Reply to Octav Marghitu's comment on "Entangled Dynamos and Joule Heating in the Earth's Ionosphere" by

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This reply is slightly refined compared to the my reply in the public discussion.

1 Replies to comments by Referee 1

Cited referee comments are in red, replies in magenta.

I thank the referee, Octav Marghitum, for the interest in the manuscript and the time spent reading it, and for the helpful comments.

1. Using two reference systems has obvious merits, but it is at the same time challenging, in particular by introducing two instances of the Poynting flux. This is detailed in the Discussion section, though I think that the clarity of the message may benefit from sub-sectioning and some re-arrangement:

1a. More specifically, the three paras from p.12, L17 ("We claim that. . .") up to p.13, L21 (". . .and heating effects") could be moved to p.9, L 26, after the para describing the main features of the model. The first part of Section 5, up to this point, together with the three paras, could make the first sub-section of the Discussion, emphasizing the need for two reference systems.

I have moved the discussion on the Poynting flux in different references frames to the location suggested by the referee. Also it is slightly modfied:

We claim that there is Poynting flux from N to S as well as from S to N, each transporting electrodynamic energy from a dynamo to a load. Adding both Poynting fluxes would give zero (in the symmetric case), but this is not a meaningful view. The Poynting flux $\boldsymbol{S} = \boldsymbol{E} \times \Delta\boldsymbol{B}/\mu_0$, where $\boldsymbol{E}$ includes the motional field, is frame dependent, as well as the term $\boldsymbol{J} \cdot \boldsymbol{E}$. There are infinitely many possible reference frames, and in each of these Poynting's theorem is of course valid. But only frames with the physical material at rest, in this case of zero neutral wind are special, are the "laboratory frame" with the $\boldsymbol{J} \cdot \boldsymbol{E}^*$ term and the ionospheric Ohm's law giving the dissipation. We argue that it is in this frame where $\boldsymbol{J} \cdot \boldsymbol{E}$ represents the neutral dynamo's power in Wm^{-2} and the Poynting flux the amount and direction of electromagnetic energy being transported from the dynamo to the load. On each magnetic flux tube the neutral winds at each conjugate end define so two "laboratory" frames connected to physical material. In each of the two frames one end is the location of the load. At the other end is a dynamo where $\boldsymbol{J} \cdot \boldsymbol{E} = \boldsymbol{J} \cdot (\boldsymbol{E}^* - \Delta\boldsymbol{u} \times \boldsymbol{B}) < 0$

matching the dissipation at the load. When switching the reference frames the roles also switch, and the Poynting flux between both ends flips to the opposite direction. The neutral dynamo power is so determined by the neutral wind difference at the conjugate points.

1b. The rest of the Discussion could be organized in two more sub-sections, one on quantitative estimates of Sq Joule heating (from p.9, L26 up to p.12, L16), and one on applying the model to high latitudes (from p.13, L22 to the end of the Section).

Subjections were added to the long section "Discussion":

1.1 The Model of Entangled Dynamos

1.2 Estimation of the Joule Heating Power

1.3 The Atmosphere, a Dynamo for Space?

2. Speaking about high latitudes, these are associated in the paper with open field lines, both in the last part of the Discussion and in the Conclusions (e.g., p. 16, L8). As a matter of fact, much of the energy dissipation takes place in the auroral region, which is believed to be threaded (mostly) by closed field lines, that connect the two hemispheres via the plasma sheet in the magnetosphere. However, in this case plasma parameters do not preclude any more parallel electric fields (e.g., much lower density compared to plasmasphere). The open field lines are in general associated with the polar cap, where energy dissipation is limited. As of now, the discussion on high latitudes refers mainly to open field lines / polar cap, while the specific case of the auroral region is just touched a bit, implicitly, in the second last para of the Conclusions. Please complete the Discussion and Conclusions by addressing explicitly the auroral region, where the key feature is the parallel electric field on closed field lines.

The manuscript clarifies how the atmosphere dynamo works and what its effects are. There is no intention to present a new comprehensive theory/model of interaction between ionosphere-thermosphere and space, and of auroral processes. For the aurora the atmosphere dynamo is not expected to play an important role. To isolate the atmosphere dynamo from ionosphere-magnetosphere coupling, the plasma, including the one all along closed field-lines between conjugate points, is assumed to be "passive". It means that the plasma only reacts to neutral dynamics. Observationally the Sq perturbations are clearly visible on quiet days even up to high latitudes, suggesting that the isolated treatment of Sq is in principle testable. On moderate to active days Sq gets buried in larger geomagnetic disturbances even at mid-latitudes. Then the space plasma is not "passive" but has its own dynamics including, at times, the parallel fields mentioned by the referee. Addressing the auroral region on closed field-lines in the same fashion as the mid-latitudes is beyond the scope of the manuscript. It will be attempted in a future work.

The high latitudes are mentioned in the manuscript, because it had been suggested that particularly there, probably on open field-lines, the atmosphere dynamo would be significant andtransport energy into space, statistically, on average. Also this would be a small effect having probably little relation with aurora and parallel electric fields.

To take into account the referee's point, the co-existence of Sq driven by entangled atmosphere dynamos with substorms, auroras etc is acknowledged in the 2^{nd} last paragraph which is slightly reformulated:

On closed field-lines the currents and fields of entangled dynamos can coexist with currents and fields induced by plasma motion in the magnetosphere driven by interaction with the solar wind, to use a generic term. This includes sub-storms, including auroral features sometimes associated with E-fields parallel to $\boldsymbol{B}$, high-latitude plasma convection, its occasional penetration towards lower latitudes etc.

3. The mapping between the two hemispheres could be emphasized by adding the two respective reference systems, (x, y, z), N and S, on the side of Figs 3 and 4, with the x axis pointing northward in N and southward in S. This would also clarify the '+' sign in Equation 5. It would help as well to add J_N and J_S explicitly before Eq. (5), $J_N = \Sigma_N E_N^*$ and $J_S = -\Sigma_S E_S^*$.

Labeled arrows for the X and Y axis were added to Figures 5–6. Equation 5 was added as the referee suggests:

...for the current calculation the frames in N and S are not the same:

$$J_N = \Sigma_N E_N^*,\ J_S = -\Sigma_S E_S^*; \tag{5}$$

$$J_N + J_S = \Sigma_N E_N^* + \Sigma_S E_S^* = 0 \tag{6}$$

4. The proxy in Eq. (15) is probably derived by assuming that ion-neutral collision frequency and ion gyro-frequency are roughly equal in the dissipation layer Δz. Please make this clear.

Text is added:

...with $B = 35000$ nT as an average value of the magnetic field strength at mid latitudes and the factor $e/2B$ giving the conductivity where ion gyro and ion-neutral collision frequencies are equal.

p.3, Fig. 1: Please increase the figure (zonal wind arrows are not visible) and font size (in particular for the Legend).

I have revised the Figure. Now it shows the neutral wind relative to the Earths continents, as we tend to imagine it. Later in the manuscript it is then argued that the Earth fixed system is actually irrelevant, only wind differences matter.

L4: Perhaps complete the sentence with: "...on the E side, which is the standard form of Lorentz transformation for non-relativistic velocities, u."

The sentence is completed:

Please note that in many publications this equation is written with the $+\boldsymbol{u} \times \boldsymbol{B}$ term on the $\boldsymbol{E}$ side , which is the standard form of the Lorentz transformation for non-relativistic velocities $\boldsymbol{u}$.

Eq. (3): Delete Σ_P in the second term.

The second term should not have a factor Σ_P, it is deleted.

p.4, L13: ...connecting either the latitude lines '1', or the latitude lines '2', or both.

The statement is modfied to:

But this configuration of $\boldsymbol{E}$ implies a potential drop along magnetic field lines connecting either latitude circles "1" or latitude circles "2" or along both these field lines.

L15: are from of Galilei

changed to:

We ~~therefore~~ reject the initial idea that the only electric fields ~~are from of~~are those of Galilei coordinate transformations from neutral to observer frames.

p.5, L9: current => FACs

Changed.

p.6, L3: frame => frame with

"with" is added.

L6: surrendered => relaxed (?) changed.

L11: an opportunity => a stronger motivation (?) changed.

p.7, L1: closeS: closes

p.9, L27: and or or

The statement is deleted after comment by referee 2. Instead text in section "Conclusions and Outlook", 9^{th} paragraph outlines how a computer algorithm could handle relative neutral wind differences in a way that is consistent with the theory described in the manuscript:

L29: and simulations => nor simulations (?)

The statement is deleted after comment by referee 2.

p.10, L9: but => therefore changed.

L15: from a with

The statement is changed to:

. . . and deviations from a field that is with respect to the dipole equator perfectly symmetric ~~field~~.

L22: given => given as well (?)

The statement is changed to:

Other explanations for the semi-diurnal component in Sq have been given as well (confirm Yamazaki and Maute, 2017).

L32: Delete 'also'. Please explain briefly 'opposite polarity'.

"polarity" is changed to "direction", "also" deleted

p.11, L30: integrated => integrated over "over" added.

p.12, L23: to the load => to the load in the opposite hemisphere

"in the opposite hemisphere" is added.

L30: as a being "a" is deleted.

p.13, Eq. (16): According to Eq. (2), I think this should be written as E^star(z)- u(z)B(z)=const. (if mapping is neglected), i.e., electric field in a given, unique reference system, is constant.

Correct, the sign is changed. I think that this is the mapping condition, at least for the case of only zonal winds.

L19: the describe ... confirm Figure 1

"prescribed" is changed to "described".

L27: It is well accepted => please provide reference.

"It is well accepted" is deleted. Perhaps surprisingly I could not find a reference where this is explicitly stated, and also referee 2 had objections.

p.14, Eq. (17): The '+' sign on the r.h.s. should be '-', similar to Eq. (2).

Eq. (18): Both '+'signs on the r.h.s. should be '-': the first, same as above; the second, satellite velocity with respect to neutral atmosphere is $v_orb - u$.

All signs are changed, I had myself become confused by the different notation than Kelley's.

L23: Considered => Considered first (?)

Throughout the manuscript only a "passive" plasma is considered, adding "first" would not fit.

2 Other Changes

Changes were made according to comments by referee 2, please confirm the reply for a list.

According to my own comment in section "Preliminaries"

~~, and also the cross-B current~~.

was deleted. Fukushima's contribution is reformulated as:

Fukushima (1979) had suggested that there are electric potential differences between conjugate points of only a few Volts.

References that were added are:

Cosgrove, R. B., Bahcivan, H., Chen, S., Strangeway, R. J., Ortega, J., Alhassan, M., Xu, Y., Welie, M. V., Rehberger, J., Musielak, S., and Cahill, N.: Empirical model of Poynting flux derived from FAST data and a cusp signature, Journal of Geophysical Research: Space Physics, 119, 411–430, https://doi.org/10.1002/2013JA019105, 2014.

Drob, D. P., e. a.: An update to the Horizontal Wind Model (HWM): The quiet time thermosphere, Earth and Space Science, 2, 301–319, https://doi.org/10.1002/2014EA000089, 2015.

Richmond, A. D.: On the ionospheric application of Poynting's theorem, Journal of Geophysical Research: Space Physics, 115, https://doi.org/10.1029/2010JA015768, 2010.

Reply to anonymous Referee 2's comment on "Entangled Dynamos and Joule Heating in the Earth's Ionosphere" by

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This reply is slightly refined compared to the my reply in the public discussion.

1 Replies to comments by Referee 2

Cited referee comments are in red, replies in magenta.

I thank the referee for the interest in the manuscript and the time spent reading it, and for the helpful comments. The referee's main objection is that the manuscript is difficult to understand. She or he then summarizes "that a correct picture only emerges when the processes at conjugate locations in the hemispheres are considered simultaneously." Yes, this is the main point regarding the Sq system, and I'm relieved that at least this point has been reasonably comprehensible.

The presentation of examples could be a little bit more constructive and easier understandable of the readers. It is good that scenarios in different reference frames are outlined, but it would be helpful to focus more on the frame independent quantities. These are, e.g. B-fields, currents, energy dissipation, and velocity difference between plasma drift and wind velocity. I find it not helpful when you state that in the case of Fig. 3 the NH is the sink and SH the dynamo and in case of Fig.4, where you just have changed the reference frame, NH is the dynamo and SH the dynamo. You should have described what actually happens, it is the competing wind-generated E-fields in the two hemispheres that prevents the plasma from moving thus gives equal frictional heating in both hemispheres.

Reply

One of the really important points is that a frame-independent E^* is created as a result of neutral wind differences at conjugate points. So E^* is one of the frame independent quantities and it is THE focus of the manuscript. A "wind-generated E-field" is frame dependent, per definition. Whether there is wind, how much and in which direction depends on the choice of the reference frame. I think that the referee's point is contradictory: First I'm encouraged to focus more on frame independent quantities, but then the referees explanation of what "actually happens" is in terms of the frame dependent wind.

