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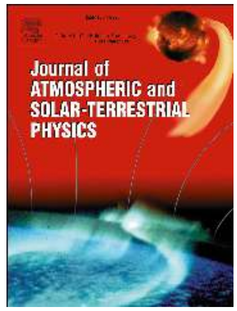

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RELATIONSHIP BETWEEN *PC* INDEX AND MAGNETOSPHERIC FIELD-ALIGNED CURRENTS MEASURED BY SWARM SATELLITES

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Abstract. The relationship between the magnetospheric field-aligned currents (FAC) monitored by the Swarm satellites and the magnetic activity PC index (which is a proxy of the solar wind energy incoming into the magnetosphere) is examined. It is shown that current intensities measured in the R1 and R2 FAC layers at the poleward and equtorward boundaries of the auroral oval are well correlated, the R2 currents being evidently secondary in relation to R1 currents and correlation in the dawn and dusk oval sectors being better than in the noon and night sectors. There is evident relationship between the PC index and the intensity of field-aligned currents in the R1 dawn and dusk layers: increase of FAC intensity in the course of substorm development is accompanied by increasing the PC index values. Correlation between PC and FAC intensities in the R2 dawn and dusk layers is also observed, but it is much weaker. No correlation is observed between PC and field-aligned currents in the midnight as well as in the noon sectors ahead of the substorm expansion phase. The results are indicative of the R1 field-aligned currents as a driver of the polar cap magnetic activity (PC index) and currents in the R2 layer.

Key words: magnetospheric field-aligned currents, auroral oval, PC index of magnetic activity, magnetospheric substorms

1. Introduction

Evidence of magnetospheric field-aligned currents was firstly obtained by [*Zmuda et al.*, 1966] as the transverse magnetic disturbances ΔB measured on board the OGO 4 spacecraft at altitude of 1100 km. The first field-aligned currents patterns presented by *Zmuda and Armstrong* [1970, 1974] were verified by measurements on board the Triad spacecraft [*Iijima and Potemra*, 1976a,b]. The standard pattern of the magnetospheric field-aligned currents (FAC) includes a layer of currents on the poleward boundary of the auroral oval, flowing into the ionosphere in the dawn side and flowing out of the ionosphere in the dusk side (FAC Region 1), and a layer of currents on the equatorward boundary of the oval (FAC Region 2), with oppositely directed field-aligned currents (**Figure 1a**). Currents in Region 1 are observed permanently, even during quiet conditions, where as Region 2 currents are detected in periods of magnetic disturbances in the auroral zone (magnetospheric substorms), the current density in Region 1 being statistically larger than the current density in Region 2 at all local times except the midnight sector during active periods. Experimental data are evidence that currents intensity in the Region 1 FAC layer is strongly dependent on southward interplanetary magnetic field (IMF) [*Langel,* 1975; *McDiarmid et al.,* 1977; *Iijima and Potemra*, 1982] and the appropriate interplanetary electric field [*Bythrow and Potemra,* 1983]. The existing experimental data distinctly indicate that both Region 1 and 2 field-aligned currents flow within the auroral oval (see reviews by *Burch* [1988] and *Kamide* [1988]. During active periods ($|AL|$ > 100 nT) the average latitude width of Regions 1 and 2 increases by 20–30% and complicated small-scale structures are superimposed upon the large-scale field-aligned current features, the most distinguished of them being ”current wedge” providing closure of the tail-neutral sheet currents through the nighttime/evening auroral ionosphere during the substorm explosive phase [*Birkeland,* 1908].

Under conditions of the prolonged northward IMF the field-aligned currents of reverse polarity are observed in the near-pole area (at latitudes of $\Phi > 75°$) [*McDiarmid et al*., 1977, 1978a,b]. These currents (designated as NBZ) flow into the ionosphere in the post-noon sector and flow out of the ionosphere in the prenoon sector of the polar cap. Once more FAC pattern (“cusp FAC region”), with current features strongly dependent on the IMF azimuthal component, is observed in the noon sector of the auroral oval. The corresponding FAC system consists of two current sheets [*Wilhjelm et al.,* 1978], one of which is located on the equatorward side of the cusp, i.e. in Region 1, whereas the other sheet is located on the poleward boundary of the cusp (Region 3). The field-aligned currents in these sheets flow in the oppositely directions determined by sign of the IMF B_Y component. Polarity of currents in the “cusp FAC systems” in the northern and southern hemispheres is opposite.

Numerical simulations of the ionospheric electric field and currents generated by different field-aligned current patterns were carried out by *Gizler et al.,* [1979] and *Troshichev et al.* [1979] based on the actual distribution of ionospheric conductivity in the summer polar cap and on satellite data of field-aligned currents [*Iijima and Potemra*, 1976a,*b*]. The conclusion was made that various FAC patterns are responsible for different types of the polar magnetic disturbances. The Region 1 currents (strongly related to southward IMF) generate specific DP2 magnetic disturbances [*Obayashi,* 1967; *Nishida*, 1968a,b], for which the equivalent current system is composed of two vortices with currents flowing sunward in the near-pole region, the foci of the DP2 current vortices being located just in the sites of Region 1 FAC maximal intensity at the morning and evening poleward boundaries of the auroral oval [*Troshichev*, 1982]. DP2 current system resembles the substorm DP1 system, however, unlike substorms, DP2 system does not include electrojets in the auroral zone.

Thus, within about one decade (1970–1980) it became clear that the polar cap electric fields and currents, and the corresponding magnetic disturbances are generated by the magnetospheric field-aligned currents, structure and intensity of which are determined by the solar wind. So far the polar cap magnetic activity is controlled by the solar wind, it can be considered as a signature of the geoeffective solar wind impact on the magnetosphere. The corresponding *PC* index, characterizing the polar cap magnetic activity, affected by the interplanetary electric field, has been introduced [*Troshichev and Andrezen,* 1985; *Troshichev et al.,* 1988], the polar cap magnetic activity being determined by the magnitude of the DP2 magnetic disturbances (δF) observed at the near-polar stations Thule (Greenland) and Vostok (Antarctica), the interplanetary electric field E_{KL} being determined by formula of *Kan and Lee* [1979]:

$$E_{KL}=Vsw\ [B_Y^2 + B_Z^2]^{1/2}\ sin^2(\theta/2), \quad (1)$$

where Vsw is the solar wind velocity, B_Y and B_Z are the IMF the azimuthal and vertical components, and Θ is a clock angle between the IMF tangential component and the geomagnetic dipole. Connection between the interplanetary electric field E_{KL} and δF values was arranged as linear with statistically justified coefficients of regression $\boldsymbol{\alpha}$ (slope) and $\boldsymbol{\beta}$ (intersection):

$$\delta F = \alpha\, E_{KL} + \beta \quad (2)$$

The regression coefficients were derived, with 5 min resolution, for any UT moment of each day of year on the basis of δF and E_{KL} data for 1995-2005 [*Troshichev et al.,* 2011]. The *PC* index serves as a measure of the E_{KL} field affecting the magnetosphere, irrespective of local time LT, season and hemisphere. The method of the *PC* derivation is described in detail in [*Troshichev and Janzhura*, 2012].

The *PC* index was endorsed at the XXII IAGA Scientific Assembly (Mexico, 2013) as a proxy for energy that enters into the magnetosphere during solar wind-magnetosphere coupling. The following experimental facts are indicative of this statement [*Troshichev et al.,* 2014; *Troshichev and Sormakov,* 2015; *Troshichev and Sormakov,* 2017]: the PC index responds to the $\boldsymbol{E_{KL}}$ field variations with time delays ΔT, values of ΔT being dependent on the $\boldsymbol{E_{KL}}$ growth rate (dE_{KL}/dt); the PC index increase always precedes the magnetic substorms development; the substorm intensity (*AL* index) being linearly related to the *PC* value; the magnetic storms start when the *PC* index steadily (on a time lapse more 1 hour) exceeds the threshold > 1.5 mV/m, the storm intensity (Dst_{MIN}) being linearly related to the values PC_{MAX} preceding the storm maximum.

In this paper we consider, for the first time, the relationship between the *PC* index and the magnetospheric field-aligned currents during the substorm growth phases. The aim of the study is to demonstrate relation of the PC index to current intensity in the R1 and R2 FAC systems in course of substorm development. With this aim the following issues are examined: the relationship between the R1 and R2 FAC intensities in different MLT sectors (morning, evening, noon and midnight); relationship the PC value and R1 and R2 FAC intensities in the morning/evening and noon/midnight MLT sectors; seasonal dependency of relationships between PC and FAC intensities in the R1 and R2 layers.

