3D-Cowling Channel Model in the Sq Current System

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KTN
TIK
CHD
ZYK
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PTK
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BJI
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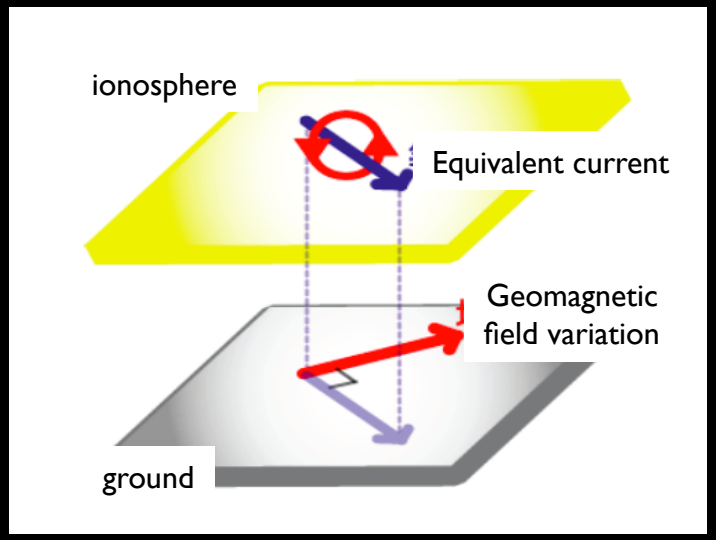
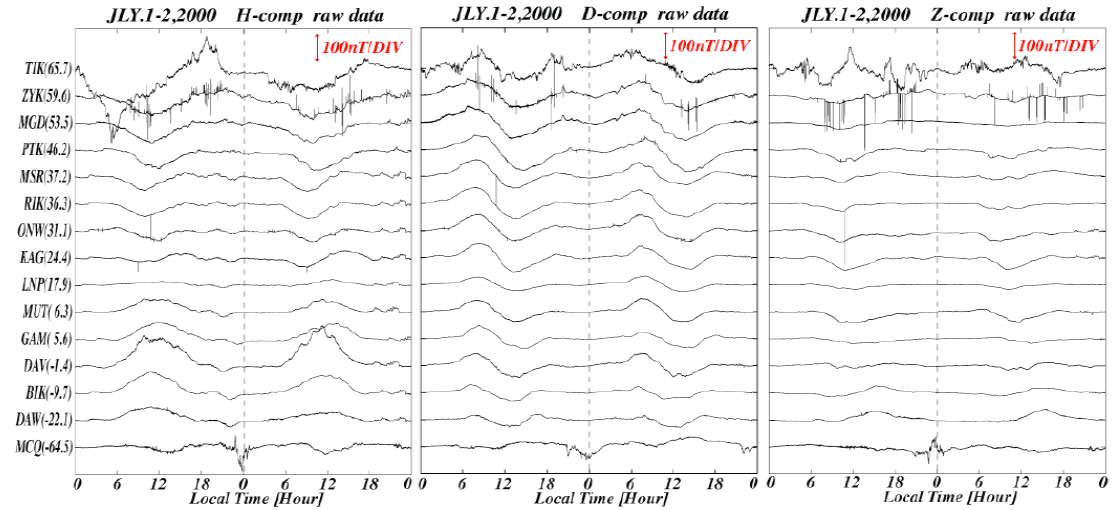

ionosphere
Equivalent current
Geomagnetic
field variation
ground


JLY.1-2,2000 H-comp raw data
JLY.1-2,2000 D-comp raw data
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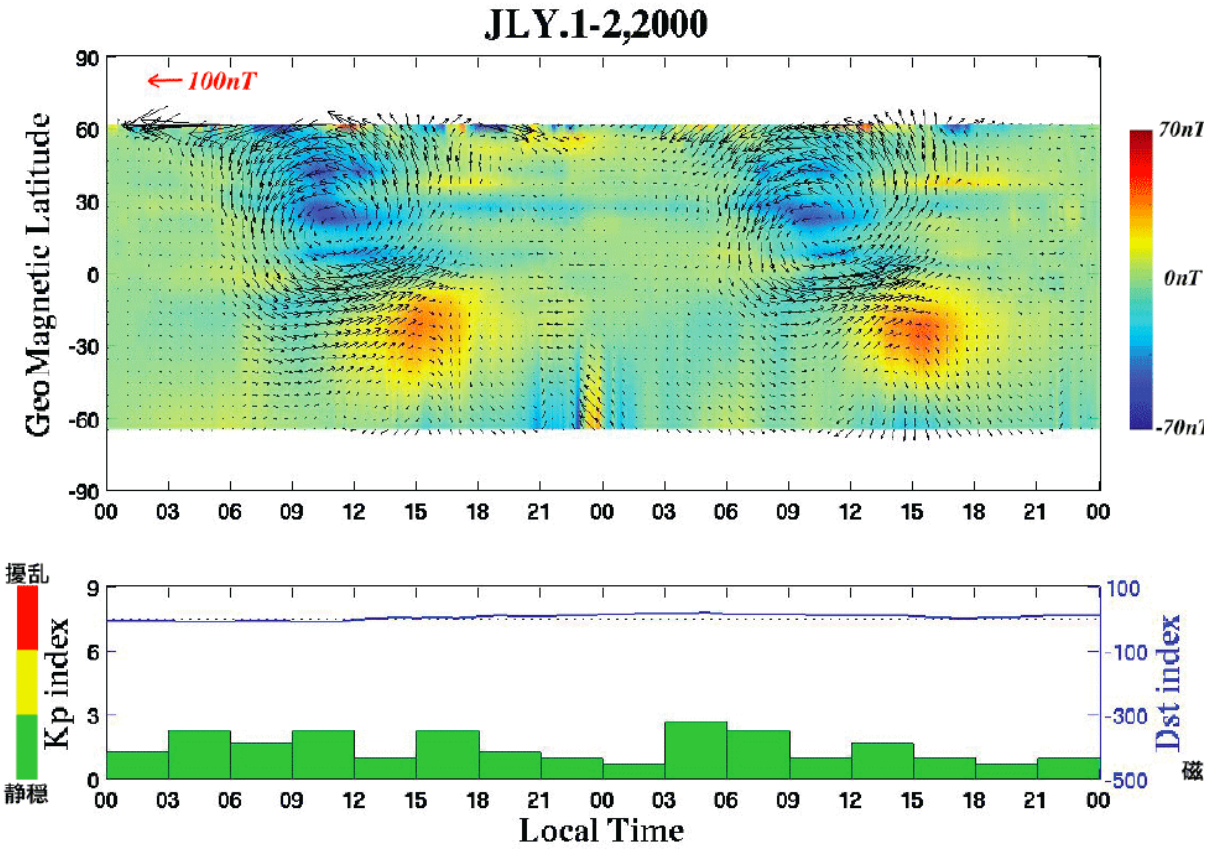
100nT/DIV
TIK(65.7)
ZYK(59.6)
MGD(53.5)
PTK(46.2)
MSR(37.2)
RIK(36.3)
ONW(31.1)
KAG(24.4)
LNP(17.9)
MUT(6.3)
GAM(5.6)
DAV(-1.4)
BIK(-9.7)
DAW(-22.1)
MCQ(-64.5)
Local Time [Hour]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Kp index
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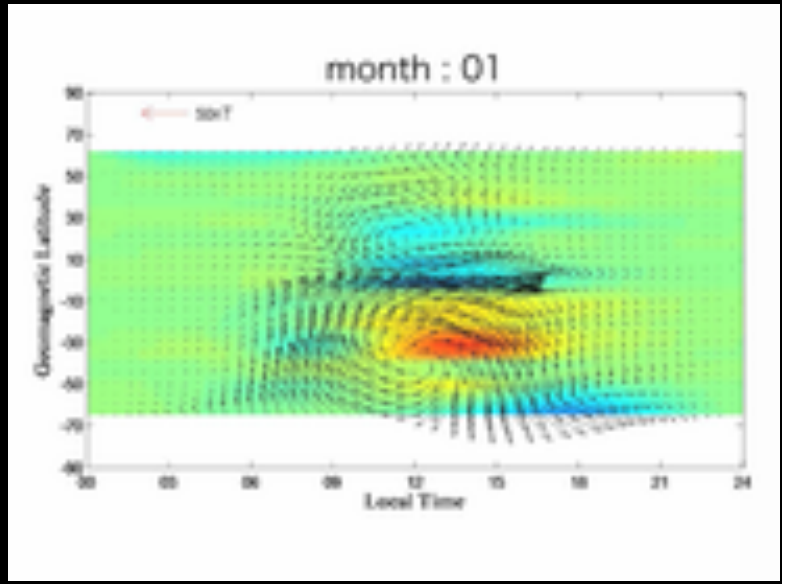
Local Time

Plan for this lecture

1. Framework: how to produce the polarization field
2. Cowling mechanism in the 2D-Auroral electrojet
3. Hall-Pedersen two-layer model
4. Inductive Cowling channel
5. Cowling system in the Sq current system

   From 2D to 3D
6. Summary



Ionospheric current in the ionosphere

$$\mathbf{j} = \sigma_P \mathbf{E} - \sigma_H \hat{e}_B \times \mathbf{E}$$

$\hat{e}_B$ Unit vector of main field

Pedersen current

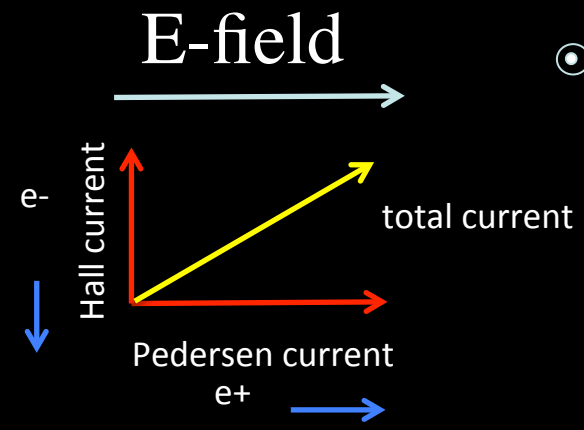
Current in the direction of E-field $\sigma_P \mathbf{E}$ carried by ions

Hall current

Current in the of –E×B direction (anti- parallel to ionospheric flow) $-\sigma_H \hat{e}_B \times \mathbf{E}$ carried by electrons

Joule dissipation due to the Pedersen current (Hall current does not contribute to..)

$$\mathbf{j} \cdot \mathbf{E} = \sigma_P \mathrm{E}^2$$



- Important note : ionospheric current is composed of Ped- and Hall current

・perpendicular each other
・different carriers
・different conductivity

Special characteristic of planet atmosphere: weak-ionized and strong magnetic field

How to determine the current system (not the components)

$$\nabla \cdot \mathbf{j} + \frac{\partial}{\partial t}\rho_C = 0 \longrightarrow \nabla \cdot \mathbf{j} \simeq 0$$

Ionospheic current have to be closed inside the ionosphere
and/or closed via the magnetospheric current (field-aligned current :FAC)

$$\nabla_{//} \cdot \mathbf{j}_{//} + \nabla_{\perp} \cdot \mathbf{j}_{\perp} = 0$$

$$j_{//} = \nabla_{\perp} \cdot \left(\Sigma_P \mathbf{E} + \Sigma_H \hat{e}_B \times \mathbf{E} \right)$$

Relation between electric field, conductivity, current distribution is always regulated by this current closure relation

Origin of electric field on the ionosphere

$$\mathbf{E} = \mathbf{E}^{\mathrm{M}\downarrow\mathrm{I}} + \mathbf{v}^{atm} \times \mathbf{B} - \nabla_{\perp}\Phi$$

magnetospheric input — atmospheric dynamo — Electrostatic electric field

Electromotive force for driving ionospheric current system

Secondary generated polarization field for continuity

$$\vec{\varepsilon} \equiv \mathbf{E}^{\mathrm{M}\downarrow\mathrm{I}} + \mathbf{v}^{atm} \times \mathbf{B}$$

Current closure -relation

$$j_{//} = \nabla_{\perp} \cdot \left(\Sigma_P \left[\vec{\varepsilon} - \nabla_{\perp}\Phi \right] + \Sigma_H \hat{e}_B \times \left[\vec{\varepsilon} - \nabla_{\perp}\Phi \right] \right)$$

Two-dimensional elliptic type differential eq.

$$\hat{A}\nabla_{\perp}^2\Phi + \hat{B}\nabla_{\perp}\Phi + \hat{C}_G = 0$$

We can solve it for Φ if $\left(j_{//}, \Sigma_P, \Sigma_H, \vec{\varepsilon}\right)$ are known