To make it clearer, that I'm moving away from the frame-dependent quantities and focusing on frame independence, Undoubtedly Sq variations have to do with neutral motion, but a neutral wind $\boldsymbol{u}$ and associated motional field $\boldsymbol{u} \times \boldsymbol{B}$ is frame dependent. In the frame of the neutral gas both are zero. So what exactly drives the Sq currents and fields?

is added in section Introduction, and

It is here important to note that $\boldsymbol{E}^*$ is a frame-independent field driving currents according to Equation 1. The frame-dependent motional $\boldsymbol{u} \times \boldsymbol{B}$ does not drive any currents, it is not a real field.

is added to section "Preliminaries".

The referee points out the significance of the velocity difference between plasma drift and wind velocity. No doubt that this velocity difference is important. However, its magnitude and direction are a complicated functions of the ratio of the ion-neutral collision and the ion gyro frequencies. At the bottom of the dynamo region the velocity difference vector is small and in the direction of the frame independent $\boldsymbol{E}^*$, and at the top it is $\boldsymbol{E}^* \times \boldsymbol{B}/B^2$, with a transition in both magnitude and flow angle in between. To describe mathematically the velocity difference between plasma drift and wind velocity would require to discuss this issue and involve equations that are much more complicated than the ones given for the E^*, Equations 4–7. To include the velocity difference between plasma drift and wind velocity in the Figures 3–6. I would need to show the vectors for a specific ratio of these frequencies and decide which ratio. These complications which would not contribute to a better understanding are circumvented by the commonly well-know height integration (confirm section "Preliminaries", 1^{st} paragraph). In other words, the ionosphere in each hemisphere is treated as "thin". Moreover, adopting the E and j paradigm (confirm section "Preliminaries", 2^nd paragraph) this velocity difference between plasma drift and wind velocity is only an effect of E^*. The cause of everything is non-mapping neutral gas velocities at conjugate points. Therefore the velocity difference between plasma drift and wind velocity is admitted:

Instead, the plasma will establish an electric field $\boldsymbol{E^*}$ (perpendicular to $\boldsymbol{B}$) ~~including an $\boldsymbol{E^*} \times \boldsymbol{B}$ drift in the plasmaphere,~~ such that potentials along $\boldsymbol{B}$ are avoided. The non-zero $\boldsymbol{E^*}$ implies that the plasma in the plasmasphere drifts, and that there is a velocity difference between plasma and neutral gas. We ~~therefore~~ reject the initial idea that the only electric fields are from of Galilei coordinate transformations from neutral to observer frames.

The velocity difference between plasma drift and wind velocity is not quantified further in the equations and shown in the Figures, for the reasons described above.

Abstract: The dynamo effect is not limited to different winds in the two hemispheres. Also differences in conductivity, B-field strength, field configuration, etc. can be responsible generating currents.

Reply:

Simple wind differences in the two hemispheres are the exclusive driver indeed only for a symmetric magnetic field, like a centered dipole (which is assumed for the examples and equations in the manuscript). If an asymmetric B-field is considered, like a non-centered dipole, then, for the 1-d case of only zonal winds, instead of a wind difference $u_N - u_S$ the expression $u_N B_N - u_S B_S$ has to be non-zero in order to drive a dynamo (rather entangled dynamos). Differences in conductivities are discussed in the section "Asymmetric Dynamos".

I insist that differences in conductivities do not generate the currents, and they are exclusively caused by relative wind differences at conjugate points. Differences in conductivities only affect the magnitude of non-zero currents, how strong the Joule heating is, and how it is partitioned between the hemispheres. A dynamo effect is limited to neutral winds that do not map at conjugate points. Differences in the B-field strength and configuration at conjugate points affect the mapping condition. For a symmetric B-field the mapping conditions is simply that the wind difference is zero. There is no dynamo effect if winds are (for symmetric B-field exactly) mirror-symmetric between magnetic hemispheres. Such non-dynamo winds may have complicated structures like vortices, shears etc., still they don't have any dynamo effect or cause magnetic perturbations.

The abstract is modified:

...where a dynamo effect is obtained only in case of winds perpendicular to the magnetic field $\boldsymbol{B}$ that ~~spatially vary~~ do not map along $\boldsymbol{B}$. ~~Uniform winds~~ Winds where $\boldsymbol{u} \times \boldsymbol{B}$ is constant have no effect.

In section "Asymmetric Dynamos" (page 9, lines 1–5) I appended

Asymmetry can also be in the magnetic field, with different field strengths in both hemispheres, $B_N \neq B_S$. Rather than the simple difference Δu then winds at conjugate points don't map if

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

is not zero, and Δw replaces $\Delta u B$ in Equations 4–11. A magnetic asymmetry between hemispheres changes the mapping condition, but it does not cause asymmetry of E^* or Joule heating.

Pg. 9, line 7: In the past versions of first-principle ionospheric electrodynamic models the relation E+uxB = 0 was actually maintained by adjusting the wind velocity u. In the latest version of TIEGCM also other currents such as gravity-driven or plasma pressure gradient currents are considered. Therefore, these models now have a 3D electrodynamic solver that maintains current continuity and equal potentials at conjugate locations. For more details see Richmond and Maute (2014) doi:10.1002/9781118704417.ch6

Reply: I have deleted

~~Presumably such potential differences implicitely exist also in global circulation models (GCMs) that include the thermosphere.~~

Instead text in section "Conclusions and Outlook", 9^{th} paragraph outlines how a CGM computer algorithm could handle relative neutral wind differences in a way that is consistent with the theory described in the manuscript:

A numerical simulation that applied directly the motional field $\boldsymbol{u} \times \boldsymbol{B}$ to calculate currents would be incorrect. Instead the relative neutral winds (and $\boldsymbol{B}$) at both conjugate points can be used to obtain the frame-independent $\boldsymbol{E}^*$, Equations 6–7 for the here discussed very simplified case of no meridional winds and symmetric $\boldsymbol{B}$. $\boldsymbol{E}^*$ drives the current according to Ohm's law, Equation 1. For purely zonal neutral winds and symmetric $\boldsymbol{B}$ Equations 6–8 apply.

Line 25: I would suggest to change to ". . .dependence only on relative motion between plasma and neutral gas, no reference to absolute frames."

Reply: The text is changed to

1. ...

2. and dependence only on relative ~~motions~~ differences of the neutral wind Δu and between plasma and neutral gas, no reference to ~~absolute frames~~ an absolute neutral wind u.

The point in the manuscript is that a relative motion of the neutral gas at conjugate points, i. e. $u_N \neq u_S$, is the cause. It induces a relative motion between neutrals and plasma, currents and Joule heating. So relative motion between plasma and neutral gas is only an effect, not the cause.

Lines 26–29: It is not clear to me what these sentences want to state.

Reply: I have deleted the original lines 26–29, please see the text on numerical simulations added in section "Conclusions and Outlook", 9^{th} expressing in a better way what I wanted to state.

Pg. 10, lines 24-28: Here again, it would be instructive to address also the difference between plasma drift and wind. In particular, since the local plasma drift is the prime measurement of satellites in the ionosphere, not E-field.

Reply: The text has been changed to

However, a current-driving, "Ohmic" $\boldsymbol{E}^*$ and corresponding relative motion between u and plasma must exist to drive the interdynamo currents (equation 8 as well as any Hall currents. A non-zero $\boldsymbol{E}^*$ is not created by a local non-zero u in the Earth-fixed frame. It has a non-local origin, for example ~~created if~~ when the local thermospheric wind is zero relative to the observatory, but strong at the conjugate point. No effect is observed, if there is a strong local thermospheric wind, and the same strong wind at the conjugate point.

The difference between plasma drift and wind is now mentioned, but not included in Equations and Figures, for the reasons described above. The text is intended to highlight the non-local cause of the Sq variations. Again, I oppose to the notion that the dynamo is because of local neutral wind in some absolute reference frame. Rather it is caused by differences in the neutral motion along a magnetic field line. This brings in a non-local origin/cause of the relative plasma-neutral drift and E^*. Point measurements of drift or E-field with a single satellite exist of course, but they do not directly reveal this non-locality, and I need to argue in such a theoretical manner which is perhaps difficult to understand.

Pg. 11, line 5: Concerning inter-hemispheric field-aligned currents (IHFAC) there are more recent results of their mean properties, e.g. Lühr et al. (2020) doi:10.1002/2019JA027419. Furthermore, it has been noticed that these IHFACs do not originate from the Sq focus but there is a group of IHFACs located equatorward of the focus, and another group of IHFACs with mainly opposite current directions is emanating from mid-latitudes above the focus (see Park et al., 2020, accepted, doi:10.1002/2019JA027694)

Reply: I have added both references. The model of a jet-like zonal wind difference between conjugate points does show the IHFAC at the edges of the neutral wind jets (pse see Figures 3–6). This model is constructed to show the dynamo principle in the simplest possible configuration. It is not meant to have all the important elements of the real Sq. But if I imagine the interhemispheric neutral wind difference as two large vortices, one in each hemisphere, then FACs should connect the edges of the vortices. The inner edges would be circular-like around the focui. A polar orbiting satellite should then detect between equator and pole at mid-laitudes two pairs of FACs with opposite polarity. This seems to me similar as Park and Lühr (2020) describe their results. By closing the jet-like Δu from the manuscript into a vortex the results might become more consistent with the latest Swarm analysis. However, treating such a more complicated, albeit more realistic configuration is beyond the scope of the manuscript where only sketch-like, analytical solutions are presented.

Line 10: The sentence correctly states that wind energy is extracted from one hemisphere and dissipated as Joule heating in the other. But unfortunately, no estimate of the energy transfer from the summer to the winter hemisphere, relative to the total energy, is given. Only the total energy is estimated. Here again we like to stress the very different IHFAC configurations for June and December solstices although no such seasonal differences are obvious from ground-based maps of Sq patterns.

Reply: The Joule heating in each hemisphere is given in equations 9 and 10. Depending on assumptions for the seasonal variations of the Pederen conductances the seasonally varying energy transfer could be estimated. However, I think, that a more elaborate modeling would be needed to get results that could be meaningfully compared with the Swarm results. This would be out of the scope of this manuscript. A non-aligned and also non-centered dipole axis should result in differences in the IHFACs between June and December solstices, but I cannot say how large the effect would be. Ground-based Sq maps and IHFACs measured in LEO would differ if the ratio between Hall and Pedersen conductances is not constant and depends on season and $\boldsymbol{B}$. This is certainly the case, but again it is difficult to assess how large the effect would be without further more detailed investigation.

Pg. 12, lines 19ff: You start again stressing the frame dependence of Poynting flux. This is for me the wrong definition. Poynting flux as such is frame independent. Here again the velocity differences between plasma and neutral in both hemispheres would give a unique picture.

Reply:

The Poynting flux $\boldsymbol{S}$ is defined as $\boldsymbol{E} \times \boldsymbol{B}/\mu_0$, with $\boldsymbol{E}$ including the motional field, as it would be measured by an instrument resting in this frame. Thus $\boldsymbol{S}$ is frame dependent. I'm not aware that other definitions have been suggested or used anywhere in the literature, and why the definition used in the manuscript should be "wrong".

An alternative definition would always use the frame-independent field: $\boldsymbol{S}^* = \boldsymbol{E}^* \times \boldsymbol{B}$. $\boldsymbol{S} = \boldsymbol{S}^*$ only in the frame of the neutral gas. Then Poynting's theorem (for the stationary case) $\nabla \cdot \boldsymbol{S}^* = -\boldsymbol{J} \cdot \boldsymbol{E}^*$ always describes an energy transfer into the ionosphere and dissipation by Joule heating. As mentioned in section "Introduction", $\boldsymbol{J} \cdot \boldsymbol{E}^* >= 0$ always according to Ohm's law. Then Poynting's theorem would not allow for a dynamo where $\boldsymbol{J} \cdot \boldsymbol{E} < 0$. This doesn't seem right to me.

The velocity differences between plasma and neutral in both hemispheres are of course unique and frame-independent, but they describe always friction, which is another name for Joule heating (Vasyliunas and Song, 2005). Only with the frame dependent definition of $\boldsymbol{S}$, as in the manuscript, the complete picture with dynamos transfering the generated energy to the loads into the opposite hemispheres becomes clear.

Pg. 15, line 2: It is not clear what is meant by "an isolated neutral wind in a plasma would not result in any steady state dynamo effect."

Reply: The text has been deleted. Instead the first paragraph of section "Conclusions and Outlook" states what I think is the overall picture:

It is not the neutral wind itself, defined as any non-zero neutral velocity $\boldsymbol{u}$ in an Earth-fixed frame that causes a dynamo. Rather relative neutral gas motions which do not map between magnetically conjugate points drive Sq currents, magnetic pertubations and Joule heating. A wind system that is mirror symmetric across the magnetic equator, for symmetric $\boldsymbol{B}$, does not act as dynamo. Lorentz forces $\boldsymbol{j} \times \boldsymbol{B}$ drive the wind system towards such symmetry while the solar heat input and non-inertial (Coriolis) forces not aligned to the geomagnetic field drive it away.

