We would like to thank the reviewers for their valuable comments and suggestions. We have studied all comments carefully and these comments have helped us to significantly improve our manuscript. Following the reviewers' comments, we revised the manuscript. Our responses to the reviewers' comments and corresponding changes with page and line numbers in the revised manuscript are both detailed below in blue text. We mark the major changes in the track-change manuscript.

Reviewer #1 comments (RC1):

This paper uses the same methodology developed in a previous study (Chu et al., 2016) for deriving sporadic E properties from COSMIC GPS data. This study goes further by examining both the occurrence frequency and strength, as a function of season, latitude, longitude and height. A number of interesting observations are made. The authors then show that some of these observations can be explained by using winds from a global chemistry-climate model (WACCM) to calculate wind shear and hence ion convergence.

Response: Thank you for your positive comments. Many studies have reported the geographical distribution and seasonal variation in global Es layers retrieved from GPS RO signals, and nearly all of these works focused on the EsOR. The global climatology of the intensity of Es layers has not been fully studied. Our study is to investigate the global intensity of Es layers and compare the results of Es intensity with previous studies on the EsOR.

One curious omission is discussion of gravity waves, which are not explicitly resolved in WACCM if their horizontal wavelengths are smaller that ~200 km. Many of these waves penetrate into the lower thermosphere, and appear to be a major cause of sporadic E layers in the polar cap, where the near-vertical magnetic field reduces significantly the effectives of wind-shear in converging ions into layers. The authors appear to be using winds averaged over an unspecified period to determine wind shear – yet there is no discussion of how valid this is, since sporadic E often have short lifetimes of only hours.

Response: Following your suggestion, we further discussed about the role of gravity waves in the formation of Es layers in the polar cap in the revised manuscript.

The wind shear mechanism does not work efficiently at either auroral zones or the magnetic equator *(Haldoupis, 2012)*; therefore, the strong Es layers in the Earth's polar regions could be initially caused by gravity waves *(Bautista et al., 1998; MacDougall et al., 2000a, b)*. In the simulations, the gravity waves with horizontal wavelengths smaller than ~200 km are not explicitly resolved in WACCM *(Liu et al, 2014)*. In particular, the vertical motion of gravity waves dominates the formation of Es layer in the polar cap, where the near-vertical magnetic field significantly reduces the effectives of wind-shear in converging ions into layers. Polar cap gravity waves were studied by *Johnson et al. (1995); MacDougall et al. (1997)*. These layers are maintained in an ionized state by charge exchange of neutral metal atoms with NO^+ and O_2^+ ions by photoionization. These studies found that the vertical motion of gravity waves is very efficient in concentrating polar gap Es layers. The short-lived polar cap Es layers in winter appear to be associated with gravity waves. The polar cap Es layers in summer are long-lasting thin layers.

These initial concentrations of metallic ions persist and change into long-lived Es because of ambient metallic ions. The Es layers at the cusp latitude are relatively different from those at the polar cap. The cusp Es could be associated with the convergence of ionization by the electric fields *(MacDougall and Jayachandran, 2005).*

Changes: Please see page 2 lines 2-4. "At high magnetic latitudes, the vertical motion of gravity waves is very efficient in concentrating ionization of Es becuase the magnetic field lines are nearly vertical in the polar gap *(Bautista et al., 1998; MacDougall et al., 2000a, b; MacDougall and Jayachandran, 2005)*."

Please see page 5 lines 2-5. "A difference between the Es intensity and EsOR distributions is at high latitudes: that is, the occurrence rates of Es are generally low *(Arras et al., 2008)*, but the intensity of Es is relatively high. This pattern is more evident over the magnetic poles, which is likely the result of vertical motions of gravity waves in concentrating the ionization of Es layers *(MacDougall et al., 2000a, b).*

Please see page 7 lines 29-page 8 lines 13. "In our investigations, the global climatology of the intensity of Es layers is found to also have a seasonal dependence, with a pronounced maximum over midlatitudes in the summer hemisphere, as shown in Figure 5. …The cusp Es could be associated with convergence of ionization by the electric fields *(MacDougall and Jayachandran, 2005)*."

Another point is that the height distribution of sporadic E (Figure 1) shows a relatively large proportion of layers appearing between 40 and 90 km. This is dismissed here as an artefact, based on the fact that sporadic E should not form below 90 km because the ion-neutral collision frequency is too high (page 3). The explanation for the artefact is unclear – reference is made to an "RO" event, though this term is not defined in the paper – but appears to be caused by slant viewing geometries. If that is the case, how reliable is the entire distribution of layers, including those above 90 km? The authors ought to show that the distribution they are using agrees with ionosonde measurements at a particular location.

Response: Thanks for your comments. In the revised manuscript, we included more references and explain the artefact more clearly. Most of the artefact are caused by integrated influence rather than slant viewing geometries. The Es layer over lower altitudes (between 40 and 90 km) should be some artefact resulting from mapping effect integrated along the LEO-GPS ray. As a result of the integrated influence either in the SNR or the slant TEC, the effect of Es layers in the high altitudes could map down to the lower tangent point altitudes, which may induce pseudo multiple peaks in one RO event *(Zeng and Sokolovskiy, 2010; Yue et al., 2015).*

We added a result (Figure 2) to show the entire distribution of the daily average Es intensity from 2006 to 2014 retrieved from COSMIC within ±2.5° of latitude and longitude of one ionosonde station in Beijing (40.3N°, 116.2E°), which agrees with ionosonde measurements.

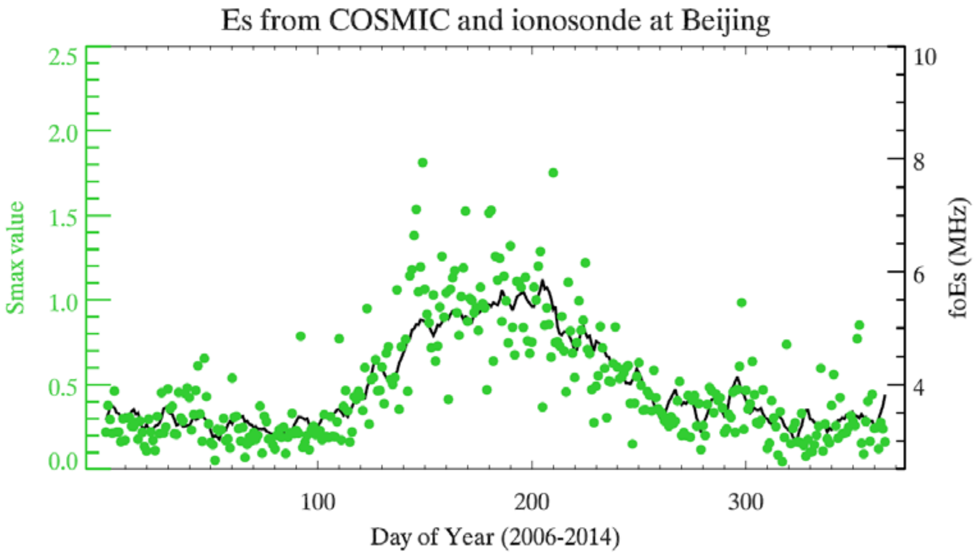

Figure 2. The entire distribution of the daily average Es intensity retrieved from COSMIC within ±2.5° of latitude and longitude of one ionosonde station and ionosonde data (foEs) in Beijing from 2006 to 2014.

Changes: Please see page 3 lines 30-page 4 lines 9. “Figure 1 shows the altitude distribution of the COSMIC S4max profiles. … Figure 2 shows the entire distribution of the daily average Es intensity from 2006 to 2014 retrieved from COSMIC within ±2.5° of latitude and longitude of one ionosonde station in Beijing (40.3N°, 116.2E°), which agrees with the ionosonde measurements (foEs).”

The paper ends on a vague and rather disappointing note: “It indicates that, in addition to the vertical windshear effects, other processes such as magnetic field effects, meteoric mass influx into the earth’s atmosphere and chemical processes of metallic ions are also likely to play an dominant role in the geographical and seasonal variations of Es layers.” There is no attempt to explain how these “chemical processes”, the meteoric mass influx, or unspecified “magnetic field effects” could explain the observations which do not accord with the wind shear theory.

Response: Thanks for your comments.

In the revised manuscript, we fulfilled the discussion section, according to the reviewer’s comments. We discussed more about the gravity waves and their dominant role in the polar gap Es layer *(MacDougall et al., 2000a, b)*. The wind shear mechanism does not work efficiently at either auroral zones or the magnetic equator *(Haldoupis, 2012)*; therefore, the Es layer in the North and South Poles are likely associated with polar gap gravity waves. The wind shear mechanism is inefficient at high geomagnetic latitudes because the magnetic field is nearly vertical. It is found that an initiation of Es layers caused by gravity wave vertical motion could account for the properties of poleward Es layers. The Es layers at the cusp latitude are relatively different from those in the polar cap. The cusp Es could be associated with convergence of ionization by the electric fields *(MacDougall et al., 2005)*.

Many studies have investigated the global climatology of the Es layer occurrence rate (EsOR) but the global climatology of the intensity of Es layers has not be been fully studied. The purpose of the present paper is to study the global intensity of Es layer. Several new and interesting observations of Es intensity are presented. Our modest effort is to present our understanding of the layered phenomena of the Es layer as the topic is relevant in the special issue: layered phenomena in the mesopause region. Firstly, the high-latitude Es layers are quite intense in our study although their occurrence rate is low as reported in *Chu et al. (2014); Shinagawa et al. (2017)*. Secondly, a noticeable global gap of Es is observed near the magnetic equator. Thirdly, clear features and geographical distribution with dependence of geomagnetic latitudes can be seen in the geomagnetic latitudes of 60-80° because of the increased spatial resolution.

As for the mechanism for the observations, our study shows the elemental mechanism responsible for Es layers based on the wind shear theory could explain the seasonal dependence of Es intensity (97-114 km) but it is hard to explain the Es seasonal dependence at higher altitudes. The wind shear theory is considered the primary theory to explain the physical production of Es layers *(Whitehead, 1989; Haldoupis et al., 2007)*, although the overall morphology of Es has not be fully explained by wind shear effect until now, as shown in Figure 9 and Figure 10 in our study. In the simulation of wind shear theory explanation for the Es seasonal variation, we calculated the vertical ion convergence by using winds from a global chemistry-climate model (WACCM). In Section 6, we conclude the results of this study. It also notes that, to accurately understand the distribution of global metallic ions, we need to further investigate the geographical and seasonal variations in Es layers combined with the ground-based ionosonde observations. We are also trying to explain those phenomena in theory and another work of more comprehensive modelling are in progress and hope to be subsequently able to explain the phenomena. We hope our effort of this study as the relevant topic in the special issue in ACP could attract more attention and researches in mechanism of the Es formation, which is an ongoing problem in the ionosphere since 1961 *(Whitehead 1961; Whitehead 1989)*.

