Ionospheric energy input in response to changes in solar wind driving: Statistics from the SuperDARN and AMPERE campaigns

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Abstract

For over a decade, the Super Dual Auroral Radar Network (SuperDARN) and the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) have been measuring ionospheric convection and field-aligned currents in the high-latitude regions, respectively. Using both, whole hemisphere maps of the magnetosphere-ionosphere energy transfer rate (the Poynting flux) have been generated with a time resolution of two minutes between 2010 and 2017. These uniquely data driven Poynting flux patterns are used in this study to perform a superposed epoch analysis of the northern hemisphere ionospheric response to transitions of the IMF B_z component. We discuss the difference in the distribution of Poynting flux between the magnetosphere-ionosphere Dungey cycle "switching on" and "switching off" to solar wind driving, revealing that they are not symmetric temporally or spatially.

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Key Points:

- SuperDARN and AMPERE derived Poynting flux distributions are generated with a two-minute resolution.
- A superposed epoch analysis is performed for transitions of the IMF B_z component.
- There is spatial and temporal asymmetry to how the Poynting flux morphology responds to opposite B_z transitions.

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Abstract

For over a decade, the Super Dual Auroral Radar Network (SuperDARN) and the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) have been measuring ionospheric convection and field-aligned currents in the high-latitude regions, respectively. Using both, whole hemisphere maps of the magnetosphere-ionosphere energy transfer rate (the Poynting flux) have been generated with a time resolution of two minutes between 2010 and 2017. These uniquely data driven Poynting flux patterns are used in this study to perform a superposed epoch analysis of the northern hemisphere ionospheric response to transitions of the IMF B_z component. We discuss the difference in the distribution of Poynting flux between the magnetosphere-ionosphere Dungey cycle "switching on" and "switching off" to solar wind driving, revealing that they are not symmetric temporally or spatially.

Plain Language Summary

The Earth's high-latitude upper atmosphere (the ionosphere, upwards of 100km in altitude) is consistently bombarded with solar energy that takes the form of electric currents aligned with Earth's magnetic field. The magnetosphere has two generalised states, "open" and "closed". Open is when the Earth and solar magnetic fields connect to each other on the dayside, allowing energy into the atmosphere from the solar wind. Closed is when the fields do not connect (or do not connect simply) and thus not as much energy enters the atmosphere. The open or closed criteria depends on the direction of the solar magnetic field, which varies constantly. In this study, we utilise nearly 8 years of data to generate average patterns of ionospheric energy input at various intervals before and after the solar-magnetosphere system transitions from open to closed, and vice versa. We discuss the spatial and temporal timescales upon which the energy varies in response to the relatively symmetric transitions, finding that they do not result in symmetric changes in the ionospheric energy input patterns.

1 Introduction

In 2009, the Iridium constellation of satellites began consistently delivering magnetic field data at their orbital altitude of ∼780 km to be processed as part of the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE; Anderson et al., 2014). AMPERE has allowed for the derivation of global-scale perturbation magnetic fields at F-region ionospheric altitudes (at a typical 10-minute resolution), which are subsequently processed into patterns of the high-latitude field-aligned currents (FACs). Overlapping with the entirety of the AMPERE dataset from its inception to the present day has been consistent measurements of ionospheric plasma flows from the Super Dual Auroral Radar Network (SuperDARN; Greenwald et al., 1995). As of 2021, the SuperDARN consists of 36 high-frequency radars in both the northern and southern hemispheres that are used conjunctively to generate instantaneous patterns of the high-latitude ionospheric convection pattern (Chisham et al., 2007; Nishitani et al., 2019), at a two-minute resolution.

SuperDARN derived convection, or electric potential (Φ), patterns can be converted to the electric field ($\mathbf{E}$) via the relation $\mathbf{E} = -\nabla\Phi$. AMPERE derived perturbation magnetic fields ($\delta\mathbf{B}$), based on the assumption that the magnetic field is near-vertical at high latitudes, can then be used in conjunction with $\mathbf{E}$ to calculate the total energy transferred between the magnetosphere and ionosphere through field aligned currents (FACs), the Poynting flux ($\mathbf{S}_{||}$), using Poynting's theorem:

$$\mathbf{S}_{||} = -\frac{1}{\mu_0}\left(\mathbf{E} \times \delta\mathbf{B}\right) \cdot \hat{\mathbf{r}} \tag{1}$$

where $\hat{\mathbf{r}}$ is the unit vector parallel to the geomagnetic field and μ_0 is the permeability of free space. Previously, a dataset of Poynting flux patterns for the northern hemisphere ionosphere has been generated for the entire overlapping AMPERE-SuperDARN datasets between 2010 and 2017 using Equation 1, which have been shown to be consistent with several models and observations (Billett et al., 2021).

