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Does the South Atlantic Anomaly influence the ionospheric Sq current system? Inferences from analysis of ground-based magnetic data

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Abstract

We study if and how the South Atlantic Anomaly influences the ionospheric solar quiet (Sq) current system. Geomagnetically quiet days are processed for the years 1990 and 2011, and the Sq foci tracks are analyzed. The two datasets allow to investigate the influence of the observatory network and the solar activity on the Sq source determination. The computed tracks result in pronounced bands in the northern and southern hemisphere, which seem to neither follow the geographic nor the geomagnetic or dip equator. Remarkably, we observe a distinct scattering of the tracks over the South Atlantic Anomaly. This systematic scattering is due to a larger shift of the southern hemisphere focus northwards during the northern summer solstice and southwards during the southern summer solstice. The physical mechanism of this systematic effect remains unclear. The longitudinal variations of the Sq foci are believed to have their origin from an influence of non-migrating tides as reported in recent studies and the anomalous weak amplitude of the geomagnetic main field over the South Atlantic Anomaly.

Keywords: Geomagnetic daily variation; South Atlantic Anomaly; Ionospheric Sq current system

Background

As a prelude to upcoming electromagnetic (EM) induction studies to determine the three-dimensional (3-D) conductivity structure of the Earth's upper mantle using the solar quiet (Sq) geomagnetic data, it is important to have a clear understanding of the Sq current system variability with respect to local and universal times, day, season, and longitude. A vast literature exists which addresses various aspects of this problem (Fatkullin and Feldstein 1965; Hasegawa 1960; Matsushita and Maeda 1965; Pedatella et al. 2011; Stening 1971; Stening et al. 2007; Stening and Winch 2013; Takeda 1999, 2002, among others). In this paper, we revisit the problem by looking closely at the longitudinal behavior of the Sq foci tracks with the question in mind whether the South Atlantic Anomaly (SAA) influences the Sq current system. The Sq current system is flowing at a 110-km altitude in the thin ionospheric E-layer and has a double vortex structure,

with an anticlockwise (clockwise) whorl in the northern (southern) hemisphere. It is driven by atmospheric tides in the ambient magnetic field of the Earth. These tides are in their turn produced by solar heating of the atmosphere on the sunlit side of the Earth. The interested reader is referred to (Campbell 1989; Olsen 1997; Richmond 1995) for details on the physics behind this current system. The Sq current system is stationary in the Earth-Sun line due to its solar origin with the Earth rotating underneath it. Because of this rotation, one can expect a modulation of Sq by the Earth's main magnetic field, with its most striking mid-latitude feature being the SAA. The SAA describes a low intensity magnetic field area, which spans from east of Africa over the Atlantic Ocean to South America. The SAA is of great interest to the scientific community as well as to the public because high-intensity solar corpuscular radiation can penetrate the Earth's orbit in the SAA region due to the weak main magnetic field. Such penetration can affect or harm the electronic systems of man-made devices such as satellites (Heirtzler 2002).

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Methods

In this section, we introduce the used datasets. We then briefly discuss the methodology on Sq source determination and the computation and analysis of the Sq foci tracks.

Data

The determination of the Sq current system is based on the analysis of data from the global geomagnetic observatory network. To determine the Sq current system from ground-based data, a regular distribution of the observatory sites is desired; however, it is well known that the global network is over-represented by observatories in the northern hemisphere with a distinct concentration in Europe. Figure 1 shows the locations of the observatories from the *Intermagnet* network in the years of 1990 and 2011 alongside with additional observatories which are not part of the *Intermagnet* network. To investigate the robustness of the Sq source determination with respect to the irregular observatory distribution, we exploit two datasets.