Origin of current divergence producing polarization charge

$$j_{//} = \Sigma_P \nabla_\perp \cdot \mathbf{E} + \nabla_\perp \Sigma_P \cdot \mathbf{E} - \left(\hat{e}_B \times \nabla_\perp \Sigma_H\right) \cdot \mathbf{E} - \Sigma_H \hat{e}_B \cdot \left(\nabla_\perp \times \mathbf{E}\right)$$

Due to Pedersen current divergence

Due to Hall current divergence

Space charge density $\rho_C = \dfrac{\nabla_\perp \cdot \mathbf{E}}{\varepsilon_0}$

Polarization charge density

Dynamo induced charge density

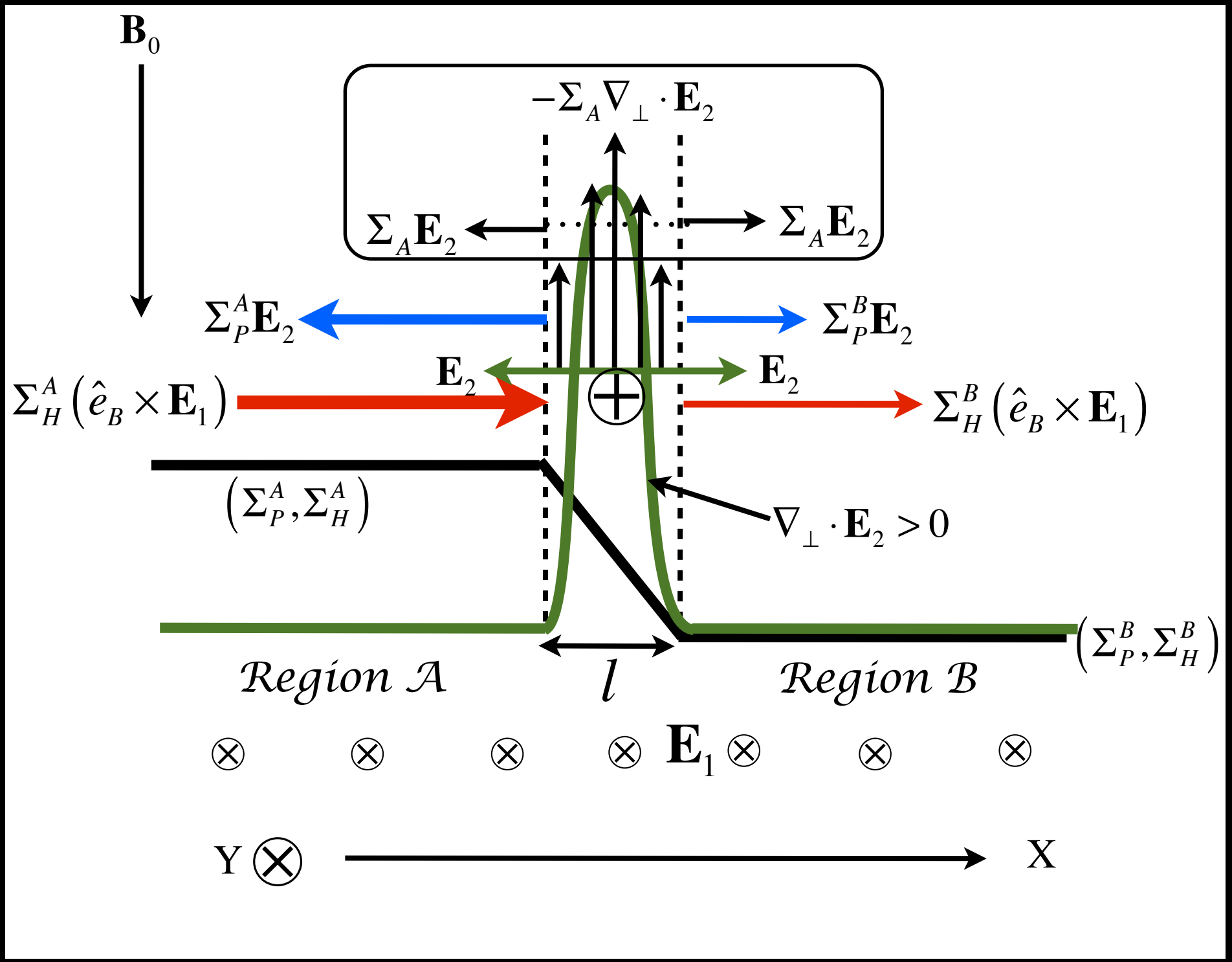
$$-\nabla_\perp^2 \Phi = -\frac{j_{//}}{\Sigma_P} - \frac{\nabla_\perp \Sigma_P \cdot \mathbf{E}}{\Sigma_P} - \frac{\left(\hat{e}_B \times \nabla_\perp \Sigma_H\right) \cdot \mathbf{E}}{\Sigma_P} - \nabla_\perp \cdot \vec{\varepsilon}$$

FAC-closure via Pedersen current

Pedersen current across the conductivity gradient

Hall current across the conductivity gradient

Space charge densities (source of electric field) are induced by current divergence in the ionosphere and divergence of emf-fields in which, polarization charge are produced to satisfy the current closure relation!!


$\mathbf{B}_0$
$-\Sigma_A \nabla_\perp \cdot \mathbf{E}_2$
$\Sigma_A \mathbf{E}_2$
$\Sigma_A \mathbf{E}_2$
$\Sigma_P^A \mathbf{E}_2$
$\Sigma_P^B \mathbf{E}_2$
$\mathbf{E}_2$
$\mathbf{E}_2$
$\Sigma_H^A \left(\hat{e}_B \times \mathbf{E}_1\right)$
$\Sigma_H^B \left(\hat{e}_B \times \mathbf{E}_1\right)$
$\left(\Sigma_P^A, \Sigma_H^A\right)$
$\nabla_\perp \cdot \mathbf{E}_2 > 0$
$\left(\Sigma_P^B, \Sigma_H^B\right)$
Region A
l
Region B
$\mathbf{E}_1$
Y
X

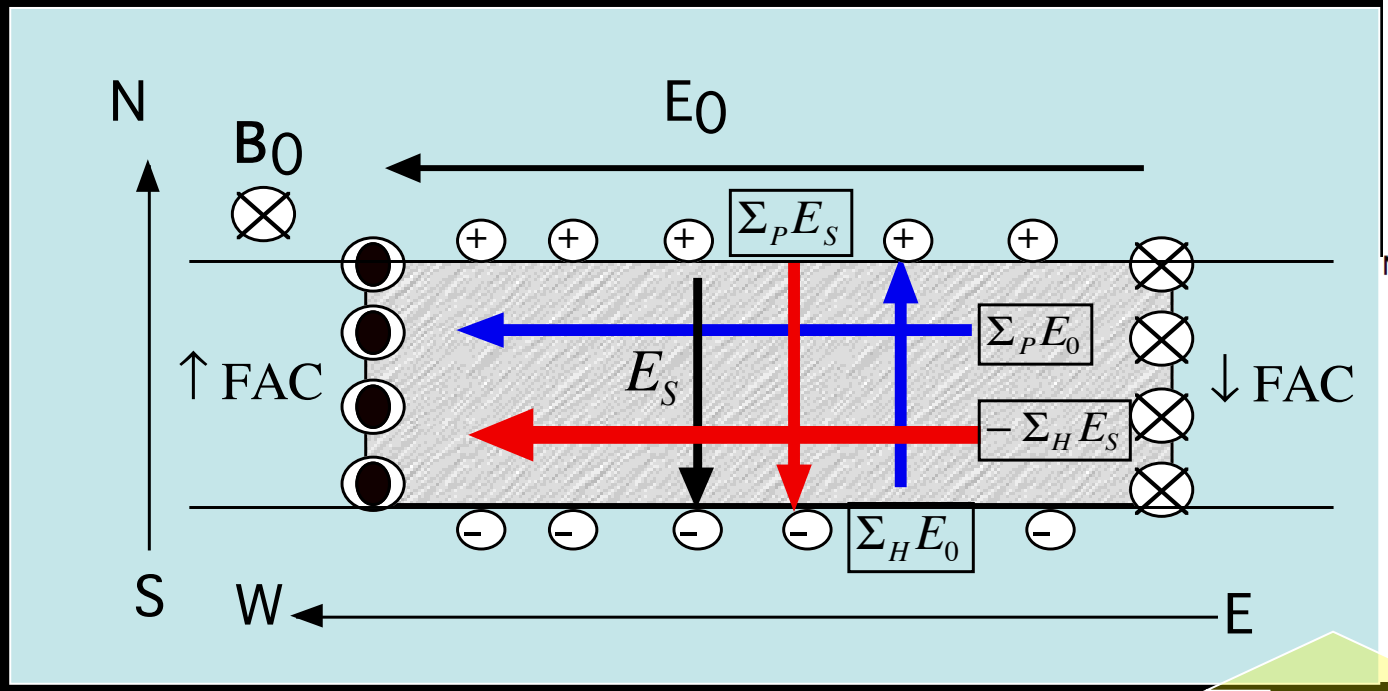
The Cowling mechanism

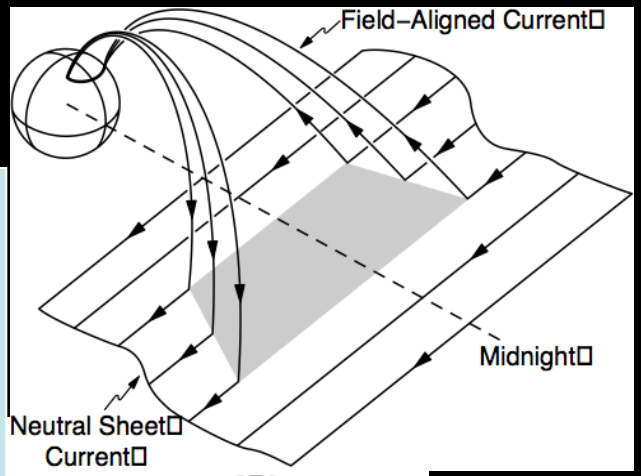
Polarization process due to the Hall current
divergence by excitation of secondary e-field and Pedersen current
(anti-parallel Hall-Pedersen current circuit)

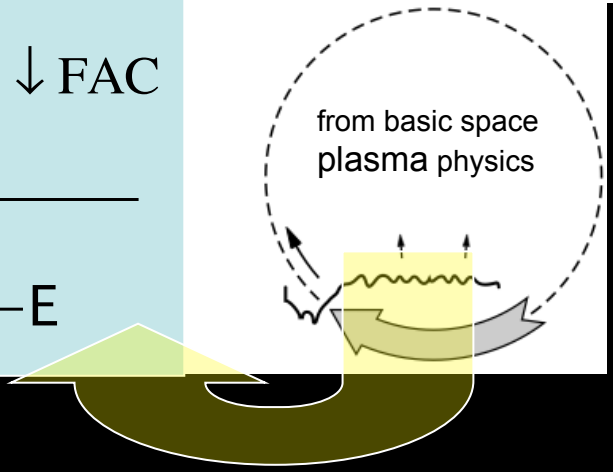
Generation process of electrojet due to the superposition between primary Pedersen current and secondary Hall current so-called Cowling Effect
(parallel Hall-Pedersen current channel)

2-D Cowling Channel

Formation of Cowling channel in the westward traveling surge







Perfect Cowling channel model

- Cancellation of Northward current

  $J_{NS} = \Sigma_P E_s + \Sigma_H E_0 = 0 \rightarrow E_s = -(\Sigma_H^2/\Sigma_P) E_0$

  ——What is physical substance of the cancellation effect between Hall and Pedersen current in the NS-current system?