2. Method of the analysis

Our analysis is based on the FAC data obtained in course of the ESA's Swarm mission launched in November 2013 into a nearpolar orbit [*Olsen et al.,* 2013]. The final constellation of the three-satellite mission was achieved on 17 April 2014, the two satellites, Swarm A and Swarm C, being flown side by side, separated by 1.4° in longitude, at an altitude of about 460 km. Method of estimation of the FAC density by data of Swarm measurements is described in [*Ritter et al.,* 2013; *Lühr et al.,* 2015a,b]. We used, without any additional processing, the data on FAC data presented at http://www.terrapub.co.jp/journals/EPS/pdf/2013/6511/65111285.pdf., which is the official product of the ESA's Swarm mission.

According to this document, the field-aligned currents are assigned as positive, if they flow into the ionosphere, and negative if they flow out of the ionosphere. It means that Swarm satellites, crossing the northern polar cap from dusk to dawn (see **Figure 1b**), will register at the evening polar cap side at first the positive (flowing dawn) Region 2 field-aligned currents and then the negative (flowing up) Region 1 FACs, afterwards, at the morning side of the polar cap, the satellites will register the positive (flowing dawn) Region 1 FACs and then the negative (flowing up) Region 2 FACs. The Swarm satellites intersecting the southern polar region in course of the same orbit will cross the FAC layers in opposite order: at first the negative (flowing up) Region 2 FACs, then positive (flowing dawn) Region 1 FACs, afterwards the negative (flowing up) Region 1 FACs and positive (flowing down) Region 2 FACs. Owing to their orbital configurations after half of year the Swarm satellites intersect the northern polar region from dawn to dusk, and the entire succession of the FAC layer crossing changes for opposite. It means that the Swarm satellites crossover all sectors of the auroral zone through the year and provide information on the field-aligned currents in different LT intervals.

According to Swarm data, the appropriate R1 and R2 FAC layers in the morning/evening sectors are similar in width at the growth stage of substorm (see as an example, Figure 2). In this case, the peak FAC density in R1 and R2 layers can be applied to examine the relationships between the R1 and R2 FAC intensities, as well as relationships between R1/R2 FAC intensities and the corresponding *PC* values. Just peak FAC density in R1 and R2 current layers of the flowing down and flowing up field-aligned currents fixed in course of the each particular crossing the auroral oval are examined further as the indicators of the R1 and R2 FAC intensity.

The polar cap magnetic activity can be affected not only by the R1 and R2 FAC patterns, but also by the NBZ field-aligned currents happened within the polar cap during the magnetic quiescence, and the multiple FAC structures, typical of the nighttime auroral oval during the substorm expansion phase. To eliminate a possible effect of these currents and to reveal a regular relationship between the FAC intensity in R1 and R2 layers and the *PC* index in course of substorm development, we restricted our examination to the isolated substorms that started against the background of magnetic quiescence. Taking into account that the magnetic substorm onsets are always preceded by the *PC*-index growth [*Troshichev et al.,* 2014], the isolated substorms with steadily rising *PC* index during the growth phase were chosen for analysis. This allowed to correlate the *PC* index increase with the FAC intensity of the R1 and R2 current layers in period preceding the substorm sudden onset, and, therefore, ahead of development of FAC systems responsible for the substorm expansion phase.

Figure 2 shows, as a typical example, the time evolution of the *PCN* (blue), *PCS* (red) and *PCmean* (black) indices (upper panel), growth of magnetic disturbance (*AL* index) in the auroral zone (2^{nd} panel), and the corresponding changes in the FAC intensity, registered by Swarm satellites A(black), B(red) and C(blue) in the northern (3^{rd} panel) and southern (4^{th} panel) polar caps in the course of isolated substorms on 22-23 September 2014. As it is established, the positive FAC values in Figure 2 are assigned for downward (flowing into ionosphere) field-aligned currents, the negative FAC values are assigned for upward (flowing out of the ionosphere) currents. Only substorms with distinct FAC signatures, fixed by all Swarm satellites were included in the analysis. In case of multi-layered current structures, the first and last current layers (i.e. the layers located at the poleward and equtorward boundaries of the auroral oval) were examined.

22 isolated substorms, satisfying the above criteria, have been chosen for analysis. The Swarm orbits in the northern and southern polar caps in course of these 22 substorms are shown in **Figure 3**, the orbits related to different days being marked by different colors. One can see that measurements of the FAC intensity in R1 and R2 layers were performed in different MLT sectors over the year. In course of substorm on 22-23 September 2014, shown in Figure 2, three Swarm satellites intersected the northern and southern polar caps 5 times, two crossings of the R1 and R2 FAC layers being occurred in each intersection. As a result, 30 crossings of the R1 and R2 FAC layers took place during only this single substorm (3 satellites *x* 5 polar cap intersection *x* 2 R1 and R2 FAC layers). The total number of the R1and R2 FAC layers crossings for 22 substorms turned to be exceeded N=500. This number was reduced to 460 owing to exclusion of multi-layers current structures of unclear nature and random outliers in FAC measurements. Data on the maximal positive and negative FAC quantities measured by the

Swarm satellites in course of these 460 FAC layer crossings were compared with the appropriate the *PC* indices (i.e. with *PC* indices related to the UT moment of layer crossing).

3. Results of the analysis:

3.1 Correlation between intensities of currents in the R1 and R2 FAC regions

The FAC intensities in the R1 and R2 layers determined by the Swarm satellites were examined separately for morning, evening, noon and midnight sectors. The corresponding relationships between the R1 and R2 FAC intensities are shown in **Figure 4.** As Figure 4a shows, the field-aligned currents in the morning and evening sectors of the auroral zone demonstrate the strong regularity: the R1 FACs are always downwards (flowing into the ionosphere) in the morning sector and always upwards (flowing out of the ionosphere) in the evening sector, whereas the R2 FACs are always upward in the morning sector and downward in the evening sector. Current intensities in R1 and R2 FAC layers are well correlated, in doing so the FAC intensity in Region 1 is nearly twice as large as that in Region 2, in full agreement with statistical results of *Iijima and Potemra* [1978]. This result testifies that R1 currents close not only across the polar cap, but also across the electrojet regions (to connect with R2). It means that generation of the cross-polar cap electric potential and the polar cap magnetic activity (*PC* index) is related to the R1 currents, the influence of R2 FAC currents and auroral electrojects being regarded as negligible. Notice that relationship between intensities the R1 and R2 currents in the morning sector is better than in the evening sector. The phenomenon may be assigned to disorganizing effect of the westward electrojet, which is the most significant in the aftermidnight sector in active periods.

In contrast to the morning/evening sectors, the R1 and R2 FAC currents in the noon and midnight sectors can be both positive and negative, the downwards R2 currents being strongly related to R1 upward currents, and the upward R2 currents being unambiguously related to R1 downward currents. This phenomenon seems to be concerned with three-layer FAC structure in the midnight and noon sectors of the auroral oval (see Figure 1). We suggest that three-layer structures of field-aligned currents shown in Figure 1, present the purely statistical result, whereas two FAC layers are fixed in actuality in course of each auroral oval crossing. The FAC polarity (downward- or upward-flowing currents) in these two layers will depend on whether morning or evening type of FAC structure expands to noon (or midnight) sector. It may be safely suggested that the IMF B_Y component will affect such expansion. As this takes place, dependency of R2 currents on the R1 intensity in the noon and midnight sectors is even more effective than in the morning and evening sectors: the value of slope coefficient, connecting R2 FAC intensity with R1 FAC intensity, increases from 0.52-0.54 to 0.58-0.62, with correlation improving from R=0.74-0.76 to R=0.82. It might be well to point that the correlation in the midnight sector seems to be poorer for positive than for negative R1 FAC intensities, whereas in the noon sector the opposite tendency seems to be act. This question deserves further investigation.