Dataset 1 comprises the observatory data recorded during the Australian Wide Array of Geomagnetic Stations (AWAGS) project in addition to the global *Intermagnet* data. Within the AWAGS project, all three components of the geomagnetic field were measured with a sampling interval of 1 min between November 1989 and December 1990 using 53 portable vector magnetometers, from hereon referred to as year 1990 since the majority of the data was recorded in 1990. The instruments were deployed over the Australian mainland with an average site spacing of 275 km (Chamalaun and Barton 1993). Top plots in Figure 1 shows the locations of the *Intermagnet* observatories (left) and the AWAGS sites (right). Dataset 2 comprises *Intermagnet* observatory data from the year 2011. Location of the observatories for this year
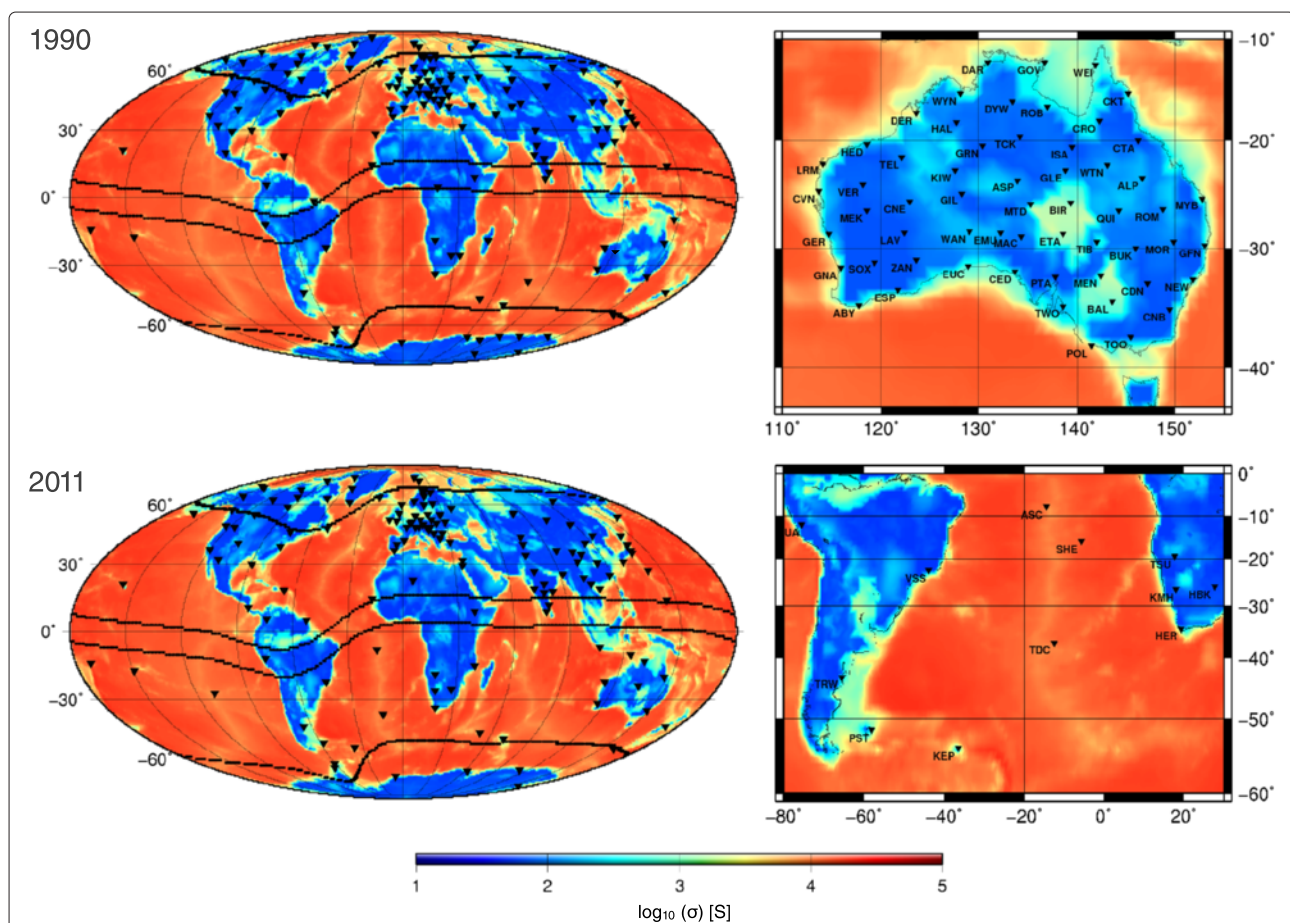