This study utilises the new dataset of northern hemisphere Poynting flux maps to examine its statistical response to changes in solar wind driving conditions, primarily after sustained transitions of the Interplanetary Magnetic Field (IMF) B_z component in Geocentric Solar Magnetospheric (GSM) coordinates. These types of IMF transitions are akin to "switching on" ($B_z > 0$ to $B_z < 0$) and "switching off" ($B_z < 0$ to $B_z > 0$) magnetospheric driving of the ionosphere via reconnection at the magnetopause, inducing the Earth's Dungey cycle (Dungey, 1961; Cowley & Lockwood, 1992). Although this is a simplistic view of magnetosphere-ionosphere coupling given that magnetopause reconnection can still occur at the magnetopause when the IMF B_z is positive (Onsager et al., 2001), whether the IMF vector is southward ($B_z < 0$) or northward ($B_z > 0$)

orientated is the most significant indicator of magnetospheric energy input into the ionosphere (Milan, 2009).

The "switching on" of the magnetosphere-ionosphere driving system (i.e., a positive-to-negative IMF B_z transition) has been extensively studied. For example, the ionospheric electric field is known to respond dynamically to changes in the near-Earth solar wind on the order of minutes (e.g. Murr & Hughes, 2001; Yu & Ridley, 2009; Snekvik et al., 2017). This response begins on the dayside and progresses to the nightside, with the ionospheric electric field fully reconfiguring to a negative B_z orientation within tens of minutes (e.g. Murr & Hughes, 2001; Dods et al., 2017). The global FACs system finish developing much later, on the order of hours (Coxon et al., 2019). Ionospheric conductivity is also known to play an important role in the rate of FAC formation, contributing to seasonal asymmetries (Coxon et al., 2016).

Negative to positive turnings of the IMF B_z have less commonly been studied. Lobe reconnection under positive B_z results in the development of a new FAC system (NBZ; Iijima et al., 1984), thus lowering the decay rate of the total dayside current and bringing it more in line with the total nightside current decay (Milan et al., 2018). Decay rates are further complicated by the different responses of reconnection driven magnetospheric convection and viscous interaction or flywheel driven convection under positive B_z (Bhattarai et al., 2012). Low nightside conductance may in fact result in faster nightside FAC decay due to weaker line-tying of magnetic field lines (Moretto et al., 2018, 2021).

In this paper, we present the response of the northern hemispheric Poynting flux to the aforementioned B_z transitions as a superposed epoch analysis. We discuss how the overlapping SuperDARN and AMPERE data sets were used to do this in section 2. Results are shown in section 3, whilst we discuss the differences in how Poynting flux increases or decreases depending on the B_z transition in section 4.

2 Data processing

Maps of the high-latitude Poynting flux were generated for each overlapping AMPERE $\delta\mathbf{B}$ map and SuperDARN convection pattern in the northern hemisphere using the method described by Waters et al. (2004). In short, both $\delta\mathbf{B}$ from AMPERE and $\mathbf{E}$ from the SuperDARN are placed into an equal area (∼200x400 km) grid poleward of 60° AACGM (Shepherd, 2014) latitude which is also fixed in local time, where each cell is 2° of latitude tall. Equation 1 is then used to derive the Poynting flux on the same grid. All latitudes and magnetic local times (MLTs) mentioned henceforth are referring to AACGM latitude and local time, respectively.

As the global SuperDARN convection patterns are spherical harmonic fits to the plasma velocity data from individual radars (Ruohoniemi & Baker, 1998), a threshold of 200 gridded SuperDARN line-of-sight velocity data points per pattern is imposed before using them to calculate the Poynting flux. This ensures there is generally a good spread of real radar velocity data across most local times for any given convection map and reduces the amount of "usable" SuperDARN convection patterns for Poynting flux measurements by around 55% (Billett et al., 2018). The SuperDARN radar data is also filtered so that E-region ionospheric backscatter is removed, giving the convection patterns an assumed F-region altitude of approximately 250 km. Convection patterns use SuperDARN data integrated over two minutes.

The AMPERE data is assumed to be from an altitude of 780 km, which is subsequently scaled to an altitude of 250 km to match the SuperDARN data. This is done using the 3/2 relationship described by Knipp et al. (2014) and results in $\delta\mathbf{B}$ being approximately 1.12 times larger than measured. $\delta\mathbf{B}$ maps have a two-minute resolution and a sliding 10-minute integration window, so when combined with SuperDARN data, Poynting flux maps are calculated at a two-minutes resolution.