3.2 Relationship between *PC* and the R1 and R2 FAC intensities in the dawn/dusk sectors

Examination of the time evolution of the *PC* index and the R1 FAC intensity in course of individual substorm shows that increase of the R1 FAC intensity in the dawn/dusk sectors is always accompanied by growth of the *PC* index (see, as example, Figure 2), even occasional drops in the FAC intensity are followed by a short-term *PC* decay. The statistical relationships between the *PC* values and intensities of the R1 and R2 field-aligned currents in the dawn (06 MLT ± 4h) and dusk (18 MLT ± 4h) sectors are shown in **Figure 5(a) and 5(b)**, the downwards and upwards currents being assigned as positive and negative currents, correspondingly. The upper panel in Figure 5a demonstrates relationship between *PC* and R1 currents for polar cap intersections in January, February, March, October and November of 2014, the middle panel – for intersections in June, July andAugust of 2014, and lower panel – for all intersections. As Figure 5a shows, the *PC* value evidently correlates with the intensity of the R1 field-aligned currents in the morning as well as in the evening sector of the auroral zone, the correlation in the evening sector (R=-0.62) being lower than in the morning sector (R=0.66). A certain degree of dispersion in the relationships is expectable: the *PC* index represents the magnetic effect related to the integral intensity of the field-aligned currents in both the dawn and dusk sectors of the R1 FAC layer, whereas the measurements of field-aligned currents on board of Swarm satellites concern only that point, where satellite orbit intersects the layer, at the same time the current intensity in other sites of the layer may be different. Moreover, the method of *PC* derivation eliminates effects of the IMF B_Y component in the polar cap magnetic activity, whereas the Swarm measurements take into account this effect.

Since field-aligned currents in R1 and R2 layers well correlate in both morning and evening sectors, there is reason to believe that the intensity of currents in the R2 layer should be also related to the PC index. Indeed, a correlation between *PC* and R2 FAC intensity (for all intersections), while not so good, is observed (**Fig. 5b**), the correlation in the evening sector being lower (R=-0.51) than that in the morning sector (R=0.56). We consider the larger dispersion of data in the evening sector and lower correlation between *PC* and the dusk field-aligned currents as a result of changeability of FAC structures in the evening sector typical of active periods.

The availability of the satellite orbits crossing the southern and northern polar caps in various months of 2014 makes it possible to examine a season effect in relations between *PC* and field-aligned currents. Combining the data of Swarm measurements in opposite hemispheres by local seasons we received the relationships presented in **Figure 6**, the intervals with *PC*>3.5 mV/m, typical of the substorm expansive phase associated with auroral particle precipitation and, correspondingly, with sharp increase of the ionospheric conductivity, being excluded from examination. The results presented in Figure 6a demonstrate that the linear relationship between the *PC* values and the R1 FAC intensity is actually distinct for summer and winter seasons: the R1 FAC intensity in the summer polar cap is about twice as high as in the winter cap under conditions of the same *PC* index. The similar, but much weaker regularity is typical of the R2 FAC layer (Figure 6b).

3.3 Relationship between *PC* and the R1 and R2 FAC intensities in the noon/night sectors

Figures 7 (a) and 7(b) show relationships between values of *PC* and intensity of the R1 and R2 field-aligned currents measured by SWARM satellites in the noon (12 MLT ± 2h) and midnight (24 MLT ± 2h) sectors. In contrast to the field-aligned currents in the dawn and dusk sectors, where the FAC direction (downward or upward) is strongly regulated by layer (R1 or R2) and sector (morning or evening), the field-aligned currents in the noon and night sectors of the R1 and R2 FAC layers may be of any polarity, the downwards currents in one layer being related to upward currents in other layer and vice versa. The main reason of this phenomenon is influence of the IMF B_Y component on the field-aligned currents distribution. According to the measurements taken by the Viking spacecraft (Erlandson *et al.*, 1988), the meridian that separates dawnside and duskside currents in Region 1 in the northern hemisphere is shifted to magnetic local times before noon when $B_Y < 0$, and toward the afternoon side when $B_Y > 0$. In the southern polar region, the dependence of field-aligned currents on the IMF azimuthal component is quite opposite to that in the northern hemisphere. Magnetic activity in the near-pole region is regulated mainly by the R1 FAC intensity in morning and evening sectors and only slightly affected by the field-aligned currents in the noon and night R1 layer. As a result, the *PC* index does not correlate practically with the R1 and R2 FAC intensities in the noon and midnight sectors (coefficients of correlation lie in the range of R=-0.19 to R=0.33).

4. Discussion

Data on the field-aligned currents measured by Swarm satellites in course of 460 crossings of the R1 and R2 FAC layers during 22 isolated storms have been used to study relationship between the *PC* index and field-aligned currents on the substorm growth phase. The results of analysis are the following:

- The field-aligned currents in the R1 FAC layer are always flowing into the ionosphere in the morning sector and flowing out of the ionosphere in the evening sector, whereas the R2 FACs are always flowing out of the ionosphere in the morning sector and flowing into the ionosphere in the evening sector (Figure 4). Current intensities in R1 and R2 FAC layers are well correlated, the FAC intensity in Region 1 being nearly twice as large as that in Region 2 (Figure 4).
- Increase of R1 FAC intensity in the dawn/dusk sectors is always accompanied by the *PC* index growth, the same regularity is seen in case of R2 currents, but linkage between *PC* and R2 FAC intensity is much weaker than between *PC* and R1 FAC intensity (Figure 5).
- Relationship between *PC* and field-aligned currents in R1 layer is distinct in summer and winter seasons: the R1 FAC intensity in the summer polar cap is about twice as high as in the winter cap under conditions of the same *PC* index. The same dependency is valid for R2 layer, but it is much more poor (Figure 6).
- The field-aligned currents in the noon and midnight sectors of R1 and R2 FAC layers can be both positive and negative, the downwards currents in one layer being related to upward currents in other layer and vice versa. Correlation between the *PC* index and R1 and R2 FAC intensities in in the noon and midnight sectors is practically absent (Figure7).

It should be noted that our conclusions concerning the relationships between R1 and R2 FAC intensities and their seasonal dependency are in full agreement with results obtained more than 30 years ago. Indeed, Iijima and Potemra [1978] have indicated that the currents in Region 1 are observed permanently, even during quiet conditions, whereas Region 2 currents are detected in periods of magnetic disturbances in the auroral zone. For all that, the current density in Region 1 is statistically larger than the current density in Region 2 at all local times except active periods in the after-midnight local time sector, where the westward electrojet is the most active. As for seasonal dependency of the field-aligned currents, it was shown [*Fujii et al.*,1981; *Ohtani et al.*,2005] that intensity of Region 1 currents in the winter hemisphere is lowered by the factor of 2-3 in comparison with that in the summer hemisphere. All these results are indicative that the field-aligned currents in Region 1 are primary in relation to R2 currents, and, therefore, increase of the R1 field–aligned currents should be regarded as the main reason for *PC* growth and, correspondingly, for substorm growth phase.

As for the last researches, we would like to note the results of *Laundal et al.* [2015] and *Coxon et al.* [2014]. Like to results *Troshichev et al*., [1979], the results of *Laundal et al.* [2015] show that the polar cap magnetic disturbances in conditions of the sunlight well-conductive ionosphere are generated mainly by Hall currents, which are actual horizontal ionospheric currents caused by actual R1 field-aligned currents in the dawn and dusk sectors of the auroral oval, whereas magnetic disturbances in the dark winter polar cap with low-conductive ionosphere are mainly due to distant effect of actual field-aligned currents. Thus, magnetospheric field-aligned currents serve as a driver of the polar magnetic disturbances irrespective of conductivity of the polar cap ionosphere.

As this takes place, the Region 1 FAC intensity is seasonally dependent [*Fujii et al.,* 1981; *Ohtani et al.*, 2005] since the summer high-conductive polar cap ionosphere provides the better conditions for the FAC closing than the winter ionosphere. The polar cap magnetic activity being powered by the field-aligned currents (and, therefore, by the solar wind parameters) turns out to be controlled also by the ionospheric conductivity, which is maintained by the solar UV irradiation and is subjected to MLT and seasonal variations. The *PC* index was designated to estimate effects of the solar wind impact on the polar cap magnetic activity. In order to exclude the ionospheric conductivity effects, the *PC* index is calculated with reference to quiet daily magnetic variation and with allowance for statistically justified coefficients $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$, which determine a link between $\boldsymbol{E_{KL}}$ field and magnetic disturbance $\boldsymbol{\delta F}$ for each moment of any day of the year (see introduction). It means that the same values of *PC* index can be related to different intensities of the field-aligned currents in the summer and winter polar caps. It is just regularity that is observed in Figure 6: for the same *PC* value the R1 FAC intensity in the summer polar cap is about twice as higher as in the winter cap.