Changes: Please see page 7 lines 29-page 8 lines 13. “In our investigations, the global climatology of the intensity of Es layers is found to also have a seasonal dependence, with a pronounced maximum over midlatitudes in the summer hemisphere, as shown in Figure 5. …The cusp Es could be associated with convergence of ionization by the electric fields *(MacDougall and Jayachandran, 2005)*.”

Please see page 9 lines 20-27. “Although the wind shear theory for the Es formation was conceived and formulated in 1960s *(Whitehead, 1961)*, its importance for understanding the formation of Es must have escaped attention. This study implies that, in addition to the vertical wind shear effects, other processes, such as the vertical motion of gravity waves, magnetic field effects, meteoric mass influx into Earth’s atmosphere and the chemical processes of metallic ions, should also be considered, which could play a dominant role in the geographical and seasonal variations in Es layers. To accurately understand and properly quantify the properties of Es layers at a global scale that are also associated with the distribution of global metallic ions, we need to combine more ground-based ionosonde data with satellite observations and extensively study the geographical and seasonal variations in Es layers.”

Specific points which need to be addressed:

p. 4, line 10: why do you state “may be caused”? You have applied several different models, including WACCM. What do they tell you about the anomalies? The specified dynamics version of WACCM would be quite informative. You also give no details about the version of WACCM output that you use, etc.

Response: In addition to the seasonal variability of Es layers, the distribution of Es also has an interannual variability. In this paper, we focus on the seasonal variability of Es by using the WACCM wind to examine the wind shear effect. In Section 4, we find that, the wind shear theory could not fully explain the Es seasonal dependence in the simulation in view of the present findings. Figure 2 also shows a modification in Es latitudinal extension. Detailed investigations on this specific cause will be a topic of further studies.

Following your suggestion, we give more details about the version of WACCM output we use in the revised manuscript. Version 4 of the WACCM (WACCM4) is a global climate model with interactive chemistry, developed at the National Center for Atmospheric Research (NCAR) *(Marsh et al., 2013)*. A specified dynamics run of WACCM4 (SD-WACCM4) was constrained by the Modern-Era Retrospective Analysis for Research and Applications (MERRA). SD-WACCM4 is used to simulate the global distribution of the divergence of ion velocity from the period of 2006 to 2014, which is consistent with the period of Es observations from the COSMIC occultation data.

Changes: Please see page 6 lines 11-15. “Version 4 of the WACCM (WACCM4) is a global climate model with interactive chemistry, developed at the National Center for Atmospheric Research (NCAR) *(Marsh et al., 2013)*. A specified dynamics run of WACCM4 (SD-WACCM4) was constrained by the Modern-Era Retrospective Analysis for Research and Applications (MERRA). SD-WACCM4 is used to simulate the global distribution of the divergence of ion velocity from the period of 2006 to 2014, which is consistent with the period of Es observations from the COSMIC occultation data.”

p. 4, line 17: surely the wind shear mechanism should be most effective at the geomagnetic equator when the magnetic field is horizontal? Why do you state that a vertical component is required for ion convergence?

Response: Thanks for your comments. It is important to note that the wind shear mechanism does not work efficiently at either auroral zones or the magnetic equator *(Haldoupis, 2012)*. The wind shear mechanism is inefficient at high geomagnetic latitudes because the magnetic field is nearly vertical. At the geomagnetic equator when the magnetic field is horizontal, in the zonal wind shear action, ions move vertically by Lorentz forcing. But they fail to converge into a layer because they are withheld by the magnetized electrons. The plasma maintains locally neutral. For a meridional wind shear process, ions move along the magnetic field lines with no Lorentz forces acted upon.

Therefore, a noticeable gap near the magnetic equator is expected, explained by the vanishing vertical component of the geomagnetic field lines which keeps the ionized particles from effectively vertically converging. This gap could also be found in the distribution of EsOR though it is not as evident in *Arras et al. (2008)*.

In the revised manuscript, we have explained it in more details.

Changes: Please see page 4 lines 25-31. "When the magnetic field is horizontal at the geomagnetic equator, under the zonal wind shear action, ions move vertically by Lorentz forcing. However, they fail to converge into a layer because they are withheld by magnetized electrons. The plasma remains locally neutral. For a meridional wind shear process, ions move along the magnetic field lines with no Lorentz forces acted upon *(Haldoupis, 2012)*. Therefore, a noticeable gap near the magnetic equator could be expected, which is explained by the vanishing vertical component of the geomagnetic field lines, keeping the ionized particles from effectively vertically converging. This gap could also be found in the distribution of EsOR although it is not as evident in *Arras et al. (2008)*."

p. 4, line 32: the sentence "The ionization of Es layers is persistently magnetic fields trapped in the polar regions" make no sense.

Response: Thanks for your comments. The sentence was removed in the revised manuscript.

Changes: Done.

p. 5, line 18: the sentence "One of the unsolved issues in the ionosphere is that the well pronounced seasonal dependence of mid-latitude Es layers does not have a comprehensive explanation, which is inexplicable from the windshear theory" contradicts your own conclusion that wind shear does explain many of the mid-latitude features!

Response: Thanks for your comments. This sentence is changed as "one of the unsolved issues in the ionosphere is that the overall morphology including the seasonal dependence of Es layers does not have a comprehensive explanation *(Whitehead, 1989; Haldoupis et al., 2007)*."

The wind shear theory was formulated by *Whitehead (1961)*. In his review article *Whitehead (1989)*, it stated that the wind shear theory is the primary theory to explain Es layers. However, it does not explain the overall morphology of sporadic E, in particular the large summer maximum. That is the motivation of our simulation study in Section 4. In our simulations, we found the ion convergence could explain the seasonal dependence of mid-latitude Es layers at altitudes between 97 and 114 km but failed to explain at altitudes between 114 and 128 km. So we concluded that the convergence of vertical ion velocity could not fully but partially explain the seasonal dependence of Es intensity.

Changes: Please see page 5 lines 30-31. "One of the unsolved issues in the ionosphere is that the overall morphology, including the seasonal dependence of Es layers, does not have a comprehensive explanation *(Whitehead, 1989; Haldoupis et al., 2007)*."

p. 5, line 24: you suddenly mention Fe^+ ions here. Why only Fe^+, where do they come from? What is the evidence?

Response: Sorry for the unclear statement. It is true that the equation (1) of ion velocity w_i is a general expression, not a specific expression only for Fe^+. In the revised manuscript, we changed this sentence.

Changes: Please see page 6 lines 3-4. "From the wind shear theory *(e.g., Nygren et al., 1984; Mathews, 1998; Kirkwood and Nilsson, 2000)*, the vertical ion velocity w_i induced by the neutral wind is described by equation (1):"

p. 6, line 1: why do you take the wind from WACCM, and the atmospheric composition from MSIS? This is inconsistent. This calculation should be performed using composition and winds from the same model.

Response: Thanks for your comments. In this paper, to compare with previous studies, the neutral wind is provided by output from WACCM and the ion-neutral frequency is calculated by the atmospheric composition from MSIS-00 atmospheric model in accordance with *Chu et al. (2014)*. Thus, the result both of simulations and Es intensity can be compared with the simulation and the Es layer occurrence rate (EsOR) results from *Chu et al. (2014)*.

Besides, WACCM cannot directly provide atmospheric density estimates and its atmospheric density would also be calculated based on the ideal gas law.

We also compare the atmospheric density from MSIS-00 and WACCM. They have the similar spatial variation. The determining factor for the divergence of ion velocity variation is the wind field.

Changes: Please see page 6 lines 15-17. "To compare with previous studies, the neutral wind is provided by the output from WACCM, and the ion-neutral frequency is calculated by the atmospheric composition from the MSIS-00 atmospheric model in accordance with *Chu et al. (2014)*."

p. 6, line 19: the windshear theory does not explain formation of Es layers at high geomagnetic latitudes, because the magnetic field is nearly vertical. There is evidence that within the polar cap gravity waves play a dominant role in Es formation (see, e.g. the papers by John MacDougall from Western Ontario). This is not discussed anywhere.

Response: Following your suggestion, we included the discussion of the role of the vertical motion of gravity waves in the formation of the polar cap Es layer *(Bautista et al., 1998; MacDougall et al., 2000a, b; MacDougall and Jayachandran, 2005)*.

Changes: Please see page 2 lines 2-4. "At high magnetic latitudes, the vertical motion of gravity waves is very efficient in concentrating ionization of Es becuase the magnetic field lines are nearly vertical in the polar gap *(Bautista et al., 1998; MacDougall et al., 2000a, b; MacDougall* *and Jayachandran, 2005).*"

Please see page 5 lines 2-5. "A difference between the Es intensity and EsOR distributions is at high latitudes: that is, the occurrence rates of Es are generally low *(Arras et al., 2008)*, but the intensity of Es is relatively high. This pattern is more evident over the magnetic poles, which is likely the result of vertical motions of gravity waves in concentrating the ionization of Es layers *(MacDougall 5 et al., 2000a, b)*."

Please see page 7 lines 29-page 8 lines 13. "In our investigations, the global climatology of the intensity of Es layers is found to also have a seasonal dependence, with a pronounced maximum over midlatitudes in the summer hemisphere, as shown in Figure 5. …The cusp Es could be associated with convergence of ionization by the electric fields *(MacDougall and Jayachandran, 2005)*."

p. 6, line 25: did you derive equation (3) here? If not, it should be referenced.

Response: Yes, the equation (3) is correctly derived from the basic steady-state ion momentum equation, with the declination angle D into consideration.

p. 6, line 32: why are the regions of ion convergence different when the magnetic declination angle is included? You seem to imply that agreement with the observations is worse. What does that imply? Is equation (3) incorrect?

