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

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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 electrostatic 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.

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 electrostatic 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 should and 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, an electrostatic $\boldsymbol{E}^*$ 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 ncessary 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 electrostatic 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.