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Behavior of the quiet day ionospheric current system in the European region

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Abstract. The ionospheric current system for magnetic quiet days deduced from geomagnetic field daily variations taken throughout Europe at sunspot minimum has been studied. Special attention was paid to the selection of the representative quiet days, showing the inadequacy of relying on the mean of the five international quiet days per month. We used the technique of spherical cap harmonic analysis to separate the external and internal parts of the field variation from which the derivation of the equivalent current functions is straightforward. This method provides a motion picture representation of the *Sq* system through the screen formed by the spherical cap, allowing the study of continuous variations with universal time. Detailed features of the current contours can be represented with such a regional analysis. We found a strong day-to-day variability of the focus position along with some complexities that differ from the standard *Sq* current behavior. The average monthly or seasonal patterns are therefore averages of heterogeneous behaviors in many occasions. Possible explanations to these complex structures are considered.

1. Introduction

Among the geomagnetic variations of external origin, the most smooth and regular variation is that observed in the magnetograms on magnetically quiet days, being known as "solar quiet variation," or simply as *Sq*. Their origin has been attributed to ionospheric current systems flowing in the so-called dynamo region, simultaneously with the corresponding induced telluric currents. Although the actual current systems which produce the magnetic field variations are rather complex, they can be quite well approximated by two two-dimensional current systems flowing on spherical shells at specific distances, one above the Earth's surface and the other under it. They are called equivalent currents, in the sense that their effect in the recorded magnetic field at ground is equivalent to that of the actual currents. The systems are essentially formed by two vortices, one in each hemisphere with foci at temperate latitudes and about one hour before local noon, although the variability of these positions is certainly a matter of investigation. Figure 1 schematically depicts these systems. The overhead vortex in the northern hemisphere circulates anticlockwise while the overhead vortex in the southern hemisphere moves clockwise; the underground vortices circulate in the opposite directions.

For the study of the related ionospheric dynamics or the Earth's mantle conductivity, it is therefore of great value to have a method of separating the field due to external primary sources from the field due to the internal sources induced by the primary ones, these varying in time. The method traditionally used to analyze geomagnetic variations in their global scale has been the spherical harmonic analysis (SHA), which enables one to separate the potential in external and internal parts. However, detailed features of those fields can be represented only by determining an excessively large number of spherical harmonic coefficients which, in turn, are limited by the amount of available data. As *Malin* [1973] pointed out, this means that in regions, such as Europe where many observatories are available, much of the detail is lost. An alternative method of analysis has also been used based on surface integral formulae [*Price and Wilkins*, 1963; *Hobbs and Price*, 1970], although in this case it is necessary to interpolate from observatories to a grid before analysis.

In regular conditions the ionospheric current system is generally assumed to be one which remains approximately constant in form over a given day, fixed with respect to the Sun, which is equivalent to assume that the variations only depend on the latitude and the local time. Since an important factor is the longitudinal variation of the morphology and strength of the Earth's main magnetic

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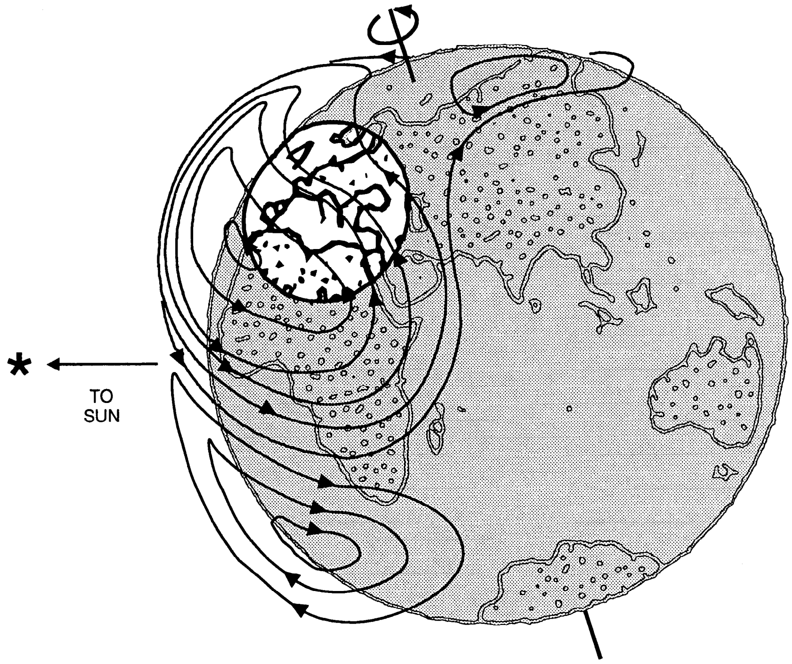

Figure 1. Schematic representation of the *Sq* current systems and of the spherical cap which monitors the motions of the northern hemisphere vortex as it crosses Europe.

