JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. A12, 1446, doi:10.1029/2003JA009956, 2003

Role of unstable sporadic-*E* layers in the generation of midlatitude spread *F*

Christos Haldoupis,[1] Michael C. Kelley,[2] Glenn C. Hussey,[3] and Sergei Shalimov[4]

Received 24 March 2003; revised 4 August 2003; accepted 9 September 2003; published 23 December 2003.

[1] There is growing experimental evidence to suggest that mesoscale spread *F* is linked to the occurrence of midlatitude coherent backscatter from patchy sporadic-*E* layers, which are unstable to the gradient-drift and Farley-Buneman plasma instabilities. To validate this suggestion, we have compared *E*-region backscatter and spread-*F* ionosonde recordings from about 100 days of joint operation during summer and found a one-to-one relation in the occurrence of both phenomena. Also, midlatitude backscatter studies over the last few years have shown the existence of enhanced electric fields inside patchy sporadic *E*. These are believed to be polarization fields set up locally by neutral winds that transport the plasma patches horizontally, and by the relatively large Hall-to-Pedersen conductivity ratios at *E*-region altitudes. Moreover, midlatitude echoes were found to be associated with mostly westward drifting sporadic-*E* patches with typical scale lengths from 10 to more than 100 km and perturbed eastward electric fields from a few to maybe more than 10 to 15 mV/m. We propose that the enhanced polarization fields set up inside unstable sporadic-*E* patches can easily map up the magnetic field lines to the *F* region and thus contribute to the formation of midlatitude spread *F*. This new mechanism for spread-*F* generation is basically an image process that can account for key observational properties of the phenomenon. These include the rapid plasma upwelling and the abrupt changes in height (uplifts) of the *F* layer, as well as the scale sizes involved and morphological characteristics. *INDEX TERMS:* 2435 Ionosphere: Ionospheric disturbances; 2443 Ionosphere: Midlatitude ionosphere; 2439 Ionosphere: Ionospheric irregularities; 2437 Ionosphere: Ionospheric dynamics; 2411 Ionosphere: Electric fields (2712); *KEYWORDS:* ionosphere, plasma instabilities, plasma irregularities, coherent scatter radar, ionosonde, midlatitude spread *F*

Citation: Haldoupis, C., M. C. Kelley, G. C. Hussey, and S. Shalimov, Role of unstable sporadic-*E* layers in the generation of midlatitude spread *F*, *J. Geophys. Res.*, *108*(A12), 1446, doi:10.1029/2003JA009956, 2003.

1. Introduction

[2] Midlatitude spread *F* is identified in the ionograms by the multiplicity and height spreading of the *F*-region trace, resulting from strong undulations and irregular plasma structuring in the *F*-region electron density. Many of these disturbances are attributed to the passage of large-scale atmospheric gravity waves which can impose a wavelike altitude modulation in the *F* layer [*Bowman*, 1990] but also to electrodynamic forces and large-scale plasma instabilities [*Kelley and Fukao*, 1991; *Miller et al.*, 1997]. The latter applies in particular to mesoscale spread *F* with scales from a few tens to many tens of kilometers that occurs overwhelmingly in the summer nighttime. Midlatitude spread *F* has been studied for many years, but its understanding remains incomplete despite considerable progress [e.g., see *Kelley et al.*, 2002].

[3] With respect to mesoscale spread *F*, incoherent scatter measurements from Arecibo [*Behnke*, 1979; *Behnke et al.*, 1985; *Miller et al.*, 1997; *Swartz et al.*, 2002] and coherent-backscatter recordings from aspect-sensitive meter-scale *F*-region irregularities [*Fukao et al.*, 1991; *Swartz et al.*, 2000], as well as airglow imaging observations [*Kelley et al.*, 2000], established a key property of the phenomenon: the existence of regions characterized by rapid turbulent upwelling and abrupt plasma uplifts. An uplift in the *F* region can be caused by upward and northward $\mathbf{E} \times \mathbf{B}$ plasma drifts driven by a zonal eastward electric field and/or a meridional southward wind. The rapid upwelling of meter-scale irregularities observed by *Fukao et al.* [1991], which seems to be accounted for only in terms of $\mathbf{E} \times \mathbf{B}$ motions, and the large electric fields inside spread *F* measured by *Behnke* [1979] and inferred by *Swartz et al.* [2002], imply that the *F*-region uplifts are caused by eastward electric fields rather than southward neutral winds.

[4] In this work, we postulate that the eastward electric fields required for the *F*-region uplifts, and therefore the generation of spread *F*, are mapped up along the field lines from within strongly unstable sporadic-*E* layers (E_s). This

[1]Physics Department, University of Crete, Iraklion, Greece.
[2]School of Electrical and Computer Engineering, Cornell University, Ithaca, New York, USA.
[3]Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, Canada.
[4]Institute of Physics of the Earth, Moscow, Russia.

0148-0227/03/2003JA009956$09.00

interpretation emerged from our recent understanding of the unstable patchy E_s and from growing experimental evidence of a link between mesoscale spread *F* and unstable sporadic *E*. The latter has been suggested by the MU (Middle and Upper atmosphere) radar observations of *Fukao et al.* [1991], the recent multiinstrument observations of *Swartz et al.* [2002], and the long-term studies of Bowman on a relationship between spread *F* and spread E_s [e.g., see *Bowman et al.*, 1994, and references therein].

[5] In the present paper we present new experimental evidence showing that midlatitude *E*-region coherent backscatter from sporadic-*E* layers is accompanied almost always by the appearance of spread *F*. Then we describe and discuss a new mechanism for spread-*F* generation in which the key role is played by zonal polarization electric fields set up within westward drifting E_s plasma patches and mapping up to *F*-region altitudes. These ideas are supported by two case studies presented in the companion paper [*Kelley et al.*, 2003], but first we start with a summary of our present knowledge of unstable E_s.

