Response of the incompressible ionosphere to the compression of the magnetosphere during the geomagnetic sudden commencements

磁気嵐急始時の非圧縮性電離圏の応答

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Electric fields are observed with the HF Doppler sounder in midlatitudes and magnetometers at the equator

$$\Delta f = -\frac{2f}{c}\frac{E}{B}\sin\theta\cos I$$

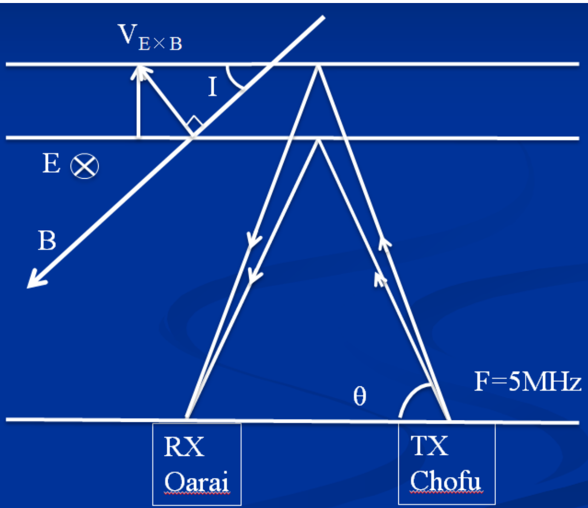
$f = 5$ [MHz], $I = 49°$, $B = 46000$ [nT]

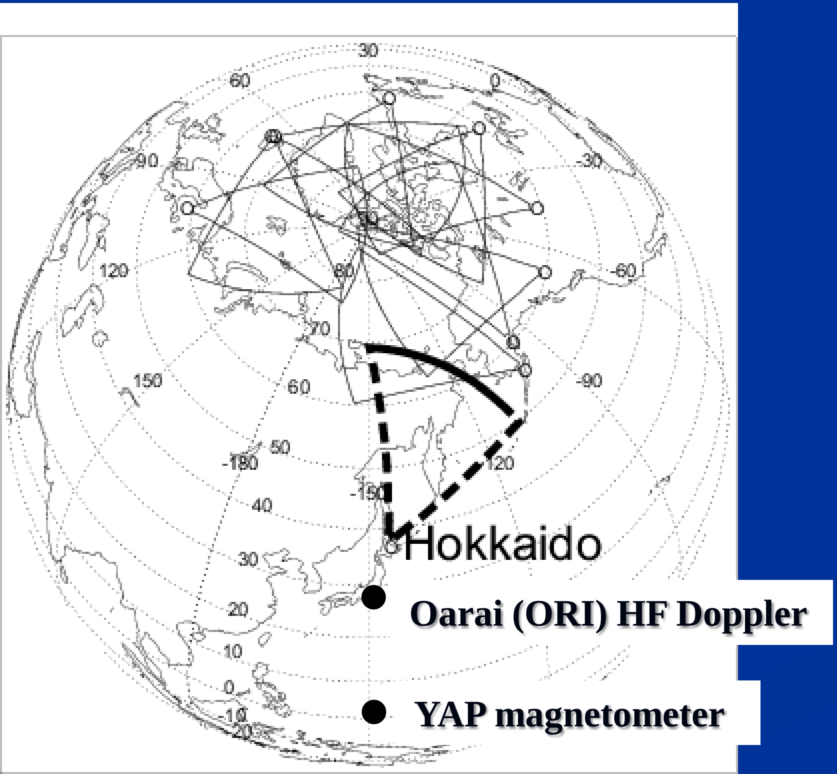
$\theta = 78.2°$ (distance = 120, reflection height = 300km)

$V_{vert} = -30.6\ \Delta f$ [m/s]

$E = -2.15\ \Delta f$ [mV/m]

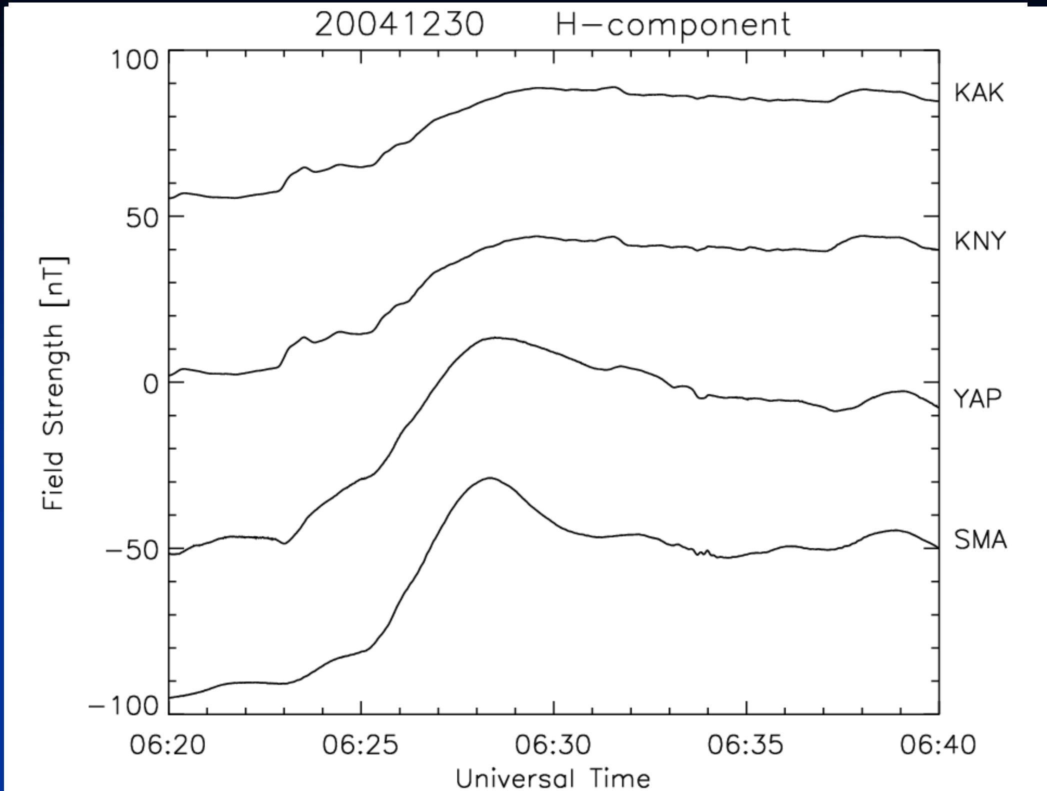
HF Doppler (HFD) sounder in Tokyo

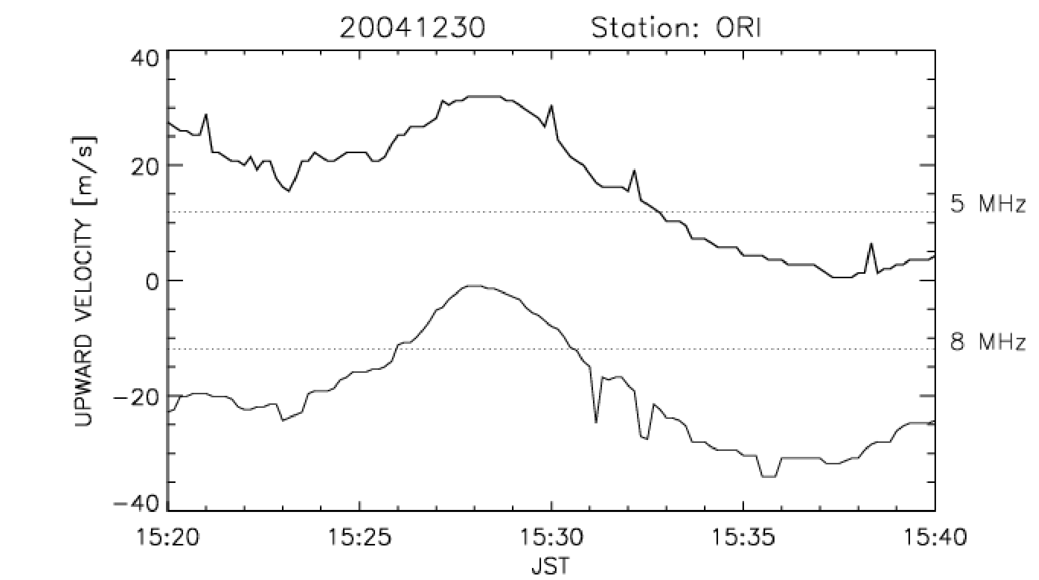




When the ionosphere moves downward, we observe a positive HF Doppler frequency that is caused by a westward electric field.

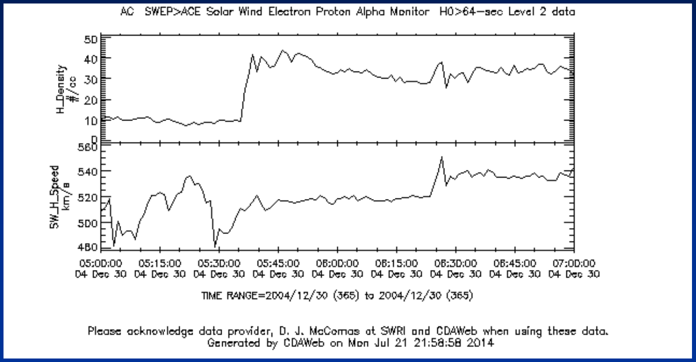
Cowling conductivity: $\sigma_C = \sigma_P + \frac{\sigma_H^2}{\sigma_P}$





