The effect of ionospheric conductivity in the electric fields at intermediate and small scales observed by the FAST satellite

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Abstract. Physical mechanisms of magnetosphere-ionosphere coupling at intermediate (1-100 km) and small (< 1 km) scales are not fully understood as yet. The prevailing viewpoint is that this coupling is by means of dispersive Alfvén waves, which include non-uniformity of perturbations on perpendicular scales the order of the electron inertia length or ion gyroradius. However, the interpretation in terms of waves, either freely propagating or standing, seems to be inconsistent with the seasonal variation in the small-scale electric fields observed in the topside ionosphere, which, on the other hand, can be readily explained, assuming static current circuits. Previously, the seasonal variation was addressed in a detailed study by *Heppner et al.*, [1993], where ac electric field data of the *Dynamics Explorer 2* (DE-2) satellite (altitudes from 300 km to 900 km) were employed. Here we investigate this effect by highly resolved FAST observations of the dc electric fields at altitudes near FAST apogee (h = 4000 km) and clarify if it can be reasonably understood within the wave framework (e.g., *Lysak* [1998]) or static framework (e.g., *Golovchanskay*a [2007]).

1. Previous results

Through the last decades, the high-latitude electric and magnetic fluctuations observed in the topside ionosphere on the scales from tens of meters to several hundreds of kilometers (a sample is given in Figure 1) have been extensively investigated. It is known that they have a magnetospheric origin [*Gurnett et al.*, 1984], exhibit a clear connection to the Birkeland field-aligned currents [*Golovchanskaya et al.*, 2006] and possess scale invariance, a signature of non-linear dynamics or turbulence [*Tam et al.*, 2005; *Kozelov and Golovchanskaya*, 2006].

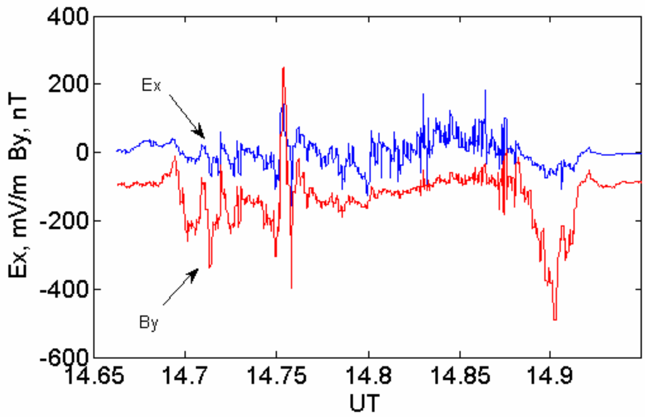

Figure 1. A sample of strongly variable along-track electric field *Ex* (blue) and cross-track magnetic field *By* (red) measured with 16 s^{-1} (~ 0.5 km) resolution by DE-2 on 25 November (day 329) 1981, UT = 1440–1456; the hourly *Bz* IMF and *By* IMF are 13.4 nT and −17.9 nT. The geomagnetic field according to the International Geomagnetic Reference Field (IGRF) model is subtracted from the magnetic data.

An intriguing feature of the variable fields of the type shown in Figure 1 is their seasonal asymmetry. Specifically, the electric fields are, in average, by factor three enhanced under winter conditions as compared to summer conditions, while the magnetic fields are mostly invariable or slightly (by factor ~ 1.5) reduced under winter conditions. This feature was first reported for intermediate scales by *Vickrey et al.* [1986] with using the data from the drift meter and magnetometer on board the HILAT satellite. Their conclusion was that at scale sizes between 80 km and 3 km the magnetosphere tends to behave as a constant current source, that is independent of ionospheric conductivity, rather than a constant voltage source. A theoretical framework for such a conclusion was given by *Lysak* [1985].

More in detail and on larger statistics this effect was investigated by *Golovchanskaya* [2007] with using DE-2 electric and magnetic field measurements with 16 s^{-1} (~ 0.5 km) resolution. The results are illustrated in Figures 2 and 3.