2. Unstable Sporadic-*E* Layers and Polarization Electric Fields

[6] Midlatitude sporadic-*E* layers are metallic-ion layers that prevail mostly between 100 and 115 km, where they are sustained by positive vertical wind shears in the zonal wind or simply by prevailing westward winds. The term "unstable E_s," used throughout the text, refers to the situation where sporadic *E* is destabilized by gradient-drift and/or two-stream plasma instabilities [e.g., see *Kelley*, 1989]. This leads to the generation of aspect-sensitive plasma irregularities, which can coherently scatter radio waves that are perpendicular to the Earth's magnetic field. The unstable E_s has been studied extensively over the last 15 years with midlatitude backscatter radars observing at small angles to the magnetic meridian [e.g., see *Hysell and Burcham*, 2000, and references therein].

[7] *Hussey et al.* [1998] found that unstable E_s associates with spread E_s, referring to patchy and spatially structured sporadic *E* rather than to continuous blanketing-type layers. This could imply a link between unstable E_s and spread *F*, given the close relationship between spread E_s and spread *F* reported in several ionosonde studies by Bowman. As shown by *Haldoupis and Schlegel* [1996], the unstable E_s is a summer nighttime phenomenon, exactly as is midlatitude spread *F*. In addition, the E_s-related echoes are found to possess mostly negative-mean Doppler shifts corresponding to northward and upward (away) velocities with magnitudes usually less than 100 m/s but also at times well above this limit, sometimes even exceeding 300 m/s [e.g., see *Haldoupis et al.*, 1997; *Swartz et al.*, 2002]. Since the echoes are attributable to $\mathbf{E} \times \mathbf{B}$ drifting irregularities, the observed Doppler velocities are interpreted as being due to enhanced eastward electric fields of several millivolts per meter, well above the ambient dynamo fields at midlatitude [e.g., see *Kelley*, 1989].

[8] Several E_s backscatter studies show that the echoes occur intermittently and last from a few minutes to a few hours, often being subject to pronounced periodicities. The most spectacular periodicities, which came to be known as *QP* (quasi-periodic) echoes, are best manifested in range-time-intensity (RTI) plots as sequential sloping striations of scatter with periods from a few minutes to about 30 minutes and range rates, dR/dt, from about 20 to 100 m/s, which are mostly negative and attributable to southward neutral winds [e.g., see *Yamamoto et al.*, 1991; *Hysell and Burcham*, 2000; *Hysell et al.*, 2002]. Studies with the Valensole radar in the south of France [e.g., *Bourdillon et al.*, 1995; *Haldoupis et al.*, 2001], which provided large azimuthal scans of 86°, showed that midlatitude scatter relates to individual plasma structures, presumably patches of sporadic *E* that drift across the radar field of view with the neutral wind. Also, the zonal scale lengths of the unstable plasma patches were found to extend from several kilometers to many tens of kilometers, mostly between 20 and 100 km. Moreover, these unstable E_s patches were found to drift westward prior to 0200 hours local time, with speeds ranging from about 30 to 150 m/s.

[9] The relatively large westward motions of the unstable E_s patches, which have been observed in several (including radio interferometer) experiments [*Yamamoto et al.*, 1992; *Bourdillon et al.*, 1995; *Hysell et al.*, 2002; *Haldoupis et al.*, 2003, and references therein], seem to constitute a key property of the phenomenon and are most likely a source of free energy. For example, a westward wind can form and sustain a sporadic-*E* patch at *E*-region altitudes by exercising a downward Lorentz force on the ions, which are slowed down below by collisions and forced into a layer. Also, as discussed below, a westward wind can help polarize a plasma patch which can then become unstable to the gradient-drift instability, and even to the two-stream instability. Finally, we note that the westward bulk motions reported for unstable E_s are comparable with the westward velocities of traveling mesoscale spread-*F* structures, as measured by *Behnke* [1979], *Fukao et al.* [1991], and *Swartz et al.* [2002].

[10] After the detection of Farley-Buneman waves (type-1 echoes) at midlatitude by *Schlegel and Haldoupis* [1994], it was realized that the large, negative Doppler velocities of the echoes can only be due to elevated zonal electric fields inside E_s, which can reach values of at least an order of magnitude higher than the ambient-mean dynamo fields. The existence of such fields is now understood in terms of a simple polarization process proposed by *Haldoupis et al.* [1996], which is the same as it is at the magnetic equator but with the geometry turned on its side. This requires a sporadic-*E* plasma patch with sharp, horizontal conductivity gradients at its edges that play the same role that vertical gradients play at the magnetic equator. Sharp gradients in the zonal direction, in particular, and the need to maintain a divergence-free current flow in this direction can lead to a zonal polarization electric field,

$$E_x^p \simeq \frac{\sigma_H}{\sigma_P} E_y,$$

which is considerably higher than the driving meridional field, E_y, because the Hall-to-Pedersen conductivity ratio can easily be larger by a factor of 10 in the *E* region.

[11] In this polarization process, note that an eastward polarization electric field is driven by a southward meridional field. Arecibo incoherent scatter measurements show that premidnight ambient meridional electric fields, E_y, are

typically southward in the quiet summertime with an average magnitude somewhat above 1 mV/m [e.g., see *Kelley*, 1989]. Given that the unstable patches are drifting with the wind mostly westward, it is likely that the strong eastward polarization fields inside E_s are driven mainly by a wind-induced, southward $\mathbf{U_x} \times \mathbf{B}$ field in addition to the weaker dynamo field, E_y^0. Note that zonal polarization fields set up in this way, combined with proper sign electron density gradients, are thought to be responsible for destabilizing the E_s plasma to the gradient-drift instability, and less often to the Farley-Buneman instability [e.g., *Haldoupis et al.*, 1997; *Hysell and Burcham*, 2000].

[12] The final value of E_x^p would depend on the polarization field that builds up in the meridional direction and the current-closure system coupling to the *F* region via field-aligned currents. If the integrated Pedersen conductivity in the region above E_s is comparable to that inside the patch, then the effective value of the Hall-to-Pedersen conductivity ratio and hence E_x^p will be reduced accordingly. The problem of current closure in the *F* region was treated analytically by *Shalimov et al.* [1998] and numerically by *Hysell and Burcham* [2000]. They found that this polarization process can account for the elevated eastward electric fields of several millivolts per meter, which are often implied from backscatter Doppler measurements. They have also shown that the polarization process can be much more effective for meridionally elongated sporadic-*E* patches and/or enhanced ambient and wind-induced southward fields.