SC-1

Solar wind density and speed



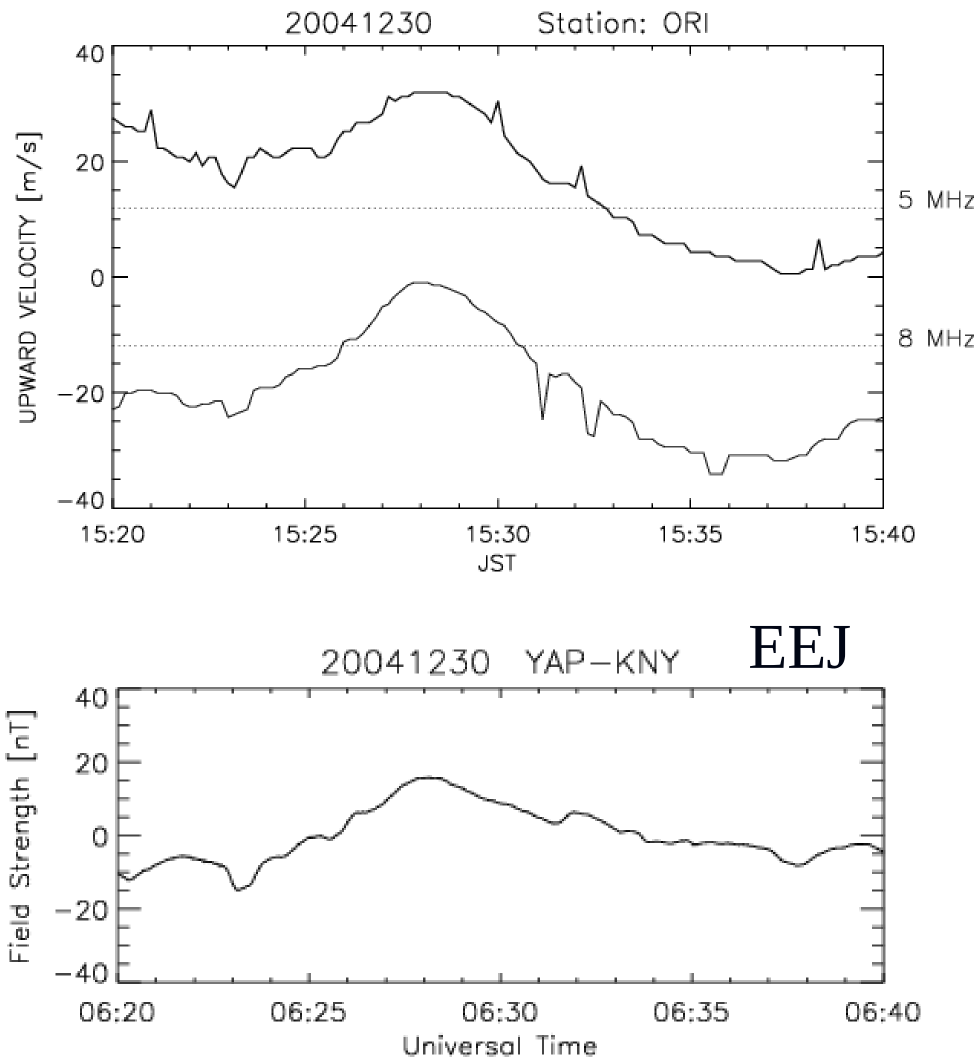
$\Delta H > 0$

The magnetosphere is compressed,

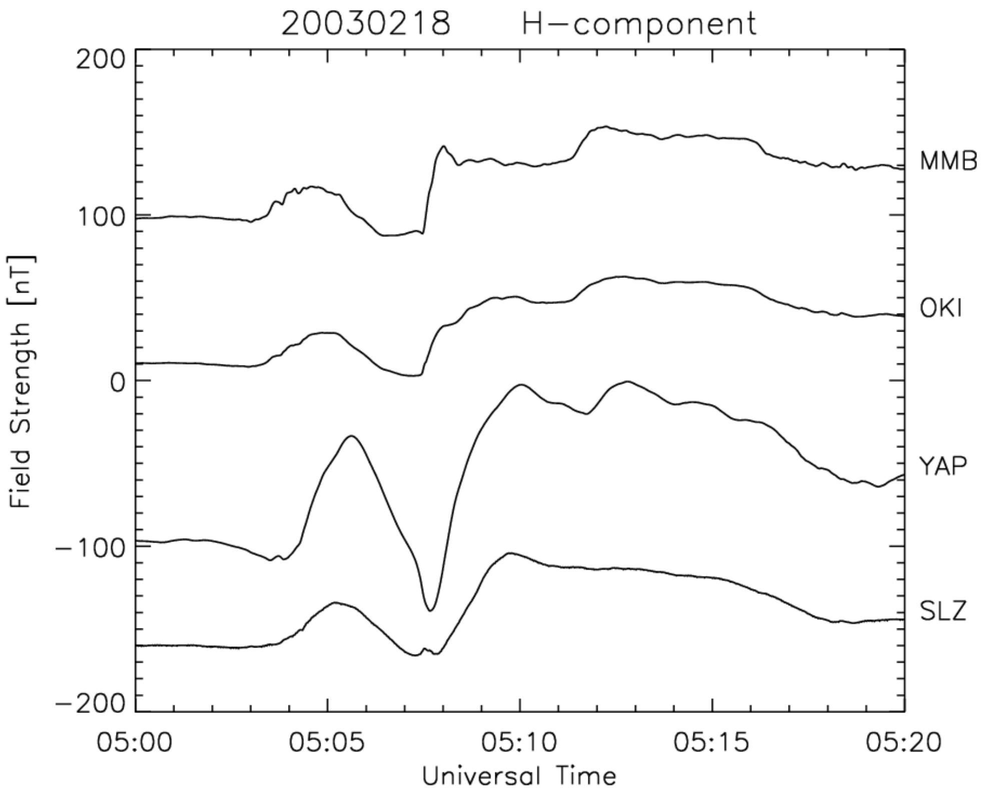
$V_{vert} > 0$

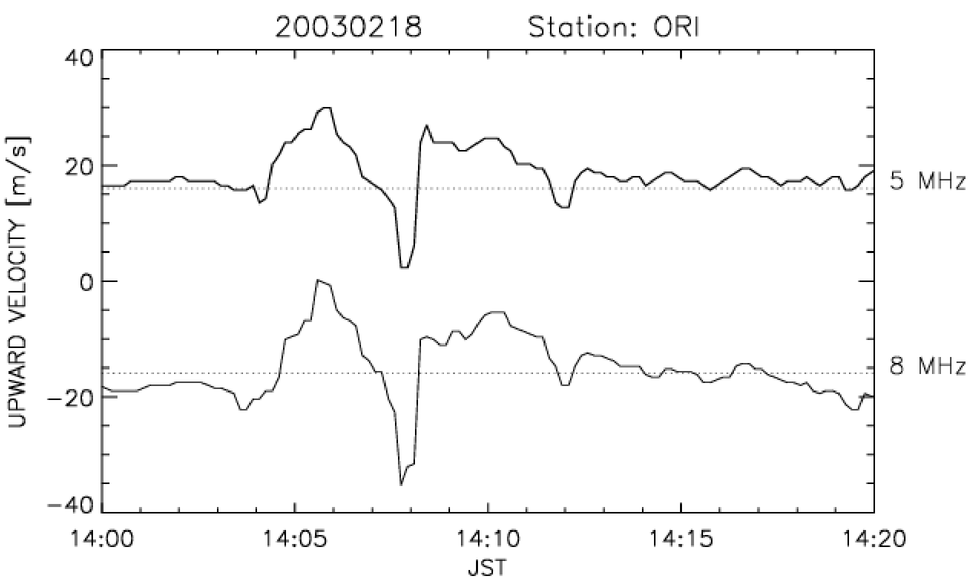
The ionosphere moves upward.

SC-1



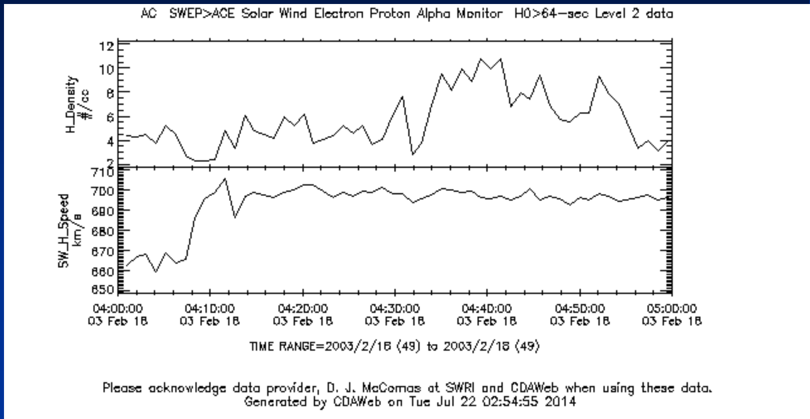
The upward motion at low latitude and the EEJ at the equator are caused by the eastward electric field propagated with ionospheric currents from the polar ionosphere.





SC-2

Solar wind density and speed

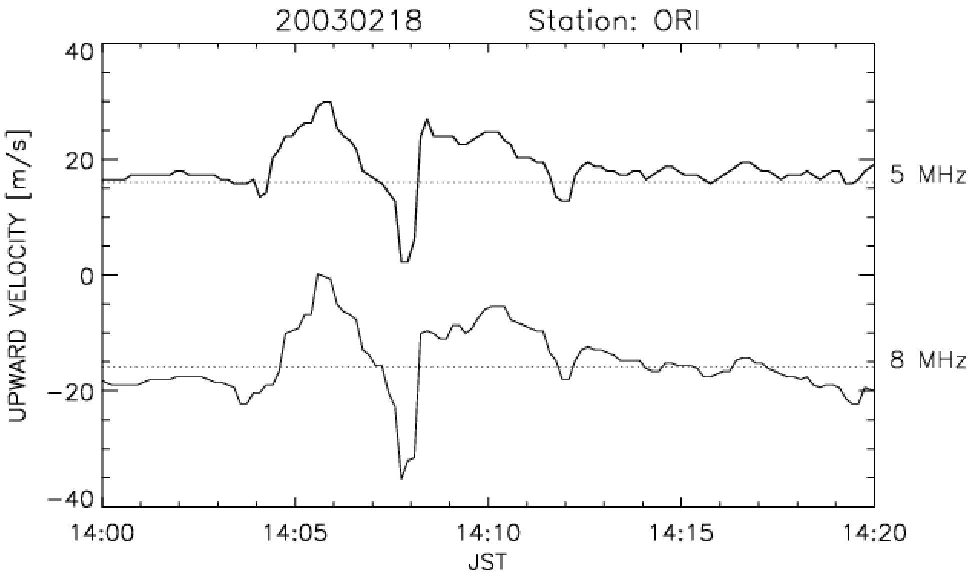


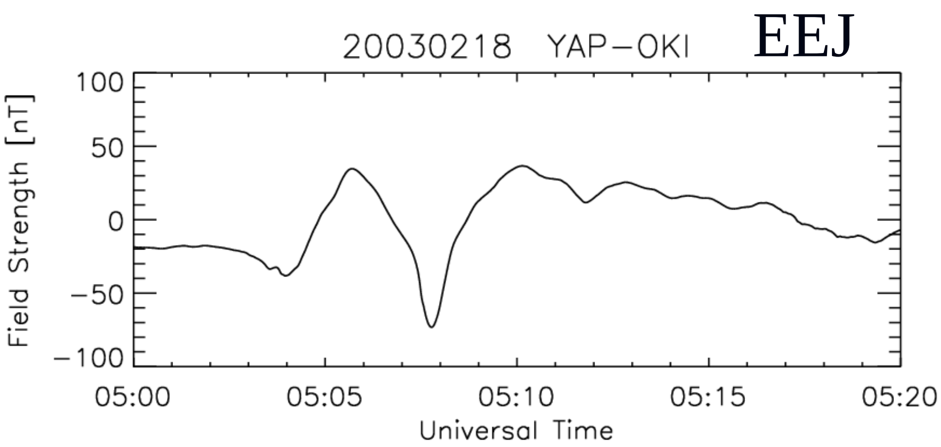
$\Delta H > 0\ (< 0)$

The magnetosphere is compressed (rarefied).