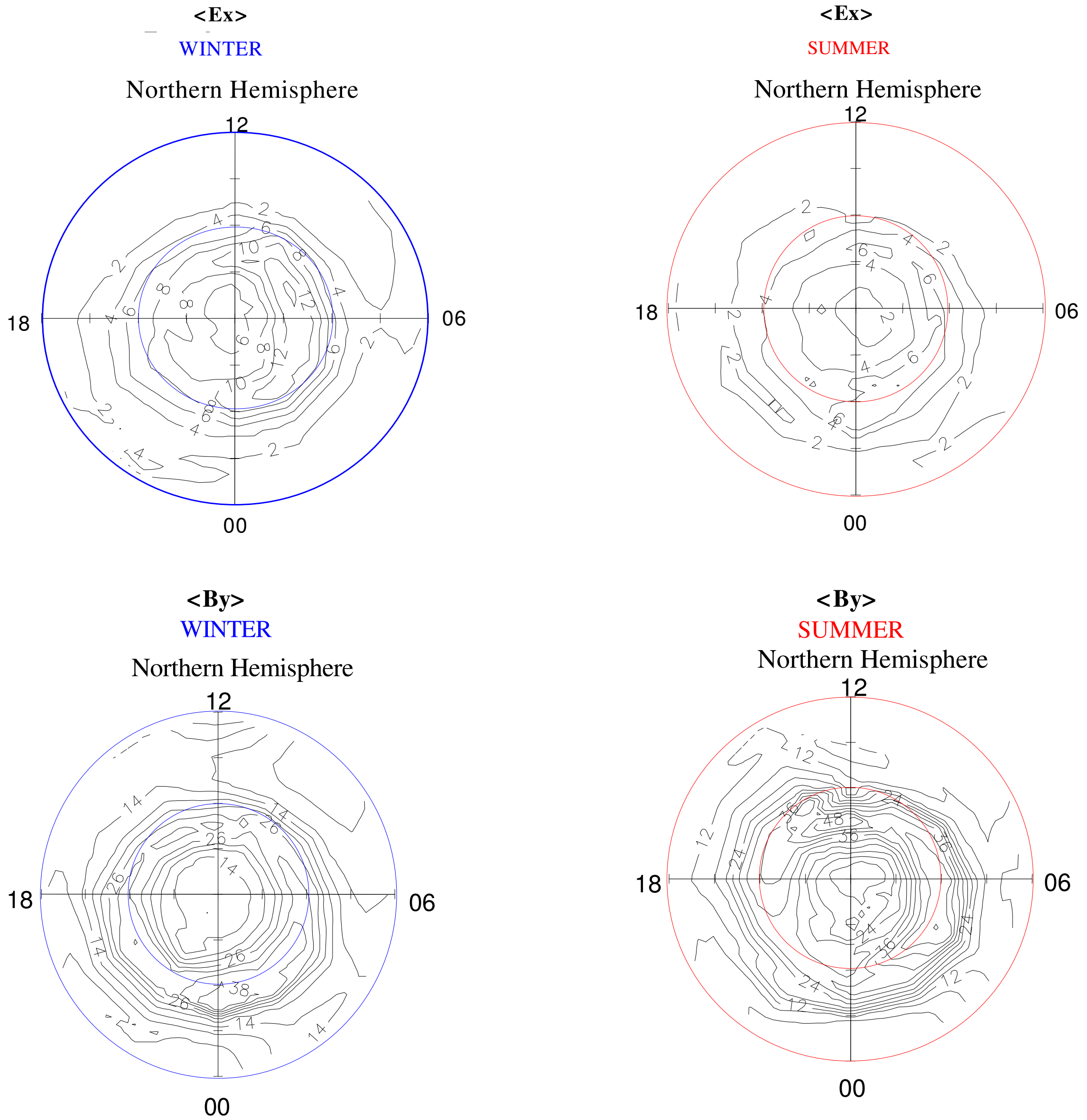

Figure 2. Distributions in the INV LAT - MLT coordinates of high-pass filtered, cutoff scale 100 km, (top) electric and (bottom) magnetic fields observed by DE2 in the Northern Hemisphere during (left) winter and (right) summer seasons. Latitude contours mark 50° and 70° INV LAT; [*Golovchanskaya,* 2007].