[13] In the present paper we postulate that the large eastward electric fields inside unstable E_s patches can map up along the magnetic-field lines to the *F* region to produce rapid $\mathbf{E} \times \mathbf{B}$ plasma upwelling and *F*-region uplifts, thus generating mesoscale spread *F*. Before we discuss this, however, we first provide some more experimental evidence on the link between spread *F* and unstable E_s.

3. More Evidence for a Link Between Spread *F* and Unstable E_s

[14] Following suggestions that spread *F* occurs in conjunction with unstable E_s, we considered testing this theory by revisiting an older data set composed of common-volume observations of 50-MHz Doppler backscatter and ionosonde recordings carried out over the southern Aegean Sea from 23 June to 3 October 1996. The objective of this experiment was to investigate the relation between midlatitude *E*-region coherent backscatter and sporadic-*E* layers. The experiment included the Sporadic *E* Scatter radio system (SESCAT), a 50-MHz continuous-wave Doppler radar located on the northern coastline of Crete that was capable of observing coherent echoes from a fixed *E*-region area about 160 km to the north, and a Canadian Advanced Digital Ionosonde (CADI) that was placed beneath the SESCAT field of view on the island of Milos. Details about the experiment and its findings (which revealed a close relation between backscatter and spread E_s) are given by *Hussey et al.* [1998].

[15] For the purposes of this work we have tried a first comparison between CADI spread *F* and SESCAT observations. Keeping in mind that midlatitude backscatter is strictly a nighttime phenomenon, we considered only the period from 1700 to 0300 UT (LT = UT + 3) when vertical incidence ionograms were recorded every 2 min. The idea was to inspect the data using quick-look plots and to search for a relationship between the two phenomena. Surprisingly, we found a one-to-one relation in the occurrence of strong to moderate SESCAT echoes and CADI spread *F*. During nights with a few short-lived, low-intensity echoes or no echoes at all, spread *F* was absent in the measured ionograms.

[16] The inspection of the two data sets indeed suggests a connection between the two phenomena. We need to stress, however, that the initiation and duration of backscatter does not usually coincide with that of spread *F*. The latter normally starts somewhat later but often persists longer, sometimes until sunrise, after which the *F*-region structures are washed out by photoionization. In addition, the *E* region observed by SESCAT maps to the *F* region at about 160 km south over the island of Crete; thus some differences in the occurrence of the phenomena are to be anticipated.

[17] Figure 1 shows a typical active night of strong backscatter as observed by SESCAT. The bottom plate is a Doppler spectrogram showing a sequence of echo bursts that lasts from 10 to 40 min, having mostly broad spectra attributable to $\mathbf{E} \times \mathbf{B}$ drifting irregularities. The upper panel shows that the mean Doppler velocities of the echoes are negative, ranging from a few tens to more than 200 m/s, due to northward and upward irregularity motions. These motions are indicative of local eastward electric fields that range from a few millivolts per meter to more than 10 mV/m; that is, they are considerably elevated relative to typical midlatitude zonal electric fields [e.g., see *Kelley*, 1989]. The picture depicted in Figure 1 represents a common case for the SESCAT observations which is particularly valid for premidnight strong-echo occurrences. In addition to the negative Doppler shifts, recent SESCAT interferometer measurements by *Haldoupis et al.* [2003] show that the echoing regions undergo westward bulk motions, presumably due to a zonal wind, with speeds between 20 and 150 m/s.

[18] Inspection of all CADI ionograms during the same night as in Figure 1 shows that spread *F* appeared shortly after about 1735 UT, it intensified with time (especially after about 1930 UT), and it remained present well after about 2215 UT, when the coherent echoes become very weak and nearly absent. The occurrence of spread *F* can be seen in Figure 2, which presents ionogram samples in a time sequence spanning over the entire night of 14–15 July from 1700 to 0230 UT.

[19] To obtain an unbiased statistical estimate of the correlation between the unstable E_s and spread *F*, is almost a formidable task. An important reason is the difficulty one faces in quantifying spread *F* from the ionogram records. To put it simply, spread *F* is easy to be recognized by visual ionogram inspection but difficult to be parameterized. Another serious problem comes from the presence of blanketing sporadic *E* layers, which mask part or the whole of the *F*-region traces. Here, additional difficulties arise because the unstable E_s area viewed by SESCAT does not connect electrically to the overhead *F* region monitored by CADI. As well, the field of view and the extent of the observed *E* and *F* regions by the two instruments may be quite different. Keeping all this in mind, we attempt here only a rough statistical investigation by correlating the relative occurrence of the two phenomena.