Response: Thanks for your comments. The magnetic declination angle currently ranges from -30° to 26°; therefore its influence on the vertical ion velocity w_i is expected. The expression of vertical ion velocity was often omitted and mathematically simplified with angle D=0, that is

$$w_i = \frac{r_i \cos I}{1+r_i^2} \times U - \frac{\sin I \cos I}{1+r_i^2} \times V + \frac{r_i^2 + \sin^2 I}{1+r_i^2} \times W$$

To further investigate the magnetic field effects on the wind shear processes of Es formation, in this study, we take the magnetic declination angle D included in equation (3). The region with large value of D has a different result in the simulation which can be seen in Figure 10. The agreement with the observations becomes worse, which could imply that the cause of global Es layers remains a mystery because it cannot be fully accounted for by the wind shear effect *(Whitehead 1989, Haldoupis 2007)*. The formation of mid-latitude Es layers could be partially explained by the wind shear theory. The investigation of causes of seasonal variability in Es should lead to more detailed studies to fully understand and properly quantify the properties of Es layers.

The equation (3) is correct, which is derived from the basic steady-state ion momentum equation.

Changes: Please see page 7 lines 18-21. "The agreement with the observations becomes worse, which could imply that the cause of global Es layers remains a mystery because it cannot be fully accounted for by the wind shear effect *(Whitehead, 1989; Haldoupis et al., 2007)*. The formation of mid-latitude Es layers could be partially explained by the wind shear theory. The investigation of causes of seasonal variability in Es should lead to more detailed studies to fully understand and properly quantify the properties of Es layers."

p. 7, line 11: why would energetic particle precipitation and cosmic rays generate Es in the polar region? Most cosmic ray ionization occurs around the tropopause, and EPP would not create a thin layer of ions.

Response: Thanks for your comments. In this revised manuscript, we remove this sentence and include the role of the vertical motion of gravity waves in the formation of Es layers in the polar cap.

Changes: Please see page 8 lines 2-4. "The wind shear mechanism does not work efficiently at either auroral zones or the magnetic equator *(Haldoupis 2012)*; therefore, the strong Es layers in the Earth's polar regions could be initially caused by gravity waves *(Bautista et al., 1998; MacDougall et al., 2000a, b)*."

p. 8, line 2: I thought this range of IDP input had been considerably reduced in the Carrillo-Sanchez et al., GRL 2016 paper (which followed the one you cite). What difference would it make anyway to sporadic E formation?

Response: Thanks for your comments. We have read and cited this paper. *Carrillo-Sanchez et al. (2016)* employed a different approach to get an estimate of the total input mass (43±14 tons per day), but the estimates of the global Interplanetary Dust Particles (IDPs) are different, depending on the methods used to make the estimate *(Carrillo-Sanchez et al., 2016; Plane, 2012). Carrillo-Sanchez et al. (2016)* estimated the IDP from three observations to constrain the relative contributions of each dust source, with lidar observations of the vertical Na and Fe fluxes.

The behaviour and climatology of the Es layer are related to the distribution of meteoric smoke particles (MSPs) deposition, which provide a permanent sink for gas-phase metallic compounds. The global IDP input could influence the total MSP volume densities to the earth's surface. If the upper range of estimates is correct, then the vertical transport should be considerably faster than is generally thought to be the case, so that metallic ions (the Es layer) transports vertically and is removed more rapidly in order to sustain a higher rate of injection; vice versa *(Plane, 2012)*. Besides, to estimate the meteoric mass influx accurately, as one of the processes determining the Es formation, could help precisely study the geographical and seasonal variations in Es layers.

Changes: Please see page 9 lines 2-7. "The global input of meteoric material is well established to enhance the mesospheric metal layers and Es layers *(Plane, 2004; Carrillo-Sánchez et al., 2015; Plane et al., 2015)*, but the daily amount is still not well defined, and estimates of the global interplanetary dust particles (IDPs) range from 5–270 tonnes per day *(Plane, 2012; Carrillo-Sánchez et al., 2016)*. These effects of meteoric ablation are significantly influenced by the magnitude of the IDP input by two orders of magnitude uncertainty. On the other hand, this fact also highlights the importance of fundamental understanding of the global climatology of Es layers."

Corrections: Need to indicate in the figure captions for Figure 3, 4, 5, 6, 7, 8 and 9 whether this is data averaged over the whole period or for a single year.

References: many do not have the complete initials of the authors
p. 1, line 3: “show a high . . . distribution and . . .”
p.1, line 6: “ . . .bands. Simulations results show that . . .”
p. 1, line 12: “. . .layers are thin-layered . . .”
p. 1, line 19: “equatorial region”
p. 2, line 1: “. . .irregularities and their sharp . . ..”
p. 2, line 33: “. . . models, namely the Whole . . .”
p. 3, line 2: “. . . time. Section 5. . .”
p. 3, line 6: “. . .behind earth’s . . .”
p. 3, line 7: “. . .signal is received at . . .”
p. 3, line 16: “. . .time series . . .”
p. 6, line 9: “. . . seasons. They also showed . . .”
p. 7, line 31: “. . .provides a much greater . . .”
There are many other grammatical errors in the paper which need to be corrected.

Response: Thanks. We have corrected it.

Reviewer #3 comments (RC2)**:**
This paper reports some novel data and modelling on the occurrence and intensity of global Sporadic E layers and provides some interesting perspectives on the formation mechanisms of these layers. The data are derived from measurements of the S4 index from radio occultation measurements made by the COSMIC satellite constellation and the global distribution of Sporadic E which they reveal is similar to those derived from previous studies, with a strong occurrence peak in the mid-latitudes of the summer hemisphere. The authors comment on some interesting distinctions between occurrence and intensity of sporadic E layers; for example they notes that high-latitude layers, while being lower occurrence, tend to be quite intense when they do arise.

Response: Thank you for your positive comments.

Many papers have reported the global climatology of the Es layer occurrence rate (EsOR) by using satellite GPS RO measurements *(Wu et al., 2005; Arras et al., 2008; Chu et al., 2014; Shinagawa et al., 2017)*, but the global climatology of the intensity of the Es layers has not be been fully studied. The purpose of the present paper is to study the global intensity of Es layers and compare the results of Es intensity with previous studies on the EsOR.

These are interesting data sets, but are somewhat spoiled by their relatively poor presentation. For example it would be nice to have seen graphs of global Sporadic-E occurrence and global Sporadic-E intensity in the same format, whereas what we actually see is a map of global occurrence (presumably averaged across seasons) in Figure 3 and then separate maps of intensity for each season in Figure 4.

Response: Sorry for the misleading captions of Figure 4 and Figure 5 (formerly Figure 3 and Figure 4). Figure 4 is the global geographical distributions of the Es average intensity from 2006-2014, and Figure 5 is the Es average intensity from 2006-2014 for four different seasons. We have revised the captions of Figure 4 and Figure 5 and made it clearer.

Changes: Please see page 17 and page 18.

The most interesting part of the study is the attempt to explain the occurrence and intensity of the Sporadic E layers in terms of modelled neutral wind convergence, using wind fields from the WACCM model. This provides qualitative agreement with the observations, if it is assumed that the layers are due to neutral wind convergences in the lower E-region (97-114 km) but strongly suggests that wind convergences at higher E-region altitudes cannot explain the observations. A nice feature of the wind field modelling is that the magnetic declination has been properly included in the calculations and it is demonstrated that allowing for this factor changes the expected distribution of the modelled wind convergences significantly.

Response: Thank you for your positive comments. Our study focus on the global climatology of the intensity of Es layers, which has not been fully studied. Several new observations and modelling of Es are presented. Then, the global intensity of Es layers can be compared with previous studies on the EsOR.

Unfortunately, however, the paper is not able to make any firm conclusions, because the correspondence between the modelled wind convergences and the occurrences and intensities of the Sporadic E layers remains only qualitative at best. This almost certainly illustrates the deficiencies of the modelling assumptions. The wind fields, for example, are obviously idealised and must have significantly greater variability than the modelling suggests, an idea reinforced by the inter-annual changes in the occurrence data shown in Figure 2. In addition the authors comment on various other factors such as the variability of the meteor flux, the effects of geomagnetic storms and the effect of meteorological processes, any and all of which could result in differences between the modelling and the observations, but which would be hard to account for without much more complicated modelling. As a result, the interesting features which are observed are not very well explained.

Response: Thanks for your comments. The focus of the present paper is the global climatology of the intensity of Es layers. By comparing the intensity and the occurrence rate of Es layers, several new and interesting observations of Es intensity are presented. Firstly, the high-latitude Es layers are quite intense in our study although the Es occurrence rate is low as reported in *Chu et al. (2014); Shinagawa et al. (2017)*. Secondly, a noticeable global gap of Es is observed near the magnetic equator. Thirdly, clear features and geographical distribution with dependence of geomagnetic latitudes can be seen in the geomagnetic latitude of 60-80° because of the increased spatial resolution.

In Section 4, we simulated the global mean divergence of the vertical ion velocity using WACCM wind field from 2006 to 2014. The simulation result in Figure 8 shows that the elemental mechanism responsible for Es layers based on the wind shear theory could explain the seasonal dependence of Es intensity (97-114 km). It is also consistent with *Chu et al. (2014)*.

However, more attention should be paid to the results of Figure 9 and Figure 10: that is some disagreements between simulations and results. The simulation in Figure 9 indicates that the wind shear theory alone has difficulty explaining the Es seasonal dependence at higher altitudes (114-128 km), although the wind shear theory is considered the primary theory to explain the physical production of Es layers *(Whitehead, 1989; Haldoupis et al., 2007)*. Thus, the magnetic declination has been properly included in the expression of vertical ion velocity and in the simulation, on the basis of the steady-state ion momentum equation. The agreement with observations becomes worse in Figure 10, which could imply that the cause of global Es layers remains a mystery and should lead to more detailed studies to identify and quantify the formation of Es layers. Please note that the wind shear theory was conceived and formulated by *Whitehead (1961)*. It was stated in *Whitehead (1989)* that "*We conclude that the wind shear theory is the only viable theory that explains the detailed production of the layers. Nevertheless, it does not explain the overall morphology of sporadic E, in particular the large summer maximum.*''

I agree that more complicated modelling is needed to well explain the interesting observations of the Es intensity. Our purpose here is to report the new observations of the global climatology of the Es intensity and try to explain the Es seasonal dependence by the wind shear theory in the simulation.

We are also trying to explain those phenomena, considering more other factors in theory. Another work of more comprehensive modelling is in progress and hope to be subsequently able to quantitatively explain the phenomena and disagreements between observations and simulations from the wind shear theory. We hope this paper could attract more attention to the ongoing mystery of the Es seasonal dependence. It is desirable to combine more ground-based ionosonde data with satellite observations, and study the spatial Es variations and regional features in more details

Changes: Please see page 9 lines 9-27. "In this study, we investigate the long-term climatology of the intensity of Es layers on the basis of S4max data retrieved from COSMIC GPS RO measurements. …Although the wind shear theory for the Es formation was conceived and formulated in 1960s *(Whitehead, 1961)*, its importance for understanding the formation of Es must have escaped attention. … To accurately understand and properly quantify the properties of Es layers at a global scale that are also associated with the distribution of global metallic ions, we need to combine more ground-based ionosonde data with satellite observations and extensively study the geographical and seasonal variations in Es layers.