Coxon et al.[2014] carried out the examination of the R1 and R2 field-aligned currents observed by AMPERE spacecraft during substorms observed in period of 2010-2012. Being interested in the large-scale morphology of the R1 and R2 FAC systems, authors examined the current density along each MLT to identify signatures associated with R1 and R2 currents, then these signatures were integrated over both latitude and longitude, and absolute values of the two total (dawn and dusk) R1 currents were averaged as well as absolute values of the two total R2 currents. A superposed epoch analysis method has been used to derive relationship between the mean intensities of R1 and R2 currents (J_1 and J_2), oval colatitudes (L_1 and L_2), geomagnetic indices analogous to the magnetic activity indices AU and AL, and the dayside reconnection rate Φ_D, taken in the following form [*Milan et al.,* 2012]:

$$\Phi_D = L_{eff}\, Vx\, [B_Y^2 + B_Z^2]^{1/2} \sin^{9/2}(\theta/2), \quad (3)$$

where L_{eff} is an effective length scale and *Vx* is radial (X) component of the solar wind velocity. The analysis of *Coxon et al.* [2014] covered the period from 2h before the substorm onset (T=0) to 2h after. It was found that the current ovals expand and contract over the course of a substorm cycle and that currents increase in magnitude approaching substorn onset and are further enhanced in the expansion phase. The AMPERE data also demonstrate the seasonal dependency of the R1 FAC intensity, but, according to *Coxon et al.* [2015], the dependency is not the same in opposite hemispheres: in the southern polar cap the seasonal effect magnitude is three times greater than in the northern cap. The reasons of such distinction remain unclear and the phenomenon needs in further investigation.

It should be noted a similarity between the $\boldsymbol{E_{KL}}$ field and the dayside reconnection rate Φ_D . Indeed, if we compare expression (1) and (3), we found that $\Phi_D = L_{eff} E_{KL} sin^{5/2}(\theta/2)$. Therefore, we can expect a certain agreement between our results and results of *Coxon et al.* [2014]. Actually, both studies demonstrate that current intensity in R1 and R2 layers increases along with *PC* (Φ_D) while approaching the substorm onset. However, as distinct from *Coxon et al.* [2014] who examined the averaged FAC characteristics over the layers R1 and R2, we can assert that intensity of R1 currents in all sectors (dawn, dusk, noon, midnight) is ~1.65 times larger than intensity of R2 currents, indicating convincingly that the R2 currents are secondary in relation to R1 currents. This result is in agreement qualitatively, but not quantitatively, with results of *Coxon et al.* [2014], which demonstrate excess of R1 currents above R2 currents lying in range of 1.05÷1.2. We suggest that this inconsistency is a result of total averaging the FAC characteristics made by *Coxon et al.* [2014].

We can assert also that evident increase of FAC intensity in course of substorm growth phase occurs only in the dawn and dusk FAC layers (see Figure 5). As this takes place, the R1 field-aligned current intensification is accompanied by evident *PC* growth, whereas correlation between *PC* and R2 FAC intensities in the dawn and dusk layers is much weaker and seems to be a consequence of high correlation between R1 and R2 currents. Our results demonstrate (see Figure 7) that the R1 and R2 currents in the noon and midnight sectors do not correlate with *PC* index at all. It implies that field-aligned currents in these sectors are not related to substorm development in course of the growth phase (i.e. before the substorm sudden onset) and, therefore, closure of nighttime FAC through the ionosphere is a distinguishing feature exclusively of the substorm expansion phase.

The results of *Coxon et al.* [2014] are indicative of strong relation of the R1 field-aligned currents to the dayside reconnection rate Φ_D. Our results are indicative of strong relation of field-aligned currents to the polar cap magnetic activity (PC index). Following Dungey's concept, *Coxon et al.* [2014] explain the relationship between R1 FAC and Φ_D by magnetic reconnection between the interplanetary magnetic field and terrestrial field lines at the magnetopause, creation of open magnetic flux interconnecting the interplanetary medium to the polar regions, motion of the open flux tubes from the dayside to the nightside, and subsequent reconnection of the open field lines in the magnetosphere tail, which drives under the certain conditions the substorm development [*Dungey,* 1961]. According to our point of view [*Troshichev and Janzhura,* 2012] the R1 field-aligned currents are generated within the magnetosphere in course of solar wind-magnetosphere interaction. Results of experimental studies [*Iijima et al, 1977; Wing and Newell, 1998,2000; Xing et al., 2009*] and the results of model simulations [*Yang et al.,1994; Yamamoto et a., 1996; Shiokawa et al., 1997*] give evidence of plasma pressure gradients in the magnetosphere as the driving force for both R1 and R2 FAC systems.

It should be noted that examination of relationships between R1 and R2 field-aligned currents and *PC* index, as well as relationships between R1 and R2 field-aligned currents and reconnection rate $\Phi_{D,}$ can not answer by itself what mechanism is responsible for the R1 and R2 FAC generation. To solve the problem another evidences should be taken into account. In this connection we would like to draw attention to results of mapping of the R1 and R2 FAC patterns to the equatorial plane. Such analysis was fulfilled by *Potemra* [1978], with use of the *Fairfield and Mead* [1975] model of magnetic field, and by *Antonova et al.* [2006], with use of the "short" and "long" advanced magnetosphere models of *Tsyganenko* [1996, 2002]. Results of all mappings demonstrate, in spite of difference in models, that both R1 and R2 field-aligned current systems are located whithin the closed magnetosphere. The same conclusion was made by *Chan and Russel* [2000] when analyzing the data on field-aligned currents measured by ISEE 1 and 2 satellites at altitudes 2-9 R_E. It means that generators of the R1 FAC systems are positioned within the closed magnetosphere, not on the dayside magnetopause.

Furthermore, measurements of magnetic field and plasma parameters made in the dayside magnetosheath (the region separating magnetopause from bow shock) are indicative of turbulent properties of plasma inside the layer and inconsistency between the magnetic field polarities on the inner and outer magneto-layer boundaries [*Antonova et al.,* 2012; *Pulinets et al.,* 2014]. These experimental facts are in conflict with Dungey's concept which postulates the immediate contact between geomagnetic and interplanetary magnetic fields at the dayside magnetopause and, as a result, their interconnection. Thus, making allowance to the sum total of the experimental facts we come to conclusion that the polar cap magnetic activity (*PC* index) is initiated by the field-aligned currents which are generated within the magnetosphere in response to the solar wind action.

Conclusions

Analysis of relationship between the *PC* index and field-aligned currents measured by Swarm satellites has demonstrated that increase of FAC intensity in dawn and dusk sectors of the poleward auroral oval boundary (R1 FAC layer) in course of substorm development is evidently accompanied by the *PC* growth. The currents on the equatorward oval boundary (R2 FAC layer) seem to be secondary in relation to R1 currents. Correlation between *PC* and field-aligned currents in the midnight as well as in the noon sectors was not found during the substorm growth phase. These results are indicative of the R1 field-aligned currents as a driver of the polar cap magnetic activity (*PC* index) and currents in the R2 layer.

Results of numerical simulations [*Gizler et al.,* 1979 and *Troshichev et al.,* 1979] have demonstrated that structure of DP2 disturbances in conditions of the well-conductive summer ionosphere is determined by the ionospheric Hall currents, since magnetic effect of the ionospheric Pedersen currents (closing the dawn and dusk parts of the R1 field-aligned currents) is roughly annihilated by distant magnetic effect of the field-aligned currents, in full agreement with theorem of *Fukushima* [1969]. However, magnetic disturbances in the winter polar cap, with low-conductive ionosphere, are mainly due to distant effect of the magnetospheric field-aligned currents [*Troshichev et al*., 1979]. The same conclusion was made recently by *Laundal et al.* [2015] while comparing the ground-based magnetic field measurements from SuperMAG [*Gjerloev*, 2012] with space-based magnetic field measurements and associated Birkeland currents from AMPERE [*Anderson et al.*, 2000; *Waters et al.*, 2001] and electric field measurements from Cluster [*Paschmann et al.*, 1997].

Acknowledgments:

Swarm data is publically available from https://earth.esa.int/web/guest/swarm/data-access. The authors thank Claudia Stolle and Jürgen Matzka for fruitful discussions. The on-line produced *PCN* and *PCS* indices (as well as the archive *PCN* and *PCS* data) are published at the website: http://pcindex.org.

