Dear Dr. Andrew J. Kavanagh and Dr. Christoph Jacobi,

On behalf of my co-authors, we thank you very much for giving us an opportunity to revise our manuscript entitled "The research on small-scale structures of ice particle density and electron density in the mesopause region"(#angeo-2019-10). We would like to express our great appreciation to you and reviewers for some constructive comments and suggestions on our manuscript. Based on the comments and requests, we have made careful modification on the original manuscript. We attached revised manuscript and every question from the reviewers was summarized.

Looking forward to hearing from you.

Thank you and best regards!

Yours sincerely

Ruihuan Tian

Dear Reviewers,

Thank you for your insightful comments concerning our manuscript entitled “The research on small-scale structures of ice particle density and electron density in the mesopause region”. Those comments are all valuable and very helpful for revising and improving our paper, as well as the important guiding significance to our researches. We have studied these comments carefully and have made corrections which we hope make our paper more acceptable. The responds to the comments are as following. Once again, special thanks to you for good comments and hope that the correction will meet with approval.

Responses to Reviewer 1

This manuscript describes development of a model and associated calculations for ultimately determining the ice particle and electron density in the mesopause region. The electron density structures are particularly important for producing Polar Mesospheric Summer Echoes PMSEs and one ultimate goal of this work is to contribute to an understanding of the PMSE source region. The model utilizes a growth model for the ice particles (collision and adsorption of water vapor and condensation nuclei), and a velocity model (dependent on the ice particle mass and dependent on gravity and neutral drag forces) to ultimately determine the ice particle density with altitude. A charging model (OML with CEC) and quasi-neutrality is then used to determine the electron density knowing the ice particle density. Results of using this model are used to show a reduction in electron density in the source region. These reductions produce radar scatter associated with PMSE.

The manuscript is relatively well organized and well laid out. There are some issues with English grammar and style that clearly should be addressed (there is not an unreasonably large number of these English issues, however).

Response

Thank you very much for pointing it out. We have gone over the text and some English usage and grammar mistakes have been revised to make it easier to understand.

However, there are some serious issues that preclude publication in Annales Geophysicae AG at this time. A key issue is that the authors have not made a persuasive case of the contribution to the field of this work. They have presented a model and some calculations but not effective tie these to observations to lend credibility to the model results. Also they have not articulated a well-defined, focused issue in the field they want to address. There has been past work in this field with previous models. There is no substantive discussion on how their model is an improvement over past models and what unresolved issues they have been able to solve that past models have not.

Response

Thank you very much for your valuable and thoughtful comments.

It is believed that small scale electron density fluctuations can cause PMSE phenomenon (Rapp and Lübken 2004). And previous works (Lie-Svendsen, et al. 2003;Rapp and Lübken 2003) have shown that ice particle irregularities on meter scale can create electron density fluctuations on the similar scale due to plasma attachment by particles and plasma diffusion. In their models, the ice particle density profile is given directly, with an embedded small scale Gaussian structure. However, the formation mechanism of these small-scale particle density structures has not been fully understood. In view of this, the aim of our study is trying to explain the formation of these ice particle irregularities through the growth and movement model. The analysis of relevant previous work and the purpose of this paper have been added in the introduction.

Meanwhile, to make our model results more accurate and credible, we have modified the plasma model according to the detailed comments below, which includes dynamic continuity equations for ice particles with various charges and ions, momentum equation for ions and electrons, and quasi-neutral condition. The results of the revised model are in agreement with previous work by Lie-Svenson et al. (Lie‐Svendsen, et al. 2003), e.g., for particles with radii of 11 nm or less, electron density is anti-correlated to charged ice particle density and ion density, which is in line with most rocket observations.

We have modified the charging model in the second section, and have added a comparison with previous work in the third section.

Therefore, the paper is not suitable for publication in AG in its current form. There must be major revisions and the authors must address these key issues. Further details of some of the critical weaknesses are as follows:

1. The last sentence (line 23-25) of the Abstract is indicative of the major problem. This sentence is vague. Why is this work important? The rest of the abstract has not made a case for this. In fact, the last sentence is very well known to be the case from other work! No novelty of this work is stated.

Response

Thank you very much for pointing it out. We are sorry for our unclearly description on the innovation and significance of this manuscript.

The main value of this paper is to propose a possible mechanism for the formation of small scale ice particle density irregularities in PMSE region based on particle growth and movement model, while the structure of ice particle density is always assumed to be some specific profiles in previous work(Chen and Scales 2005;Lie‐Svendsen, et al. 2003;Mahmoudian and Scales 2013;Rapp and Lübken 2003;Scales and Ganguli 2004).

A statement of the purpose and significance of this article has been added to the abstract section.

2. The authors mention another well-known work in this field (Lie-Svenson et al. 2003). How is this work an advance over the past work? This should at least be clearly shown since Lie-Svenson is often used as a benchmark work. Also, the work of Lie-Svenson shows the importance of using ion mass (through the ion

continuity equation) on the electron and ion structures in the PMSE source region. The work has been validated through experimental observations. Some of these effects have been described by the work of A. Mahmoudian, On the signature of positively charged dust particles on plasma irregularities in the mesosphere, J. Atmos. Sol. Terr. Phys., 2013 which is based on earlier work by Chen and Scales, JGR 2005. Therefore, this implies the authors work is not consistent with observations since it does not contain ion inertia (it just assumes the Boltzmann approximation)? No direct substantive comparison with data has been shown in this work to lend any validity.

Response

Thank you very much for your instructive suggestions.

Lie-Svenson et al. studied the plasma response to initially given small-scale ice particle perturbations in the mesopause region. The formation process of these small-scale structures of ice particle density is still not fully understood. The aim of our study is trying to explain the formation of these small-scale ice particle density structures based on the growth and movement model of particles. The analysis of relevant previous work and the purpose of this paper have been added in the introduction section.

After studying the previous work and observations carefully, we find that the assumption of ion immobility in our previous manuscript version was not accurate. So we modify the plasma model in the revised manuscript according to Lie-Svenson et al.’s theory (Lie‐Svendsen, et al. 2003). The revised plasma model considers production, loss and transport of ions and electrons, and dynamic particle charging. Some more detailed description on the modified plasma model has been made in the model section 2.

According to the revised model, for particles with radii of 11 nm or less, electron density is anti-correlated to ion and charged ice particle density near the boundary of condensation region. It is in agreement with previous work by Lie-Svenson et al. (Lie‐Svendsen, et al. 2003) and most rocket observations(Rapp and Lübken 2004).

Detailed results analysis and comparison with previous work have been added in the results and discussion section 3.

3. What inaccuracies are introduced into the model due to the fact that an equilibrium charge is considered (equation 22). Lie-Svenson et al and other work consider a dynamically time varying particle charge. This would appear to be particularly important since the ice particle mass/radius is changing.

Response

Thank you very much for pointing it out.

According to research of Lie‐Svendsen et al. (Lie‐Svendsen, et al. 2003), the assumption of chemical equilibrium would overestimate the electron depletion and seriously underestimate the ion enhancement, i.e., the equilibrium charge is indeed not a valid approximation in studying plasma response to small-scale ice particle irregularities. In view of this, we have modified the plasma model with dynamic particle charging considered.

In our study, it is assumed that condensation nuclei enter the condensation region with a fixed flux. They grow by absorbing water vapor and move under the action of gravity and neutral drag force. Note that, the charge to mass ratio of ice particles is very low, the electric field force on the particles can be ignored compared to the other two forces, so the dynamic particle charge does not affect the formation of the final particle density profile. Ice particle density will form stable small-scale structures after several hours. The particles keep entering and leaving the condensation region, but as long as the external environment does not change, the distribution of particle density and radius remains unchanged. Then the influence of these stable small-scale structures on electron and ion density is studied by the modified charging model just like Lie‐Svendsen et al. did in their work (Lie‐Svendsen, et al. 2003).

The more detailed description of the modified plasma model has been added in the model section 2.

4. In the model section 2, there appears to be too much detail when the primary equation for the ice particle velocity model is equation 8 (perhaps equation 1

should be stated for completeness). The rest of the approximations may be useful but they can be much more succinctly summarized to shorten this section and eliminate all the equations. The final simplified collision equations may also be useful.

Response

Thank you very much for your instructive suggestions. We have summarized the approximate conditions into words to make the article more concise.

5. In general, one could strongly argue that the plasma (and charging) is much less well modeled in the model equations in section 2 than previous models (ie. Lie-Svenson et al., Chen and Scales). Therefore, it is highly questionable if the current work is an advance since there is no comparison using these past modeling approaches. This, again, goes back to the key issue with the manuscript.

