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Comparing Monte Carlo simulations, mean particle theory estimates, and observations of H^+ and O^+ outflows at high altitudes and latitudes.

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Abstract. We carried out a comparison study between the results of Monte Carlo simulations, estimates of mean particle theory, and available observations in different regions of earth magnetosphere (aurora, polar wind, central polar cap, and cusp) for H^+ and O^+ ions outflow at high latitudes and altitudes. We present altitude profiles for mean perpendicular energy $W_\perp$, mean parallel energy $W_\parallel$, and mean total energy W_{total}. Monte Carlo simulations are obtained by using Barghouthi model [Barghouthi, 2008], mean particle theory estimates are obtained by using Chang et al. [1986], and corresponding observations are obtained from different available publications. As a results of comparisons in different regions we have found that; 1) Monte Carlo simulations and mean particle theory give similar results in auroral regions and produce no agreement in polar wind region, this is due to the strength of wave particle interaction which dominates the effects of external forces in aurora and competes with them in polar wind region, 2) using altitude dependent diffusion coefficients produce high energies, not reasonable, at middle and high altitudes, therefor it is recommended to use velocity and altitude diffusion coefficients, 3) comparison with observations in polar wind region and auroral region gives excellent agreement in aurora and good agreement in polar wind, this is due to the implement of the appropriate velocity and altitude diffusion coefficient, 4) in the central polar cap and cusp we have obtained excellent agreement for both methods and observations, 5) due to the these comparisons we can claim that the wavelength of the electromagnetic wave existed in those regions (polar wind and aurora) is 8km and the altitude and velocity diffusion coefficients that have been used in Monte Carlo simulation and mean particle theory are appropriate to be used in different studies in these regions.

1 Introduction

Many studies (analytical, modelling, and observations) are developed to investigate the behaviour of ion outflow (e.g. O^+ and H^+) from polar regions of the planet Earth to outer space, and to find its characteristics such as velocity distribution, temperature, density, drift velocity and heat flux. Research and development processes are still going on to gather as much information as possible about the flow of these ions, including the energy and its components (parallel, perpendicular, and total energy), which will be the topic of this research.

Different researchers have been investigating the ion outflow at high altitudes and latitudes. Chang et al. [1986] introduced the mean particle theory, which describes the perpendicular heating of ions in a dipole magnetic field. They proposed that the intense broad band electric field fluctuations observed in the frequency range of (0-100 Hz) could be the cause of the transverse activation of ions through cyclonic resonance heating with left-handed polarized electromagnetic waves. Additionally, using a set of equations that described the motion of the ion in the geomagnetic field, they determined the parallel and perpendicular energies in accordance with the mean particle theory. Retterer et al. [1987] demonstrated how oxygen ions form conic distributions in the auroral zone of the Earth and used the diffusion equation to explain ion velocity distributions that obtained by using Monte Carlo method.

Barakat and Barghouthi [1994a, and b] upgraded the Monte Carlo simulation and investigated the impact of wave particle interaction (WPI) on $H^+$and O^+ ion outflow in the polar wind. The electrostatic field, gravity, and geomagnetic field lines are considered in the model. These two studies considered as a parametric study because they used constant values for the quasilinear velocity diffusion rates along the simulation tube, the velocity distribution function and its velocity moments profiles were simulated and presented for both ions. Barghouthi [1997] and Barghouthi et al. [1998] processed the data obtained from plasma wave instrument (PWI) on board space dynamics explorer 1 and calculated the altitude dependence of the velocity diffusion rate, they presented the effect of altitude-dependent wave-particle interaction (WPI) on $H^+$and O^+ ion outflow in the polar cap and auroral zone using Monte Carlo simulation. Additionally, Barghouthi [1997] investigated the model by comparing the energy estimates from the mean particle theory [Chang et al. 1986] with the corresponding energy results produced by Monte Carlo simulation in the auroral region. Despite the absence of supporting observations, there was strong agreement between the Monte Carlo simulations and the estimates of the mean particle theory.

Bouhram et al. [2002, 2003a, 2003b, 2004] developed a two-dimensional, Monte Carlo model for ion outflow from the dayside cusp/cleft, which is associated with transverse ion heating, they examined the cusp cleft region's transverse heating and ion outflow. They used their model to interpret the Cluster observations, i.e. saturation of transverse energization rate, in terms of finite perpendicular wavelength effects in the wave-particle interactions.

Barghouthi and Atout [2006] concentrated on the Monte Carlo simulations of toroidal H^+ and O^+ velocity distributions at high altitudes equatorward of the cusp by using a suitable form for velocity diffusion coefficient $D_\perp$. The results of the Monte Carlo simulations, toroidal $H^+$and O^+ velocity distributions and $H^+$and O^+ ion temperatures were compared to the toroidal $H^+$and O^+ ion distributions and $H^+$and O^+ ion temperatures that were observed at high altitudes equatorward of the cusp [Huddleston et al., 2000], these comparisons produced a reasonable agreement.