In this study, a superposed epoch analysis of the Poynting flux with an epoch spacing of two minutes was carried out for sustained transitions of the IMF B_z component. IMF data is obtained from the 1-minute resolution OMNI dataset (retrieved from `http://omniweb.gsfc.nasa.gov`) and is time shifted forward by 10 minutes to account for the travel between the magnetopause and ionosphere. "Sustained" transitions are defined as intervals where B_z was constantly northward (southward) orientated for at least 30 minutes prior to becoming southward (northward), upon which the sign of B_z remained the same for an additional 30 minutes. Using 30 minutes prior to the transition allows time for the ionosphere to be "settled" under the initial negative or positive B_z by epoch t_0. 30 minutes after the transition gives a window to examine the Poynting flux response to the IMF change, which is long enough for the ionospheric electric field to converge to state equivalent to statistical patterns on average (Grocott & Milan, 2014). In order to maintain a high number of Poynting flux maps for averaging, no B_z magnitude threshold was imposed and the IMF B_y component was not considered.

3 Results

The results of the Poynting flux superposed epoch analysis, for sustained north-to-south and south-to-north IMF B_z transitions, are shown in Figure 1. There were 1301 north-to-south and 1307 south-to-north transitions during the SuperDARN-AMPERE overlap period, but only Poynting flux maps which met the 200 SuperDARN data point threshold were used in the average for each epoch (the total in each denoted by the number in the top left of the sub-plots). There was no transition bias towards a specific year, season, sign of B_y or magnitude of B_z.

The patterns shown in Figure 1 are from 4 minutes prior to the IMF transition to 30 minutes after in two-minute intervals. Epochs prior to $\mathrm{t}_0 - 4$ are not shown here as they do not vary significantly from $\mathrm{t}_0 - 4$. Only positive (downward) Poynting fluxes are shown, as negative (upward) values are nearly always small, thus averaging out. This is to be expected because the ionosphere is on average a passive load to the magnetosphere, not vice versa. We note that more Poynting maps meet the 200 SuperDARN data point criteria when the IMF is southward, signifying the SuperDARN radars receiving more ionospheric backscatter during more geomagnetically active periods.

For the north-to-south transition in Figure 1a, there are regions of enhanced downward Poynting flux (PF) that are consistent in their morphology throughout all epochs. These are lower latitude enhancements around 70° latitude on both the dawn and dusk sides, as well as a higher latitude enhancement around 80° latitude centred slightly duskward of noon MLT. Before t_0, the highest PF magnitude is in the high-latitude dayside region. From t_0 to t_0+30, PF gradually increases starting at dayside local times and eventually affecting nightside local times. The largest PF magnitudes at t_0+30 are located around 80° latitude centred on noon MLT, as well as around 70° latitude in the 05-09 and 13-18 MLT regions. PF is noticeably smaller for nightside local times, and non-existent near midnight for all latitudes. There is a gradual movement of dawn and duskside enhanced PF equatorward between t_0 and t_0+30.

In Figure 1b, the IMF B_z south-to-north transition of downward Poynting flux is shown. Before t_0, the magnitudes are similar to that in the t_0+30 epoch of the northward-