Response

Thank you very much for pointing it out. We are sorry for using a very rough plasma model in our original text. The plasma model has been modified, which considers production, loss and transport of ions and electrons, and dynamic particle charging. We have made some more detailed description on the modified plasma model in the model section 2.

The improvement of this study over previous work is to present a possible formation mechanism of small-scale ice particle structures. The analysis of relevant previous work and the research purpose of this paper have been added in the introduction section.

6. The model results in Section 3 show some promising trends but these must be more closely compared to observational data. Also, there appear to be no direct linkages to a specific observation the authors are trying to understand. The authors should strive to do more than demonstrate their model does what is expected from the basic physics. Only general comparisons are made to

observations, which is not enough for a novel contribution.

Response

Thank you very much for your instructive suggestions.

The main purpose of this paper is to present a possible explanation on the formation of the small-scale ice particle irregularities in PMSE region. Through the growth model, we obtain ice particle density structure at meter scale near the boundary of condensation region, which is consistent with the assumed ice particle density structure scale in the theoretical calculations of previous work (Lie-Svendsen, et al. 2003;Rapp and Lübken 2003), and is consistent with observations by the sounding rocket flight ECT02 in July 1994 (Rapp and Lübken 2004). Based on the modified plasma model, for particles with radii of 11 nm or less, electron density is anti-correlated to density of ions and charged ice particles, which are in agreement with rocket observations by the sounding rocket flight SCT-06 in August 1993 (Lie-Svendsen, et al. 2003) and the sounding rocket flight ECT02 in July 1994 (Rapp and Lübken 2004), respectively.

Detailed results analysis and comparison with previous work have been added in the results and discussion section 3.

7. Again, the authors should strive to see if their model is consistent with observations. For example, the average number of charges is less than one (see line 264) with values of 0.2 and 0.3. Does this indicate that the charging model (using a simple equilibrium charge) is insufficient? Doesn't the particle growth impact what charging model is used. Does the fact that the average charge is less than 1.0 indicate there are positive, negative, and uncharged particles? This has been observed/postulated during experiments? The current simple OLM equilibrium charging model does not take the fact of dynamic particle growth into consideration and may likely be inadequate for what the authors are trying to do (with such small initial particle sizes). This has not been commented on at all. For such low particle charges would a stochastic model (e.g. Mahmoudian) be better.

Response

Thank you very much for your valuable and instructive comments.

The particle radius in this study is less than 11 nm, and an ice particle carries two negative elementary charges at most. The quantized stochastic charging model (Robertson and Sternovsky 2008) is more appropriate to determine the particle charge. Therefore, we modify the plasma model and use the quantized stochastic charging model to calculate the capture rates of electrons and ions by ice particles. The results show that for particles with a radius about 5 nm, the proportion of particles carrying one negative charge is about 97%. For particles with radii ranging from 7 nm to 11 nm, the proportion of particles carrying one negative charge ranges from 97.5% to 85.1%, and that value for particles carrying two negative charges is in 0.53% - 13.6%, which is consistent with observations by Havnes et al. (Havnes, et al. 1996) and numerical results by Rapp and Lübken (Rapp and Lübken 2001).

As we have said before in the response to comment 3, the dynamic particle charging process does not affect the formation of the final particle density profile, i.e., the particle charging process is negligible when calculating the particle density structure based on the particle growth and motion model. After the stable particle density profile is obtained, the corresponding electron and ion density are calculated according to the modified charging model. In this case, ice particle density structure and radius keep stable, which means that the influence of dust growth and motion on charging process is negligible.

More detailed results analysis and comparison with previous work have been added in the results and discussion section 3 and detailed description on the modified plasma model have been made in the model section 2.

8. Figure 3 and 4 appear to show the electron density structures. These appear to be on the space scale of 10 meters or less. How do these results compare with other models, e.g. Lie-Svenson et al. Also why are these results an advance over these past modeling results?

Response

Thank you very much for pointing it out.

The small-scale electron density structures are the consequences of ice particle density irregularities. The main improvement of this paper is to propose a possible formation mechanism of the ice particle density irregularities based on particle growth and movement model, while previous work directly sets the particle density structure to a specific form. The scale and position of the ice particle density irregularities are affected by particle radius distribution function, neutral wind speed, and water vapor density etc. For example, the particle density profiles for different radius distribution functions $F(R_0) = A\exp[-(R_0 - R_{00})^2 / \Delta^2]$ are shown in Fig. 1.

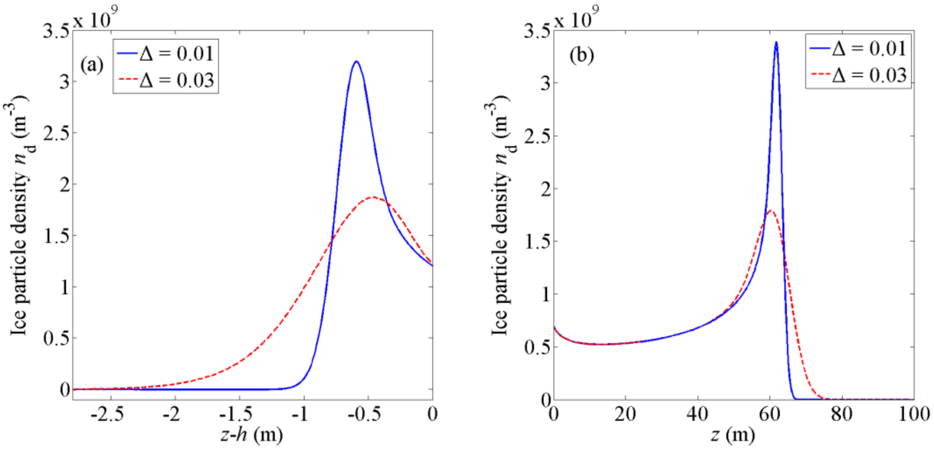

Figure 1 The ice particle density distribution near the (a) upper boundary and (b) lower boundary of the condensation layer for different radius distribution functions. In (a) the center of the radius distribution function R_{00} = 1.08. In (b) R_{00} = 0.8. The solid blue line: Δ = 0.01 and A = 56.4; the red dotted line: Δ = 0.03 and A = 18.8.

Summary: This manuscript is not suitable for publication in AG at this time. If the authors consider a revision (which should be major) the key points the authors should consider are:

1. Making stronger case for why this work is superior to past models (i.e. Lie-Svenson). Certainly the author’s model is inferior in terms of the model of the ionospheric plasma (no ion inertia) and charging (no dynamical variation) model. A possible advantage is the ice particle growth model but this would appear to be problematic as well without properly doing the charging model

correctly. If the novelty in the ice particle growth does not counterbalance the weakness in plasma and charging models, then there is no real contribution or advance in the modeling.

Response

Thank you very much for your instructive suggestions.

The main improvement of this paper is to propose a possible mechanism for the formation of small-scale ice particle density irregularities based on particle growth and movement model, while the particle density structure in previous work was always assumed as some specific forms.

After consulting previous work and observations, we find that the assumption of ion immobility in our original manuscript is not accurate and the equilibrium charge is not a valid approximation for studying plasma response to small-scale ice particle irregularities. So we modified the plasma model used in this paper by considering the production, loss and transport of ions and electrons, and dynamic particle charging processes.

2. There is no substantive comparison with observational data or a focus of an important unresolved scientific issue addressed. This was not clearly articulated and again is a substantial weakness in the paper. It should be addressed in a summary/discussion section and also noted in the Abstract.

Response

Thank you very much for pointing it out. We are sorry for not comparing the results with the observations.

The modified model shows that, for particles with radii of 11 nm or less, the electron density is anti-correlated to ion and charged ice particle density, which is in line with rocket observations by the sounding rocket flight SCT-06 in August 1993 (Lie-Svendsen, et al. 2003) and the sounding rocket flight ECT02 in July 1994 (Rapp and Lübken 2004), respectively. We have added more detailed results analysis and comparison with previous work in the results and discussion section 3.

The main purpose of this paper is to present a possible explanation of the origin of the small-scale ice particle irregularities in PMSE region. Previous works (Lie - Svendsen, et al. 2003;Rapp and Lübken 2003) have shown that ice particle density irregularities on meter scale can create electron density fluctuations on the similar scale, which can cause PMSE phenomenon. In their models, however, the ice particle density profile is given initially, such as small scale Gaussian structure. The aim of our study is trying to present a possible explanation on the formation of these ice particle irregularities through the growth and movement model. The analysis of relevant previous work and the research purpose of this paper have been added in the introduction to make the paper more coherent. Also, a statement of the purpose and value of this article has been added to the abstract section.