Barghouthi [2008] employed the Monte Carlo simulation to determine the temperatures and velocity distributions of $H^+$and O^+ ions at high altitudes in the equatorward portion of the cusp by using different forms of the altitude and velocity dependent diffusion coefficient, $D_\perp(r, v_\perp)$ (RCC model, Bouhram model, and Barghouthi model), and compared between their simulation results with the corresponding observations of Huddleston et al. [2000], the simulation results of Barghouthi model were in excellent agreement with observations. In addition, Barghouthi [2008] presented much evidence, i.e., comparisons between Monte Carlo simulations results obtained by using Barghouthi model for H^+ and O^+ ions outflows with the corresponding observations obtained from different publications at different altitudes in the auroral region, that support Barghouthi model.

Waara et al. [2010] presented a case study of considerable heating of outflowing oxygen ions at high altitude (12 R_E) above the polar cap (up to 8 keV) perpendicular to the geomagnetic field. The distribution functions' shape suggests that the majority of the heating takes place locally (within 0.2–0.4 R_E of altitude). They discovered that it is unlikely that the locally observed wave fields can explain the observed ion energization because there are several events at lower altitudes. Furthermore, it is unlikely that the ions have migrated from an energizing location nearby to the observation site. This shows that at high altitudes, additional, fundamentally distinct ion energization pathways exist. One explanation is that the ions' magnetic moment is not conserved, which would lead to slower outflow velocities and a longer ion energization period.

Waara et al. [2011] they provide the average values of coefficient which can be used to describing the diffusion in ion velocity at various altitude which can be consider a useful way to study ion outflow behaviour and their energies. The average energies of O^{+} can be explained by the observed average wave in high altitudes range (8 - 15 $\mathrm{R_E}$) in cusp and mantle regions according to their test particle calculations. They expected the relation between electric and magnetic field spectral density according to their results and the diffusion confection of O^{+} increases with altitude.

Barghouthi et al. [2012] compared the simulation results of ion outflow (density, drift velocity, perpendicular and parallel temperatures, and ion velocity distributions at different altitudes) in two different regions, polar wind and auroral region, based on the Barghouthi model. They found that wave particle interactions have a greater impact in the auroral zone than they do in the polar wind region, and that they have a greater impact on the energizing of O^{+} ions than H^{+} ions.

Barghouthi et al. [2016] updated the Monte Carlo model by taking into account the effects of gravity, ambipolar electric field, centrifugal acceleration, mirror force and wave particle interactions to study O^{+} and H^{+} ions outflow above the polar cap, they changed various parameters like (centrifugal acceleration, velocity diffusion coefficients, and boundary conditions at lower-altitude), they compared their results with the observations obtained by different instruments on board Cluster spacecraft, their results were in good agreement with observed data.

In this study, our main objective is to compare between the simulation results (perpendicular energies $\mathrm{W}_{\perp}$, parallel energies $\mathrm{W}_{\parallel}$, and the total energies $\mathrm{W}_{\mathrm{total}}$) of O^{+} and H^{+} ions obtained by using Monte Carlo model (Barghouthi model) and mean particle theory, and available observations in different regions of earth magnetosphere (polar wind, auroral region, cusp, and central polar cap).

2 Formulations

2.1 Monte Carlo simulation

The motion of the plasma's constituents and interactions between plasma species can be precisely defined via Monte Carlo simulation. When working with plasma, it is practical to characterize each species using a different velocity distribution function. $f_s\ (\mathbf{v}_s, \mathbf{r}_s, t)$. The velocity distribution function is defined such that $f_s\ (\mathbf{v}_s, \mathbf{r}_s, t) d\mathbf{v}_s d\mathbf{r}_s$ represents the number of particles of species s which at time t have velocity between $\mathbf{v}_s$ and $\mathbf{v}_s + d\mathbf{v}_s$ and positions between $\mathbf{r}_s$ and $\mathbf{r}_s + d\mathbf{r}_s$. The net result of collisions and interactions, and the movement of species in phase space under the influence of external forces define the evolution of the species velocity distribution function throughout time [Schunk, 1977]. The well-known Boltzmann equation provides a mathematical representation of this evolution:

$$\frac{\partial f_s}{\partial \mathrm{t}} + \mathbf{v}_s . \nabla f_s + \left(\frac{e_s}{m_s}\right)\left[\boldsymbol{E} + \frac{\mathbf{v_s} \times \mathbf{B}}{c}\right] . \nabla_{v_s} f_s = \frac{\delta f_s}{\delta t} \qquad (1)$$

In this equation, the left-hand side represents the evolution of the velocity distribution function $f_s\ (\mathbf{v}_s, \mathbf{r}_s, t)$ under the effects of external forces, and the right-hand side represents the Boltzmann collision integral, here it represents the rate at which f_s changed as a result of wave particle interactions in the region of study. In the above equation, E is the polarization electric field, B is the geomagnetic field, c is the speed of light, ∇ is the coordinate space gradient, and ∇_{v_s} is the velocity space gradient, and e_s and m_s are the charge and mass of species s, respectively. The suitable expression for $\left(\frac{\delta f_s}{\delta t}\right)$ in case of wave particle interactions is given by Retterer et al. [1987], they considered the effects of (WPI) as particles diffusion in the velocity space.

$$\left.\frac{\delta f}{\delta t}\right|_{WPI} = \left(\frac{1}{v_\perp}\right)\frac{\partial}{\partial v_\perp}\left[D_\perp v_\perp \frac{\partial f}{\partial v_\perp}\right] \tag{2}$$

where $D_\perp$ is provided by Retterer et al. [1987] and represents the quasi-linear velocity diffusion rate perpendicular to the geomagnetic field,

$$D_\perp = (\eta q^2/4m^2)|E_x(\omega = \Omega)|^2 \tag{3}$$

where $|E_x(\omega)|^2$ is the measured spectral density of the electromagnetic turbulence, η is the proportion of the measured spectral density by plasma wave instrument (PWI) on board dynamic explorer 1 (DE-1) spacecraft that corresponds to the left-hand polarized wave, q is the ion's charge, m is the ion's mass, Ω is the ion's gyrofrequency, and ω is the angular frequency of the electromagnetic turbulence.