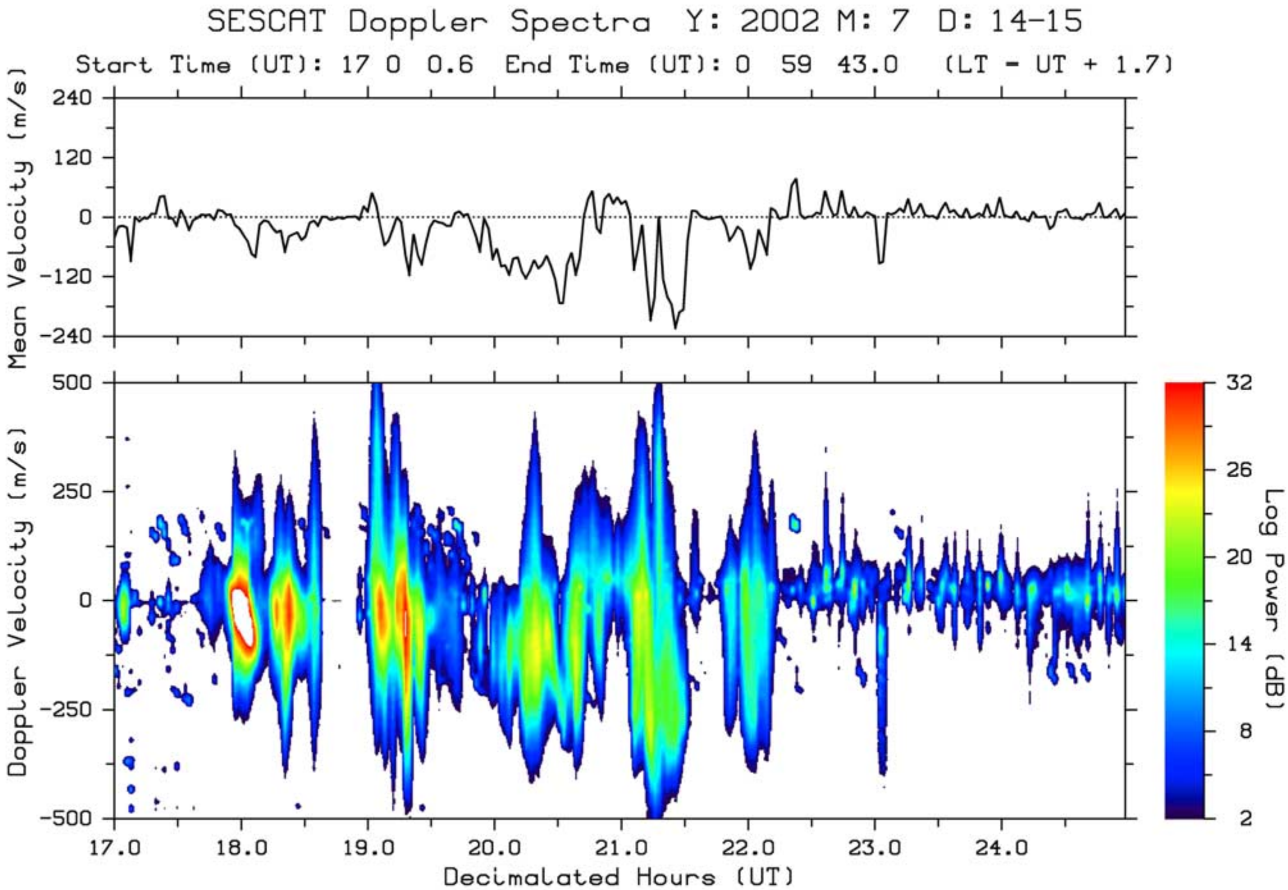

Figure 1. A Doppler spectrogram (bottom) of a typical midlatitude *E*-region coherent backscatter event and mean Doppler velocity in meters per second (top), as measured by SESCAT at 50 MHz during the night of 14–15 July 1996.

[20] In comparing the E_s backscatter and spread *F* occurrences, the two data sets were inspected during the 8-hour nighttime interval from 1800 to 0200 UT (LT = UT + 1.7 h) when ionograms were taken every 2 min. The above nighttime period was reduced to an effective period by subtracting the intervals of blanketing sporadic *E*. In this procedure, a night would be omitted if blanketing E_s lasted more than 2 hours. Once the effective nighttime period was determined, the SESCAT echo occurrence was quantified by computing the total duration of scatter in minutes for echoes with a SNR greater than 2 dB. Similarly, the total spread *F* occurrence was measured also in minutes, following its visual identification in sequential ionograms. Next, both occurrences were expressed as percentages of the nighttime intervals under inspection. Note that the occurrences of unstable E_s and spread *F* during a given does not necessarily imply that there was coincidence in time of the two phenomena.

[21] Figure 3 is a scatter plot showing how the spread *F* and backscatter occurrence estimates compare for a total of 85 nights during the 102-day period under consideration, from 23 June to 3 October. The rest of the nights were not usable, either because SESCAT was not operating or the CADI data were characterized by enhanced blanketing E_s activity. It is important to stress that out of the 85 nights used in Figure 3, 21 were "quiet" nights marked by the complete absence of both E_s backscatter and spread *F*. As seen in Figure 3, there is considerable scatter in the points but also a significant degree of correlation between the two phenomena, signified by a linear correlation coefficient $r = 0.82$.

4. A New Mechanism for Generating Mesoscale Spread *F*

[22] Based on the SESCAT/CADI comparisons presented above and the published results reviewed in the preceding sections, we conclude that there must be a connection between mesoscale spread *F* and unstable sporadic *E*. This result is in agreement with a similar conclusion made by *Swartz et al.* [2002]. We postulate that this relation is sustained through electrical coupling of the two ionospheric regions, which allows mapping of electric fields up (down) the Earth's magnetic-field lines. Here we introduce a new idea which can serve as a mechanism for generating mesoscale spread *F* at midlatitudes, as illustrated in Figure 4.

[23] The schematic in Figure 4 shows highly conducting sporadic-*E* patches of metallic-ion plasma with abrupt boundaries drifting with the neutral wind in the nighttime *E* region. In the rectangular coordinate system, $\hat{x}$ is pointing horizontally to the east, $\hat{y}$ is perpendicular to the magnetic

