GIC as a return current of the global ionospheric currents during space weather disturbances

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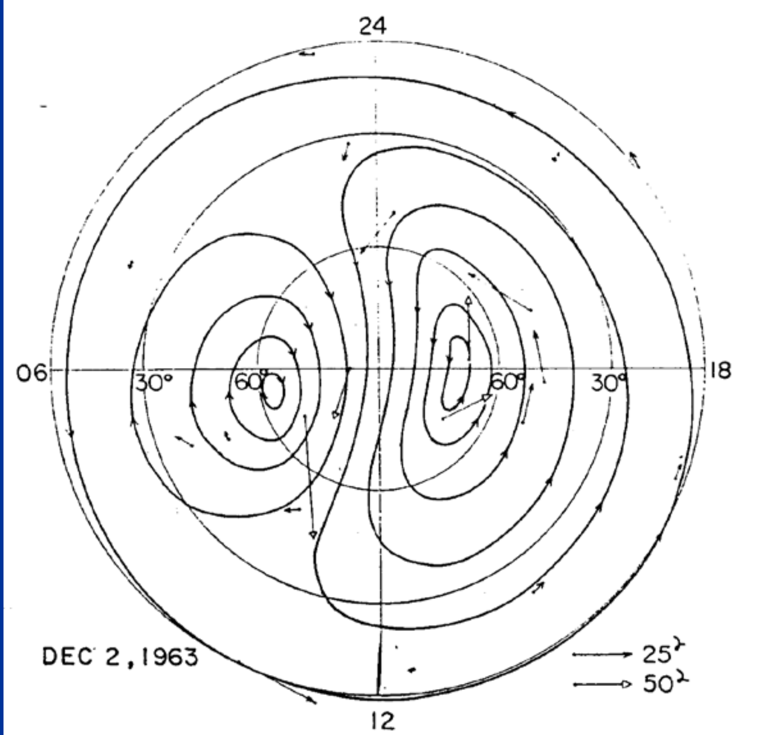
Motivation and purpose

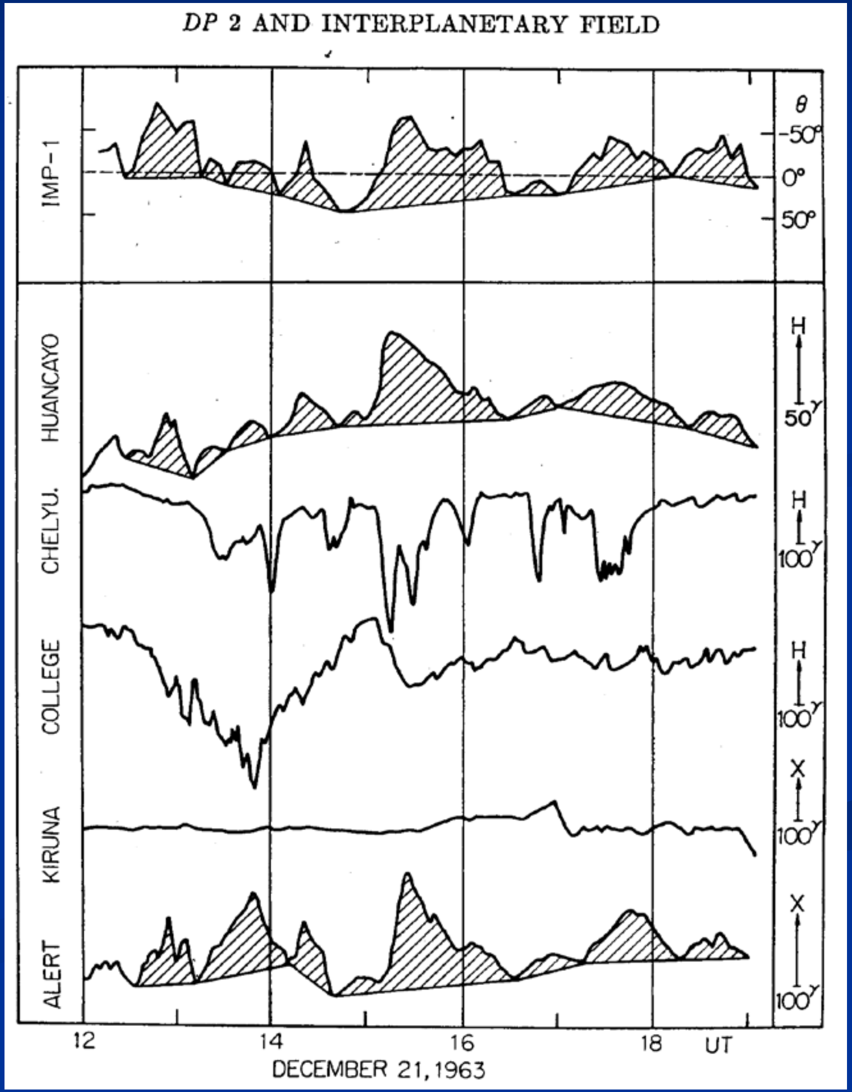
- The midlatitude GICs are well correlated with the D-component magnetic field [Watari et al., 2009] and are subject to diurnal and seasonal variations [Braendlein et al., JGR 2012]. The GIC has been suggested to be a return of the ionospheric currents.
- To understand the GIC in the ionosphere-ground current circuit, we examined the correlation between the GIC and equatorial electrojet (EEJ) as well as midlatitude H and D during the quasi-periodic DP2 fluctuations, SC, Pi2 and so on.
- To explain the flow of the ionospheric currents into the ground, we apply the magnetosphere-ionosphere-ground transmission line model [Kikuchi, 2014].

Quasi-periodic DP2 magnetic fluctuations at high latitude and equator correlated with the IMF

Quasi-periodic DP2 magnetic fluctuations are caused by convection electric fields controlled by the IMF.

(Nishida, JGR 1968)





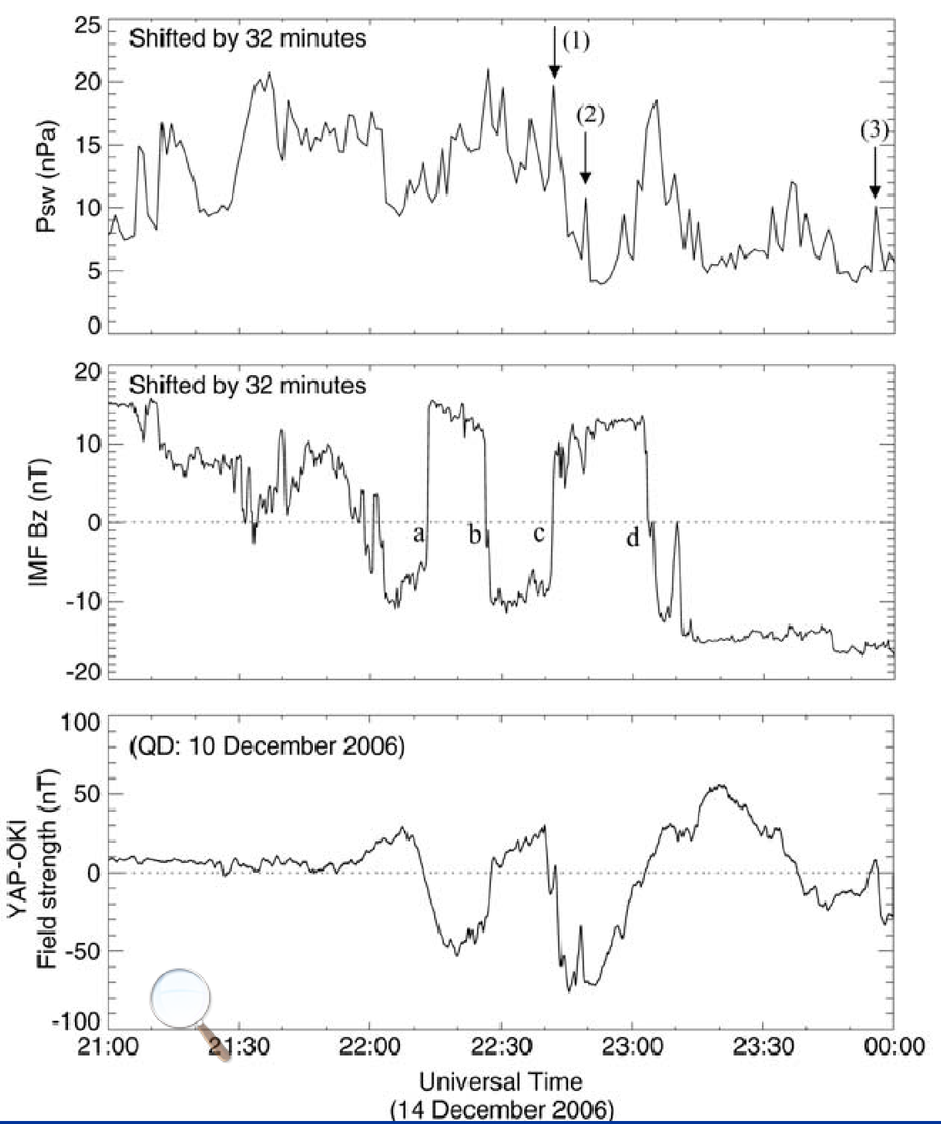
Quasi-periodic DP2 fluctuations caused by IMF Bz fluctuations