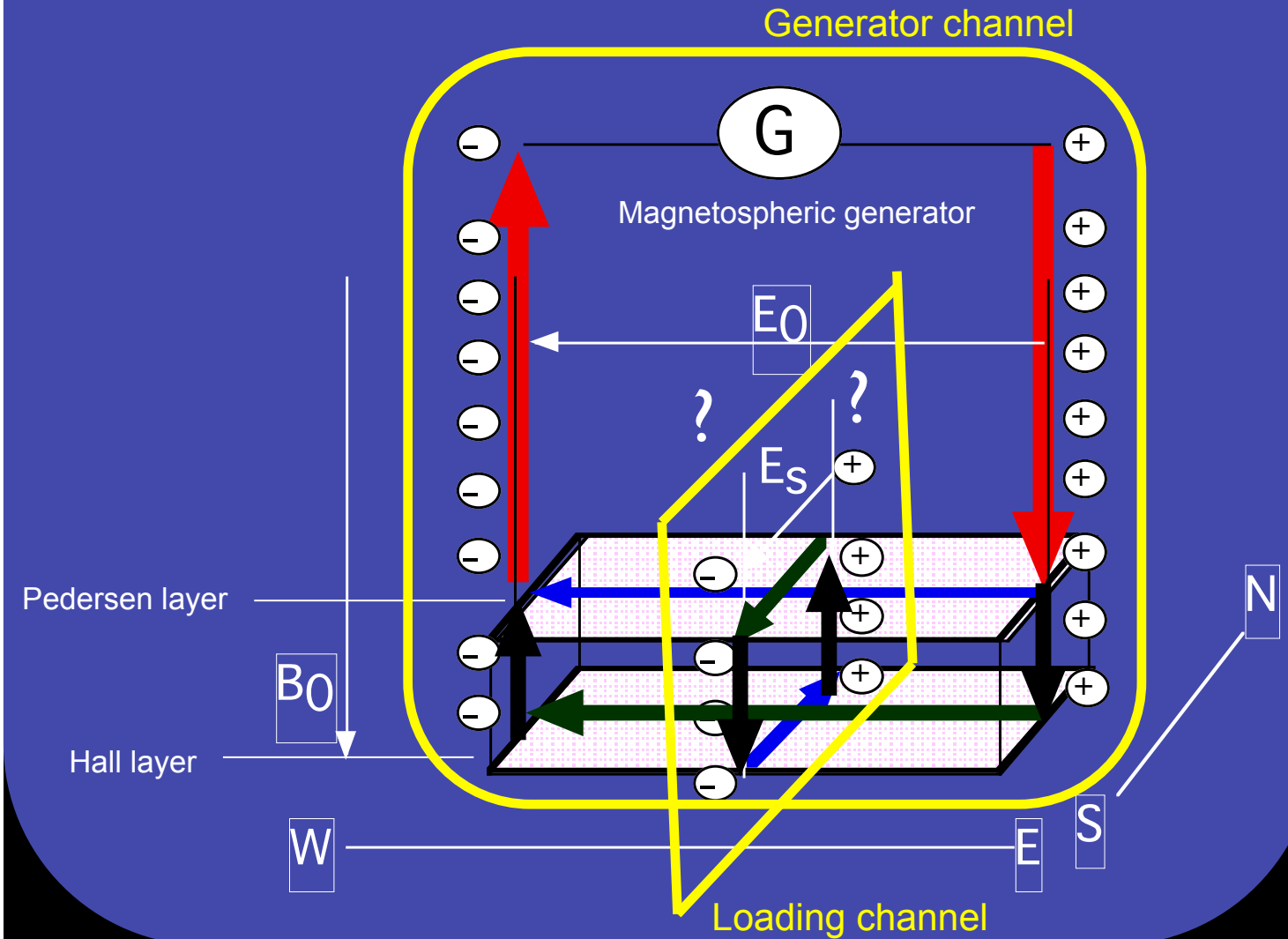
- Enhancement of Westward Current

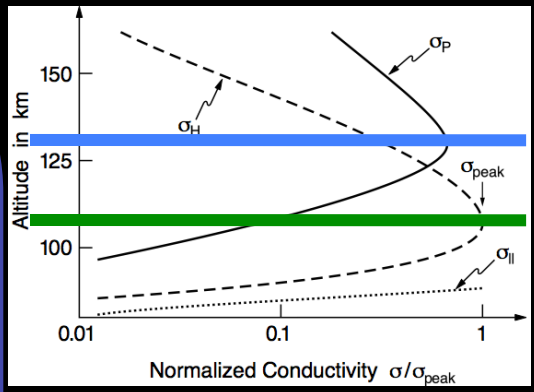
  $J_{EW} = \Sigma_P E_0 - \Sigma_H E_s = (\Sigma_P + \Sigma_H^2/\Sigma_P) E_0$

  ——Does Cowling Hall current in the EW direction couple to the FAC?

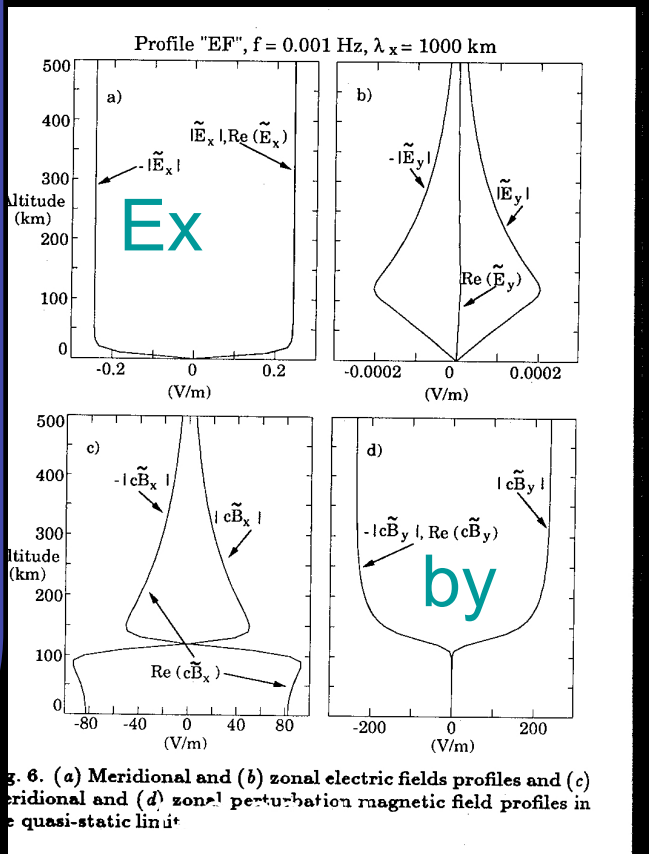
3-D Cowling Channel

- 2- current layer model
- Hall-Pedersen layer closure via the vertical Field-aligned Current (FAC)





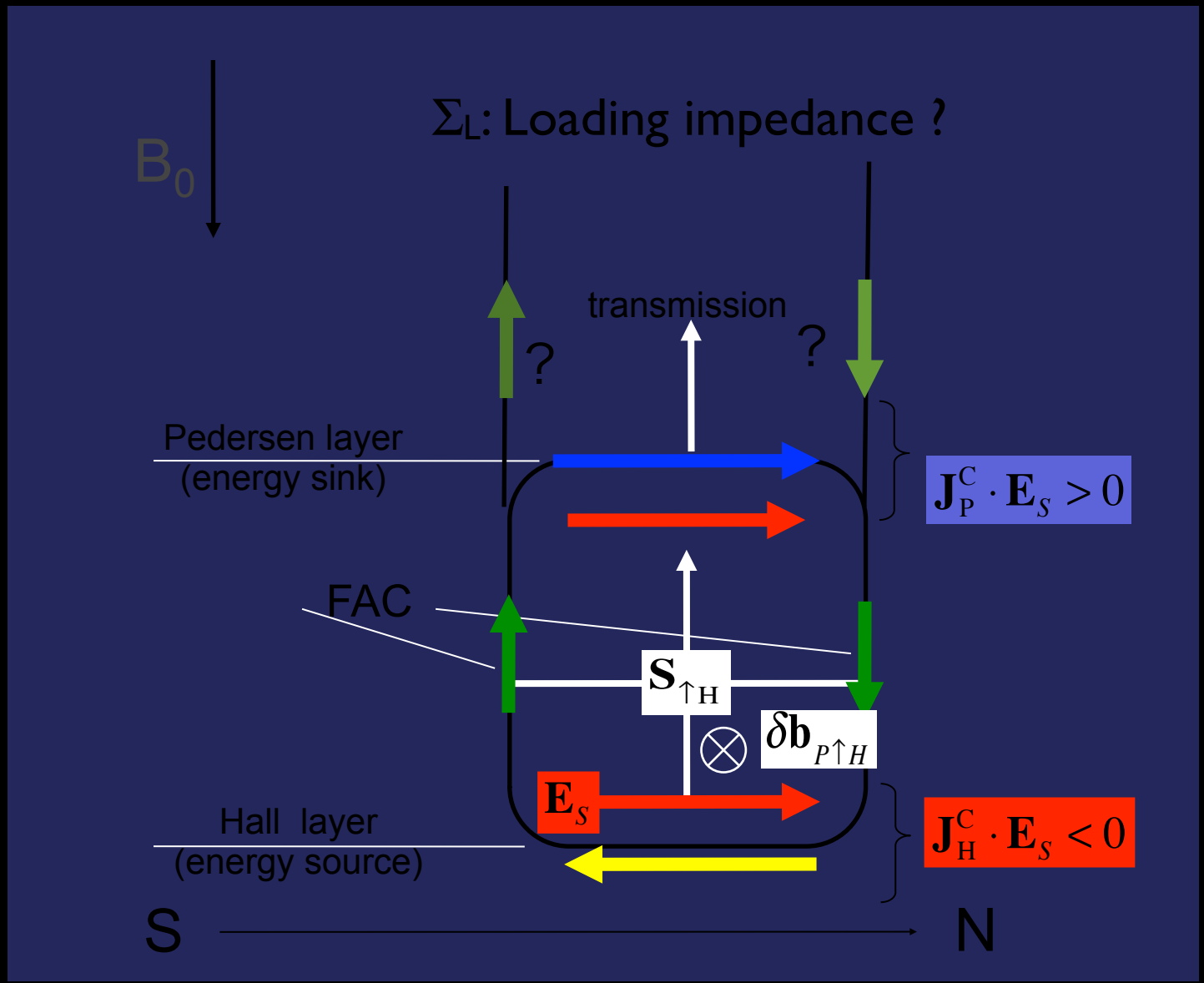
From Knudsen et al., JGR, 1992



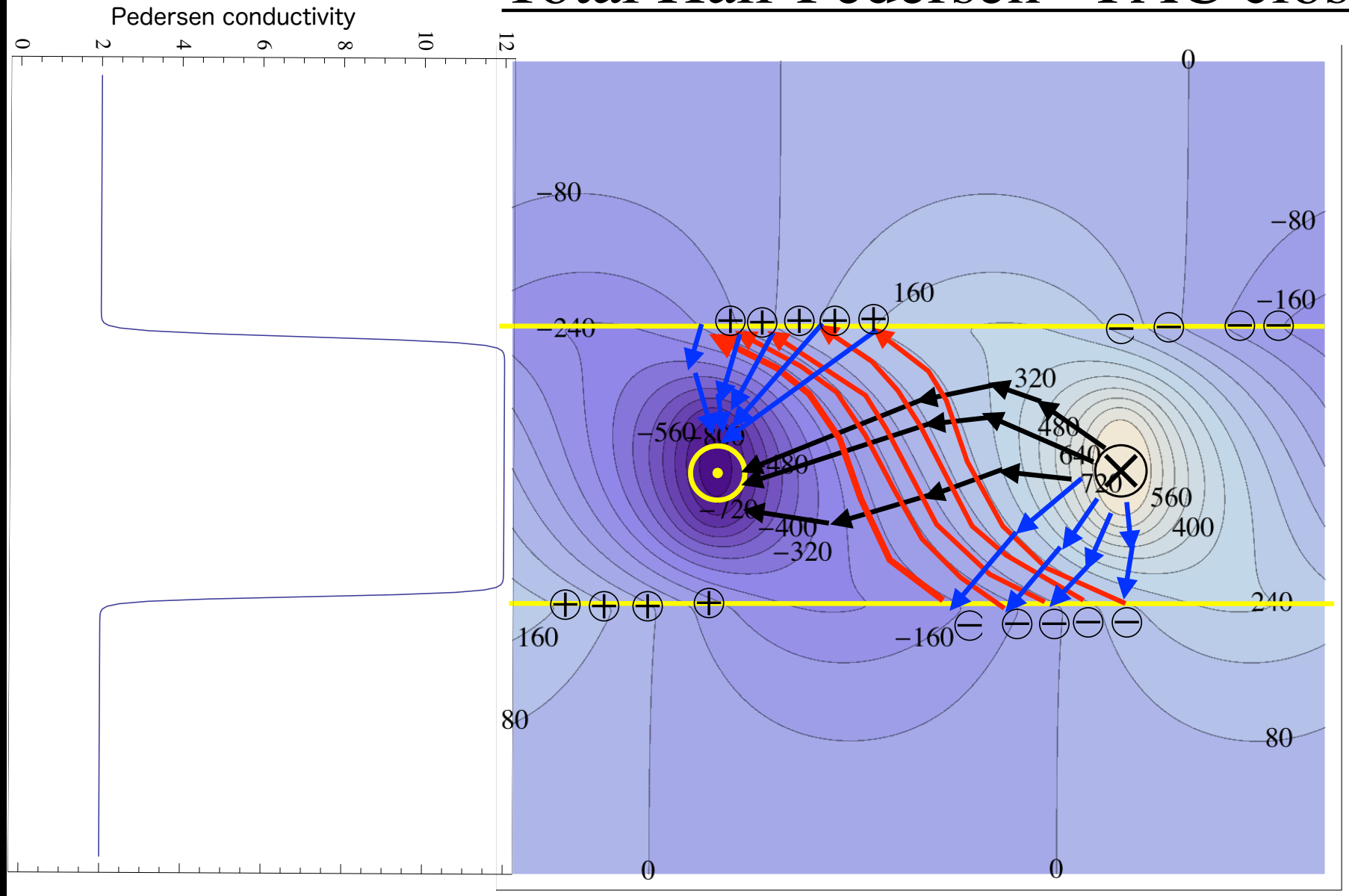
g. 6. (a) Meridional and (b) zonal electric fields profiles and (c) ridional and (d) zonal perturbation magnetic field profiles in e quasi-static limit

Important issue :

How much of the Hall current can be flow out to the magnetosphere as magnetospheric FAC?



