Electrodynamic Coupling and Dissipation of Thermospheric Winds

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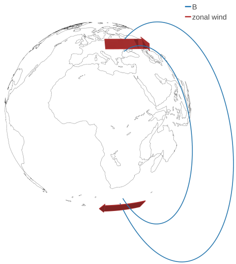
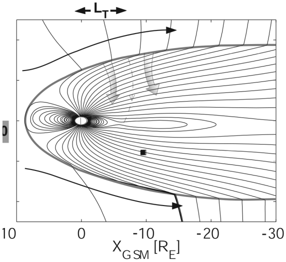


Introduction

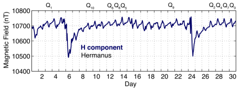


Rosenqvist et al., 2006

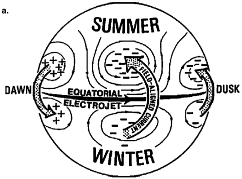
- we know/understand Joule/frictional heating at high latitudes:

1. the plasma in space, above the ionosphere, needs to move/convect,
2. driven by magnetosheath flow, magnetic reconnection, pressure gradients, . . .
3. the plasma avoids $E_{||}$ (electric potential non-const along $\vec{B}$);
4. therefore in the ionosphere the plasma is forced to move through the neutral gas,
5. this causes $\rightarrow$ frictional heating.

How about mid-latitudes?



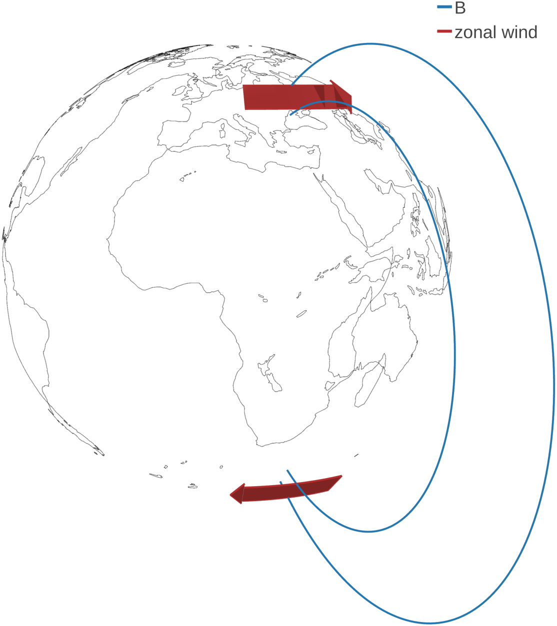
Yamazaki and Maute, 2017



Fukushima, 1979

- *Sq* variations are observed (Graham, Cassini, Gauss, . . .)
- Balfour Stewart: “. . . by air currents in the upper atmosphere . . . ”,
- Sydney Chapman (1924): atmospheric dynamo theory, *Sq* is caused by winds;
- Is this really correct?
- My answer: No!

For better understanding: the simplest possible scenario?



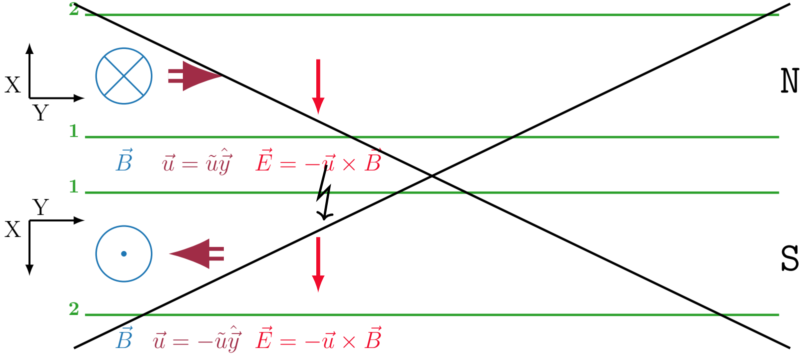


Figure: Collapsed 2-d view of the scenario as seen from above the ionospheric dynamo region. The latitude circles labeled "1" and "2" are magnetically connected, respectively. We assume that the electric field $\vec{E}$ is only the motional one, from the zonal wind. The lightning bolt symbolizes an electrical short circuit along $\vec{B}$ by electrons that would occur for this $\vec{E}$. The large black cross indicates that this scenario is rejected as a possible electric field configuration.