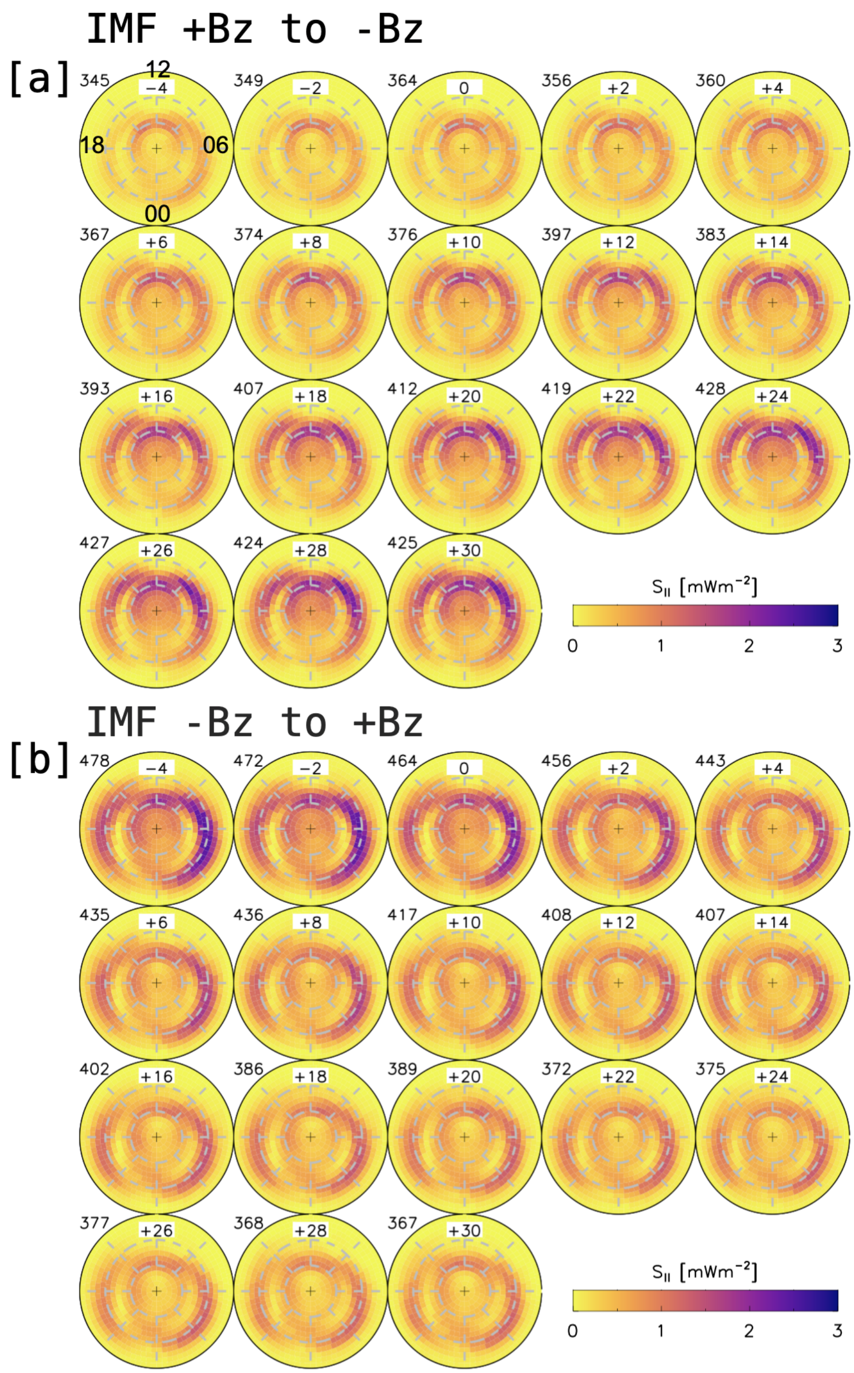

Figure 1. Superposed epoch maps of the downward Poynting flux from $t_0 - 4$ to $t_0 + 30$, for [a] northward-to-southward and [b] southward-to-northward IMF B_z transitions. Plots are polar projections in AACGM latitude and local time. Noon is to the top and dawn is to the right of each plot. Concentric circles separate 10° of latitude, down to a 60° minimum. Numbers in the top left of each plot denote the number of averages in each epoch.

to-southward transition shown in 1a, but the enhanced dawnside PF extends significantly closer to midnight MLT. At +2 minutes, there appears to be a steep decrease in PF magnitude when compared to t_0, which is particularly evident in the high-latitude dayside and lower latitude dawnside regions. A similar sharp change after t_0 does not seem to be present for the B_z northward-to-southward transition in Figure 1a. At t_0+30 in Figure 1b, the PF is decreased at all local times from t_0.

To further examine the changes in downward Poynting flux magnitudes after the IMF B_z transitions, Figure 2 shows sets of time series plots from 30 minutes prior to 30 minutes after a transition. The data has been averaged over four local time sectors 6 hours in width each: the nightside (21-03 MLT, red diamonds), dawnside (03-09 MLT, blue squares), dayside (09-15 MLT, yellow circles) and duskside (15-21 MLT, green triangles). The time series have also been area integrated both below and above 75° latitude to differentiate between Poynting flux variations in the lower and higher latitude regions identified previously. The result is the total inbound power for 8 sectors, which we refer to as Poynting flux power (PFP).

Figure 2a shows the B_z north-to-south transition for the lower latitude (<75°) region. Prior to t_0, dawnside and nightside PFP is the largest (∼0.3 GW), followed by duskside (∼0.25 GW) and dayside (<0.05 GW). Dawn and duskside PFP increase after t_0 at a steady rate, to 0.9 and 0.8 GW respectively at t_0+30, with duskside PFP overtaking the magnitude of nightside PFP. Dayside PFP increases to 0.2 GW after t_0, whilst nightside PFP changes very little.