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Scales W., Ganguli G.: Investigation of plasma irregularity sources associated with charged dust in the Earth’s mesosphere, Advances in Space Research, 34, 2402-2408, 2004.

Responses to Reviewer 2

This paper presents a model where they investigate whether gravity, the neutral drag force, and ice particle growth by adsorption of water vapor can explain why ice particles near the polar mesospause are frequently seen to be confined into small-scale structures in summer. Much has now been understood about these ice particles, and we know how, once these small-scale structures have been created, the polar mesosphere summer radar echoes (PMSE) arise. However, we still do not have a good understanding of the formation mechanism of these small-scale structures, which this paper aims to improve. I therefore think that a paper on this topic is well worth publishing. However, I do have some minor questions regarding their model, which should be resolved before this paper is considered for publication. 1. In line 126, "Substituting Eq. (9) into Eq. (2)…" should be changed to "Substituting Eq. (9) into Eq. (3)…"

Response

Thank you very much for pointing it out. We have corrected this incorrect description.

2. In line 133-134, there are two predicates in the sentence "It is set that z0 = 0 for the lower boundary and z0 = h for the upper one, here h is the distance between the two boundaries."

Response

Thank you very much for pointing it out. We have corrected this grammatical error and gone over the text further. Some English usage and grammar mistakes have been revised to make it easier to understand.

3. Authors should add some new references showing new progress in pmse.

Response

Thank you very much for your instructive suggestions. We have added more references about influence of small-scale particle density structures on plasma in PMSE region in the introduction.

The research on small-scale structures of ice particle density and electron density in the mesopause region

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Abstract. A growth and motion model is developed to give a possible explanation on the formation of ice particle density irregularities with meter scale, which are the major players in the generation and persistence of small scale electron density fluctuations that can cause polar mesosphere summer echoes (PMSE) phenomenon. The evolution of radius, velocity, and number density of ice particles in mesopause region is investigated based on the growth and motion model. In the growth model, meteoric dust from outer atmosphere and grains moving upward with the neutral wind from the mesosphere bottom serve as nuclei upon which water vapor can condense in the cold and moist condition. And the motion of the ice particles is mainly controlled by gravity and the neutral drag force. It is shown that, for certain nucleus radius, the velocity of particles can be reversed at particular height, which leads to local gathering of particles near the boundary layer and stable small-scale ice particle density structures. Then the influence of these stable small-scale structures on electron and ion density is studied by a charging model, which considers the production, loss and transport of electrons and ions, and dynamic particle charging processes. The results show that, for particles with radii of 11 nm or less, the electron density is anti-correlated to charged ice particle density and ion density due to plasma attachment by particles and plasma diffusion, which is in accordance with most rocket observations.

1 Introduction

The polar mesosphere summer echoes (PMSE) are strong radar echoes from the polar mesopause in summer(Rapp and Lübken 2004). One of the features of PMSE is that the spectra widths of echoes are much narrower than that of incoherent scatter (being due to the Brownian movement of electrons)(Röttger, et al. 1988;Röttger, et al. 1990). And it has been proposed that the PMSEs are radar waves coherently scattered by the irregularities of the refractive index which are mainly determined by electron density(Rapp and Lübken 2004). Furthermore, the efficient scattering occurs when the spatial scale of electron density structures is half of the radar wavelength, the so-called Bragg scale. For typical VHF radars, the scale is about 3 m(Rapp and Lübken 2004). Experimentally, in the ECT02 campaign(Lübken, et al. 1998), the sounding rocket with electron probe has detected electron density irregularities on the order of meters during the simultaneous observation of PMSE, which provides a vital argument for that small-scale electron density structures can indeed create strong radar echoes.

Lots of researches indicate that small scale ice particle density irregularities in the PMSE region play a key role in creating and maintaining small-scale structures of electron density (Chen and Scales 2005;Lie‐Svendsen, et al. 2003;Mahmoudian and Scales 2013;Rapp and Lübken 2003;Scales and Ganguli 2004). Markus Rapp and Franz-Josef Lübken investigated electron diffusion in the vicinity of charged particles revisited (Rapp and Lübken 2003). They developed coupled diffusion equations for electrons, charged aerosol particles, and positive ions subject to the initial condition of anti-correlated perturbations in the charged aerosol and electron distribution. These solutions showed that electron perturbations were anti-correlated to both perturbations in the distributions of negatively charged aerosol particles and positive ions. And the lifetime of these perturbations was determined by aerosol particle diffusion. For particles with radii larger than ~ 10 nm, electron number density perturbations could maintain for several hours after the initial creation mechanism of particle density perturbations stopped. Ø. Lie-Svendsen et al studied the response of the mesopause plasma to small-scale aerosol particle density perturbations based on time-dependent, one-dimensional, coupled continuity and momentum equations for an arbitrary number of charged and neutral particle species (Lie‐Svendsen, et al. 2003). The results were consistent with the solution of Markus Rapp's model that particle density structures on the order of a few meters could lead to small-scale electron density perturbations due to electron attachment and ambipolar diffusion.

In all researches mentioned above, the aerosol particle density profiles were directly set as specific small scale structures such as Gaussian, hyperbolic tangent or sinusoidal. And the formation processes of these small-scale particle density structures have always been neglected, though they are helpful to understand PMSE phenomenon better. In view of this, the purpose of this study is trying to explain the formation of these ice particle irregularities through a growth and motion model. The growth of particles is based on collision and adsorption process of water vapor and condensation nuclei. The particle movement is mainly controlled by the gravity and the neutral drag force. With the obtained ice particle density structures, the corresponding electron and ion density is calculated based on a charging model, in which the dynamic continuity equations for ice particles with various charges and ions, momentum equation for ions and electrons, and quasi-neutral condition are included.

2 Model

In this section the equations of the growth and motion model of condensation nuclei and the charging model of ice particles are described.

The simulation is carried out at summer polar mesopause region between 80 ~ 90 km, where the water vapor carried by neutral gas is supposed to move upwards at a constant speed(Garcia and Solomon 1985). It is assumed that micrometeorites enter the study region at a certain flux from the upper boundary, and volcanic ash or particles ejected by aircraft rise into the region from the lower boundary. These grains serve as condensation cores. With the temperature lower than the frost point(Körner and Sonnemann 2001), the water vapor molecules that touch the surface of the grains due to thermal motion can easily condense into ice, which makes condensation cores become ice particles and keep growing. In this article, we will only discuss the growth, motion and charging of particles inside the condensation layer. Meantime, only vertical transport of particles and plasma is considered in this paper, because the horizontal gradients of transport parameters are much smaller than the vertical ones(Lie‐Svendsen, et al. 2003).

For growing ice particles, the dynamic equation for variable mass object is applied:

$$m_{\mathrm{d}}\frac{\mathrm{d}\boldsymbol{u}_{\mathrm{d}}}{\mathrm{d}t}+(\boldsymbol{u}_{\mathrm{d}}-\boldsymbol{u})\frac{\mathrm{d}m_{\mathrm{d}}}{\mathrm{d}t}=m_{\mathrm{d}}\boldsymbol{g}-\mu_{\mathrm{dn}}m_{\mathrm{d}}(\boldsymbol{u}_{\mathrm{d}}-\boldsymbol{u})+q_{\mathrm{d}}\boldsymbol{E} \tag{1}$$

where m_{d}, $\boldsymbol{u}_{\mathrm{d}}$ and q_{d} are the mass, velocity, and charge of ice particles respectively. $\boldsymbol{u}$ is the velocity of neutral gas; $\boldsymbol{g}$ is the gravitational acceleration; μ_{dn} is the collision frequency between ice particles and gas; and $\boldsymbol{E}$ is the electric field. The electric force has trivial effect on the motion of ice particles, because the charge-mass ratio of particles is usually very small(Jensen and Thomas 1988;Pfaff, et al. 2001). The inertial term is also negligible since its magnitude is much smaller that gravity (Garcia and Solomon 1985).

We assume that all water molecules colliding with ice particles during thermal motion can condense on them for the water vapor is oversaturated(Lübken 1999). Ignoring reverse process such as sublimation, the mass change rate for ice particles is $\mu_{\mathrm{wd}} m_{\mathrm{w}}$. The collision frequency $\mu_{\mathrm{wd}} = n_{\mathrm{w}} \pi r_{\mathrm{d}}^2 v_{\mathrm{w}}$ based on the hard-sphere collision model(Lieberman and Lichtenberg 2005). m_{w}, n_{w} and v_{w} are mass, number density and thermal velocity of water molecules, respectively.