Solar wind dynamic pressure

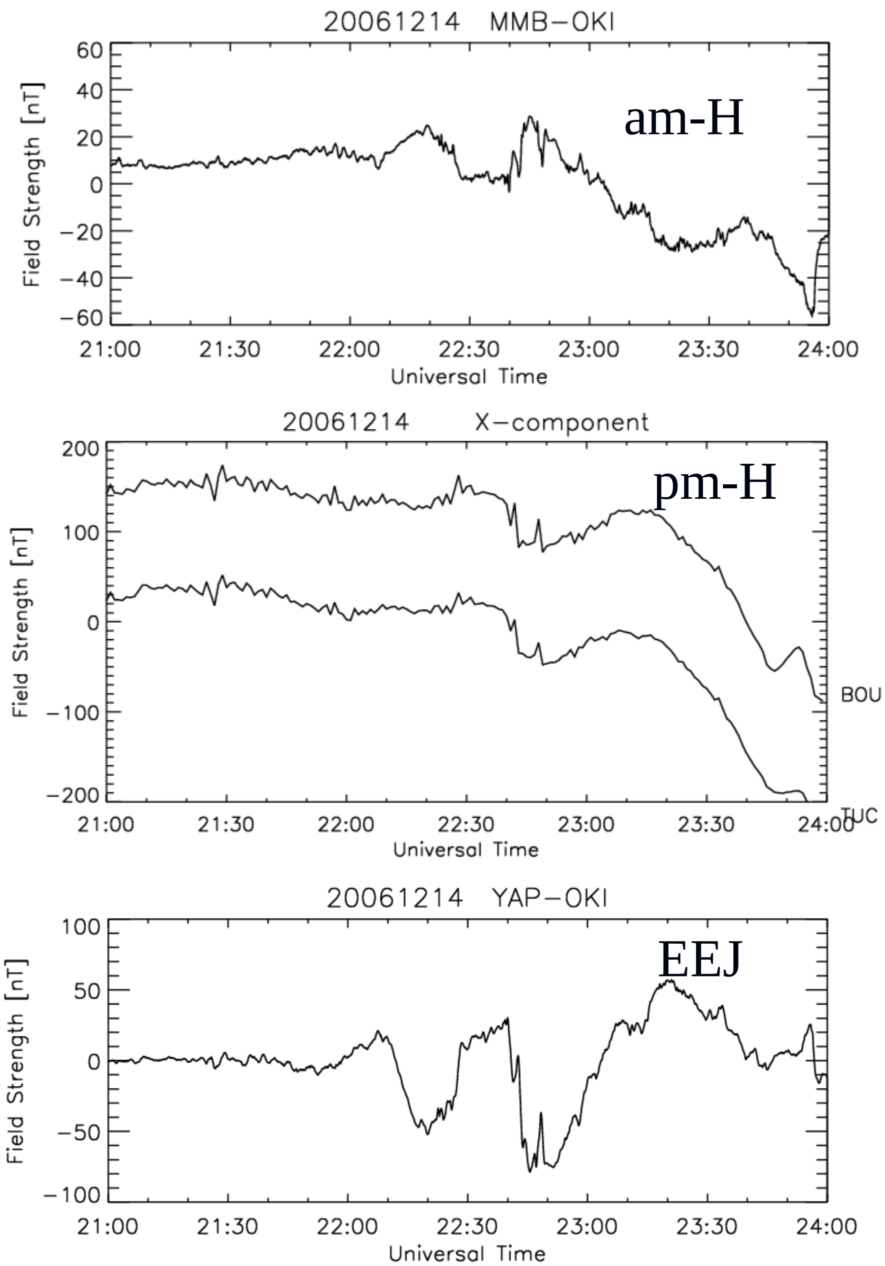
Interplanetary magnetic field (IMF)

Equatorial electrojet (EEJ)

(Kikuchi et al., JGR 2010)



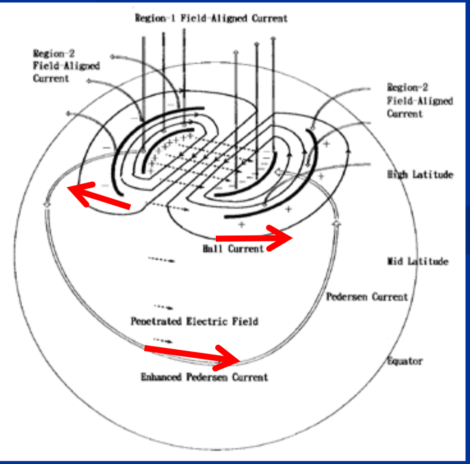
DP2 currents at mid-equatorial latitudes (H/X-component)



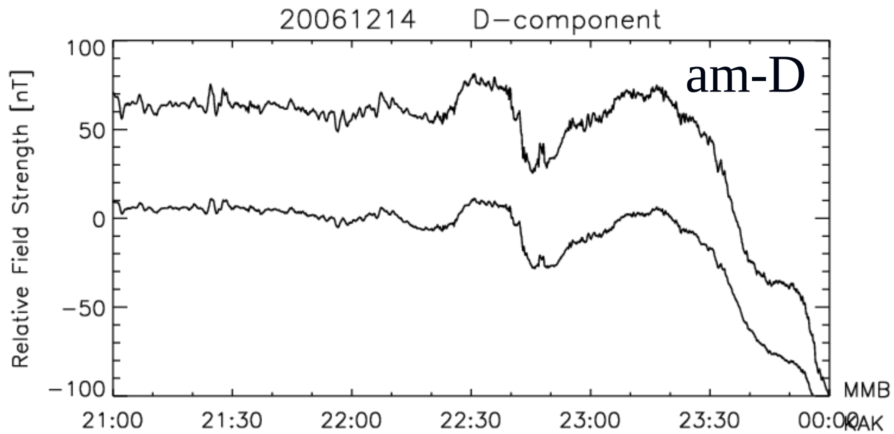
The am-H and pm-H components are anti-correlated with each other at mid latitudes.

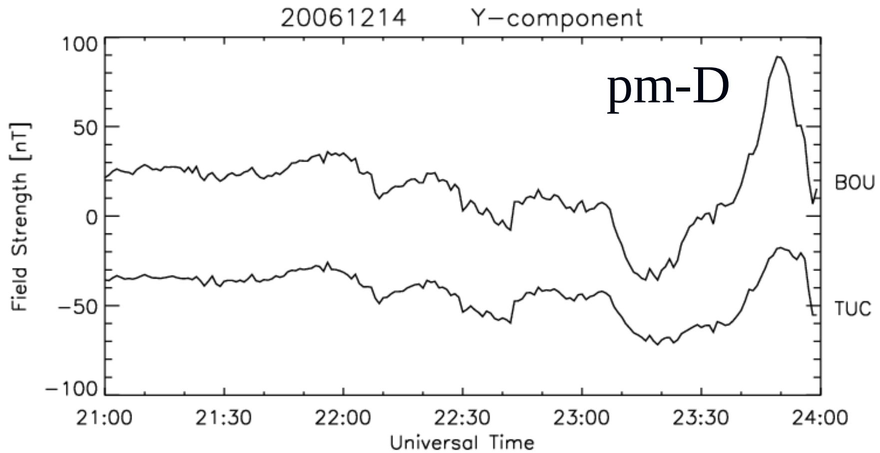
EEJ is correlated with pm-H and anti-correlated with am-H.