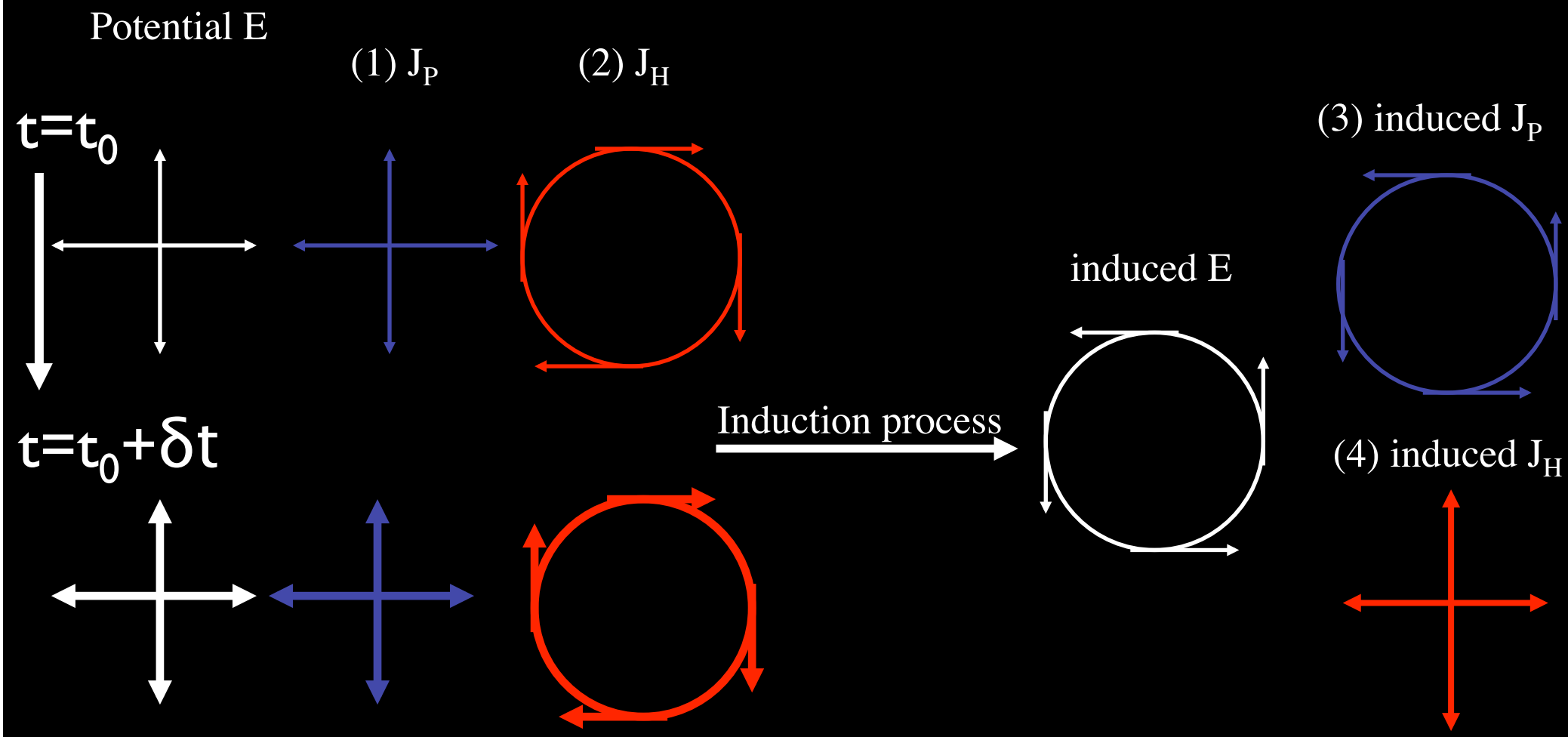
Total Hall-Pedersen - FAC closure



primary-FAC -Pedersen - Primary FAC

primary-FAC-Pedersen - total Hall - Pedersen - primary-FAC

Inductive Cowling effect (2D)



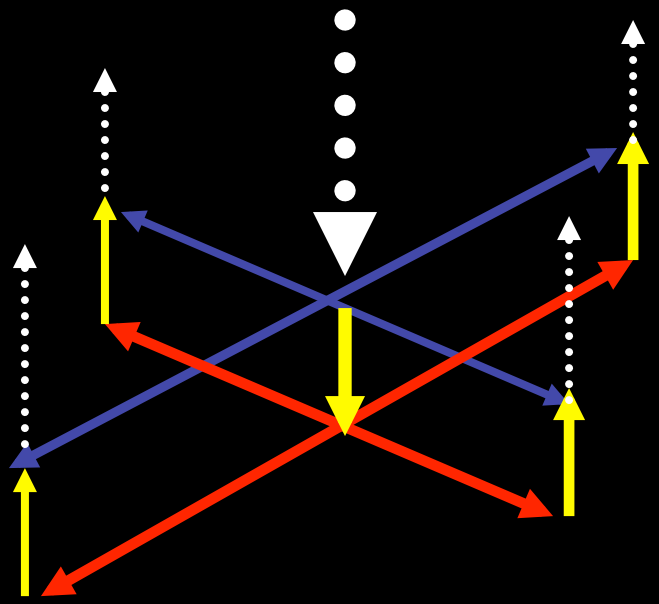
(2)-(3): Cowling anti-parallel channel (Coupled by magnetic flux)

(1)-(4): Cowling parallel channel (Coupled by induced FAC)

Inductive Cowling Channel (3D)