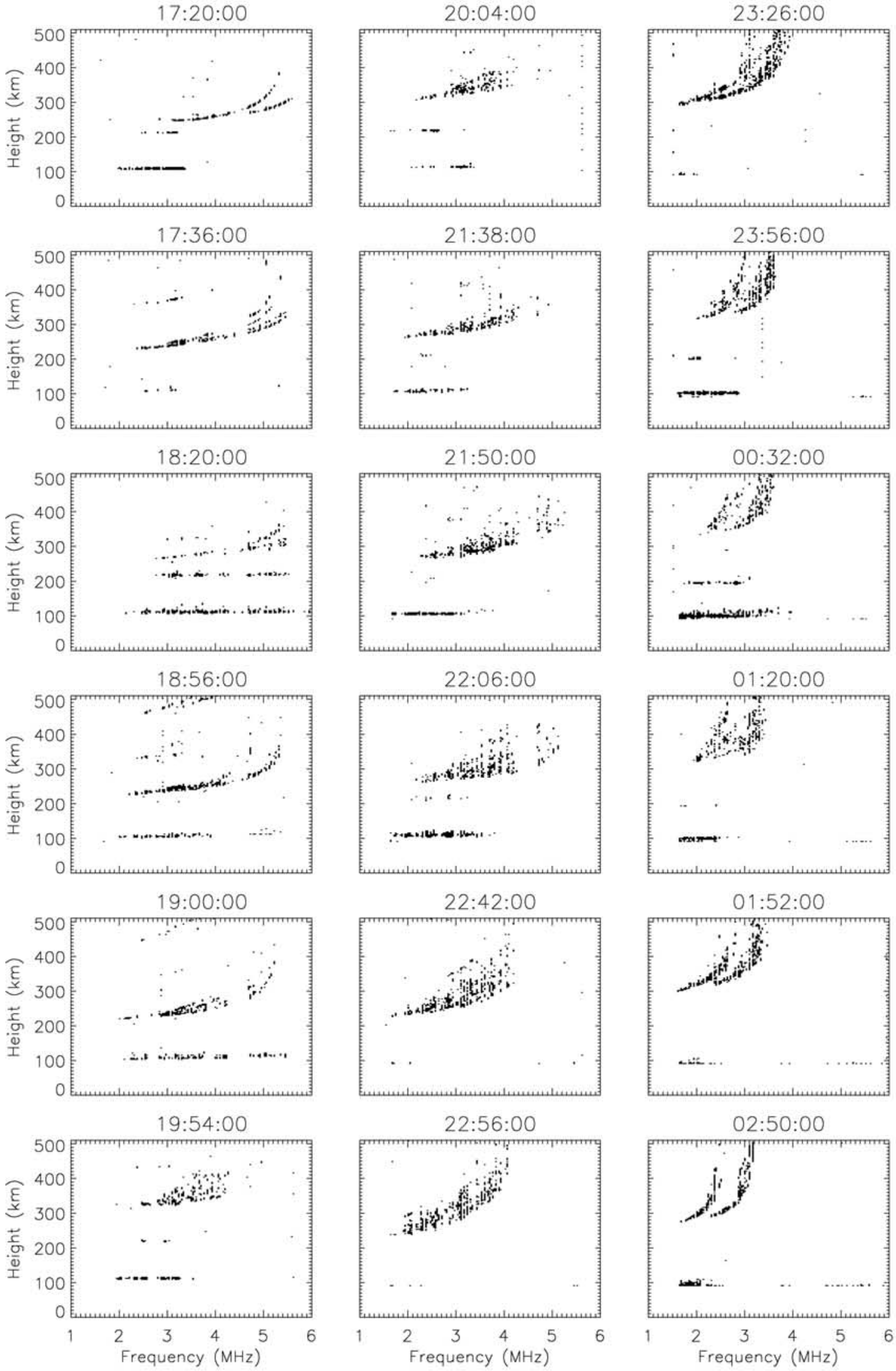

Figure 2. Sequential Canadian Advanced Digital Ionosonde (CADI) ionogram samples showing the occurrence of strong spread *F* during the night of 14–15 July when, as shown in Figure 1, sporadic-*E* layers are strongly unstable to meter-scale plasma irregularities with large northward and upward Doppler velocities.

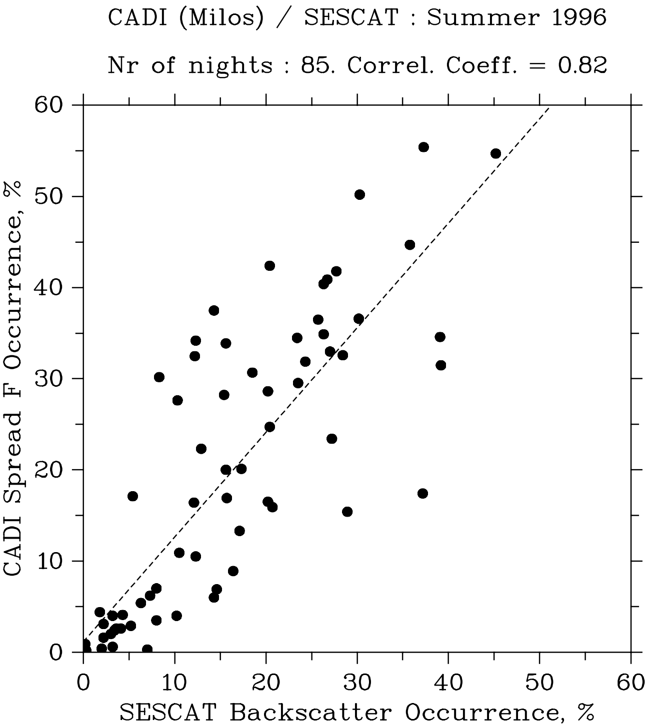

Figure 3. Scatter plot showing a reasonable degree of correlation between the occurrence of E_s-related backscatter, as observed by the Sporadic E Scatter experiment (SESCAT) in the E region, and the occurrence of spread F as measured by a Canadian advanced digital ionosonde (CADI) which was located in the island of Milos, nearly beneath the SESCAT viewing area. The occurrences are expressed as percent of time over the same nighttime interval.

field pointing southward and downward, and $\hat{z}$ is along **B**. For simplicity, we ignore any bulk meridional motions and assume that the patches are drifting westward, as suggested by experiment. As explained in section 2, the total meridional field, $E_y = E_y^0 - U_x B$ in the reference frame of the patch drifting with the neutrals, can drive stronger eastward polarization fields, $E_x^p \simeq (\sigma_H/\sigma_P)E_y$, which in turn can cause northward and upward Hall electron drifts. These electron drifts in conjunction with ambient meridional density gradients can destabilize the plasma, even at times they might be strong enough to excite the Farley-Buneman instability. In addition, they may also polarize the patch in the meridional direction, as shown in Figure 4, with a secondary polarization field E_y^p acting to reduce E_x^p. A steady state prevails when divergence-free conditions are established inside the patch through field-aligned current closures. The closure details, which depend upon the ionospheric conductivities and the patch dimensions, are described by *Shalimov et al.* [1998] and will not be considered in the present discussion. Finally, as shown in Figure 4, a westward electric field may also set in secondarily inside regions of low electron density as a result of the oppositely charged edges of neighboring E_s patches.