The collision frequency between air molecules and ice particles in the neutral drag force term is(Schunk 1977)

$$\mu_{\mathrm{dn}} = \frac{8}{3\sqrt{\pi}} \frac{n_{\mathrm{n}} m_{\mathrm{n}}}{m_{\mathrm{d}} + m_{\mathrm{n}}} \sqrt{\frac{2k_{\mathrm{B}} T_{\mathrm{g}} (m_{\mathrm{d}} + m_{\mathrm{n}})}{m_{\mathrm{d}} m_{\mathrm{n}}}} \pi (r_{\mathrm{d}} + r_{\mathrm{n}})^2 \tag{2}$$

where n_{n}, m_{n}, and r_{n} are number density, mean molecule mass, and effective radius of neutral molecule, respectively. T_{g} is the gas temperature. The neutral molecule mass m_{n} is assumed as $28.96 m_{\mathrm{u}}$. $\mathrm{m_u}$ is the proton mass.

From Eq. (1) we can get the velocity of ice particles

$$\boldsymbol{u}_{\mathrm{d}} = \boldsymbol{u} + \frac{m_{\mathrm{d}}}{\mu_{\mathrm{dn}} m_{\mathrm{d}} + \mu_{\mathrm{wd}} m_{\mathrm{w}}} \boldsymbol{g} \tag{3}$$

With the facts that $n_{\mathrm{w}} \ll n_{\mathrm{n}}$(Seele and Hartogh 1999), $m_{\mathrm{w}} \ll m_{\mathrm{d}}$, $m_{\mathrm{n}} \ll m_{\mathrm{d}}$, $r_{\mathrm{n}} \ll r_{\mathrm{d}}$ and $v_{\mathrm{n}} \sim v_{\mathrm{w}}$, and taking vertical up to be the positive direction, the velocity of ice particles is simplified as

$$u_{\mathrm{d}} = u - g/\mu_{\mathrm{dn}} \tag{4}$$

Ice particles are composed of condensation nuclei and attached ice. The mass of a single ice particle is

$$m_{\mathrm{d}} = \frac{4}{3} \pi r_0^3 \rho_0 + \frac{4}{3} \pi (r_{\mathrm{d}}^3 - r_0^3) \rho_{\mathrm{d}} \tag{5}$$

where r_0 and ρ_0 are the initial radius and mass density of condensation nuclei, and ρ_{d} is the mass density of ice.

Based on the expressions of m_{d} and μ_{dn}, the relationship between ice particle velocity and radius is

$$u_{\mathrm{d}} = u - \frac{g}{n_{\mathrm{n}} m_{\mathrm{n}} v_{\mathrm{n}}} [\rho_{\mathrm{d}} r_{\mathrm{d}} + (\rho_0 - \rho_{\mathrm{d}}) \frac{r_0^3}{r_{\mathrm{d}}^2}] \tag{6}$$

At the upper and lower boundaries of study region, with $r_{\mathrm{d}} = r_0$ the initial velocity of condensation nuclei is

$$u_{\mathrm{d0}} = u(1 - r_0/r_{\mathrm{c}}) \tag{7}$$

r_{c} is the critical radius

$$r_{\mathrm{c}} = n_{\mathrm{n}} m_{\mathrm{n}} v_{\mathrm{n}} u/(g \rho_0) \tag{8}$$

When the radius of condensation nuclei $r_0 > r_c$, gravity is larger than the neutral drag force, $v_{d0} < 0$, and particles move downwards. Otherwise, particles move upwards.

Based on the relation of m_d with r_d, the change rate of ice particle radius is

$$\frac{\mathrm{d}r_{\mathrm{d}}}{\mathrm{d}t} = \frac{1}{4}\frac{n_{\mathrm{w}} m_{\mathrm{w}} v_{\mathrm{w}}}{\rho_{\mathrm{d}}} = c \tag{9}$$

It is easy to so that the ice particle radius increases linearly with time

$$r_{\mathrm{d}} = r_0 + ct \tag{10}$$

Then the particle trajectory can be obtained by the following integral

$$z - z_0 = \int_0^t u_{\mathrm{d}} \mathrm{d}t = c^{-1} \int_{r_0}^{r_{\mathrm{d}}} u_{\mathrm{d}} \mathrm{d}r_{\mathrm{d}} \tag{11}$$

z_0 is the reference height where condensation nuclei enter the studied region. It is set that $z_0 = 0$ for the lower boundary and $z_0 = h$ for the upper one, where h is the distance between the two boundaries.

We assume that the condensation nucleus radius ranging from $r_{0\min}$ to $r_{0\max}$ has a certain distribution function $f(r_0)$. The density of condensation nuclei with radius in a small scale $r_0 \to r_0 + \mathrm{d}r_0$ is $\mathrm{d}n(r_0) = f(r_0)\,\mathrm{d}r_0$, and their velocity is u_{d0}. When these particles arrive at height z, their radius increases to $r_d(r_0, z)$, the corresponding number density turns into $\mathrm{d}n(r_0, z)$, and the velocity becomes $u_d(r_0, z) = v_d[r_0, r_d(r_0, z)]$. According to the particle-conservation law, we have

$$u_{\mathrm{d}0} \mathrm{d}n(r_0) = u_{\mathrm{d}}(r_0, z) \mathrm{d}n(r_0, z) \tag{12}$$

Then the number density of ice particles at height z can be obtained by

$$n_{\mathrm{d}}(z) = \int \mathrm{d}n(r_0, z) = \int_{r_{0\min}}^{r_{0\max}} \frac{u_{\mathrm{d}0} f(r_0)}{u_{\mathrm{d}}(r_0, z)} \mathrm{d}r_0 \tag{13}$$

The average ice particle radius at height z is

$$\bar{r}_{\mathrm{d}}(z) = \frac{\int r_{\mathrm{d}}(z) \mathrm{d}n(r_0, z)}{n_{\mathrm{d}}(z)} \tag{14}$$

Through integrating all the condensation nucleus radii, stable distribution of n_d and r_d can be obtained. The particles keep entering and leaving the condensation region, but as long as the external environment does not change, the distribution of particle density and radius remains unchanged. Then the influence of these stable n_d and r_d profiles on electron and ion density is calculated.

Considering generation, recombination, and loss on particles, the continuity equation for ion density can be written as

$$\frac{\partial n_{\mathrm{i}}}{\partial t} + \frac{\partial (n_{\mathrm{i}} u_{\mathrm{i}})}{\partial z} = Q - \alpha n_{\mathrm{i}} n_{\mathrm{e}} - D^{+} n_{\mathrm{i}} \tag{15}$$

Ignoring gravity, the drift velocity of ions u_i is determined by

$$u_{\mathrm{i}} = \frac{eE}{m_{\mathrm{i}}\mu_{\mathrm{in}}} - \frac{k_{\mathrm{B}}T_{\mathrm{g}}}{m_{\mathrm{i}}\mu_{\mathrm{in}}}\frac{1}{n_{\mathrm{i}}}\frac{\partial n_{\mathrm{i}}}{\partial z} \tag{16}$$

The electric field E is mainly determined by electron density gradient because the diffusion coefficient and mobility of electrons are much larger than that of ions:

$$E = -\frac{k_{\mathrm{B}}T_{\mathrm{g}}}{e}\frac{1}{n_{\mathrm{e}}}\frac{\partial n_{\mathrm{e}}}{\partial z} \tag{17}$$

In the typical PMSE layer, there are several kinds of ions carrying one unit positive charge: N_2^+, O_2^+, NO^+ and $H^+(H_2O)_n$. According to Ref. (Reid 1990), the averaged ion parameters n_{i}, m_{i}, and T_{g} are applied to describe the density, mass, and temperature of ions, respectively, and the averaged ion mass m_{i} is set as $50m_{\mathrm{u}}$. According to Hill and Bowhill's theory (Hill and Bowhill 1977), the ion-neutral collision frequency is

$$\begin{aligned}\mu_{\mathrm{in}} = 2.6\times10^{-15}n_{\mathrm{n}}\Bigg(&0.78\frac{28}{M_{\mathrm{i}}+28}\sqrt{1.74\frac{M_{\mathrm{i}}+28}{28M_{\mathrm{i}}}}\\ &+0.21\frac{32}{M_{\mathrm{i}}+32}\sqrt{1.57\frac{M_{\mathrm{i}}+32}{32M_{\mathrm{i}}}}+0.01\frac{40}{M_{\mathrm{i}}+40}\sqrt{1.64\frac{M_{\mathrm{i}}+40}{40M_{\mathrm{i}}}}\Bigg)\end{aligned} \tag{18}$$

where $M_{\mathrm{i}} = m_{\mathrm{i}}/m_{\mathrm{u}}$.