Figure 1 Location of observatory sites for the years 1990 and 2011. The observatories (black triangles) are plotted on top of the surface shell conductance map of (Manoj et al. 2006), which is used in the S3D method to correct for the ocean effect. Black lines show the minimum and maximum dip latitude (+6° and +60°, and −6° and −60°) in between which the mid-latitude observatories are located that were used to determine Sq current system. Top: year 1990 global map (left) with regional map of the AWAGS network (right). Bottom: year 2011 global map (left) with regional map of the South Atlantic (right).

are shown in the bottom plots of Figure 1. The left plot depicts their distribution on a global scale and the right plot demonstrates the observatories in the SAA region.

Dataset 1 allows to balance the *Intermagnet* network, which has a cluster in the European region, with the AWAGS observation sites in order to investigate the influence of the observatory distribution on the Sq source determination. dataset 2, with observatories directly in the region of the SAA - which have not yet been installed in 1990 - allows to investigate whether additional data from the region of interest influences the results. Further, dataset 1 was recorded during a solar cycle maximum and dataset 2 during a solar cycle minimum. This allows for investigating the dependence of the Sq foci tracks on the solar activity.

Bearing in mind the spatial irregularity of *Intermagnet* data, it is strongly desirable to analyze the signals captured during time spans when the source has a spatial structure as simple as possible. The common consensus is that the spatially simplest Sq source geometry is observed during geomagnetically quiet days. As a threshold to separate quiet days from active days, we use the concept of *truly quiet* days, which is based on the geomagnetic *aa*-index (Mayaud 1973). The *aa*-index uses data from two nearly antipodal observatories, which are nowadays Hartland (HAD) observatory in England and the Canberra (CNB) observatory in Australia. With these two stations, which are not influenced by the auroral zone and are well balanced in the north-south as well as in the east-west directions, this geomagnetic index is sensitive to the day-night change of the Sq current system. The *aa*-index is computed in nanotesla (nT) and gives an absolute value for the magnetic activity. Following (Mayaud 1973), we characterize the day as *truly quiet* if $aa < 20$ nT over 48 h, centered on 12:00 UTC and 0.00°E. This criterion assures that the actual Sq day of interest is not influenced by an enhanced geomagnetic activity 12 h before and after the Sq day of interest.

Using this as threshold, we compute the Sq foci tracks of 39 *truly quiet* Sq days in dataset 1 and 129 *truly quiet* Sq days in dataset 2 (Table 1). The time series of the three components of the magnetic field at each observation site for the selected days are then Fourier transformed, and the corresponding spectra for six time harmonics are estimated. These spectra serve as input data for the source determination.

Sq source determination

To determine the Sq source, we exploit the S3D method presented in (Koch and Kuvshinov 2013). It is an attractive alternative to the classic potential method of (Gauss 1838) as used for example by (Schmucker 1999). The potential method is not capable of dealing with a 3-D conductivity model as *a priori* information, which is of particular

Table 1 Summary of Sq days and the resulting median latitudes with respect to seasons and region

	SAA	AUS
Dataset 1 (1990)		
NS (16)	-27 ± 5.9 *(34 ± 5.7)*	-25 ± 5.9 *(33 ± 5.7)*
EQ (7)	-35 ± 5.7 *(33 ± 3.7)*	-25 ± 5.7 *(29 ± 3.7)*
SS (16)	-40 ± 5.1 *(31 ± 2.9)*	-29 ± 5.1 *(31 ± 2.9)*
Dataset 2 (2011)		
NS (25)	-30 ± 5.8 *(36 ± 3.4)*	-25 ± 5.8 *(31 ± 3.4)*
EQ (71)	-36 ± 6.6 *(35 ± 5.4)*	-26 ± 6.6 *(30 ± 5.4)*
SS (23)	-41 ± 5.2 *(30 ± 4.5)*	-27 ± 5.2 *(31 ± 4.5)*