The language of the paper could be improved. It is occasionally imprecise, so that the meaning can be hard to decrypt. There are also some mistakes in spelling and grammar. These are not really what weaken the paper, however. The fundamental problem is that the processes which produce the Sporadic E layers are likely to have such a complex variability that no simple model can do a good job of characterizing them, and this is what the study ultimately shows.

Response: Thanks for your comments. We apologize for the mistakes in spelling and grammar. We have corrected it. As non-native English speakers, we have tried our best to improve the language of the paper and undertaken a further proof-reading and update of the manuscript. We present our study of the global climatology of the intensity of Es layers. We report some new observations of the global climatology of the intensity of Es layers, which have several different features from the occurrence rate of Es layers in *Chu et al. (2014); Shinagawa et al. (2017)*. The simulation results in our study shows that the convergence of the vertical ion velocity could partially explain the seasonal dependence of the Es intensity while some disagreements between simulations and observations should be paid more attention. Although the wind shear theory for the Es formation was conceived and formulated in 1960s *(Whitehead 1961)*, its importance for understanding the formation of Es must have escaped attention. We hope our modest effort of this study as the relevant topic in the special issue in ACP: layered phenomena in the mesopause region could attract more attention and researches in mechanism of Es formation, to better understand and properly quantify the properties of Es layers in the mesosphere and lower thermosphere region.

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The global climatology of the intensity of the ionospheric sporadic E layer

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Abstract. On the basis of S4max data retrieved from COSMIC GPS radio occultation measurements, the long-term climatology of the intensity of E_s layers is investigated for the period from December 2006 to January 2014. ~~The global~~ Global maps of E_s intensity ~~shows a high spatial resolution geographical distributions~~ show the high-spatial-resolution geographical distribution and strong seasonal dependence of E_s layers. The maximum intensity of E_s occurs ~~in~~ over the midlatitudes, and its value in summer is 2–3 times larger than that in winter. A relatively strong E_s layer is observed at the North and South Poles, with a distinct boundary dividing the ~~middle latitudes~~ midlatitudes and high latitudes along the 60°–80° geomagnetic latitude ~~bands. Besides, simulation results shows~~ band. The simulation results show that the convergence of vertical ion velocity could partially explain the seasonal dependence of E_s intensity. Furthermore, some disagreements between the distributions of the calculated divergence of vertical ion velocity and the observed E_s intensity indicate that other processes~~such as~~ , such as the vertical motions of gravity waves, magnetic field effects, meteoric mass influx into ~~the earth~~Earth's atmosphere and the chemical processes of metallic ions, should also be considered, ~~which~~ as they may also play an important role in the spatial and seasonal variations ~~of~~ in E_s layers.

1 Introduction

~~The ionospheric~~ Ionospheric sporadic E (E_s) layers are ~~known as~~ thin-layered structures ~~of intensehigh electron density~~ with intense, high electron densities at 90–130 km altitudes. Rocket-borne mass spectrometric measurements ~~proved~~ have shown that the E_s layer ~~is mostly~~ mostly result from the ionization of metal atoms, such as Fe^+, Mg^+, and Na^+ (Kopp, 1997; Grebowsky and Aikin, 2002). The E_s layer ~~is mainly at midlatitudes and~~ mainly resides over midlatitudes and is relatively absent at the geomagnetic equator and high latitudes (Whitehead, 1989). It is widely accepted that the mechanism responsible for the E_s layer formation at midlatitudes is the ~~windshear~~ wind shear theory, in which the zonal and meridional winds provide ~~the vertical~~

~~windshear~~ vertical wind shear convergence nodes. As a result, ~~the~~ long-lived metallic ions are forced to converge towards the wind shear null to form a thin layer of intense metallic ionization(Whitehead, 1961; Macleod, 1966; Whitehead, 1970; Nygren et al., 1984; Whitehead, 1989; Haldoupis, 2012). In the ~~equatoral~~ equatorial region, the physical process of E_s irregularities is attributed to the gradient-drift instabilities associated with the equatorial electrojet (Tsunoda, 2008). At high magnetic latitudes, the vertical motion of gravity waves is very efficient in concentrating the ionization of E_s because the magnetic field lines are nearly vertical in the polar gap (Bautista et al., 1998; MacDougall et al., 2000a, b; MacDougall and Jayachandran, 2005) . The E_s layer generally has a vertical scale of 1 km or less, but its horizontal scale can extend up to several hundreds of ~~kilometers~~kilometres. Consequently, ~~the~~ intense E_s plasma irregularities and ~~its~~ their sharp vertical electron density gradients seriously affect radio communications and navigation systems (Pavelyev et al., 2007). Furthermore, these effects on ~~the GPS~~global positioning system (GPS) radio occultation (RO) signals detected by ~~low Earth-orbit~~ low-Earth-orbit (LEO) satellites can be exploited for ~~lower~~ lower-level atmospheric and ionospheric global investigations (Rocken et al., 2000; Hocke and Tsuda, 2001; Schreiner et al., 2007; Yue et al., 2010, 2011).

Observations of E_s layers ~~were~~ have been widely investigated from ground-based radars (e.g., Farley, 1985; Whitehead, 1989; Kelly, 1989; Chu and Wang, 1997; Mathews, 1998). In addition to ground-based radars, the scintillations of GPS RO were employed to extensively investigate ~~the~~ E_s layers over the past decades (Wu et al., 2005; Arras et al., 2008; Zeng and Sokolovskiy, 2010; Chu et al., 2011). A global map of E_s layers was first presented based on a ~~meridian~~ meridional chain of ionosonde stations (Leighton et al., 1962). In recent years, ~~on the basis of~~ based on GPS RO measurements, ~~the knowledge of~~ knowledge of the global E_s layer occurrence rate ~~,~~ (hereafter called E_sOR~~, has been advanced remarkably~~) has been remarkably advanced. Wu et al. (2005) used ~~variances of the~~ phase and signal-to-noise ratio (SNR) variations from ∼6000 GPS/~~CHAMP~~ Challenging Minisatellite Payload (CHAMP) occultations to study the global climatology of E_sOR. Arras et al. (2008) investigated the global E_sOR distribution, with a resolution of 5°×5°~~based on the~~ , based on CHAMP, GRACE (Gravity Recovery and Climate Experiment), and COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) occultation data. These previous studies of global E_sOR maps show a strong seasonal variation~~with the~~ , with a summer maximum in the ~~middle latitudes~~midlatitudes. Chu et al. (2014) employed ~~the~~ COSMIC measurements to study the global morphology of E_sOR and the ~~result of~~ results of the theoretical simulations suggested that the E_sOR seasonal variation is likely attributed to the convergence of the metallic ion flux caused by ~~the~~ vertical wind shear. Shinagawa et al. (2017) calculated the global distribution of the vertical ion convergence and showed that ~~the~~ local and seasonal variations in the wind shear distribution could partially account for the geographical and seasonal variation ~~of~~ in E_sOR.

~~There have been a lot of papers reporting~~ Many papers have reported the geographical distribution and seasonal variation ~~of~~ in global E_s layers retrieved from GPS RO signals, and nearly all ~~these works were on the occurrence rate of~~ of these works focused on the E_sOR. The global climatology of the intensity of E_s layers ~~.~~ has not been fully studied. The purpose of the present paper is to study the global intensity of E_s layers ~~,~~ and compare the results of E_s intensity with ~~the previous studies of~~ previous studies on the E_sOR. The occurrence of E_s layers can cause both ~~the~~ SNR fluctuations and relative slant total electron content (TEC) peaks ~~(?). Sometimes~~(Yue et al., 2015). Sometimes, the SNR has specific U-shape structures in the amplitude of GPS RO signals, as reported by ~~Zeng and Sokolovskiy (2010)~~Zeng and Sokolovskiy (2010); Yue et al. (2015). The obvious increase of in slant TEC occurring around at approximately 92 km implies the ionization enhancement in the E_s. In this study, the scintillation index (S4 index) data measured from SNR fluctuations of in the L1 channel of the COSMIC GPS RO profiles at altitudes between 90 and 130 km for the period from December 2006 to January 2014 are employed to study the global climatology of the ionization of E_s layers. Section 2 describes the used data sets and procedure procedures adopted to derive the S4 index. In Section 3, the global long-term behaviors behaviours of E_s layers with a high spatial resolution are presented and compared with the previous E_sOR results, including the latitude-day, latitude-longitude , and altitude-latitude distribution, seasonal variations, distributions; seasonal variations; and geomagnetic dependence of E_s layers. In section Section 4, on the basis of the windshear wind shear theory combined with several global-scale models, i.e., namely the Whole Atmosphere Community Climate Model (WACCM) (Marsh et al., 2013), the NRL Naval Research Laboratory (NRL) Mass Spectrometer and Incoherent Scatter (MSIS)-00 atmospheric model (Picone et al., 2002), and the International Geomagnetic Reference Field (IGRF)-12 geomagnetic field model (Thébault et al., 2015), we calculate the global distribution of the divergence of metallic ion velocity to compare for comparison with the observations of E_s layers from COSMIC satellites. The effect of the magnetic declination angle effect on the divergence of the metallic ion velocity in the simulation of E_s is investigated for the first time. The section Section 5 is presents the discussion and conclusions of this paper.