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Figure captions:

Figure 1. (a) Pattern of field-aligned currents derived from Triad data (Iijims and Potemra, 1976a), (b) R1 and R2 FAC layers as they are registered by Swarm spacecraft

Figure 2. Example of time evolution of the *PCN* (blue), *PCS* (red) and *PCmean* (black) indices, variation of AL index and the corresponding changes in the FAC intensity, registered by Swarm satellites A(black), B(red) and C(blue) in the northern (3^{rd} panel) and southern (4^{th} panel) polar caps in the course of isolated substorms on 22-23 September 2014. The peak FAC density in R1 and R2 layers fixed by Swarm B spacecraft in course of the auroral oval crossing in period from 01:37 to 01:53 are marked by vertical lines.

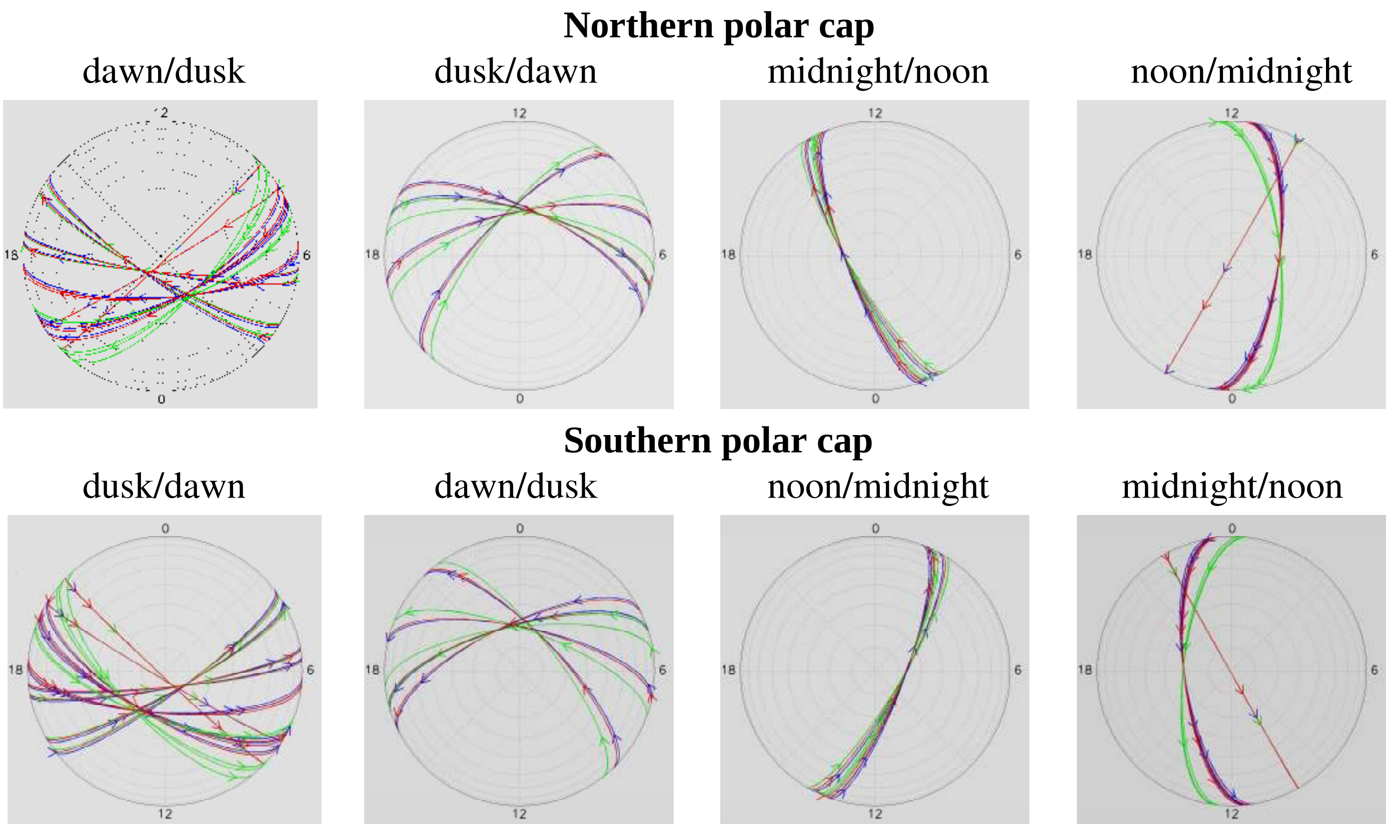
Figure 3. Orbits of Swarm satellites in the northern and southern polar caps in course of 22 selected substorms, the orbits related to different days are marked by different colors.

Figure 4. Correlation between the R1 and R2 FAC intensities in the dawn, dusk, noon and midnight sectors.

Figure 5. Statistical relationships between the *PC* index and the R1 FAC intensity (**a**) in the dawn (06 MLT ± 4h) and dusk (18 MLT ± 4h) sectors for polar cap intersections in January, February, March, October and November (upper panel), June, July and August of 2014 (middle panel), in summary (lower panel) and (**b**) in the noon (12 MLT ± 2h) and midnight (24 MLT ± 2h) sectors in summary.

Figure 6. Statistical relationships between the R1 and R2 FAC intensity and *PC* index in the dawn and dusk sectors for summer and winter seasons.

Figure 7. Statistical relationships between the R1 and R2 FAC intensity and *PC* index in the noon and night sectors.



Jan. 24 (23:18)
Feb. 03 (11:53)
Mar. 02 (22:13)
Mar. 06 (10:26)
Mar. 21 (12:56)
Mar. 26 (03:56)

Oct. 29 (04:56)
Nov. 02 (09:39)
Nov. 04 (05:14)
Nov. 18 (20:39)
Nov. 19 (21:39)

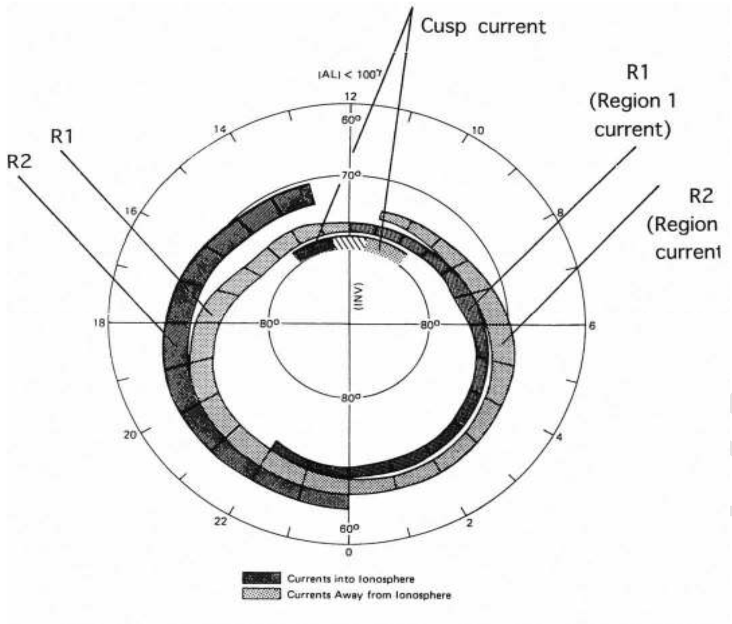
June 08 (01:07)
July 03 (03:23)
July 25 (04:51)
Aug. 01 (08:16)

April 14 (03:28)
April 18 (20:50)
April 19 (22:29)

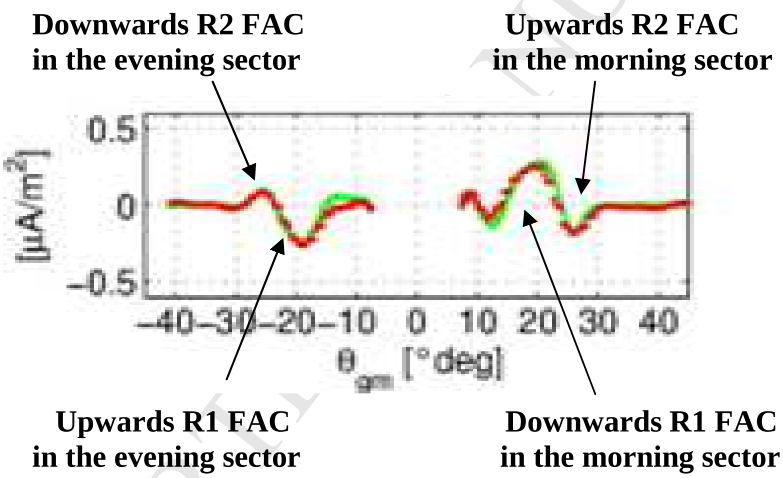
Jan. 12 (03:50)
Sep. 22 (09:22)
Sep. 22 (23:00)
Sep. 24 (06:05)