field, some amount of the longitudinal variations are usually taken into account by using dip latitude rather than geographical latitude. A way to isolate the distinct field variation over a restricted region like a continent is to consider that, since the Earth rotates 360° under that fixed system, a station observes the 24 hours of this regular variation. Then, in principle, with data only from a group of observatories distributed in latitude over a narrow sector of the Earth it is possible to carry out a spherical analysis [*Campbell*, 1983; *Campbell and Schiffmacher*, 1985, 1987, 1988; *Campbell et al.*, 1993]. Moreover, in these studies, that narrow sector only covers a hemisphere, the other is covered by mirroring the former using the expected field reversals and seasonal differences. This is a way of "filling-in" the remainder of the sphere based on fairly realistic assumptions, and imposing the distinct behavior of the variation over such a continent to be the same all over the globe. However, this still restricts the model to wavelengths comparable to those of the global models. Similar procedures have been used for the regional modeling of the main field and have been termed as regional SHA [*Haines*, 1990].

A recent alternative for the regional analysis of geomagnetic variations has been proposed by *Haines and Torta* [1994]. They used spherical cap harmonic analysis (SCHA) technique [*Haines*, 1985] to show that it incorporates the external-internal separation and can be used when data are not available over the entire sphere, or a detailed study is specially desired over a particular region. Longitudinal dependence is included and the model proportionates values of the field components, the associated equivalent currents, or the current functions, at any point of the cap and at any instant. Special care must be taken, however, when the spherical cap is small, since the very different wavelength contents of the phenomenon and that of the basis functions can prejudice a proper external-internal field separation [*Torta and De Santis*, 1996]. In any case, since the real and modeled separated fields are approximately in phase, the analyses for relatively small caps can still afford reliable information about the dynamics of the ionospheric current system.

In the study of *Haines and Torta* [1994], as an example of application of the method, an analysis of the regular daily variation for a particular day was developed. However, the equivalent current systems are usually calculated as an average for some quiet days. Nevertheless, it has not to be forgotten that the intrinsic nature and treatment of the phenomenon are the same in both cases. On the other hand, geomagnetic data recorded in years corresponding to minima in the solar cycle are typically the best for representing the *Sq* in its purest form. With this in mind, the aim of this paper is to investigate UT variations of *Sq* over the European continent, with the analysis of data corresponding to some selected quiet days of each month of 1987, the most recent year of minimum magnetic activity (e.g., *Solar Geophysical Data*, no. 585, part 1, p. 138, 1993). Such an analysis has allowed us to detail the changes of the ionospheric current systems through the year and through the screen formed by the spherical cap. This screen essentially monitors the motions of the northern hemisphere vortex as it crosses Europe (see Figure 1).

During the initial stage of the present investigation it was realized that on some days a priori conceived as quiet there still were certain complexities in the corresponding equivalent current systems, making it difficult to obtain an ionospheric system representative of an absolutely quiet variation field, even in average. Various wind systems and thermotidal motions might be origin of those complexities. We believe that the contours shown are a more realistic representation of the *Sq* current system for the region under concern that could be obtained from global models, which tend to smooth local distinct behaviors.

2. Selection and Reduction of the Data

The study was made with data from the network of European stations, where the density of geomagnetic observatories is greater than anywhere else in the world. A northern limit to the area of study was defined by the fact that stations poleward of about 63°N show a character in both daily variation and range which are distinctly different to those south of this latitude, as pointed out by *Greener and Schlapp* [1979], and are attributed to the so-called S_q^p [*Nagata and Kokubun*, 1962], which is suggested to be generated by the quiet solar plasma wind crossing the lines of geomagnetic force in the geomagnetic cavity plasma. Thus, main concern lies in midlatitudes. On the other hand, and for the sake of dealing with a distribution as uniform as possible and thus allowing for a well-conditioned regression matrix, we did not consider the measurements of some observatories lying in very densely covered areas, such as in central Europe. As a result of these selections, we relied on a total of 32 observatories, their locations shown in Figure 2.

The source of data were the mean hourly values of the three geomagnetic field components recorded in 1987 by the different geomagnetic observatories. Many of them were already available in digital form at the World Data Centers (WDC), although the amount of work needed to collect and retype the data from the observatories which had not sent their values to the WDC was still important. As in the work of *Haines and Torta* [1994], the values for the *Sq* variations were obtained by subtracting, from the observatory hourly means, a trend determined by the two local midnight levels on each side of the quiet day (a local midnight level being a four-hourly mean centered on local midnight, as suggested by *Price and Wilkins* [1963]), in order to remove the noncyclic variation as well as the main field. This is based on the assumption that the noncyclic variation is linear between local midnights. In a very few cases, and specially in the northernmost observatories, when a selected quiet day is preceded or followed by a day that becomes disturbed during the nighttime, just before or after the concerned midnight, respectively, this procedure is unsuitable. In those cases, the monthly average midnight levels were computed without considering those disturbed hourly means.