2 Data and Procedure of Deriving the S4 indexIndex

The COSMIC global data sets used in this study are the COSMIC-GPS amplitude scintillation S4 indices. The GPS radio signal is signals are received by the precise orbit determination antennas of COSMIC for each GPS RO when a GPS sets or rises behind earths' atmosphereEarth's atmosphere, as seen by the low-earth-orbit (LEO) LEO satellite. Once the GPS signal received at LEOis received at the LEO satellite, the onboard algorithm of the GPS receiver measures SNR intensity fluctuations from the raw 50 Hz L1 amplitude measurements, which is are then recorded in the data stream at a 1 Hz rate at the ground receiver in order to minimize the data record size (Syndergaard et al., 2006). The raw scintillation measurement measurements from the receiver is therefore the RMS are therefore the root mean square (RMS) of the SNR intensity fluctuation over one second , in one second (i.e., σ_I), which can be expressed as : $\sigma_I = \sqrt{\langle (I - \langle I \rangle)^2 \rangle}$. I is the the represents the square of the L1 SNR, and the bracket $\langle\rangle$ denotes the one second averaged value. The S4 indices are reconstructed by the COSMIC Data Analysis and Archive Center (CDAAC) ground processing after these σ_I data are downloaded (Rocken et al., 2000). During the procedure of deriving the S4 indices, two additional steps are included in the ground processing. The first step is to assume that the SNR intensity fluctuations have Gaussian distributions so as to calculate an approximate value of $\langle I \rangle$ from σ_I and $\langle \mathrm{SNR} \rangle$. The second is to apply a low pass filter to the time serious series of $\langle I \rangle$ to get obtain a new average of the intensity $\langle I \rangle_{new}$ at each second to replace the $\langle I \rangle$ in the calculation of the S4 indices. After these steps, a long-term detrended S4 scintillation index can be reconstructed by the CDAAC ground processing. Further details on the procedure of deriving the S4 index along with some individual example figures can be found in the report of Ko and Yeh (2010).

In the present study, the COSMIC global data sets specifically denote the maximum value of S4 (S4max). The COSMIC global S4max data include the S4max value , and geographic latitude, longitude, altitude as well as and local time on which

~~the~~ S4max was detected. The computed detrended S4max index is available from 28 December 2006 onwards ~~in~~ on the CDAAC website (http://cdaac-www.cosmic.ucar.edu/cdaac). The long-term global climatology of the E_s intensity is investigated based on the global S4max data from December 2006 to January 2014. Figure 1 shows the altitude distribution of the COSMIC S4max profiles. A considerable ~~numbers~~ number of profiles are distributed at altitudes between 40 and 130 km, with a peak number at ~~around~~ approximately 100 km. Information on E_s layers can be extracted from amplitude fluctuations in the SNR profiles (Wu et al., 2005). Please note that as a result of the ~~integral~~ integrated influence either in the SNR or the slant TEC along the LEO-GPS ray, the effect of E_s layers ~~in the~~ at high altitudes could map down to the lower tangent point altitudes, which may ~~induce pseudo~~ virtually induce multiple peaks in one RO event ~~(Zeng and Sokolovskiy, 2010)~~ (Zeng and Sokolovskiy, 2010; Yue et al., 2015). In Figure 1, the occurrence of sporadic E can be seen down to 40 km as a result of the ~~localization~~ integral problem of RO ~~measurement~~measurements. In fact, E_s layers could not be formed by the wind shear theory below 90 km because of the high ion-neutral collision frequencies. The E_s layer over ~~the lower altitude~~ lower altitudes (between 40 and 90 km) should be some artefact resulting from ~~mapping effect~~the mapping effect integrated along the LEO-GPS ray. Therefore, the S4max values ~~which appear in the altitude range~~ that appear in altitudes ranging between 90 and 130 km are used to study the E_s layers in the lower ionosphere region. Figure 2 shows the entire distribution of the daily average Es intensity from 2006 to 2014 retrieved from COSMIC within $\pm$ 2.5° latitude and longitude of one ionosonde station in Beijing ($40.3°N, 116.2°E$), which agrees with the ionosonde measurements (f_oEs). The global morphology of the E_s intensity is presented, and its altitude and seasonal dependences are given at a high spatial resolution because of the large COSMIC RO data sets ~~with a high vertical resolution~~which have high vertical resolutions.

3 Observations

~~Figure 2 shows~~ Figure 3 shows the long-term time series of the E_s values, with a resolution of 5° ~~latitudes~~ latitude × 5 days. As shown, the E_s layer is mainly a ~~sporadic layered~~ sporadic-layered phenomenon in the summer hemisphere, as is known from former E_sOR studies (Leighton et al., 1962; Wu, 2006; Arras et al., 2008; Chu et al., 2014). In Figure ~~2~~3, it is clear that the intensity of E_s is enhanced in the northern (southern) summer hemisphere from May to September (from November to March), with a maximum in June (December) ~~,~~ (i.e., one month ahead of the E_sOR maximum (Chu et al., 2014)). In addition, the seasonal E_s layer also has ~~an~~ interannual variability. Compared with the intense Es activity in the summers of 2010 and 2011~~summers~~, the intensity of E_s is lower in the northern summers in 2012 and 2013~~northern summers. It~~ , respectively. This result may be caused by anomalies ~~of wind fields~~ in the wind field in the upper atmosphere and a corresponding reduction ~~of vertical windshear~~ in the vertical wind shear associated with E_s formation.

The map in Figure ~~3~~ 4 shows the global geographical distributions of the E_s ~~values~~ average intensity, with a significantly improved spatial resolution of ~~a~~ 1° × 1°~~grid~~. The red and green solid curves represent the northern and southern geomagnetic latitude contours of 60°, 70°, and 80°, respectively. The geomagnetic equator is also plotted ~~in~~ with a yellow curve. The E_s layers ~~dominantly distribute~~ are predominantly distributed with S4max ~~value~~ values exceeding 0.7 ~~in the middle latitudes~~at midlatitudes. Because of the increased spatial resolution, the regional features and longitudinal variations become visible. The intensity of E_s is much weaker ~~in~~ at the lower latitudes ~~of~~ in both hemispheres, especially ~~a~~ in the noticeable gap near the magnetic equator. ~~It could be~~ When the magnetic field is horizontal at the geomagnetic equator, under the zonal wind shear action, ions move vertically by Lorentz forcing. However, they fail to converge into a layer because they are withheld by magnetized electrons. The plasma remains locally neutral. For a meridional wind shear process, ions move along the magnetic field lines with no Lorentz forces acted upon (Haldoupis, 2012). Therefore, a noticeable gap near the magnetic equator could be expected, which is explained by the vanishing vertical component of the geomagnetic field lines~~which keep~~, keeping the ionized particles from effectively vertically converging. This gap could also be found in the distribution of E_sOR although it is not as evident in Arras et al. (2008).

Furthermore, the E_s longitudinal variations ~~of~~ in the geomagnetic field are also clearly shown. The decrease ~~of the~~ in E_s intensity can be seen clearly in the Southern Atlantic Anomaly (SAA) zone and the northern American region with ~~dependence of geomagnetic latitudes~~geomagnetic latitude. The region of large E_s intensity exists in the ~~Northern~~ North Africa and North Atlantic regions, Southeast Asian region, ~~Southern~~ South Africa and South Pacific regions. A difference between the E_s intensity and E_sOR distributions is ~~in the high latitudes,~~ at high latitudes: that is, the occurrence rates of E_s ~~is~~ are generally low (Arras et al., 2008), but the intensity of E_s is relatively high. ~~It appears more evident in~~ This pattern is more evident over the magnetic poles, ~~likely as a result of intense solar activities~~which is likely the result of vertical motions of gravity waves in concentrating the ionization of E_s layers (MacDougall et al., 2000a, b). The lower panels ~~depicts~~ depict the northern and southern polar views of the distributions of E_s ~~values~~intensity, and these views make the ~~signature more clear~~features clearer.

The maps in Figure ~~4~~ 5 show the geographical distribution of E_s intensity for four different seasons in a 1°× 1° grid. The distribution of E_s layers shows a significant seasonal dependence. The intensity of the E_s layers in the ~~middle latitudes~~ midlatitudes of the summer hemisphere is 2–3 times larger than that in the winter hemisphere. During equinox seasons, the intensity of the E_s layers ~~is moderate covering around the globe~~ moderately covers the entire globe, and a distinct boundary dividing the ~~middle latitudes~~ midlatitudes and high latitudes is visible along the 60°–80° geomagnetic latitude ~~bands~~band. From the polar views ~~of~~ during each season, it can be seen that the E_s layers remain ~~in~~ at a relatively high level ~~at~~ in the North and South Poles. ~~It~~This characteristic could be attributed to ~~the~~ high energy radiation~~and particle precipitations. The ionization of E_s layers is persistently magnetic fields trapped in the polar regions~~, particle precipitation and polar gap gravity waves.

Figure ~~5~~ 6 shows the altitude-latitude distribution of the E_s intensity with a resolution of 1 km altitude × 1° latitude. The intensity of E_s ~~distributes~~ is distributed at altitudes between 95 and 125 km. The ~~most dense~~ densest patches of E_s exist at altitudes exceeding 110 km~~. It~~, which is different from the E_sOR altitude-latitude distribution ~~which~~ that dominates at 95–110 km~~with the peak around~~, with a peak at approximately 105 km in the ~~middle latitudes~~ midlatitudes of 25°–45°(Arras et al., 2008). The E_s intensity has a broader latitudinal extent of 10°S–75°S in the Southern Hemisphere, compared with 10°N–60°N in the Northern Hemisphere.

Figure ~~6~~ 7 presents the seasonal variation in the altitude-latitude distributions of the E_s intensity for the same temporal period and ~~same~~ spatial resolution as ~~in Figure 5. It is clearly that, the~~ those in Figure 6. The E_s intensity for the summer and winter solstices clearly has a significantly broader latitudinal extent ~~to~~ towards the high latitude region. ~~Besides~~In addition, the overall ~~intensity of~~ intensities of the E_s layers ~~increases~~ increase, spanning a larger vertical extent during the solstices. In general, the E_s intensity exceeding 0.65 values ~~distributes~~ is distributed at altitudes of 100–125 km in the southern summer and at altitudes of 90–130 km in the northern summer. During equinox seasons, the E_s intensity is moderate and its altitude-latitude distribution is relatively symmetric.

4 Wind Shear Theory Explanation for E_s Seasonal Variation

The global climatology of the intensity of E_s layers is investigated from the COSMIC occultation data employing the GPS RO technique. One of the pronounced ~~variability~~ variabilities in E_s layers is the seasonal variation~~with maximum appearing~~ , with a maximum appearance in the summer hemisphere. Although the mechanism for ~~the~~ E_s layer formation is widely accepted~~that~~ , these dense and thin layers of metallic ion plasma are formed by the vertical ion convergence of neutral wind shear. The overall morphology of E_s layers cannot be explained by the ~~windshear~~ wind shear theory. One of the unsolved issues in the ionosphere is that the ~~well pronounced~~ overall morphology, including the seasonal dependence of ~~mid-latitude E_s layers~~Es layers, does not have a comprehensive explanation ~~, which is inexplicable from the windshear theory~~ (Whitehead, 1989; Haldoupis et al., 2007).