$V_{vert} > 0\ (< 0)$

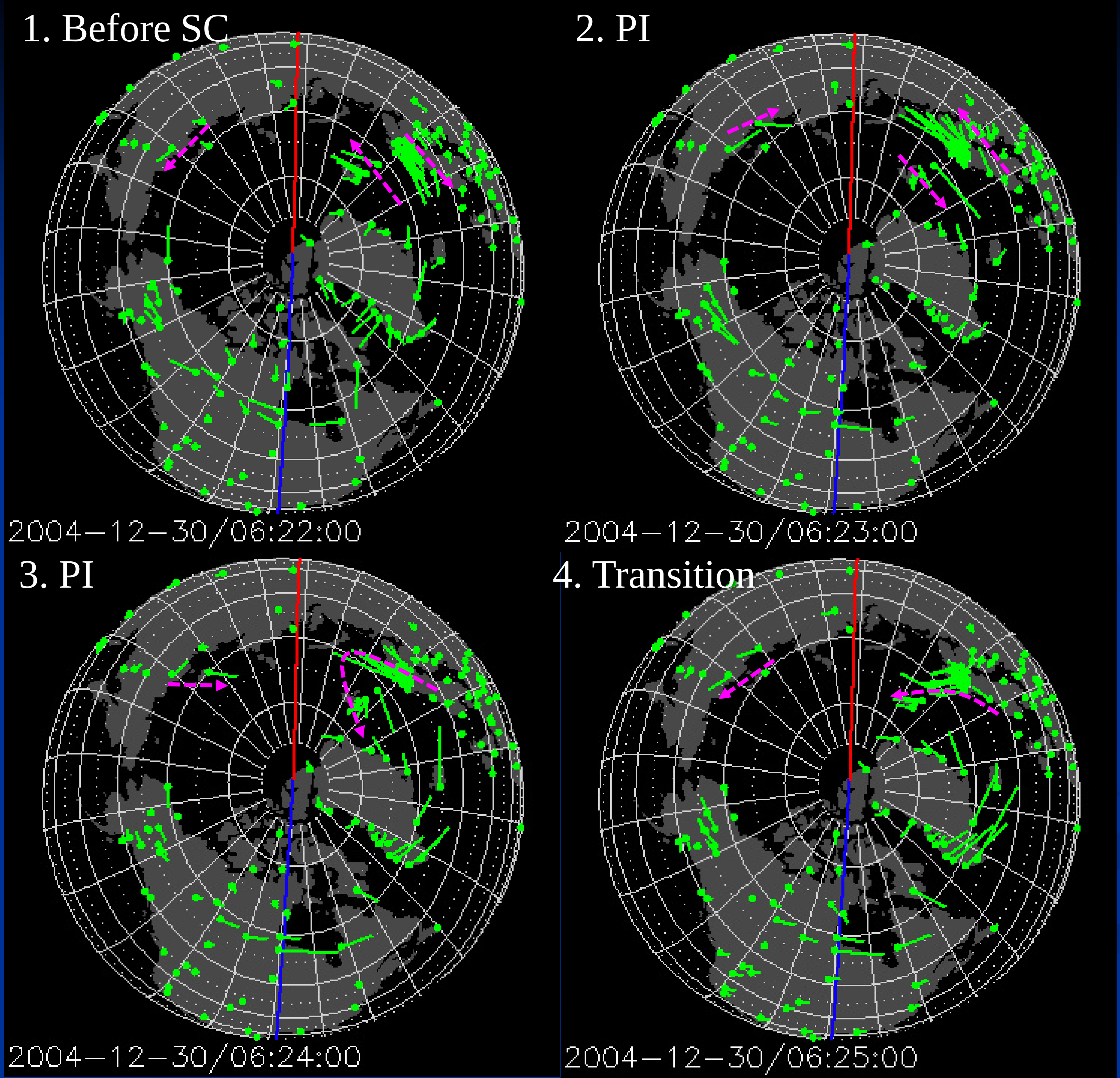
The ionosphere moves upward (downward).





SC-2

The upward (downward) motion at low latitude and the EEJ (CEJ) at the equator are caused by the eastward (westward) electric field propagated with ionospheric currents from the polar ionosphere.



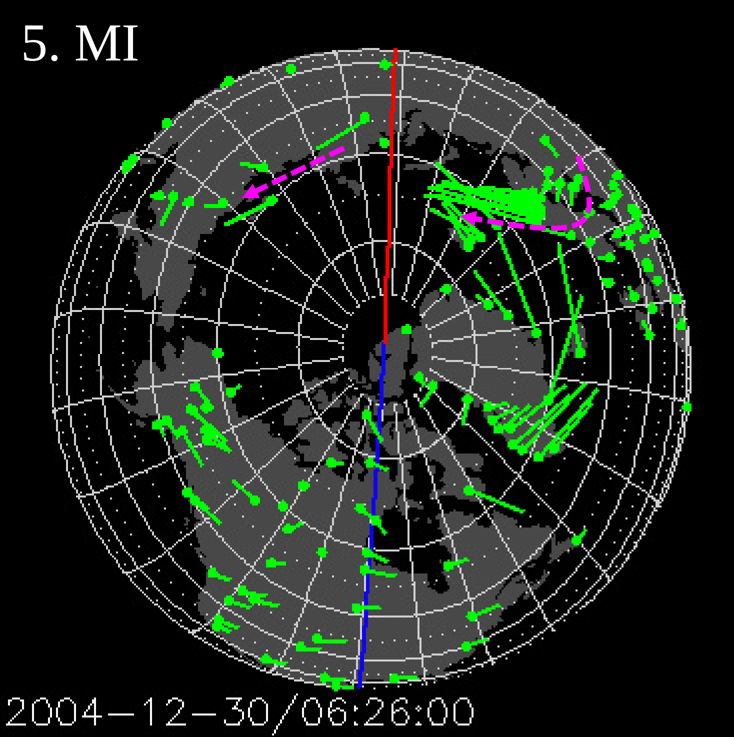
SC-1

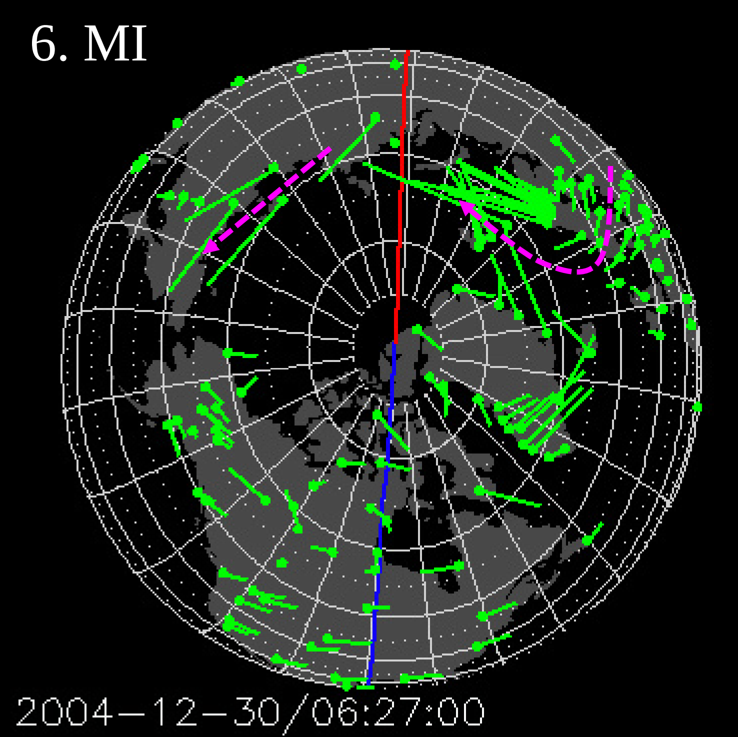
Counter-clockwise current vortex in the morning