A rather critical decision had to be adopted for the selection of the representative quietest days. It is well known that the definition of the International Quiet Days (IQDs) is very relative: they are the five quietest days of each month according to the index *Kp*, but this does not necessarily mean the absence of any magnetospheric disturbance [*Mayaud*, 1965a]. A preliminary study based on monthly averages using directly the IQDs showed a lack of consistency among the current patterns on their annual evolution, because the degree of quietness is not equal month by month and because of the strong day-to-day variability of the system itself. In some months, the *Sq* variation was so heterogeneous throughout the five quietest days that the average pattern become inconsistent with the preceding or following monthly averages. Some monthly averages were, furthermore, intrinsically incongruent, since they showed unrealistic temporal evolutions. We identified this by examining the trace of the focus as it crossed Europe and found that in many occasions it did not move at a constant velocity or presented sudden latitudinal excursions.

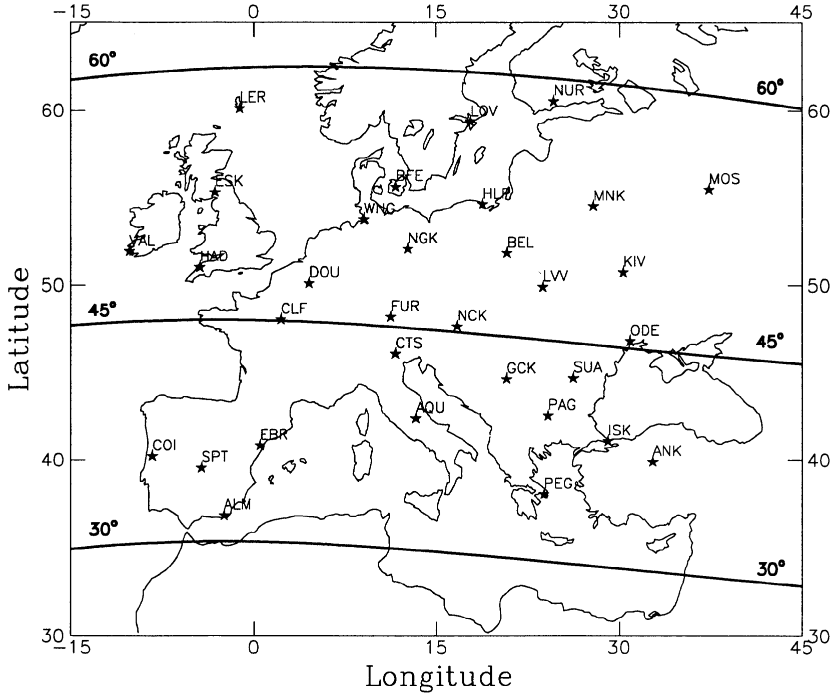

Figure 2. Locations of geomagnetic observatories (identified by their International Association of Geomagnetism and Aeronomy code) used in this study. Dip latitudes 30°, 45°, and 60° are shown.

In order to better examine the periods as free as possible from magnetospheric contaminations, we relied on the *AE* and *Dst* indices [*Berthelier and Menvielle*, 1993], in a similar way to that employed by *Campbell* [1979]. By this procedure, a certain number of days were selected by the requirement of having all hourly values of indices below specified levels, determined by the percentage of all days in the year for which that requirement is accomplished. As suggested by *Campbell* [1979], the positive (*Dst+*) and negative (*Dst-*) parts of *Dst* were treated separately, as if they were two different indices, because they characterize different stages of the magnetospheric disturbance. The increase of *Dst+* occurs at the beginning of the active period when the solar wind compresses the magnetospheric cavity. *Dst+* assumes positive but usually low values. For 1987 the average of the hourly values of *Dst+* was 6. On the contrary, the average of *Dst-* was -17. Negative values of *Dst*, usually lasting for several days, indicate the slow recovery of the magnetosphere to the undisturbed conditions. Zero *Dst* values are included in the count of *Dst+*. The recorded extreme values of *Dst* were +47 and -100. The *AE* index is a measure of the amplitude of the auroral electrojet current, clearly enhanced in periods of magnetic activity. The average value of hourly *AE* index was 184 in 1987, and its extreme value, 1465. The fraction of days in the year for which all hourly index values were below given levels is depicted in Figure 3. The behavior of these traces for 1987 seems to be more similar to the one showed by *Campbell* [1979] for 1958, an active year, than that to the one for 1965, a quiet year. As stated by *Campbell* [1979] himself, this may be a result of the difference in the selection of stations for his derivation of the *Dst* indices (Honolulu, San Juan, and Hermanus, from 1957 through 1963, and replacing Hermanus by Kakioka thereafter) and the actual derivation, which uses all four stations.