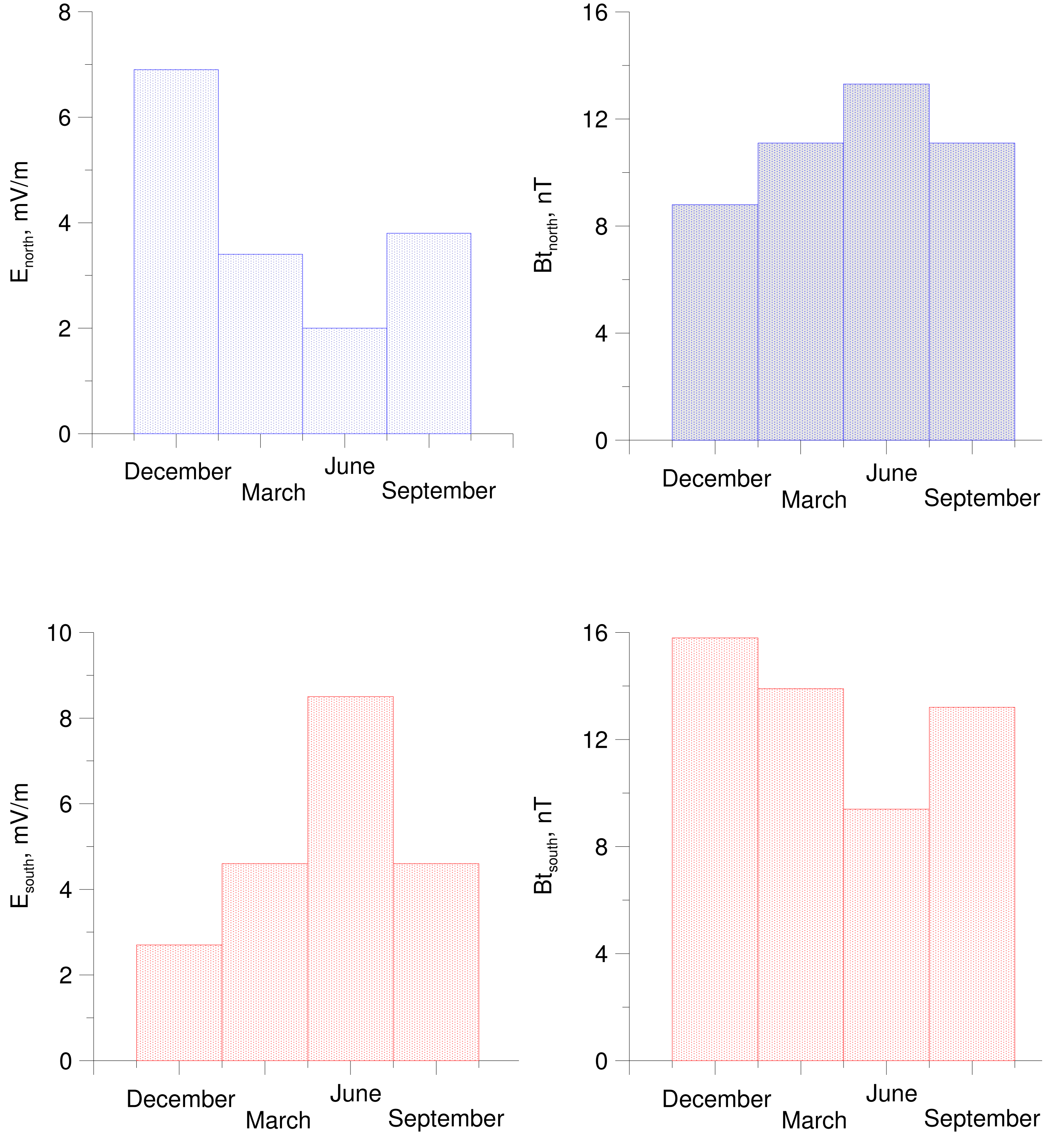

Figure 3. Averaged over INV LAT >75° (left) electric and (right) magnetic field fluctuations observed by DE2 in different months in the (top) Northern Hemisphere and (bottom) Southern Hemisphere; [*Golovchanskaya,* 2007].

Heppner et al. [1993] investigated the seasonal effect in the high-latitude electric field variability by DE-2 ac electric field measurements. From Figure 4, where the effect is shown in different pass bands, one can see that it is present up to frequencies 256-512 Hz (scales ~ 15-30 m).