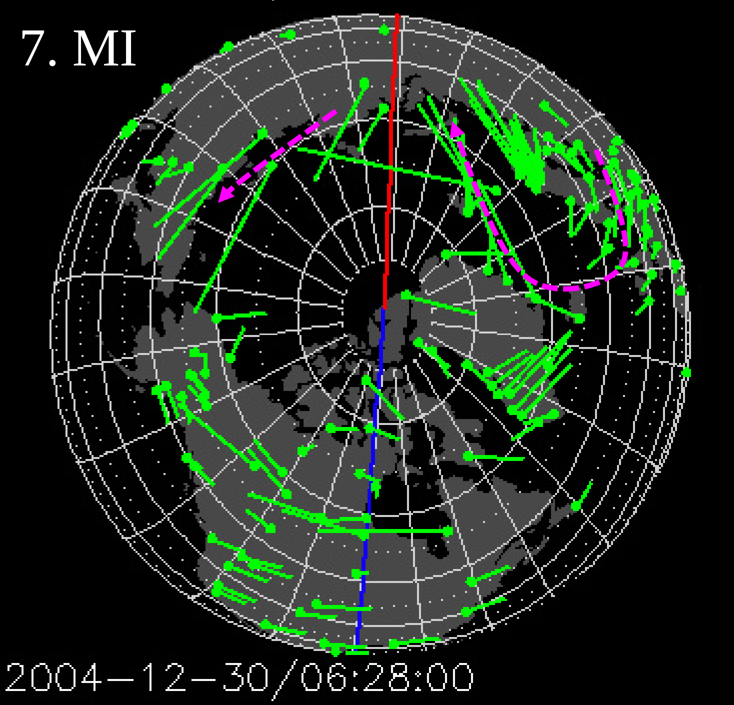
↓

Upward FAC of PI

SC/SI-1





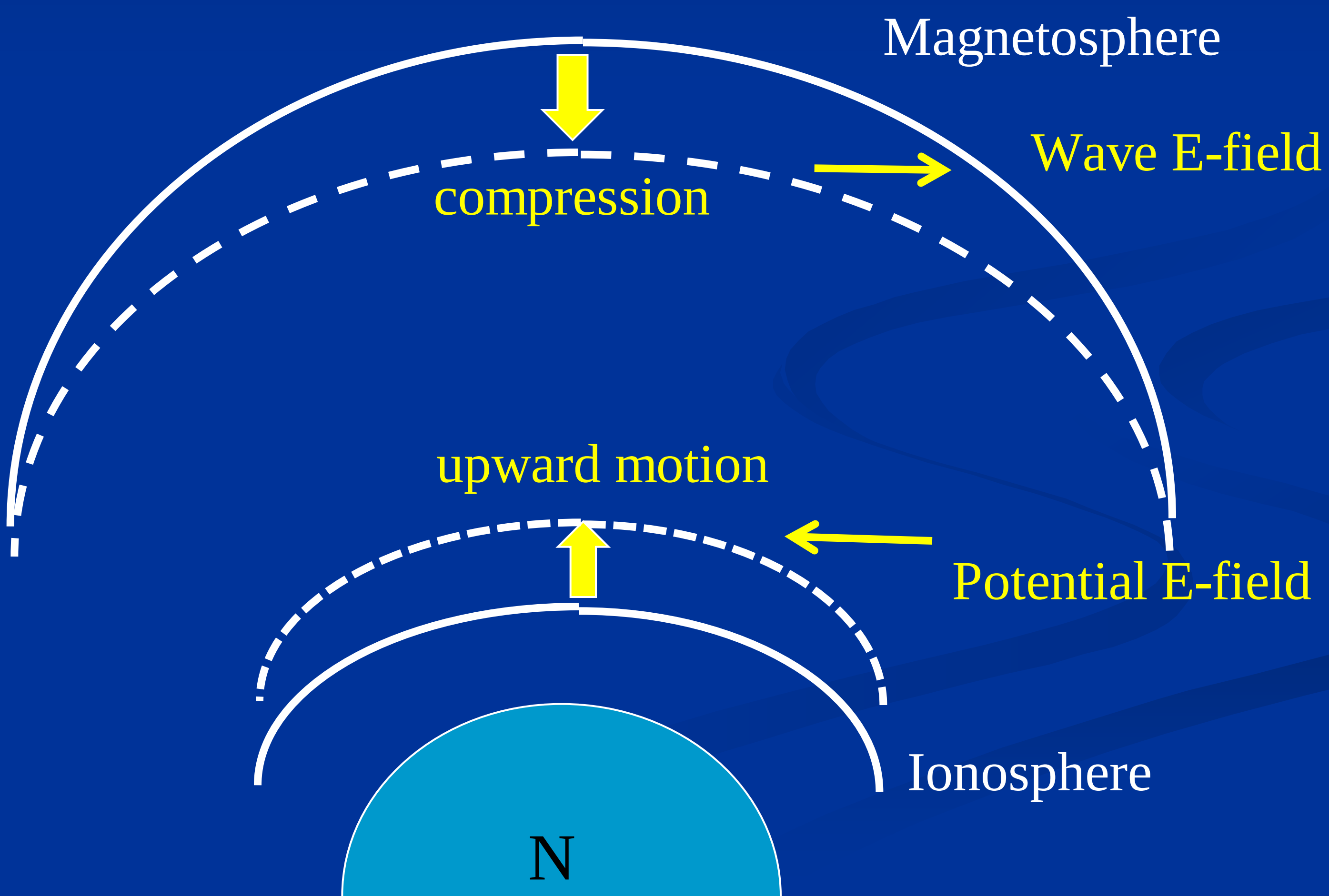


Clockwise current vortex in the morning

↓

Downward FAC of MI

The compressional MHD waves do not compress the dayside ionosphere. The ionosphere is moved upward by the electric field associated with the ionospheric currents.



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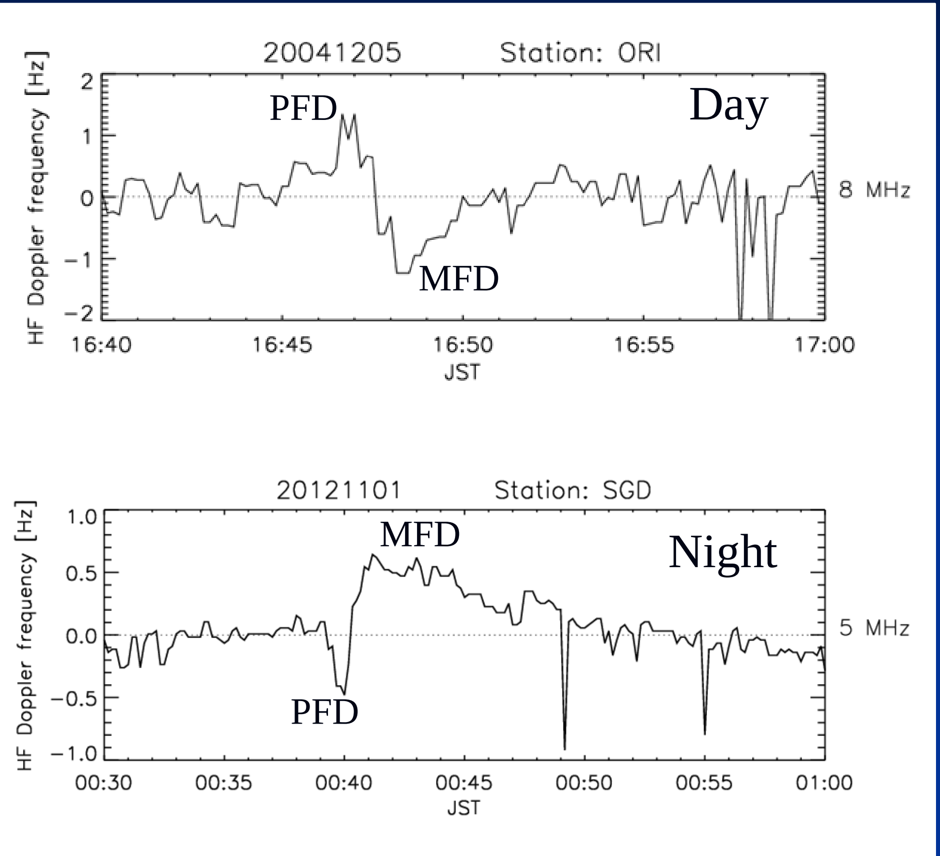
HF Doppler observation of the SC electric fields



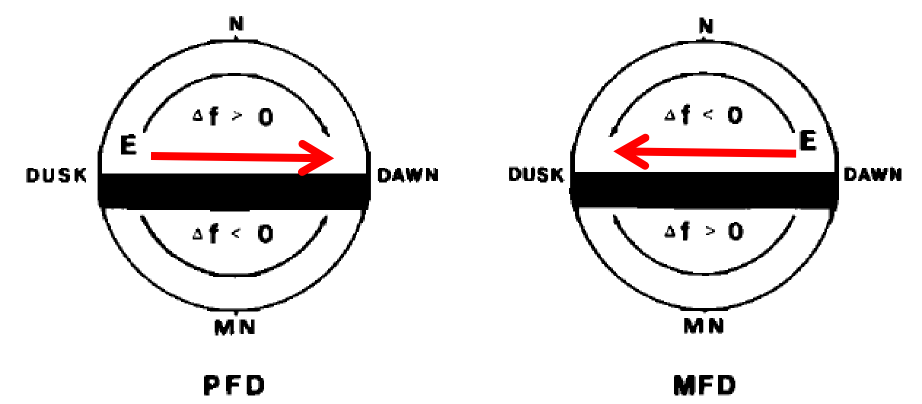


Fig. 6. Directions of electric fields associated with the PFD and MFD. The PFD is caused by a dusk-to-dawn electric field and the MFD by a dawn-to-dusk electric field.

SC-associated HFD (SCF) is (+ -) in the day and (- +) in the night. SCF is composed of PFD (preliminary HFD) and MFD (main HFD) .

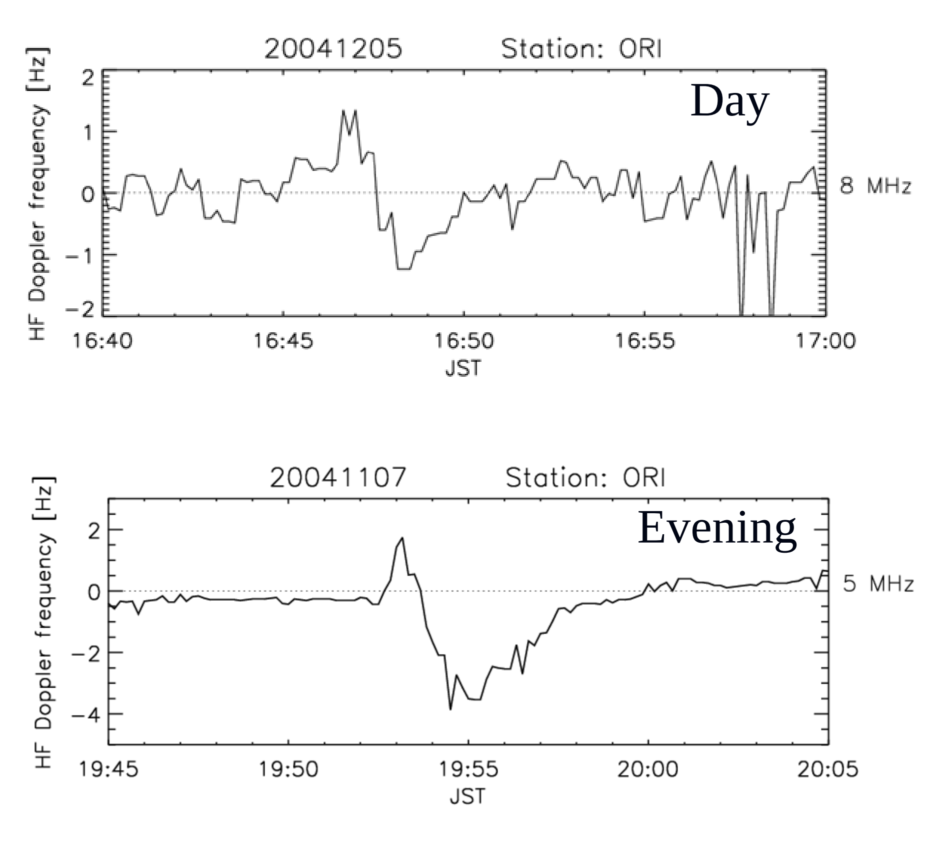
PFD and MFD are caused by the dusk-to-dawn PI and dawn-to-dusk MI electric fields, respectively (Kikuchi et al., JGR 1985).

Evening anomaly of the SC electric fields

SCF in the evening is (+ -) same as the daytime SCF.

SCF(+ -) is observed from 06 to 22h in local time.