This kind of selection allows one to obtain a certain number of days having the lowest values of the three indices for the whole year. By examining the values that the indices took throughout the selected days, we concluded that this procedure is also somewhat relative, though based in a yearly basis, rather than in a monthly basis, as for the IQDs. Thus, for the active year of 1958, *Campbell* [1979] provided a selection of days for which *Dst+* was allowed to amount to +3, and *Dst-* to -31; while for 1965, a quiet year, up to +11 and -5, respectively. Adopting the same percentage cuts, the allowed extreme *Dst* hourly indices for 1987 are 0 and -18 with a 44% level cut, or +2 and -20 with a 52% level cut. All these values correspond to an updated version for the determination of *Dst* [*Sugiura and Kamei*, 1991]. Hence the selection for a particular year directly depends on the shape of the traces of Figure 3, rather than on the absolute values of the indices.

Only an examination of the individual magnetograms and their associated current systems could give an idea of the most suitable levels for the final selection of days. This showed how beyond certain levels some of the selected days contained appreciable contaminations, usually corresponding to recovery phase periods after a magnetic storm. Of course, the corrections for the noncyclic change tend to cancel the disturbance effect of the storm recovery phases, but this change is not always linear and sometimes the events overlap, causing unavoidable deformations of the current system. A 50% level cut (which provided a selection of days with $Dst+\leq 1$, $Dst-\geq -20$, and $AE\leq 442$) was considered as an acceptable compromise. However, the days with highest hourly *AE* indices happened to still show influences of the contamination resulting from returning currents of the auroral electrojet at high latitudes. Thus, from that previous selection were only retained the days with hourly $AE<375$.

In Table 1 we list the quiet days as selected by the above mentioned considerations, indicating the maximum hourly values of the indices. The average *AE* value for the day is also included. Notice that most of the days contained no positive *Dst* values. Notice also that, with such a restrictive selection, May and October, 2 months particularly disturbed, are left without any representative day. Nevertheless, the quietest day (according to *AE* and *Dst* indices) of each of these months are parenthetically indicated in Table 1, because their slightly disturbed variation will be still used to fill the corresponding gaps in the month-by-month representation.

In summary, we found the usual equinoctial enhancement of geomagnetic disturbance phenomena,

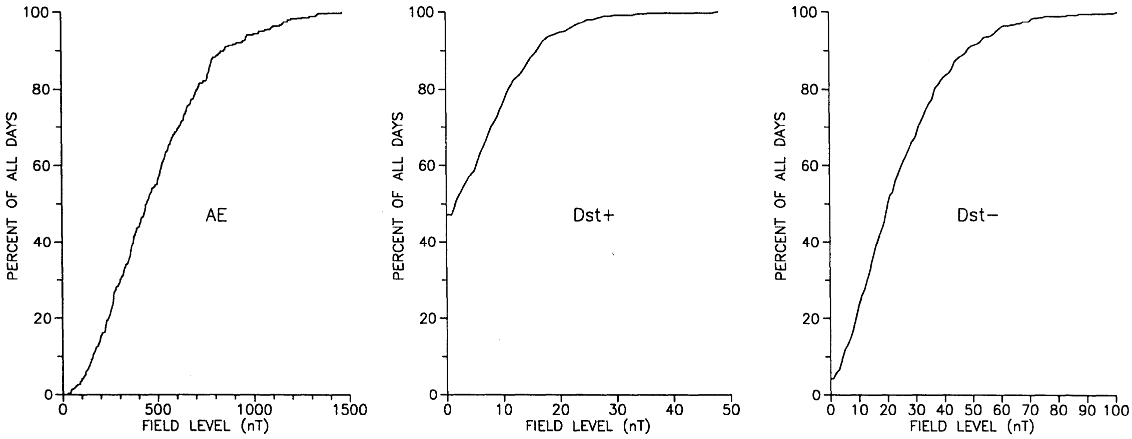

Figure 3. Percentage of all days in 1987 when all hourly index values of (left) *AE*, (middle) *Dst+*, and (right) *Dst-* were below the corresponding field levels.