For the higher latitude (<75°) B_z north-to-south transition (Figure 2b), all regions average a PFP between 0.2 and 0.4 GW before t_0. Dayside PFP is largest and undergoes the most significant increase between t_0 and t_0+30, up to ∼ 1.1 GW. Dawn and duskside PFP remain comparable as they increase to 0.7 GW, while nightside PFP increases very gradually to 0.35 GW.

In Figure 2c, the B_z south-to-north transition for the lower latitude region is shown. From before t_0 to t_0+30, dawnside PFP decreases from 1.4 to 0.6 GW, duskside from 1.05 to 0.5 GW, nightside from 0.6 to 0.5 GW and dayside from 0.35 to 0.1 GW. We note that the PFP magnitudes at the beginning (t_0-30) of the epoch analysis, in particular on the dawn and dusk sides, are larger than corresponding magnitudes at t_0+30 in figure 2a (i.e., the reverse B_z transition). This implies that 30 minutes is not long enough

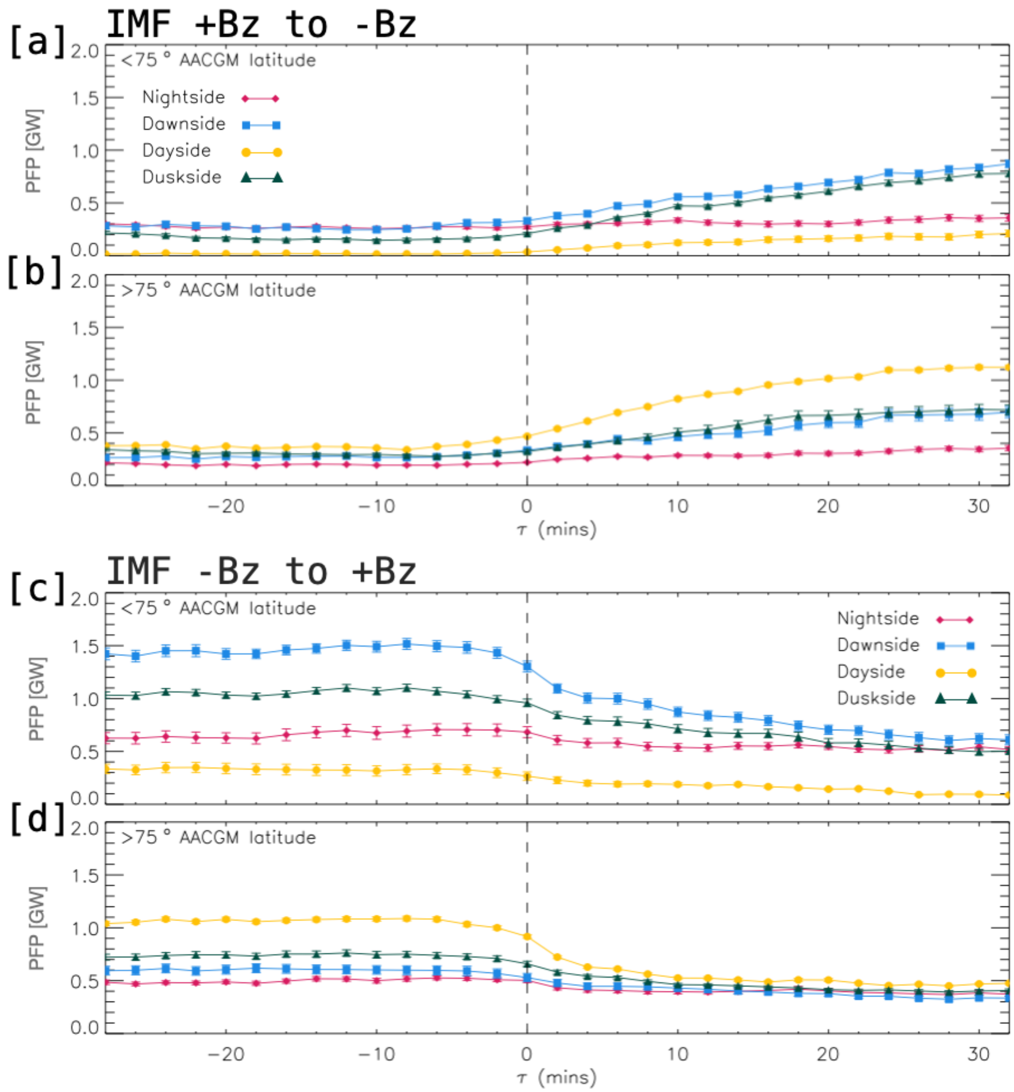

Figure 2. Superposed epoch time series of the downward Poynting flux averaged over nightside, dawnside, dayside and duskside local times. [a] and [b]: northward-to-southward transitions. [c] and [d]: southward-to-northward transitions. Averages are also split into below ([a] and [c]) and above ([b] and [d]) 75° latitude. Standard errors are also shown, but are often smaller than the plotting symbols used.

for the Poynting flux magnitude to stabilise to the new IMF orientation, which will be commented on further in the discussion section.