(Kikuchi et al., JGR 1985)



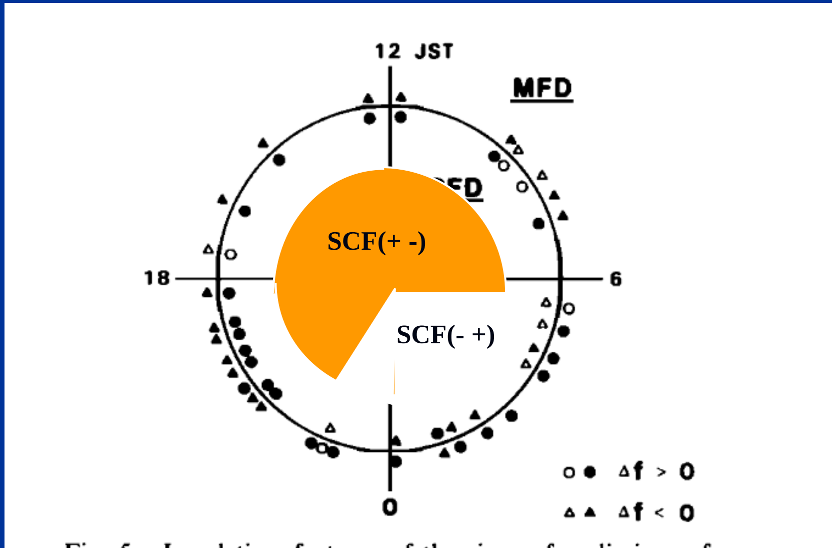
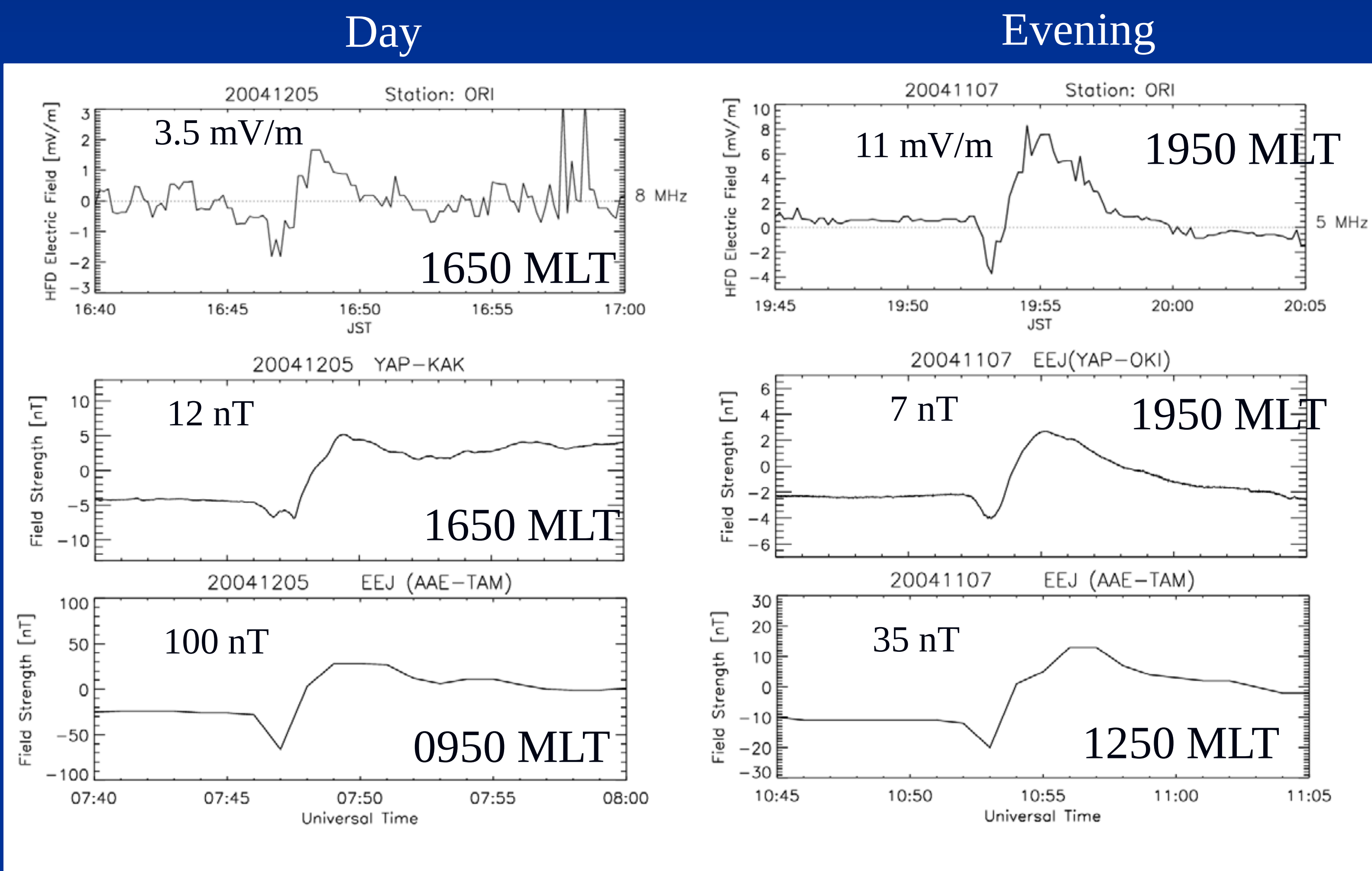


Fig. 5. Local time features of the signs of preliminary frequency deviations (PFD's) and main frequency deviations (MFD's) of SCF's. The SCF(+ −) appears in the daytime and evening sectors and the SCF(− +) in the nighttime sector. The solid circles and triangles indicate that the SCF was observed at more than two stations.

Evening enhancement of the SC electric fields

The electric field is 3 times stronger in the evening than in the day, whereas the EEJ is 3 times stronger in the day than in the evening.



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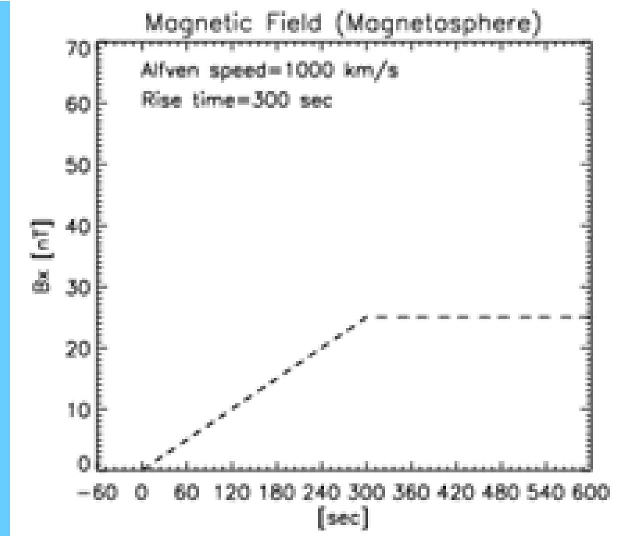
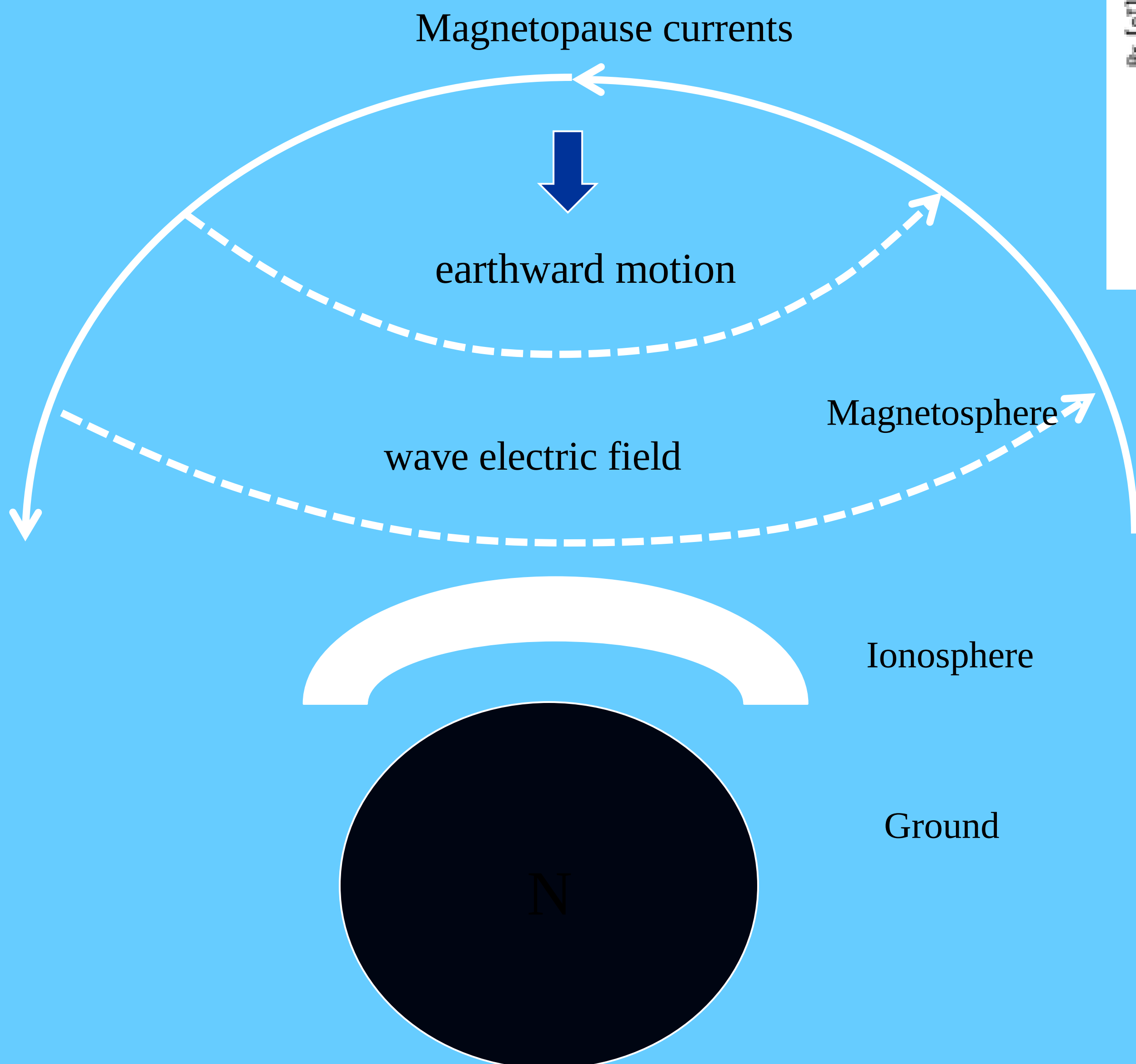
$$B_x\left[t, z=0\right] = \frac{B_0}{t_0}\left[t \cdot U(t) - (t - t_0)U(t - t_0)\right]$$