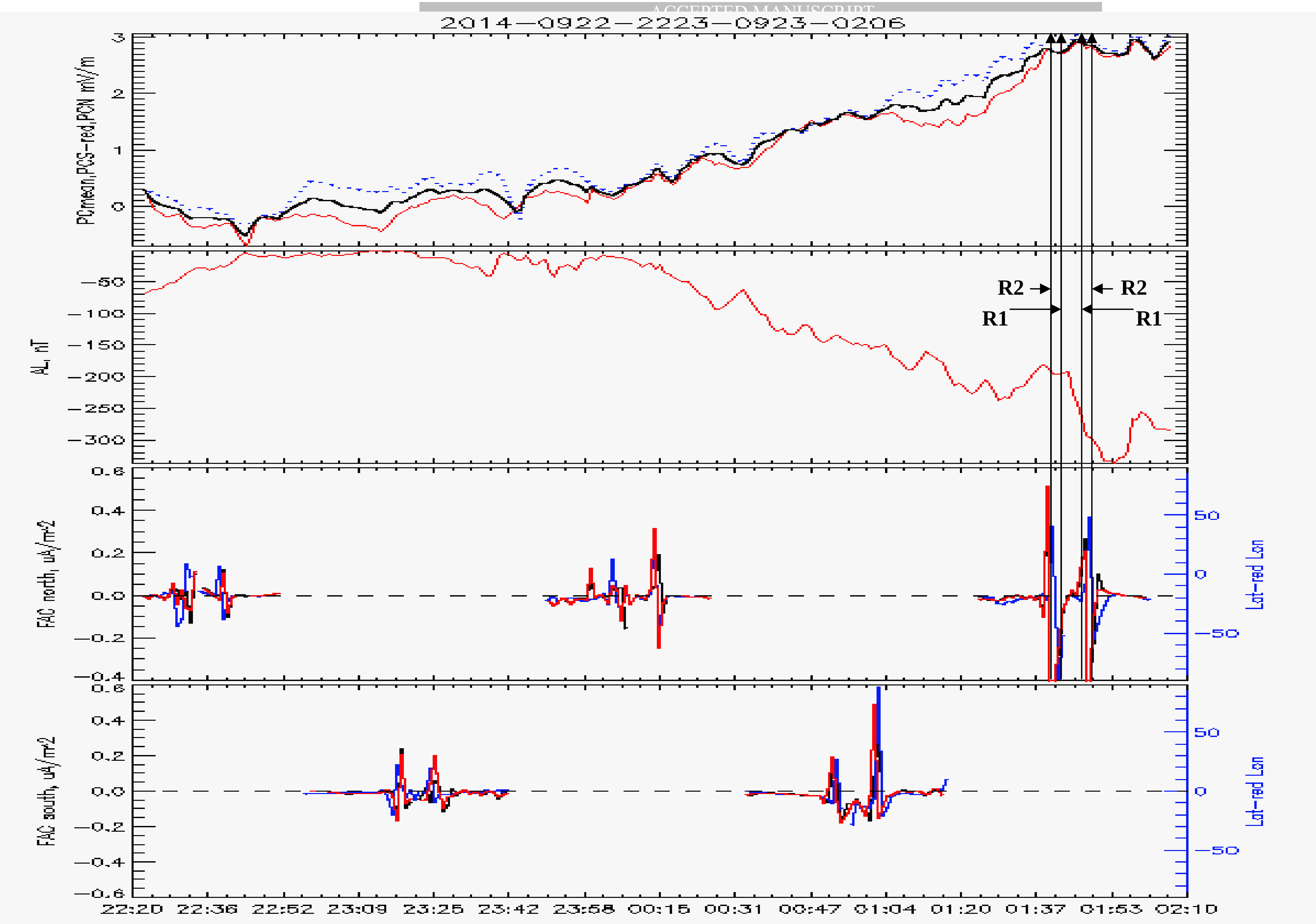
Figure 3

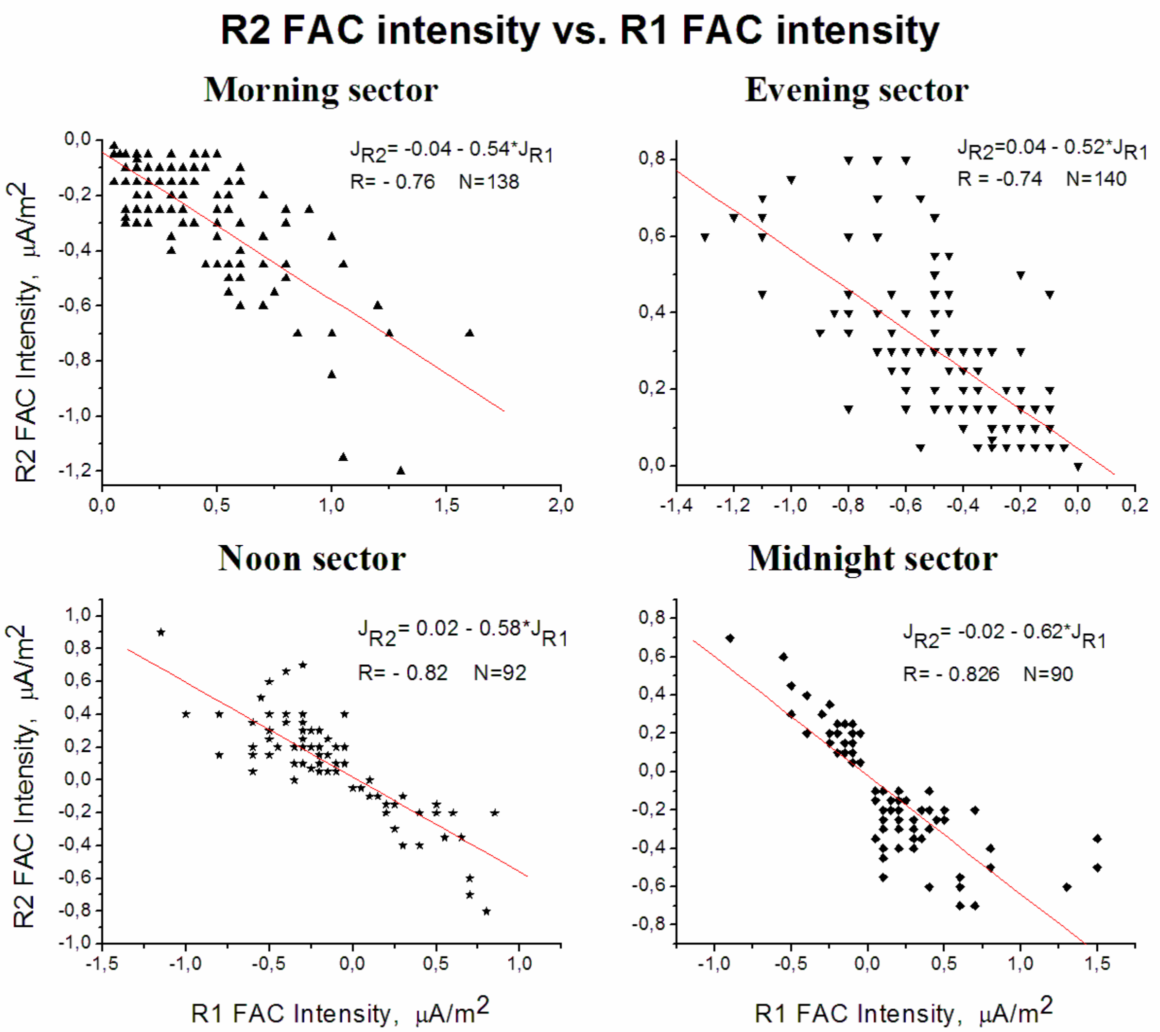
(a)