The days for the two datasets are grouped into three sub-categories: NS stands for northern summer days, SS for southern summer days and EQ for the equinoctial transition days. The number in brackets behind the season represents the number of *truly quiet days* in the sub category. We computed the latitudes over two longitudinal sectors for the northern and southern hemisphere. The sector SAA stands for -15° longitude and AUS for the Australian sector at 135° longitude. The numbers represent the seasonal median ± the maximum standard deviation of the day-to-day tracks in the respective sub-category. Figures without brackets stand for the southern hemisphere tracks, figures with brackets and italicized stand for the northern hemisphere tracks. We observe a significant scatter of over 10° in the SAA for the southern hemisphere tracks.

importance to account for the ocean effect (Kuvshinov 2008). The reader is referred to the explanation of the S3D method in (Koch and Kuvshinov 2013) for further details. The Sq source is represented by a specific set of 11 SH coefficients for the 24-h time harmonic and by sets of 12 SH coefficients for the rest of the five time harmonics (12, 8, 6, 4.8, 4 h), as suggested by (Schmucker 1999). It is noted here that for the Sq source determination, we use only mid-latitude observatories in between $\pm 6°$ and $\pm 60°$ dip latitude to avoid effects from polar and equatorial electrojets.

Analysis of Sq foci tracks

We investigate the longitudinal as well as the day-to-day and seasonal variability of the Sq current system. We consider the positions of the Sq foci as proxy for the variability. To estimate the positions of the northern and southern Sq foci for each hour and each day, we first synthesize the Sq current system in a form of the current function on a 1° × 1° regular grid, assigning the current system to the surface of the Earth ($a = 6371\ km$):

$$\Psi(\vec{r}, t) = Re\left(\frac{a}{\mu_0} \sum_{p=1}^{6} \sum_{l,k} \frac{2l+1}{l+1} \epsilon_l^k(\omega_p) Y_l^k(\theta, \phi) e^{i\omega_p t} \right).$$

(1)

Here, $Y_k^l(\theta, \phi)$ is the spherical harmonic of degree k and order l, μ_0 is the magnetic permeability of free space, $\vec{r} = (a, \theta, \phi)$ with θ and ϕ designating geographic colatitude; and longitude, $\sum_{l,k}$ is a short-hand expression for the double sum over k and l, and ω_p is the angular