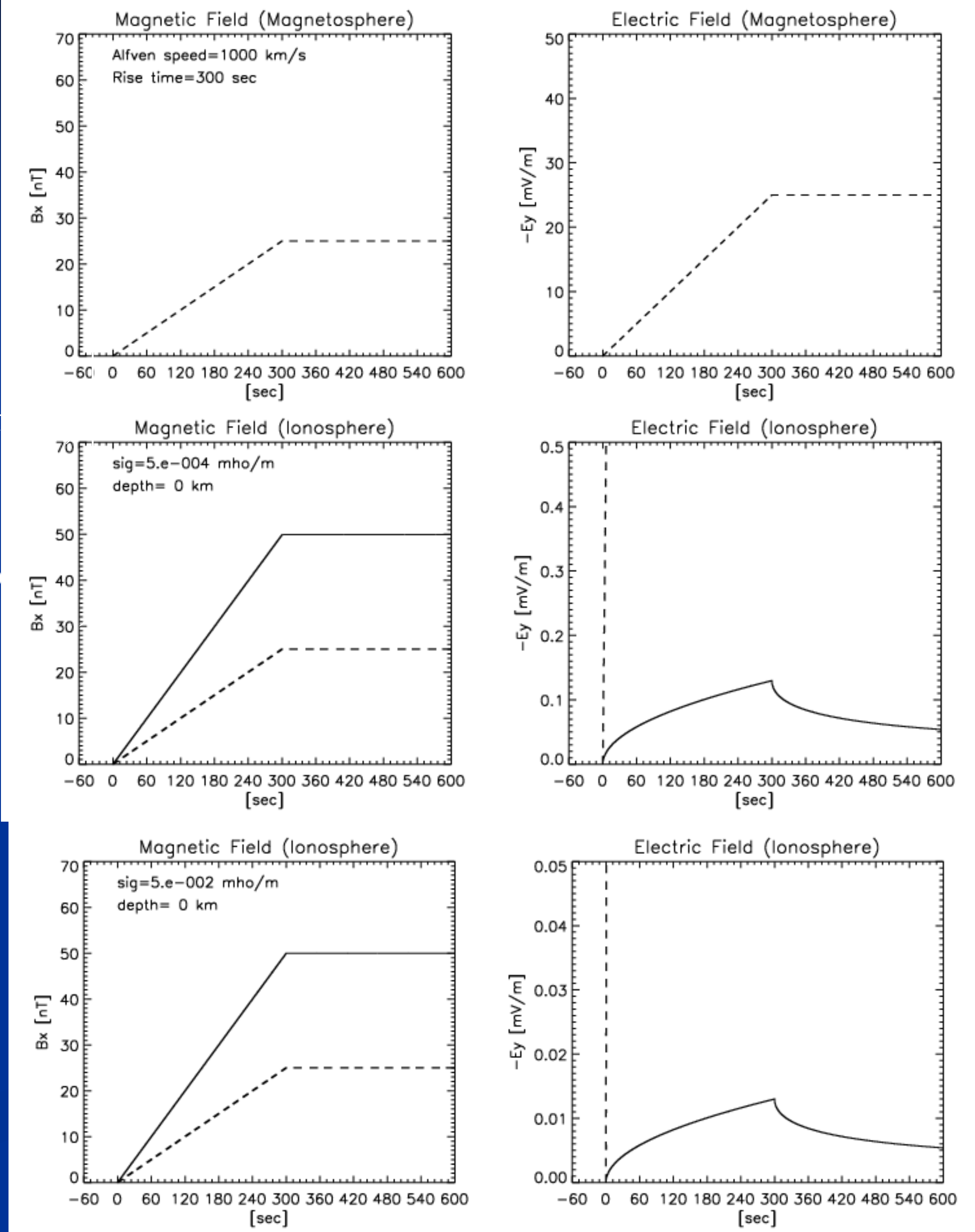
$$\frac{\partial^2 B_x}{\partial t^2} - V_A^2 \frac{\partial^2 B_x}{\partial z^2} = 0$$

$$\frac{\partial B_x}{\partial t} - \frac{1}{\mu_0 \sigma} \frac{\partial^2 B_x}{\partial z^2} = 0$$

Electric field at the surface of the conducting ionosphere

$$B_{xI}=2\frac{B_0}{t_0}\left\{\begin{array}{l}\left(t+\frac{z}{V_A}+\frac{1}{2}z^2\mu_0\sigma\right)erfc\left(\frac{z\sqrt{\mu_0\sigma}}{2\sqrt{t}}\right)U(t)\\ -\left(\frac{2}{V_A\sqrt{\mu_0\sigma}}+z\sqrt{\mu_0\sigma}\right)\sqrt{\frac{t}{\pi}}e^{-\frac{z^2\mu_0\sigma}{4t}}U(t)\\ -\left(t-t_0+\frac{z}{V_A}+\frac{1}{2}z^2\mu_0\sigma\right)erfc\left(\frac{z\sqrt{\mu_0\sigma}}{2\sqrt{t-t_0}}\right)U(t-t_0)\\ +\left(\frac{2}{V_A\sqrt{\mu_0\sigma}}+z\sqrt{\mu_0\sigma}\right)\sqrt{\frac{t-t_0}{\pi}}e^{-\frac{z^2\mu_0\sigma}{4(t-t_0)}}U(t-t_0)\end{array}\right.$$

$$E_{yI}=-2\frac{B_0}{t_0}\left(\begin{array}{l}-\left(z+\frac{1}{V_A\mu_0\sigma}\right)erfc\left[\frac{z\sqrt{\mu_0\sigma}}{2\sqrt{t}}\right]U[t]\\ +\frac{2}{\sqrt{\pi}}\frac{1}{\sqrt{\mu_0\sigma}}\sqrt{t}e^{-\frac{z^2\mu_0\sigma}{4t}}U[t]\\ +\left(z+\frac{1}{V_A\mu_0\sigma}\right)erfc\left[\frac{z\sqrt{\mu_0\sigma}}{2\sqrt{t-t_0}}\right]U[t-t_0]\\ -\frac{2}{\sqrt{\pi}}\frac{1}{\sqrt{\mu_0\sigma}}\sqrt{t-t_0}e^{-\frac{z^2\mu_0\sigma}{4(t-t_0)}}U[t-t_0]\end{array}\right)$$



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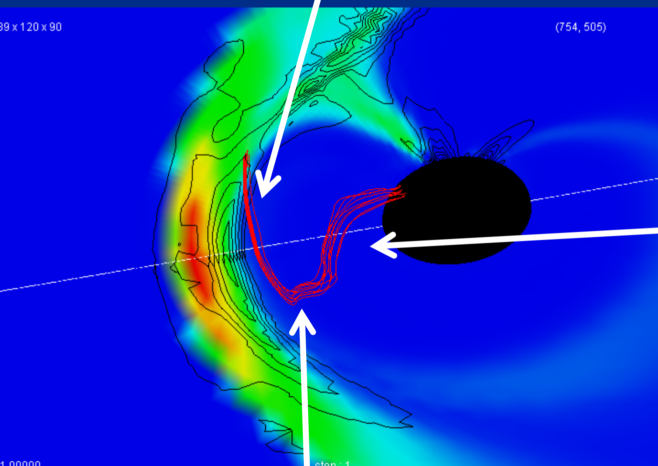
Global MHD simulation of the PI and MI field-aligned currents and their dynamos