Table 1. Quiet Days of Low *Dst+*, *Dst-*, and *AE* indices

Day	AE_{max}	AE_{ave}	$Dst+_{max}$	$Dst-_{max}$
	January			
24	281	130	-	-18
26	250	101	-	-13
	February			
26	269	78	-	-15
	March			
2*	135	56	-	-20
29	349	82	-	-19
30*	318	101	-	-20
	April			
2	265	110	-	-17
6	271	92	-	-12
21*	260	71	-	-11
28*	91	41	1	-13
	May			
(2	454	134	1	-8)
	June			
3	159	76	1	-8
22*	274	114	-	-13
	July			
19	372	206	-	-16
23	314	142	1	-11
	August			
18*	307	142	-	-19
21*	319	144	-	-14
	September			
8	364	158	-	-13
19*	149	56	-	-19
	October			
(6*	188	84	-	-21)
	November			
8*	100	38	1	-10
17*	72	31	-	-19
29*	38	19	-	-18
30*	109	23	-	-19
	December			
7	176	66	-	-19
8*	24	18	-	-13
13*	140	60	-	-18
14	165	71	-	-18
27*	56	31	-	-9

AE_{max}, $Dst+_{max}$, and $Dst-_{max}$ indicate the maximum hourly value of the corresponding index for the selected day. AE_{ave} is the average *AE* value for the day. See text for the days indicated parenthetically.

*One of the 5 IQDs.

specially reflected in May and October, along with a general enhancement in the second half of the year, probably indicating the beginning of the positive slope in the activity cycle. The latter did not preclude, however, the possibility of extracting a good number of days in November and December with an acceptable degree of quietness. In the months in which several days data were used together to obtain the current function, the days' hourly values were simply averaged.

3. Model Analyses and Equivalent Current Representations

As described by *Haines and Torta* [1994], the modeling can be done just spatially for each of the 24 hours separately or spatially and temporally. Spatial-temporal analyses can be done either by expressing each spatial coefficient as a Fourier series (a combined analysis), or in two steps, determining first 24 hourly different models and then expanding the SCH coefficients of these 24 separate models as functions of time, again as a Fourier series or as any other convenient temporal expansion. Spatial-temporal analyses obviously ensure smoother variations than simply looking at snapshots of the current system evolution. Both alternatives, in their turn, provide similar results; the last one being more appropriate when one wishes to analyze over many days and perhaps add seasonal or longer term dependences (there is however a practical computational limit in the number of coefficients able to be estimated by a combined analysis like this). Since we finally relied on individual quiet days and thus not in a continuous basis, we chose a combined spatial-temporal analysis, being it the most directly attainable approach.

The European network of geomagnetic observatories is basically covered by a cap with half-angle of 18°, with the pole of the cap appropriately located near the centre of the region. The horizontal and radial wavelengths associated with a SCH expansion with boundary at colatitude Θ_0=18° are intrinsically much more rapidly varying than the *Sq* field to be modelled which, by its nature, presents a rather smooth spatial structure. This fact might produce improper external-internal field separations [*Torta and De Santis*, 1996], though the overall pattern of the external current functions are still followed with certain reliability. As stated in the Introduction, the situation substantially improves with bigger caps. A way to ensure a greater area covered by measurements in a realistic manner consists in triplicating the observations by considering the values $C(T-1,\lambda)$ and $C(T+1,\lambda)$ to represent $C(T,\lambda-15°)$ and $C(T,\lambda+15°)$ respectively, where C denotes any of the X, Y or Z components at epoch T (in UT hours) and λ the geographic longitude of the observatory. This procedure, already used by *Sugiura and Hagan* [1967], on the other hand, guarantees a smooth temporal representation because it converts the hourly representation of *Sq* into a running average over 3 hours centered at the specified epoch. This is, of course, made at expenses of loosing some of the freedom allowed for the longitude dependence, since the 3-hour running averages are taken by considering time differences to be equivalent to longitude differences within each three-hour interval. To ensure this approximation be as realistic as possible, the side fictitious stations were really located at λ-15° and λ+15° but their geographic latitude were determined by the dip parallel that passes over the location of the original observatory. It is known that the *Sq* vortices and the overall system essentially follow lines of equal magnetic dip, or in other words, parallel to the dip equator. Dip latitudes, θ^*, are defined by

$$2 \tan\theta^* = \tan I \qquad (1)$$

where I is the magnetic inclination which was taken from IGRF [e.g., *Langel*, 1992].

With the extra observations supplied by the above mentioned procedure the region covered by the data roughly fills up a wide band of a 30° cap, being, obviously, their central part, corresponding to the European continent, the most weighted by a denser number of observations. With this procedure, moreover, we provide a better spatial control in some areas, specially in the Mediterranean, where there are actually too few observatories to precisely monitor the focus of the *Sq* system, usually located in those latitudes. The upper and lower areas of the cap away from that band are not covered but, in our opinion, this is not an important inconvenience for well fitting the central area in which we are really interested. Some experiments with synthetic *Sq* data confirmed this fact [*Torta and De Santis*, 1996]. With a 30° cap, SCHA provide basis functions starting with degree n_k=3.1, which correspond to spatial wavelengths of approximately 13,000 km. It is here reminded that SCHA differs from traditional SHA essentially by the presence of associated Legendre functions with noninteger degrees n_k which, in their turn, depend on the order m. The potential expansion assumes therefore the following form:

$$\begin{aligned} V = R \sum_{k=1}^{K_e} \sum_{m=0}^{k} \left(\frac{r}{R}\right)^{n_k(m)} P^m_{n_k(m)}(\cos\Theta) \\ \cdot \left\{g_k^{m,e}(t) \cos m\Lambda + h_k^{m,e}(t) \sin m\Lambda\right\} \\ + R \sum_{k=0}^{K_i} \sum_{m=0}^{k} \left(\frac{R}{r}\right)^{n_k(m)+1} P^m_{n_k(m)}(\cos\Theta) \\ \cdot \left\{g_k^{m,i}(t) \cos m\Lambda + h_k^{m,i}(t) \sin m\Lambda\right\} \end{aligned} \tag{2}$$

where Θ and Λ are the colatitude and longitude, respectively, in spherical cap coordinates; thus being necessary to transform from geographical geocentric coordinates to spherical cap coordinates before analysis. The extra integer index k is chosen to order, with increasing value, the different roots n at a given m. The $g^{m}{}_{k}$ and $g^{m}{}_{k}$ are the spherical cap harmonic coefficients of order m and index k, for external or internal sources according to the additional suffix e or i, respectively. The noninteger degrees are found as the roots of the following equations [*Haines*, 1985]:

$$\frac{dP^m_{n_k(m)}(\cos\Theta_0)}{d\Theta} = 0 \qquad k-m = \text{even} \tag{3}$$

$$P^m_{n_k(m)}(\cos\Theta_0) = 0 \qquad k-m = \text{odd} \tag{4}$$

The nature of the very quiet-day variation field, being in addition smoothed by the particular running average, does not justify to extend both external and internal expansions beyond k=4. This represents a maximum degree of 12.9, or minimum wavelength of approximately 3000 km. This was confirmed after performing the analyses with the coefficient estimation procedure described, for example, by *Haines and Torta* [1994, p. 504], which actually did not provide significant coefficients beyond that limit. Time dependence was represented by a fourth-degree Fourier expansion, as it has become traditional for the temporal representation of the *Sq* field.

Month-by-month analyses of the average quiet field furnished twelve sets of spherical cap harmonic coefficients. The lowest standard errors of fits corresponded to the winter months, which present the lowest daily range; and, accordingly, the highest errors appeared during summer months. They ranged between 1.1 nT in December and 3.1 nT in July. The overall rms deviation for the 12 analyses was 2.2 nT. From such monthly combined spatial-temporal models the associated equivalent external and internal current densities or current functions throughout the average quiet day are easily obtained [*Haines and Torta*, 1994, Equations (17) to (20), or (23) and (24), respectively]. Thus, in Figure 4 we show the monthly ionospheric current functions, all at the same specific time (0930 UT), corresponding in average to the hour in which the focus position is centered on our restricted window. Contours are plotted each 5 kiloamperes; the difference in the current function between two contours gives the current in kiloamperes flowing between those two contours. The actual labels are unimportant; they are just an indication of the direction of the flow. They show whether the contours lie around a maximum (counterclockwise flow) or around a minimum (clockwise flow).

Some outstanding features are evident from such a representation. Intense currents appeared in summer months, which progressively faded through equinoxes to winter solstice, although in September the current density is of the same order as the mean solstitial one. As stated before, May and October plots must be regarded with some precaution, since some of the hourly magnetic activity indices of their representative days showed values beyond the limits up to which a day has been considered as sufficiently quiet. The main handicap in these months is that they were left with only one representative day which, unfortunately, presented some short-term (1 to 2 hours) disturbances of magnetospheric origin (K=3 on individual magnetograms) that shifted the local midnight levels from which the base line of the daily variation was computed. Since the disturbance occurred at the same universal time, it only influenced the midnight levels of the observatories in the eastern (or western) part of the region and not in the others. This can capriciously shape the resultant current system.

During winter the focus of the counterclockwise current vortex was considerably south of the viewing region and suffered from apparent penetrations of the southern hemisphere current vortex into the northern hemisphere. This is not clear enough in Figure 4, being it formed by snapshots at a given time. Figure 5, however, illustrates the temporal evolution of the current system, for the particular case of December 27. Rather than showing the whole system as global analyses do, our representation of the system over the concerned latitudes has to be regarded with an inspection of its temporal evolution. Thus, by looking through the plots from 0600 UT to 1500 UT, we recognize an apparent invasion from the southern hemisphere system which flows clockwise, in form of some isolines which outline a pair of new vortices, one in each side of the westward currents that may belong to the counterclockwise vortex centered a long way to the south. This phenomenon is frequently recorded during the winter solstice on a given hemisphere. Unlike *Mayaud* [1965b],