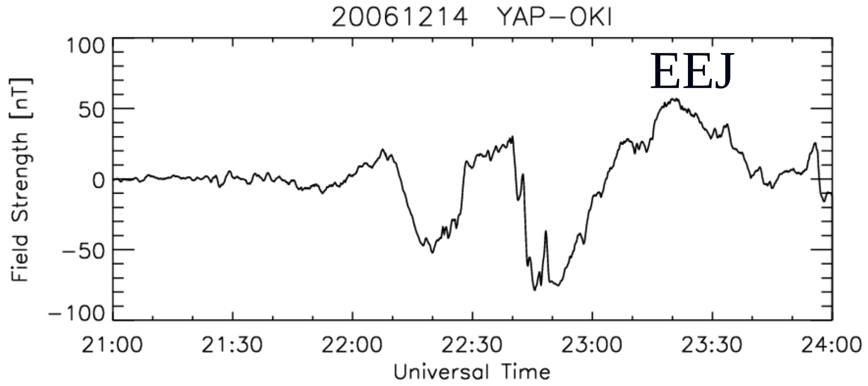
am: morning
pm: afternoon



DP2 currents at mid-equatorial latitudes (D/Y-component)

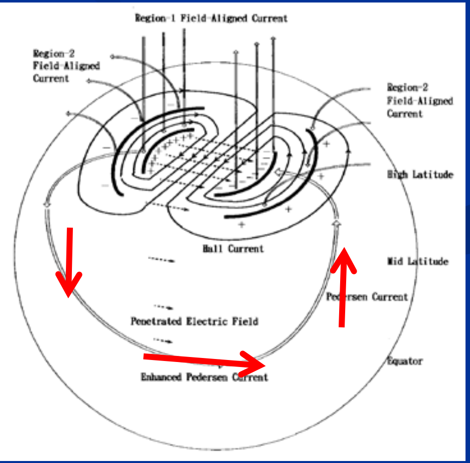




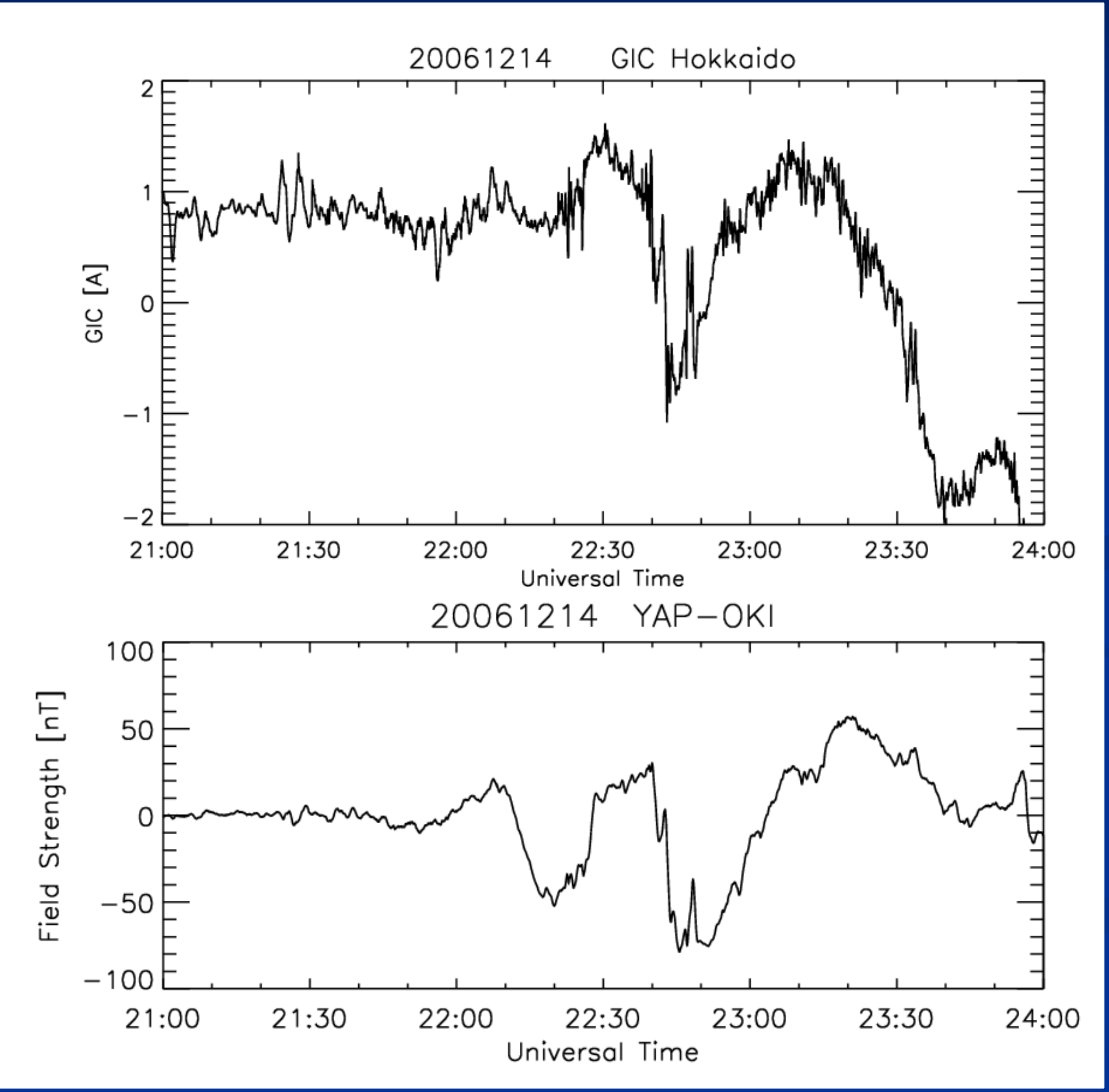


The am-D and pm-D components are anti-correlated with each other at mid latitudes.

EEJ is correlated with am-D and anti-correlated with pm-D.



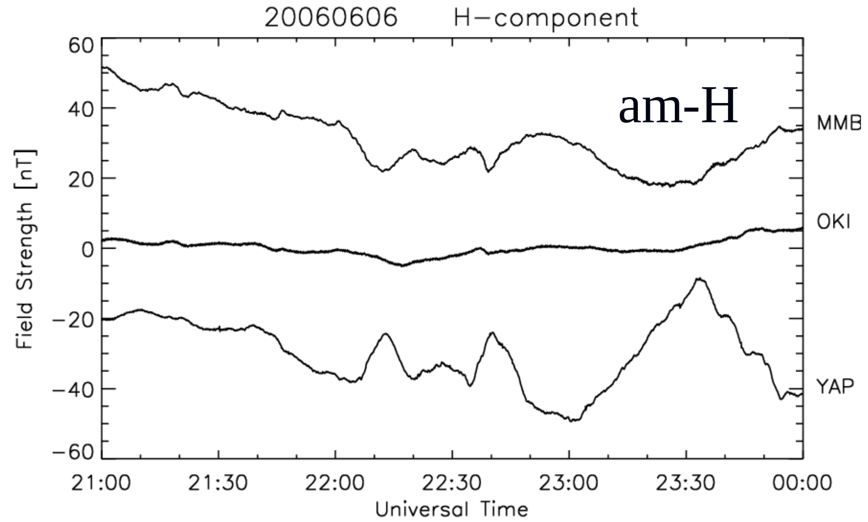
GIC in the morning sector during the DP2 event

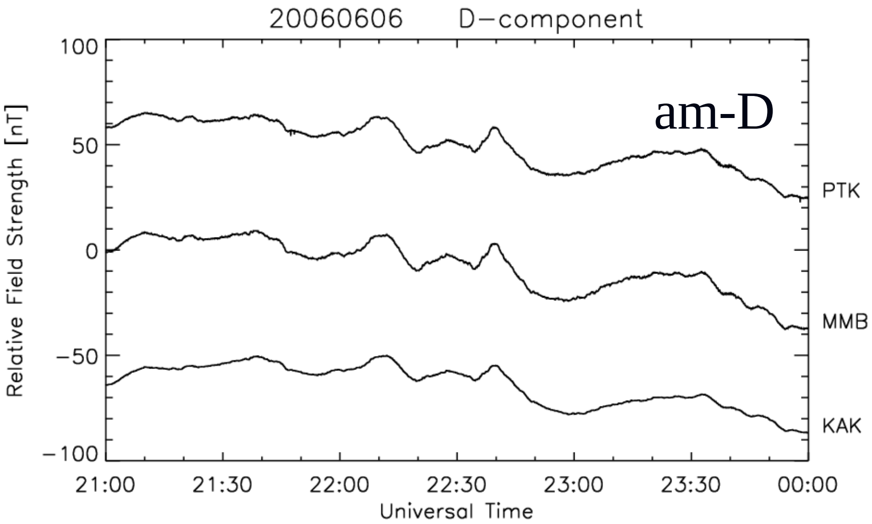


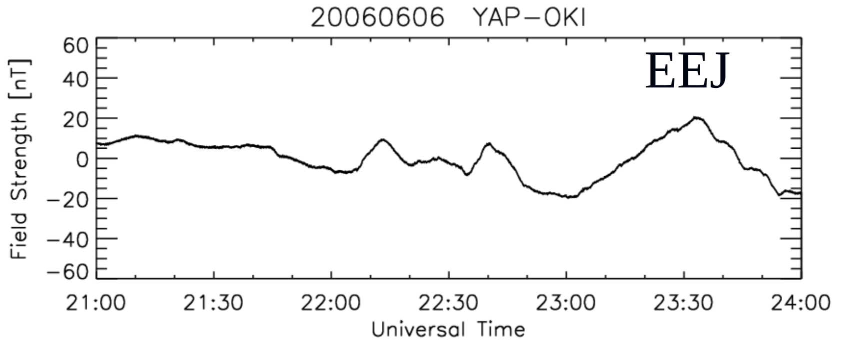
The am-GIC is correlated with EEJ.