[24] Next, we postulate that the electric fields inside sporadic-E plasma patches map up along the field lines to F-region altitudes. The effectiveness of mapping depends on the zonal extent of the E_s patch, l_x, and Farley's mapping factor, $(\sigma_0/\sigma_P)^{1/2}$, where σ_0 is the parallel or specific conductivity and σ_P is the Pedersen conductivity. So, the mapping distance along **B** is

$$l_z = l_x\sqrt{\frac{\sigma_0}{\sigma_P}}.$$

If we adopt a rather conservative value near 10 for $(\sigma_0/\sigma_P)^{1/2}$ as suggested by *Swartz et al.* [2002], then l_x needs to be greater than about 15 km for the polarization fields, E_x^p, to map to F-region altitudes higher than 250 km. These scale sizes are below the mean zonal extents measured for unstable E_s layers by the Valensole radar [e.g., see *Bourdillon et al.*, 1995]; thus we conclude that many of the E_s patches are sufficiently large for their polarization fields to map up to F-region altitudes. Note that the typical zonal E_s scales measured by the Valensole radar range from between 20 and more than 100 km, which seem to compare well with the spread-F azimuthal scales measured, for example, by *Fukao et al.* [1991].

[25] The eastward fields mapped to the F region will act upon the magnetized plasma and thus impact upward and northward **E** × **B** drifts, causing F-region uplifts and therefore spread F. If we take a magnetic dip angle of about 50° and consider an eastward E_x^p field of 5 mV/m, this will cause a northward and upward **E** × **B** drift of about 110 m/s to act upon an F-region volume and thereby produce a vertical plasma uplift of 60 km in about 10 min. For a larger eastward electric field of 12 mV/m, the northward and upward drifts will be 250 m/s, and an F-region uplift of 60 km will form in only 4 min. These estimates are in agreement with the measurements of *Behnke* [1979] and *Swartz et al.* [2002], who quoted uplifts of 30 to 100 km, and also with the negative (away) Doppler velocities measured by *Fukao et al.* [1991].

[26] As discussed previously, the enhanced eastward fields cause northward and upward **E** × **B** electron drifts in the E region and set up secondary meridional polarization fields, depicted in Figure 4 by the dashed line E_y^p vectors inside the E_s patches. We suggest that these fields can also lead to some limited (because of collisions) E_s plasma uplifts as well, since the ions must move up to maintain plasma neutrality. This could then explain the vertical distortions of a few kilometers in sporadic E observed by *Swartz et al.* [2002] during times of strong E-region instability conditions and coherent echoes with large negative Doppler shifts.

[27] The remarkable observations of *Fukao et al.* [1991] showed that the spread-F plasma patches, dominated by negative (away) Doppler velocities, often displayed at their edges positive (toward) Doppler velocities, which implies southward and downward **E** × **B** plasma motions there. On rare occasions, the same experiments detected F-region patches of scatter with negative (away) Doppler motions alternating with patches of backscatter having positive (toward) Doppler velocities. These Doppler-polarity reversals in the spread-F plasma structures may also be understood in terms of the conceptual model shown in Figure 4. The reason might be that the electric fields in the low-conductivity areas between sequential E_s patches reverse polarity and point westward. These fields appear because of

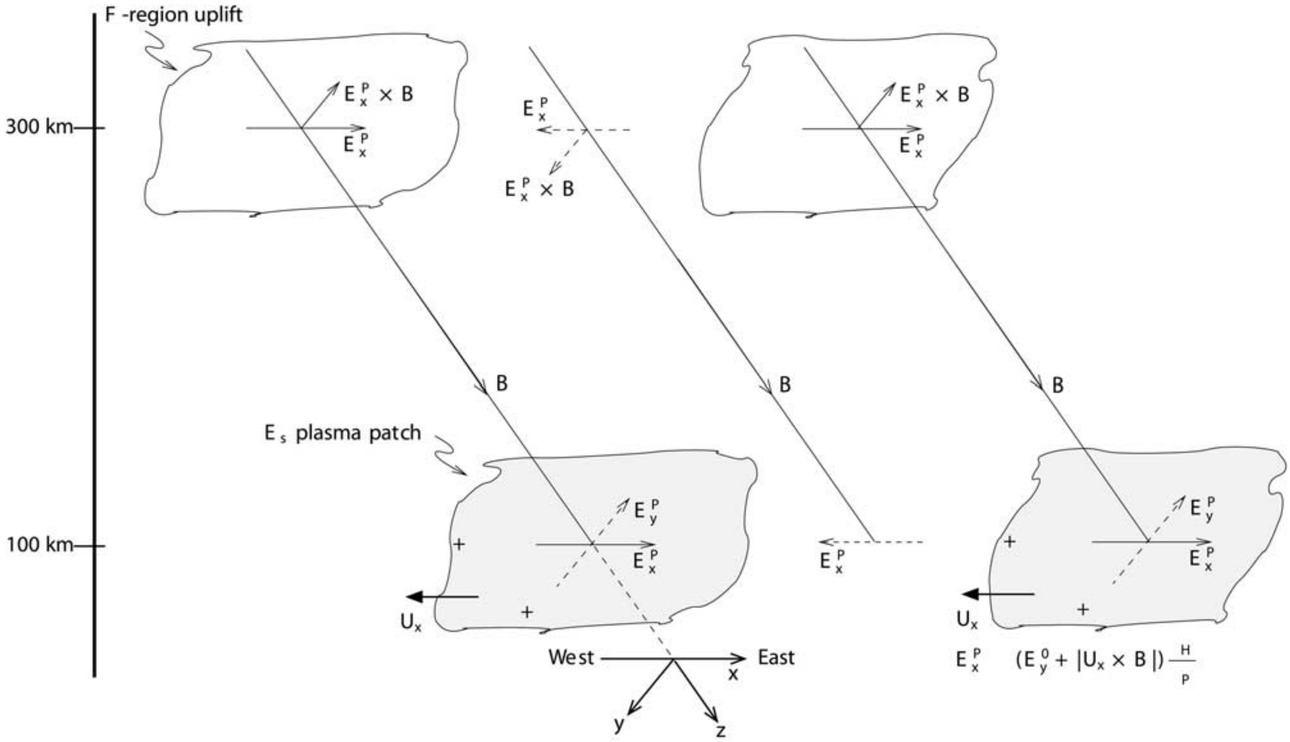

Figure 4. Schematic illustrating a new mechanism for generation of mesoscale spread *F* at midlatitudes. In this process, the eastward polarization electric fields set up inside unstable sporadic-*E* plasma patches can map along the magnetic-field lines up to the *F* region. There, they cause rapid upward and northward **E** $\times$ **B** plasma transport that creates abrupt *F*-region uplifts and mesoscale spread *F*. They could also create inside E_s northward and upward polarization fields (designated here with dashed lines) which act, also in conjunction with field-aligned current closures, to establish a divergence free current flow; these secondary polarization fields can also map up to the *F* region and cause westward plasma transport. Also, a westward field might prevail between the drifting patches because the neighboring edges are oppositely charged. For more details, see text.

