

The role of electric field and neutral wind in the generation of polar cap sporadic E

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Abstract. This paper investigates the roles of electric field and neutral wind in the generation of sporadic-E layers within the polar cap. Two Es layers above Svalbard, observed by the EISCAT Svalbard Radar (ESR), were chosen for investigation. The radar experiment contains four beam directions, and this was used for determining the electric field. The neutral wind was obtained from the HWM93 model. Formation of Es layers was calculated by integrating the continuity equation under the action of driving forces due to neutral wind and electric field. A flat height profile of metal ions was assumed in the beginning. The calculation gives the time variation of the layer, which can be compared with observations. In one case the electric field was shown to be the main driving agent in layer generation. In the other case the electric field was weak and the layer was produced mainly by the neutral wind, but the electric field had influence on the height of the layer. A fairly good agreement between the variations of the observed and calculated layer altitudes was obtained and some agreement between the intensity variations was also found.

Keywords. Ionosphere (Electric fields and currents; Plasma convection; Polar ionosphere)

1 Introduction

Sporadic-E (Es) layers are thin horizontal layers with a vertical extent of 0.5–5 km and densities at least two-three times higher than the background plasma. They are commonly detected at heights between 95 and 130 km. They form by vertical convergence of ionospheric plasma caused by appropriate structures in the vertical shear of neutral wind and/or favourable electric field directions (Nygrén et al., 1984; Whitehead, 1989; Mathews, 1998; Kirkwood and Nilsson,

2000). It has been shown that Es layers are observed even inside the polar cap, despite the very high inclination of the geomagnetic field there (Wan et al., 1999; MacDougall et al., 2000a; Voiculescu et al., 2006). Experimental and theoretical findings support the idea that the electric field is the main driving factor of Es layer formation within the polar cap (Parkinson et al., 1998; Wan et al., 1999; Bedey and Watkins, 2001; MacDougall and Jayachandran, 2005; Voiculescu et al., 2006; Nygrén et al., 2006), although there are calculations showing that gravity waves might also play a role (MacDougall et al., 2000b).

In their study of southern polar cap Es layers, Wan et al. (1999) investigated the link between ionospheric electric fields, interplanetary magnetic field (IMF) and Es layers at Casey (–81° CGM Lat). They concluded that most of the characteristics of the relationship could be explained in terms of the convective electric field effect on ion dynamics. MacDougall et al. (2000b) noted that, during Es observations, the convection velocity was low, and attributed the Es formation to gravity waves. Later, MacDougall and Jayachandran (2005) argued that Es layers observed at 77° CGM Lat could be explained by a two-step mechanism involving horizontal convergence of ionisation followed by vertical convergence, both under the effect of electric field. Voiculescu et al. (2006) and Nygrén et al. (2006) investigated the statistical relation of polar cap electric field and the occurrence of sporadic E at two polar cap sites, Longyearbyen and Thule, using electric fields given by the APL model based on IMF data (Ruohoniemi and Greenwald, 1996). It was shown in these studies that the layer occurrence was in most cases in reasonable agreement with the electric field theory of sporadic E.

All of the above proves that electric field has a major role in the generation of polar cap sporadic E but it also rises some questions about the effect of neutral wind, which obviously has its own effect on ion motion (i.e. Voiculescu and Ignat, 2005). The aim of the present paper is to study how well the electric field and neutral wind are able to reproduce the

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observed layers. Two examples of sporadic E observed by the ESR incoherent scatter radar on Svalbard were chosen for this study. In these two cases the radar experiment consists of four different beam directions, which allows the determination of electric field from the F region ion velocities. The neutral wind was obtained from the HWM93 (Hedin et al., 1991, 1996). The development of sporadic E under the action of these driving agents was calculated by integrating the one-dimensional continuity equation.

2 Method

The sporadic E observations were given by the ESR incoherent scatter radar on Svalbard (78.2° N, 16.0° E; 75.2° CGM Lat, 112° CGM Lon). The experiment consisted of a cycle of four beam directions; one vertical, one in the meridional plane with an elevation of 82° (field-aligned direction) and the remaining two at azimuths of 144° and 172° (SE sector) with elevations of 67° and 63°, respectively. The E-region range resolution was 3 km.