Lines 4-9: I cannot agree with the suggested principle of Sq generation. The midlatitude winds are only marginally affected by the plasma dynamics. Therefore, it is the difference in plasma drift response to the winds in conjugate points (depending on conductivity, B-field strength, wind velocity, etc.) that is communicated along field lines between the hemispheres. Again, the resulting local velocity difference between plasma and neutrals drives the electrodynamic processes. The 12-hour period of the Sq signal is mainly dictated by the atmospheric semidiurnal tide, which is clearly dominating at mid latitudes. Longitudinal variations of the various involved quantities play only a minor role.

Reply: I have clarified in the replies and changes to the manuscript that the wind differences are the ultimate cause of, and the referee can hopefully agree to this suggested principle of Sq generation. The dependence on conductances and B-field strength pointed out by the referee is discussed in the manuscript, also that these are not the cause, not a necessary condition. That the local velocity difference between plasma and neutrals is a result of the winds is nowhere disputed in the manuscript. The velocity difference indicates friction and generation of heat which is the same process as what is commonly also called Joule heating, the name used in the manuscript. Lines 4-9 in the original manuscript do not describe the suggested principle of Sq generation, this is described before. The lines point out an anticipated consequence from the peculiar misalignment of the geomagnetic field with respect to the rotation axis, namely a 12 hour modulation. The misalignment is not necessary for Sq currents, it only adds an expected semidiurnal component. For example, Saturn has no axial misalignment but IHFACs were detected and attributed to wind differences at conjugate points (Khurana et al., 2018).

The lines are revised to:

We suggest that the Earth's magnetic Sq variations are driven by neutral wind differences at conjugate points. The main dipole geomagnetic field is tilted with respect to the Earth's rotation axis as well as it is not centered, making it a strongly misaligned rotator. This ~~would explain~~ might contribute to the presence of a 12-hour component in Sq variations. Drob et al. (2015) state that the average neutral wind is partially, mostly at high latitudes, magnetically aligned even at quiet time. $\boldsymbol{J} \times \boldsymbol{B}$ forces of the entangled dynamos, confirm Figures 5–6 act to align to neutral wind to magnetic coordinates, while pressure gradients caused by solar EUV and Coriolis forces have no geomagnetic relation. The dynamo currents are modulated by the product of the Pedersen conductances in both hemispheres resulting also in a 24 hour component of the variations at a fixed point on the Earth. In addition the Sq variations reflect of course also dynamics of the neutral atmosphere itself including any semidiurnal component ~~, in as far as it involves wind differences at conjugate points~~.

Last line: As mentioned above, the 3D electrodynamic solver in TIEGCM avoids potential drops between conjugate points.

Reply: As described alreay in replies above the text has been replaced to describe how numerical calculations would need to be done in order to be consistent with manuscript and physically correct. The text does not refer specifically to TIEGCM.

2 References

Drob, D. P., e. a.: An update to the Horizontal Wind Model (HWM): The quiet time thermosphere, Earth and Space Science, 2, 301–319, https://doi.org/10.1002/2014EA000089, 2015.

Khurana, K. K., Dougherty, M. K., Provan, G., Hunt, G. J., Kivelson, M. G., Cowley, S. W. H., Southwood, D. J., and Russell, C. T.: Discovery of Atmospheric-Wind-Driven Electric Currents in Saturn's Magnetosphere in the Gap Between Saturn and its Rings, Geophysical Research Letters, 45, 10,068–10,074, https://doi.org/10.1029/2018GL078256, 2018.

3 Other Changes

A first clarification has been added in section "Preliminaries":

Adding to paraphrased text book knowledge it is here important to note that $\boldsymbol{E}^*$ is a frame-independent field driving currents according to Equation 1. The frame-dependent motional $\boldsymbol{u} \times \boldsymbol{B}$ does not drive any currents, it is not a real field.

Changes were made according to comments by referee 2, please confirm the reply for a list.

According to my own comment in section "Preliminaries"

~~, and also the cross-B current~~.

was deleted. Fukushima's contribution is reformulated as:

Fukushima (1979) had suggested that there are electric potential differences between conjugate points of only a few Volts.

References that were added are:

Cosgrove, R. B., Bahcivan, H., Chen, S., Strangeway, R. J., Ortega, J., Alhassan, M., Xu, Y., Welie, M. V., Rehberger, J., Musielak, S., and Cahill, N.: Empirical model of Poynting flux derived from FAST data and a cusp

signature, Journal of Geophysical Research: Space Physics, 119, 411–430, https://doi.org/10.1002/2013JA019105, 2014.

Drob, D. P., e. a.: An update to the Horizontal Wind Model (HWM): The quiet time thermosphere, Earth and Space Science, 2, 301–319, https://doi.org/10.1002/2014EA000089, 2015.

Richmond, A. D.: On the ionospheric application of Poynting's theorem, Journal of Geophysical Research: Space Physics, 115, https://doi.org/10.1029/2010JA015768, 2010.

Reply to David Knudsen's comment on “Entangled Dynamos and Joule Heating in the Earth's Ionosphere” by

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This reply is slightly refined compared to the my reply in the public discussion.

1 Replies to comments by Referee 3

Cited referee comments are in red, replies in magenta.

I thank the referee, David Knudsen, for the interest in the manuscript and the time spent reading it, and for the helpful comments.

1) The paper discusses the motivation for using the term “entanglement” in analogy with its use in quantum mechanics. To my knowledge this term is used exclusively for a quantum mechanical effect that does not apply here. The term “coupled” is used in circuit applications which are direct analogs of the simple system considered here, and I suggest is the more appropriate (and clearer) term.

Reply:

“Coupled” in “coupled dynamos” would not describe well some of important points of the manuscript. An essential point is that the dynamos only exist because of the mismatched or not mapping neutral winds at conjugate points in a dipole-like magnetic field configuration. “Uncoupled” there are no dynamos. This is different from a ionosphere and a magnetosphere which may exist independently (examples are Venus and Mars having only ionospheres and Mercury having only a magnetosphere), but can be coupled for planets like the Earth. Therefore I don't want a title having “coupled dynamos”, as it could imply that without the interhemispheric coupling there were still the dynamos in each hemisphere. A title like “Interhemisphere coupling of the ionosphere-thermosphere and Joule heating” seems too general, unspecific.

There are cases in classical physics where “entangled” is being used, for example Islam and Archer (2001), “Non-linear rheology of highly entangled polymer solutions in start-up and steady shear flow.”.

The original word used by Schrödinger is the German “verschränkt”, which can alternatively be translated to English as “crossed.”

An alternative translation is “crossed”, like in “crossed arms”. “Crossed” would also be an approriate word describing here “crossed dynamos”. There are similarities with entangled states known from quantum mechanics:

has been added in section 5.1

It is true that essential features of quantum mechanical entanglement do not apply here: There is no quantization and no probability interpretation. For example, by considering another spatial direction John Bell arrived at his famous inequality predicting the statistical outcome of a large number of measurements. Here one will have to consider not only zonal, but also meridional winds to establish a more realistic model. This is mentioned in the manuscript. But the outcome of taking into account the other spatial direction will certainly not resemble Bell's inequality in any way, as probabilities aren't involved. However, as mentioned in the manuscript, the "entangled dynamos" do have an element of action at a distance which, in the quantum mechanical case, Einstein had called "spooky" (="gespenstisch").

2) In the discussion about open field lines (p14) the author states "it is doubtful that the neutral gas can act as a dynamo for the collisionless plasma in space over larger areas." As the author notes elsewhere in the paper, changes in electric field perpendicular B propagate along B as an Alfven wave. This change in electric field will change plasma drift velocity along B, will have associated with it electric currents and magnetic perturbations, and the energy content of the flux tube will change accordingly.

Consider a scenario with steady southward IMF leading to a large polar cap with open field lines. Furthermore let the solar wind speed be small so that solar-wind-driven Poynting flux into the polar cap is negligible. Next let the neutral wind in the ionosphere increase starting from zero. The result will be an Alfven wave launched upward along B, which will increase the energy density of the flux tube relative to the initial, undis- turbed state. The rate of energy transfer will be associated with an upward Poynting vector, and the correct interpretation is that the neutral wind is acting as a dynamo to drive plasma motions in the collisionless region above the ionosphere. In this case the collisionless flux tube acts as a load with characteristic impedance $\mu_0 * V_A$ (as opposed to $1/Sigma_P$ in the case of a conjugate ionosphere).

I agree that it may be challenging to determine the appropriate frame in which to carry out this analysis, however I believe it is incorrect to say that the neutral wind cannot act as a dynamo on open field lines, regardless of the size of the region. I suggest that the claim quoted at the beginning of this point be removed, that the related text be removed or corrected, and that clarification of this point be left to a future communication.

Reply: The statement that the the neutral wind cannot act as a dynamo on open field lines refers to a steady state. The manuscript generally describes only the steady state as mentioned in the introduction. The statement has been changed to

. . . doubtful that the neutral gas can act as dynamo for the collisionless plasma in space ~~on average~~in a steady state over larger areas. Temporal variations of a neutral wind would in principle excite Alfvén waves adjusting the mechanical stress balance between ionosphere-thermosphere and space plasma which, however, does not lead to any dynamo driven dissipation in space.

The situation described by the referee is not a steady state, and is certainly not the explanation for the average upward Poynting flux found in satellite data. The ionosphere-magnetosphere system on open field-lines readjusts very quickly (by transmitting an Alfvén waves) and reaches a new quasi-steady state. Unless there would a continuous sufficiently rapid temporal change of the neutral wind which the large inertia of the neutral gas prevents.

On open field-lines steady state current systems are involved in an exchange of momentum between Earth and the magnetosphere, see also Vasyliūnas (2007). This is a mechanical process based on Newton's second law, the conservation of momentum (not energy). Currents and the $\boldsymbol{j} \times \boldsymbol{B}$ force are independent of the reference frame (in the non-relativistic limit). Undisputably this process takes place in a quasi-steady state. A consistent pattern of the FAC shows up when averaging a large amount of satellite measurements (Iijima and Potemra, 1976).

In some publications it is stated, that this process of mechanical momentum transfer changes the kinetic energy in the ionosphere-thermosphere. This consideration, however, is frame dependent. Any chosen frame would arbitrarily define how much kinetic energy is in the ionosphere-thermosphere, and whether the momentum exchange between ionosphere and magnetosphere increases or decreases it. Therefore, after realising the inherent frame dependence of the $\boldsymbol{u} \times \boldsymbol{B}$ field, I have stayed away in the manuscript from a discussion of the kinetic energy.

Relevant is rather the conversion to thermal energy. This energy is frame independent, and the conversion, in the thermodynamic sense, is irreversible. The space plasma is generally assumed to be collisionless. Still dissipation, i.e. conversion to thermal energy, can take place at special locations. A prominent example is the bow shock. However, it is not plausible that the neutral atmosphere is in any way connected to such processes.

Thus, returning to the scenario of the referee, the thermal energy density of a flux tube with collisionless plasma does not increase because of a neutral wind at the bottom. This is consistent with the electric field and the Poynting flux in the frame of the plasma being zero. If there is a temporal change, as noted by the referee, then Alfvén waves are generated. After the wave has faded away and a new steady state is reached the thermal energy density of the plasma on the flux tube would be unchanged, and there has been no dynamo action by the neutral wind. But an exchange of momentum between ionosphere-thermosphere and space plasma has taken place.

3) P3, L10: it should be stated explicitly here and perhaps elsewhere that u(z) is assumed to be constant within each ionosphere. This is not clear as written.

Reply:

$\boldsymbol{u}$ and $\boldsymbol{B}$ are also assumed constant over the altitude range where there is significant collisional interaction with the plasma. In other words, the ionosphere is assumed to be thin.

has been added.

Grammar and language usage:

P1 L11: evenly matched -> comparable (evenly matched implies they are directly competing with/opposing one another) L15: scholarly in -> in scholarly changed as suggested.

P2: L5: with also further -> also with further (or drop “also”) L7: “within two latitude circles” -> “within two constant-latitude rings” L9: in the southern hemisphere a westward (easterly) wind -> with a westward (easterly) wind in the southern hemisphere. L10: and a magnetic field aligned cartesion -> and a magnetic field-aligned cartesian L10: A ionosphere -> An ionosphere L12: interfer -> interfere L13: do play any role -> play any role L27:

scholarly treated -> treated in a scholarly manner L29-31 word order: In the frame of the neutral gas in the dynamo region, roughly at altitudes of 90-350 km where collisions are significant, an electric field E* drives Pedersen and Hall currents. ... changed as suggested, except for using "circles of latitude" instead of "constant-latitude rings" because it is a fixed expression in geodesy (https://en.wikipedia.org/wiki/Circle_of_latitude)

Figure 1 caption: allows to -> allows one to changed as suggested.