opposite-polarity charge buildup at the neighboring edges of sequential E_s patches. If these westward fields also map up the field lines to the *F* region at times, then they can cause southward and downward plasma drifts and thus explain the positive (toward) Doppler motions of *Fukao et al.* [1991] quite nicely.

5. Discussion and Concluding Comments

[28] There is an important observational aspect of mesoscale spread *F* that needs also to be considered, which has to do with the predominantly westward motions of spread-*F* plasma structures that often attain speeds higher than 100 m/s. For example, *Fukao et al.* [1991] measured westward bulk motions nearing 125 and 185 m/s in two cases. These sizable westward drifts also contradict the Perkins instability mechanism proposed as the process behind mesoscale spread *F*, which predicts eastward motions [e.g., see *Kelley and Fukao*, 1991].

[29] What is the reason for these large westward motions in spread *F*? This puzzling question has been around for some time now, but there seems to be no satisfactory explanation yet [e.g., see *Kelley et al.*, 2002]. It is interesting that the unstable E_s patches are also observed to move overwhelmingly westward with speeds as high as 150 m/s [e.g., see *Haldoupis et al.*, 2001; *Haldoupis et al.*, 2003]. These observations suggest the intriguing option that the *E*-region patches somehow track the spread-*F* structures, a possibility also inferred by *Swartz et al.* [2002] and mentioned in earlier ionosonde studies by *Bowman* [1985]. This option, however, is hard to understand because bulk plasma motions in the *E* region are controlled by winds, since the ions are strongly collisional, whereas in the *F* region both ions and electrons are strongly magnetized, dominated by the **E** $\times$ **B** drifts.

[30] In the framework of our proposed mechanism for spread *F*, there is a possibility that the westward spread-*F* drifts are due to a northward and upward electric field which might have its origin in a meridional polarization field inside an unstable E_s, as shown in Figure 4, and which maps up to the *F* region. Possibly, these meridional polarization fields can be enhanced further by southward winds in the same way that westward winds act to create the eastward polarization fields under consideration. Subsequently, in this case the strong south-westward *E*-region winds [e.g., see *Larsen*, 2002] may control both the E_s and spread-*F* bulk motions. On the other hand, the combined action of the meridional and zonal winds on the E_s patch will, at steady state, adjust the zonal and meridional polarization fields accordingly. For example, a northward polarization field inside the patch, sustained by a southward wind, will act to reduce the eastward polarization field, and

if it is sufficiently strong, it could even reverse its polarity. We agree that these ideas are tentative and need to be considered more closely in a detailed theoretical study, probably a three-dimensional model similar to that of *Shalimov et al.* [1998] that deals with the polarization process inside a sporadic-*E* plasma patch drifting horizontally with the wind in the southwest direction and the polarization fields building up inside the patch.

[31] Alternatively, one cannot exclude an explanation which assumes that the westward spread *F* motions are due to wave propagation rather than mass transport. For example a westward propagating wave of zonal polarization field E_x in the *F* region, caused by a westward transport of E_s patches due to a westward *E*-region wind as shown in Figure 4, could account for an apparent westward propagation of the *F*-region structures. This option, suggested by one of the reviewers, is certainly worth considering.

[32] In summary, the proposed new mechanism seems to be capable of explaining key observational properties of midlatitude spread *F* at the mesoscale and has the advantage of having a simple physical base, in accord with existing experimental evidence and knowledge. On the other hand, we wish to stress that the proposed mechanism may not be capable of explaining all forms of spread *F*, and more experimental and theoretical testing and investigation is needed. Finally, it was after the acceptance of this and its companion paper that there came to our attention a relevant study on coupled E_s/*F*-region electrodynamics by *Tsunoda and Cosgrove* [2001].

[33] **Acknowledgments.** This work was initiated while M. C. Kelley of Cornell University was visiting the University of Crete, Greece as a Fulbright Fellow. Support for the completion of this work was provided in part by the European Office of Aerospace Research and Development (EOARD), Air Force Office of Scientific Research, Air Force Research Laboratory, under contracts F61775-01-WE004 and FA8655-03-1-3028 to C. Haldoupis, and in part by an operating grant to G. C. Hussey by the National Science and Engineering Research Council (NSERC) of Canada. We wish to thank E. Kudeki who, acting as a reviewer of the paper, provided constructive criticism and interesting suggestions.

[34] Arthur Richmond thanks Erhan Kudeki and another reviewer for their assistance in evaluating this paper.

References

Behnke, R. A., *F*-layer height bands in the nocturnal ionosphere over Arecibo, *J. Geophys. Res.*, *84*, 974, 1979.

Behnke, R. A., M. C. Kelley, G. Gonzales, and M. Larsen, Dynamics of the Arecibo ionosphere: A case study approach, *J. Geophys. Res.*, *90*, 4448, 1985.

Bourdillon, A., C. Haldoupis, and J. Delloue, High-frequency Doppler radar observations of magnetic aspect sensitive irregularities in the midlatitude *E* region ionosphere, *J. Geophys. Res.*, *100*, 21,503, 1995.

Bowman, G. G., Some aspects of mid-latitude spread-*E* and its relationship with spread-*F*, *Planet. Space Sci.*, *33*, 1081, 1985.

Bowman, G. G., A review of some recent work on mid-latitude spread-*F* occurrence as detected by ionosondes, *J. Geomagn. Geolectr.*, *42*, 109, 1990.