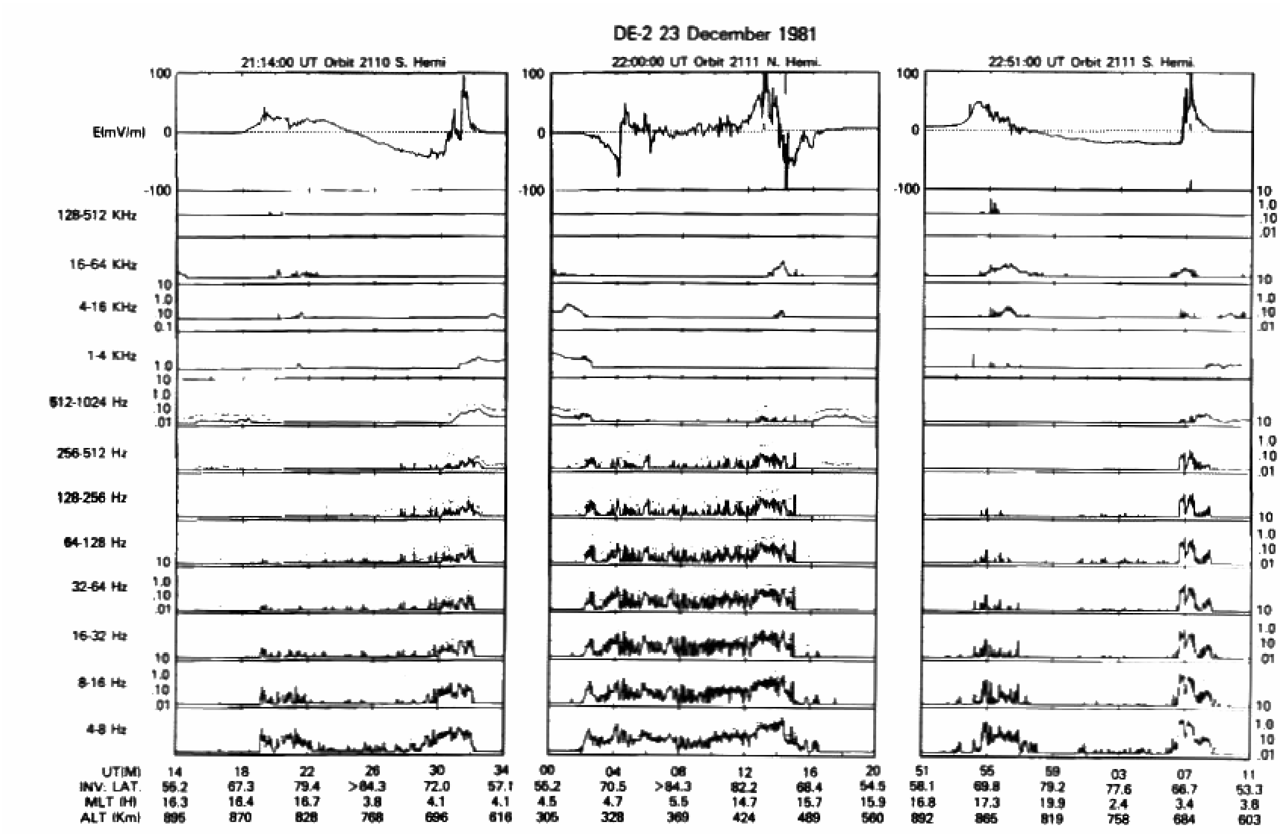

Figure 4. A sequence of south-north-south polar DE-2 passes near the time of winter solstice in the northern hemisphere; [*Heppner et. al.,* 1993].

2. Seasonal effect in small-scale electric fields by FAST observations

Figure 5 presents the results of seasonal effect investigation by FAST measurements of electric and magnetic fields with resolution 512 s^{-1} (128 s^{-1}) at altitude ~ 4000 km. Specifically, we regressed *log(σ)*, *σ* the standard deviation, to *log(s)*, *s* the scale, for (top) electric field fluctuations and (bottom) magnetic field fluctuations sorted according to season (all MLTs, solar wind and geomagnetic conditions were included). In total, forty FAST passes into the auroral zone (twenty for winter conditions and twenty for summer conditions) were considered. One can see that the seasonal variation, that is, a dependence of field fluctuation power on the ionospheric conductance, is clearly observed. The effect is pronounced in the electric field and is nearly absent in the magnetic field. Moreover, in the electric field it persists down to very small scales (~ 14 m), which is consistent with the previous finding of *Heppner* [1993].

The lack of seasonal asymmetry in the magnetic perturbations supports the claim of *Vickrey et al.* [1986] and *Lysak* [1985] that at intermediate and small scales the magnetospheric generator is the current generator, independent of ionospheric conductance.