Suggests that the GIC is connected with the global DP2 currents.

Another GIC event in the morning sector

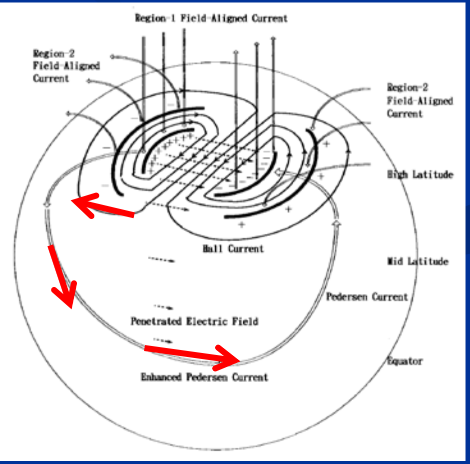




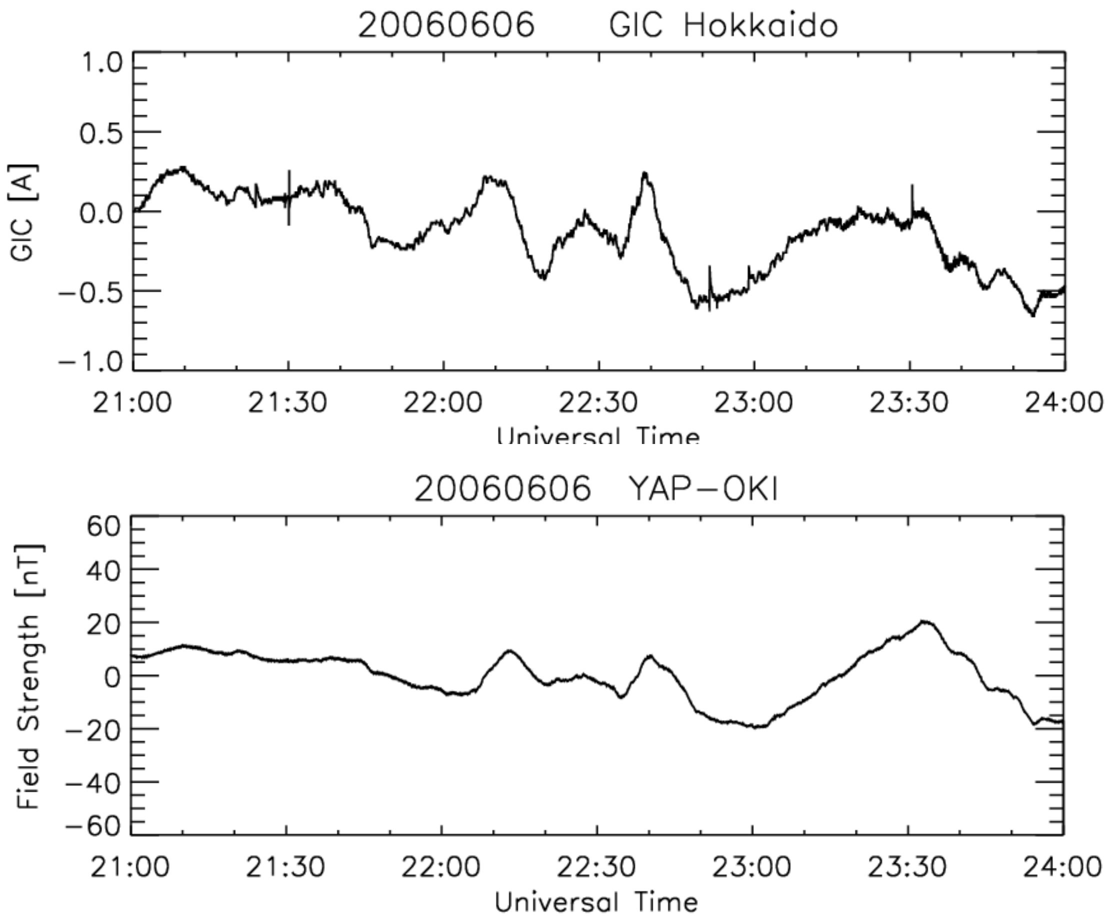


The am-H and am-D components are anti-correlated with each other at mid latitudes.

EEJ is correlated with am-D and anti-correlated with am-H.



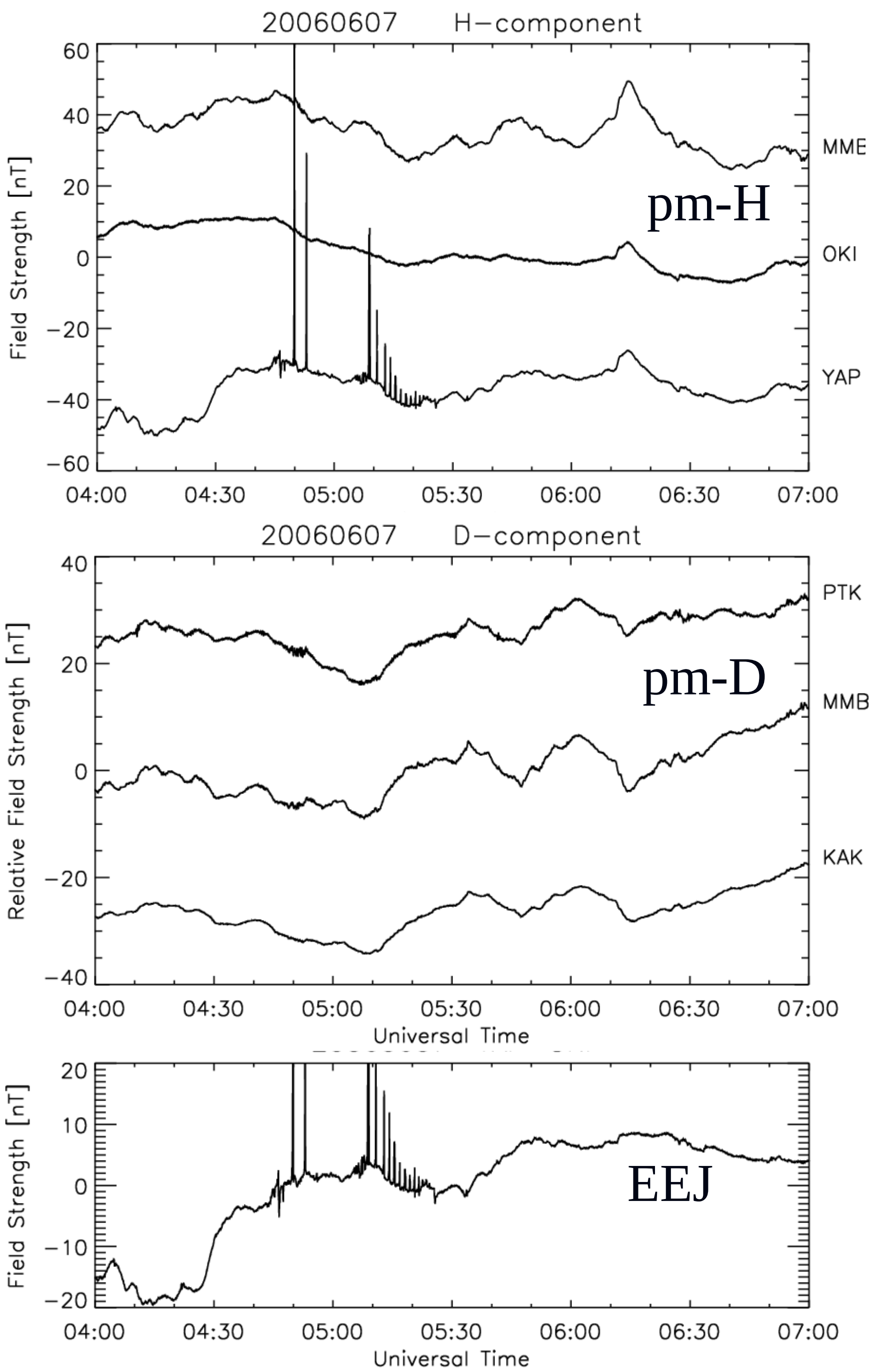
GIC in the morning sector during the DP2 event



The am-GIC is correlated with EEJ.

