \( N^+ \) number density due to changes in the solar flux are also presented in Figure 1. The abundances of both \( N^+ \) and \( O^+ \) ions decrease as the solar activity (represented by F10.7 index as a proxy in the model) decreases, but \( H^+ \) abundances are less affected. The 7iPWOM predicts higher heavy ion number densities in the sunlit and summer conditions, compared with dark and winter conditions. One of biggest improvement the 7iPWOM brings is the capability to capture the seasonal variation of \( He^+ \) ions, which at 1,000 km altitude in the winter season is 1 order magnitude larger than the summer, a feature the 3iPWOM does not capture. This significant seasonal variation of \( He^+ \) ions is due to the “winter helium bulge,” which is an increase of helium neutral concentration at the exobase (Keating & Prior, 1968; Liu et al., 2014; Raitt et al., 1978).

During solar minimum, the 7iPWOM \( N^+ \) densities are lower compared to the AE-C data, especially above the 400 km altitude. A likely explanation is that the role of molecular ions becomes important during the solar minimum. Figure 2a1 shows the production rate of \( N^+ \) ions during the solar maximum summer noon, and the SE production is the most important reaction. This indicates that \( N^+ \) production is highly sensitive to solar activity. Therefore, the roles of the chemical reactions relevant to \( N^+ \) have been elevated during low solar flux activity, meaning that the productions of \( N^+ \) via charge transfer between \( He^+ \) and \( N_2 \) and, between \( N_2^+ \) and \( N \), become important.

#### 4.3.1. The Role of Chemistry

The chemical scheme plays a major role in determining the sources and losses of ionospheric plasma (Schunk & Nagy, 2009). Figure 2a1–a4 shows the production and loss of \( N^+ \) and \( O^+ \) ions via various chemical reactions as described in Table 1. In addition to production via SE production, heavy ions below 500 km altitude and over 6 hours local time.
can be produced by chemical reactions involving \( \text{N}^+ \), molecular ions, and neutral nitrogen-relevant species. Chemical reactions related to \( \text{N}^+ \) and molecular ions are important to produce heavy ions in the low altitude (Figure 2a1–a4), while as the altitude increases, the recombination reactions with \( e^- \) and the charge exchange of neutral \( \text{H} \) with heavy ions start to dominate, and can efficiently remove heavy ions from the polar wind. For example, the resonant charge exchange between \( \text{H}^+ \) and \( \text{O} \) is the major source for \( \text{O}^+ \) ions production (Banks & Kockarts, 1973; Yau et al., 2007). However, the charge exchange between \( \text{N}^+ \) and \( \text{O} \) can be the third important chemical reaction to produce \( \text{O}^+ \) ions and remove \( \text{N}^+ \). Figure 2a4 shows that the charge exchange between \( \text{O}^+ \) and \( \text{NO} \), and the recombination of \( e^- \) and \( \text{O}^+ \) efficiently remove \( \text{O}^+ \) at low altitudes. During solar maximum summer noon conditions, the \( \text{O}^+ \) number density in the 7iPWOM chemical equilibrium solution of is \( 4.86 \times 10^4 \) cm\(^{-3} \), only 57% of that in the 3iPWOM solution, which is originally \( 1.17 \times 10^5 \) cm\(^{-3} \). On the other hand, the number density of \( \text{N}^+ \) and molecular ions are \( 5.73 \times 10^3 \) cm\(^{-3} \) and \( 7.2 \times 10^4 \) cm\(^{-3} \). However, the total ion number density based on 7iPWOM (\( 1.21 \times 10^5 \) cm\(^{-3} \)) and 3iPWOM (\( 1.17 \times 10^5 \) cm\(^{-3} \)) are similar. The presence of \( \text{N}^+ \) in the ionospheric outflow largely redistributes the ion composition into different ion species and alters their altitude profile.