Cusp current
|AL| < 100γ
R1
(Region 1
current)
R2
(Region
current
R1
R2
Currents into Ionosphere
Currents Away from Ionosphere

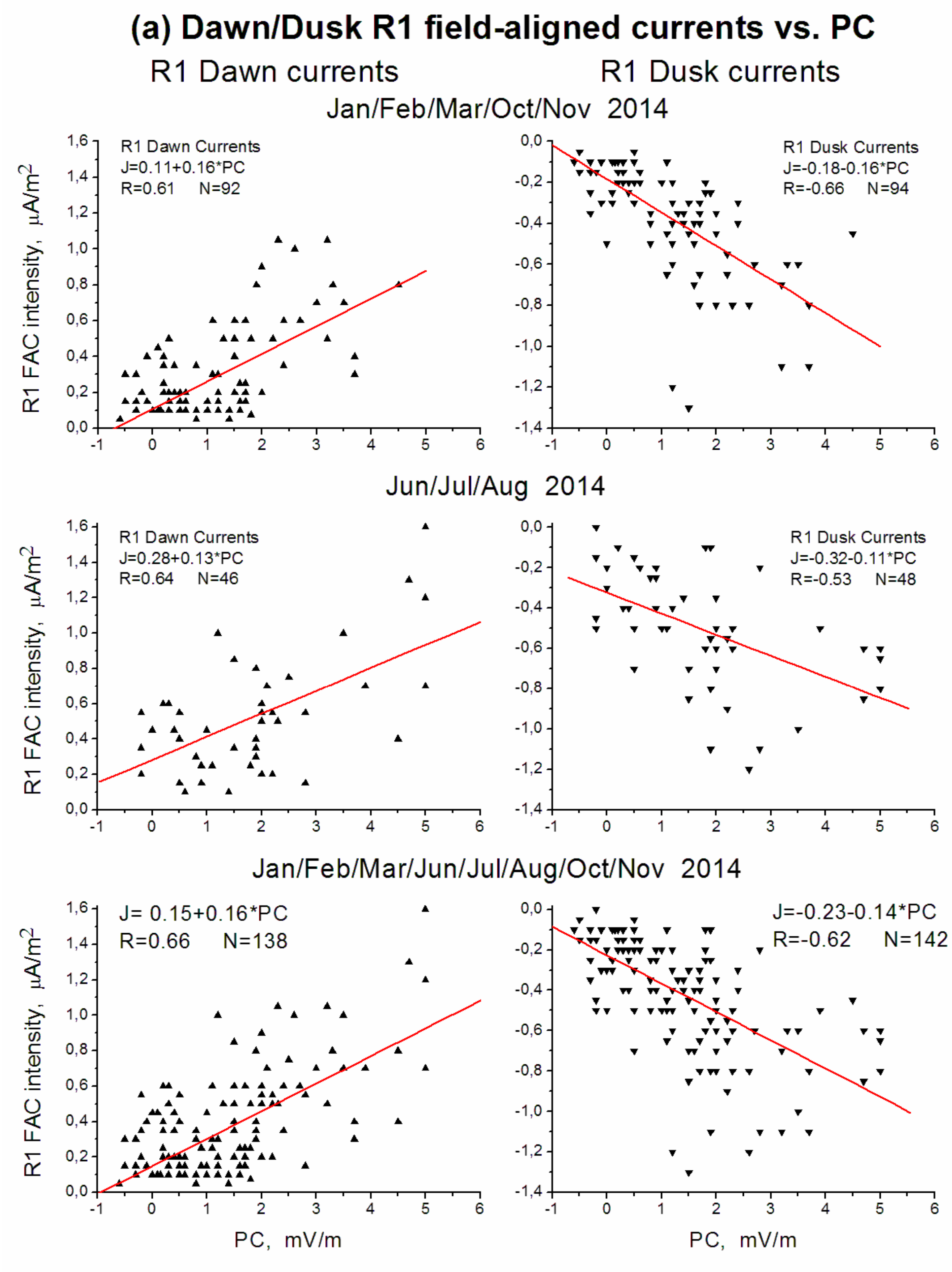
(b)


Downwards R2 FAC
in the evening sector
Upwards R2 FAC
in the morning sector
[μA/m²]
θ_gm [°deg]
Upwards R1 FAC
in the evening sector
Downwards R1 FAC
in the morning sector

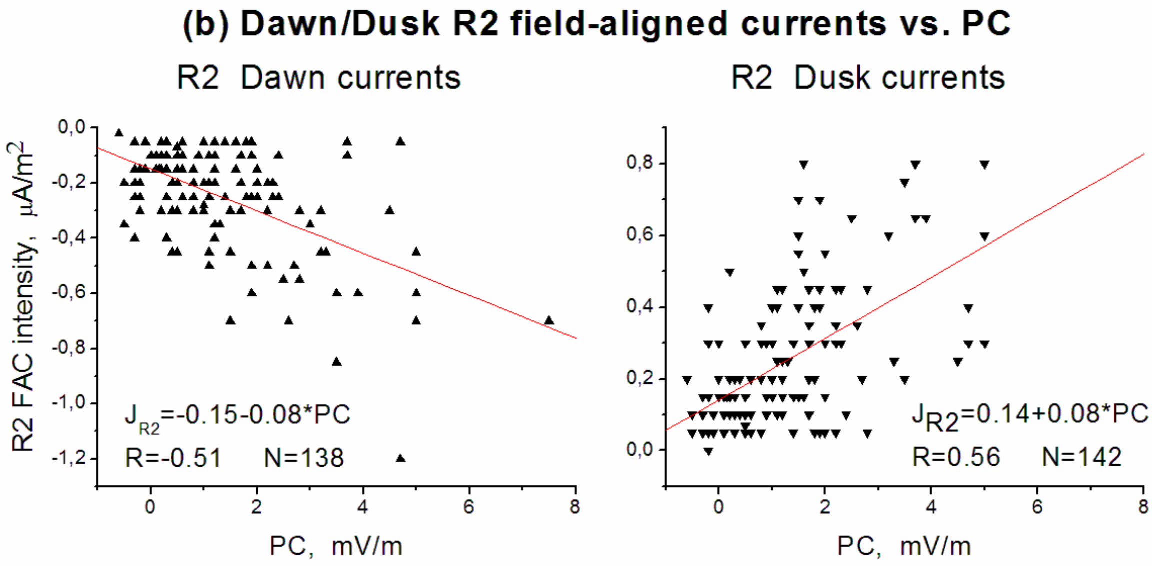

2014-0922-2223-0923-0206
PCmean,PCS-red,PCN mV/m
AL, nT
FAC north, uA/m^2
FAC south, uA/m^2
Lat-red Lon
R2
R1
R2
R1
22:20 22:36 22:52 23:09 23:25 23:42 23:58 00:15 00:31 00:47 01:04 01:20 01:37 01:53 02:10