The electric field was determined from the F-region plasma velocity measurements using a program based on stochastic inversion. It applies velocity profiles from all four beam directions and gives two perpendicular electric field components and the field-aligned ion velocity profile. In principle, the beam-aligned plasma velocities could also be used to derive the E-region neutral wind velocities. This implies a model of ion-neutral collision frequency which is needed in the calculation of the ion mobility tensor. A computer program was created for this purpose, but the results turned out to be too inaccurate to be applicable in the calculations. The reason is that, even after heavy smoothing, the noise in the resulting wind profiles creates artificial vertical wind shears. Since wind shears are important in layer formation, the unrealistic wind shears prevented reasonable altitude variation of the layer in the numerical integration. Hence the only possibility was to rely on a wind model; the HWM93 model (Hedin et al., 1991, 1996) was applied. It takes into account the annual variation, the solar F10.7 flux and the magnetic activity in terms of the A_p index.

The layer development was calculated by solving the continuity equation as described in Nygrén et al. (2006). A difference is that, in this paper, the calculated ion velocity is caused by both electric field and neutral wind rather than mere electric field. The vertical ion velocity due to electric field can be written as

$$v_{zE} = e(k_P E_{N\perp} + k_H E_E) \cos I \quad (1)$$

and that due to horizontal neutral wind is

$$v_{zu} = \frac{1}{k_{\parallel}} (k_P u_N \sin^2 I + k_H u_E \sin I) - u_N \cos^2 I. \quad (2)$$

Here $E_{N\perp}$, E_E , u_N and u_E are the local magnetic northward and eastward components of electric field and neutral wind,

I is the magnetic inclination angle, and k_P , k_H and k_{\parallel} are the Pedersen, Hall and field-aligned ion mobilities. It is assumed that electric field is perpendicular to the geomagnetic field and neutral wind is horizontal. The mobilities can be calculated from the well-known formulas using the ion mass, the ion-neutral collision frequency and the geomagnetic induction. It is essential to take ambipolar diffusion into account when solving the continuity equation; otherwise the ions would be quickly packed into an extremely thin sheet. Ambipolar diffusion also makes the layer decay, if the compression due to the driving forces disappears.

A constant metallic ion density profile at an altitude range 90–180 km with smoothed Gaussian ends both above and below was used as a start profile of integration. The ion-neutral collision frequency was calculated in the way described by Nygrén et al. (2006), assuming Fe^+ ions. The MSISE-90 model (Hedin, 1991) was used for neutral density and temperature, and a constant value of 51.5 μT for the geomagnetic induction and an inclination angle of 82° was used at all altitudes.

3 Results

3.1 Layer on 2 July 1999

Figure 1 shows a layer observed on 2 July 1999. The electron density observed by the radar is shown in the top panel. Next comes the calculated Fe^+ ion density caused by the measured electric field only, then the layer caused by model neutral wind only and after that then the same due to the combined action of the measured electric field and the model neutral wind. These densities are shown in arbitrary units. The time step in the integration was 1 s. Most of the ions are collected into a layer after some time from the start of integration, and after that the layer behaviour no more depends on the start density profile; i.e. the arbitrary start profile is not a limitation. The two bottom panels indicate the direction and intensity of the electric field. Field directions favouring the appearance of a layer (i.e. directions from north to south via west, see e.g. Nygrén et al., 2006) are indicated by gray shading.

The radar measurement in Fig. 1 indicates the presence of a faint layer just after 15:00 UT. It descends from 130 km altitude to 120 km, where it is greatly intensified at 15:30 UT. The layer then continues descending down to 95 km at a speed of about 20 km/h. The layer is temporarily weakened at 16:25 UT, but is again intensified at 16:45 UT. After 17:00 UT the layer practically disappears, although a faint layer may still be present afterwards.

The electric field intensity varies between 10 mV/m and 30 mV/m. The field first points slightly westwards from north and gradually turns to a nearly southward direction. At about 16:40 UT it starts turning back northwards and makes a full round back to south via west, north and east. Between