Bowman, G. G., S. Fukao, M. Yamamoto, and K. Igarashi, MU radar recorded field-aligned irregularities in the *F*2 region and associated sporadic-*E* disturbances, *J. Geomagn. Geolectr.*, *46*, 873, 1994.

Fukao, S., M. C. Kelley, T. Shirakawa, T. Takami, M. Yamamoto, T. Tsuda, and S. Kato, Turbulent upwelling of the mid-latitude ionosphere: 1. Observational results by the MU radar, *J. Geophys. Res.*, *96*, 3725, 1991.

Haldoupis, C., and K. Schlegel, Characteristics of midlatitude coherent backscatter from the ionospheric *E* region obtained with Sporadic E Scatter experiment, *J. Geophys. Res.*, *101*, 13,387, 1996.

Haldoupis, C., K. Schlegel, and D. T. Farley, An explanation for type 1 radar echoes from the midlatitude *E*-region ionosphere, *Geophys. Res. Lett.*, *23*, 97, 1996.

Haldoupis, C., D. T. Farley, and K. Schlegel, Type-1 echoes from the midlatitude *E*-region ionosphere, *Ann. Geophys.*, *15*, 908, 1997.

Haldoupis, C., G. C. Hussey, A. Bourdillon, and J. Delloue, Azimuth-time-intensity striations of quasiperiodic radar echoes from the midlatitude *E* region ionosphere, *Geophys. Res. Lett.*, *28*, 1933, 2001.

Haldoupis, C., A. Bourdillon, A. Kamburelis, G. C. Hussey, and J. A. Koehler, 50 MHz continuous wave interferometer observations of the unstable midlatitude *E* region ionosphere, *Ann. Geophys.*, *21*, 1589, 2003.

Hussey, G. C., K. Schlegel, and C. Haldoupis, Simultaneous 50-MHz coherent backscatter and digital ionosonde observations in the midlatitude *E* region, *J. Geophys. Res.*, *103*, 6991, 1998.

Hysell, D. L., and J. D. Burcham, The 30-MHz radar interferometer studies of midlatitude *E* region irregularities, *J. Geophys. Res.*, *105*, 12,797, 2000.

Hysell, D. L., M. Yamamoto, and S. Fukao, Imaging radar observations and theory of type I and type II quasiperiodic echoes, *J. Geophys. Res.*, *107*(A11), 1360, doi:10.1029/2002JA009292, 2002.

Kelley, M. C., *The Earth's Ionosphere: Plasma Physics and Electrodynamics*, Academic, San Diego, Calif., 1989.

Kelley, M. C., and S. Fukao, Turbulent upwelling of the mid-latitude ionosphere: 2. Theoretical framework, *J. Geophys. Res.*, *96*, 3747, 1991.

Kelley, M. C., J. J. Makela, W. E. Swartz, S. C. Collins, S. Thonnard, N. Aponte, and C. A. Tepley, Caribbean Ionosphere Campaign, year one: Airglow and plasma observations during two intense midlatitude spread-*F* events, *Geophys. Res. Lett.*, *27*, 2825, 2000.

Kelley, M. C., J. J. Makela, and J. J. Saito, The mid-latitude *F* region at the mesoscale: Some progress at last, *J. Atmos. Sol. Terr. Phys.*, *64*, 1525, 2002.

Larsen, M. F., Winds and shears in the mesosphere and lower thermosphere: Results from four decades of chemical release wind measurements, *J. Geophys. Res.*, *107*(A8), 1215, doi:10.1029/2001JA000218, 2002.

Miller, C. A., W. E. Swartz, M. C. Kelley, M. Mendillo, D. Nottingham, J. Scali, and B. Reinisch, Electrodynamics of midlatitude spread *F*: 1. Observations of unstable, gravity wave-induced ionospheric electric fields at tropical latitudes, *J. Geophys. Res.*, *102*, 11,521, 1997.

Schlegel, K., and C. Haldoupis, Observation of the modified two-stream plasma instability in the midlatitude *E* region ionosphere, *J. Geophys. Res.*, *99*, 6219, 1994.

Shalimov, S., C. Haldoupis, and K. Schlegel, Large polarization electric fields associated with midlatitude sporadic *E*, *J. Geophys. Res.*, *103*, 11,617, 1998.

Swartz, W. E., J. J. Makela, and M. C. Kelley, First observations of coherent scatter from the midlatitude *F* region in the Caribbean, *Geophys. Res. Lett.*, *27*, 935, 2000.

Swartz, W. E., et al., First observations of an *F*-region turbulent upwelling coincident with severe *E*-region plasma and neutral atmosphere perturbations, *J. Atmos. Sol. Terr. Phys.*, *64*, 1545, 2002.

Tsunoda, R. T., and R. B. Cosgrove, Coupled electrodynamics in the nighttime midlatitude ionosphere, *Geophys. Res. Lett.*, *28*, 4171, 2001.

Yamamoto, M., S. Fukao, R. F. Woodman, T. Ogawa, T. Tsuda, and S. Kato, Midlatitude *E* region field-aligned irregularities observed with the MU radar, *J. Geophys. Res.*, *96*, 15,943, 1991.

Yamamoto, M., S. Fukao, R. F., T. Ogawa, T. Tsuda, and S. Kato, A morphological study on mid-latitude *E*-region field-aligned irregularities observed with the MU radar, *J. Atmos. Terr. Phys.*, *54*, 769, 1992.

C. Haldoupis, Physics Department, University of Crete, Iraklion, Crete, Greece 71003. (chald@physics.uoc.gr)

G. C. Hussey, Department of Physics and Engineering Physics, University of Saskatchewan, 116 Science Place, Saskatoon, SK, Canada S7N-5E2. (hussey@dansas.usask.ca)

M. C. Kelley, School of Electrical and Computer Engineering, 318 Rhodes Hall, Cornell University, Ithaca, NY 14853, USA. (mikek@ece.cornell.edu)

S. Shalimov, Institute of Physics of the Earth, Moscow, Russia 123810. (shalimov@uipe-ras.scgis.ru)