frequency. Figure 2 shows an example of the synthesized current function for six time instances on the day 1990-05-15. We then define the positions of the northern and the southern Sq foci for each hour of the day as the position where the value of the synthesized current function Ψ reaches the extrema for the respective hour and respective geomagnetic hemisphere (divided along the dip equator). We restrict the search area to day-time regions only, by computing the solar terminator of each individual day.
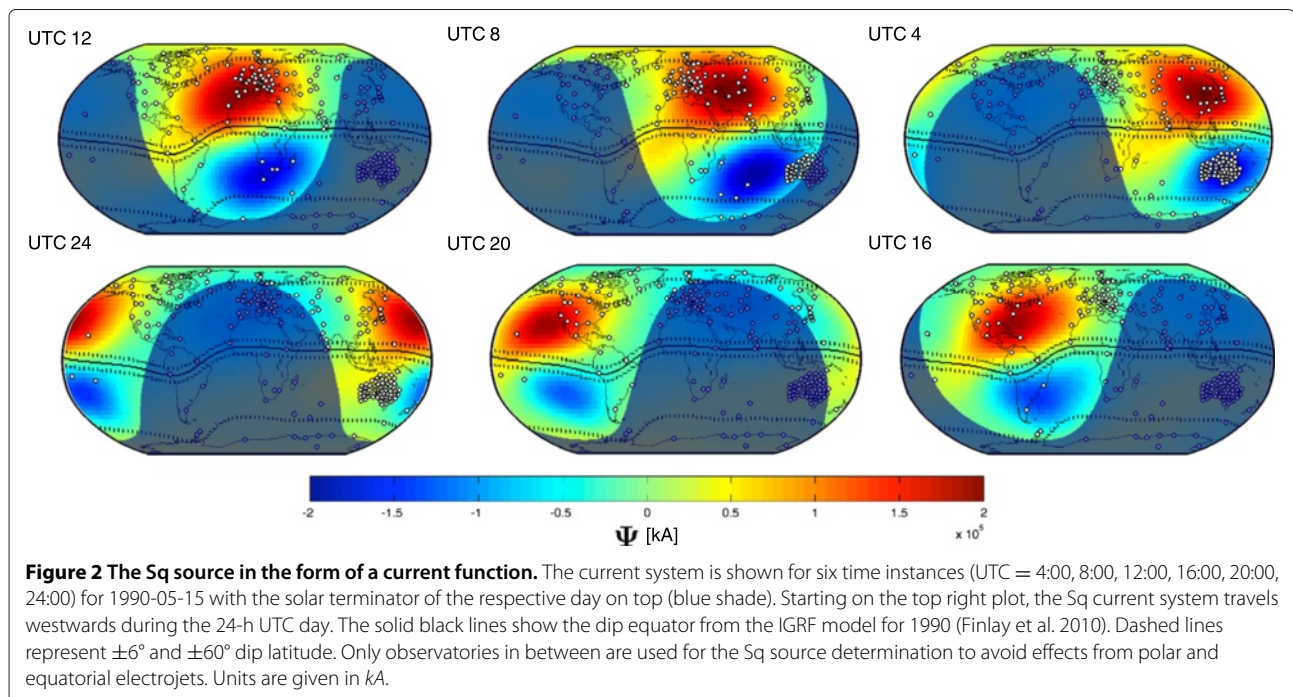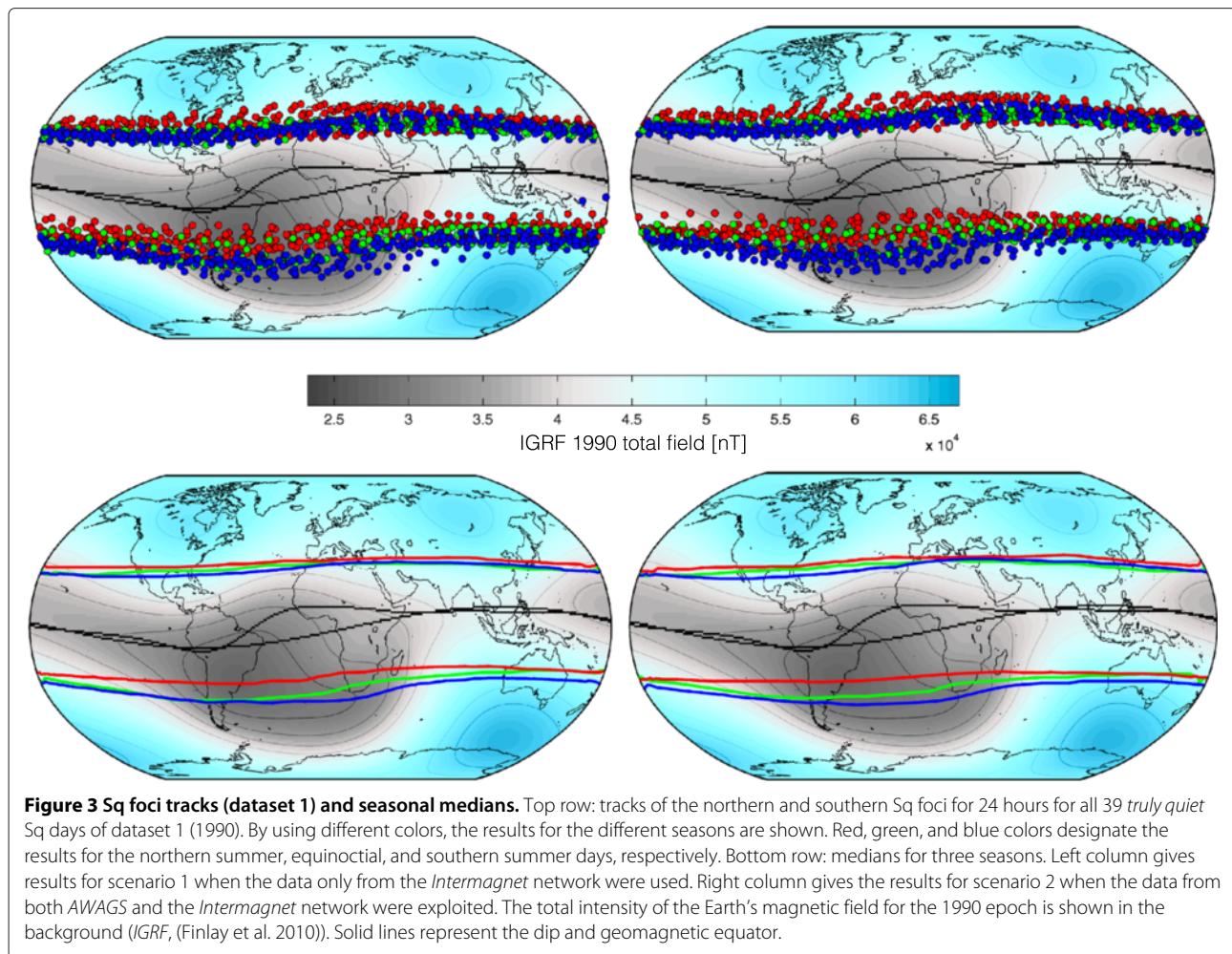
Results and discussion