~~The seasonal~~ Seasonal dependence is found not only in the E_s intensity but also in ~~the former~~ previous studies of E_sOR variations (Wu et al., 2005; Arras et al., 2008; Chu et al., 2014). Chu et al. (2014) simulated the global distribution of the convergence of metallic ion flux caused by ~~the~~ vertical wind shear, suggesting ~~the maximum of~~ that the maximum E_s in summer and minimum of E_s in winter are likely caused by the vertical ~~windshear~~ wind shear effect.

From the wind shear theory (e.g., Nygren et al., 1984; Mathews, 1998; Kirkwood and Nilsson, 2000), the vertical ~~Fe^+~~ ion velocity w_i induced by the neutral wind is described by equation (1):

$$w_i = \frac{r_i cosI}{1+r_i^2} \times U - \frac{sinIcosI}{1+r_i^2} \times V + \frac{r_i^2 + sin^2 I}{1+r_i^2} \times W \quad (1)$$

where I ~~is~~ represents the magnetic inclination angle that is defined ~~positive (~~as positive (i.e., downward direction) in the Northern Hemisphere, r_i ~~is~~ represents the ratio of the ion-neutral collision frequency (ν_i) to the ion gyrofrequency (ω_i), and the neutral wind velocity V$_n$=(U,V,W) components are in the zonal (positive for eastward), meridional (positive for northward), and vertical (positive for upward) directions. Therefore, the ~~favorable~~ favourable wind field for E_s layer formation is where there is a negative $\frac{\mathrm{d}w_i}{\mathrm{d}z}$ relationship, indicating an ion-convergence region.

~~Our study has the following simulations of~~ Version 4 of the WACCM (WACCM4) is a global climate model with interactive chemistry, developed at the National Center for Atmospheric Research (NCAR) (Marsh et al., 2013). A specified dynamics run of WACCM4 (SD-WACCM4) was constrained by the Modern-Era Retrospective Analysis for Research and Applications (MERRA). SD-WACCM4 is used to simulate the global distribution of the divergence of ion velocity ~~in comparison with previous studies. The~~ from the period of 2006 to 2014, which is consistent with the period of E_s observations from the COSMIC occultation data. To compare with previous studies, the neutral wind is provided by the output from WACCM, and the ion-neutral frequency is calculated by the atmospheric composition from the MSIS-00 atmospheric model in accordance with Chu et al. (2014). The global distributions of the geomagnetic field and magnetic inclination angle at 100 km are estimated from the IGRF-12 model. The calculation of ion velocity is binned and averaged in a 1° latitude × 1° longitude grid at WACCM altitude levels from 0–130 km.

Figure 7 8 presents simulation results of the global distributions of the monthly mean divergence of in vertical ion velocity in the altitude range between 97 and 114 km in January and July. The negative (positive) $\frac{\mathrm{d}w_i}{\mathrm{d}z}$ represents ratio represents the convergence (divergence) of the Fe^+ ion ions in units of $ms^{-1}km^{-1}$. It shows Ihe results show a good correlation between the simulated distributions of the monthly mean divergence of vertical ion velocity in Figure 7 8 and the geographical distribution of E_s intensity measured from the COSMIC GPS RO profiles in Figure 4. 5. Chu et al. (2014) simulated the global distributions of the mean divergence of the Fe^+ concentration flux at altitudes of 94–115 km for in all four seasons. It The study also showed a similar simulation result of the distributions of divergence of in the Fe^+ concentration flux, which is well correlated with the COSMIC-measured E_sOR distribution. The simulation of the divergence of vertical ion velocity supports the wind shear theory for the E_s formation and also indicates indicates that the seasonal dependence of E_s layers is likely attributed to the convergence of vertical ion velocity driven by the neutral wind.

Furthermore, we also notice that the E_s intensity distributes is distributed at relatively higher altitudes of 95–125 km compared with the E_sOR at 90–120 km. The most dense densest patches of E_s exit exist above 115 km, and the E_s layer has a broader vertical extent in summer, as shown in Figure 5 and Figure 6. 7. In the simulation, the distributions of the monthly mean divergence of the vertical ion velocity in the at an altitude range of 114–128 km in January and July are shown in Figure 8. 9. In contrast to the distributions of the divergence of vertical ion velocity between 97 and 114 km in Figure 7, Figure 8 8, Figure 9 shows an ion-divergence region at altitudes of 114–128 km in summer at over midlatitudes as a result of different zonal and meridional winds. It suggests that a single windshear theory likely has difficulty in These results suggest that the wind shear theory alone has difficulty explaining the E_s layer formation seasonal dependence at higher altitudes (114–128 km), although the wind shear theory is considered the primary theory to explain the physical production of E_s layers (Whitehead, 1989; Haldoupis et al., 2007).

In previous studies of the windshear theory for the on the wind shear theory for E_s layer formation, the magnetic declination angle effect is neglected in the calculation of the vertical ion velocity w_i induced by the neutral wind. The steady-state ion momentum equation is:

$$m\frac{\mathrm{d}\boldsymbol{v}_i}{\mathrm{d}t} = 0 = e(\boldsymbol{E} + \boldsymbol{v}_i \times \boldsymbol{B}) - M\nu_{in}(\boldsymbol{v}_i - \boldsymbol{V}_n) \quad (2)$$

On the basis of the steady-state ion momentum equation, the euqation equation (1) of for the vertical ion velocity w_i is extended to take the magnetic declination angle D into consideration as follows:

$$w_i = \frac{r_i cosDcosI - sinDsinIcosI}{1 + r_i^2} \times U - \frac{r_i sinDcosI + cosDsinIcosI}{1 + r_i^2} \times V + \frac{r_i^2 + sin^2 I}{1 + r_i^2} \times W \quad (3)$$

The magnetic declination angle currently ranges from -30° (west) to 26° (east). The ; therefore its influence on the vertical ion velocity w_i is expected. The effect of the magnetic declination angle effect on the divergence of in ion velocity in the simulation of E_s is investigated. Figure ~~9~~ 10 presents the global distributions of the monthly mean divergence ~~of~~ in vertical ion velocity ~~in the altitude range of~~ at altitudes ranging from 97–114 km with the consideration of the magnetic declination angle. ~~It~~ The figure shows a seasonal dependence, with ion-convergence regions in summer and ion-divergence regions in winter. However, the morphology of the divergence of the vertical ion velocity is different from that without the magnetic declination angle ~~considered shown in Figure 7.~~ considere in Figure 8. In January, ~~the~~ strong ion convergence appears in the SAA region. In July, ~~the Asiaand~~ Asia, Europe, and the North Pacific tend to be ~~the~~ regions of ion convergence. The agreement with the observations becomes worse, which could imply that the cause of global E_s layers remains a mystery because it cannot be fully accounted for by the wind shear effect (Whitehead, 1989; Haldoupis et al., 2007). The formation of mid-latitude E_s layers could be partially explained by the wind shear theory. The investigation of the causes of seasonal variability in E_s should lead to more detailed studies to fully understand and properly quantify the properties of E_s layers.

5 Discussion

The seasonal and geographical dependences of E_sOR have been widely studied by ionospheric observations since 1960s (Leighton et al., 1962; Smith, 1978; Wu et al., 2005; Arras et al., 2008; Zeng and Sokolovskiy, 2010), but~~so far~~, thus far, the overall morphology of E_s is still not well explained. The seasonal dependence of E_s layers remains ~~a long-going mystery~~an ongoing mystery, as it is unexpected in the classical ~~windshear~~ wind shear theory reported in the review ~~paper~~ article of Whitehead (1989). ~~In recent time~~Recently, Chu et al. (2014) simulated the distribution of the convergence of the Fe^+ concentration flux and indicated that the vertical ion convergence caused by neutral wind could be responsible for the seasonal dependence of E_s.

In our investigations, ~~it is found that the~~ the global climatology of the intensity of E_s layers ~~has~~ is found to also have a seasonal dependence, with a pronounced maximum ~~in the~~ over midlatitudes in the summer hemisphere, as shown in Figure ~~4.~~ 5. The E_s intensity has ~~a~~ similar seasonal and spatial distributions ~~to~~ as the E_sOR, but the E_s layer has a relatively large intensity and a small E_sOR value at the North and South Poles. The wind shear mechanism does not work efficiently at either auroral zones or the magnetic equator (Haldoupis, 2012); therefore, the strong E_s layers in the Earth~~'~~'s polar regions could be ~~caused by the solar energetic particles and cosmic rays.~~ initially caused by gravity waves (Bautista et al., 1998; MacDougall et al., 2000a, b). In the simulations, the gravity waves with horizontal wavelengths smaller than ~200 km are not explicitly resolved in WACCM (Liu et al., 2014). In particular, the vertical motion of gravity waves dominates the formation of the E_s layer in the polar cap, where the near-vertical magnetic field significantly reduces the effectives of wind-shear in converging ions into layers. Polar cap gravity waves have been studied by Johnson et al. (1995); MacDougall et al. (1997). These layers are maintained in an ionized state by charge exchange of neutral metal atoms with NO^+ and $O_2{}^+$ ions by photoionization. These studies found that the vertical motion of gravity waves is very efficient in concentrating polar cap E_s layers. The short-lived polar cap E_s layers in winter appear to be associated with gravity waves. The polar cap E_s layers in summer are long-lasting thin layers. These initial concentrations of metallic ions persist and change into long-lived E_s because of ambient metallic ions.

The E_s layers at the cusp latitude are relatively different from those at the polar cap. The cusp E_s could be associated with the convergence of ionization by the electric fields (MacDougall and Jayachandran, 2005).

On the other hand, ~~the simulation of the~~ simulating the global distributions of the monthly mean divergence of vertical ion velocity in an altitude range between 97 and 114 km shows an ion-convergence region in the summer midlatitudes, which is similar to the simulation results of Chu et al. (2014). ~~It~~ This result suggests that the seasonal dependence of E_s is ~~likey~~ likely attributed to the vertical convergence of ions driven by ~~the~~ neutral wind. However, some disagreements between the distributions of the calculated divergence of vertical ion velocity and observed E_s intensity are found. For example, there are ion-divergence regions in the midlatitudes in winter in Figure ~~7~~8, but the dissipation of E_s is observed in the 60°–80° geomagnetic latitude ~~bands. The most dense~~ band. The densest E_s layer appears above 115 km~~higher than~~ , which is higher than the E_sOR. Another discrepancy is that the simulated divergence of vertical ion velocity in ~~the~~ an altitude range between 114 and 128 km has a positive $\frac{\mathrm{d}w_i}{\mathrm{d}z}$ ratio in the summer hemisphere~~. It~~ , which indicates an ion-divergence region of ions in contrast to the observed summer maximum of E_s intensity in the summer midlatitudes.