Dayside PFP is dominant at high latitudes for the B_z south-to-north transition (Figure 2d), dropping from 1.05 before t_0 to 0.5 GW at t_0+30. Duskside, dawnside and nightside PFP have lower initial magnitudes of 0.7, 0.6 and 0.5 GW respectively, all decreasing to ∼0.35-0.4 GW. We note that for south-to-north B_z transitions (both Figure 2d and e), the initial PFP decrease after t_0 appears sharper at all local times than the corresponding increase in the north-to-south transition (Figure 2a and b).

From Figure 2, it is evident that different local times and latitudinal regions respond at different rates to an IMF B_z transition. In Figure 3, maps of the Poynting flux percentage increase (for B_z north-to-south transitions, [a]) and percentage decrease (for south-to-north transitions, [b]) from t_0 are shown. Epochs shown are from t_0+2 minutes to t_0+30 minutes. Only the percentage increase or decrease is shown for respective transitions because on average, the Poynting flux does not decrease for B_z north-to-south transitions and vice versa. This is not strictly true for single events and localised regions where very small PF fluctuations can occur in both the positive and negative direction, irregardless of B_z transition. Small localised fluctuations, defined as a <0.1 mWm^{-2} increase or decrease from t_0, are however removed from Figure 3. Figure 3 is not to illustrate the magnitude of Poynting flux changes in certain regions, but more as an indication of the rate of Poynting flux change normalised by initial magnitudes at t_0

In Figure 3a, large percentage enhancements of the Poynting flux (+100% or more) within 10 minutes of the B_z north-to-south transition occur on the dayside and propagate towards the nightside, mainly between 65-75° latitude and near the pole. In particular, the post-noon sector PF appears to increase the fastest. The nightside propagation continues with increasing epoch up to 30 minutes after the transition, where percentage increases from t_0 reach nearly +400% on the dayside in the post- and pre-noon sectors. There is a clear gradual expansion of the enhancement regions equatorward with increasing epoch, particularly on the nightside a few hours pre- and post-midnight, where there are large percentage enhancements near 60° latitude at t_0+30.

Within 10 minutes of a B_z south-to-north transition (Figure 3b), Poynting flux percentage decreases of several tens of percent appear to occur both on the day and nightside simultaneously. This initial decrease occurs across most local times and is roughly confined to near the pole (particularly on the dayside), as well as between 65-75° latitude on the dawn and dusk sides. PF continues to decrease on the dawn and dusk sides with increasing epoch, decreasing first at lower latitudes and then later at higher latitudes. By t_0+30, PF decreases by as much as 80% at lower latitudes on the dawn and dusk sides have occurred.