The resulting Sq foci tracks for the two datasets are shown in Figures 3 and 4.

Sq foci tracks for dataset 1 (1990): Dataset 1 allows to investigate if the unbalanced *Intermagnet* network is capable of obtaining a robust determination of the Sq source by balancing it with the 53 non-permanent AWAGS stations in Australia. The left plots in Figure 3 depict the tracks for scenario 1, when only data from the *Intermagnet* network were used. The right plots present tracks for scenario 2, when data from the *Intermagnet* and AWAGS network were used. The different colors represent results for the different seasons. The red, green, and blue colors denote the results for the northern summer (May, June, July), equinoctial (February, March, April, August, September, October), and southern summer days (November, December, January), respectively (Table 1). The upper plots show the positions of the Sq foci for each day and the lower ones the median values for the

different seasons. The tracks of the Sq foci for all days and all seasons and for the two scenarios manifest as two pronounced mid-latitude bands. One can see that the tracks and the computed seasonal medians neither follow the geographic equator nor the geomagnetic equator and the dip equator. By comparing the results of the two scenarios, we find that the foci tracks are independent of the observatory network which is used to determine the Sq system with respect to the standard deviation (cf. Table 1).

We observe that, overall, the northern tracks are less scattered than the southern tracks. Moreover, we find that the southern Sq tracks show large sensitivity to the seasons in the area of the SAA, where the Earth's main magnetic field is particularly weak. Indeed, we observe a scattered patch of the southern tracks, which is traced from the east of Africa to the east coast of South America. The nature of the scattering appears to be systematic with respect to the seasonal change, best seen in the visualization of the seasonal medians, due to a larger shift of the southern hemisphere