The production rate for ions and electrons Q is chosen as 3.6×10^7 $\mathrm{m^{-3}s^{-1}}$ and electron-ion recombination coefficient α is set as 10^{-12} $\mathrm{m^3s^{-1}}$ (Lie-Svendsen, et al. 2003). Then the undisturbed density of ions and electrons $n_0 = 6 \times 10^9$ $\mathrm{m^{-3}}$. The loss coefficient of ions on ice particles $D^+ = \Sigma n_q v_{\mathrm{i},q}$, where n_q is the number density of the q-charged ice particles, and $v_{\mathrm{i},q}$ represents the capture rate of ions by particles with q charges. According to the quantized stochastic charging model (Robertson and Sternovsky 2008):

$$v_{i,q\le0} = \pi r_{\mathrm{d}}^2 c_{\mathrm{i}}\left(1 + C_q\sqrt{\frac{e^2}{16\varepsilon_0 k_{\mathrm{B}}T_{\mathrm{g}}r_{\mathrm{d}}}} + D_q\frac{e^2}{4\pi\varepsilon_0 k_{\mathrm{B}}T_{\mathrm{g}}r_{\mathrm{d}}}\right) \tag{19}$$

The particle radius r_{d} used here is the averaged radius $\bar{r}_{\mathrm{d}}$, which is obtained according to Eq. (14). The ion thermal velocity $c_{\mathrm{i}} = (8k_{\mathrm{B}}T_{\mathrm{g}}/\pi m_{\mathrm{i}})$. k_{B} is Boltzmann's constant and ε_0 is the permittivity of vacuum. C_q and D_q are given in Table 1 of Robertson and Sternovsky's work (Robertson and Sternovsky 2008). And the corresponding capture rates of electrons by particles (Robertson and Sternovsky 2008) are written as

$$v_{\mathrm{e},q\ge0} = \pi r_{\mathrm{d}}^2 c_{\mathrm{e}}\left(1 + C_q\sqrt{\frac{e^2}{16\varepsilon_0 k_{\mathrm{B}}T_{\mathrm{g}}r_{\mathrm{d}}}} + D_q\frac{e^2}{4\pi\varepsilon_0 k_{\mathrm{B}}T_{\mathrm{g}}r_{\mathrm{d}}}\right) \tag{20}$$

$$v_{\mathrm{e},q<0} = \pi r_\mathrm{d}^2 \gamma^2 c_\mathrm{e} \exp\left[-\frac{|q| e^2}{4\pi\varepsilon_0 k_\mathrm{B} T_\mathrm{g} r_\mathrm{d} \gamma} \left(1 - \frac{1}{2\gamma\left(\gamma^2 - 1\right)|q|} \right) \right] \tag{21}$$

The thermal velocity of electrons $c_\mathrm{e} = (8k_\mathrm{B}T_\mathrm{g}/\pi m_\mathrm{e})$, and the value of γ for each q is referred from Natanson's paper (Natanson 1960).

Although the distribution of total particle density $n_\mathrm{d} = \Sigma n_q$ has reached stable state under the effects of gravity and neutral drag force, the number density of the q-charged ice particles n_q is dynamic in the charging process. The continuity equation for q-charged ice particles is

$$\frac{\partial n_q}{\partial t} = n_{q+1} v_{\mathrm{e},q+1} n_\mathrm{e} + n_{q\text{-}1} v_{\mathrm{i},q\text{-}1} n_\mathrm{i} - (n_q v_{\mathrm{e},q} n_\mathrm{e} + n_q v_{\mathrm{i},q} n_\mathrm{i}) \tag{22}$$

According to the growth and motion model, the maximum radius of ice particles involved in this study is about 11 nm (see below), which is similar to the ice particle radius (10 nm) used in the paper of Lie-Svendsen et al. (Lie-Svendsen, et al. 2003;Rapp and Lübken 2001). So based on their work, it is assumed that a single particle carries two negative charges at most, i.e., q = -2, -1, 0 and +1 in this study.

According to the typical parameters in PMSE region(Rapp and Lübken 2001), the plasma Debye length λ_D is estimated to be about 9 mm, which is much smaller than the vertical spatial scale of PMSE layer. So the dusty plasma satisfies the quasi-neutral condition:

$$n_\mathrm{i} + \sum_q q n_q = n_\mathrm{e} \tag{23}$$

In subsequent calculations, parameters are taken in the atmospheric environment at altitude of 85 km. The number density of neutrals $n_\mathrm{n} = 2.3\times10^{20}$ m^{-3}(Hill, et al. 1999), the number density of water vapor $n_\mathrm{w} = 2.5\times10^{14}$ m^{-3}(Seele and Hartogh 1999), temperature T_g = 150 K, the mass density of ice $\rho_\mathrm{d} = 1\times10^3$ kg/m^3, the velocity of neutral wind u = 3 cm/s(Garcia and Solomon 1985), the mass density of condensation nucleus $\rho_0 = 2.7\times10^3$ kg/m^3, and the growth rate of ice particles $c \approx 7.8\times10^{-4}$ nm/s. In this work, we only consider the growth and movement of condensation nucleus which fall from the upper boundary with initial radius $r_0 > r_\mathrm{c}$ and rise from lower boundary with $r_0 \leq r_\mathrm{c}$.

3 Results and discussion

For simplicity, dimensionless parameters are used:

$$V_\mathrm{d} = v_\mathrm{d}/u, \quad \rho = \rho_\mathrm{d}/\rho_0, \quad R_0 = r_0/r_\mathrm{c}, \quad R_\mathrm{d} = r_\mathrm{d}/r_\mathrm{c}$$

$$T = t/t_\mathrm{c}, \quad Z = (z - z_0)/z_\mathrm{c}$$

where $t_\mathrm{c} = r_\mathrm{c}/c$, which represents the time it takes for ice particle radius r_d growing to

$r_\mathrm{d} + r_\mathrm{c}$, and $z_\mathrm{c} = ut_\mathrm{c}$ is the distance that neutral wind moves during the time t_c. In this study $r_\mathrm{c} = 4.2$ nm, $t_\mathrm{c} \approx 5385$ s, and $z_\mathrm{c} \approx 161$ m.

The expression for dimensionless ice particle velocity is

$$V_\mathrm{d} = 1 - \rho R_\mathrm{d} - (1-\rho)\frac{R_0{}^3}{R_\mathrm{d}{}^2} \tag{24}$$

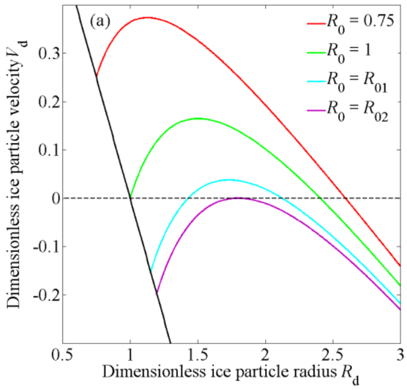
The expressions for dimensionless position coordinate of particles based on T and R_d are

$$Z(R_0, T) = T - \frac{1}{2}\rho T(T + 2R_0) - (1-\rho)R_0{}^2\frac{T}{T + R_0} \tag{25}$$

$$Z(R_0, R_\mathrm{d}) = R_\mathrm{d} - R_0 - \frac{1}{2}\rho(R_\mathrm{d}{}^2 - R_0{}^2) + (1-\rho)R_0{}^3\left(\frac{1}{R_\mathrm{d}} - \frac{1}{R_0}\right) \tag{26}$$

The relation between V_d and R_d is illustrated in Fig. 1(a), which shows that condensation nuclei with initial radius $R_0 \leq 1$ rise into the PMSE region through the lower boundary, while particles with $R_0 > 1$ fall into the region from the upper boundary. At the beginning, the upward-moving particles accelerate and the downward ones decelerate due to $\partial V_\mathrm{d}/\partial R_\mathrm{d} = 2 - 3\rho > 0$ when $R_\mathrm{d} = R_0$. Later, with the increase of R_d, $\partial V_\mathrm{d}/\partial R_\mathrm{d} < 0$, all particles will move with a downward acceleration, which makes them move downward eventually.