The expression of the velocity diffusion rate $D_\perp$ as given in Eq. (3) is independent of velocity and depends on position (altitude) via changes in the ion gyrofrequency, Ω, along the geomagnetic field lines. By examining experimental data of electric field spectral density obtained by plasma wave instrument (PWI) onboard the DE-1 satellite (i.e. for high solar activity conditions), Barghouthi [1997] and Barghouti et al. [1998] calculated the altitude dependence of ($D_\perp$). They came up with the following expressions for the velocity diffusion coefficient $D_\perp$ in the polar wind region [Barghouthi et al., 1998] as follows:

$$D_\perp(r) = \left\{\begin{matrix} 5.77\times 10^3 \left(\frac{r}{\mathrm{R_E}}\right)^{7.95} cm^2 s^{-3}, \text{for } \mathrm{H^+} \\ 9.55\times 10^2 \left(\frac{r}{\mathrm{R_E}}\right)^{13.3} cm^2 s^{-3}, \text{for } \mathrm{O^+} \end{matrix}\right\} \tag{4}$$

In the auroral region, $D_\perp(r)$ is given by Barghouthi [1997] as follows:

$$D_\perp(r) = \left\{\begin{matrix} 4.45\times 10^7 \left(\frac{r}{\mathrm{R_E}}\right)^{7.95} cm^2 s^{-3}, \text{for } \mathrm{H^+} \\ 6.94\times 10^5 \left(\frac{r}{\mathrm{R_E}}\right)^{13.3} cm^2 s^{-3}, \text{for } \mathrm{O^+} \end{matrix}\right\} \tag{5}$$

In central polar cap (CPC) and cusp regions, $D_\perp(r)$ is given by Nilsson et al. [2013] as follows:

For central polar cape region

$$D_\perp(r) = \left\{\begin{matrix} 20 \left(\frac{r}{\mathrm{R_E}}\right)^{9.77} cm^2 s^{-3}, \text{for } \mathrm{H^+} \\ 0.5\times 10^5 \left(\frac{r}{\mathrm{R_E}}\right)^{5.5} cm^2 s^{-3}, \text{for } \mathrm{O^+} \end{matrix}\right\} \tag{6}$$

and for cusp region

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$$D_\perp(r) = \begin{Bmatrix} 1.01\times10^6 \left(\frac{r}{\mathrm{R_E}}\right)^{5.61} cm^2 s^{-3}, \text{for } \mathrm{H^+} \\ 2.5\times10^4 \left(\frac{r}{\mathrm{R_E}}\right)^{6.4} cm^2 s^{-3}, \text{for } \mathrm{O^+} \end{Bmatrix} \tag{7}$$

The diffusion coefficient was given a new form by Barghouthi [2008], who discovered that it is a velocity-dependent in addition to altitude-dependent.

$$D_\perp(r, v_\perp) = D_\perp(r) \begin{Bmatrix} 1 & \text{for } \left(\frac{k_\perp v_\perp}{\Omega_i}\right) < 1 \\ \left(\frac{k_\perp v_\perp}{\Omega_i}\right)^{-3} & \text{for } \left(\frac{k_\perp v_\perp}{\Omega_i}\right) \geq 1 \end{Bmatrix} \tag{8}$$

Where $D_\perp(r, v_\perp)$ is the quasi-linear velocity diffusion rate perpendicular to the geomagnetic field lines (altitude and velocity dependent), Ω_i is the ion gyrofrequency and $k_\perp$ is perpendicular wave number and related to the characteristic perpendicular wavelength of the electromagnetic turbulence $\lambda_\perp$.

By solving Boltzmann equation, Eq. (1), using Monte Carlo technique the velocity distribution functions were obtained for each species (in this study, $\mathrm{O^+}$and $\mathrm{H^+}$ ions) and its velocity moments, i.e. density n_s , drift velocity u_s, and parallel $\mathrm{T}_{s\parallel}$ and perpendicular $\mathrm{T}_{s\perp}$ temperatures. The moments considered here are defined as follows [Barghouthi, 1997]:

$$n_s = \int f_s d\mathbf{v}_s \tag{9}$$

$$u_s = \frac{1}{n_s}\int v_{s\parallel} f_s d\mathbf{v}_s \tag{10}$$

$$\mathrm{T}_{s\parallel} = \frac{m_s}{n_s k}\int \left(v_{s\parallel} - u_s\right)^2 f_s d\mathbf{v}_s \tag{11}$$

$$\mathrm{T}_{s\perp} = \frac{m_s}{2n_s k}\int (v_{s\perp})^2 f_s d\mathbf{v}_s \tag{12}$$

These Monte Carlo results will be used to calculate the mean parallel energy, mean perpendicular energy, and total mean energy as given in the following expressions [Barghouthi, 1997], respectively:

$$W_{s\parallel} = \frac{1}{2} m {u_s}^2 + \frac{1}{2} k \mathrm{T}_{s\parallel} \tag{13}$$

$$W_{s\perp} = k \mathrm{T}_{s\perp} \tag{14}$$

$$W_s = W_{s\parallel} + W_{s\perp} \tag{15}$$

Where u_s, $\mathrm{T}_{s\parallel}$ and $\mathrm{T}_{s\perp}$ are given by equations (10), (11) and (12), respectively and $W_{s\parallel}$and $W_{s\perp}$are the mean parallel and perpendicular energies, respectively; W_s is the total mean energy; and s denotes the type of the ion ($\mathrm{O^+}$or $\mathrm{H^+}$), k is Boltzmann constant.