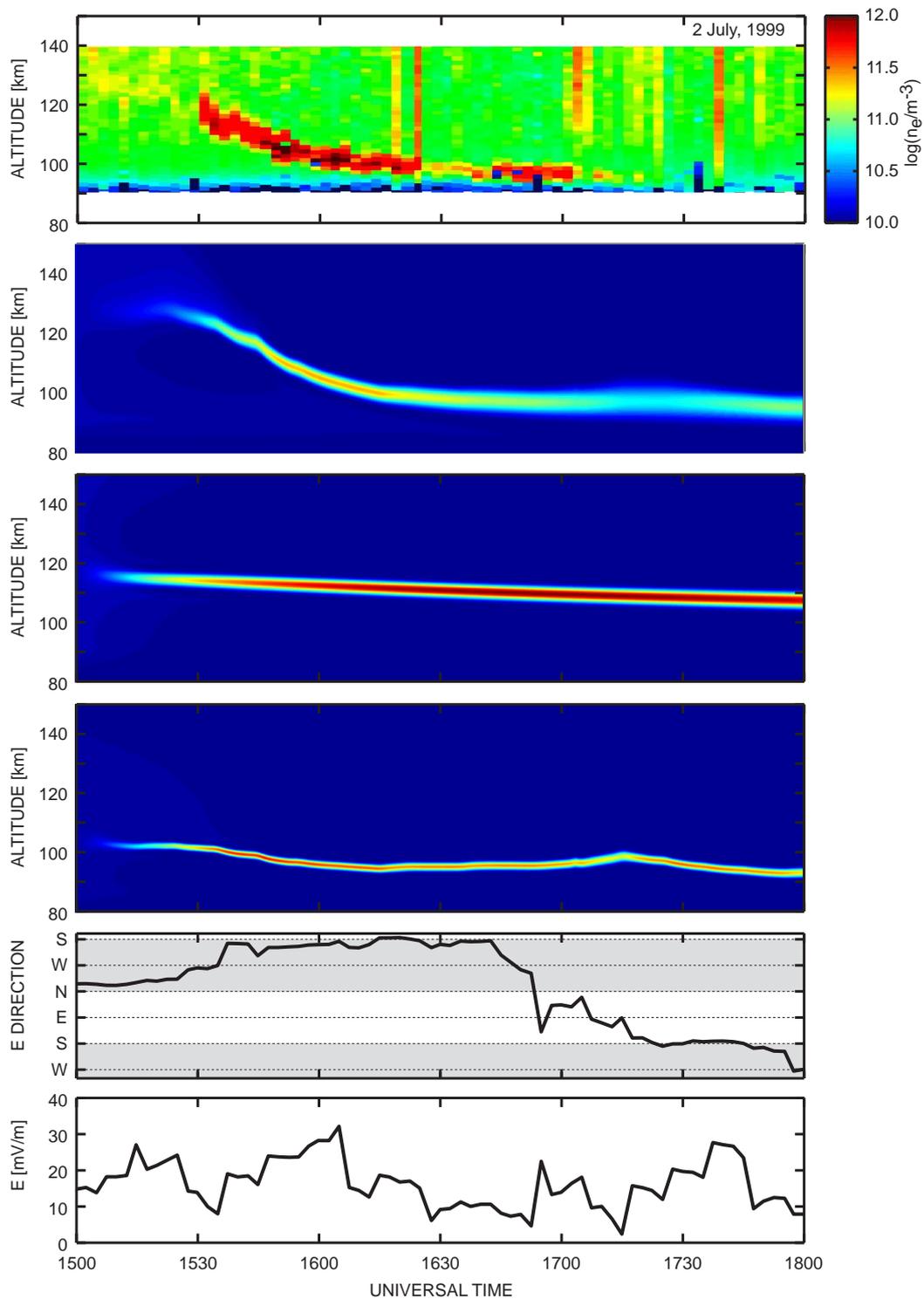


Fig. 1. Top panel: Radar observations of E region electron density above Svalbard on 2 July 1999. Second panel: Calculated time development of Fe^+ ion density starting from a flat background under the action of electric field only. Third panel: Same as second panel under the action of neutral wind only. Fourth panel: Same as second panel under the actions of both electric field and neutral wind. The two bottom panels: The direction and intensity of the ionospheric electric field, respectively. Here S, W, N and E mean local geomagnetic south, west, north and east. The electric field theory roughly predicts layer production when the field direction lies within the NW sector (vertical compression towards some fixed height) or within the SW sector (downward flow at all altitudes). These sectors are indicated by gray shading. For details, see the text.