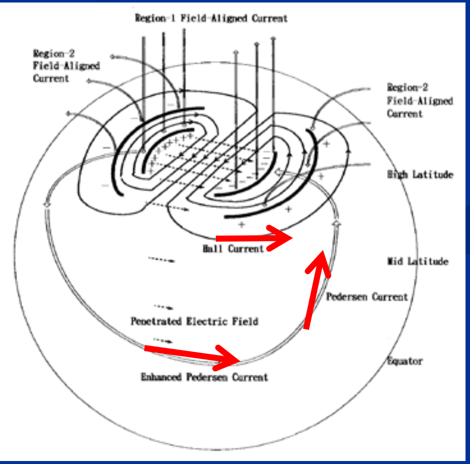
Suggests that the GIC is connected with the global DP2 currents.

GIC in the afternoon sector during the DP2 event

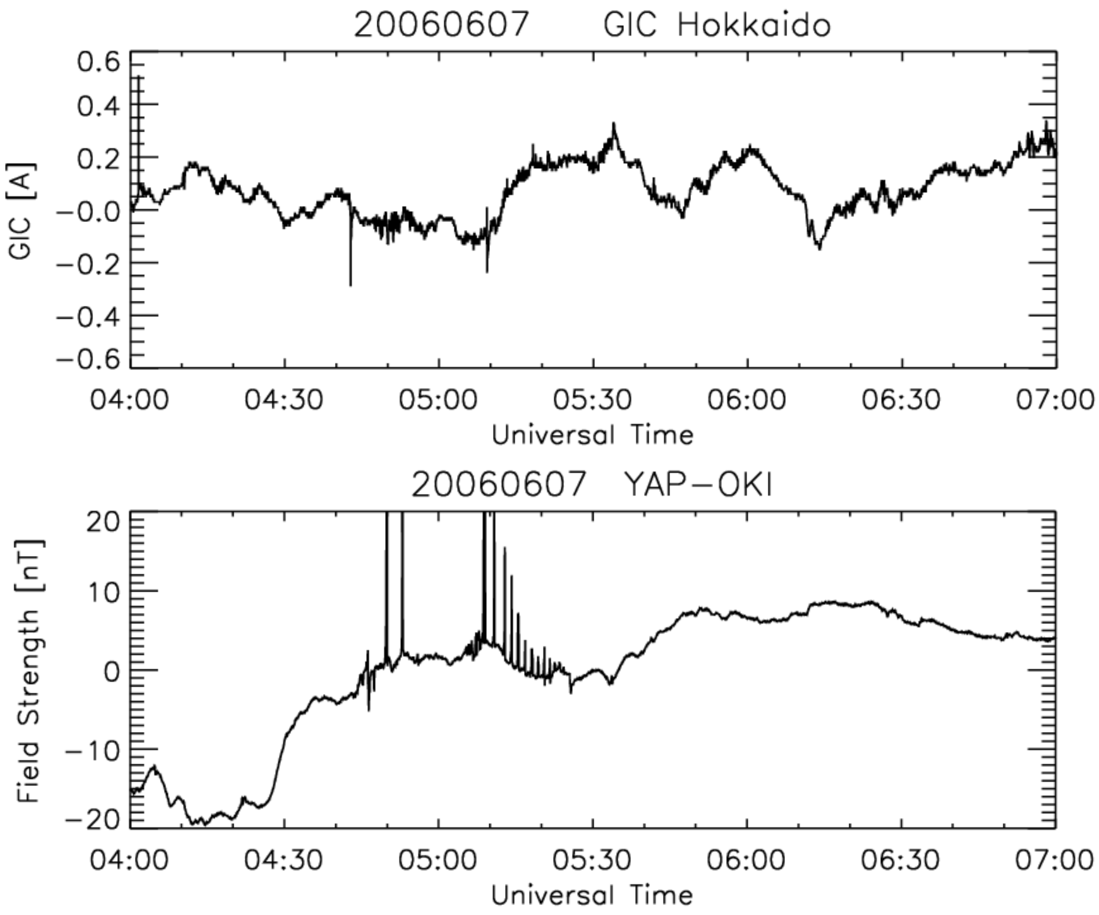


The pm-H and pm-D components are anti-correlated with each other at mid latitudes.

EEJ is correlated with pm-H and anti-correlated with pm-D.



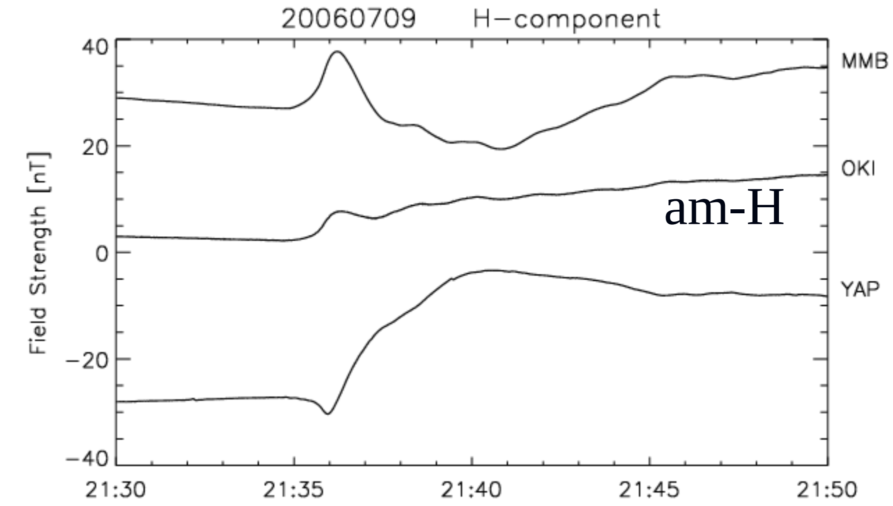
GIC in the afternoon sector during the DP2 event

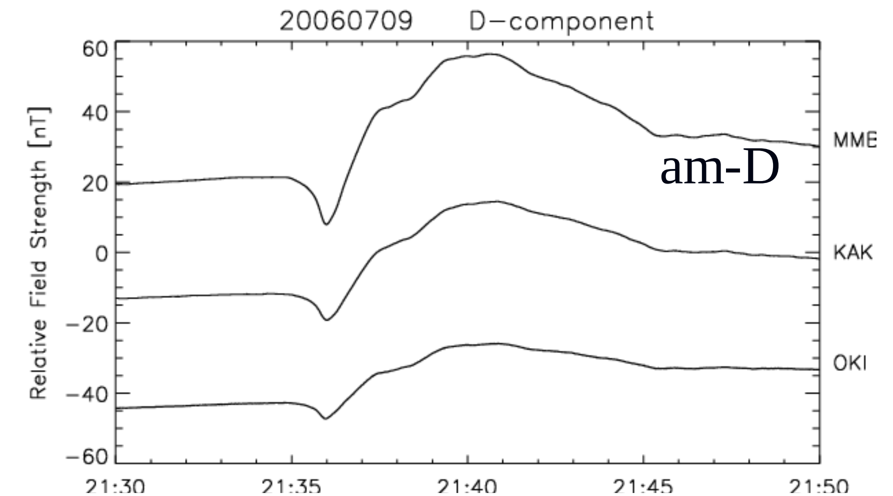


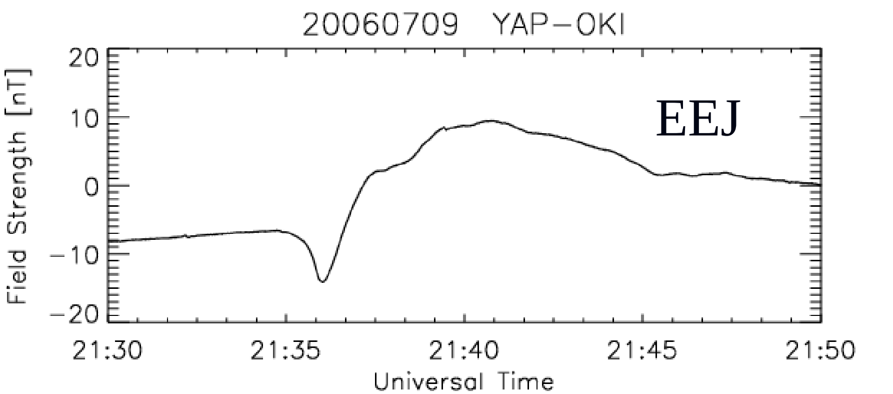
The pm-GIC is anti-correlated with EEJ.