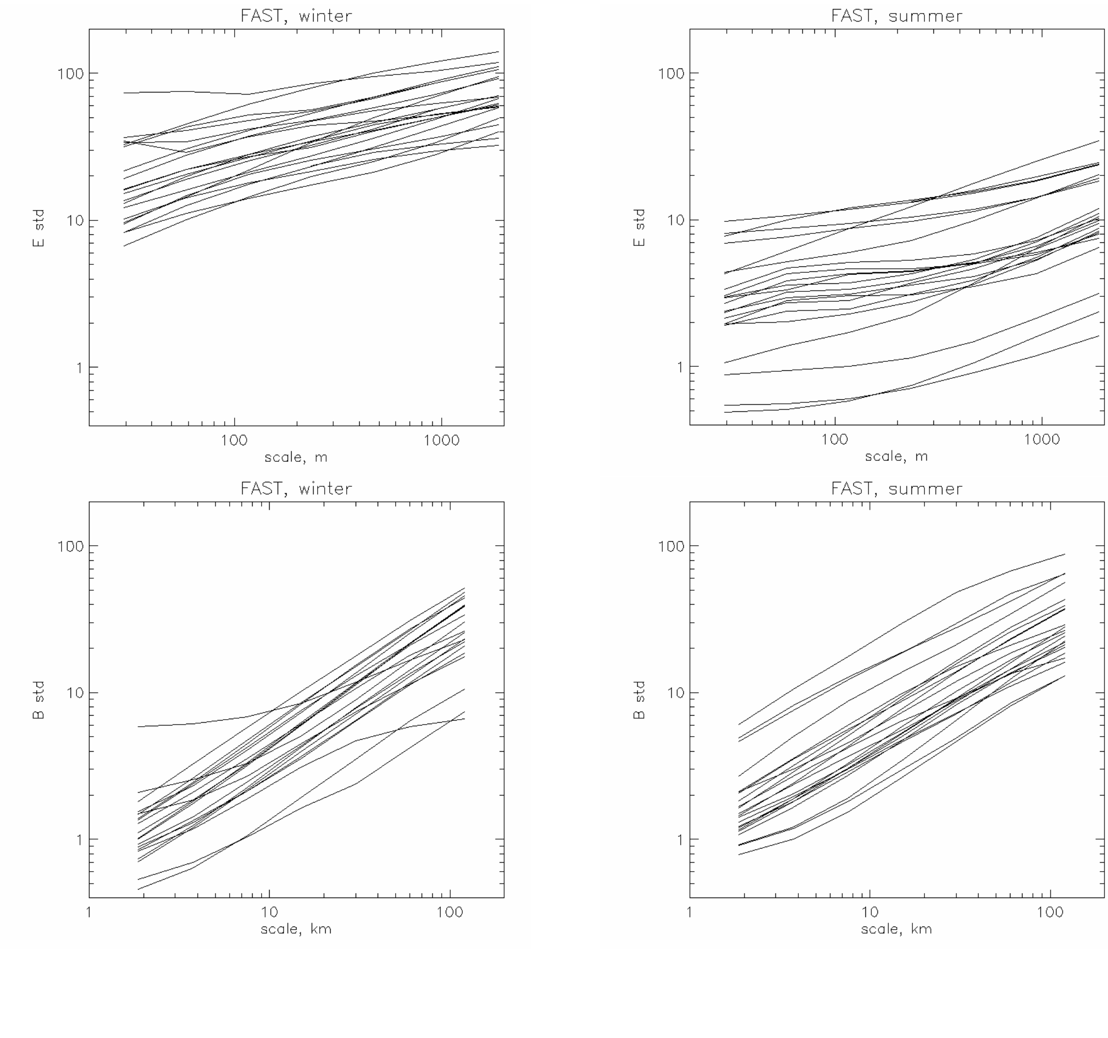

Figure 5. *log(σ)-log(s)* regressions (*σ* the standard deviation and *s* the scale) for (top) electric field fluctuations and (bottom) magnetic field fluctuations, (left) in winter and (right) in summer by FAST observations at 4000 km altitudes. The resolution of electric (magnetic) field measurements is 512 s^{-1} (128 s^{-1}), which corresponds to the spatial resolution of 14 m (56 m) (the FAST velocity is taken 7 km/s).

3. Interpretation within the static models

The seasonal effect described above was interpreted by several authors within the static approach. The interpretation given by *Volkov and Maltsev* [1986] was based on the assumption of field-aligned potential drop arising in the small-scale current circuits under asymmetric conductance conditions in the ionosphere of two hemispheres. It was suggested that the perturbed FACs $\delta j_w^{\|}$ and $\delta j_s^{\|}$ immediately link the generator region to the ionosphere of the winter and summer hemispheres (Figure 6, top). Since in this case the electric potential at the footprints of the magnetic field lines in the two hemispheres is different, a field-aligned potential drop is inevitably present in the problem, which, according to [*Lyons*, 1980, 1981], under certain approximations, can be related to the perturbed field-aligned currents as

$$\varphi_m - \varphi_w = R_w^{\|} \cdot \delta j_w^{\|} \qquad (1)$$

$$\varphi_m - \varphi_s = R_s^{\|} \cdot \delta j_s^{\|}$$

where φ_m is the electric potential in the magnetospheric generator of the fields, φ_w, φ_s are the potentials and $R_w^{\|}$, $R_s^{\|}$ the parallel resistance in the wintertime and summertime ionosphere, respectively.