P3: L6: top ionosphere -> topside ionosphere L7: v the ion or electron drift -> and v is the ion or electron drift L9 suggest: "For constant B, E(z) is also constant (where z is the coordinate along B). L12: request -> require L14: analogous -> analogously changed as suggested.

P4: L2: top -> topside L11: In both, -> In both (remove comma) L15: Galilei -> Galilean (search and replace throughout) changed as suggested.

P5: L3: wind twice -> wind is twice changed as suggested.

P6: L3: suggest: The title of this section, "Symmetric Dynamos", does not necessarily refer to symmetrically opposing zonal winds in an Earth-fixed frame as drawn in Figure 1 (IS THIS WHAT IS INTENDED?) changed to:

The title of this section "Symmetric Dynamos" does not refer to the zonal winds that are symmetrically opposing in an Earth fixed frame as drawn in Figure 1. The same results are obtained for any wind difference that is equal to this symmetric case. "Symmetric" rather refers to ...

The point here is the insight that the absolute winds, symmetric in a certain reference frame or not, are irrelevant. Only the wind difference is important.

L12: . . .instead of guessing them. Assumptions include:

Requirements that apply for both the symmetric and asymmetric cases include:

has been added.

P7: L1: The current loop between N and S closes exactly (add s to "close") changed as suggested.

P8: A similar analysis was later performed with the Oerstedt. . . (add "the") Arguing with -> Arguing on the basis of already Fukushima (1979) -> Fukushima (1979) already ... changed as suggested.

P9: L7: suggest: . . .would be the result if the condition E + uxB = 0 determined E exclusively L10+: A wind without any variations along B would not force the plasma to establish an E*, and consequently could not drive currents nor a dynamo due to zero electric field in the neutral frame. changed as suggested.

P10: L9: but here it is an outlook for the future -> but here is left for future work. L12: convenien -> convenient L14+: Sentence beginning with "But probably more. . .": But more decisive factors are probably the tilt of the geomagnetic field's dipole axis, its offset from the Earth's centre, and deviations of the symmetric field with respect to the dipole equator. (Is that what is meant?) changed as suggested (by referee 1).

L16: Suggest: These also cause differences near equinoxes ... changed as suggested.

L33: may only little resemble -> may only slightly resemble changed as suggested.

P11: L4: The longitudinal dependence is indeed seen in the FAC pattern; please confirm . . . (use a semicolon since it separates independent clauses) L5: make it difficult -> makes it difficult L7, move “particularly” to before “consistent” (“particularly consistent” . . .) changed as suggested.

L14: Ampere -> Amperes L16: “to quite consistently between” -> “quite consistently to between” changed as suggested.

P12: L12: and does particularly not take -> and in particular does not take L15-16: with a more quantitative investigation left to a future investigation. L24: On each magnetic flux tube the neutral winds at each conjugate end provide a physical basis on which to define independent reference frames. L29: adding an in the field -> adding another definition in the field . . . changed as suggested.

P13: L4: tiny delay -> small delay changed as suggested.

L11: shallow -> narrow “shallow” means here changing slowly, with a very small derivative/slope, because the distance along the field-line through the plasmasphere over which the change occurs is very large. So I did not change “shallow”.

P14: L1: (= without collisions) -> (meaning without collisions) L6: Desired is really -> The desired expression is rather: L24: “and a neutral wind that is not constant along the magnetic field” -> “and a neutral wind that is constant within the ionosphere but different in each hemisphere. changed as suggested.

P15: L8-9: In addition the Sq variations also reflect of course the dynamics of . . . L28: implicitely -> implicitly L32: such that explicit potential drops . . . changed as suggested, or text deleted following a comment by referee 2.

P16: L3: groundbased -> ground-based L13: The here presented dual entangled model -> The dual entangled model presented here L15: not restricted to dual -> not restricted to dual systems (is this what’s intended?)

The text is now:

A three-way entanglement of the dynamos in the equatorial F and E regions might turn out to be an applicable concept.

2 References

Iijima, T., and Potemra, T. A. (1976), The amplitude distribution of field-aligned currents at northern high latitudes observed by Triad, J. Geophys. Res., 81(13), 2165– 2174, doi:10.1029/JA081i013p02165.

Islam, M.T. and Archer, L.A. (2001), Nonlinear rheology of highly entangled polymer solutions in start-up and steady shear flow. J. Polym. Sci. B Polym. Phys., 39: 2275-2289. doi:10.1002/polb.1201

Vasyliūnas, V. M.: The mechanical advantage of the magnetosphere: solar-wind-related forces in the magnetosphere-ionosphere-Earth system, Ann. Geophys., 25, 255–269, https://doi.org/10.5194/angeo-25-255-2007, 2007.

3 Other Changes

The manuscript has been changed according to referees 1 and 2 comments and my replies to these comments.

I have added

Knudsen (1990) considered the action of neutral wind dynamos at conjugate hemispheres. He concluded that the resulting fields and currents would act to equalize the neutral winds at both ends with time.

and added the thesis in the list of references.

Entangled Dynamos and Joule Heating in the Earth's Ionosphere

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Abstract. The Earth's neutral atmosphere is the driver of the well-known Solar quiet (Sq) and other magnetic variations, observed since more than 100 years. Yet the understanding of how the neutral wind can accomplish a dynamo effect has been incomplete. A new viable model is presented, where a dynamo effect is obtained only in case of winds perpendicular to the magnetic field $\boldsymbol{B}$ that ~~spatially vary~~ do not map along $\boldsymbol{B}$. ~~Uniform winds~~ Winds where $\boldsymbol{u} \times \boldsymbol{B}$ is constant have no effect. We identify Sq as being driven by wind differences at magnetically conjugate points, and not by a neutral wind per se. The view of two different but entangled dynamos is favoured, with some conceptual analogy to quantum mechanical states. Because of the large preponderance of the neutral gas mass over the ionized component in the Earth's ionosphere the dominant effect of the plasma adjusting to the winds is Joule heating. The amount of global Joule heating power from Sq is estimated, with uncertainties, to be much lower than Joule heating from ionosphere-magnetosphere coupling at high latitudes in periods of strong geomagnetic activity. However, on average both contributions could be relatively ~~evenly matched~~comparable. The global contribution of heating by ionizing solar radiation in the same height range should be 2–3 orders of magnitude larger.

1 Introduction

The interaction between the ionospheric plasma and neutral wind in the Earth's atmosphere has been described in scholarly ~~in~~ textbooks (e. g., Kelley, 2009) and numerous research articles. Still for a long time the author has felt that his understanding of the subject is incomplete. In this work we describe progress that has been finally made when thinking about the solar quiet (Sq) magnetic variations at mid latitudes. A praiseworthy review of Sq has been published recently by Yamazaki and Maute (2017). Sq is driven by a neutral dynamo. Vasyliūnas (2012) has summarized the fundamental equations for a neutral dynamo and his critical view of the understanding within the community. The conceptual difficulty of the author's interpretation of the neutral dynamo can be phrased less mathematically as follows: In the frame of the neutral gas the product $\boldsymbol{j} \cdot \boldsymbol{E}^*$, $\boldsymbol{j}$ the electric current and $\boldsymbol{E}^*$ the electric field, is in the steady state zero or positive, because of the well-known Ohm's law for the ionosphere. This indicates that Joule heating takes place (which, however, has not been addressed yet in works specificially on Sq, as far as we are aware of). A common comprehension seems to be that the dynamo effect occurs in the Earth-fixed frame where $\boldsymbol{j} \cdot (\boldsymbol{E}^* - \boldsymbol{u} \times \boldsymbol{B})$, $\boldsymbol{u}$ the neutral wind, can be negative as required for a dynamo. However, a clear justification for choosing this Earth-fixed frame over any other of the infinitely many possible frames, for example Sun-fixed or star-fixed inertial frames seems to be lacking. Undoubtedly Sq variations have to do with neutral motion, but a neutral wind $\boldsymbol{u}$ and associated motional field $\boldsymbol{u} \times \boldsymbol{B}$ is frame dependent. In the frame of the neutral gas both are zero. So what exactly drives the Sq currents and fields?

We will first present a new viable steady state model of the neutral dynamo in the Earth's ionosphere. As the title suggests, it actually involves (at least) two dynamos. A discussion of various aspects of the new model follows, with ~~also~~ further references to other works on the subject.

2 Preliminaries

A scenario is considered where the lower thermosphere within two circles of latitude ~~circles~~ in each hemisphere is connected by the dipolar geomagnetic field, as sketched in Figure 1. In the northern hemisphere branch an eastward (westerly) zonal wind flows, with a ~~in the southern hemisphere~~ a westward (easterly) wind in the southern hemisphere. A zero tilt between geodetic directions (westerly, easterly) and a magnetic field-aligned cartesion coordinates is assumed. An ionosphere with a dynamo region exists, as well as magnetized plasma in a plasmasphere (not sketched in Figure 1). The plasma adjusts to the conditions imposed by the neutral winds, but does not interfere otherwise, meaning that neither plasma pressure gradients nor electric fields penetrating from outside etc. ~~do~~ play any role. Zero meridional wind is assumed, and the deviation of the magnetic field $\boldsymbol{B}$ from a vertical inclination in the latitude range of the zonal wind is ignored. The latitude range is small, such that gradients of $\boldsymbol{u}$, $\boldsymbol{B}$ and the height-integrated Pederen conduct~~ance~~ivity Σ_P across the range are neglected. In other words, $\boldsymbol{u}$, $\boldsymbol{B}$ and Σ_P are assumed constant across the latitudes of the zonal jets. $\boldsymbol{u}$ and $\boldsymbol{B}$ are also assumed constant over the altitude range where there is significant collisional interaction with the plasma. In other words, the ionosphere is assumed to be thin. The scenario is highly simplified compared to any realistic one, in order to achieve a good physical understanding of the situation.

We strive only for a steady state description. The neutral wind in the Earth's ionosphere at mid-latitudes changes only slowly over time scales of several hours, and the plasma between hemispheres would be able to adjust within seconds, practically instanteneously, with only small amplitudes in the transients. We use the jargon and paradigms of the ionosphere community. Astrophysical dynamos (usually without a neutral gas) are typically rather described in terms of a mechanical MHD approach. Differences between the two approaches have been discussed by Parker (1996), for the high latitudes, and by Vasyliūnas (2012) for specifically the Earth's neutral wind dynamo. Both authors acknowledged that for the steady state both approaches give equivalent results, and that for highly symmetric cases, such as this one, the "traditional" ionospheric E and j paradigm is efficient and mathematically simpler. The electrodynamics of the ionosphere particularly in the steady state and with a neutral gas is ~~scholarly~~ treated in a scholarly manner by Kelley (2009).

For completeness we rephrase the most important points relevant for this work: ~~An electric field in~~ In the reference frame of the neutral gas ~~$\boldsymbol{E}^*$ drives~~ in the dynamo region, roughly at altitudes 90 km–350 km, where collisions are

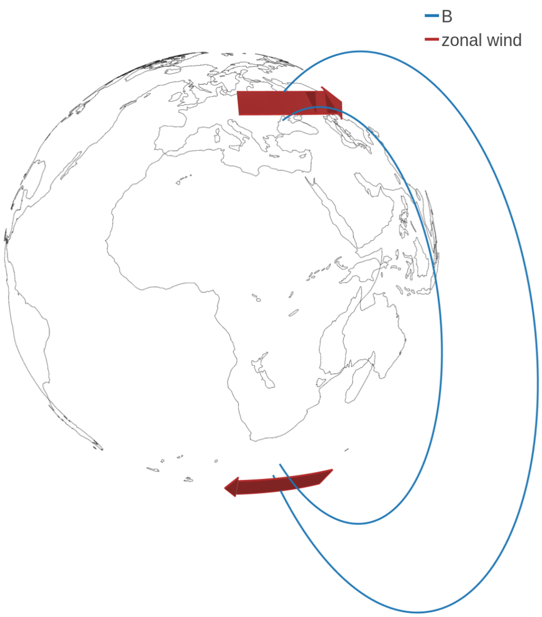

Figure 1. 3d sketch of a scenario where regions between $L = 2.5$ and 3 are magnetically connected by a dipole magnetic field. Supporting information includes this figure in html format which, when opened in a browser supporting JavaScript, allows one to change the camera view point.

significant, an electric field $\boldsymbol{E}^*$ drives Pedersen and Hall currents $\boldsymbol{J}_P$ and $\boldsymbol{J}_H$ according to Ohm's law for the ionosphere:

$$\boldsymbol{J}_P = \Sigma_P \boldsymbol{E}^*, \quad \boldsymbol{J}_H = -\Sigma_H \boldsymbol{E}^* \times \boldsymbol{B}/B. \tag{1}$$

Σ_P and Σ_H are the Pedersen and Hall conductances, $\boldsymbol{B}$ the magnetic field. The electric field $\boldsymbol{E}$ in other reference frames with the neutral gas velocity $\boldsymbol{u} \neq 0$ is

$$\boldsymbol{E} = \boldsymbol{E}^* - \boldsymbol{u} \times \boldsymbol{B}, \tag{2}$$

Please note that in many publications this equation is written with the $+\boldsymbol{u} \times \boldsymbol{B}$ term on the $\boldsymbol{E}$ side , which is the standard form of Lorentz transformation for non-relativistic velocities $\boldsymbol{u}$. Often $\boldsymbol{E}$ is measured in some frame (for example the Earth-fixed one), and the task is to estimate $\boldsymbol{E}^*$. In this work we prefer to write the relation as in Equation 2. It is here important to note that $\boldsymbol{E}^*$ is a frame-independent field driving currents according to Equation 1. The frame-dependent motional $\boldsymbol{u} \times \boldsymbol{B}$ does not drive any currents, it is not a real field.