2.2 Barghouthi model

Barghouthi model was developed to study the behaviour of ions (H^+ and O^+) outflow at high altitudes and high-latitudes, the simulation results of this model provide an excellent agreement to observations in different regions, auroral region [Barghouthi, 2008] and polar wind region [Barghouthi et al., 2011]. This model simulates different effects (gravity, polarization electric field, diverging geomagnetic field, and wave particle interactions which acts on (H^+ and O^+) ion outflow at high altitudes and high latitudes. This model emphasises the significant role of wave particle interactions that is responsible for ion heating, this effect depends on the velocity diffusion coefficient $D_\perp(r, v_\perp)$, they developed a form for this coefficient as a function of position (r/R_E) along geomagnetic field lines of the Earth and injected ion perpendicular velocity $(v_\perp)$. The different forms of velocity diffusion coefficient, $D_\perp(r, v_\perp)$ have been used in the Monte Carlo simulation to obtain O^+ and H^+ ions temperatures and velocity distribution functions at high altitudes and latitudes. In the Monte Carlo simulation, the appropriate velocity diffusion coefficient related to the specific region of study, $D_\perp(r, v_\perp)$, were used to determine the temperatures and velocity distributions of H^+ and O^+ ions at high altitudes and latitudes.

2.3 Mean particle theory

Chang et al. [1986] provided a theory for estimation of the values of the mean perpendicular, mean parallel, and total mean energies as a function of geocentric distance by including the average rate of heating for each ion in a set of equations that describe the motion of the ion along geomagnetic field lines, as follows:

$$W_{i\parallel} = \frac{9m_i}{2^{1/3}}\left[\frac{rD_\perp(r)}{(3\alpha+1)(6\alpha+11)}\right]^{2/3} \qquad (16)$$

$$W_{i\perp} = \frac{(6\alpha+2)m_i}{2^{1/3}}\left[\frac{rD_\perp(r)}{(3\alpha+1)(6\alpha+11)}\right]^{2/3} \qquad (17)$$

$$W_i = \quad W_{i\parallel} + W_{i\perp} = (3\alpha + 11/2)^{1/3} m_i \left[\frac{rD_\perp(r)}{(3\alpha+1)}\right]^{2/3} \qquad (18)$$

Where $W_\parallel$ and $W_\perp$ are the mean parallel and perpendicular energies, respectively, W_i is the total mean energy, *i* denotes the type of the ion (H^+ or O^+), and α is a fitting parameter. In that theory the mean energy ratio $W_\perp / W_\parallel$ asymptotically approaches a constant value.

3 Comparisons

Here, we will do comparison between Monte Carlo simulations and mean particle theory estimates in auroral, and polar wind regions, sub-section 3.1, and comparison between Monte Carlo simulations, mean particle theory estimates, and corresponding observations, sub-section 3.2.

3.1 Comparison between Monte Carlo simulations and estimates of mean particle theory.

By using Monte Carlo technique (i.e. Barghouthi model) and mean particle theory, we have obtained different altitude profiles for mean parallel, mean perpendicular, and total mean energies in different regions of earth magnetosphere, auroral region Fig. 1, and polar wind region Fig. 2, for H^+ (left panels) and O^+ (right panels) ions outflow. In both methods we have used suitable $D_{\perp}(r)$ for velocity diffusion coefficient in each region. In general, we have found in the auroral region (figure 1)