Magnetopause dynamo current



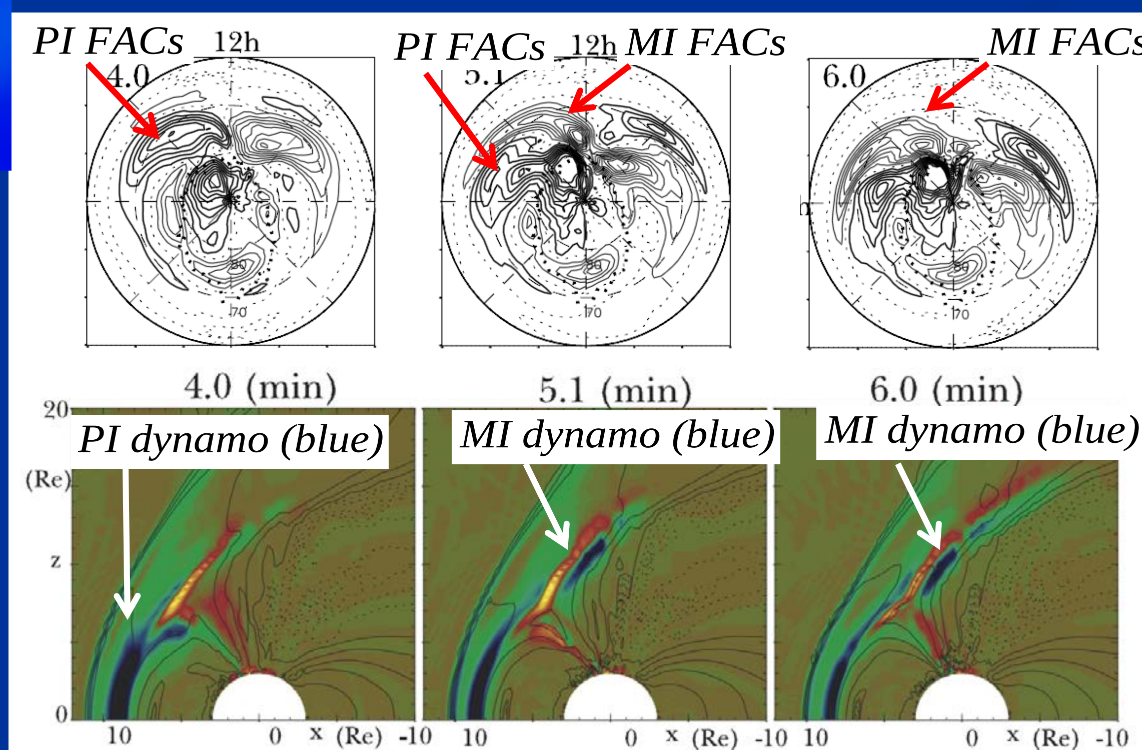
Field-aligned current

Polarization current

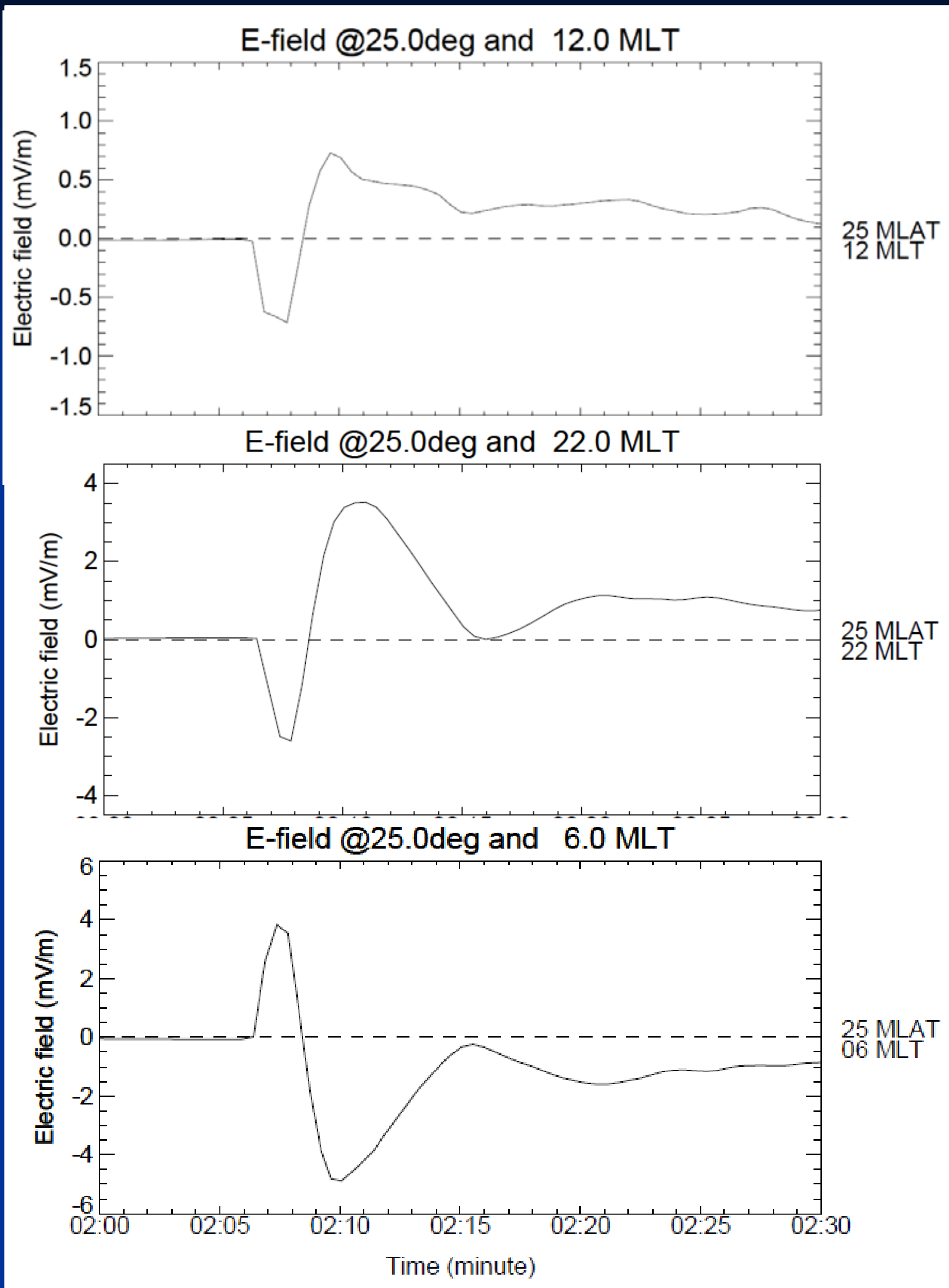
Blue color refers to JE<0

During the PI, the currents are generated at the magnetopause and flow into the polar ionosphere down the field lines.

From Fujita et al. [2003]



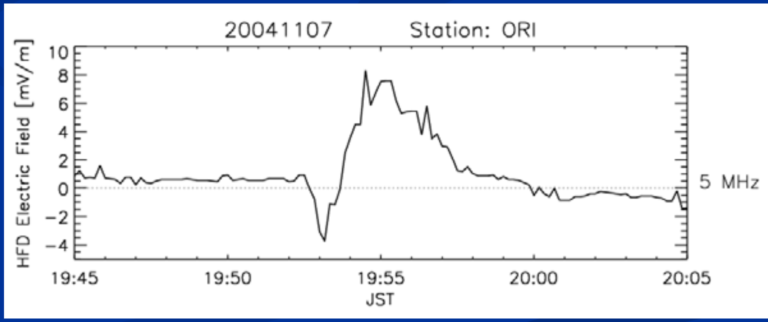
Global MHD simulation of the SC electric fields



Day

The MHD simulation reproduces the successive occurrence of the PI and MI electric fields with intensification in the evening.

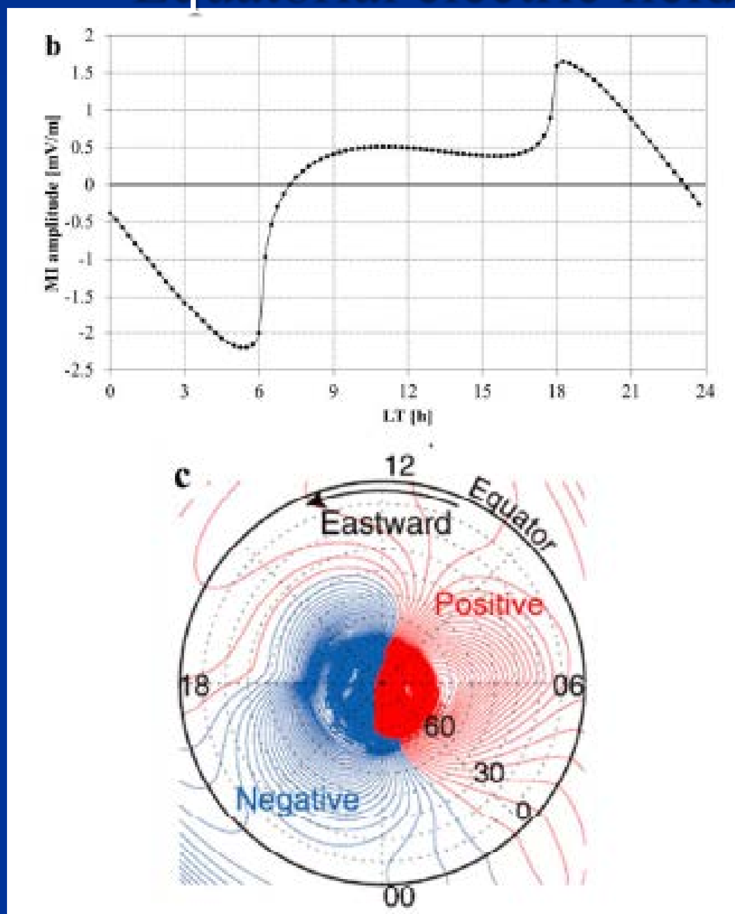
Evening

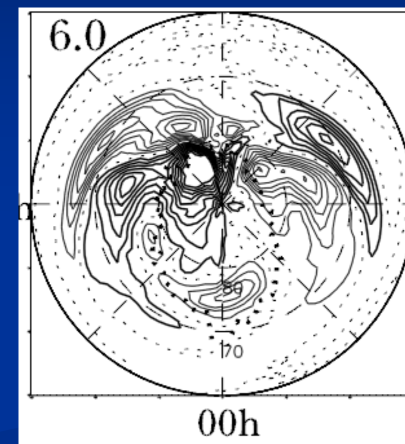


Night

Equatorial electric field and global electric potential distribution reproduced by the global model

Equatorial electric field





$$\nabla \cdot \sigma \nabla \phi_I = J_{\parallel}$$

Electric potential

Published model calculations

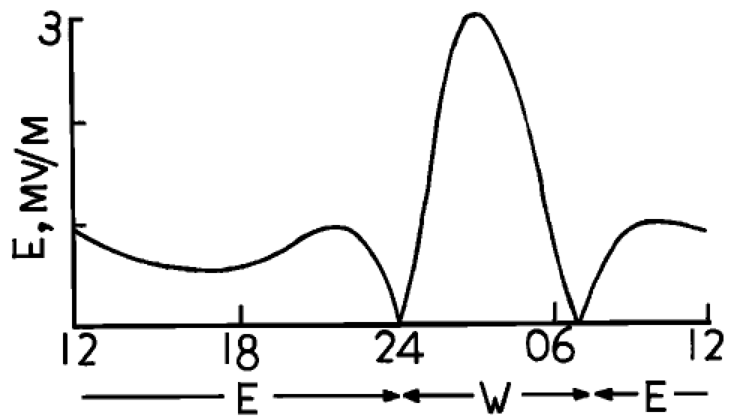


Fig. 1b. Electric field as a function of local time at the equator. The letters E and W at the bottom of the figure give the sense, east or west, of the equatorial field.

(Nopper and Carovillano, GRL 1978)

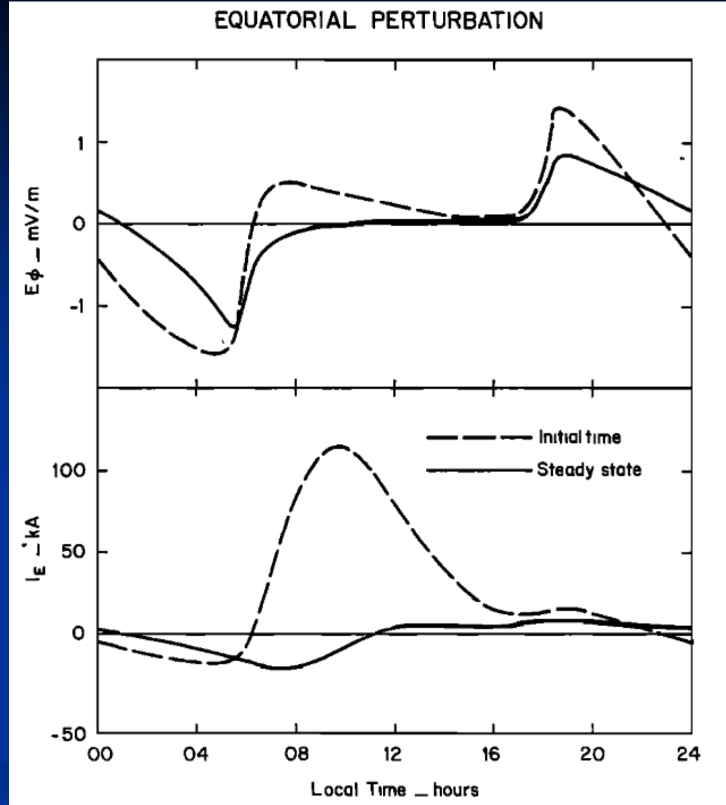
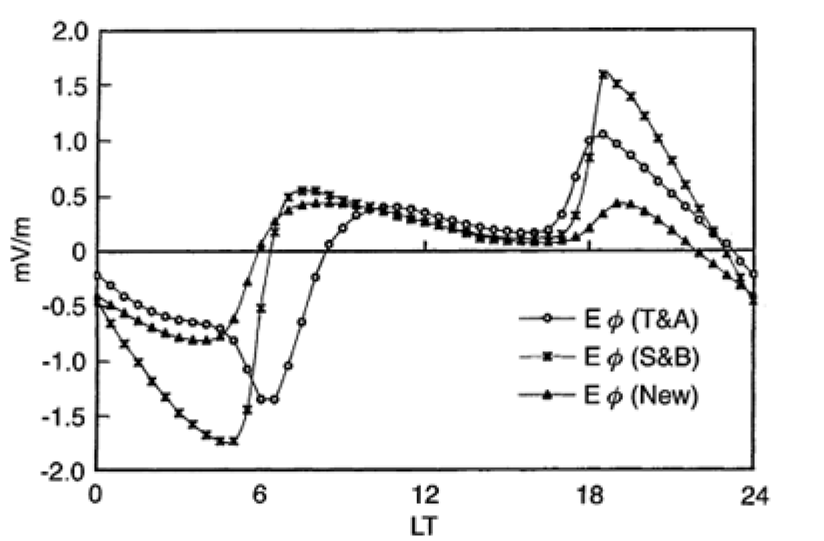