- Generator channel

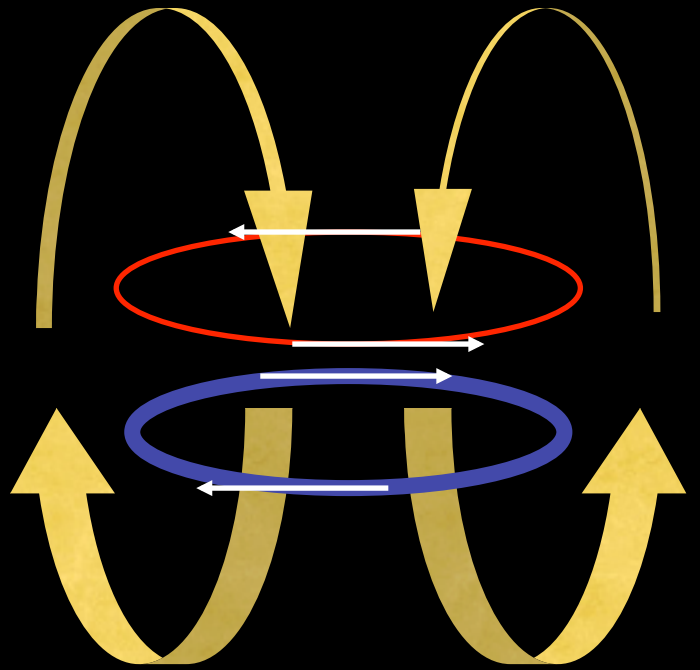
Magnetospheric FAC



induced FAC

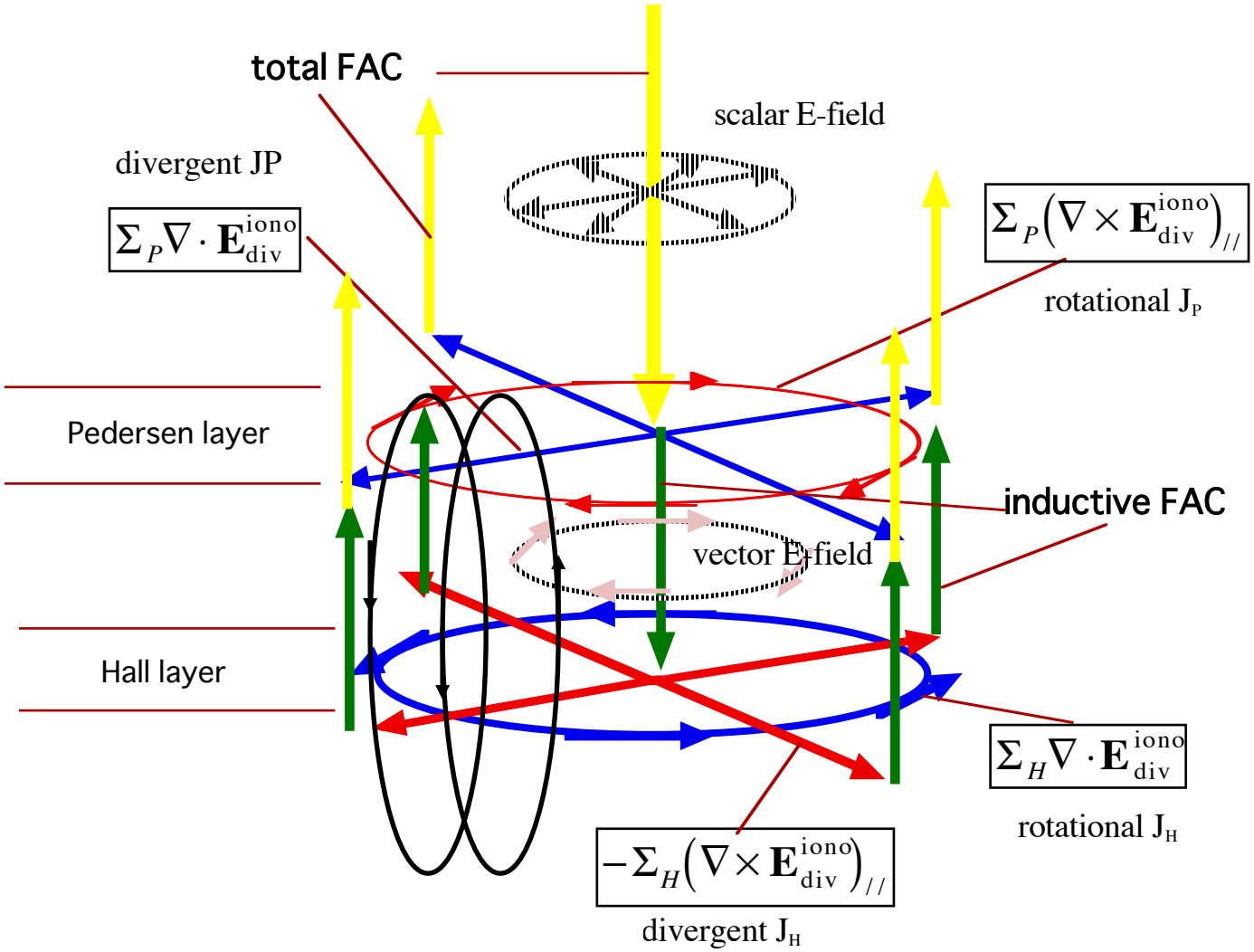
- Cowling channel

Magnetosonic surface wave

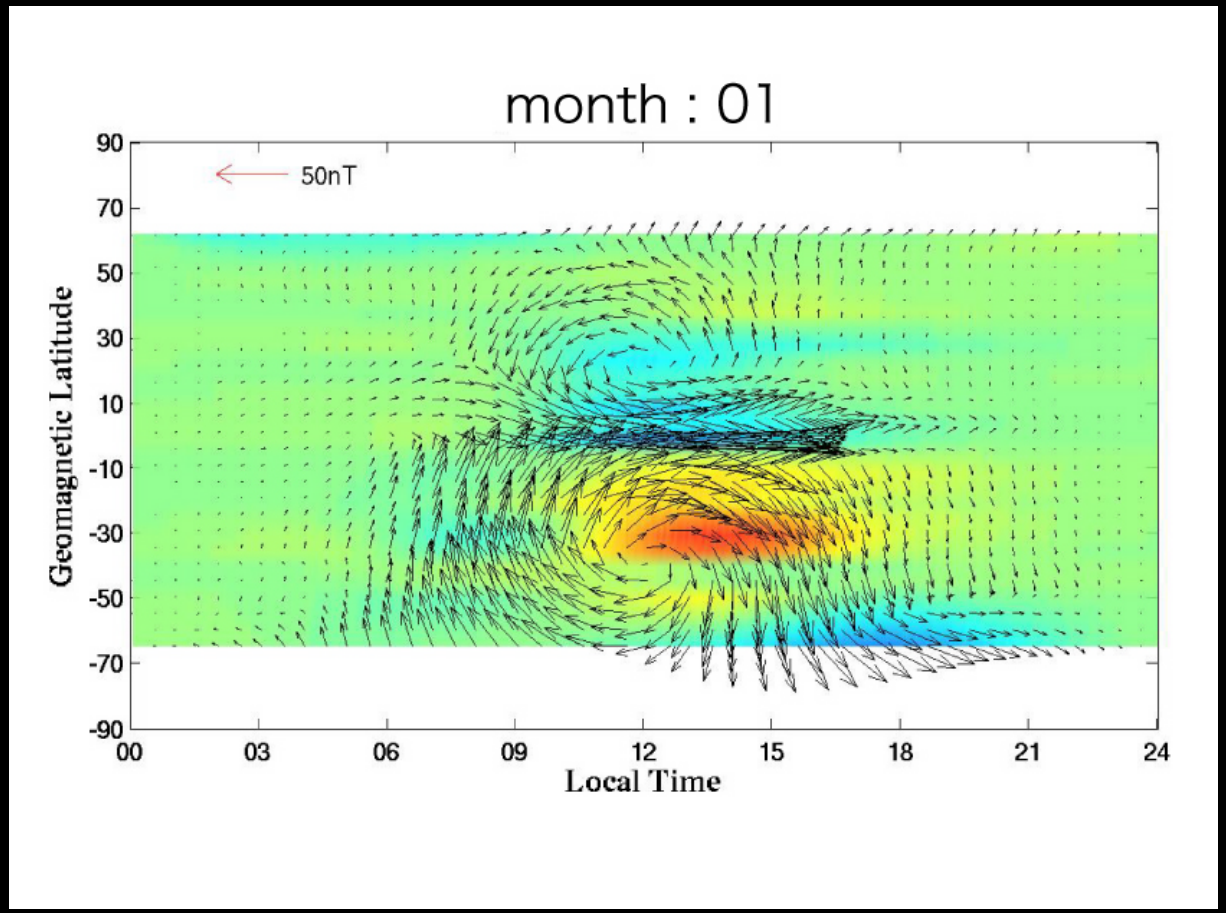


Atmospheric Poloidal wave

- Curl-free Hall current closing via the induced FAC absorbing magnetospheric energy
- of which free energy transmitted to the Joule dissipation in the Cowling channel and magnetic energy of Div-free Hall current (magnetsopheric surface wave and atmospheric poloidal wave)


total FAC
scalar E-field
divergent JP
$\Sigma_P \nabla \cdot \mathbf{E}^{\text{iono}}_{\text{div}}$
$\Sigma_P \left(\nabla \times \mathbf{E}^{\text{iono}}_{\text{div}}\right)_{//}$
rotational J_P
Pedersen layer
inductive FAC
vector E-field
Hall layer
$\Sigma_H \nabla \cdot \mathbf{E}^{\text{iono}}_{\text{div}}$
rotational J_H
$-\Sigma_H \left(\nabla \times \mathbf{E}^{\text{iono}}_{\text{div}}\right)_{//}$
divergent J_H
scalar potential driven
vector potential driven

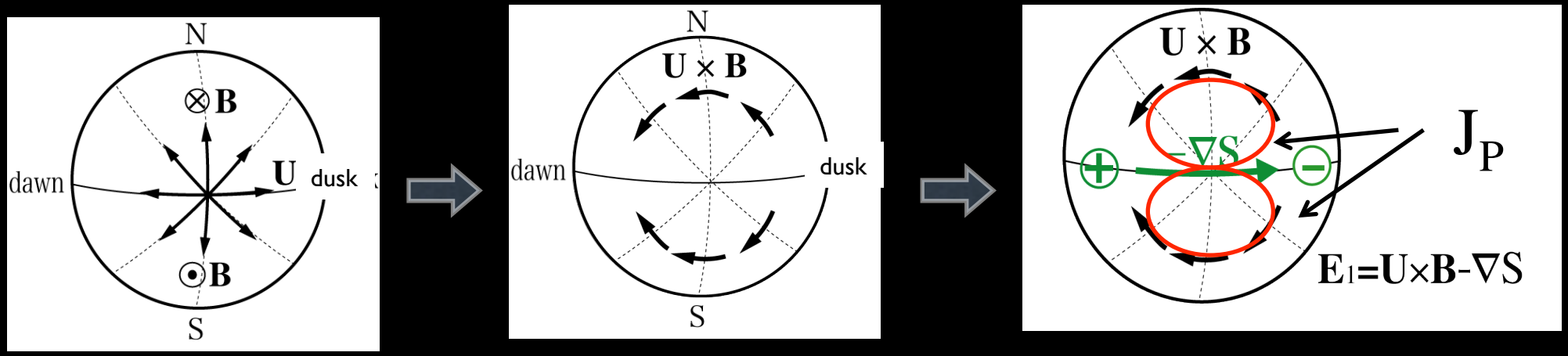
Cowling-channel in Sq-current system



Main driver of Sq current system

Thermospheric wind dynamo electric field
+
Polarization electric field

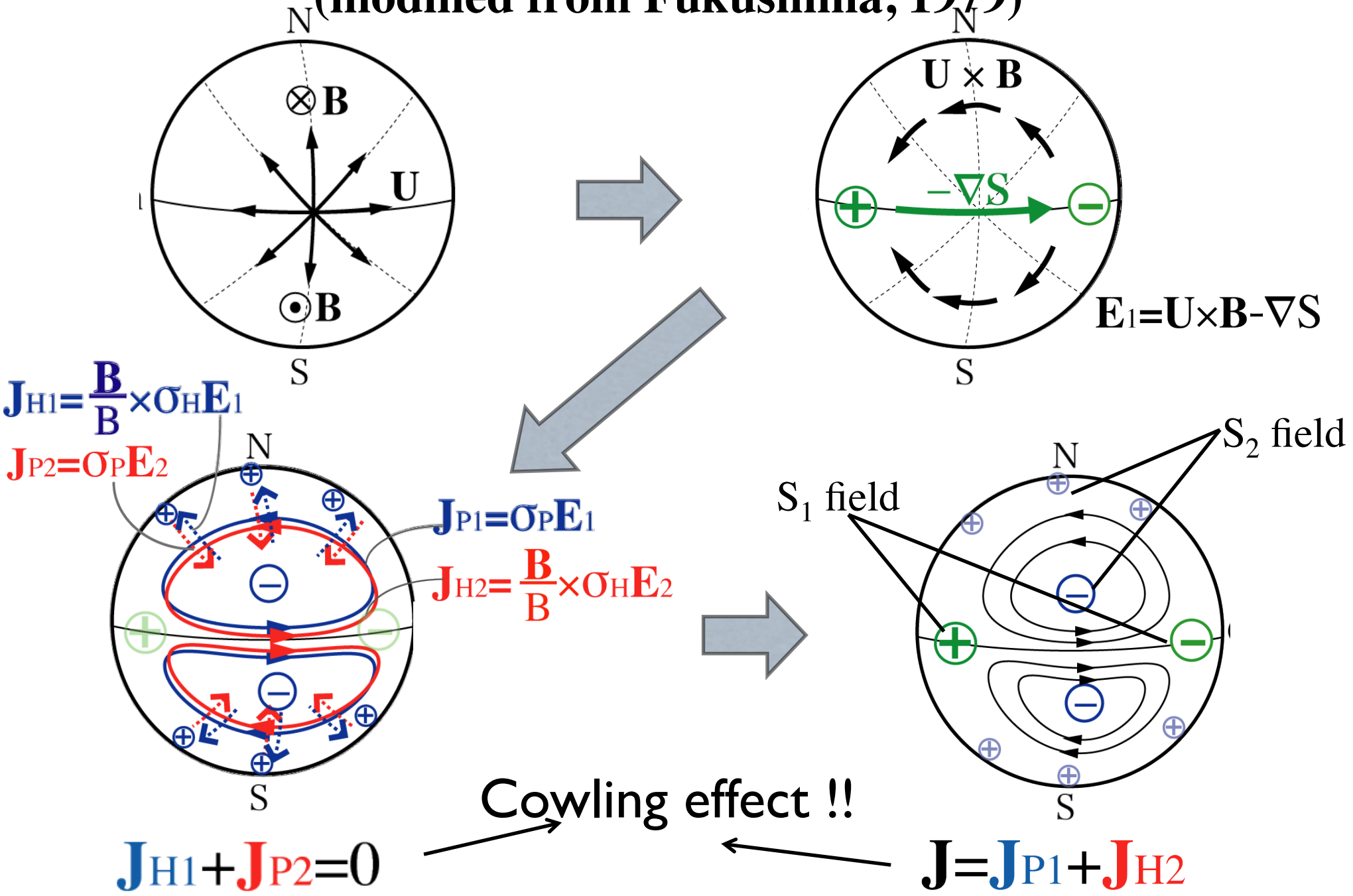
Polarization e-field is generated for elimination of "rotational-free current" produced by the dynamo e-field.



elimination process of rotation-free Pedersen current

Where is the Hall current??

Logic for Cowling effect in the Sq Current system (modified from Fukushima, 1979)



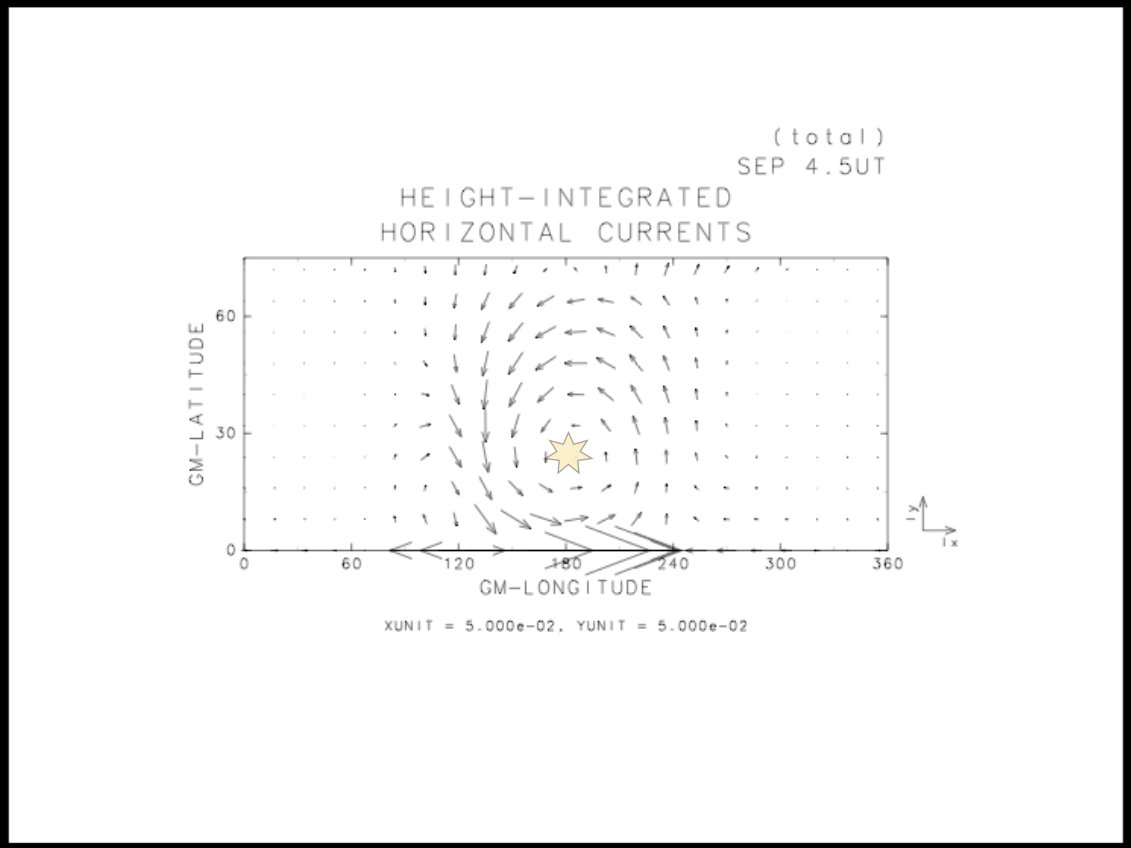
(polarization process due to the primary Hall current divergence)

(enhancement process by the secondary Hall current)

Simulation result:)
（shown by height-integration current ）

Wind model：GCM, Sept, 4.5UT, monthly-ave.
Conductivity model：,IRI95, CIRA86,
Back ground magnetic field model B0：dipole
Equi-potential assumption along B0
Current: conducting current+ closure FAC in the ionosphere