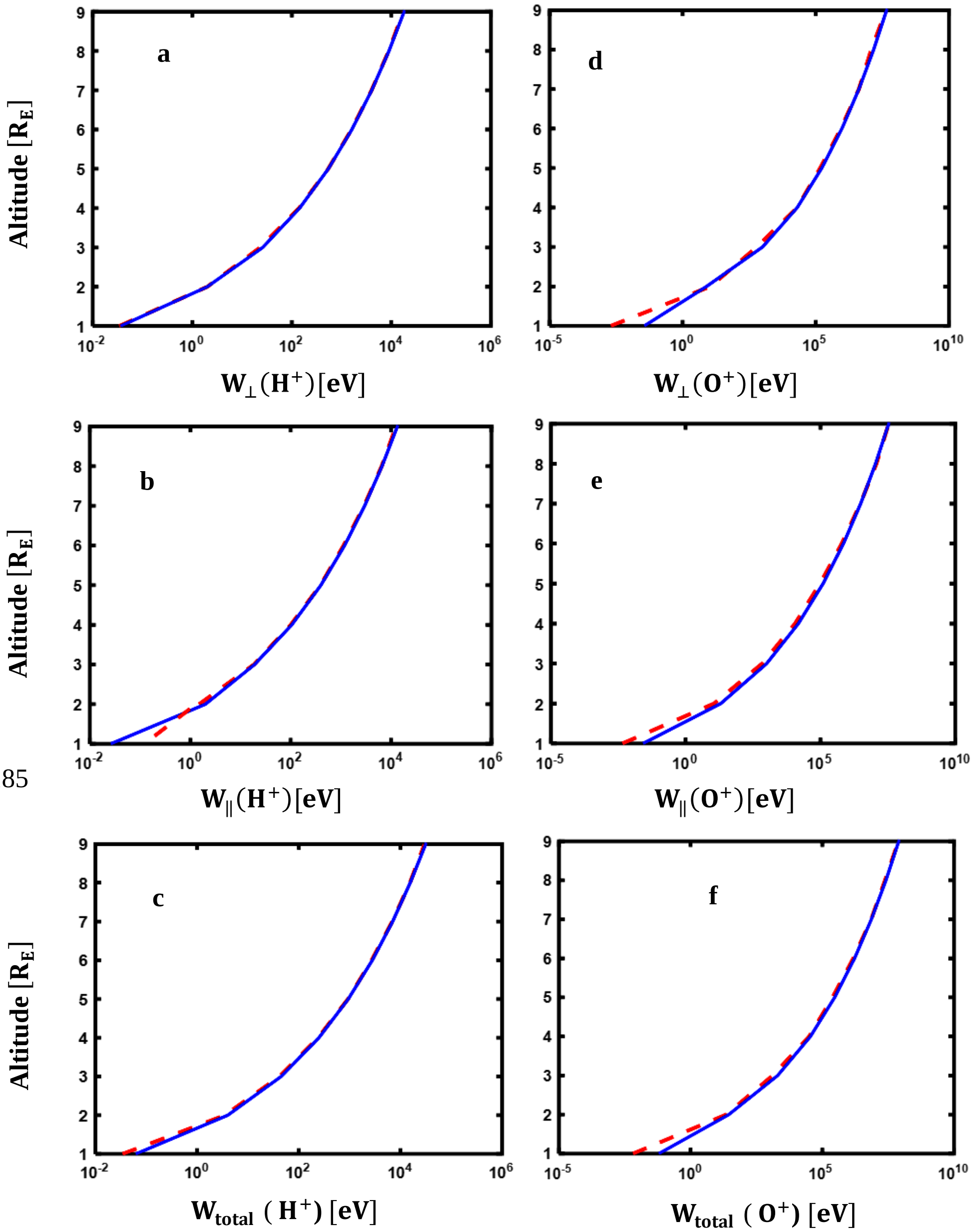

Figure 1: Altitude profiles of the estimates of the mean particle theory (blue solid lines) for auroral conditions with the Monte Carlo calculations (red dashed lines). Left panels, a, b, and c are for H^+ ions. Right panels, d, e, and f are for O^+ ions. The mean perpendicular energy $W_{\perp}$ considered here (panels a and d), mean parallel energy $W_{\parallel}$ (panels b and e) and mean total energy W_{total} (panels c and f).

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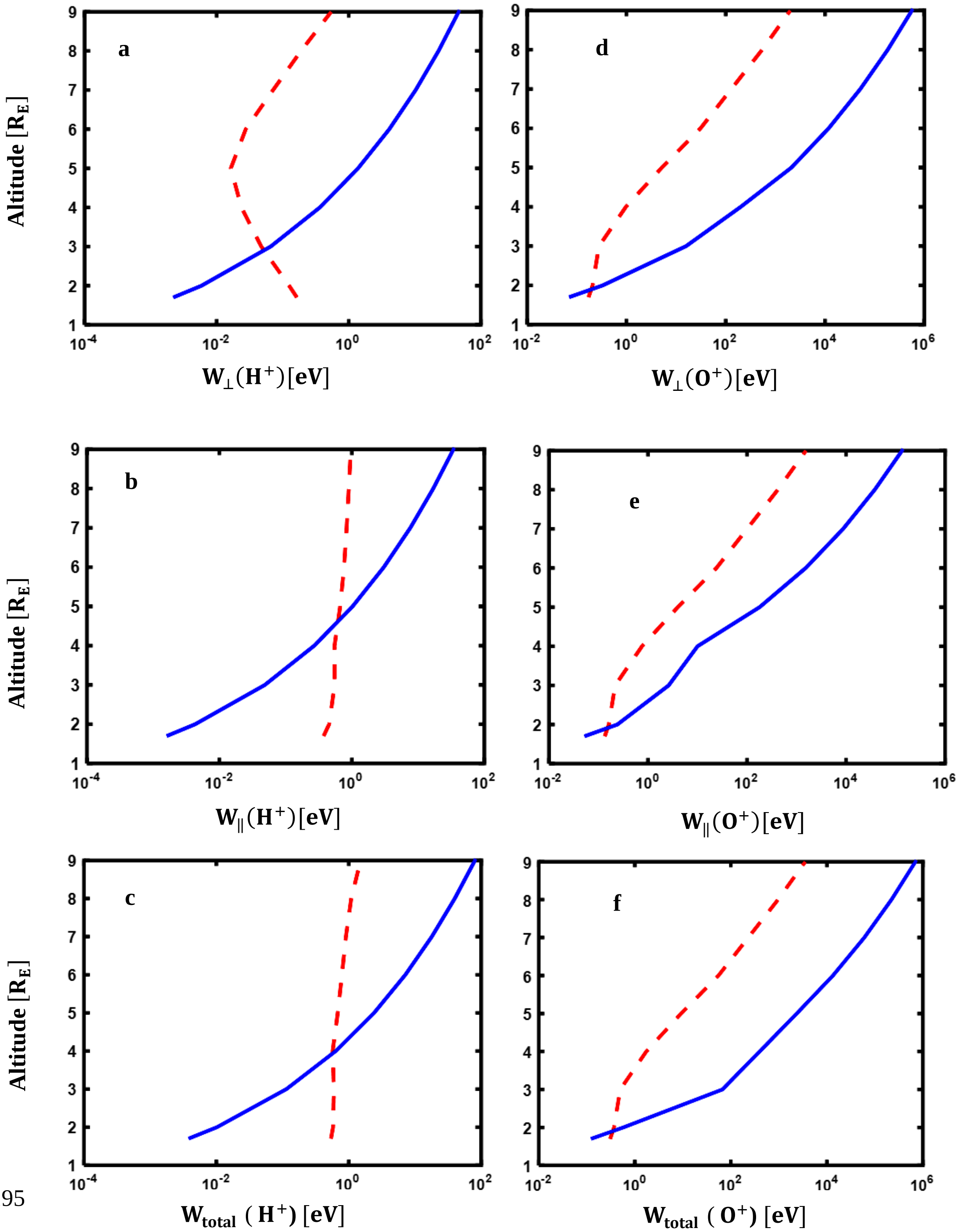