- the electric field

$$\vec{E} = \vec{E}^* + \vec{u}_n \times \vec{B}$$

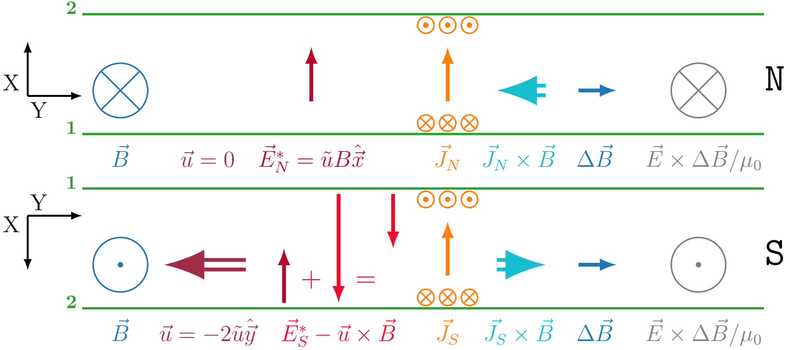
$\vec{E}^*$	electrostatic field $\nabla \cdot \vec{E}^* = \rho(\vec{x})/\epsilon_0$ frame independent (for $\ll c$)
$\vec{B}$	magnetic field, frame independent
$\vec{u}_n$	neutral wind
$\vec{u}_n \times \vec{B}$	motional electric field

- only $\vec{E}^*$ drives currents according to Ohm's law, not $\vec{u}_n \times \vec{B}$;
- if there is a wind difference $\Delta u_n \neq 0$ between N and S,
- then the plasma creates $\vec{E}^*$ such that $E_{\parallel} \neq 0$ is avoided,
- *so forcing itself through the neutral gas.*

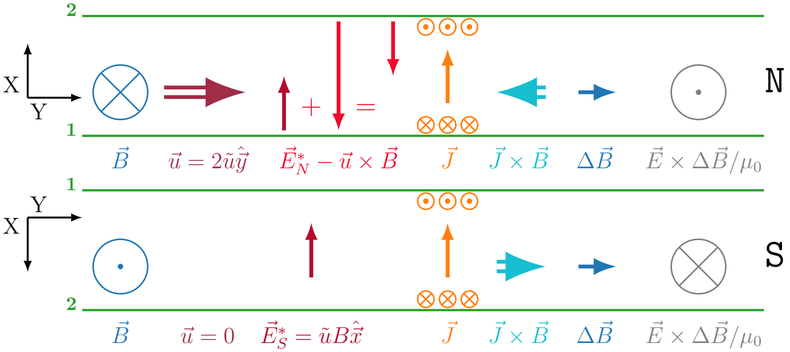
Find the consistent $\vec{E}^*$:

Requirements (for steady state thin ionosphere):

- $E_\parallel = 0$ (equipotential magnetic field-lines)
- $\nabla \vec{j} = 0$ (current continuity)



Change of reference frame $N \to S$

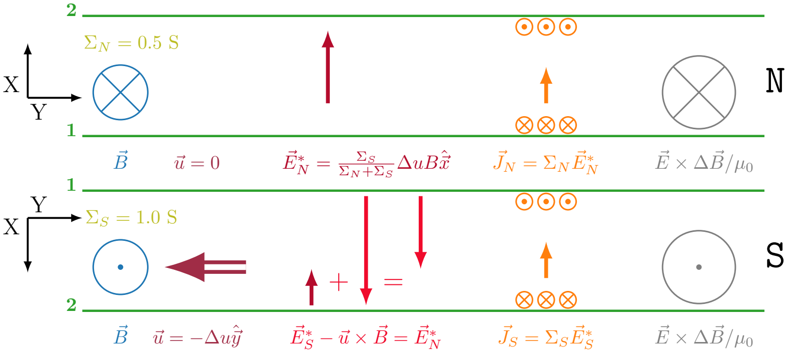


Pse see also my manuscript under public review/discussion at `https://www.ann-geophys-discuss.net/angeo-2019-71/#discussion` for further details and explanations.

Insights so far:

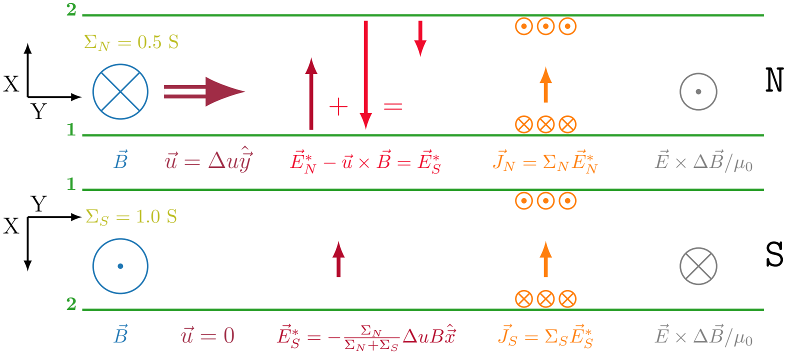
1. only wind differences $\Delta u_n(z)$, z a coordinate along $\vec{B}$, have an effect;
2. the absolute wind $\vec{u}_n$ in Earth-fixed (co-rotating) or Sun-aligned frames is irrelevant;
3. Sq disappears when the $\vec{u}_n$ pattern is symmetric with respect to the equator in magnetic coordinates
4. (for a centered dipole field);
5. variations $\Delta u_n(z)$ cause an electrostatic E^*,to avoid $E_{\|} \neq 0$;
6. this electrostatic $\vec{E}^*$ drives Pedersen currents, FACs, and Hall currents.