Figure 1(b) shows the movement curves of ice particles near the lower boundary. These particles, with an initial radius $R_0 \leq 1$, rise into the condensation layer. With the collection of ice, the grains become larger and heavier, which leads to the deceleration of the grains. And then, the grains will accelerate downward until they leave the condensation layer from the lower boundary. All particles rising from the lower boundary will retrace in the range of $Z_\mathrm{m} < Z < Z_\mathrm{M}$.



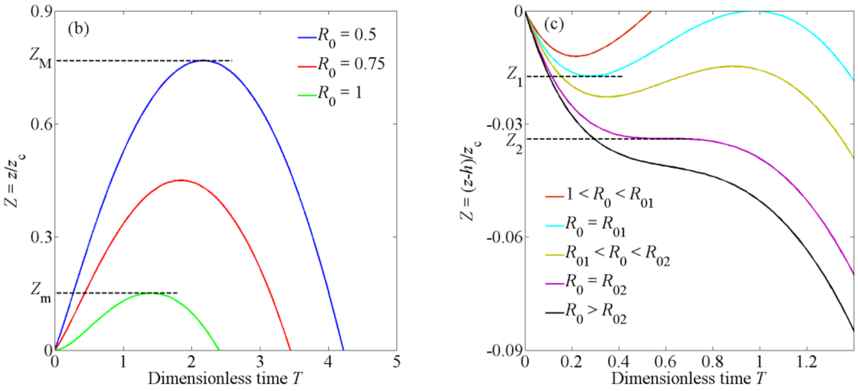


Figure 1 (a) The dependence of ice particle velocity on radius for different initial nucleus radii. The black solid line $V_{d0} = 1- R_0$ represents the distribution of initial particle velocity with respect to initial radius. (b) The movement curves of ice particles near the lower boundary. (c) The movement curves of ice particles near the upper boundary. Z_m is the maximum height that particles with initial radius $R_0 = 1$ can reach; Z_M is the maximum height that particles with initial radius $R_0 = R_{0min} = 0.5$ can reach. Based on above parameters, $Z_m = 0.1512$ and $Z_M = 0.7631$. R_{01} and R_{02} are two critical values of condensation nucleus radius. For $R_0 = R_{01}$ particles fall into the condensation layer, first retrace at height Z_1, and then retrace exactly at the upper boundary. When $R_0 = R_{02}$, the particles move down and reach the height Z_2, the velocity and acceleration are exactly zero, and then they continue to move down. According to above parameters, R_{01} and R_{02} are solved as 1.1519 and 1.19705, respectively.

Figure 1(c) shows the movement curves of ice particles near the upper boundary, which can be sorted by the value of R_0. For $1 < R_0 < R_{01}$, the neutral drag force increases faster than gravity as the particles fall. The particles decelerate to zero speed, retrace upward, and then leave the condensation layer from the upper boundary. For $R_0 = R_{01}$, the particles retrace at the height $Z = Z_1$. Then they arrive at $Z = 0$ with exactly zero velocity, and the particles move back into the condensation layer again. For $R_{01} < R_0 < R_{02}$, the particles retrace upward in the range of $Z_2 < Z < Z_1$ and move downward again before they reach the upper boundary. For $R_0 = R_{02}$, the particles decelerate downward until zero speed at $Z = Z_2$. Here, the acceleration happens to be zero. Then the gravity exceeds the drag force, and the particles accelerate downward. For $R_0 > R_{02}$, the particles keep going down after entering the condensation layer.

From Fig. 1, it is concluded that the particles with a certain range of initial radius will move up and down several times near the boundary, namely, ice particles will accumulate at that region and form some kind of small-scale density structure. The resulting number density and radius distribution of ice particles are

$$n_{\mathrm{d}}(Z) = n_0 \int_{R_{0\min}}^{R_{0\max}} \frac{V_{\mathrm{d}0} F(R_0)}{V_{\mathrm{d}}[R_0, R_{\mathrm{d}}(R_0, Z)]} \mathrm{d}R_0 \tag{27}$$

$$\bar{R}_{\mathrm{d}}(Z) = \frac{n_0}{n_{\mathrm{d}}(Z)} \int_{R_{0\min}}^{R_{0\max}} \frac{R_{\mathrm{d}}(Z) V_{\mathrm{d}0} F(R_0)}{V_{\mathrm{d}}[R_0, R_{\mathrm{d}}(R_0, Z)]} \mathrm{d}R_0 \tag{28}$$

where n_0 is the density of condensation cores at the boundary, and is assumed as 5×10^8 m^{-3} (Bardeen, et al. 2008). The normalized radius distribution function $F(R_0)$ satisfies $\int_{R_{0\min}}^{R_{0\max}} F(R_0)\mathrm{d}R_0 = 1$.

Firstly, the density and radius distribution of ice particles near the lower boundary are solved. It is shown in Fig. 1(b) that all ice particles with initial radius $R_0 \le 1$ will pass the range $0 < Z < Z_m$ twice, so they contribute twice to the calculation of particle density. And in the height range $Z_m < Z < Z_M$, only the particles that reach the Z height can contribute to the density at Z. their density and mean radius near the lower boundary are shown below:

$$n_{\mathrm{d}}(Z) = n_0 \int_{0.5}^{R_{0Z}} V_{\mathrm{d}0} F(R_0) \left[\frac{1}{V_{\mathrm{d}1}(R_0, R_{\mathrm{d}1})} + \frac{1}{|V_{\mathrm{d}2}(R_0, R_{\mathrm{d}2})|} \right] \mathrm{d}R_0 \tag{29}$$

$$\bar{R}_{\mathrm{d}}(Z) = \frac{n_0}{n_{\mathrm{d}}(Z)} \int_{0.5}^{R_{0Z}} V_{\mathrm{d}0} F(R_0) \left[\frac{R_{\mathrm{d}1}}{V_{\mathrm{d}1}(R_0, R_{\mathrm{d}1})} + \frac{R_{\mathrm{d}2}}{|V_{\mathrm{d}2}(R_0, R_{\mathrm{d}2})|} \right] \mathrm{d}R_0 \tag{30}$$

R_{d1} and R_{d2} are particle radii when particles pass through the Z height; V_{d1} and V_{d2} are their corresponding velocities; the upper limit of integral R_{0Z} can be determined by

$$R_{0Z} = \begin{cases} 1 & \text{if } 0 < Z < Z_{\mathrm{m}} \\ \text{solution of } \left(Z\left(R_{0Z}, R_{\mathrm{d}}\right) = Z\right) & \text{if } Z_{\mathrm{m}} < Z < Z_{\mathrm{M}} \end{cases} \tag{31}$$

In this study, the radius distribution function of condensation cores is assumed as Gaussian distribution

$$F(R_0) = A\exp[-(R_0 - R_{00})^2 / \Delta^2] \tag{32}$$

where the center of the radius distribution function R_{00} is chosen as 0.8, the characteristic width Δ = 0.01, and the corresponding normalized coefficient A = 56.4.

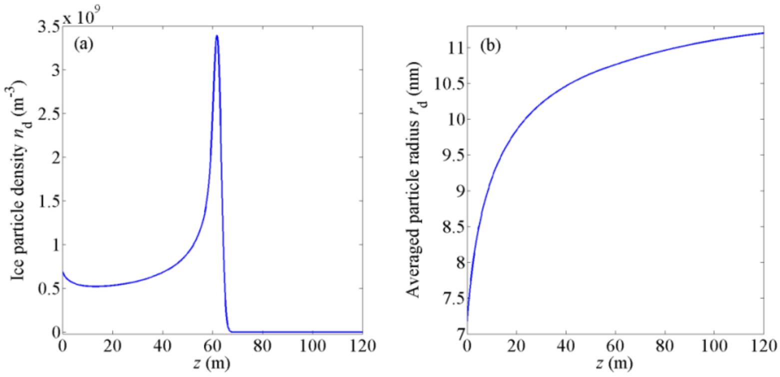
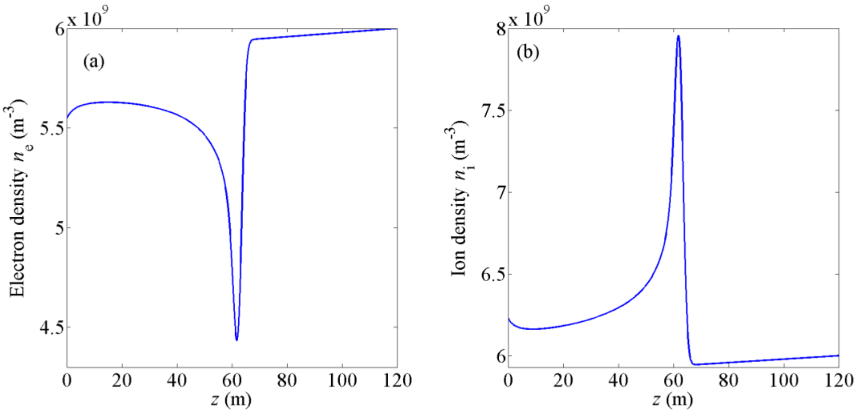


Figure 2 The distribution of (a) ice particle density and (b) mean particle radius near the lower

boundary of condensation layer.