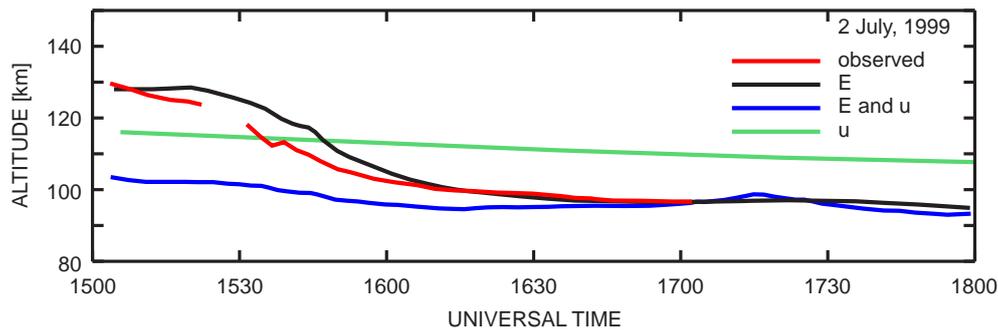


Fig. 2. Red line: Altitude of the peak of the observed layer in Fig. 1. Black line: Altitude of the calculated layer assuming the presence of electric field only. Green line: The same assuming the presence of neutral wind only. Blue line: The same assuming the presence of both electric field and neutral wind.

16:50 UT and 17:20 UT the field points in directions where the basic electric field theory does not predict layer production.

When only the effect of the electric field is taken into account, the solution of the continuity equation first produces a layer at about 130 km in height. Following the rotation of the electric field vector, the layer descends to 95 km. After the field turns into the NE and SE sectors, the layer gets weaker but is again intensified when the field direction turns back to south.

A mere neutral wind can only create a slowly descending smooth layer with no features similar to the observations. When both the electric field and the model neutral wind are taken into account, the layer starts descending slowly from 105 km with a speed of less than 5 km/h and shows a clear upward drift at times, when the electric field points in the NE and SE sectors. After that, when the field direction turns southwards, downward drift is again found.

It seems obvious that mere electric field gives the best agreement with observations. This is shown more clearly in Fig. 2, which portrays the altitudes of the layer peak taken from the four topmost panels of Fig. 1. Although neutral wind alone is able to make a layer, it has practically no resemblance with the observations. Between 15:00 and 16:15 UT the layer due to the electric field descends much in the same way as the observed one but at somewhat higher altitude. After 16:15 UT a good agreement between the observed and calculated layer is found. A much worse agreement is encountered when both electric field and neutral wind are taken into account. The altitude of this layer is clearly too low except after 16:45 UT, when a good agreement is seen. Two conclusions can be drawn. For the first, the layer is caused mainly by the electric field. For the second, the effect of the neutral wind must be to shift the layer altitude downwards. The shift due to the model wind is too big, and therefore the model must depart from the true neutral wind in this case.

To understand the results, one should first remember the main predictions of the electric field theory of Es generation

(see e.g. Nygrén et al., 2006). A layer is expected, if the electric field points roughly in some direction between local geomagnetic north and west or in some direction between local geomagnetic south and west. In the former case the ions will drift and converge toward a fixed altitude which depends on the field direction but is usually 110–115 km or higher (Nygrén et al., 1984, 2006; Kirkwood and Nilsson, 2000), but in the latter case the drift is continuously downwards. Low-altitude layers are expected only in the latter case. One should, however, notice that these predictions are based on an assumption of a constant electric field. In reality, the field intensity and directions change, and this has a major effect on the layer behaviour. The vertical layer motions must follow the vertical ion velocity at the layer altitude. Therefore, if the electric field direction changes rapidly, the layer may not be able to follow the altitude of maximum plasma convergence, and it will appear at an altitude which does not agree with the prediction of the basic electric field theory.

In the case of the present observation, the turn of electric field direction from north to south via west can well explain the downward motion of the layer calculated with a mere electric field assumption. However, the basic electric field theory would indicate that, during the northward turn after 16:40 UT, the layer would lie at higher altitudes. The subsequent field directions in the NE and SE sectors would create no layer at all. The reason why this does not happen is that the vertical ion velocity below 100-km altitude is too slow to allow the change. Therefore the layer remains close to 95 km and is slowly decayed there by diffusion. This is well visible in the second panel of Fig. 1. The intensification before 18:00 UT is due to the fact that the layer turns back to the SW sector.