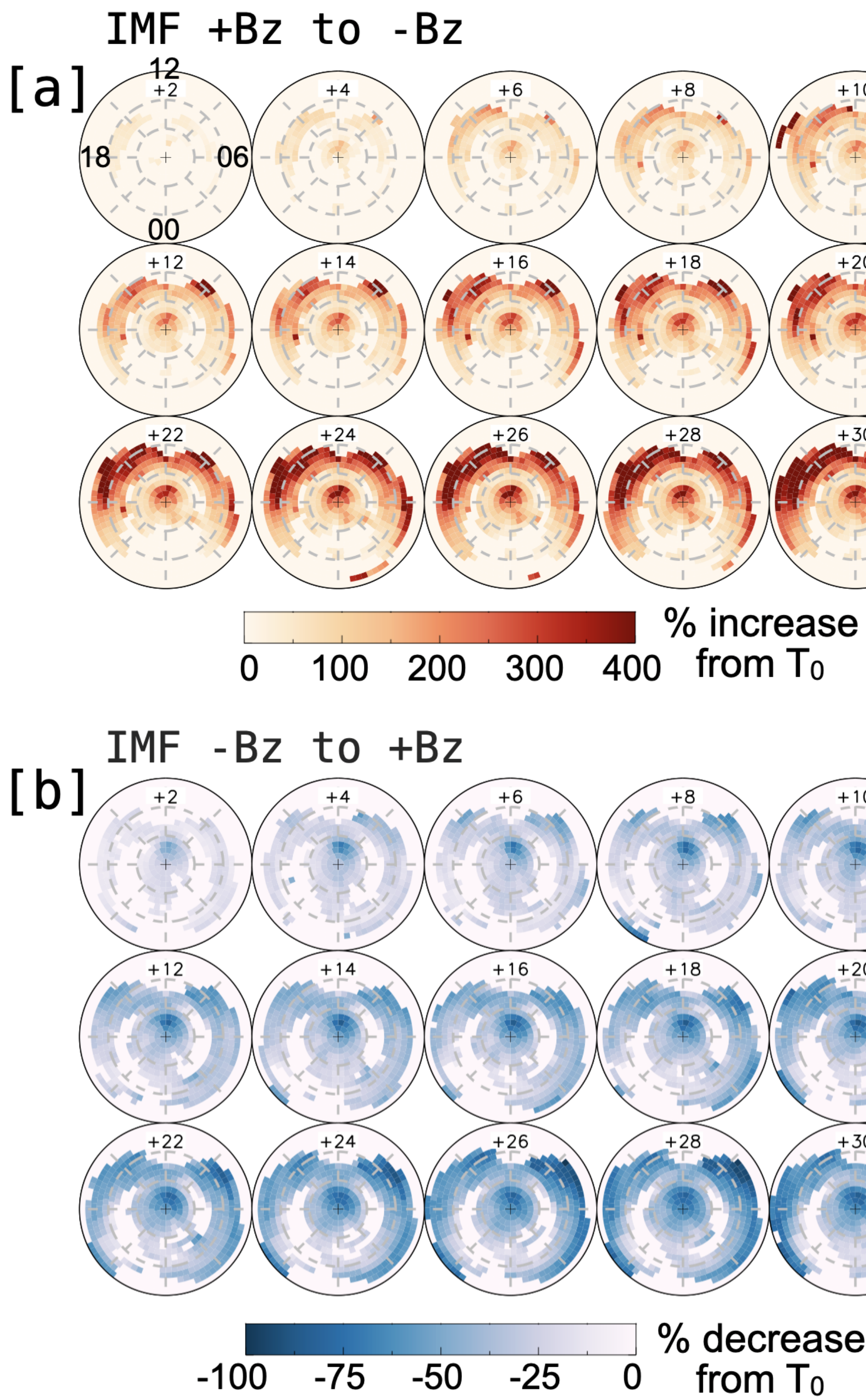

Figure 3. Poynting flux percentage change maps from epoch t_0. [a]: Percentage increase after northward-to-southward transitions. [b]: Percentage decrease after southward-to-northward transitions.

4 Discussion

The superposed epoch analysis presented in this study has shown the reconfiguration process of high-latitude Poynting flux in response to sign transitions of the IMF B_z component, with a two-minute temporal resolution and a spatial resolution of a few hundred kilometres. The Poynting flux patterns shown in this study have a similar general morphology to those in previous studies of Poynting Flux/Joule heating (e.g. Weimer, 2005; Cosgrove et al., 2014) as well as the initial manuscript that introduces this data set (Billett et al., 2021). In short, Poynting flux is mostly dissipated at the the auroral electrojets where R1/R2 FACs close on the dawn/dusk sides, as well as around the dayside cusp at $\sim$80° latitude. Many previous authors have noted that the high-latitude ionosphere responds almost instantly to IMF changes (e.g. Murr & Hughes, 2001), and we too observe a very fast (<2 minute) response of the Poynting flux for both north-to-south and south-to-north B_z transitions. The differences between the magnitude of Poynting flux before a transition and 30 minutes after are drastic, but the timescales of which changes occur in local time are gradual and not symmetric for opposite B_z transitions.

We have found that 30 minutes is not long enough for the morphology of Poynting flux to fully reconfigure after an IMF transition, but is long enough to reveal significant asymmetries between the two transitions types shown here. Figure 2a and d for example shows that PFP in the low latitude dawn and dusk sectors do not totally converge to pre-transition magnitudes of the opposite transition. The full Poynting flux reconfiguration timescale is thus consistent with FAC reconfiguration timescales reported by previous authors (e.g. Anderson et al., 2018; Coxon et al., 2019). Our results are also in agreement with Moretto et al. (2021), in that most of the Poynting flux reconfigures within 30 minutes following a B_z transition. The high-latitude dayside region, the area dominated by Poynting flux into the cusp, conversely appears to completely reconfigure within 30 minutes of a B_z transition. As the cusp region is typically close to the boundary between open and closed (to the solar wind) geomagnetic field lines, the shorter reconfiguration time is perhaps not surprising.