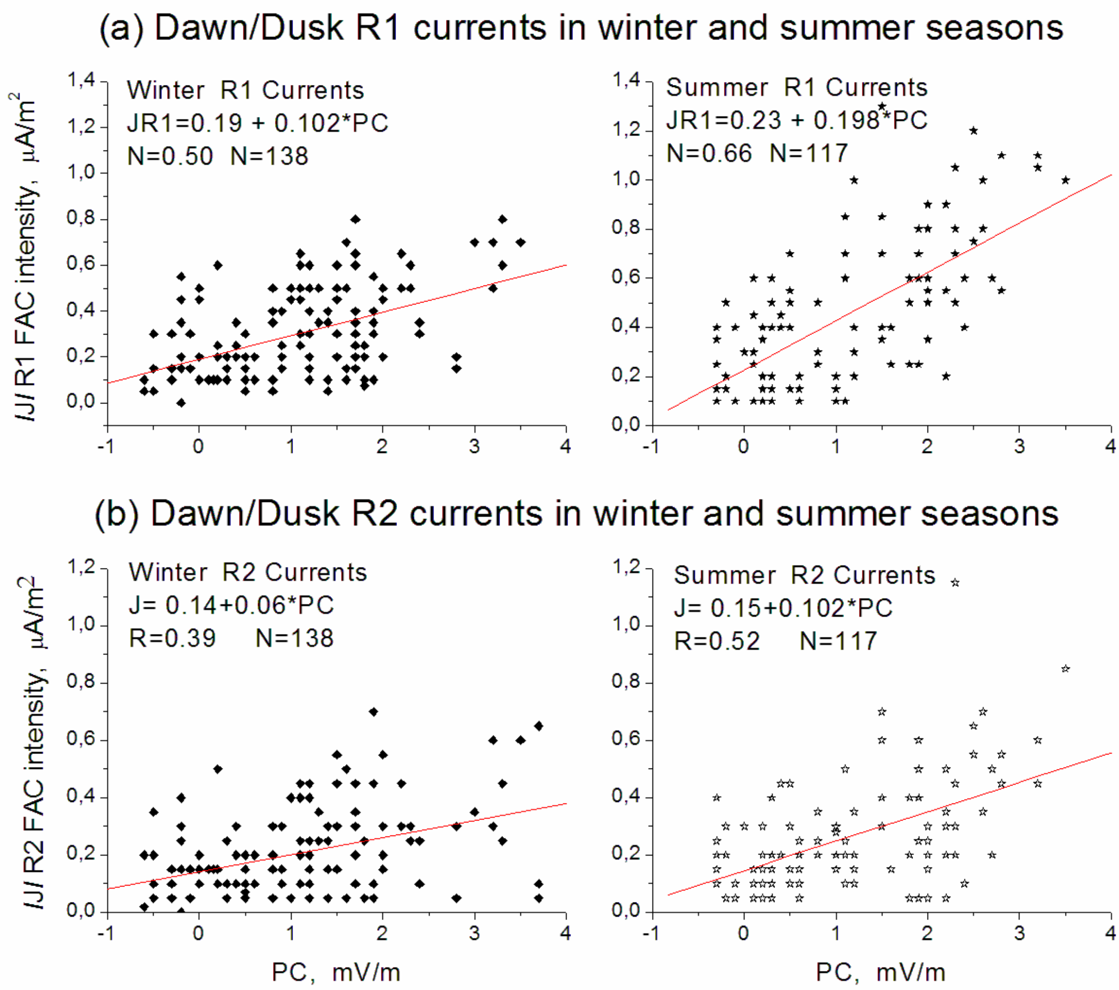
R2 FAC intensity vs. R1 FAC intensity
Morning sector
Evening sector
Noon sector
Midnight sector
J_{R2}= -0.04 - 0.54*J_{R1}
R= - 0.76 N=138
J_{R2}=0.04 - 0.52*J_{R1}
R = -0.74 N=140
J_{R2}= 0.02 - 0.58*J_{R1}
R= - 0.82 N=92
J_{R2}= -0.02 - 0.62*J_{R1}
R= - 0.826 N=90
R2 FAC Intensity, μA/m2
R1 FAC Intensity, μA/m2

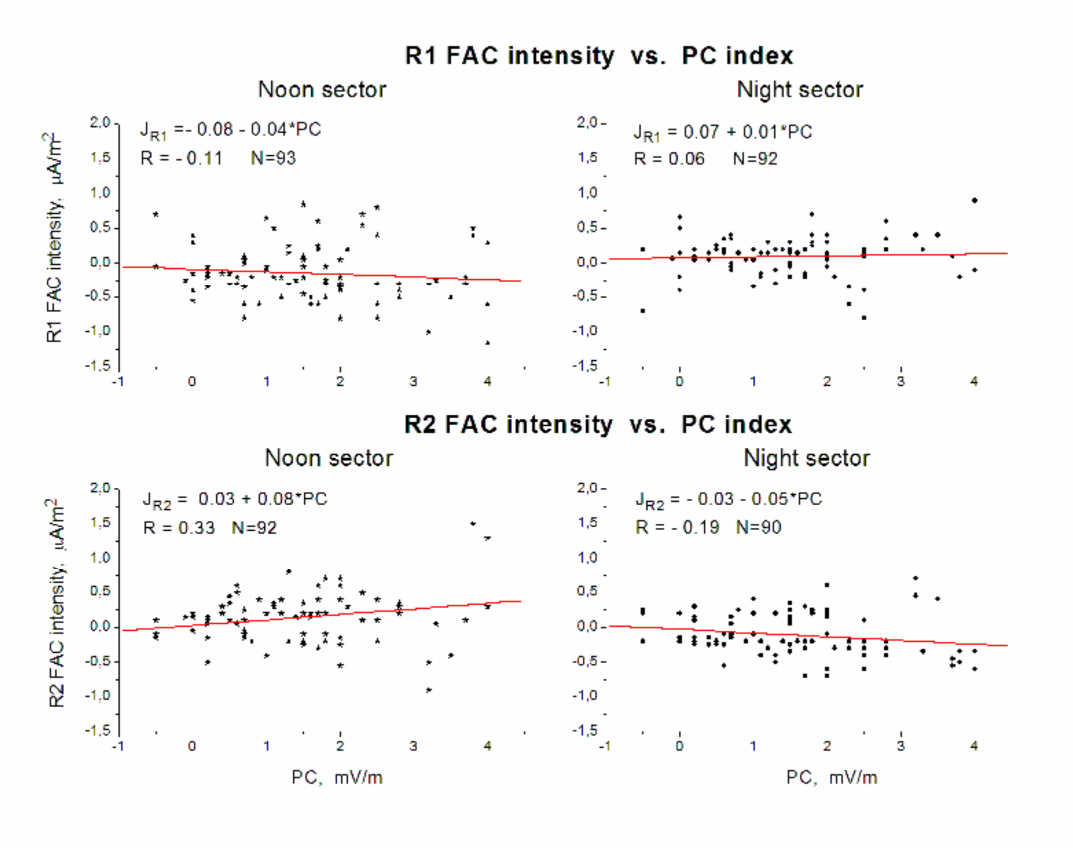


(a) Dawn/Dusk R1 field-aligned currents vs. PC
R1 Dawn currents
R1 Dusk currents
Jan/Feb/Mar/Oct/Nov 2014
R1 Dawn Currents
J=0.11+0.16*PC
R=0.61 N=92
R1 Dusk Currents
J=-0.18-0.16*PC
R=-0.66 N=94
Jun/Jul/Aug 2014
R1 Dawn Currents
J=0.28+0.13*PC
R=0.64 N=46
R1 Dusk Currents
J=-0.32-0.11*PC
R=-0.53 N=48
Jan/Feb/Mar/Jun/Jul/Aug/Oct/Nov 2014
J= 0.15+0.16*PC
R=0.66 N=138
J=-0.23-0.14*PC
R=-0.62 N=142
R1 FAC intensity, μA/m2
PC, mV/m



(b) Dawn/Dusk R2 field-aligned currents vs. PC
R2 Dawn currents
R2 Dusk currents
R2 FAC intensity, μA/m2
PC, mV/m
PC, mV/m
JR2=-0.15-0.08*PC
R=-0.51 N=138
JR2=0.14+0.08*PC
R=0.56 N=142


(a) Dawn/Dusk R1 currents in winter and summer seasons
Winter R1 Currents
JR1=0.19 + 0.102*PC
N=0.50 N=138
Summer R1 Currents
JR1=0.23 + 0.198*PC
N=0.66 N=117
IJI R1 FAC intensity, μA/m2
(b) Dawn/Dusk R2 currents in winter and summer seasons
Winter R2 Currents
J= 0.14+0.06*PC
R=0.39 N=138
Summer R2 Currents
J= 0.15+0.102*PC
R=0.52 N=117
IJI R2 FAC intensity, μA/m2
PC, mV/m
PC, mV/m


R1 FAC intensity vs. PC index
Noon sector
Night sector
J_R1 =- 0.08 - 0.04*PC
R = - 0.11 N=93
J_R1 = 0.07 + 0.01*PC
R = 0.06 N=92
R1 FAC intensity, μA/m²
R2 FAC intensity vs. PC index
Noon sector
Night sector
J_R2 = 0.03 + 0.08*PC
R = 0.33 N=92
J_R2 = - 0.03 - 0.05*PC
R = - 0.19 N=90
R2 FAC intensity, μA/m²
PC, mV/m
PC, mV/m

The R1 and R2 FAC intensities are well correlated in the dawn and dusk sectors, the R2 currents being secondary relative to R1 currents.
Increase of PC index in course of substorm growth phase follows the field-aligned current intensification in the dawn and dusk R1 FAC layers.
Correlation between R1 and R2 currents in the midnight and noon sectors is insignificant,
Correlation between PC and FAC intensity in the midnight and noon R1 FAC layers during the growth phase was not found.