3.2 Layer on 7 July 1999

A second example, shown in Fig. 3, is from 7 July 1999. Here the radar observation contains a layer close to 105 km, starting somewhere within the data gap and ending at about 19:15 UT. There are also some faint indications of a

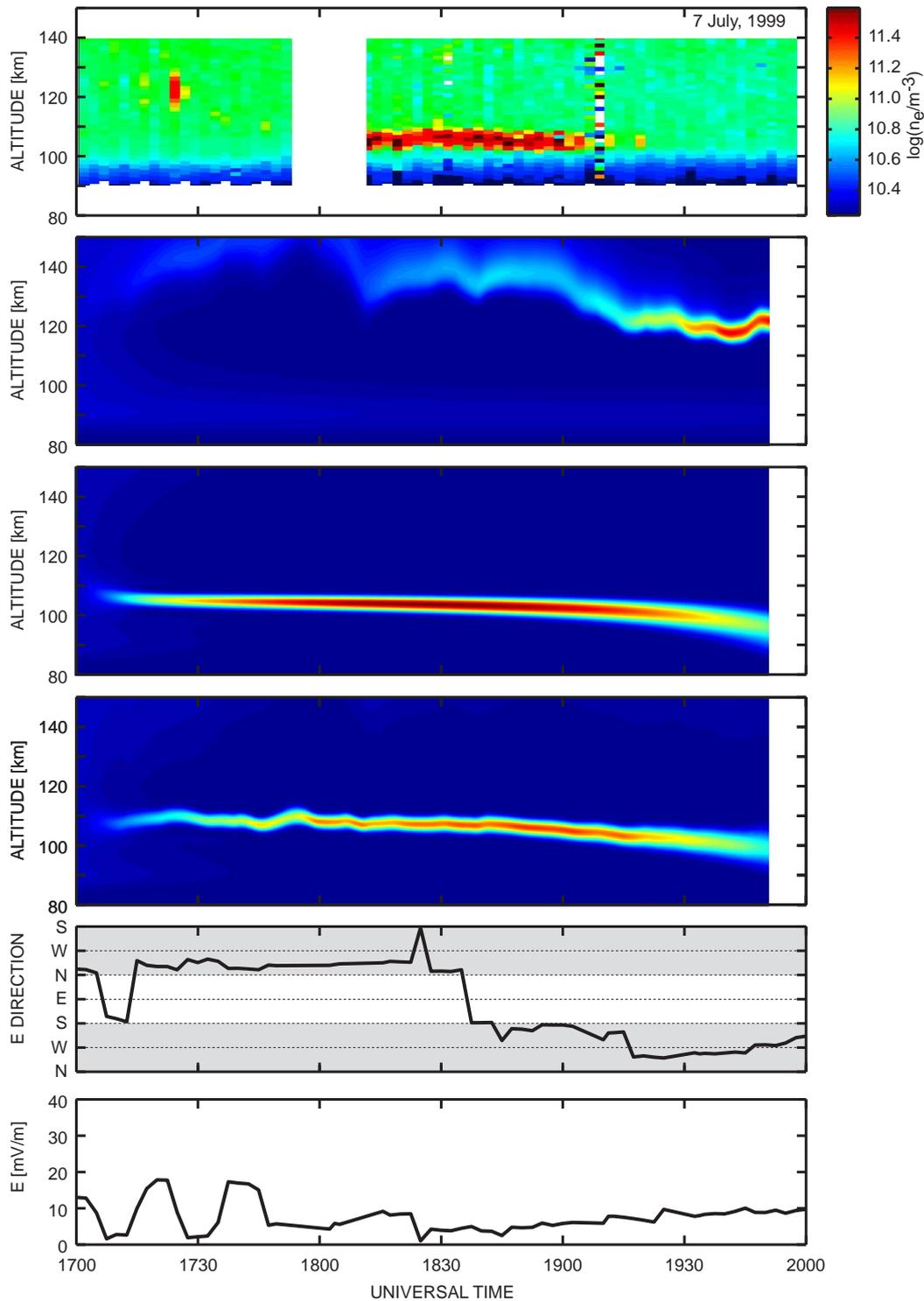


Fig. 3. Same as Fig. 1 for 7 July 1999.

descending layer before the data gap. The electric field is mostly very weak; during the presence of the layer the field strength is usually 5 mV/m or below. First the electric field points mainly in the NW sector, but after 18:30 it turns to

the SW sector and, later, to the NW sector. The solution of the continuity equation using only the electric field produces a thick and faint layer at great altitudes, except after 19:30, when a thin layer close to 120 km is created.