Following *Sugiura et al.* [1982], it is typically suggested that the small-scale FACs predominantly close in the meridional plane, so that

$$\delta j_w^{\|} = -\Sigma_w \frac{\partial^2}{\partial x^2}\varphi_w$$

$$\delta j_s^{\|} = -\Sigma_s \frac{\partial^2}{\partial x^2}\varphi_s \qquad (2)$$

where Σ_w and Σ_s are the ionospheric Pedersen conductances; x indicates the north-south direction, x=0 refers to the center of FAC sheet.

Volkov and Maltsev [1986] considered that $\delta j_w^{\|}$ and $\delta j_s^{\|}$ are generated in the inner magnetosphere by the *Vasyliunas* [1970] mechanism and thus implied $\delta j_w^{\|} + \delta j_s^{\|} = f = 2\cdot\mathbf{e}_{\|}[\nabla V\times\nabla p]$, where V is the magnetic volume, p the plasma pressure, $\mathbf{e}_{\|}$ the unit vector along the magnetic field.

For a special case of

$$\delta j_w^{\|} + \delta j_s^{\|} = f_0 = const \qquad \text{for } |x| < a$$

$$\delta j_w^{\|} + \delta j_s^{\|} = 0 \qquad \text{for } |x| > a \qquad (3)$$

a being the characteristic scale of the FAC sheet, the solution of the set of equations (1), (2), and (3) takes the form

$$\delta j_{w,s}^{\|} = \pm A\cdot \mathrm{ch}(kx) + f_0\cdot\frac{\Sigma_{w,s}}{\Sigma_w + \Sigma_s} \qquad \text{for } |x| < a$$

$$\delta j_{w,s}^{\|} = \pm B\cdot\exp(-k\,|\,x\,|) \qquad \text{for } |x| > a \qquad (4)$$

The associated electric fields are

$$\delta E_{w,s} = f_0[\frac{x}{\Sigma_w + \Sigma_s} \mp \frac{C}{k\cdot\Sigma_{w,s}}\exp(-ka)\cdot \mathrm{sh}(kx)] \qquad \text{for } |x| \le a$$

$$\delta E_{w,s} = f_0[\frac{a}{\Sigma_w + \Sigma_s} \mp \frac{C}{k\cdot\Sigma_{w,s}}\exp(-k\,|\,x\,|)\cdot \mathrm{sh}(ka)] \qquad \text{for } |x| \ge a \qquad (5)$$

In (4), (5) the upper (lower) sign refers to the winter (summer) hemisphere; *A*, *B* are constants which are the same for both hemispheres; the hyperbolic sine and cosine functions are defined as $\mathrm{sh}(kx)=\dfrac{\exp(kx)-\exp(-kx)}{2}$, $\mathrm{ch}(kx)=\dfrac{\exp(kx)+\exp(-kx)}{2}$; the coefficients k and C are given by

$$C=\frac{R_w^{\|}\Sigma_w-R_s^{\|}\Sigma_s}{(R_w^{\|}+R_s^{\|})(\Sigma_w+\Sigma_s)}$$

$$k=\sqrt{\frac{\Sigma_w+\Sigma_s}{(R_w^{\|}+R_s^{\|})\Sigma_w\cdot\Sigma_s}} \tag{6}$$

The second term in the square brackets in formulas (5) differs both by sign and by magnitude for the winter and summer hemispheres, thus making δE season dependent. Taking into account relations (6), it is seen that, if the conductivity along the magnetic field lines is perfect ($R_w^{\|}=R_s^{\|}=0$), this term tends to zero, and the seasonal asymmetry in the electric fields vanishes. We also note that expression (6) for k generalizes the relation of *Lyons* [1980], specifying the inverse width of a precipitation region, for the case of asymmetric conditions in the two hemispheres.

Golovchanskaya [2007] noted that the above explanation may be not applicable to the field fluctuations at very high latitudes, which are associated with highly stretched or open magnetic field lines, where the time required to establish Alfvén-wave communication between the hemispheres is very large (>1 hour) or infinite. In addition, the FACs needed to produce the field-aligned potential drop should exceed a certain threshold, of a few μA/m^2 or more, which is typically not the case in the polar cap. She assumed that the FACs in the generator region are linked to the ionosphere of only one hemisphere and to the front of an Alfvén wave propagating to infinity (Figure 6, bottom) and demonstrated reasonable values of Σ_w, Σ_s, and Σ_A, the Alfvén conductivity, derived from the observed seasonal variation in the fields, under such an assumption.