For both B_z transitions, there is a region close to the pole on the dayside that experiences a large percentage increase or decrease in downward Poynting flux (Figure 3). This region is on newly opened field lines following a southward transition, and connected to the magnetospheric lobes following a northward transition. The Poynting flux magnitude is not particularly large near the pole compared to the main regions of enhancement, but the change that occurs there is drastic probably because the electric field rapidly changes in response to IMF orientation fluctuations. During southward IMF for example, **E** is strongly duskward near the pole (i.e. anti-sunward convection) and starts decreasing within a few minutes following a northward turning (Knipp et al., 1991). The opposite also occurs quickly for the north-to-south transition.

Evident in our analysis is the expanding-contracting polar cap (Cowley & Lockwood, 1992). After IMF B_z north-to-south transitions for example, we can clearly see an immediate increase of the dayside downward Poynting flux, followed by increases at local times gradually approaching nightside local times (Figure 3a). This is in agreement with magnetopause reconnection transferring flux into the polar cap and causing it to expand, activating R1 and R2 field aligned currents on the dayside. Anderson et al. (2018) noted that night side FAC activation was lagged approximately 30 minutes after the onset of dayside currents, caused by the release of magnetic flux build up in the magnetotail, which would explain why Poynting flux increases appear heavily dayside dominant for the first 30 minutes following a B_z north-to-south transition. A future study in this area could focus on Poynting flux changes later than 30 minutes post IMF transition, examining in more depth the dayside-to-nightside morphology changes.

A perhaps surprising result is that for B_z south-to-north transitions, the decrease of Poynting flux at both dayside and nightside local times seem relatively symmetric (Figure 3b), with perhaps a slightly faster decrease on the dayside. It would perhaps be expected that the sudden ending of magnetopause reconnection would cause dayside Poynting flux to decrease whilst nightside reconnection lingers, causing a lagged nightside response (in line with the $\sim$30-minute reconfiguration times of the ionospheric electric field; Grocott & Milan, 2014). As this is not the case, the relatively symmetric decrease of Poynting flux at most local times could be due to the neutral wind flywheel effect maintaining the ionospheric electric field. That is, after the winds were previously enhanced by ion-neutral collisions (whilst the ionosphere was being actively driven by magnetopause reconnection), they maintained ionospheric plasma circulation when the IMF turned northward (e.g. Deng et al., 1991).

In addition to the ionospheric electric field, the Poynting flux is also controlled by magnetic perturbations from FACs. The role of the ionospheric Pedersen conductance plays an important role in the generation and decay of FACs, thus impacting the decay of Poynting flux after the south-to-north B_z transition. A higher conductance can result in slower FAC formation or decay (Moretto et al., 2021), so the lower conductance of the nightside compared to the dayside would result in faster nightside FAC decay. Immediately after a northward transition of B_z however, following the extended period of southward B_z, substorms and the auroral oval may still be active and thus contribute to higher conductance in the nightside auroral zones. Additionally, on the dayside, the generation of NBZ currents following a northward IMF transition impede dayside FAC decay (Milan et al., 2018). After a B_z northward transition, there must be a complicated balance between conductance at various dayside and nightside local times for the Poynting flux to decrease roughly at the same rate.

5 Summary

In summary, we have performed a superposed epoch analysis of the high-latitude northern hemisphere Poynting flux to changes in the IMF B_z component. The analysis was carried out using ∼7.5 years of overlapping SuperDARN and AMPERE data at a 2-minute resolution, allowing for a data driven look at how the magnitude and morphology of Poynting flux changes when then Dungey cycle is switched “on” or “off”. Our key results are that:

- B_z positive-to-negative and negative-to-positive transitions are not symmetric in how Poynting flux increases or decreases. For positive-to-negative, there is a clear dayside-to-nightside progression of the increasing Poynting flux. For negative-to-positive transitions, Poynting flux decreases simultaneously at most local times, with dayside Poynting flux decreasing only slightly faster than that on the nightside.
- Total reconfiguration times of the Poynting flux morphology and magnitudes are longer than 30 minutes, except in the high-latitude cusp region where it is roughly 30 minutes.

It is likely that there is a complicated interplay between ionospheric conductance on the dayside and nightside, which is affecting Poynting flux decay rates for B_z negative-to-positive transitions and resulting in the near simultaneous decrease at most local times. For example, lingering auroral activity on the nightside or the formation of NBZ currents on the dayside could be lengthening or shortening field-aligned current decay rates respectively. There is also a potential impact from thermospheric winds, as they could maintain the ionospheric electric field after northward B_z turnings due to the flywheel effect.

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