Suggests that the GIC is connected with the global DP2 currents.

GIC in the morning sector during the SC event

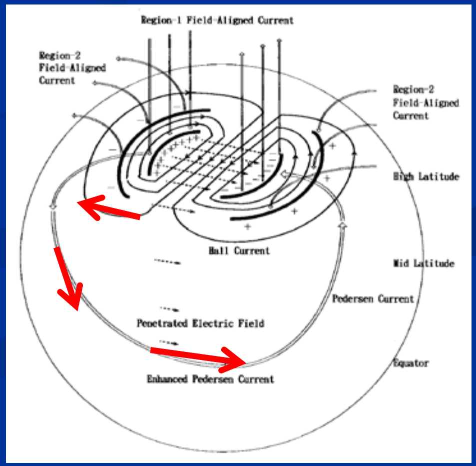




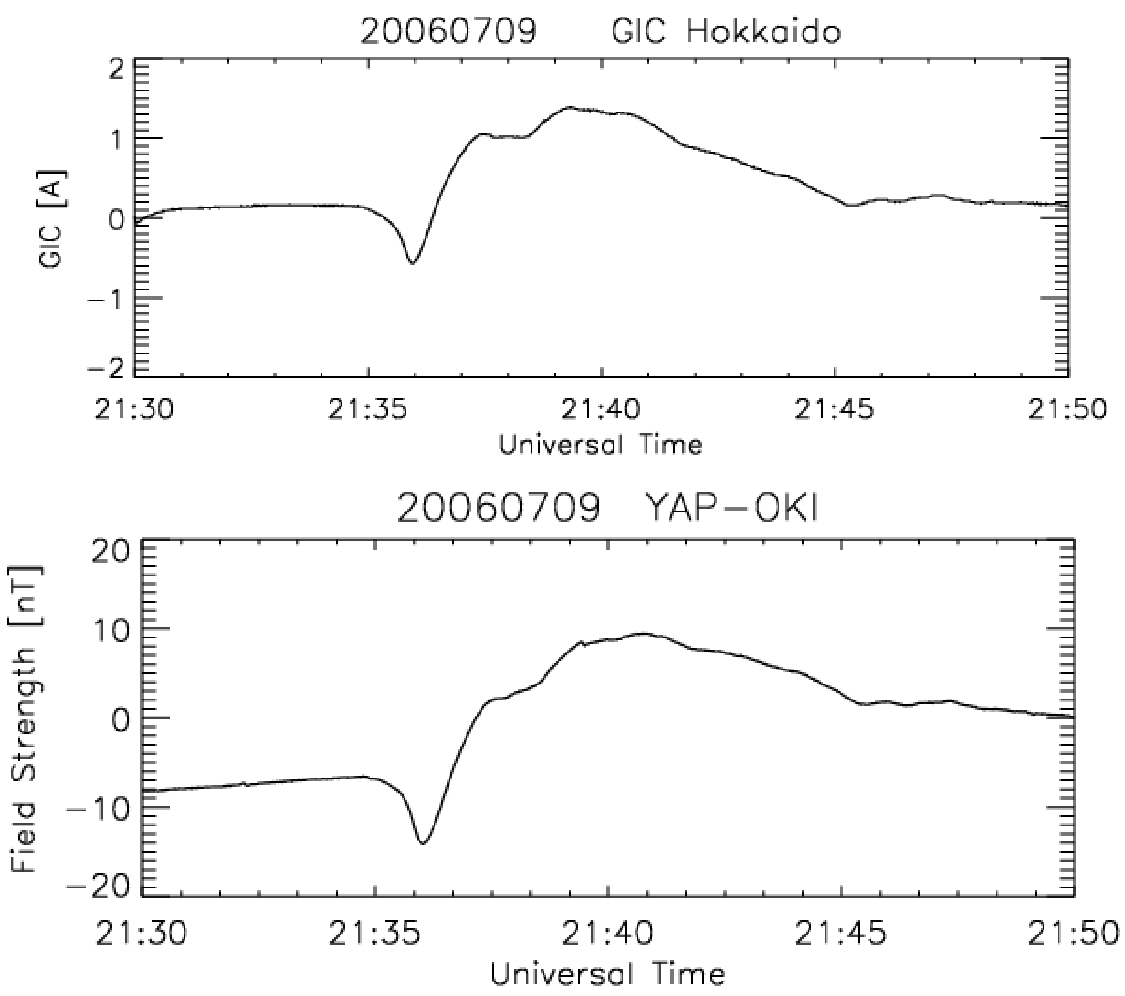


The am-H and am-D components are anti-correlated with each other at mid latitudes.

EEJ is correlated with am-D and anti-correlated with am-H.



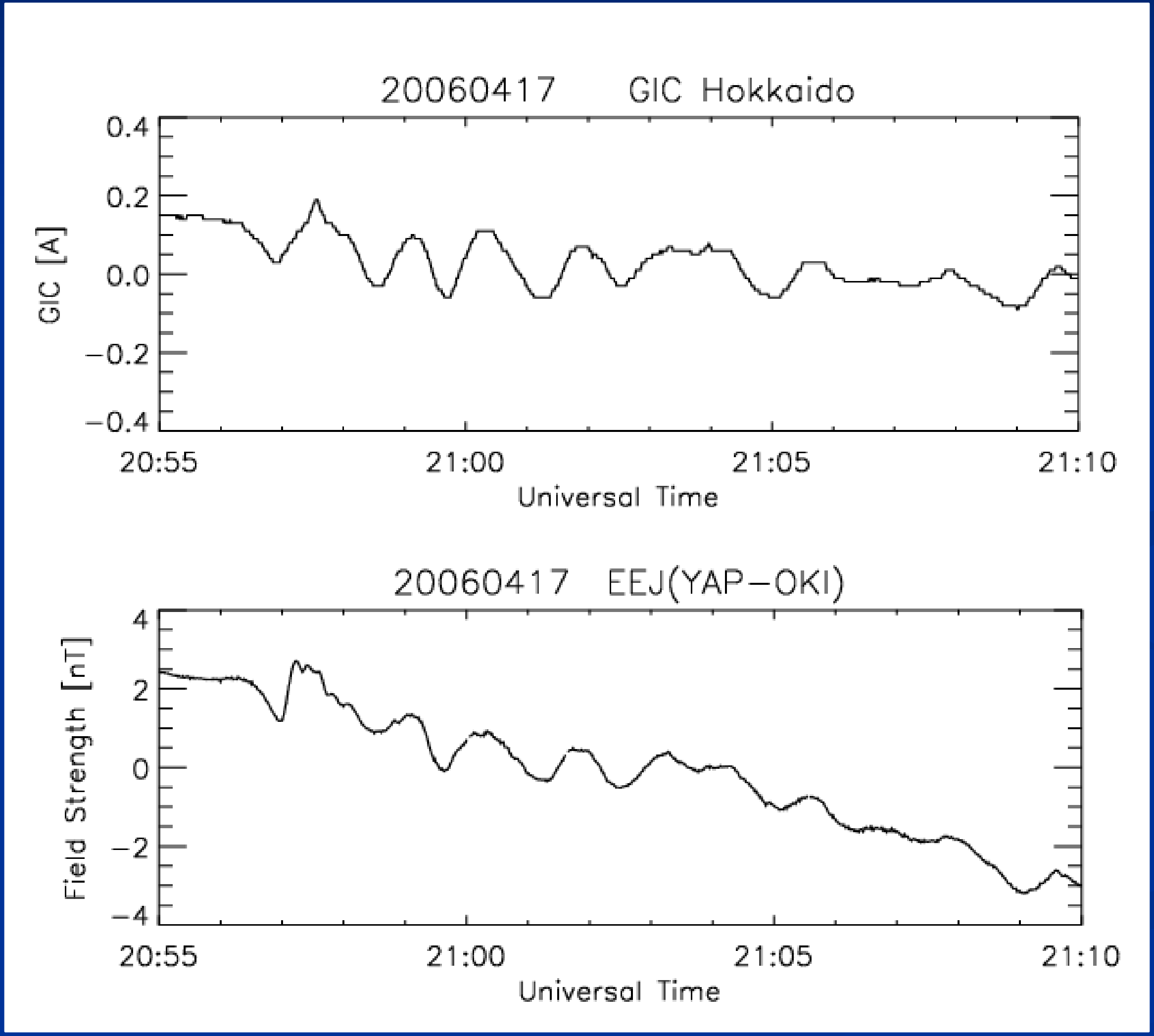
GIC in the morning sector during the SC event



The am-GIC is correlated with EEJ.

Suggests that the GIC is connected with the global SC currents.

GIC in the morning sector during the Pi2 event



The am-GIC is correlated with EEJ.