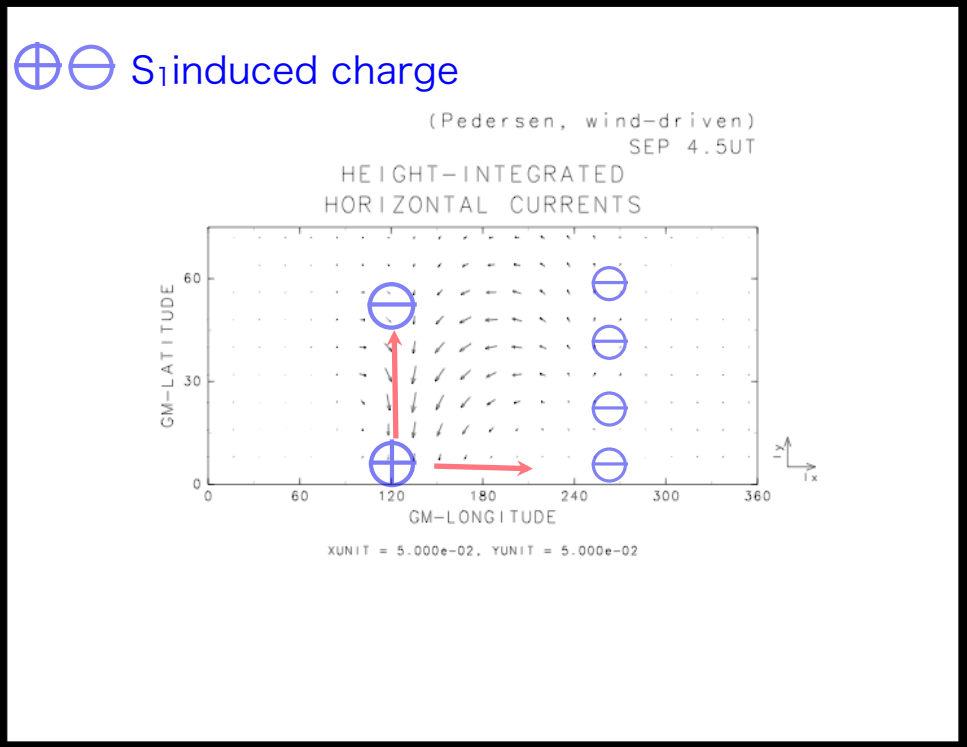
Sq-total current

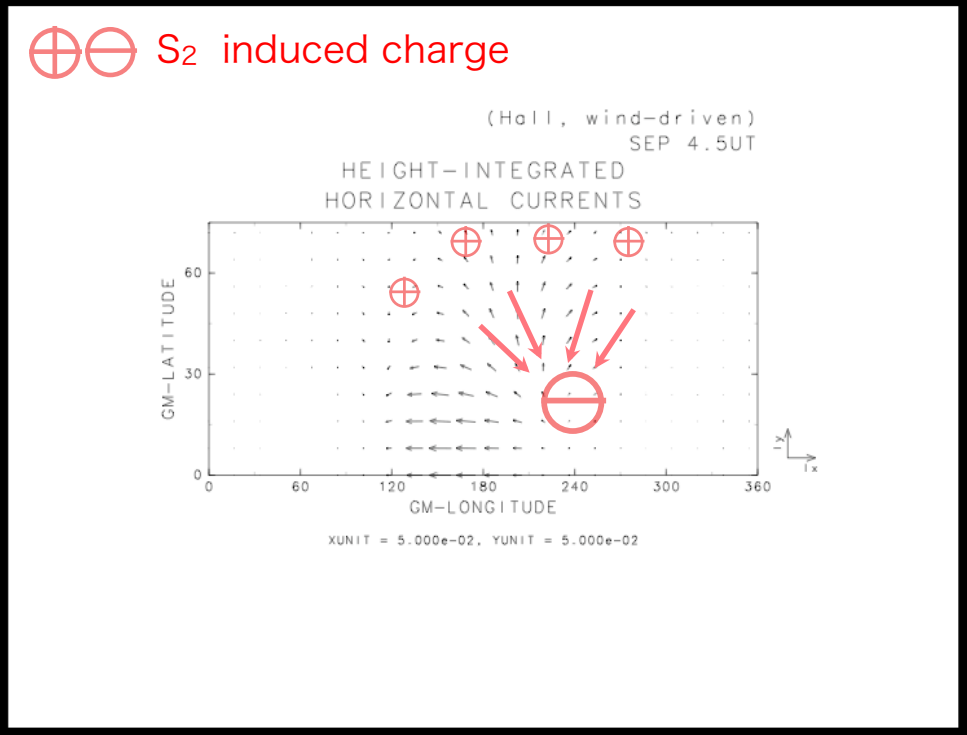


Primary current driven by wind-dynamo

Wind-driven Pedersen current

Wind-driven Hall current



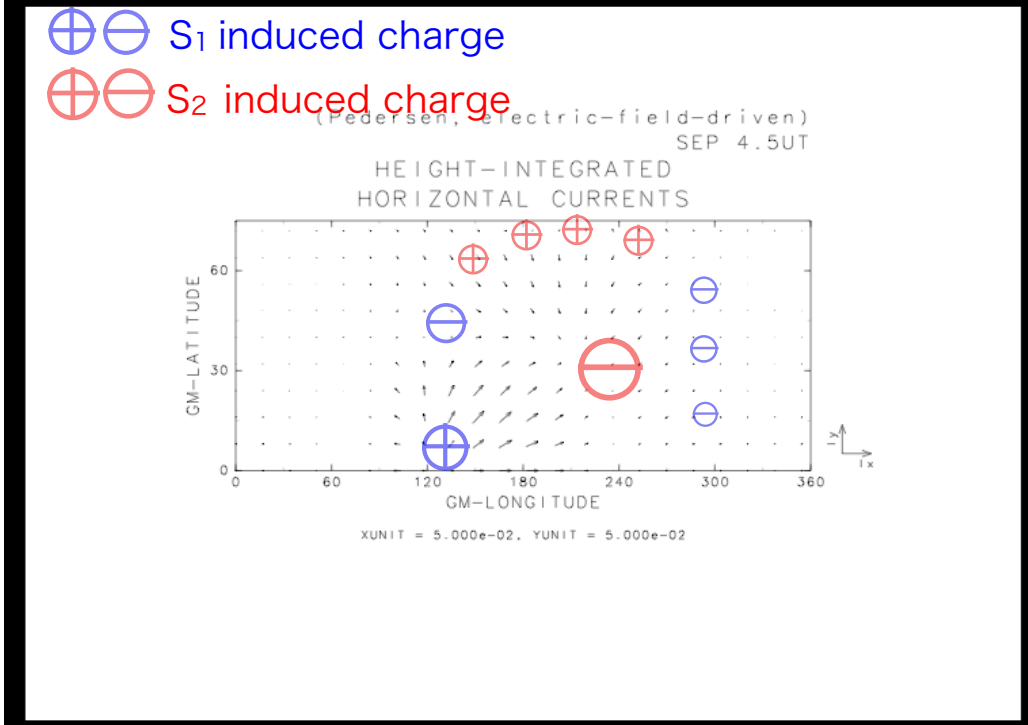


S1 field generation

S2 field generation

Polarization current excited by total polarization (S_1+ S_2) fields

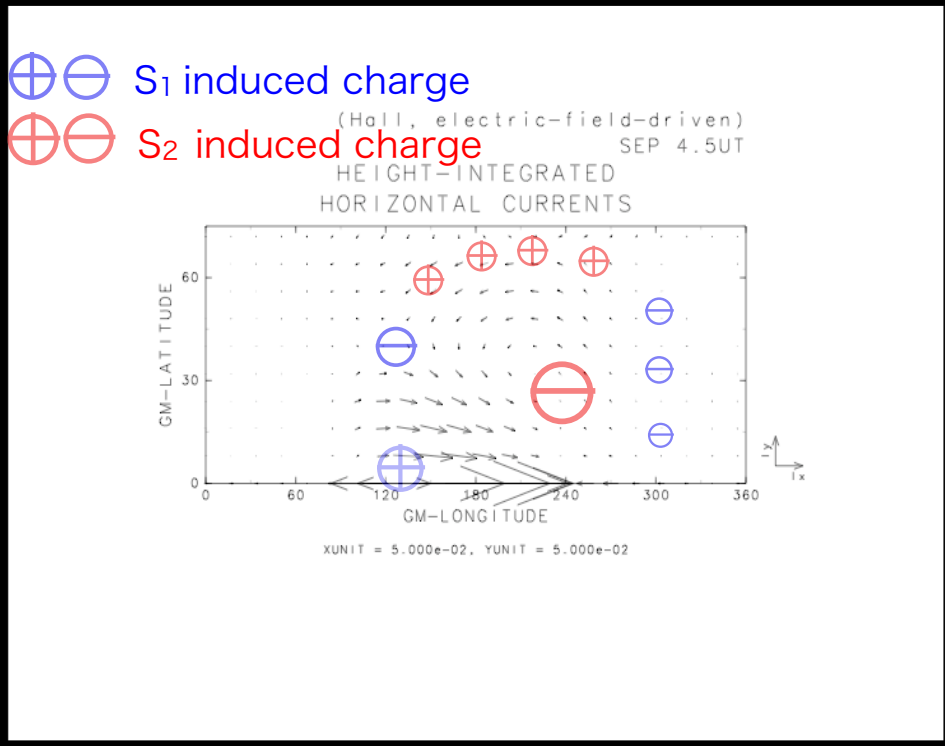
polarizationl-field driven Pedersen current



Role of s1-field driven Pedersen current → cancellation of wind-driven Pedersen current divergence

Role of s2-field driven Pedersen current→ cancellation of wind-driven Hall current divergence

polarization-field driven Hall current

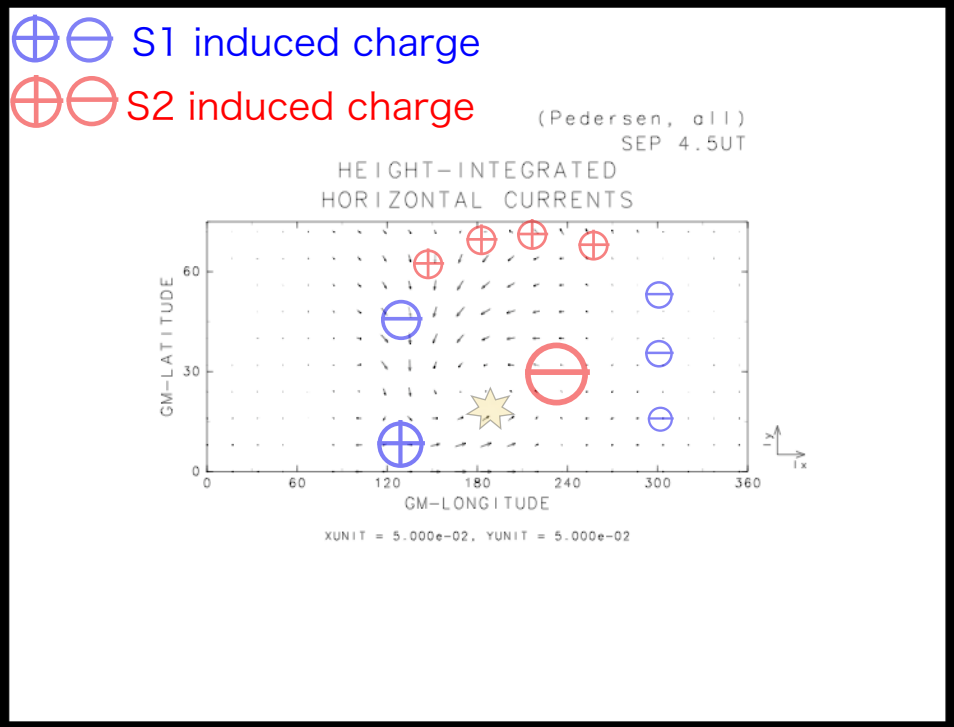


Role of s1-field driven Hall current → shielding of wind-driven Hall current divergence