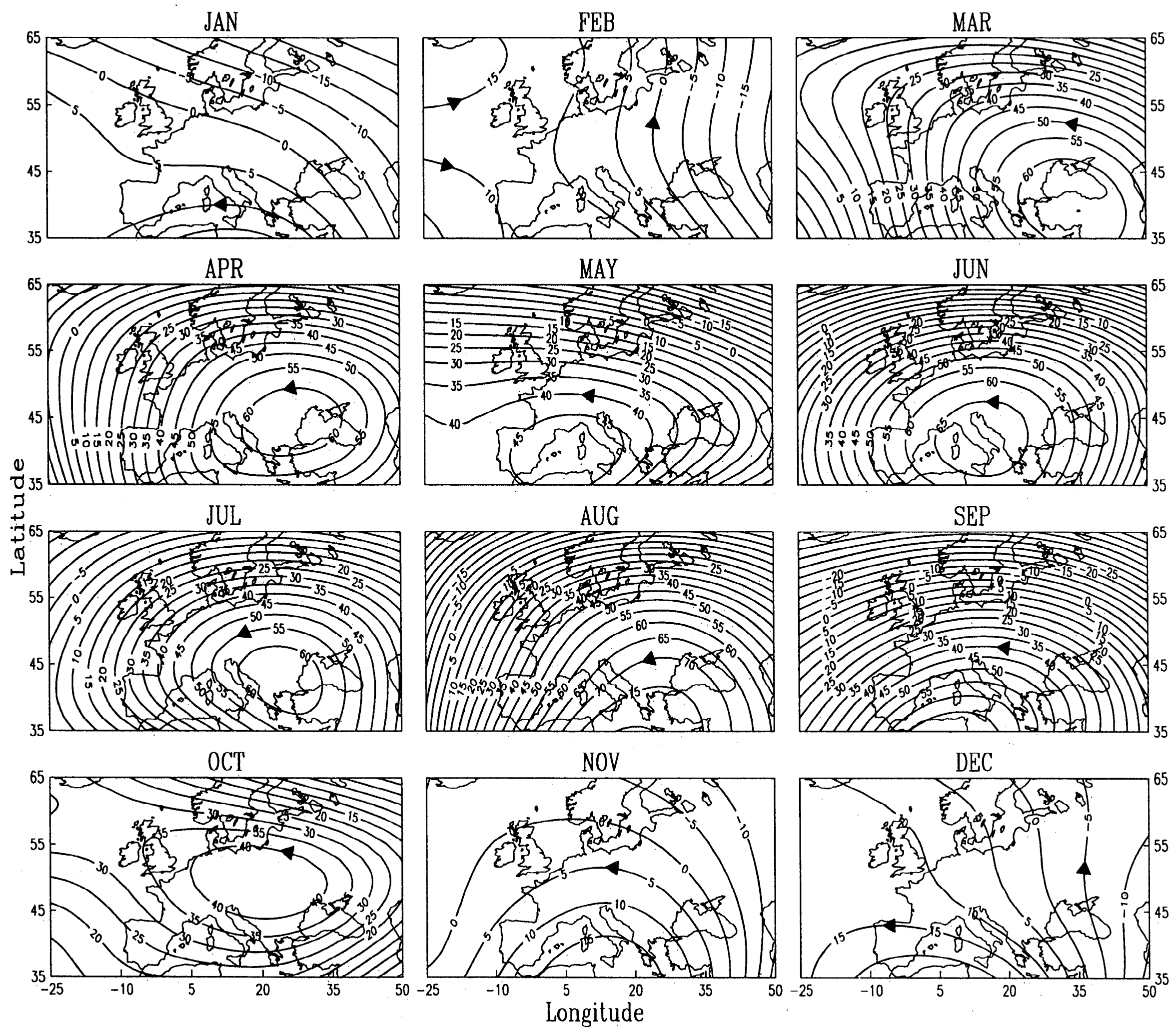

Figure 4. Contours of ionospheric equivalent current function evaluated at 0930 UT for the averages of quiet days (listed in Table 1) in the 12 months of 1987. Contour spacing is 5 kA. Arrowheads indicate direction of the current flow.

who stated that the invasion is generally more important during the morning that during the afternoon, we certified that usually the current density of the afternoon invasion loop was higher than the one for the morning loop.

A rather repetitive feature is a difference in the current density found in both sides of the current vortex, being always, in these occasions, more intense in the eastern side than in the western side. A direct effect is the asymmetry of the measured variation of the magnetic declination, which tends to take higher negative afternoon values than positive morning values, when we compare absolute values and assume that the variation is positive toward the east. This is equivalent to an additional superimposed meridional current, flowing from south to north. This meridional current seems to be restricted in a rather narrow longitudinal sector located in the westernmost part of Europe, because when the current system (usually with low current density in the focus region) crosses that sector, it tends to be opened by its western side. In May (see Figure 4 and Figure 6) and October (Figure 4) we find typical examples. A superimposed meridional current tends to oppose the southward current of the northern hemispheric vortex in the morning and reinforce the northward current in the afternoon. A current of this characteristics could also explain the asymmetry in the current density of both loops of the invasion from the southern hemisphere system during winter months. On the other hand, it seems impossible, from our actual distribution of observatories, to determine how far this phenomenon extends toward the Atlantic ocean.