focus northwards during the northern summer solstice and southwards during the southern summer solstice. Table 1 shows the seasonal median and its standard deviation over the SAA sector (−15° longitude) and the Australian sector (AUS; 135° longitude) if *Intermagnet* and AWAGS data were used. For dataset 1, we find a significant maximum difference of 13° in latitude between the northern summer (NS) and southern summer (SS) tracks over the SAA region and insignificant difference of 4° over the Australian region, for the southern hemisphere Sq tracks.
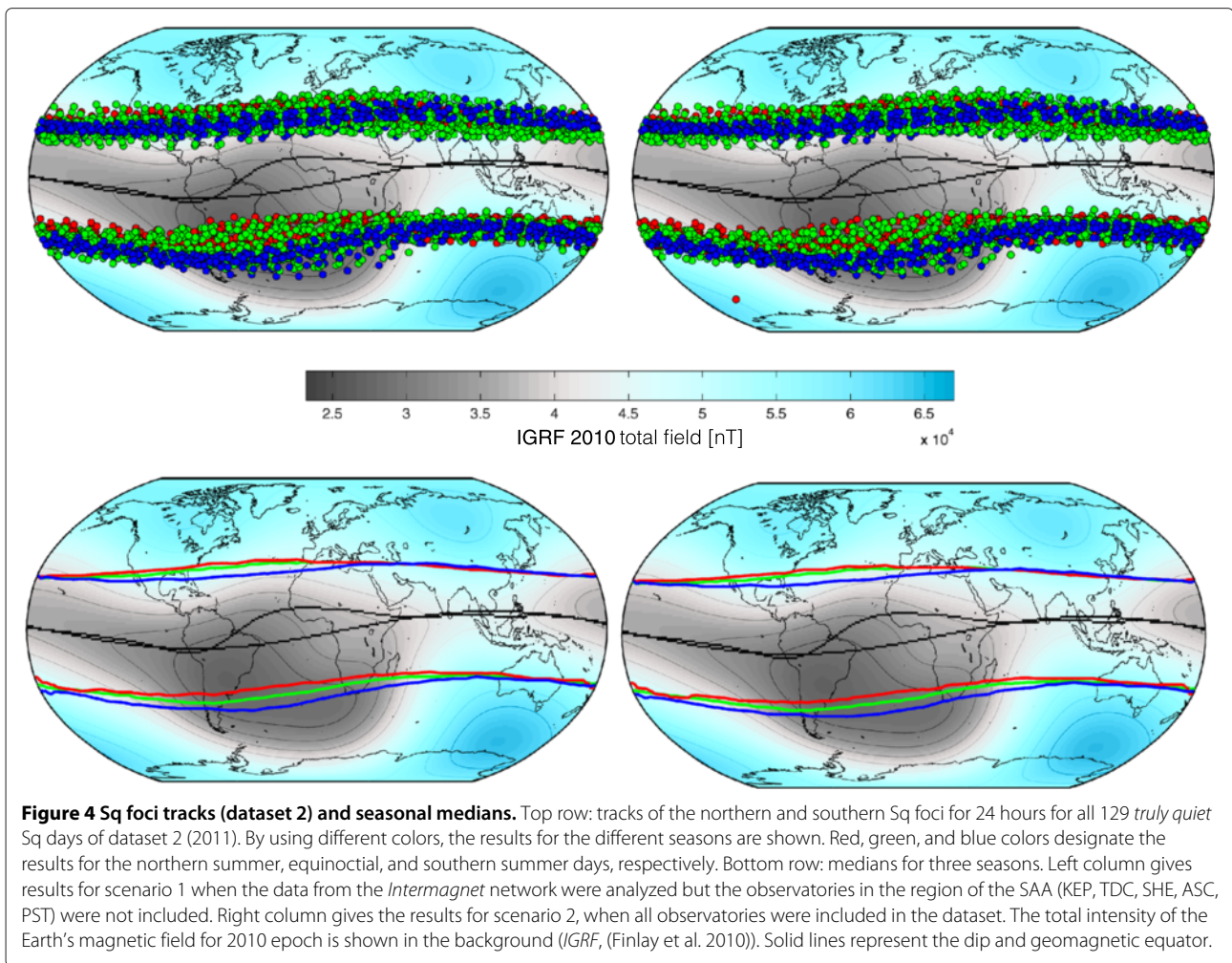

Figure 2 The Sq source in the form of a current function. The current system is shown for six time instances (UTC = 4:00, 8:00, 12:00, 16:00, 20:00, 24:00) for 1990-05-15 with the solar terminator of the respective day on top (blue shade). Starting on the top right plot, the Sq current system travels westwards during the 24-h UTC day. The solid black lines show the dip equator from the IGRF model for 1990 (Finlay et al. 2010). Dashed lines represent ±6° and ±60° dip latitude. Only observatories in between are used for the Sq source determination to avoid effects from polar and equatorial electrojets. Units are given in *kA*.

Figure 3 Sq foci tracks (dataset 1) and seasonal medians. Top row: tracks of the northern and southern Sq foci for 24 hours for all 39 *truly quiet* Sq days of dataset 1 (1990). By using different colors, the results for the different seasons are shown. Red, green, and blue colors designate the results for the northern summer, equinoctial, and southern summer days, respectively. Bottom row: medians for three seasons. Left column gives results for scenario 1 when the data only from the *Intermagnet* network were used. Right column gives the results for scenario 2 when the data from both *AWAGS* and the *Intermagnet* network were exploited. The total intensity of the Earth's magnetic field for the 1990 epoch is shown in the background (*IGRF*, (Finlay et al. 2010)). Solid lines represent the dip and geomagnetic equator.