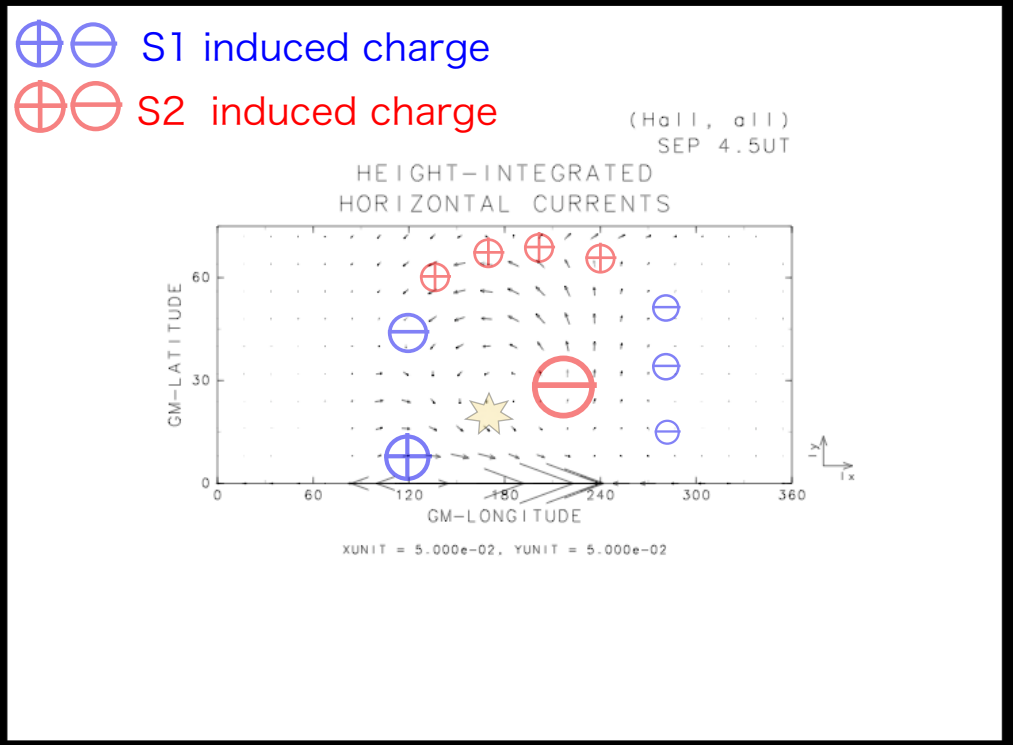
Role of s2-field driven Hall current → enhancement of divergence-free Pedersen current

Dynamo ＋Polarization (total) current

Total Pedersen Current



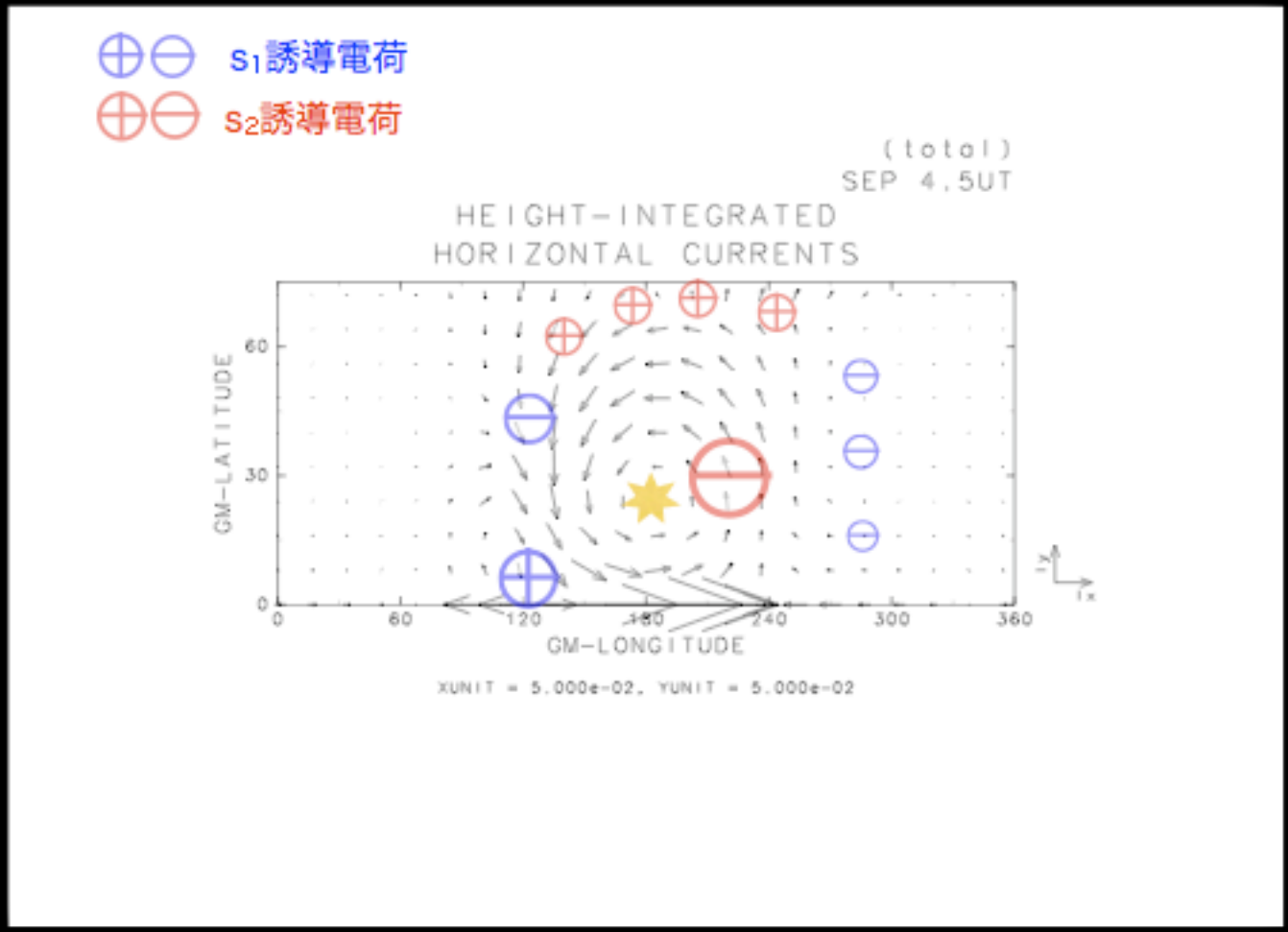
Total Hall current



1. Spiral structure of total Pedersen and Hall current → divergent part of Pedersen and Hall current are need to be mutually cancelled out

2. Foci of total Pedersen and Hall current are coincide with foci of Sq vortex current ✸
   →foci of Sq current corresponds to the null point of total electric fields

Sq total current



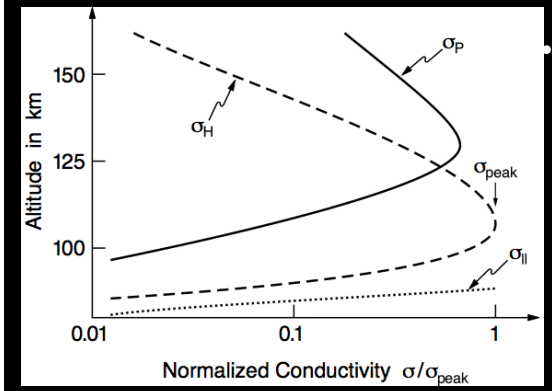
Divergent part of Pedersen and Hall current which makes total Pedersen and Hall current as spiral are need to be mutually cancelled out when they are sum upped!!

Superposition of divergence-free Pedersen and Hall current forms Sq vortex current

↓

Sq current itself is the Cowling current !!

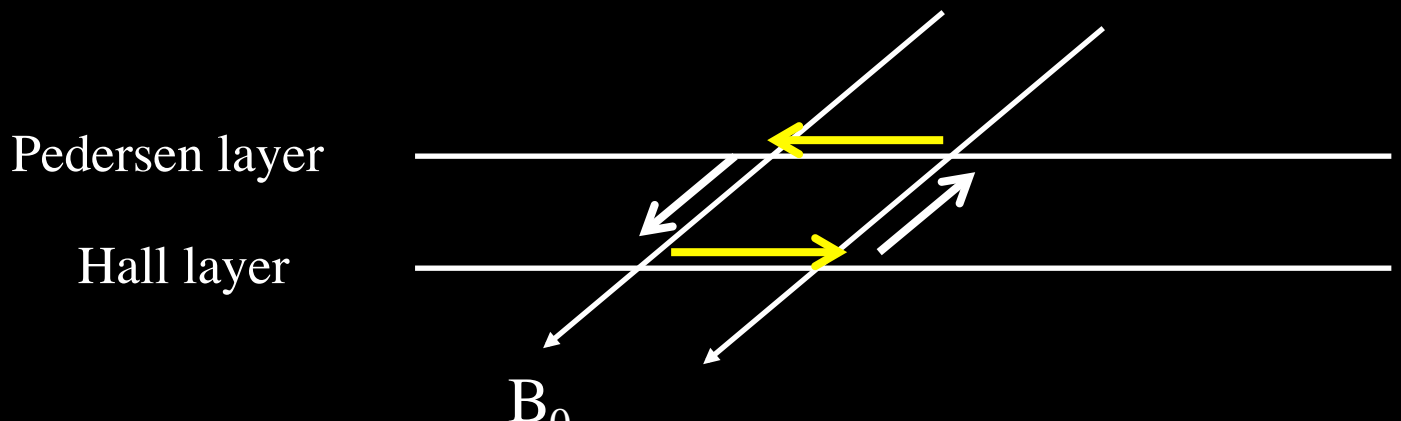
• 3D-Cowling current model



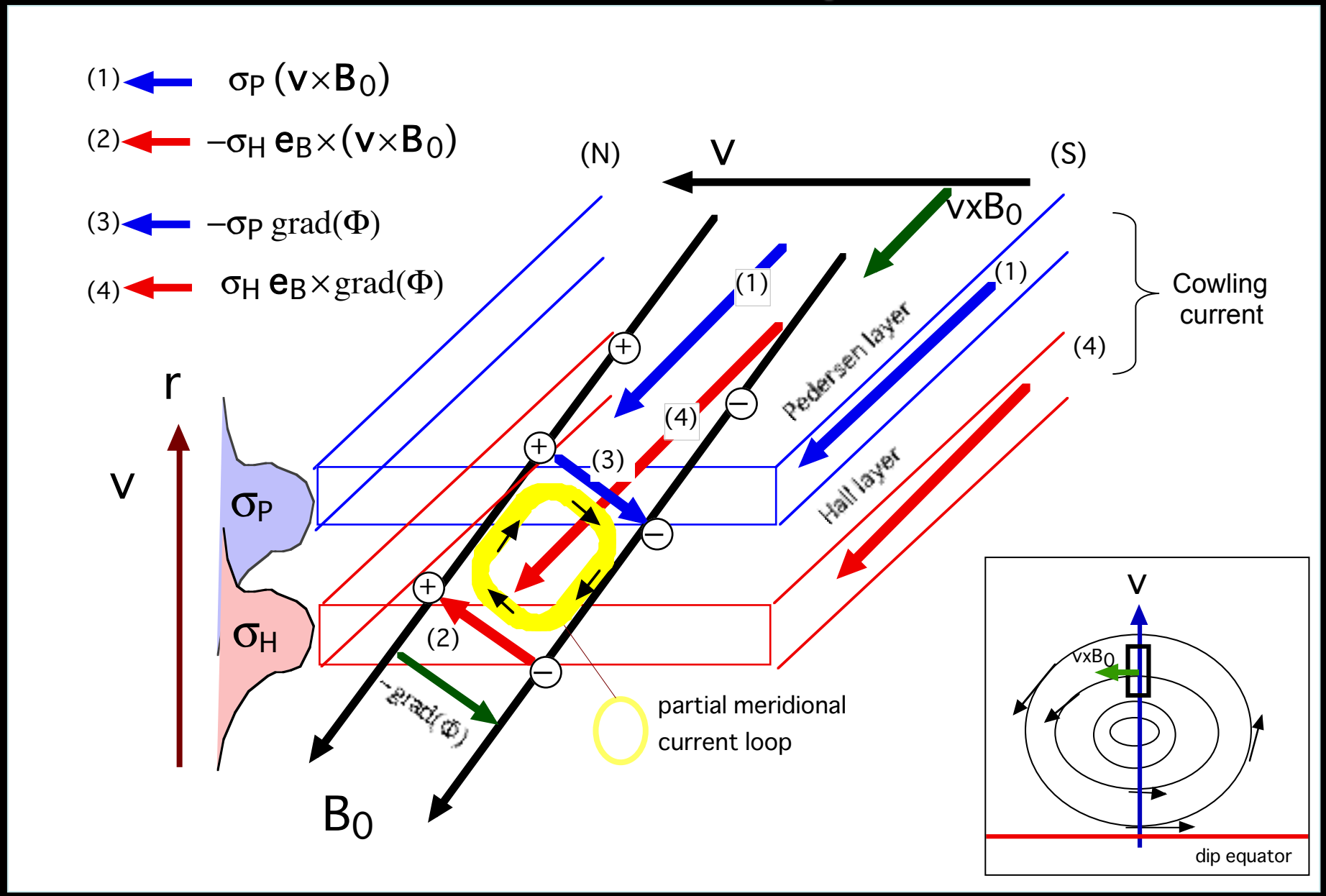
From Knudsen et al., JGR, 1992

- dominant altitude of Hall and Pedersen conductivities are different
  - The 2D-cancellation between Pedersen and Hall current means a formation of 3D-Pedersen and Hall loop-circuit