Different conductances in N and S



2-d view in the reference frame of the northern neutral gas. The current $\vec{J}$ has to be equal in both hemispheres for $\Sigma_N = 0.5$ and $\Sigma_S = 1.0$ which determines E^*_N and E^*_S. The sizes of the symbols for Poynting flux are according to the flux magnitudes.

Change of reference frame $N \to S$ (again)



The sizes of the symbols for Poynting flux in this and the previous slide are according to the flux magnitudes. For $\Sigma_S > \Sigma_N$ there is more Joule heating $J \cdot E^*_N$ and Poynting flux $S \to N$ than vice versa.

Equations

$$\Delta w = u_{y,N} B_N - u_{y,S} B_S \tag{1}$$

$$E_N^* = \frac{\Sigma_S}{\Sigma_N + \Sigma_S} \Delta w = -\frac{\Sigma_S}{\Sigma_N} E_S^* \tag{2}$$

$$E_S^* = -\frac{\Sigma_N}{\Sigma_N + \Sigma_S} \Delta w = -\frac{\Sigma_N}{\Sigma_S} E_N^* \tag{3}$$

$$J = \frac{\Sigma_N \Sigma_S}{\Sigma_N + \Sigma_S} \Delta w \tag{4}$$

$$Q_N = \Sigma_N \left(\frac{\Sigma_S}{\Sigma_N + \Sigma_S} \Delta w \right)^2 = \frac{\Sigma_S}{\Sigma_N} Q_S \tag{5}$$

Q_N and Q_S Joule heating rates in Wm^{-2}

Further Insights:

1. there is Joule heating $\vec{j} \cdot \vec{E}^* > 0$ in S,
2. driven by a dynamo, $\vec{j} \cdot \vec{E} < 0$ in N;
3. changing the reference system $N \to S$ flips the roles
4. and the direction of the Poynting vector $\vec{E} \times \vec{B}$;
5. entangled dynamos (not only coupled);
6. action at a distance:
7. e. g., the Sq at Uppsala reacts to changes of $\vec{u}_n$ at the conjugate area (south of Africa above the ocean),
8. as long as there is no symmetric local change.

How much Joule Heating?

1. the total Hall current over one day $J_{H,tot}$ is about 100 – 200 kA (Takeda, 2015).
2. Estimation as

$$Q_{J,hem} \approx \frac{J_{P,tot}^2}{\langle \Sigma_P \rangle} \approx \left(\frac{\langle \Sigma_P \rangle}{\langle \Sigma_H \rangle} \right)^2 \frac{J_{H,tot}^2}{\langle \Sigma_P \rangle},$$

3. for $\langle \Sigma_P \rangle \approx 9$ S and $\langle \Sigma_H \rangle / \langle \Sigma_P \rangle \approx 1.4$;
4. gives $Q_{J,hem} \approx 0.5 - 2$ GW per hemisphere.
5. Compare with maximum ~ 1 TW in the Halloween storm (Rosenqvist, 2006);
6. Joule heating

high latitudes	very variable depending on activity
mid latitudes	quasi-permanently, small variations.

7. is the long term average of high- and mid-latitude JH comparable?

Conclusions

1. the dynamo of the Earth's atmosphere works differently as originally suggested;
2. not a wind per se (gas motion in the Earth-fixed frame) in the conduction layers of the ionosphere makes a dynamo,
3. rather a non-constant $\vec{u}_n(z) \times \vec{B}(z)$
4. and the condition $E_{\|} = 0$ determine a frame-independent field $\vec{E}^* = -\nabla\Phi$,
5. $\vec{E}^*$ drives currents and Joule heating,
6. Lorentz $\vec{j} \times \vec{B}$ forces the neutral wind towards a situation with constant $\vec{u}_n \times \vec{B}$ on each field-line;
7. especially Sq arises from wind differences at conjugate points;
8. a similar model should apply to wind variations within a dynamo layer.