Suggests that the GIC is connected with the global Pi2 currents.

Induction or wave ?

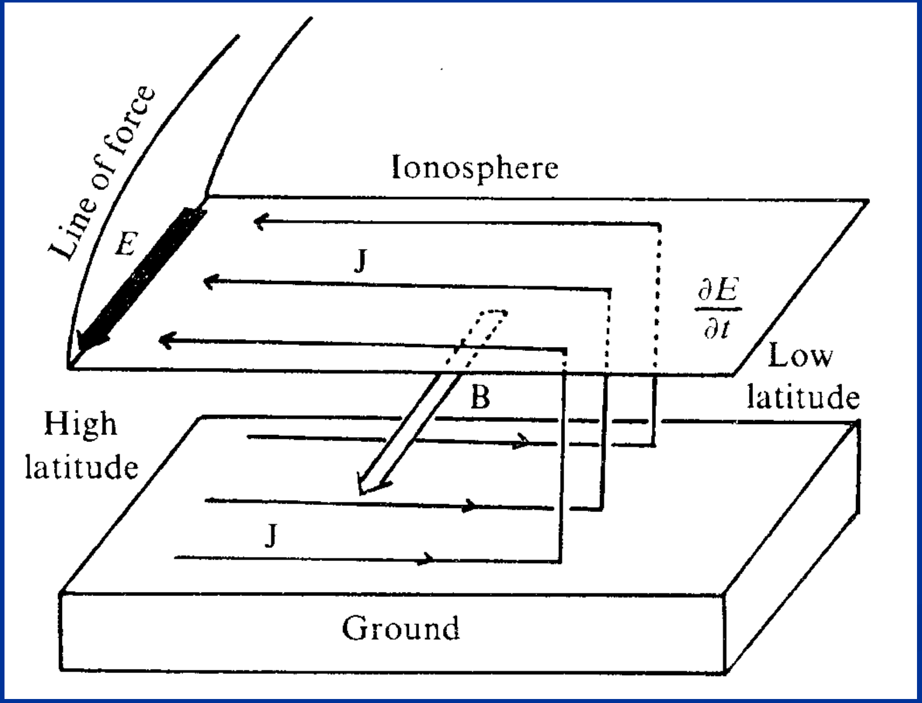
× $$-\frac{\partial B}{\partial t} = E$$

□ $$-\frac{\partial B}{\partial t} = \nabla \times E \quad \Longrightarrow \quad \frac{E}{B} = \frac{1}{\mu_0} Z$$

(Z: wave impedance)

Earth-ionosphere waveguide (transmission line) model for the polar – equatorial current circuit

(Kikuchi et al., 1978; Kikuchi and Araki, 1979)

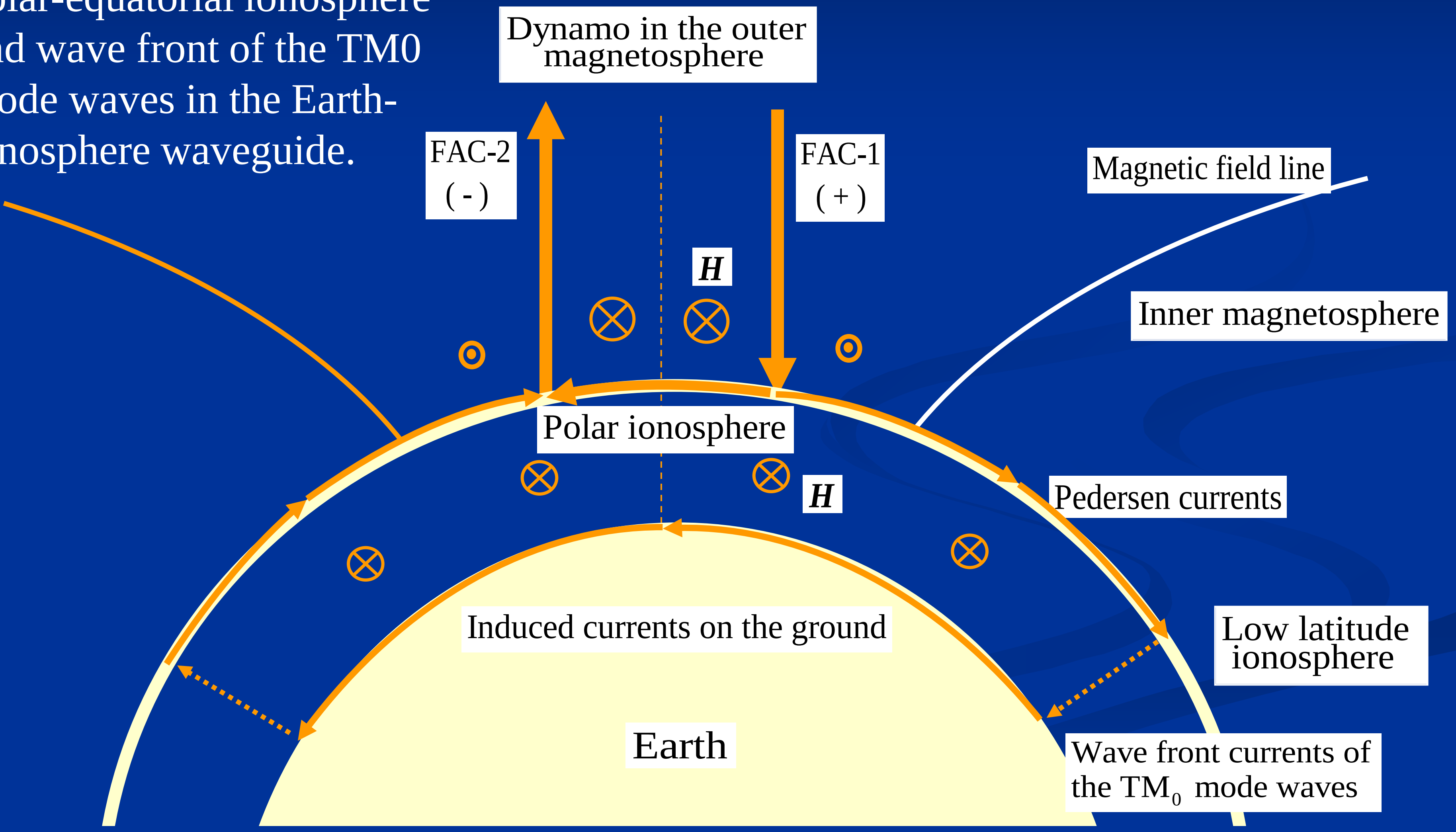


TM0 mode waves carry electric currents in the ionosphere and on the ground, which are connected by the displacement currents on the wave front.

Magnetosphere-ionosphere-ground (MIG) current circuit

(Kikuchi, JGR 2014)

DP2 currents flow into the ground from the magnetospheric dynamo down the magnetic field lines, polar-equatorial ionosphere and wave front of the TM0 mode waves in the Earth-ionosphere waveguide.



Magnetosphere-ionosphere-ground (MIG) transmission line

(Kikuchi, JGR 2014)

Transmission line parameters

$d_1 = 80{,}000$ km (length of the FAC transmission line)
$d_2 = 8{,}000$ km (length of the EIG transmission line)
$w = 2{,}000$ km (width of the FAC and EIG transmission lines)
$l = 2{,}000$ km (separation of the FAC transmission line)
$h = 100$ km (separation of the EIG transmission line)

$V_A = 1{,}000$ km (Alfven speed)
$\Sigma_1 = 8$ mho (height-integrated conductivity of the polar ionosphere)
$\Sigma_2 = 0.2$ - 30 mho (height-integrated ionospheric conductivity of the EIG)

Transmission line equation

$$\frac{\partial^2 V}{\partial x^2} = \frac{1}{V_{\mathrm{ph}}{}^2}\left[\frac{\partial^2 V}{\partial t^2} + \alpha\frac{\partial V}{\partial t}\right],$$

$$\frac{\partial^2 I}{\partial x^2} = \frac{1}{V_{\mathrm{ph}}{}^2}\left[\frac{\partial^2 I}{\partial t^2} + \alpha\frac{\partial I}{\partial t}\right],$$

where $V_{\mathrm{ph}}{}^2 = \dfrac{1}{LC}$ (phase velocity), $\alpha = \dfrac{R}{L}$ (attenuation rate).