In the topside ionosphere and plasmasphere collisions are rare and the plasma drifts such that $\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = 0$, and $\boldsymbol{v}$ is the ion or electron drift. This means that the electric field in the frame of the plasma is zero ~~, and also the cross-B current~~. The conductivity along $\boldsymbol{B}$ is very high compared to the Pedersen and Hall conductivities, and in the steady state $E_\parallel = 0$. For constant $\boldsymbol{B}$, ~~then also~~ $\boldsymbol{E}(z)$ is also constant (where z is the coordinate along $\boldsymbol{B}$~~, is constant~~). This justifies using height-integrated quantities in Equation 1. When comparing electric fields between the magnetosphere and ionosphere, $\boldsymbol{B}$ is not constant and $\boldsymbol{E}$ is said to “map” between positions along z (Kelley, 2009, Chapter 2.4). For the scenario in Figure 1 we also ~~request~~require such mapping of $\boldsymbol{E}$ between hemispheres. Owing to the highly symmetric preconditions the mapping is simply that a northward $\boldsymbol{E}$ in the northern hemisphere maps to southward in the southern hemisphere with equal magnitudes, and analogously for reversed directions of $\boldsymbol{E}$.

The Pedersen current driven by $\boldsymbol{E}^*$ is associated with Joule or frictional heating (Vasyliūnas and Song, 2005) with power in Watts per m^2

$$Q_J = \boldsymbol{J}_P \cdot \boldsymbol{E}^* = \Sigma_P \left(\boldsymbol{E}^*\right)^2 = \left(\boldsymbol{J}_P\right)^2 / \Sigma_P \tag{3}$$

The divergent $\boldsymbol{J}_P$ connects to field-aligned currents (FACs). These currents are associated with a magnetic perturbation $\Delta B = \mu_0 \Sigma_P E^*$ in the topside ionosphere (Sugiura, 1984). The difference of the Poynting flux above and below the dynamo region is $\boldsymbol{E}^* \times \Delta\boldsymbol{B}/\mu_0$ matching Q_J in Equation 3 (Richmond, 2010). For the sake of brevity we say that the Poynting flux is downward and equal to the Joule heating rate, for $\boldsymbol{E}$ in the frame of neutral gas, where $\boldsymbol{E} = \boldsymbol{E}^*$.

3 Symmetric Dynamos

Our aim is to figure out the correct electric field configuration for the scenario sketched in Figure 1. For this a collapsed 2-d view of the 3-d one, with the northern stripe of zonal neutral wind just above the southern one, is useful. Both regions are viewed from above the dynamo region, respectively. The view is shown in Figures 2-4. In a first attempt we consider the reference frame fixed to the Earth and assume that $\boldsymbol{E}^* = 0$. There are still electric fields as a result of the neutral winds in both hemispheres according to Equation 2, $\boldsymbol{E} = -\boldsymbol{u} \times \boldsymbol{B}$. This first try is sketched in Figure 2. In both the northern part N and the southern one S, $\boldsymbol{E}$ points southward, because both $\boldsymbol{u}$ and $\boldsymbol{B}$ change to opposite directions. But this configuration of $\boldsymbol{E}$ implies a potential drop along magnetic field lines connecting either latitude circles "1" or latitude circles "2" or along both these field lines. Electrons would short circuit such potential drops. Instead, the plasma will establish an electric field $\boldsymbol{E}^*$ (perpendicular to $\boldsymbol{B}$) ~~including an $\boldsymbol{E}^* \times \boldsymbol{B}$ drift in the plasmaphere,~~ such that potentials along $\boldsymbol{B}$ are avoided. The non-zero $\boldsymbol{E}^*$ implies that the plasma in the plasmasphere drifts, and that there is a velocity difference between plasma and neutral gas. We ~~therefore~~ reject the initial idea that the only electric fields ~~are from of~~are those of Galilea~~i~~n coordinate transformations from neutral to observer frames.

Now we attempt to find a consistent configuration such that $\boldsymbol{E}^* \neq 0$, i. e. a non-zero electric field in the neutral frame. Figure 3 shows the result in the same format as Figure 2, but in a reference frame where the northern neutral wind is zero, and consequently the southern easterly wind is twice as strong (both N and S are always shown in

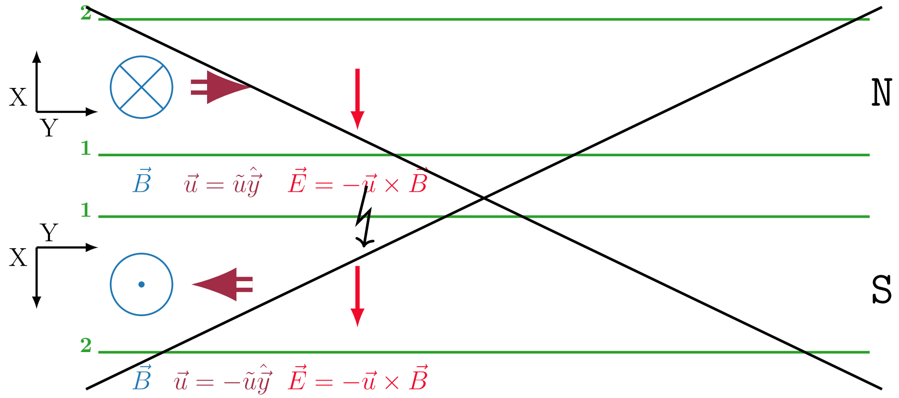

Figure 2. Collapsed 2-d view of the scenario sketched in Figure 1 with the northern and southern regions nearly adjacent to each other and as seen from above the ionospheric dynamo region. The latitude circles labeled "1" and "2" are magnetically connected, respectively. The lightning bolt symbolizes an electrical short circuit along $\boldsymbol{B}$ by electrons that would occur for the suggested $\boldsymbol{E}$. The large black cross indicates that this scenario is rejected as a possible electric field configuration, please see the text.

the same reference frame). Guided by the highly symmetric preconditions we guess that E_N^* has to point northward with magnitude $\tilde{u}B$, with the strength of the wind being $\tilde{u}$. Equations by which E^* can be determined instead of guessed are given in the following section.

E_N^* drives a northward current J_N, resulting in an westward $\boldsymbol{J}_N \times \boldsymbol{B}$ force. J_N connects to FACs at the edges of the neutral wind jet, where we assume that $\boldsymbol{u}$ and therewith $\boldsymbol{E^*}$ drop to zero. The magnetic stress ΔB from the current~~FACs~~ is eastward, from which we derive a downward Poynting flux $\boldsymbol{E}_N \times \Delta \boldsymbol{B}/\mu_0$ matching the Joule heating $J_N \cdot E_N^*$ in the N dynamo.

In S $E_S^* = \tilde{u}B$ is also northward, i. e. E_N^* and E_S^* *do not map* to each other along the magnetic field. Being still in the frame of the northern neutral gas, the southward electric field from the westerly neutral wind $-2\boldsymbol{u} \times \boldsymbol{B}$ is add and gives the total $\boldsymbol{E}$ in S. This field *does map* to E_N^* at the conjugate point, i. e. magnetic field lines are equi-potentials. The current $\boldsymbol{J_S}$ is driven by the electric field in a zero neutral wind reference frame, which is, for S, $\boldsymbol{E}_S^*$. $\boldsymbol{J}_S$ correctly closes the current loop between N and S, such that $\nabla \cdot \boldsymbol{j} = 0$. $(\boldsymbol{E}_S^* - \boldsymbol{u} \times \boldsymbol{B}) \cdot \boldsymbol{J}_S < 0$ which suggests that S is a "dynamo". This and an upward Poynting flux $\boldsymbol{E}_S \times \Delta \boldsymbol{B}/\mu_0$ is consistent with the notion, that the S dynamo drives Joule heating in N via Poynting flux from S to N.

To fully assert consistency, Figure 4 shows the 2-d scene in the reference frame where the southern neutral wind is zero. Currents, forces, and magnetic stress are invariant under Galilean~~i~~ transformation and do not change. The total electric field and the Poynting flux are not invariant and so change compared to Figure 3. It becomes clear that Joule heating also occurs in S, driven by the dynamo in N via Poynting flux from N to S. The magnitude in both hemispheres is the same because of the assumed symmetric preconditions.

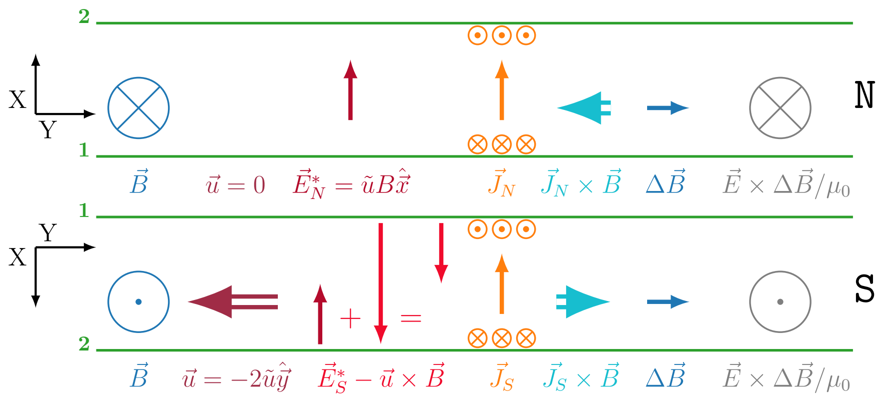

Figure 3. 2-d view like in Figure 2, but in the reference of the northern neutral gas. Electric fields E^*_N and E^*_S avoiding potential drops along $\boldsymbol{B}$ are now added, obtaining consistent electric current $\boldsymbol{J}$, $\boldsymbol{J}\times\boldsymbol{B}$ force, magnetic stress $\Delta\boldsymbol{B}$ and Poynting flux $\boldsymbol{E}\times\Delta\boldsymbol{B}/\mu_0$.

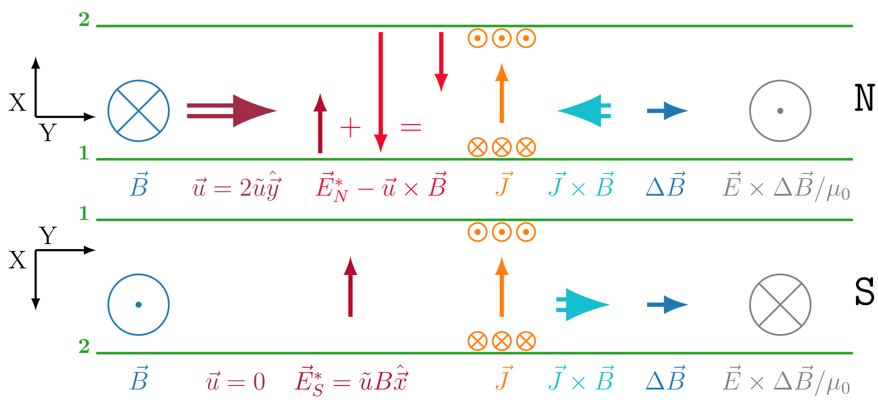

Figure 4. 2-d view like in Figure 3, but in the reference of the southern neutral gas. Electric fields E^*_N and E^*_S that are set up by the plasma to avoid $E_\parallel \neq 0$ are the same, but the $\boldsymbol{u}\times\boldsymbol{B}$ field as a result of the Galilean~~i~~ transformation from the neutral wind frame to the observer is now in the northern hemisphere. Please see the text for further discussions.

The title of this section “Symmetric Dynamos” does not refer to the zonal winds that are symmetrically opposing in an Earth fixed frame ~~symmetrically opposing zonal winds~~ as drawn in Figure 1. The same results are obtained for any ~~equal~~ wind difference that is equal to this symmetric case~~but an asymmetric zonal wind specification~~. “Symmetric” rather refers to equal ionospheric conditions at the conjugate points, equal magnetic field strengths and perfectly opposing field directions, which is partially surrendered~~relaxed~~ in the following section.