195 **Figure 2: Comparison of the estimates of the mean particle theory (blue solid lines) for polar wind conditions with the Monte Carlo calculations (red dashed lines). (right panels, d, e and f) for O^+ ions and (left panels, a, b and c) for H^+ ions and. The mean perpendicular energy $W_\perp$ represented by (panels a and d), mean parallel energy $W_{||}$ (panels b and e) and total energy (panels c and f) with electromagnetic turbulence wavelengths ($\lambda_\perp \rightarrow \infty$), and altitude dependent diffusion coefficients.**

and for $\lambda_\perp \to \infty$, an excellent agreement between Monte Carlo simulations and estimates of mean particle theory for H^+ and O^+ ions. It is worthwhile to mention that the heating, the energization, of the ions in the mean particle theory is due to the effect of wave particle interaction, only, that mainly depends on the value of the velocity diffusion coefficient. However, the energization process in the Monte Carlo model is a result of competition between wave particle interaction and external forces (gravity, polarization electric field and divergence geomagnetic field). This close agreement is due to the dominant effect of wave particle interactions that overcome the effects of external forces because of the large values of $D_\perp(r)$, in other words, wave particle interactions dominate the energization process for both ions in this auroral region.

For polar wind region and for $\lambda_\perp \to \infty$, i.e. altitude dependent velocity diffusion coefficient $D_\perp(r)$. The values of the velocity diffusion coefficient are less than those in the auroral region, see eqs. (4) and (5). According to Fig. 2 there is a poor agreement between Monte Carlo simulations and mean particle theory estimates, this is due to the contribution of the external forces in Barghouthi model that competes with the effect of wave particle interaction, however in the mean particle theory the external forces are not considered and the heating is due to wave particle interaction, only. We report here that mean particle theory is not suitable to be used in this region, and Monte Carlo simulations are more appropriate to be used as shown in Barghouthi et al. [2011] when they compared their Monte Carlo results with observations. Also, we have found that, when we use the diffusion coefficient that depends on altitude, its value becomes very large as altitude increases, and therefore the values of the energies obtained from eqs. (16), (17) and (18) turn to be very high, but when the diffusion coefficient becomes velocity and altitude dependent according to eq. (8) (i.e. $k_\perp v_\perp/\Omega) \geq 1$), the produced energies turn to be reasonable as shown in Fig.3 (blue solid lines and red dashed lines).

3.2 Comparison between Monte Carlo simulations, estimates of the mean particle theory, and available observations

In this sub-section, we present the Monte Carlo simulation results and the estimates of the mean particle theory that have corresponding observations. Barghouthi [2008] compared the Monte Carlo simulation results that obtained from Barghouthi model with the corresponding observations for H^+ and O^+ ions outflows in the auroral region at different altitudes in the simulation tube, he obtained an excellent agreement, particularly, when the typical perpendicular wavelength of the electromagnetic turbulence was 8 km. Also, he observed that there is a broad agreement between the simulation results of the polar wind for this wavelength and the corresponding observations. For these reasons, we chose to have the results of the comparison with corresponding observations when $\lambda_\perp = 8\ km$, i.e. when the velocity diffusion coefficient is altitude and velocity dependent. We will compare the outcomes of our Monte Carlo simulations, the estimates of mean particle theory, and available observations obtained from different published articles. Observations of O^+ ions at various altitudes were obtained for parallel velocity, perpendicular temperature and parallel temperature for both polar wind and auroral regions from [Nilsson et al., 2013] and observations for parallel velocity and perpendicular temperature for O^+ ions in central polar cap and cusp regions from Barghouthi et al. [2016].