The effect of the magnetic declination angle ~~effect~~ on the divergence of metallic ion velocity is investigated in the simulation of E_s for the first time in Figure ~~9. Though it shows the~~ 10. Though the figure shows marked seasonal dependence, with a strong summer ion-convergence region, the morphology of the divergence of vertical ion velocity is different from the distribution of the observed E_s intensity in Figure ~~7.~~ 5. Thus, the vertical ion convergence by itself is far from sufficient ~~to explain~~ for explaining the strong E_s summer maximum. ~~Some other~~ Other physical processes should also be considered in the geographical distribution and spatial variations in E_s layers~~which~~ , as they play important roles in determining the global morphology of E_s such as the magnetic field, ionospheric electric field, the chemical processes of metallic ions, large geomagnetic storms, and meteorological processes in the lower atmosphere ~~(e.g., Mathews, 1998; Carter and Forbes, 1999; Davis and Johnson, 2005; Johnson and Dav~~ (e.g., Bautista et al., 1998; Mathews, 1998; Carter and Forbes, 1999; MacDougall et al., 2000a, b; Davis and Johnson, 2005; MacDougall
.

Haldoupis et al. (2007) proposed that the seasonal dependence of E_s could be explained by the seasonal variation ~~of~~ in the meteor influx into the upper atmosphere. However, it has been largely accepted ~~now~~ that sporadic meteoroids ~~provides a extremely~~ provide a much greater meteor mass on average than meteor showers (Ceplecha et al., 1998; Baggaley, 2002; Janches et al., 2002; Williams and Murad, 2002). The meteoric mass influx caused by sporadic meteoroids reaches a maximum in autumn rather than summer (Janches et al., 2006). ~~It is well established that the~~ The global input of meteoric material ~~gives rise to~~ is well established to enhance the mesospheric metal layers and E_s layers (Plane, 2004; Carrillo-Sánchez et al., 2015; Plane et al., 2015), but the daily amount is still not well defined, and estimates of the global ~~Interplanetary Dust Particles (IDP~~interplanetary dust particles (IDPs) range from 5–270 tonnes per day ~~(Plane, 2012)~~(Plane, 2012; Carrillo-Sánchez et al., 2016)
. These effects of meteoric ablation are significantly influenced by the magnitude of the IDP input by two orders of magnitude uncertainty. On the other hand, this fact also highlights the importance of ~~the fundamental understanding in~~ fundamental understanding of the global climatology of E_s layers.

6 Conclusions

In this study, we investigate the long-term climatology of the intensity of E_s layers on the basis of S4max data retrieved from COSMIC GPS RO measurements. The resulting global E_s maps with a high spatial resolution presents present the geographical distributions and strong seasonal dependence of E_s intensity, which is consistent agrees with former studies of global E_sOR maps (Wu, 2006; Arras et al., 2008; Chu et al., 2014). The high E_s intensity in summer exists at altitudes of 115-125 km in the 115–125 km at 10°–60° latitudes latitude in the Northern Hemisphere, and at altitudes of 115-120115–120 km in the 10°–75° latitudes in the Southern Hemisphere.

Furthermore, the simulation results of the global distributions of the monthly mean divergence of vertical ion velocity could partially explain the seasonal dependence of E_s intensity. The magnetic declination angle effect We show that the elemental mechanism responsible for E_s layers based on the wind shear theory could explain the seasonal dependence of Es intensity (97–114 km), but it is hard to explain the Es seasonal dependence at higher altitudes (114–128 km). To further investigate the magnetic field effects on the wind shear processes of E_s formation, the effect of the magnetic declination angle on the divergence of metallic ion velocity in the simulation of E_s is investigated, and we discuss some disagreements between the distributions of the calculated divergence of vertical ion velocity and the observed E_s intensity. It indicates Although the wind shear theory for the E_s formation was conceived and formulated in 1960s (Whitehead, 1961), its importance for understanding the formation of E_s must have escaped attention. This study implies that, in addition to the vertical windshear wind shear effects, other processessuch as , such as the vertical motion of gravity waves, magnetic field effects, meteoric mass influx into the earthEarth's atmosphere and the chemical processes of metallic ionsare also likely to play an , should also be considered, which could play a dominant role in the geographical and seasonal variations in E_s layers. To accurately understand and properly quantify the properties of E_s layers .

at a global scale that are also associated with the distribution of global metallic ions, we need to combine more ground-based ionosonde data with satellite observations and extensively study the geographical and seasonal variations in E_s layers.

Author contributions. BY and XX designed the study and wrote the manuscript. XY provided the COSMIC radio occultation data and contributed significantly to the comments on an early version in the manuscript. CY and CY discussed the results of the wind shear theory simulation. BN and LH provided the manually scaled ionospheric observation at Beijing. XD contributed to the discussion of the results and the preparation of the manuscript. All authors discussed the results and commented on the manuscript at all stage.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. We acknowledge the COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) radio occultation data, the ionosonde data from the Chinese Meridian Project, the Solar-Terrestrial Environment Research Network (STERN), Data Center for Geophysics, Data Sharing Infrastructure of Earth System Science, National Science & Technology Infrastructure of China as well as the the Whole Atmosphere Community Climate Model (WACCM), NRL Mass Spectrometer and Incoherent Scatter (MSIS)-00 atmospheric model, and International Geomagnetic Reference Field (IGRF)-12 geomagnetic field model data used in this paper. This work is supported by the National Natural Science Foundation of China (41774158, 41474129, 41421063, 41804147), the open research project of CAS Large Research Infrastructures, the Youth Innovation Promotion Association of the Chinese Academy of Sciences (2011324) and the Fundamental Research Fund for the Central Universities.

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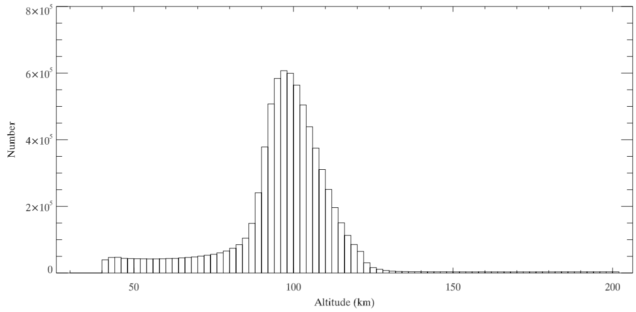


Figure 1. The altitude distribution of COSMIC S4max profiles from December 2006 to January 2014.

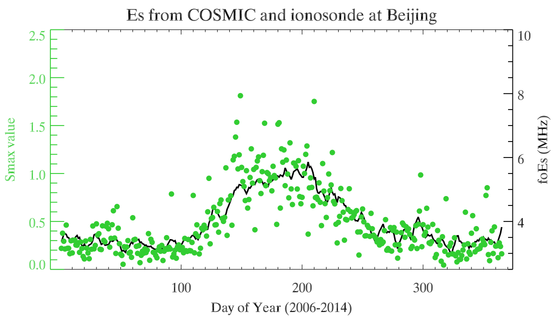


Figure 2. The entire distribution of the daily average Es intensity retrieved from COSMIC within $\pm$ 2.5° latitude and longitude of one ionosonde station and ionosonde data (f_oEs) in Beijing from 2006 to 2014.

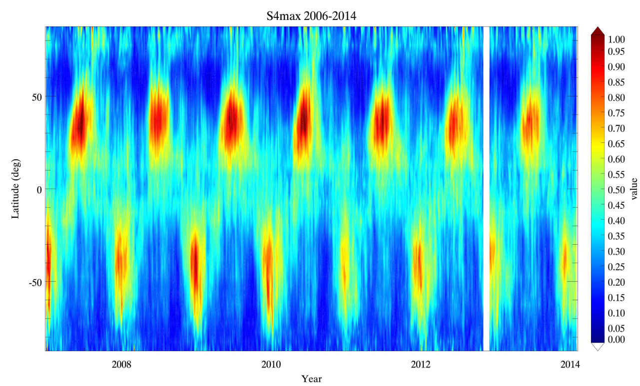


Figure 3. Time series of the E_s ~~values~~ intensity with a resolution of 5° ~~latitudes~~ latitude $\times$ 5 days for the period from December 2006 to January 2014.

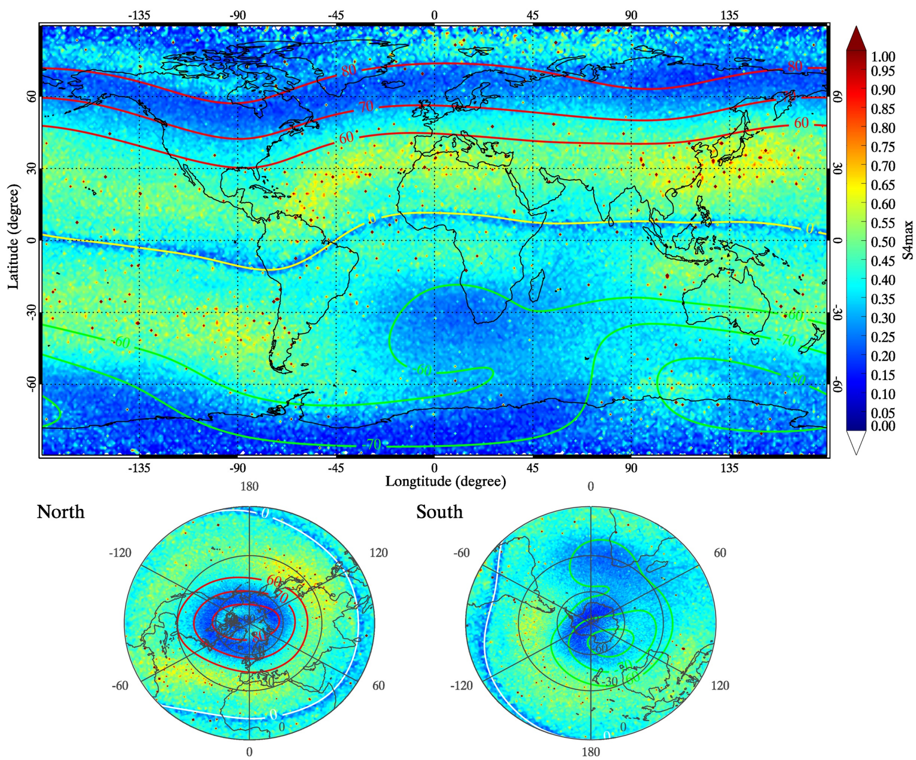


Figure 4. Global geographical distributions of the E_s ~~values~~ average intensity from 2006 to 2014, with a spatial resolution of a 1°× 1° grid. ~~Red~~ The red and green curves signify the geomagnetic latitude contours of 60°, 70°, and 80°, and the yellow curve represents the geomagnetic equator.