The obtained density and mean radius of ice particles near the lower boundary are present in Fig. 2(a) and 2(b) respectively. Figure 2(a) shows that a sharp peak appears in the density distribution of ice particles. The width at half maximum of the irregularity is about 5 meters, which is consistent with the assumed ice particle density structure scale in the theoretical work (Lie-Svendsen, et al. 2003;Rapp and Lübken 2003) and observation by the sounding rocket flight ECT02 in July 1994 (Rapp and Lübken 2004). From Fig. 2(b), we can see that the average radius of ice particles increases from 7 nm to 11 nm with height.

With the obtained density and average radius of ice particles in Fig. 2(a) and Fig. 2(b), the density distribution of electrons, ions, and charged ice particles is calculated based on the charging model described by Eq. (15) ~ (23). At the initial moment of the charging model, all ice particles are assumed to be neutral to conduct the calculation more conveniently, since the final distributions of charge are independent on the initial ice particle charge state (Lie-Svendsen, et al. 2003). The timescale of electron collected by negatively charged particles with a radius of 10 nm is about 700 s, which is the longest timescale in the charging process. And a quasi-steady state of charging can be obtained after this timescale. Therefore, the calculation is terminated after 1000 s and the results are illustrated in Fig. 3.



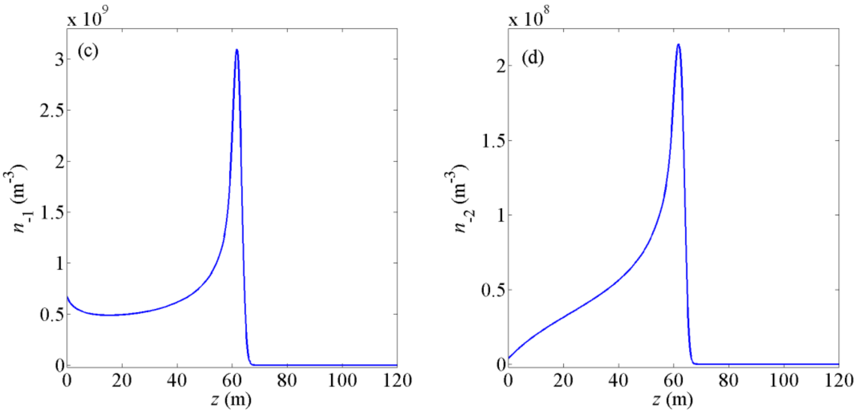


Figure 3 The number density distribution of (a) electrons n_e, (b) ions n_i, (c) particles carrying one negative charge n_{-1}, and (d) particles carrying two negative charges n_{-2} near the lower boundary of condensation layer at t = 1000 s.

Figure 3(a) shows that electron density decreases sharply around z = 60 m due to adsorption by particles. And the reduction of electron density $\Delta n_e \approx (n_{-1} + 2n_{-2})/2$, which is in line with the results under diffusion equilibrium approximations in (Lie-Svendsen, et al. 2003). Ion number density increases sharply around 60 m due to its movement under ambipolar electric field. The ambipolar diffusion process of electrons and ions has been described in detail in (Lie-Svendsen, et al. 2003). Electron density is anti-correlated to density irregularities of ions and charged ice particles due to attachment and diffusion processes. These anti-correlations are in agreement with rocket observations by the sounding rocket flight SCT-06 in August 1993 (Lie-Svendsen, et al. 2003) and the sounding rocket flight ECT02 in July 1994 (Rapp and Lübken 2004), respectively. It can be extracted from Fig. 3(c) and Fig. 3(d) that, for particles with radii ranging from 7 nm to 11 nm, the proportion of particles carrying one negative charge ranges from 97.5% to 85.1%, and that value for particles carrying two negative charges is 0.53% - 13.6%, which is consistent with observations by Havnes et al. (Havnes, et al. 1996) and numerical results by Rapp and Lübken (Rapp and Lübken 2001). The density of positively charged particles is less than 1.1×10^5 m^{-3} and is insignificant in this study.

Next, the parameters of ice particles and plasma near the upper boundary are discussed based on the movement curves of ice particles near the upper boundary, which are shown below:

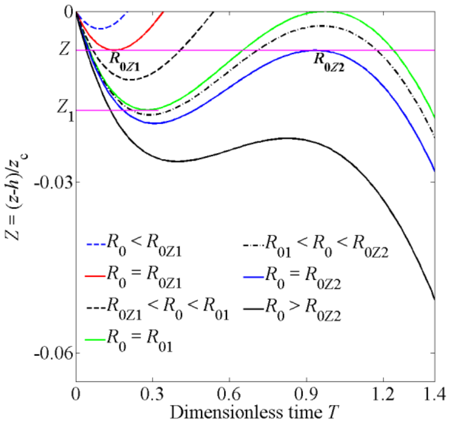


Figure 4 The movement curves of ice particles near the upper boundary. The particles with initial radius R_{0Z1} move upward after turning back at the Z height (the red line), and the particles with initial radius R_{0Z2} move downward after turning back at Z (the blue line).

For $Z_1 < Z < 0$, two kinds of particles turn back at Z: particles with initial radius R_{0Z1} and R_{0Z2}. They go upward and downward separately as shown in Fig. 4. And the values of R_{0Z1} and R_{0Z2} are determined by equations $V_d(R_{0Z}, R_d) = 0$ and $Z(R_{0Z}, R_d) = Z$. The contribution of ice particles to the density distribution near the upper boundary can be classified as follows:

(1) $R_0 < R_{0Z1}$: ice particles cannot reach Z and make no contributions to the number density.

(2) $R_{0Z1} < R_0 < R_{01}$: ice particles pass through Z twice and contribute to $n_d(Z)$ twice. The radius of particles when passing through the Z height can be obtained as R_{d31} and R_{d32} based on Eq. (26). Meanwhile their corresponding velocities are calculated as V_{d31} and V_{d32} respectively based on Eq. (24).

(3) $R_{01} < R_0 < R_{0Z2}$: ice particles pass through Z three times. The corresponding radii and velocities at Z are defined as R_{d41}, R_{d42}, R_{d43}; V_{d41}, V_{d42}, V_{d43}.

(4) $R_0 > R_{0Z2}$: ice particles pass through Z only once and their radius and velocity are R_{d5} and V_{d5}, respectively.

Substituting these parameters into Eq. (27) and (28), the density and mean radius of ice particles in the range of $Z_1 < Z < 0$ are deduced as

$$\begin{aligned} n_d(Z) = {} & n_0 \int_{R_{0Z1}}^{R_{01}} V_{d0} F(R_0) \left[\frac{1}{|V_{d31}(R_0, R_{d31})|} + \frac{1}{V_{d32}(R_0, R_{d32})} \right] dR_0 \\ & + n_0 \int_{R_{01}}^{R_{0Z2}} V_{d0} F(R_0) \left[\frac{1}{|V_{d41}(R_0, R_{d41})|} + \frac{1}{V_{d42}(R_0, R_{d42})} + \frac{1}{|V_{d43}(R_0, R_{d43})|} \right] dR_0 \\ & + n_0 \int_{R_{0Z2}}^{R_{0\max}} \frac{V_{d0} F(R_0)}{|V_{d5}(R_0, R_{d5})|} dR_0 \end{aligned} \tag{33}$$