Intrinsic impedance

$$Z_{01} = \mu_0 V_A = 1.26 \text{ ohm}$$

$$Z_{02} = \mu_0 c = 376.7 \text{ ohm}$$

Characteristic impedance

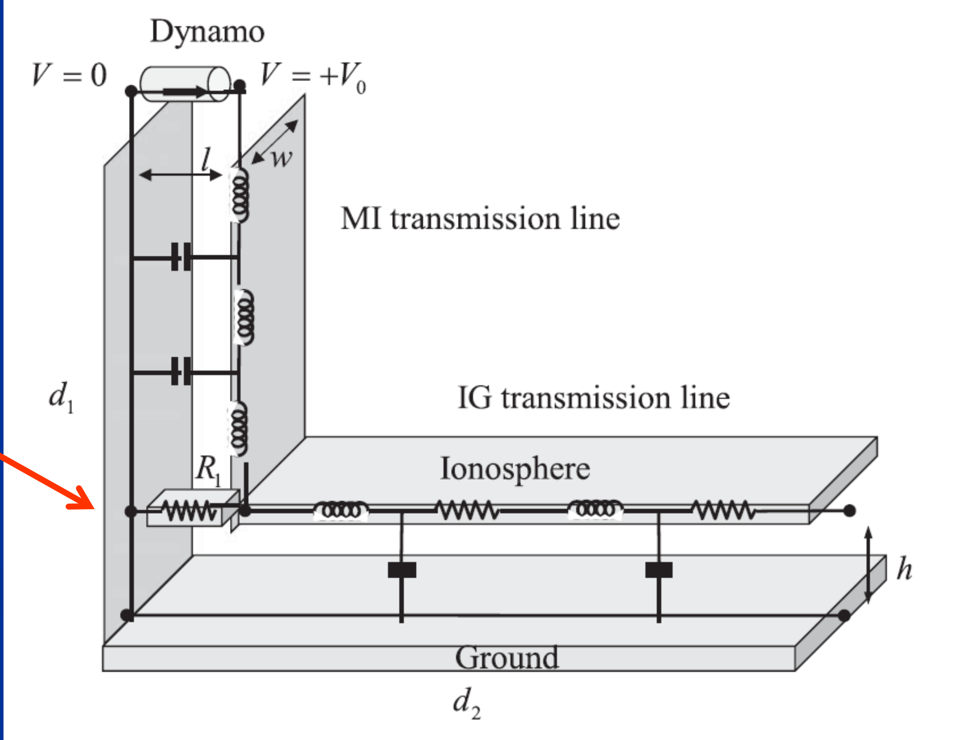
$$Z_1 = \mu_0 V_A = 1.26 \text{ ohm}$$

$$Z_2 = 376.7\frac{h}{w} = 18.8 \text{ ohm}$$

Reflection and transmission coefficients

$$C_r = \frac{R_1 Z_2 - Z_1(R_1 + Z_2)}{R_1 Z_2 + Z_1(R_1 + Z_2)} = -0.821$$

$$C_t = \frac{2R_1 Z_2}{R_1 Z_2 + Z_1(R_1 + Z_2)} = \underline{0.179}$$



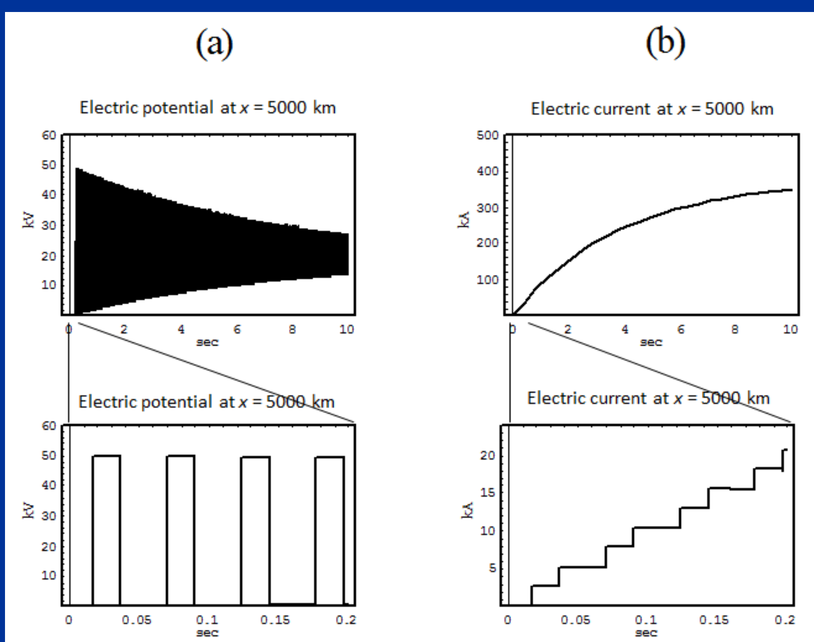
The transmitted electric and magnetic fields excite the TM0 mode wave.

Ionospheric and ground surface currents in the finite-length transmission line

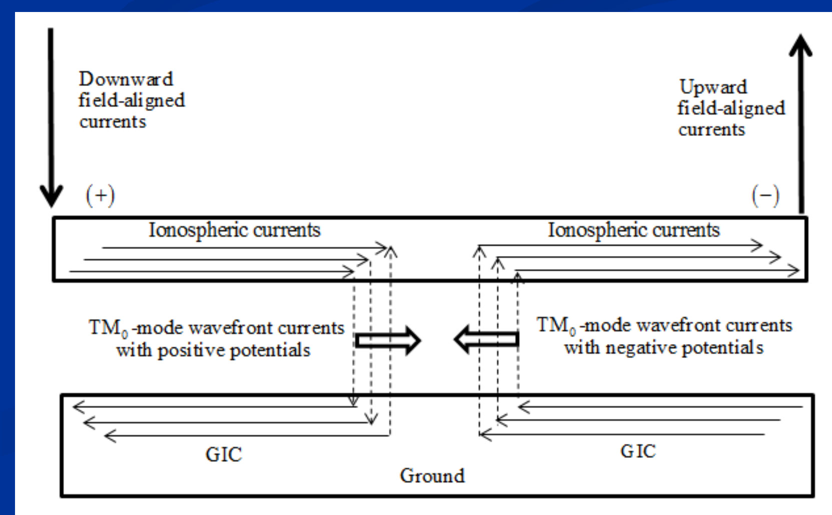
$$V_2(x,t)=V_0\left\{\begin{array}{l}\displaystyle\sum_{n=1}^{\infty}\left[e^{-\frac{\alpha}{2}t_{n1}}U(t-t_{n1})+\frac{\alpha}{2}t_{n1}\int_{t_{n1}}^{t}e^{-\frac{\alpha}{2}\tau}U(t-\tau)\frac{I_1\left(\frac{\alpha}{2}\sqrt{\tau^2-t_{n1}^{\ 2}}\right)}{\sqrt{\tau^2-t_{n1}^{\ 2}}}d\tau\right]\\ \displaystyle-\sum_{n=1}^{\infty}\left[e^{-\frac{\alpha}{2}t_{n2}}U(t-t_{n2})+\frac{\alpha}{2}t_{n2}\int_{t_{n2}}^{t}e^{-\frac{\alpha}{2}\tau}U(t-\tau)\frac{I_1\left(\frac{\alpha}{2}\sqrt{\tau^2-t_{n2}^{\ 2}}\right)}{\sqrt{\tau^2-t_{n2}^{\ 2}}}d\tau\right]\end{array}\right\} \quad (5\text{-}11)$$

$$I_2(x,t)=V_0\frac{1}{Z_2}e^{-\frac{\alpha}{2}t}\left\{\sum_{n=1}^{\infty}U(t-t_{n1})I_0\left(\frac{\alpha}{2}\sqrt{t^2-t_{n1}^{\ 2}}\right)+\sum_{n=1}^{\infty}U(t-t_{n2})I_0\left(\frac{\alpha}{2}\sqrt{t^2-t_{n2}^{\ 2}}\right)\right\} \quad (5\text{-}12)$$

$$t_{n1}=\frac{2(n-1)d_2+x}{c} \qquad t_{n2}=\frac{2nd_2-x}{c} \quad (5\text{-}13)$$



The ionospheric currents are carried by multiple TM0 mode waves propagating along the finite-length transmission line. The ionospheric currents are connected with the ground surface currents by the wave front currents of the multiple TM0 mode waves.



Summary

- The GIC has been suggested to be a return of the ionospheric currents [Watari et al., 2009; Braendlein et al., JGR 2012].
- In this paper, we have shown that the midlatitude GIC is well correlated with the equatorial electrojet as well as the midlatitude H- and D-components, suggesting that the GIC is closely connected with the global ionospheric currents developing from high latitude to the equator.
- The magnetosphere-ionosphere-ground transmission line model [Kikuchi, JGR 2014] helps understand the current flow from the ionosphere to the ground, which are connected by the wave front currents of the TM0 mode waves propagating in the Earth-ionosphere waveguide [transmission line].