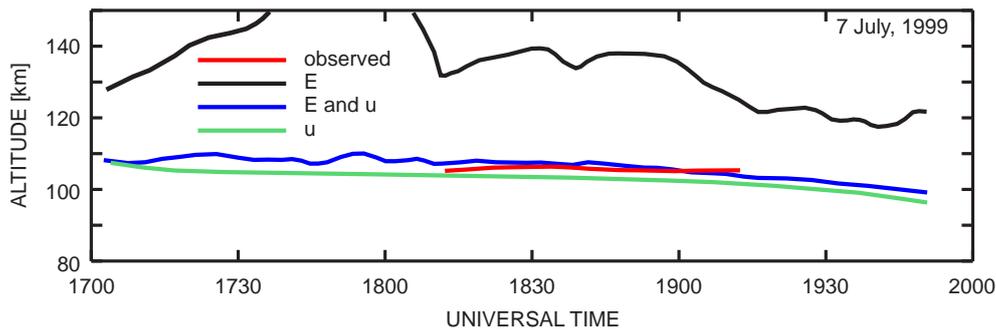


Fig. 4. Same as Fig. 2 for 7 July 1999.

The results change drastically when the neutral wind is included in the calculations. Neutral wind alone makes a layer which is nearly horizontal at the time of the observed layer, descending and decaying later in the evening. The effect of including the electric field is some vertical shift plus slight height variations. The layer starts just below 110-km altitude and stays there up to 18:30 UT. After this there is a slight decrease in the layer altitude until, after 19:00 UT, the downward drift speed increases to some extent. The layer is first weak, but is intensified just before 18:00 UT (this may match the start of the layer which lies somewhere within the data gap). After 19:15 UT the layer again gets weaker during its downward drift.

A comparison of the observed layer altitude with those obtained by calculations is shown in Fig. 4. A marked difference between the observations and the results given by mere electric field is seen, whereas the layer given by neutral wind and electric field together lies nicely at a correct height. Neutral wind alone would make a layer at a somewhat lower height. Thus the neutral wind is indeed the most important factor of layer generation, but electric field has also an effect, shifting the layer to the observed altitude. Although the calculated layer does not show such a clear drop-off in intensity as the observed one does at 19:05 UT, it still gets clearly weaker after the observed layer has disappeared.

4 Discussion and conclusions

The previous statistical studies by Voiculescu et al. (2006) and Nygrén et al. (2006) indicated that the occurrence of sporadic E within the polar cap can be mainly explained by electric field. Of course, neutral wind must have its effect in individual cases as well, as shown for instance by calculations of vertical ion convergence by Voiculescu and Ignat (2005), but it was not investigated in these studies.

The purpose of the present paper is to demonstrate the relative roles of electric field and neutral wind in the generation of polar cap sporadic E in individual events. Another goal is to simulate the observed layers using measured electric fields and model neutral winds so that the time behaviour, i.e. the

altitude and intensity variations of individual layers could be understood.

Two examples were investigated. In one of them, a rather good agreement with the observed layer was obtained, when only the observed electric field was taken into account in the calculation. When the effect of model neutral wind was included, the result was essentially worse. Hence the true neutral wind must be weaker than that given by the model, and the conclusion is that the main driving force producing the layer is due to electric field.

In the second event the electric field is weak and it could alone create only a thick layer at great altitudes. On the other hand, neutral wind and electric field together make a layer nearly precisely at a correct height. Hence we conclude that electric field is too weak to overcome the effect of neutral wind so that the layer is caused mainly by the neutral wind. In this case the role of electric field is to make a small shift in the layer altitude.

Since Es layers are drifting horizontally and they are known to have horizontal structures, it is not to be expected that one-dimensional calculations could properly reproduce the intensity variations of the observed layers. Especially, sharp layer boundaries drifting through the radar beam cannot be reproduced. However, the results show how layer intensity can be reduced by ambipolar diffusion.

The conclusion is that, indeed, when the electric field is not too small, polar cap Es layers can be caused by electric fields, which may also control their time variations, as in the first event of this study. This is in accordance with the statistical studies by Voiculescu et al. (2006) and Nygrén et al. (2006) as well as studies by Bedey and Watkins (2001) and Parkinson et al. (1998). Still, there are also cases where the neutral wind is the main reason for the appearance of the layer even within the polar cap, as in the second event of this study.

A limitation of this work is that neutral winds were taken from the HWM93 model. Wind models are not necessarily representative for high latitudes at all times, since particle precipitation and drag of neutrals by ions can affect the neutral air motion there. This is shown e.g. by Zhang

et al. (2004). In the present paper the use of a model was unavoidable, because neutral winds could not be determined with a sufficient accuracy from simultaneous incoherent scatter observations. The first example of this work demonstrates a case when the true neutral wind must clearly depart from the model.

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