4 Asymmetric Dynamos

The strengths of currents and forces, and the magnitudes of Joule heating and Poynting fluxes are proportional to the Pedersen conductance Σ_P. To edge the model a little bit towards a more realistic one, we allow now for different values Σ_N and Σ_S in each hemisphere. An obvious motivation is, that near solstices one dynamo might be sunlit while the conjugate one is not. In addition, considering the asymmetric case provides an opportunity~~a motivation~~ to write down equations for the fields $\boldsymbol{E}_N^*$ and $\boldsymbol{E}_S^*$ instead of guessing them. Requirements that apply for both the symmetric and asymmetric cases include:

1. the total electric fields in N and S using the same reference frame has to map (avoiding a non-zero $E_\parallel$). We choose arbitrarily the frame of the northern neutral gas (Figure 3):

$$E_N^* = E_S^* + \Delta u B \tag{4}$$

for given zonal wind difference $\Delta u = 2\tilde{u}$. Δu is positive for $u_{y,N} > u_{y,S}$.

2. the current loop between N and S closes exactly. In each N and S the current is determined by the electric field in the reference frame of zero neutral wind, which are $\boldsymbol{E}_N^*$ and $\boldsymbol{E}_S^*$, respectively. So for the current calculation the frames in N and S are not the same:

$$J_N = \Sigma_N E_N^*, \; J_S = -\Sigma_S E_S^*; \tag{5}$$

$$J_N + J_S = \Sigma_N E_N^* + \Sigma_S E_S^* = 0 \tag{6}$$

The solutions of equations 4 and 6 are

$$E_N^* = \frac{\Sigma_S}{\Sigma_N + \Sigma_S} \Delta u B = -\frac{\Sigma_S}{\Sigma_N} E_S^* \tag{7}$$

and

$$E_S^* = -\frac{\Sigma_N}{\Sigma_N + \Sigma_S} \Delta u B = -\frac{\Sigma_N}{\Sigma_S} E_N^* \tag{8}$$

The Pedersen current is the same in both hemispheres:

$$J = \frac{\Sigma_N \Sigma_S}{\Sigma_N + \Sigma_S} \Delta u B \tag{9}$$

Figure 5 shows how $\boldsymbol{E}^*$ gets adjusted in a situation where $\Sigma_N = 0.5$ S (or mho) and $\Sigma_S = 1.0$ S. The values are perhaps realistically a bit low, and could be more different. They were chosen so that the lengths of vectors $\boldsymbol{E}$ in Vm^{-1} and $\boldsymbol{J}$ in Am^{-1} have the same scale in the Figures, for better visual understanding. The reference frame is that of the northern neutral gas. The lower Σ_N implies a larger E_N^* compared to the values in S, and also implies stronger Joule heating which is supplied by a higher Poynting flux from S to N. Please compare with Figure 6 showing the same scenario, but in the frame of the southern neutral gas.

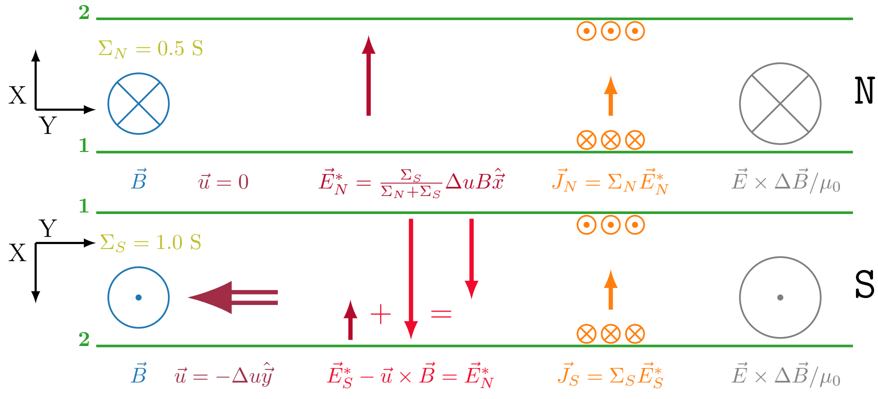

Figure 5. 2-d view like in Figure 3, in the reference frame of the northern neutral gas. The electric fields are such that for asymmetric conductances $\Sigma_N = 0.5$ and $\Sigma_S = 1.0$ the same current $\boldsymbol{J}$ is obtained. $\boldsymbol{J} \times \boldsymbol{B}$ force and magnetic stress $\Delta\boldsymbol{B}$ are omitted in this Figure. The sizes of the symbols for Poynting flux in Figure 6 and this Figure are according to the flux magnitudes having the same scale.

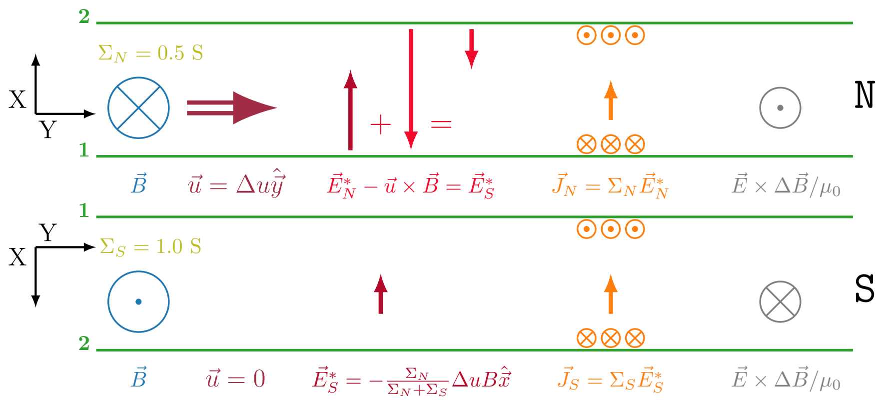

Figure 6. 2-d view like in Figure 4, in the reference of the southern neutral gas. The electric fields are such that for asymmetric conductances $\Sigma_N = 0.5$ and $\Sigma_S = 1.0$ the same current $\boldsymbol{J}$ is obtained. $\boldsymbol{J} \times \boldsymbol{B}$ force and magnetic stress $\Delta\boldsymbol{B}$ are omitted in this Figure. The sizes of the symbols for Poynting flux in Figure 5 and this Figure are according to the flux magnitudes having the same scale.

The Joule heating in each hemisphere is

$$Q_N = \Sigma_N \left(\frac{\Sigma_S}{\Sigma_N + \Sigma_S}\Delta u B\right)^2 = \frac{\Sigma_S}{\Sigma_N} Q_S \tag{10}$$

and

$$Q_S = \Sigma_S \left(\frac{\Sigma_N}{\Sigma_N + \Sigma_S}\Delta u B\right)^2 = \frac{\Sigma_N}{\Sigma_S} Q_N \tag{11}$$

and the total Joule heating

$$Q = Q_N + Q_S = \frac{\Sigma_N \Sigma_S}{\Sigma_N + \Sigma_S} (\Delta u B)^2 \tag{12}$$

A low Σ_P in either N or S reduces both the current and the total Joule heating.

Asymmetry can also be in the magnetic field, with different field strengths in both hemispheres, $B_N \neq B_S$. Rather than the simple difference Δu then winds at conjugate points don't map if

$$\Delta w = u_{y,N} B_N - u_{y,S} B_S \tag{13}$$

is not zero, and Δw replaces $\Delta u B$ in Equations 4–12. A magnetic asymmetry between hemispheres changes the mapping condition, but it does not cause asymmetry of E^* or Joule heating.

5 Discussion

5.1 The Model of Entangled Dynamos

A current system connecting both hemispheres has been suggested first by van Sabben (1966) for Sq. Evidence for interhemispheric field-aligned currents were presented first by Olsen (1997) with Magsat. Paraphrasing Yamazaki and Maute (2017), similar analysis was later performed with the Oerstedt, Champ and Swarm satellite data, see references therein. ~~Arguing with charge transport from one hemisphere to the other, already~~ Fukushima (1979) had suggested that there are electric potential differences between conjugate points of only a few Volts. ~~Presumably such potential differences implicitly exist also in global circulation models (GCMs) that include the thermosphere. A typical code will maintain specified relations between spatially neighboring and nearby grid points. But unless special care is taken a potential difference should develop between magnetically conjugate grid points which are normally not nearby to each other in a global simulation.~~

Here we have started by figuring out the electric field configuration for magnetically connected regions in different hemispheres, using a highly symmetric configuration with zonal winds only. Noting that field-aligned potentials would be the result if ~~exclusively~~ the condition $\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B} = 0$ determined $\boldsymbol{E}$ exclusively, we have rejected this possibility and instead sought a solution where plasma drifts avoid this. The drifts are associated with non-zero $\boldsymbol{E}^*$ in the reference frame of the local neutral gas.

The obtained solution automatically depends only on relative wind differences along $\boldsymbol{B}$. A wind without any variations along $\boldsymbol{B}$ would not force the plasma to establish an $\boldsymbol{E}^*$, and consequently could not ~~it then cannot~~ drive currents nor a dynamo due to the electric field in the neutral frame being zero~~, and it does not drive any dynamo~~. Vasyliūnas (2012) made a similar point. For entangled dynamos the only frames relevant are connected to locally interacting matter, namely the neutral gas (and as discussed below, the plasma). Irrelevant are aether-like absolute reference frames, as the Earth-fixed frame would be one in this context. We consider this a good agreement with fundamental physical principles.

Knudsen (1990) considered the action of neutral wind dynamos at conjugate hemispheres. He concluded that the resulting fields and currents would act to equalize the neutral winds at both ends with time.

Recently Khurana et al. (2018) and Provan et al. (2019) interpreted magnetic features during the final passes of the Cassini spacecraft in terms of neutral gas velocity differences in Saturn's upper atmosphere. There are similarities between their interpretations of the Cassini data and our model for the Earth's Sq. In the Jovian magnetosphere there is magnetic conjugacy between the ionospheres of the Io moon and its footprint in Jupiter's atmosphere which also leads to a quasi-staedy state current system connecting both regions (Huang and Hill, 1989). Entangled Joule heating as a consequence of the systems at Jupiter and Saturn had not been addressed in these studies, but should in principle occur also there.

The main features of the entangled dynamo model are

1. avoidance of field-aligned potential drops,
2. and dependence only on relative ~~motions~~ differences of the neutral wind Δu and between plasma and neutral gas, no reference to ~~absolute frames~~ an absolute neutral wind u.

We claim that there is Poynting flux from N to S as well as from S to N, each transporting electrodynamic energy from a dynamo to a load. Adding both Poynting fluxes would give zero (in the symmetric case), but this is not a meaningful view. The Poynting flux $\boldsymbol{S} = \boldsymbol{E} \times \Delta \boldsymbol{B}/\mu_0$, where $\boldsymbol{E}$ includes the motional field, is frame dependent, as well as the term $\boldsymbol{J} \cdot \boldsymbol{E}$. There are infinitely many possible reference frames, and in each of these Poynting's theorem is of course valid. But only frames with the physical material at rest, in this case of zero neutral wind are special, are the "laboratory frame" with the $\boldsymbol{J} \cdot \boldsymbol{E}^*$ term and the ionospheric Ohm's law giving the dissipation. We argue that it is in this frame where $\boldsymbol{J} \cdot \boldsymbol{E}$ represents the neutral dynamo's power in Wm^{-2} and the Poynting flux the amount and direction of electromagnetic energy being transported from the dynamo to the load in the opposite hemisphere. On each magnetic flux tube the neutral winds at each conjugate end define so two "laboratory" frames connected to physical material. In each of the two frames one end is the location of the load. At the other end is a dynamo where $\boldsymbol{J} \cdot \boldsymbol{E} = \boldsymbol{J} \cdot (\boldsymbol{E}^* - \Delta \boldsymbol{u} \times \boldsymbol{B}) < 0$ matching the dissipation at the load. When switching the reference frames the roles also switch, and the Poynting flux between both ends flips to the opposite direction. The neutral dynamo power is so determined by the neutral wind difference at the conjugate points.

~~The current system of entangled dynamos is qualitatively similar to van Sabben's. Compared to a model or description that allowed for field-aligned potential differences and or or depended, possibly implicitly, on winds in an absolute Earth fixed frame, there would be quantitative differences and divergence in details. Satellite data have not been analysed and simulations performed with such differences in mind.~~

There are complications that will need to be taken into account for a quantitative comparison with data or simulations, among them

– the tilt of the geomagnetic field with respect to geocentric or geodetic coordinates, which are the natural ones for the neutral wind;

– other deviations of the geomagnetic field from a centered dipole;

– the non-vertical inclination of $\boldsymbol{B}$ in the dynamo layers;

– meridional winds;

– the interdynamo current (equation 9) is the same in both hemispheres, a low Σ_P in one hemisphere being compensated for by a stronger E^*, and vice versa. However, the Sq ground variations are from Hall currents. If the ratio Σ_H/Σ_P is different between the conjugate points, then the Sq variations are also asymmetric.