4.3.3. The Role of Suprathermal Electron

The suprathermal electrons, even in small amounts, have been considered as an important energy source for the heavy ion outflow (Glocer et al., 2018; Khazanov et al., 1997). Figure 2a1–a2 shows a comparison of ion production and loss profiles based on the 7iPWOM (black) and 3iPWOM (colored lines); (b) altitude-dependent ion temperature profiles based on the 3iPWOM (dashed) versus 7iPWOM (solid) solutions; (c) ion production rate by SE in the 3iPWOM (dashed) versus 7iPWOM (solid). Figure 2b shows the temperature profile of \( \text{H}^+, \text{He}^+, \text{O}^+, \) and \( \text{N}^+ \) ions during summer solar maximum from 3iPWOM and the 7iPWOM, respectively. In the collision-dominated region, the temperature of ions, mainly determined by the ion-neutral-electron collision, are identical for all the ion species. However, as the altitude goes up, the temperatures of \( \text{N}^+ \) and \( \text{O}^+ \) ions decrease as the velocity of \( \text{H}^+ \) increases, meaning that the temperature of \( \text{O}^+ \) and \( \text{N}^+ \) ions are tightly coupled with cold neutral species. Compared with the ion temperatures between the 3iPWOM and 7iPWOM, the 7iPWOM mostly predicted higher ion temperatures. The temperature of \( \text{O}^+ \), \( \text{He}^+ \), and \( \text{H}^+ \) ions increase due to the additional energy contribution from \( \text{N}^+ \) ions and updated neutral species. Furthermore, Figure 2b presents the temperature of \( \text{N}^+ \) ions in high altitude, which is lower than that of \( \text{O}^+ \) ions. This might be explained by the differences in the \( \text{N}^+\text{-H} \) and \( \text{O}^+\text{-H} \) collision, which are nonresonant and resonant collision, respectively. The energy transfer rate of the resonant collision is larger than that for nonresonant collisions, causing the temperature profile of \( \text{N}^+ \) to divert earlier than other ion species. Overall, the 7iPWOM solution accounts for the collisional contribution from \( \text{N}^+ \) ions and neutral species to the momentum and energy transfer, leading to different temperature profiles between the 3iPWOM and 7iPWOM.
3iPWOM. The dashed blue line represents the production of O\(^+\) ions due to SE production within the 3iPWOM, equal to the total SE production rate, and the solid blue line shows O\(^+\) ions production rate due to SE production in the 7iPWOM. The 7iPWOM can account for the SE production rate as a function of altitude for all ion species, while the 3iPWOM assumes most of the SE production is linked to the production of O\(^+\) ions only. This improvement of the 7iPWOM might be explained by this expanded scheme of SE production.

5. Summary

We have developed a seven-ion polar wind model (7iPWOM), as an extension of the 3iPWOM of Glocer et al. (2018), which solves for the transport of H\(^+\), He\(^+\), O\(^+\), N\(^+\), and e\(^-\) and includes three static minor ion species, NO\(^+\), N\(_2\)^+\) and O\(_2\)^+\). Eight sets of numerical experiments have been conducted under various seasonal and solar conditions, and the 7iPWOM numerical model has been validated using data from the OGO-6 and AE-C satellites. Numerical simulations using the 7iPWOM suggest that (1) N\(^+\) ions play an important role in the ionospheric outflow for all conditions, and the number density of N\(^+\) ions is consistently 1 order magnitude less than O\(^+\) ions at altitudes below 1,200 km; (2) the schemes of SE production, chemistry, and collision applied in the 7iPWOM improve the polar wind solution significantly, as it leads to an improved solution for He\(^+\) ions and captures their seasonal variations; (3) the ion-electron-neutral chemistry and SE production control the production and loss of N\(^+\), and the ion-electron-neutral collisions are responsible for their upward transport; and (4) N\(^+\) ions are more likely to couple with cold neutral species, than the O\(^+\) ions. This implies that the extra energy source provided by the inclusion of N\(^+\) ions, such as through wave particle interactions, could have a profound influence on the upward transport of all polar wind ion species.

The 7iPWOM provides an updated view into the transport mechanisms behind the up-flowing of the major heavy ion species. Observations from Supra-Thermal Ion Composition Spectrometer (STICS) on board the Geotail indicates significant presence of N\(^+\) and molecular ions in the magnetosphere, especially in the storm time (Christon et al., 2020); however, their transport is not quantified, nor understood, at this time. Therefore, knowledge of the differential transport and path of energization for the ionospheric heavy ions will help interpret observations and guide the development of instrumentation for future missions.

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The PWOM model has been included in the Space Weather Modeling Framework, which is available for download (at http://csem.engin.umich.edu/tools/swmf/downloads.php). Data generated for this study is available online (at https://doi.org/10.6084/m9.f.1.11).