$$
\begin{aligned}
\bar{R}_{\mathrm{d}}(Z) = {} & \frac{n_0}{n_{\mathrm{d}}(Z)} \int_{R_{0Z1}}^{R_{01}} V_{\mathrm{d}0} F(R_0) \left[\frac{R_{\mathrm{d}31}}{|V_{\mathrm{d}31}(R_0, R_{\mathrm{d}31})|} + \frac{R_{\mathrm{d}32}}{V_{\mathrm{d}32}(R_0, R_{\mathrm{d}32})} \right] \mathrm{d}R_0 \\
& + \frac{n_0}{n_{\mathrm{d}}(Z)} \int_{R_{01}}^{R_{0Z2}} V_{\mathrm{d}0} F(R_0) \left[\frac{R_{\mathrm{d}41}}{|V_{\mathrm{d}41}(R_0, R_{\mathrm{d}41})|} + \frac{R_{\mathrm{d}42}}{V_{\mathrm{d}42}(R_0, R_{\mathrm{d}42})} + \frac{R_{\mathrm{d}43}}{|V_{\mathrm{d}43}(R_0, R_{\mathrm{d}43})|} \right] \mathrm{d}R_0 \qquad (34) \\
& + \frac{n_0}{n_{\mathrm{d}}(Z)} \int_{R_{0Z2}}^{R_{0\max}} \frac{R_{\mathrm{d}5} V_{\mathrm{d}0} F(R_0)}{|V_{\mathrm{d}5}(R_0, R_{\mathrm{d}5})|} \mathrm{d}R_0
\end{aligned}
$$

where the radius distribution function of condensation cores $F(R_0)$ are set to satisfy the Gaussian distribution with the distribution function center $R_{00} = 1.08$, the characteristic width $\Delta = 0.01$, and the corresponding normalized coefficient $A = 56.4$.

The ice particle density in the range of $Z < Z_1$ is close to zero, since only particles with initial radius $R_0 \geq R_{01}$ can arrive at the range and the number of particles in this radius range is very few based on the parameters of $F(R_0)$ set above.

At the upper boundary, the number density of condensation cores n_0 is set as 5×10^8 m^{-3}; the maximum radius of condensation cores $R_{0\max} = 1.3$. The number density and mean radius of ice particles are obtained from Eq. (33) and (34). Then the density distribution of electrons, ions, and charged ice particles is calculated further based on the charging model.

Figure 5(a) shows that there is a meter scale structure in the distribution of ice particle density, which is consistent with the assumed ice particle density structure scale in previous theoretical work (Lie‐Svendsen, et al. 2003;Rapp and Lübken 2003) and rocket observations (Rapp and Lübken 2004). The average radius of ice particles is slightly larger than 5 nm (shown in Fig. 5(b)).

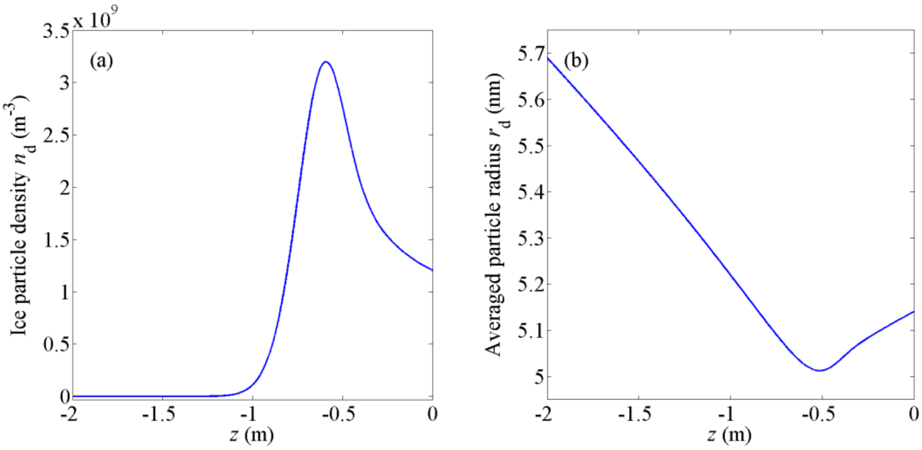


Figure 5 The distribution of (a) ice particle density and (b) mean particle radius near the upper boundary of condensation layer.

Figure 6(a) shows that, compared with ice particle density, there is a similar but anti-correlated structure in electron density profile because of the adsorption of electrons by particles. Due to ambipolar diffusion, ion density increases in the perturbed region. The reduction of electron density Δn_e and the increment of ion density Δn_i meet with the results under diffusion equilibrium approximations: $\Delta n_e \approx \Delta n_i \approx (n_{-1} + 2n_{-2})/2$ (Lie－Svendsen, et al. 2003). From Fig. 6(c) and Fig. 6(d) we can see that, 97% of the particles carry one negative charge, and particles carrying two negative charges are very few. This is reasonable for particles with radius slightly larger than 5 nanometers.

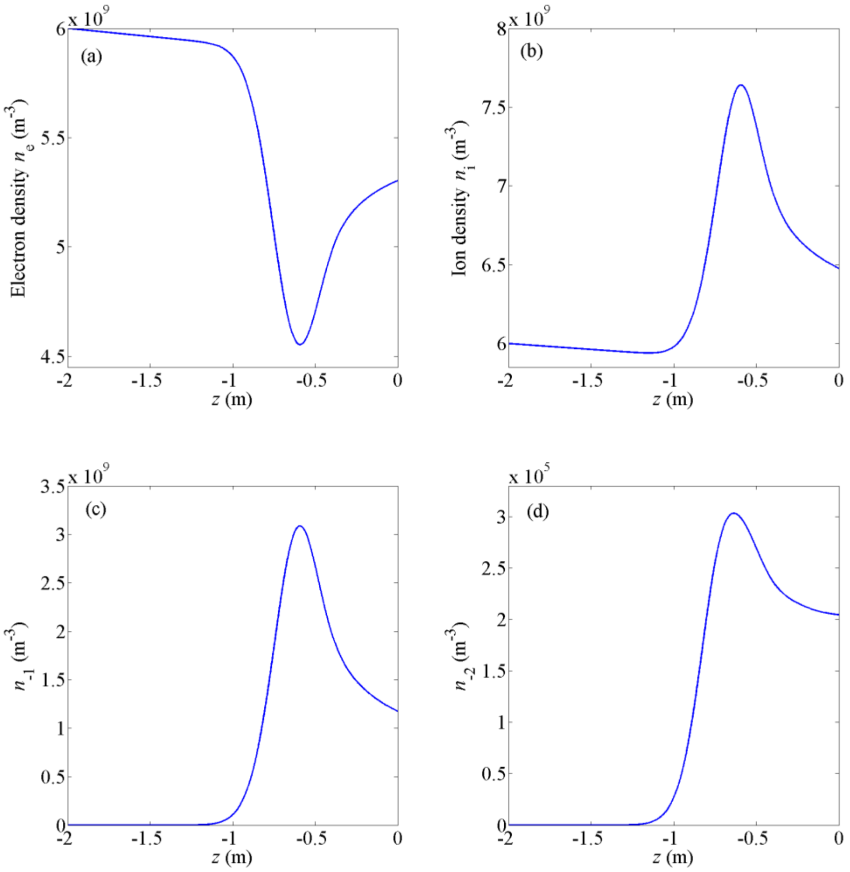


Figure 6 The number density distribution of (a) electrons, (b) ions, (c) particles carrying one negative charge, and (d) particles carrying two negative charges near the upper boundary of condensation layer at $t = 1000$ s.

4 Conclusions

In summary, a possible formation mechanism of small scale ice particle density irregularities in PMSE region is presented, and the influence of these irregularities on plasma density profile is studied. Firstly, a growth and motion model of ice particles is developed based on the adsorption of water vapor by particles and dynamic equation for variable mass object. Then the density profile of ice particles with height is investigated according to the conservation of particle number. Finally, on the basis of quasi-neutrality and the quantized stochastic charging model, the corresponding density distribution of electrons, ions, and charged ice particles is obtained. In the calculation, the parameters are chosen corresponding to an altitude of 85 km, where PMSEs are often detected.

The results show that the ice particle radius increases linearly with time. But, there is a complex relation between the velocity and radius of particles due to the different mass densities of condensation nuclei and absorbed ice. And for a certain radius of the condensation nucleus, particles can bounce and gather locally. When the radius distribution function of condensation nucleus is Gaussian, stable small-scale ice particle density structures can be obtained based on the growth and motion model. Because of the plasma attachment by ice particles and plasma diffusion, electron density decreases in the disturbed region, while ion density increases in the region, i.e., the electron density is anti-correlated to charged ice particle density and ion density, which is in consistent with most rocket observations. Furthermore, the reduction of electron density and the increment of ion density are about half the charge number density of ice particles, which is in line with the results under diffusion equilibrium approximations.

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