Fig. 17. Local time distributions of the eastward equatorial electric field (top panel) and of the total electrojet current generated by a 100 kV potential

(Senior and Blanc, JGR 1984)



(Tsunomura, Angeo 1999)

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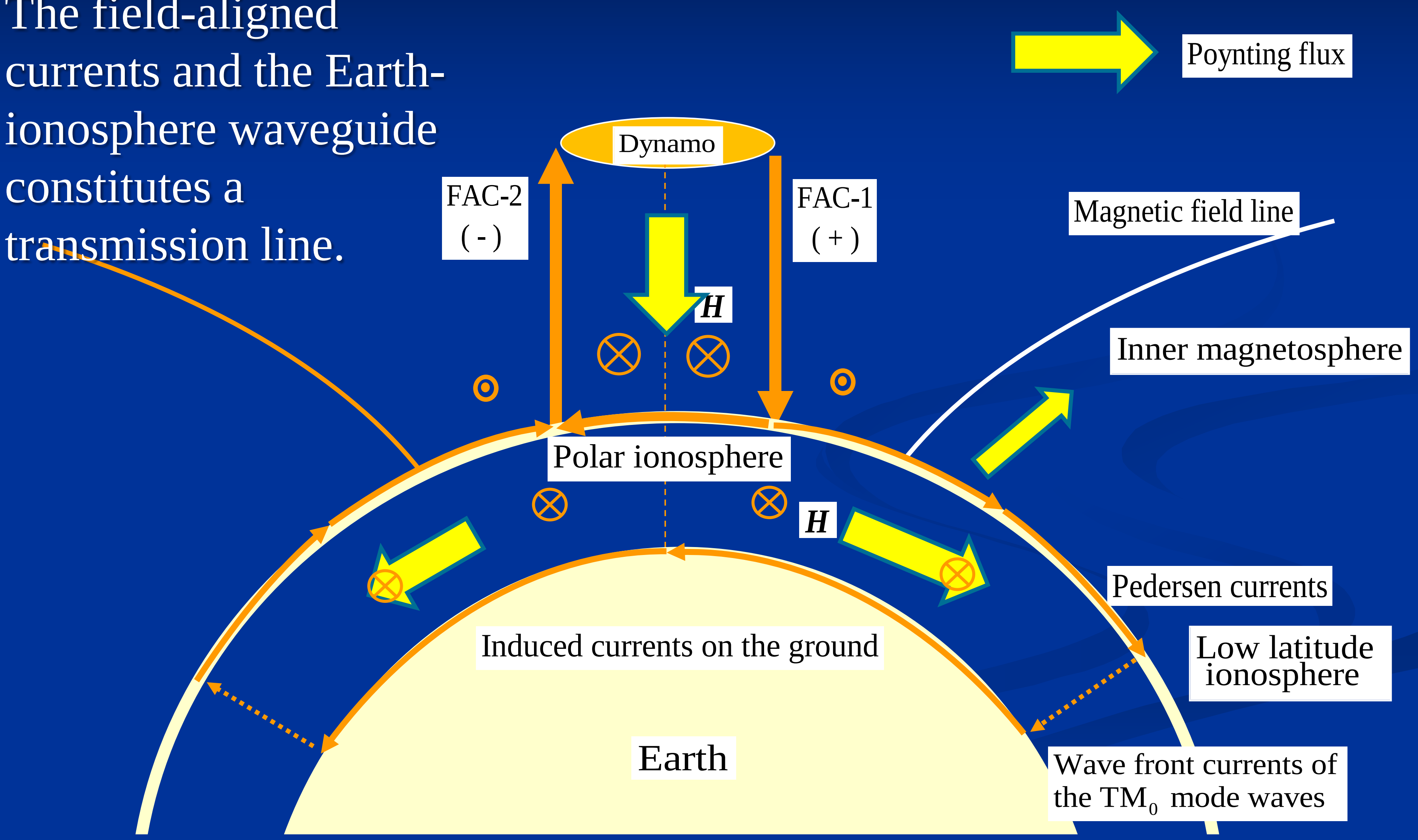
Magnetosphere-ionosphere-ground (MIG) transmission line model for the ionospheric electric potential

[Kikuchi, JGR 2014]

The field-aligned currents and the Earth-ionosphere waveguide constitutes a transmission line.



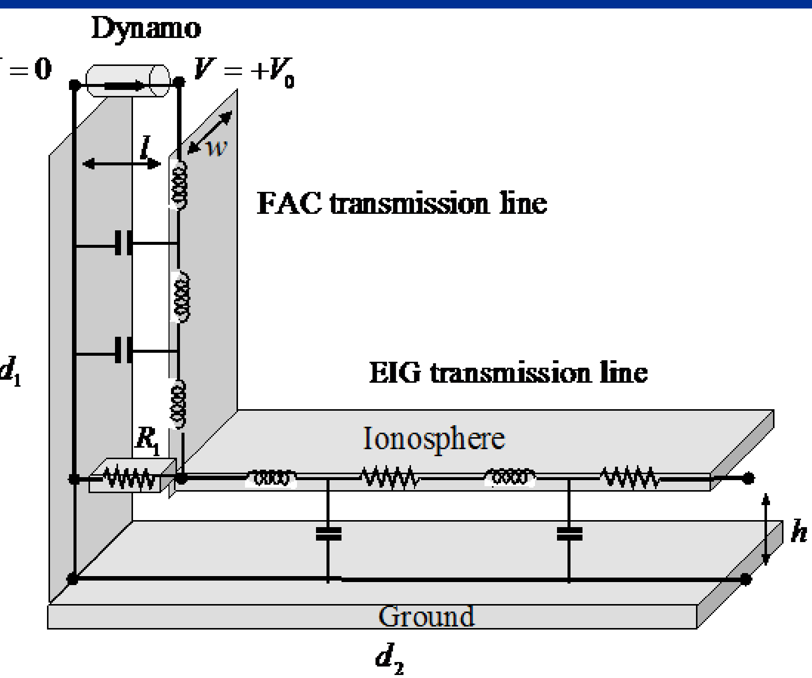
Magnetosphere-ionosphere-ground (MIG) transmission line

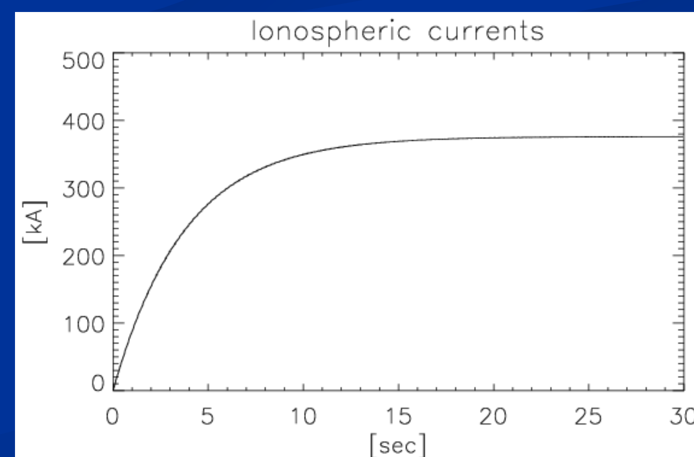
Electric potential and currents in the finite-length transmission line

$$V_2(x,t) = V_0 \left\{ \sum_{n=1}^{\infty} \left[e^{-\frac{\alpha}{2}t_{n1}} U(t-t_{n1}) + \frac{\alpha}{2} t_{n1} \int_{t_{n1}}^{t} e^{-\frac{\alpha}{2}\tau} U(t-\tau) \frac{I_1\left(\frac{\alpha}{2}\sqrt{\tau^2 - t_{n1}^2}\right)}{\sqrt{\tau^2 - t_{n1}^2}} d\tau \right] - \sum_{n=1}^{\infty} \left[e^{-\frac{\alpha}{2}t_{n2}} U(t-t_{n2}) + \frac{\alpha}{2} t_{n2} \int_{t_{n2}}^{t} e^{-\frac{\alpha}{2}\tau} U(t-\tau) \frac{I_1\left(\frac{\alpha}{2}\sqrt{\tau^2 - t_{n2}^2}\right)}{\sqrt{\tau^2 - t_{n2}^2}} d\tau \right] \right\}$$

$$I_2(x,t) = V_0 \frac{1}{Z_2} e^{-\frac{\alpha}{2}t} \left\{ \sum_{n=1}^{\infty} U(t-t_{n1}) I_0\left(\frac{\alpha}{2}\sqrt{t^2 - t_{n1}^2}\right) + \sum_{n=1}^{\infty} U(t-t_{n2}) I_0\left(\frac{\alpha}{2}\sqrt{t^2 - t_{n2}^2}\right) \right\}$$

$$t_{n1} = \frac{2(n-1)d_2 + x}{c} \qquad t_{n2} = \frac{2nd_2 - x}{c}$$





Conclusion

- The dayside midlatitude ionosphere moves upward when the magnetosphere is compressed. The upward motion is well correlated with the ionospheric currents at the equator (EEJ).
- It is suggested that the ionosphere is moved by the potential electric field transmitted with the ionospheric currents from the polar ionosphere.
- With the one-dimensional analytical model, we confirmed that the electric field of the compressional wave is severely suppressed by the conducting ionosphere and ground.
- The PI and MI electric fields are in opposite direction on the day- and night-sides except in the evening when the electric fields are in the same direction as in the daytime and the magnitude is enhanced considerably.

Conclusion (contd)

- The PI and MI electric fields and their evening enhancement are reproduced with the global MHD model of Tanaka [2007] that employs the potential solver at the inner boundary of the M-I coupling.
- The evening anomaly is derived from the asymmetric distribution of the global electric potential due to the Hall effects and day-night inhomogeneity of the ionospheric conductivity.
- With the magnetosphere-ionosphere-ground (MIG) transmission line model of Kikuchi [2014], we explained that the electric potential and currents are transmitted by the TM0 (TEM) mode waves in the Earth-ionosphere waveguide.
- The ionosphere is incompressible to the compressional waves and the incompressible ionosphere is moved by the potential electric fields associated with the ionospheric currents.