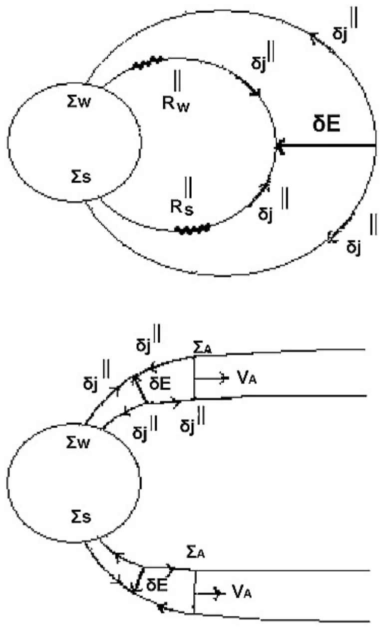

Figure 6. Sketch illustrating two manners of small-scale current closure in the meridional section of the magnetosphere within the static approach. (top) The generator region is linked by the FACs to the ionosphere of both winter and summer hemispheres. (bottom) The FACs close to the ionosphere of one hemisphere and a front of outgoing Alfvén wave.

We can see that the seasonal variation can be readily interpreted under the assumption that the field fluctuations are associated with spatial current circuits. However, it has long been known that the static model fails to explain other aspects of small-scale electric and magnetic fields at high latitudes, for instance, the electric-to-magnetic field ratio, which appears much larger than the static models predict [e.g., *Gurnett et al.*, 1984].

4. Interpretation within the wave models

An opposite view that the observed perturbations in the high-latitude fields are of electromagnetic nature, i.e., should be attributed to plasma waves, was shared by *Maltsev et al.* [1977], *Mallincrodt and Carlson* [1978], *Lysak* [1985], *Gurnett et al.* [1984] and others. All those authors supposed that Alfvén waves are an essential ingredient in explaining the low-frequency in situ satellite signals.

We shall briefly survey the proposed wave models to find out if they allow for explanation of the seasonal variation described in section 1 and 2 above.

The only way to explain the seasonal variation in the wave approach is to include ionospheric reflection. Considering that the effect persists at very small scales of 10-20 m at altitude of 4000 km (Figures 4 and 5), it would be most natural to interpret it within the model of *Mallincrodt and Carlson* [1978] (Figure 7), where the reflected Alfvén wave is shifted from the incident wave by magnetospheric convection. At altitude 4000 km, Alfvén wave forth and back transit time is a few seconds, and thereby the perturbation will be most likely removed from the reflected Alfvén wave.

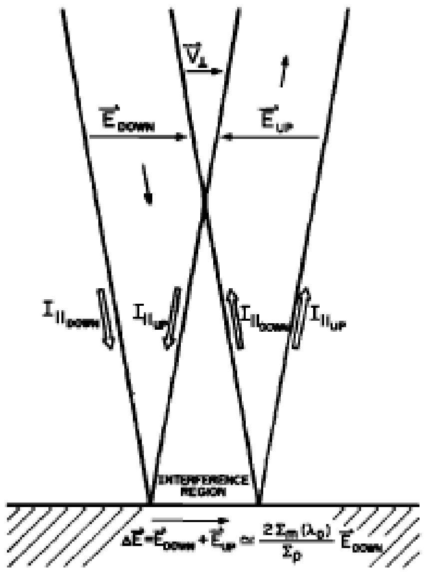

Figure 7. Cross-section of currents and fields in the vicinity of the ionosphere due to a magnetospheric source. The reflected wave has slightly less than opposite the magnitude of the incident wave and returns along a path slightly 'downstream' from the incident path owing to plasma convection.

However, it is easy to see that in the *Mallincrodt and Carlson* [1978] model the reflected electric fields are larger for larger ionospheric conductance and thus the seasonal variation has to be of opposite sense to the actually observed.

An alternative, though strongly unlikely at small scales, is a standing structure, which is a superposition of an incident wave and a wave reflected off the conducting ionosphere. Here we refer to the study of *Lysak* [1998], where the wave fields in this situation were computed. Figure 8 (from [*Lysak*, 1998]) shows the contours of the E_x/B_y ratio for the ionospheric reflection model as a function of frequency and altitude. While the ionospheric conductance adopted in the computations for the cases illustrated in Figure 8a and 8c differs by two orders of magnitude, there is no significant increase in the E-field in the low conductance case.

5. Summary

We suppose that the seasonal variation in the auroral electric fields on intermediate and small scales can tell us much about magnetosphere-ionosphere coupling at such scales. While it can be easily explained within the static approach, the observed ratios of variable electric and magnetic fields are known to be more consistent with the wave models. Presumably, a solution of the problem can be found in the scenario recently proposed by *Chang et. al* [2004], where the observed magnetic perturbations are attributed to the Alfvénic coherent structures (magnetic flux tubes), arising in the lower magnetosphere in result of non-linear dynamics of dispersive Alfvén waves, and the electric perturbations (quasi-static by nature) are produced due to the motion of the coherent structures in the external magnetic field $\vec{B}_0$, when interacting under the action of the Ampere force. Perhaps, both plausible electric-to magnetic field ratios and the proper sense of the seasonal variation (caused in this case by the breaking of the moving structures by the conductive ionosphere) can be obtained in this new and promising approach.