Figure 3 presents the results of comparisons in auroral (left panels) and polar wind (right panels) regions. The comparison results between Monte Carlo method (red dashed lines), and estimates of the mean particle theory (blue solid lines) at $\lambda_\perp = 8\ km$ with observations (minimum (doted lines), avarege (doted dashed lines) and maximam (black dashed lines)) for O^+ ions. It is very clear, in four panels, that the Monte Carlo simulation results and the estimates of the mean particle theory are very close to each other and they have excellent agreement at low altitudes, however at high altitude they have similar qualitative behaviour and good agreement, we claim that this acceptable and reasonable agreement is due the implementation of the appropriate altitude and velocity dependent diffusion coefficient in both methods. According to

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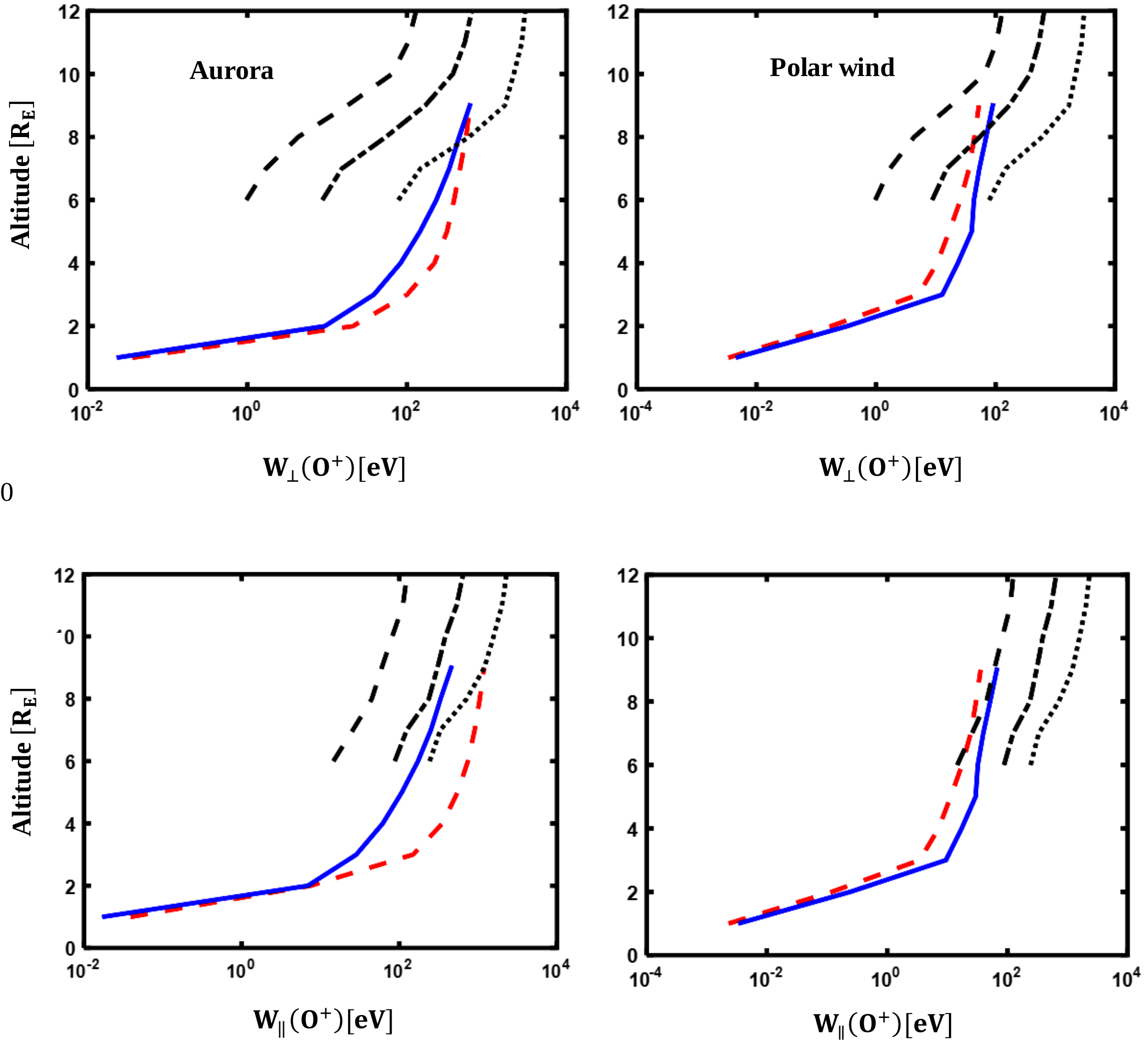

Figure 3: Comparison of the estimates of the mean particle theory (blue solid lines) and Monte Carlo calculations (red dashed lines) for auroral conditions (left panels) and polar wind conditions (right panels), in addition to observations, minimum (dott lines), avarege (dotted dashed lines) and maximam (black dashed lines) for O^+ ions. The mean perpendicular energy $W_\perp(O^+)$ considered here (top) and mean parallel energy $W_\parallel(O^+)$ (bottom), we have considered the wavelength of the electromagnetic turbulence to be $\lambda_\perp = 8km$.