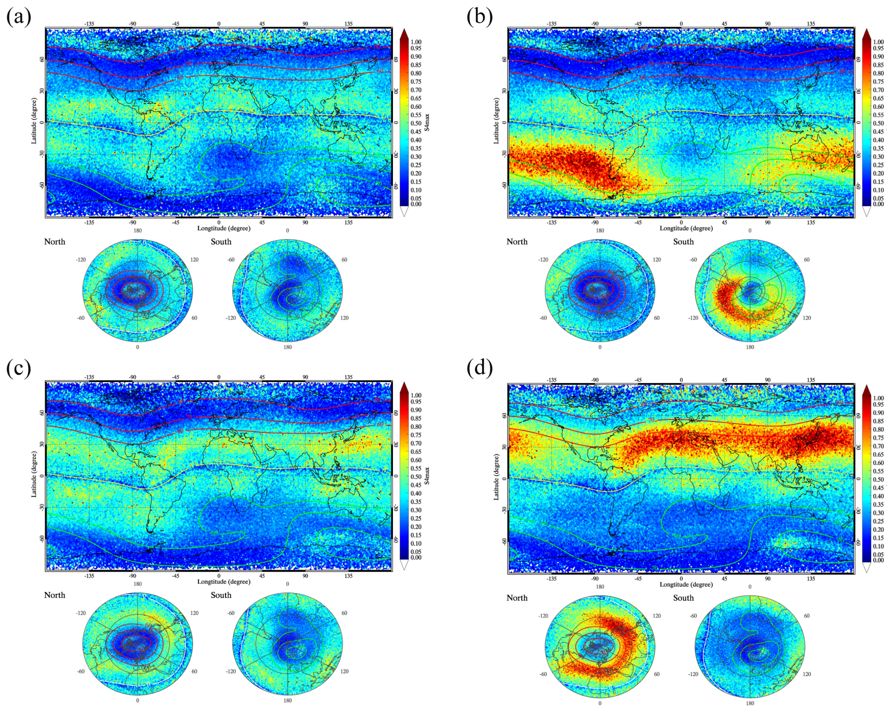


Figure 5. Seasonal variations ~~of~~ in E_s intensity from 2006 to 2014, with a spatial resolution of a $1^\circ \times 1^\circ$ grid. Plots for ~~the~~ (~~top left~~a) autumn (September, October, November), (~~top right~~b) winter (December, January, February), (~~bottom left~~c) spring (March, April, May), and (~~bottom right~~d) summer (June, July, August).

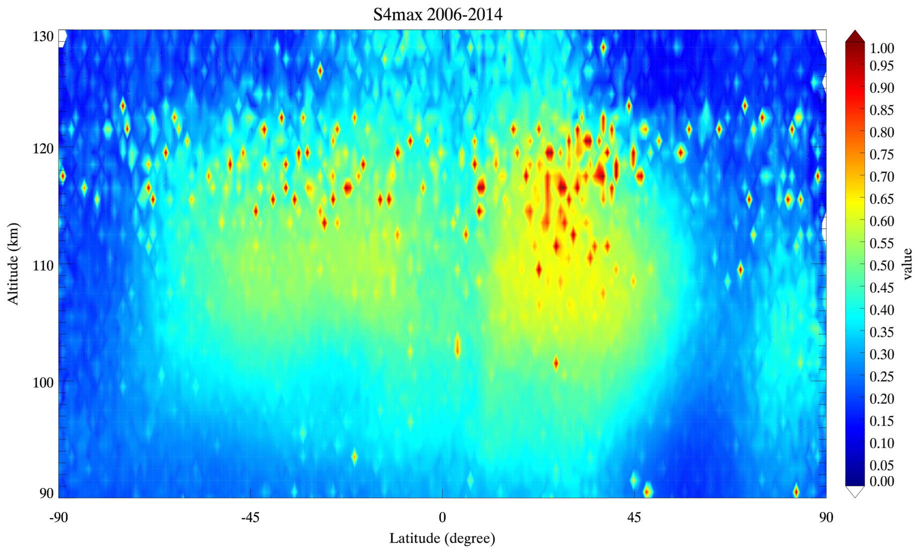


Figure 6. Altitude-latitude distribution of the E_s intensity from 2006 to 2014, with a resolution of 1 km altitude $\times$ 1° latitude.

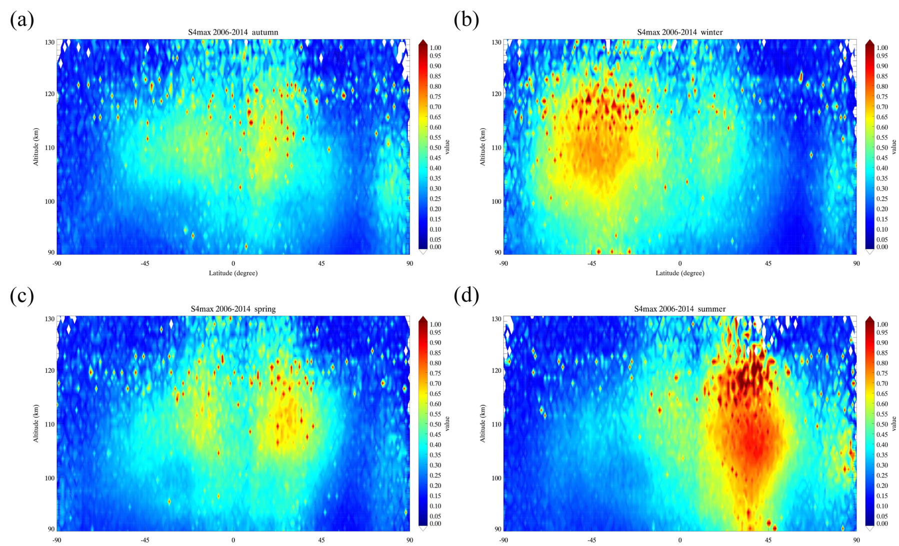


Figure 7. Seasonal ~~variation~~ variations in altitude-latitude distributions of ~~the~~ E_s intensity from 2006 to 2014 for four different seasons: (a) autumn, (b) winter, (c) spring, and (d) summer.

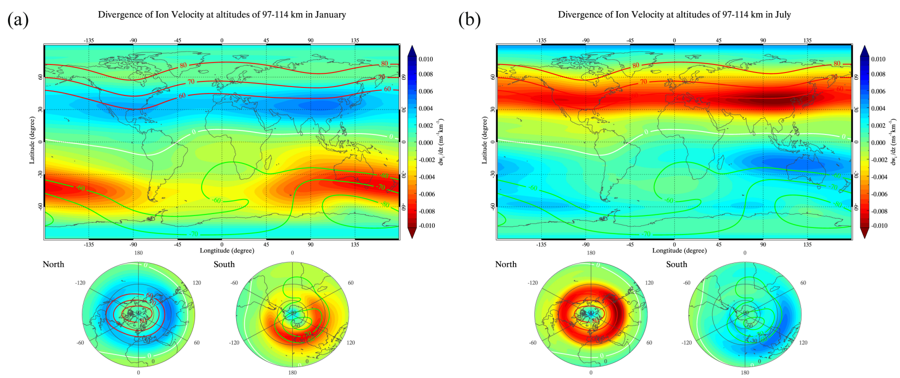


Figure 8. Simulation results of the global distributions of the monthly mean divergence of vertical ion velocity from 2006 to 2014 (~~in~~ units of $ms^{-1}km^{-1}$) ~~in the altitude range~~ at altitudes ranging between 97 and 114 km in January (a) and July (b). ~~Red~~ The red and green curves signify 60°, 70°, and 80° geomagnetic latitude contours, and the yellow curve represents the geomagnetic equator.

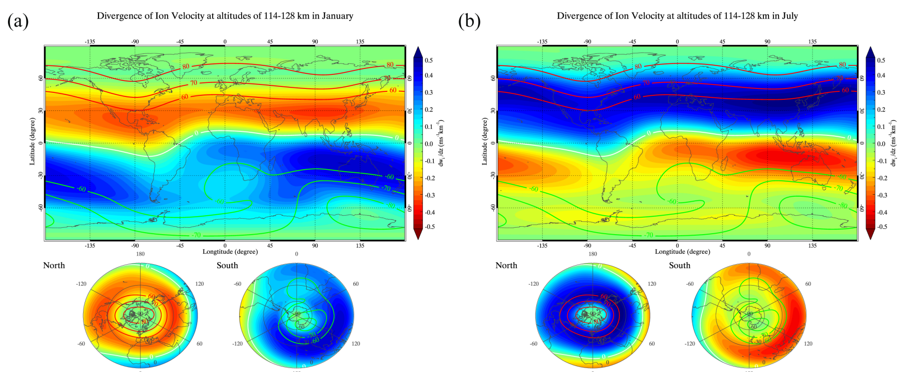
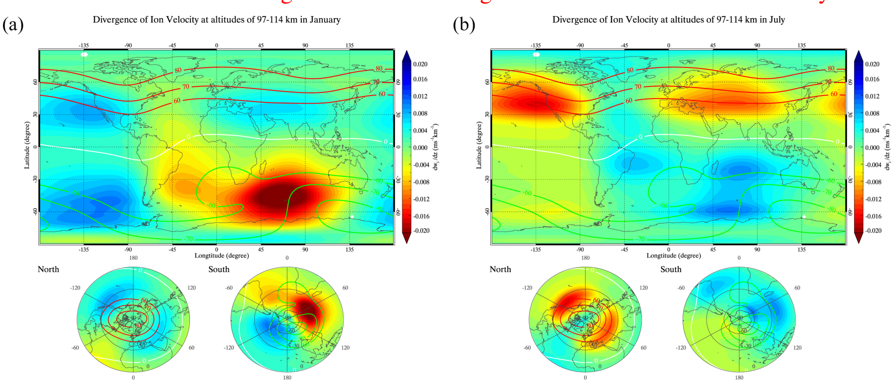


Figure 9. Same as ~~figure 7~~ Figure 8 but for the altitude range between 114 and 128 km in January (a) and July (b).

~~Same as figure 7 but for the consideration of the magnetic declination angle effect on the vertical ion velocity in January (a) and July~~



~~(b).~~

Figure 10. Same as Figure 8 but with the consideration of the effect of the magnetic declination angle on the vertical ion velocity in January (a) and July (b).