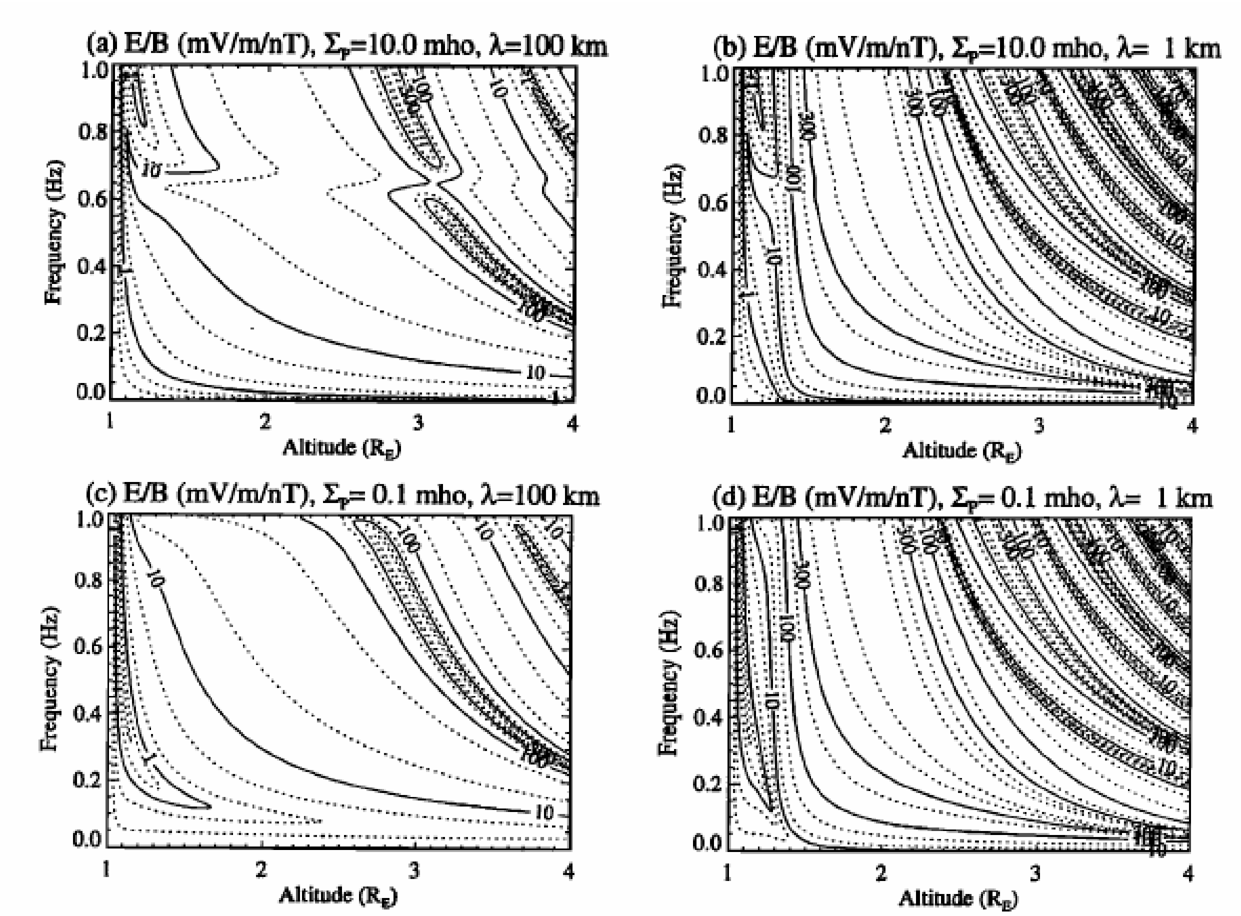

Figure 7. Contours of the Ex/By ratio for the ionospheric reflection model as a function of frequency and altitude, expressed in units of mV/m/nT, or equivalently, 1000 km/s. Panels a and b assume a Pedersen conductivity of 10 mho, while c and d assume 0.1 mho. Panels a and c are for a perpendicular wavelength of 100 km mapped to the ionosphere, while b and d are for 1 km. A value of 300 on these plots indicates a ratio of the speed of light.

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