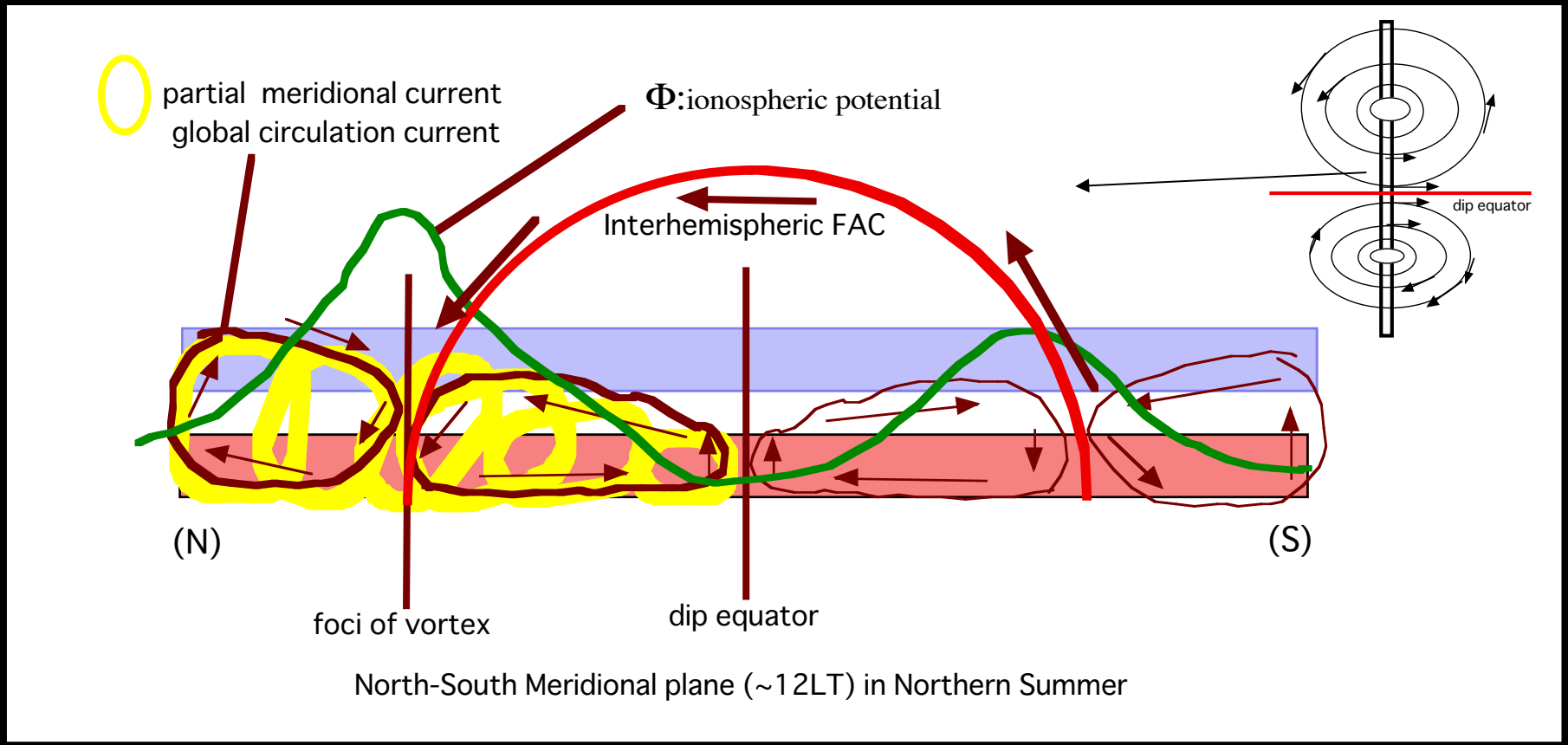
Introduction of Pedersen-Hall two layers model connected by the geomagnetic field line



Formation process of Hall-Pedersen current loop

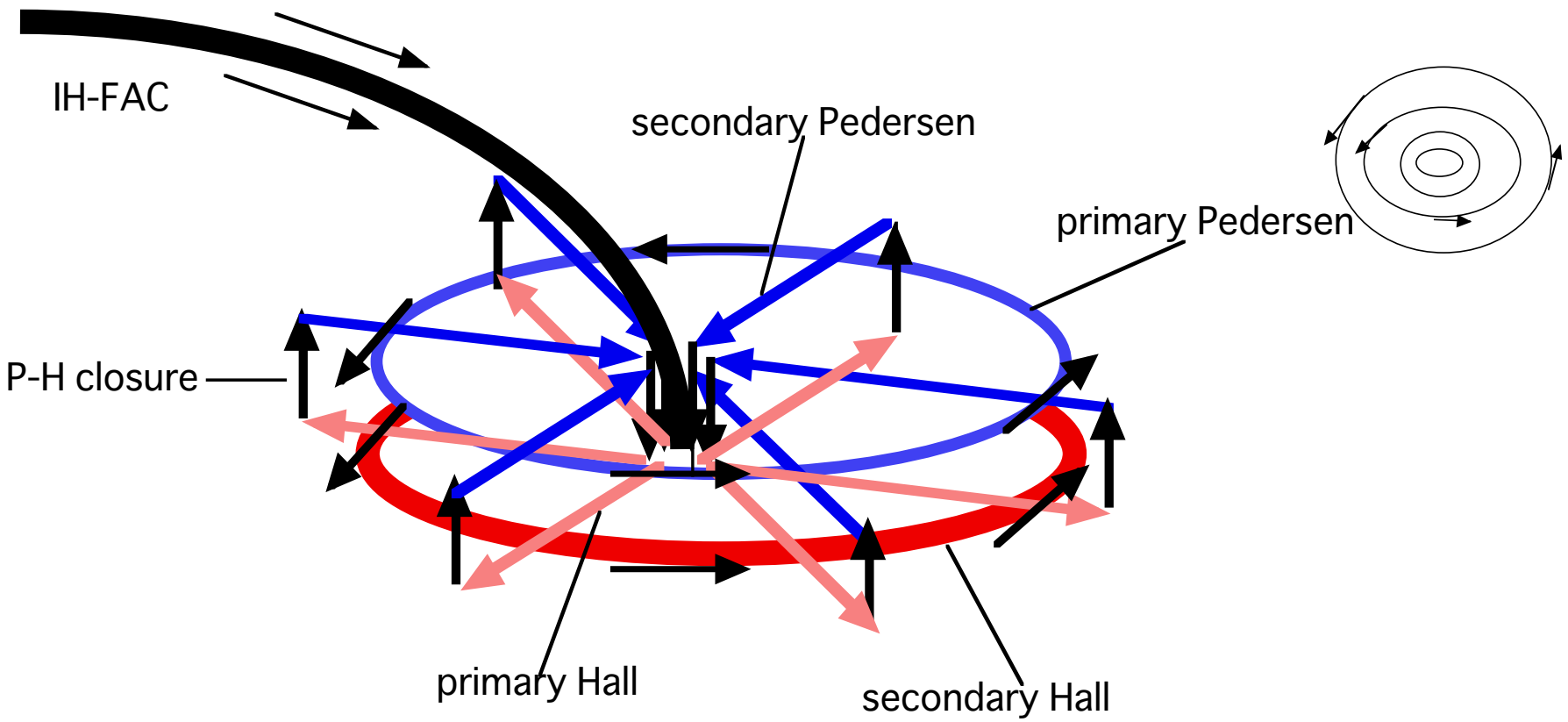


Global meridional current and Inter-hemispheric FAC



North-South Meridional plane (~12LT) in Northern Summer

Inter-hemispheric FAC and 3D Sq-circuit



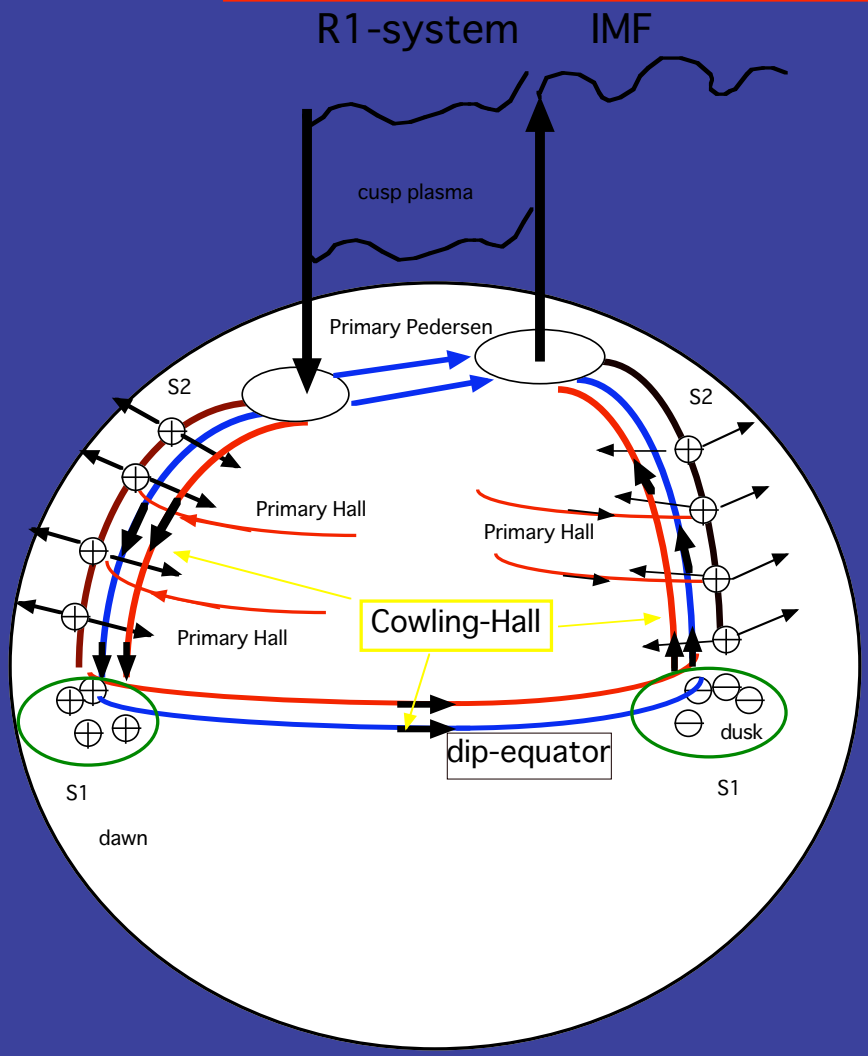
· Diverging Hall spiral current + Converging Pedersen spiral current
-> rotational Hall current +rotational Pedersen current
= Cowling Sq-current system

· Unbalanced Hall-Pedersen current in the 3D-loop produces the Inter-hemispheric FAC

Summary

- Primary current of Sq-wind dynamo current has strong divergence (both of Pedersen and Hall current)
- Especially, divergence of Hall current becomes a source of Cowling effect
- Our model predicts that both total Pedersen and Hall currents having spiral structure, which are composed of rotational and divergent current
- To satisfy a current closure condition, divergence part of Pedersen and Hall current are mutually cancel out in the 2D picture, but they forms Hall-Pedersen current loop in the 3D picture.
- 3D Hall-Pedersen current loops are expected to concentrate into to near the foci of Sq vortex, and Pedersen vortex and Hall vortex current are flows in the same direction as 3D parallel current system and forms so-called Sq current system
- Unbalanced Hall-Pedersen currents in the 3D-loop excites the inter-hemispheric FAC

Cowling channel formation between solar wind-polar cap - dip equatorial region



1. Discontinuity of primary twin vortex-Hall current accompanying R1-system

2. Charge separation along the sunrise and sunset line

3. Polar-Equatorial connected Secondary Hall current excited by this polarization field

4. Charge accumulation at dawn and dusk region at the dip-equator

the same context of EEJ

Control of EEJ by the solar wind variation

Formation of Cowling- channel along the sun rise/set line

Coupling to the solar-wind variatio

shadow sunlit

Polar-region

Φ_0

$\Phi_0 + S_2$

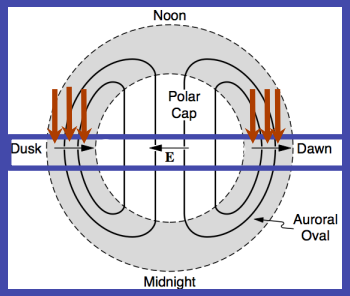
$-\nabla S_2$

Dip-equator

$\nabla \cdot (\Sigma_P \nabla S_2) \simeq -(\hat{n} \times \nabla \Sigma_H') \cdot \nabla \Phi_0$

Divergence of R1-associated Hall current

primary Hall polarization



shadow sunlit

sunlit shadov

EEJ

$Q \simeq (\hat{n} \times \nabla \Sigma_H') \cdot \nabla S_2$

Divergence of Secondary-Hall current

secondary Hall polarization

Penetration of ionospheric convection into the equatorial region along the sun-rise /set line by formation of Cowling channel