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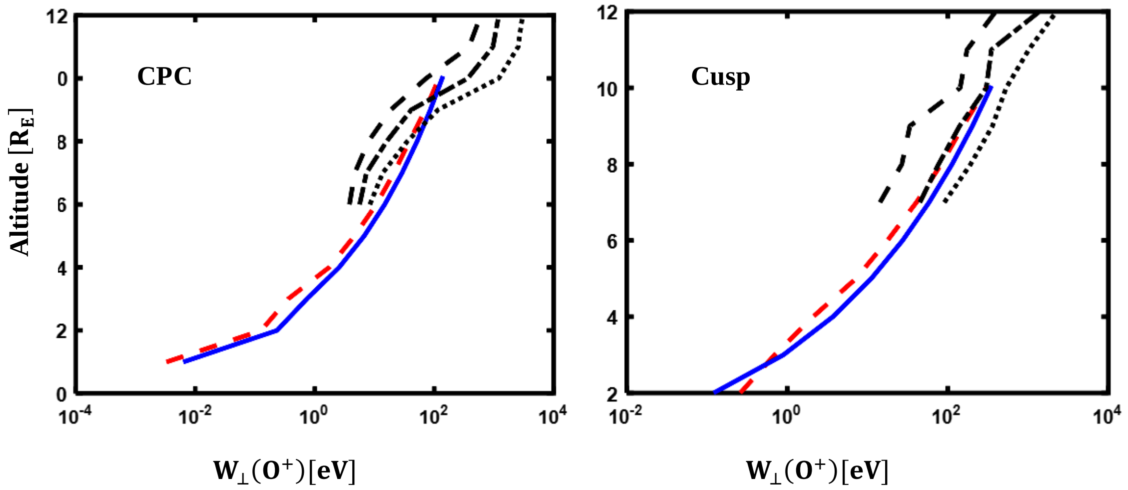

Figure 4: Comparison of the estimates of the mean particle theory (blue solid lines) with the Monte Carlo calculations (red dashed line), for central polar cap conditions (left panel) and cusp conditions (right panel) in addition to the observations (minimum (doted lines) , avarege (doted dashed lines), and maximam (black dashed lines)) for O^+ ions. Mean perpendicular energy $W_\perp(O^+)$ is considered with electromagnetic turbulence wavelength ($\lambda_\perp \to \infty$).

comparison with observations, it is obvious that the simulation results and the estimates of the mean particle theory are in the range of observations. This is evidence that $D_\perp(r, v_\perp)$ is suitable to be used in Monte Carlo simulation and in mean particle theory. To be specific, the results of perpendicular energy $W_\perp(O^+)$ from both studies, Monte Carlo and mean particle theory are in good agreement with minimum values of the observations in the auroral region, however, they are in good agreement with average values of the observations. For mean parallel energy $W_{||}(O^+)$ (Fig. 3, bottom panels), simulation results and mean particle theory estimates are close to the average and minimum values of the observations in the auroral region and they are in excellent agreement with maximum values of the observations in the polar wind region.

In central polar cap (Fig. 4, left panel) and cusp (Fig. 4, right panel) regions, we have used Nilsson et al. [2013] diffusion coefficient that is altitude dependent only, i.e. when $\lambda_\perp \to \infty$, eqs. (6) and (7), we have obtained excellent agreement, at all altitudes, between Monte Carlo simulations and the estimates of the mean particle theory. Also, we have a very good agreement with observations in both regions, all results are very close with minimum and average observations in central polar cap region and they are very close to the average values of the observations in the cusp region.

As a result of these comparisons, it is important to choose the appropriate form of the velocity diffusion coefficient in every region of study in earth magnetosphere when considering the energization, heating, process of ions.

4 Conclusions

We have compared the energy components, mean perpendicular energy $W_\perp$, mean parallel energy $W_{||}$, and total mean energy W_{total} for H^+ and O^+ ions by using Monte Carlo method and the estimates of the mean particle theory in different regions of earth magnetosphere (polar wind, auroral, central polar cap, and cusp regions). For altitude dependent diffusion coefficient, we have found excellent agreement between the results of both methods in the auroral regions and poor agreement in polar wind region, also we have found that the energy turned to be very high, not reasonable, at middle and high altitudes. Because of that we introduce the velocity and altitude dependent diffusion coefficient that produce reasonable energies at low, middle, and high altitudes in both regions. When we have compared the Monte Carlo simulations and estimates of the mean particle theory with corresponding observations, we have found good agreement between simulations, estimates and observations in all regions, i.e. polar wind, aurora, central polar cap, and cusp. Simulation results and the estimates of mean particle theory are in the same range of observations. Here, we report that the diffusion coefficients that have been used in Monte Carlo simulation and in the mean particle theory and produced acceptable agreement when compared to the corresponding observations are appropriate to be used in these regions.

For future work, we need to search for more observations in different earth magnetosphere regions in order to have more comparisons and to confirm which diffusion coefficient is more appropriate and which method gives more accurate results when compared to corresponding observations.

5 Code and data availability

The source code, data, and input files necessary to reproduce the results are available from the authors upon request (barghouthi@staff.alquds.edu).

6 Author contribution

First author (Imad Barghouthi) suggested the problem, provided the model (Barghouthi model), discussed the simulation results, and wrote the manuscript.
Second author (May Halaika) ran the model (Barghouthi model), obtained the simulation results, and plotted the figures.

7 Competing interests

The authors (Barghouthi and Halaika) declare that they do not have any competing interests.

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