Sq foci tracks for dataset 2 (2011): One shortcoming of dataset 1 is that no observatories were installed in the direct vicinity of the SAA. Dataset 2 allows to investigate if additional observatories in the region of the SAA influence the resulting Sq foci tracks. The left plots in Figure 4 depict the tracks for scenario 1 when the data from the *Intermagnet* network were analyzed, but the observatories in the region of the SAA (KEP, TDC, SHE, ASC, PST) were not included. The right column gives the results for scenario 2, when all observatories were included in the dataset. We observe that the additional observatories in the vicinity of the SAA do not significantly change the resulting Sq foci tracks.

In general, the findings confirm the results of dataset 1. Again, the tracks of the Sq foci for all days and all seasons and for the two scenarios manifest as two pronounced mid-latitude bands, and further, we find that the southern Sq tracks show large sensitivity to the seasons in the area of the SAA, regardless of additional observatories in the region. For dataset 2, we find a maximum difference of 11° in latitude between the NS and SS tracks over the SAA

region and 3° over the Australian region for the southern hemisphere Sq tracks (cf. Table 1). We deduce from these observations that the systematic scattering in the vicinity of the SAA is a robust feature. Previous studies on longitudinal and seasonal variations of Sq have shown variations not only at SAA longitudes but also at other longitude sectors (Fatkullin and Feldstein 1965; Hasegawa 1960; Matsushita and Maeda 1965; Pedatella et al. 2011; Stening 1971; Stening et al. 2007; Stening and Winch 2013; 1999, 2002) among others A direct comparison with these studies however appeared to be inconclusive due to different analysis methods and data sets.

The physical mechanism of the systematic scattering of the Sq foci tracks over the SAA remains unclear. As reported in recent studies, the longitudinal variations of Sq have their origin at least partly from an influence of non-migrating tides (e.g., Lieberman et al. 2013). Further, the ionospheric gyrofrequencies are proportional to the background magnetic field **B**, so the ionospheric conductivities decrease with increasing **B** (e.g., Richmond 1995, Stening and Winch 2013). The SAA represents an area of

Figure 4 Sq foci tracks (dataset 2) and seasonal medians. Top row: tracks of the northern and southern Sq foci for 24 hours for all 129 *truly quiet* Sq days of dataset 2 (2011). By using different colors, the results for the different seasons are shown. Red, green, and blue colors designate the results for the northern summer, equinoctial, and southern summer days, respectively. Bottom row: medians for three seasons. Left column gives results for scenario 1 when the data from the *Intermagnet* network were analyzed but the observatories in the region of the SAA (KEP, TDC, SHE, ASC, PST) were not included. Right column gives the results for scenario 2, when all observatories were included in the dataset. The total intensity of the Earth's magnetic field for 2010 epoch is shown in the background (*IGRF*, (Finlay et al. 2010)). Solid lines represent the dip and geomagnetic equator.

an anomalous weak geomagnetic field strength; hence, a combination of these processes is believed to influence the Sq foci tracks in the observed way. Numerical modeling studies could help to better understand the physical mechanism of the observed systematic Sq foci shift. Concerning the solar activity as a possible source for the variability of the Sq source system, we observe no influence since there is no significant difference between the results for datasets 1 and 2 in Table 1.

Conclusions

We have analyzed the Sq current system in terms of the Sq foci track variability with respect to longitude, day, season, and solar activity. The computed tracks result in pronounced mid-latitude bands in the northern and southern hemisphere. The computed Sq tracks seem to neither follow the geographic nor the geomagnetic or dip equators. We observe a pronounced scattering of the tracks over the SAA. Remarkably, the scattering appears to be very robust, irrespective of the dataset used. This systematic scattering manifests as a large shift of the southern

hemisphere focus northwards during northern summer and southwards during the southern solstice. The shift of the southern Sq focus tracks with respect to the seasons is clearly evident. The physical mechanism of this systematic effect remains unclear. The longitudinal variations of the Sq foci are believed to have their origin from an influence of non-migrating tides as reported in recent studies and the anomalous weak amplitude of the geomagnetic main field over the SAA.

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