This work focuses on a fundamental understanding of the ionospheric dynamo interactions. The construction of a more realistic model based on entangled dynamos and detailed comparison with data should be relatively straight forward, but~~therefore~~ here it is an outlook for the future~~is left for future work~~.

Nevertheless we find it implausible that the plasma would support potential differences between hemispheres over large scales and long times. Therefore we argue, that the Sq phenomenon is essentially driven by *wind differences* at conjugate points, and entangled dynamos are a convenient way to describe the mechanism. Interhemispheric wind differences do obviously come about when atmospheric circulation and tides are not symmetric with respect to the equator. This asymmetry maximizes near solstices. But ~~probably~~ more decisive factors are probably the tilt of the geomagnetic field's dipole axis, its offset from the Earth centre, and deviations from a field that is with respect to the dipole equator perfectly symmetric ~~field~~. These cause ~~wind~~ differences also near equinoxes when the wind pattern itself should be relatively symmetric with respect to the geodetic equator. The relatively strong semi-diurnal component of the Sq variations at the ground is consistent with a misaligned rotator being involved, as a misalignment tends to produce signals at half the rotation period. The neutral wind pattern itself in geodetic coordinates would not necessarily have a semi-diurnal component. A semi-diurnal component can get excited in the neutral wind itself by the dynamo interactions if the forcing of the thermosphere by the plasma is sufficiently effective. Other explanations for the semi-diurnal component in Sq have been given as well (confirm Yamazaki and Maute, 2017).

The Sq variations at the ground are by Hall currents, which is of course well-known and accepted. However, a current-driving, "Ohmic" $\boldsymbol{E}^*$ and corresponding relative motion between u and plasma must exist to drive the interdynamo currents (equation 9) as well as any Hall currents. A non-zero $\boldsymbol{E}^*$ is not created by a local non-zero u in the Earth-fixed frame. It has a non-local origin, for example ~~created if~~ when the local thermospheric wind is zero relative to the observatory, but strong at the conjugate point. No effect is observed, if there is a strong local thermospheric wind, and the same strong wind at the conjugate point. The local thermospheric wind relative to the observer *alone* has no significance for the entangled dynamo mechanism.

In sections 2–4 we have depicted the wind difference as jet-like, in order to achieve a good insight into the entanglement of dynamos. According to ground magnetometer observations Sq is a counter-clockwise current vortex in the northern hemisphere covering the entire dayside, and a clockwise vortex in the southern hemisphere (Yamazaki and Maute, 2017). The actual wind difference $\Delta \boldsymbol{u}$ is therefore not jet-like, but ~~also~~ vortex-like, with opposite polarity ~~direction~~ as the current. The neutral wind in geodetic coordinates may only little~~slightly~~ resemble these vortices, because magnetic ground observations provide a heavily filtered and transformed image of it: The modulation of the conductances Σ_P and Σ_H by solar ionizing radiation creates a strong diurnal component, and the misaligned near-dipolar geomagnetic field cartographically maps wind differences non-linearly and in a skewed way from the geodetic coordinate system. This mapping varies with longitude. The longitudinal dependence is indeed seen in the FAC pattern; please confirm for example with Olsen (1997) and Park et al. (2011). The spatial sparsity of ground observatories makes it difficult to simultaneously extract both diurnal and longitudinal components, while this is possible using LEO satellite data, see also Lühr et al. (2019), and Park and Lühr (2020) for recent results with the SWARM satellites.

In summary, ~~particularly~~ the semi-diurnal component and the simultaneous LT and longitudinal dependence are observational characteristics that are particularly consistent with a driver of entangled dynamos and we argue that both of these features naturally arise from it.

After some hesitation about adding another definition in the field of ionospheric physics, we have nevertheless adopted the adjective "entangled" as ~~a~~ being descriptive and concise. Entangled is originally and widely used for quantum mechanical states. As far as we are aware of, in classical physics "entangled" is nowhere prominently used, and a mixup therefore unlikely. The German "verschränkt", used originally by Schrödinger (1935) (see also Trimmer, 1980) for these quantum mechanical states, describes the situation also for conjugate ionospheric dynamos in a linguistic sense especially well. An alternative translation is "crossed", like in "crossed arms". "Crossed" would also be an approriate word describing here "crossed dynamos". There are similarities with entangled states known from quantum mechanics: An observer experiences "action at a distance" in that wind variations far away at the conjugate point control the local currents, electric field, and Joule heating. Such "action at a distance" is of course normal in classical current circuits. Wind changes are communicated with a tiny~~small~~ delay given by the Alfvén velocity through the plasmasphere. In a practical sense it is instanteneous considering how slowly the neutral wind typically changes.

Vasyliūnas (2012) concluded that steady state dynamo currents exist 1) only for a neutral wind with gradients (more precisely, if $\nabla \times (\boldsymbol{u} \times \boldsymbol{B}) \neq 0$), or 2) if boundary conditions above the dynamo region impose a non-zero current. In our entangled dynamo model gradients of the neutral wind within each dynamo were neglected, or assumed to be zero. Apparently the model belongs to Vasilyūnas' second category of possible dynamos, with the conditions in each hemisphere determining the boundary conditions at the other hemisphere. The model of entangled dynamos avoids specifying the shallow transition between $\boldsymbol{E}^*_N$ and $\boldsymbol{E}^*_S$ along z that must occur in the plasmasphere including a transition between the corresponding plasma drifts. We consider this as an advantage. Simulations and models of the neutral atmosphere normally don't extend into the plasmasphere, and most available data are from the ionosphere. However, in principle the transition would be determined by the transition of the neutral wind between hemispheres through the plasmasphere according to

$$E^*(z) - \Delta u(z) B(z) = \text{const}, \tag{14}$$

where the coordinate z along $\boldsymbol{B}$ is from the bottom of the dynamo region in S to that in N. Even though the interaction between neutral gas and plasma becomes weak, the neutral atmosphere does extend into the plasmasphere. It is of course possible the describe the entire system as one, and then the described $\boldsymbol{u}$, confirm Figure 1, has apparently $\nabla \times \boldsymbol{u} \neq 0$ fulfilling the demand of Vasyliunas' first category. But we see advantages for the concept of separate, entangled dynamos, as it efficiently focuses on the regions of strong dynamo and heating effects.

5.2 Estimation of the Joule Heating Power

A striking feature of entangled dynamos is the kinetic energy extracted from the neutral wind at one dynamo and dissipated as Joule heating at the other dynamo. We obtain a rough estimate of the total Joule heating $Q_{J,hem}$ using

$$Q_{J,hem} \approx \frac{J^2_{P,tot}}{\langle \Sigma_P \rangle} \approx \left(\frac{\langle \Sigma_P \rangle}{\langle \Sigma_H \rangle} \right)^2 \frac{J^2_{H,tot}}{\langle \Sigma_P \rangle}, \tag{15}$$

where $J_{P,tot}$ $J_{H,tot}$ are the total horizontally integrated Pedersen and Hall currents in Amperes, respectively, and $\langle \Sigma_P \rangle$ and $\langle \Sigma_H \rangle$ are average dayside values for the Pedersen and Hall conductances, respectively. Takeda (2015) determined $J_{H,tot}$ from observatory data ~~to~~ quite consistently to between about 100 and 200 kA. Ieda et al. (2014) investigated the solar zenith angle χ dependence of Σ_P and Σ_H at quiet times, i. e. without interference from particle precipitation. Adopting an "average" dayside χ of 25° we extract $\langle \Sigma_H \rangle / \langle \Sigma_P \rangle \approx 1.4$ and $\langle \Sigma_P \rangle \approx 9$ S from Ieda et al. (2014). Consequently a global estimated Joule heating power of Sq due to wind differences between conjugate points of roughly *between 0.5 and 2 GW per hemisphere* is obtained.

Generally accepted is the importance of Joule heating at high latitudes where it varies very strongly with geomagnetic activity. The high-latitude Joule heating power has mainly been estimated for major geomagnetic storms. Using EISCAT radar measurements during the Halloween storm in 2003 to scale an AMIE data assimilation (Richmond and Kamide, 1988), Rosenqvist et al. (2006) estimated the Joule heating power in the high-latitude northern hemisphere to about 2.4 TW, exceeding our estimate for Sq by three orders of magnitude. Somewhat lower peak values of about 1 TW were obtained in numerical simulations (e. g. Fedrizzi et al., 2012). However, such peak values are obtained only for times of an hour or so. The average Joule heating in storm periods would be much lower, perhaps by a factor of ten or so. Most common is actually low geomagnetic activity, when the amount of high-latiude Joule heating is poorly known. The neutral dynamo driven Joule heating is a permanent, relatively constant trickle, which when integrated over sufficiently long times, i. e. several solar rotations, may well turn out to be significant compared to the high-latitude Joule heating. The Joule heating from Sq is buried in heating from ionizing solar radiation. To compare the order of magnitude of both heating processes, we assume that an ionization and recombination consumes about 35 eV$= 5.6 \cdot 10^{-18}$ J (Rees, 1989). This value stems from laboratory mesurements of ionization by electron impact and is often used to estimate heating by electron precipitation in the aurora. We assume that it roughly applies also in case of ionization by solar radiation in the E region. The coefficient of dissociatve recombination $\alpha \approx 3.5 \cdot 10^{-13}$ m^{3}s^{-1} (Bates, 1988). We compare the heating within a layer of $\Delta z = 10$ km centered at the peak of $\sigma_P(z)$, which is typically at about 130 km altitude in the E region. Then the heating by solar radiation

$$Q_S \approx 5.6 \cdot 10^{-18} \alpha \langle N_e \rangle^2 \Delta z \tag{16}$$

in Wm^{-2}. The heating in one dayside hemisphere

$$Q_{S,hem} = \pi R_E^2 Q_S \tag{17}$$

with $R_E = 6378$ km the Earth radius. It remains to give a representative value for the electron density $\langle N_e \rangle$ matching $\langle \Sigma_P \rangle \approx 9$ S, which was used above the estimate the Sq Joule heating. To simplify the integration over height we use instead

$$\langle \Sigma_P \rangle \approx \Delta z \frac{e \langle N_e \rangle}{2B} \tag{18}$$

with $B = 35000$ nT as an average value of the magnetic field strength at mid latitudes and the factor $e/2B$ giving the conductivity where ion gyro and ion-neutral collision frequencies are equal . This gives $\langle N_e \rangle \approx 4 \cdot 10^{11}$ m^{-3} and a solar heating per hemisphere of $Q_{S,hem} \approx 400$ GW. Clearly this is only a very rough estimate and in particular does ~~particularly~~ not take into account any solar cycle variations that are certainly present. These would affect both the heating by solar radiation and by the neutral dynamos (Sq). For now we tentatively state that *the Joule heating by Sq amounts to roughly 0.1-1 % of the solar heating in the same altitude range*, with a more quantitative investigation as an outlook for the future.

~~We claim that there is Poynting flux from N to S as well as from S to N, each transporting electrodynamic energy from a dynamo to a load. Adding both Poynting fluxes would give zero (in the symmetric case), but this is not a meaningful view. The Poynting flux $\boldsymbol{E} \times \Delta \boldsymbol{B}/\mu_0$ as well as the term $\boldsymbol{J} \cdot \boldsymbol{E}$ depend on the reference frame. There are infinitely many possible reference frames, and in each of these Poynting's theorem is of course valid. But only frames of zero neutral wind are special, with the $\boldsymbol{J} \cdot \boldsymbol{E}^*$ term and the ionospheric Ohm's law giving the dissipation. We argue that it is in this frame where $\boldsymbol{J} \cdot \boldsymbol{E}$ represents the neutral dynamo's power in Wm^{-2} and the Poynting flux the amount and direction of electromagnetic energy being transported from the dynamo to the load. On each magnetic flux tube the neutral winds at each conjugate end define so two reference frames connected to physical materialprovide a physical basis o In each of the two frames one end is the location of the load. At the other end is a dynamo where $\boldsymbol{J} \cdot \boldsymbol{E} = \boldsymbol{J} \cdot (\boldsymbol{E}^* - \Delta \boldsymbol{u} \times \boldsymbol{B}) < 0$ matching the dissipation at the load. When switching the reference frames the roles also switch, and the Poynting flux between both ends flips to the opposite direction. The neutral dynamo power is so determined by the neutral wind difference at the conjugate points.~~

~~After some hesitation about adding an in the field of ionospheric physics new concept, we have nevertheless adopted the adjective "entangled" as a being descriptive and concise. Entangled is originally and widely used for~~

quantum mechanical states. As far as we are aware of, in classical physics "entangled" is nowhere prominently used, and a mixup therefore unlikely. The German "verschränkt", used originally by Schrödinger (1935) (see also Trimmer, 1980) for these quantum mechanical states, describes the situation also for conjugate ionospheric dynamos in a linguistic sense especially well. An observer experiences "action at a distance" in that wind variations far away at the conjugate point control the local currents, electric field, and Joule heating. Such "action at a distance" is of course normal in classical current circuits. Wind changes are communicated with a tiny delay given by the Alfvén velocity through the plasmasphere. In a practical sense it is instanteneous considering how slowly the neutral wind typically changes.

Vasyliūnas (2012) concluded that steady state dynamo currents exist 1) only for a neutral wind with gradients (more precisely, if $\nabla \times (\boldsymbol{u} \times \boldsymbol{B}) \neq 0$), or 2) if boundary conditions above the dynamo region impose a non-zero current. In our entangled dynamo model gradients of the neutral wind within each dynamo were neglected, or assumed to be zero. Apparently the model belongs to Vasilyūnas' second category of possible dynamos, with the conditions in each hemisphere determining the boundary conditions at the other hemisphere. The model of entangled dynamos avoids specifying the shallow transition between $\boldsymbol{E}_N^*$ and $\boldsymbol{E}_S^*$ along z that must occur in the plasmasphere including a transition between the corresponding plasma drifts. We consider this as an advantage. Simulations and models of the neutral atmosphere normally don't extend into the plasmasphere, and most available data are from the ionosphere. However, in principle the transition would be determined by the transition of the neutral wind between hemispheres through the plasmasphere according to

$$E^*(z) + \Delta u(z)\, B(z) = \text{const}, \tag{19}$$

where the coordinate z along $\boldsymbol{B}$ is from the bottom of the dynamo region in S to that in N. Even though the interaction between neutral gas and plasma becomes weak, the neutral atmosphere does extend into the plasmasphere. It is of course possible the describe the entire system as one, and then the prescribed $\boldsymbol{u}$, confirm Figure 1, has apparently $\nabla \times \boldsymbol{u} \neq 0$ fulfilling the demand of Vasyliunas' first category. But we see advantages for the concept of separate, entangled dynamos, as it efficiently focuses on the regions of strong dynamo and heating effects.

5.3 The Atmosphere, a Dynamo for Space?

Applying the entangled dynamo model in modified form to high-latitudes turns out to be instructive as well: if the magnetically connected counterpart of the neutral atmosphere is an "active" plasma in space, without a conjugate point in the opposite hemisphere, then this describes "ordinary" ionosphere-magnetosphere coupling. The "active" plasma acts as dynamo, the neutral atmosphere is the load, consistent with the established paradigms. A sketch how particularly the solar wind can act as dynamo is for example in Rosenqvist et al. (2006). The appropriate reference frame for the steady state is that of the neutral gas, the load. It is well accepted that hHigh latitude electric fields, Poynting flux and Joule heating need to be calculated in this reference frame. So far nothing special about ionosphere-magnetosphere coupling has emerged. However, looking for an entangled counterpart, we find that it is not present: the “partner" candidate for a load would be the plasma. But in the reference frame of the plasma $\boldsymbol{E} = 0$, the plasma does not dissipate energy, and also the Poynting flux in the plasma reference frame is zero. Thus it seems very doubtful that the neutral wind can act as a dynamo on open field-lines when the plasma in space is the only possible load. From ion-electron collisions there would be only a very tiny, insignificant non-zero electric field in the plasma frame. When treating the space plasma as ideal (=~~meaning~~ without collisions), a dynamo works only in the direction from space to the Earth’s atmosphere, as opposed to a system with neutral dynamos at both ends.

Measurements ~~of the electric field~~ with satellites give the electric field due to the relative motion between satellite and surrounding plasma. This $\boldsymbol{E}_s$ is ~~are~~ normally transformed to the Earth fixed frame,

$$\boldsymbol{E}_e = \boldsymbol{E}_s - \boldsymbol{v}_{orb} \times \boldsymbol{B}, \qquad (20)$$

with $\boldsymbol{v}_{orb}$ the satellite velocity in the Earth fixed frame, $\boldsymbol{E}_s$ the observed or measured electric field, and $\boldsymbol{E}_e$ the transformed one. Desired~~The desired parameter~~ is really

$$\boldsymbol{E}_n = \boldsymbol{E}_s - (\boldsymbol{v}_{orb} - \boldsymbol{u}) \times \boldsymbol{B} \qquad (21)$$

in the neutral gas frame, however, the neutral wind is unknown, or known only with large uncertainty. At high latitudes plasma drifts in the Earth fixed frame are typically much larger than the neutral wind. Therefore, Poynting flux and Joule heating may approximately be estimated in the Earth fixed frame instead of the neutral frame. A large amount of satellite data have so been processed, resulting in average spatial patterns of Joule heating and downward Poynting flux in the polar ionosphere (Gary et al., 1994; Waters et al., 2004; Cosgrove et al., 2014), which are undisputably very valuable and relevant results. In certain areas of open field-lines, however, consistently a weak upward Poynting flux is obtained. In our opinion this~~This~~ merely indicates that in these areas there is a consistent non-zero neutral wind and also relatively weak plasma drift. The Poynting flux evaluated in the Earth fixed frame, which is the “wrong” frame, can then turn out upward. In light of the discussion in the previous paragraph it seems doubtful that the neutral gas can act as dynamo for the collisionless plasma in space ~~on average~~in a steady state over larger areas. Temporal variations of a neutral wind would in principle excite Alfvén waves adjusting the mechanical stress balance between ionosphere-thermosphere and space plasma which, however, does not lead to any dynamo driven dissipation in space. To prove such a possible neutral wind dynamo against the space plasma in satellite data, the observed $\boldsymbol{E}_s$ would need to be transformed into the plasma reference frame using ion drift measurements from the satellite. The expected outcome is, within measurement uncertainties, zero. The neutral wind would not act in any significant way as a dynamo against the space plasma.

6 Conclusions and Outlook

It is not the neutral wind itself, defined as any non-zero neutral velocity $\boldsymbol{u}$ in an Earth-fixed frame that causes a dynamo. Rather relative neutral gas motions which do not map between magnetically conjugate points drive Sq currents, magnetic pertubations and Joule heating. A wind system that is mirror symmetric across the magnetic equator, for symmetric $\boldsymbol{B}$, does not act as dynamo. Lorentz forces $\boldsymbol{j} \times \boldsymbol{B}$ drive the wind system towards such symmetry while the solar heat input and non-inertial (Coriolis) forces not aligned to geomagnetic field drive it away.

~~Considered is~~ This becomes clear by considering the situation of a "passive plasma", i. e. where the electric field in the reference frame cf the neutral gas is zero, and a neutral wind that is not constant along the magnetic field ~~constant within the ionosphere but different in each hemisphere~~. From the paradigm that the plasma in the steady state avoids electric potential differences along $\boldsymbol{B}$ we conclude that the plasma then cannot remain "passive" and will be drifting with associated ~~electrostatic~~ $\boldsymbol{E}^*$ perpendicular to $\boldsymbol{B}$, so preventing any $E_\parallel \neq 0$. $\boldsymbol{E}^*$ drives currents fullfilling $\nabla \cdot \boldsymbol{j} = 0$ and Joule heating with $\boldsymbol{j} \cdot \boldsymbol{E}^* > 0$. $\boldsymbol{E}^*$ is not constant along $\boldsymbol{B}$, if $\boldsymbol{u}(z)$ varies.

We have particularly looked at the situation of two regions of interacting neutral gas and plasma in opposite hemispheres, with a dipole-like $\boldsymbol{B}$ connecting both regions and defining conjugacy. Then, for a $\boldsymbol{B}$ with symmetry between hemispheres, any difference between the neutral winds at conjugate points results in a dynamo effect. Electromagnetic energy is generated and transported to the opposite hemisphere as Poynting flux. There the energy is dominantly dissipated, due to a large mass of the neutral gas compared to the plasma. The process works in both directions, and entanglement seems a convenient and useful description of the situation. ~~We agree with Vasyliunas(2012) and others, that an isolated neutral wind in a plasma would not result in any steady state dynamo effect.~~

We suggest that the Earth's magnetic Sq variations are driven by neutral wind differences at conjugate points. The main dipole geomagnetic field is tilted with respect to the Earth's rotation axis as well as it is not centered, making it a strongly misaligned rotator. This ~~would explain~~ might contribute to the presence of a 12-hour component in Sq variations. Drob (2015) state that the average neutral wind is partially, mostly at high latitudes, magnetically aligned even at quiet time. $\boldsymbol{J} \times \boldsymbol{B}$ forces of the entangled dynamics, confirm Figures 3–4 act to align the neutral wind to magnetic coordinates, while pressure gradients caused by solar EUV and Coriolis forces have no geomagnetic relation. The dynamo currents are modulated by the product of the Pedersen conductances in both hemispheres resulting also in a 24 hour component of the variations at a fixed point on the Earth. In addition the Sq variations also reflect of course ~~also~~ dynamics of the neutral atmosphere itself including any semidiurnal component ~~, in as far as it involves wind differences at conjugate points~~.

The Joule heating driven by the neutral wind in the Earth's thermosphere is estimated to about 0.5 to 2 GW per hemisphere, quasi-permanently moving around the Earth with the Sun. According to a rough estimate of the order of magnitudes this Joule heating is about 0.1 to 1 percent of the energy consumed by ionization from solar radiation and its recombination in the same altitude range. The Joule heating by Sq is near constant compared to the high-latitude Joule heating which varies over several orders of magnitude depending on geomagnetic activity.

The prescriptions for obtaining the electrostatic~~real, Ohmic~~ field, stationary drifts and currents in the space plasma interacting with a neutral atmosphere are in general terms:

1. potential differences are avoided along $\boldsymbol{B}$ and the electric field maps;

2. field-aligned currents close across $\boldsymbol{B}$.

These are already well accepted principles in ionosphere-magnetosphere coupling in the steady state (Kelley, 2009, Chapter 2). Applying the prescriptions to the situation of a neutral wind that is not constant along a coordinate z along $\boldsymbol{B}$ has helped us to clarify that

1. the mapping electric field is $\boldsymbol{E}^* - \boldsymbol{u} \times \boldsymbol{B}$ and the mapping needs to be done in one single reference frame. The neutral gas does not define the frame unambiguously as the wind varies along z. The frame for the mapping can be choosen freely, but it must be the same frame all along z;

2. the closure current is $\sigma_P \boldsymbol{E}^*$, and it is evaluated in the reference frame of the local neutral gas, such that the frame relevant for current calculation generally changes along z.

We have not been able to present direct empirical evidence that the entangled dynamo model is the correct one for Sq. In numerous previous works a dynamo effect had, often implicitly, been attributed to a neutral wind per se (in a fixed frame, like the Earth's). A detailed analysis of existing and future data from satellites and the ground with respect to the entangled dynamo model and neutral wind differences along $\boldsymbol{B}$ is left as a future task.

~~This prescription above has the potential to guide the design of methods for simulating atmospheric and plasma circulation, such that explicitly potential drops between opposite hemispheres are avoided. We believe that this approach applied in GCMs would be realistic and may give significantly different plasma convection and neutral wind compared to methods which are currently in use and which do not enforce zero potential difference at conjugate points.~~ A numerical simulation that applied directly the motional field $\boldsymbol{u} \times \boldsymbol{B}$ to calculate currents would be incorrect. Instead the relative neutral winds (and $\boldsymbol{B}$) at both conjugate points can be used to obtain the frame-independent $\boldsymbol{E}^*$, Equations 7–8 for the here discussed very simplified case of no meridional winds and symmetric $\boldsymbol{B}$. $\boldsymbol{E}^*$ drives the current according to Ohm's law, Equation 1. For purely zonal neutral winds and symmetric $\boldsymbol{B}$ Equations 7–9 apply. AMIE-like data assimilation for estimating neutral wind differences between hemispheres from observations of FACs, for example with the Swarm mission, and ground-based magnetic data seems possible. Such neutral wind differences would then usefully constrain estimates of the absolute wind by other methods.

The concept of two-way entangled dynamos is applicable for the mid-latitudes and Sq, but not on open field lines and only with modifications at equatorial latitudes. For high latitudes we have briefly discussed the concept of the plasma in space acting as a dynamo driving Joule heating in the thermosphere (but not vice versa), which is just an alternative phrasing of well established concepts of ionosphere-magnetosphere coupling, applicable on open magnetic field-lines.

On closed field-lines the currents and fields of entangled dynamos can coexist with currents and fields induced by plasma motion in the magnetosphere driven by interaction with the solar wind, to use a generic term. This includes sub-storms, including auroral features sometimes associated with E-fields parallel to $\boldsymbol{B}$, high-latitude plasma convection, its occasional penetration towards lower latitudes etc.

Near the equator phenomena are more complex again, as is well known. ~~The here presented dual entangled model seems to have limited applicability for the equatorial ionosphere. In quantum mechanics entanglement is not restricted to dual (Greenberger et al., 1989).~~A three-way entanglement of the dynamos in the equatorial F and E regions might turn out to be an applicable concept.

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