Other features of fine structural character can be appreciated from the individual records. April 21, for instance, represents an example of an international quiet day without presenting, furthermore, appreciable magnetospheric disturbances according to the *AE* and *Dst* indices. However, the current focus in this day manifests an anomalous behavior (see Figure 7). In the central part of the system the vortex is misshapen, indicating a possible superposition of two current vortices. It appears as if it was the result of an sfe [*Veldkamp and van Sabben*, 1960; *van Sabben*, 1968; *Curto et al.*, 1994]. However, no flare was detected during that particular day (*Solar Geophysical Data*, no. 513, part 1, p.19, 1987), so that the phenomenon should be ascribed to other causes; probably to a wind variation due to a propagation from effects originated in lower strata, rather than to changes in the distribution of

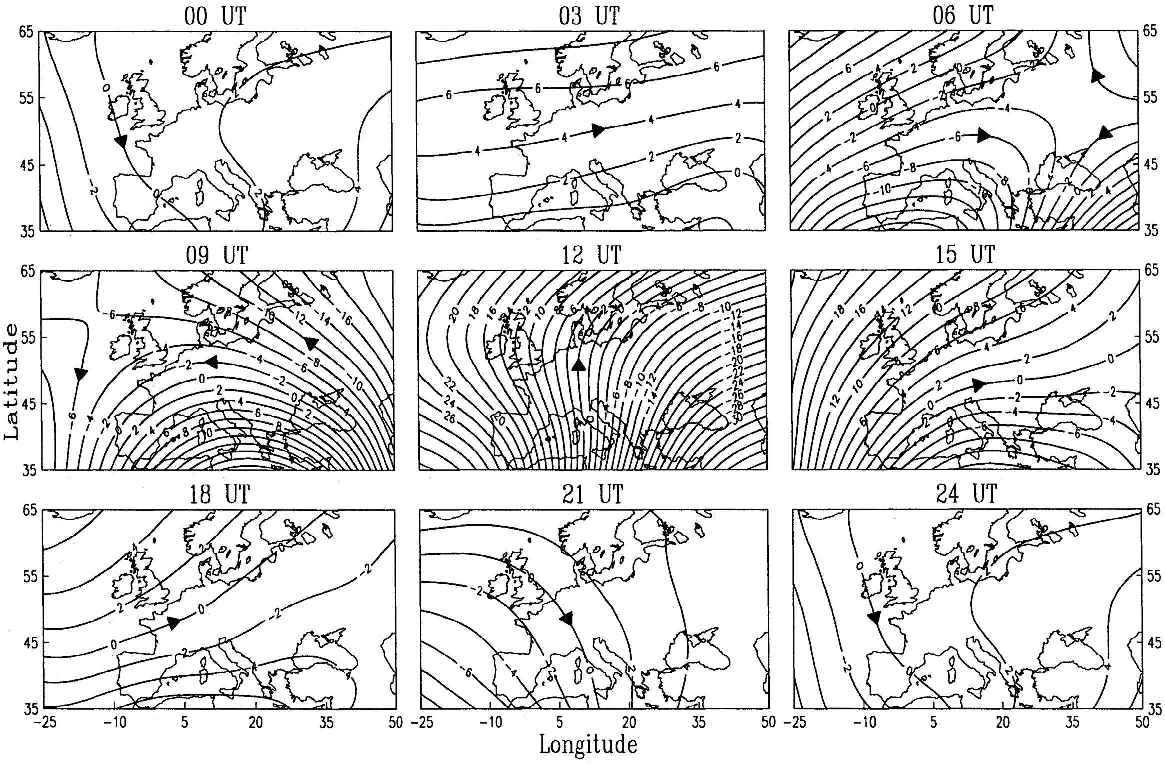

Figure 5. Contours of ionospheric equivalent current function evaluated at various times, given above each plot, for December 27, 1987, selected because it clearly shows an apparent invasion from the clockwise southern hemisphere current system. Contour spacing is 2 kA (notice the different contour spacing here employed, just for better showing the complex pattern).

ionization and conductivity. With the resolution of the global representations these particular features would be hidden.

Although it was first thought possible to show in detail month-by-month changes of the *Sq* focus position, the restrictive selection of Table 1 does not allow one to obtain a representative monthly mean behavior in several months. To show the evolution of the focus, we have grouped data into three seasons: winter or D months (January, February, November, and December), equinoxes or E months (March, April, and October) and summer or J months (May, June, July, August, and September). Notice that we have included September in the summer months, rather than in the E months as it is traditional, because of its manifested

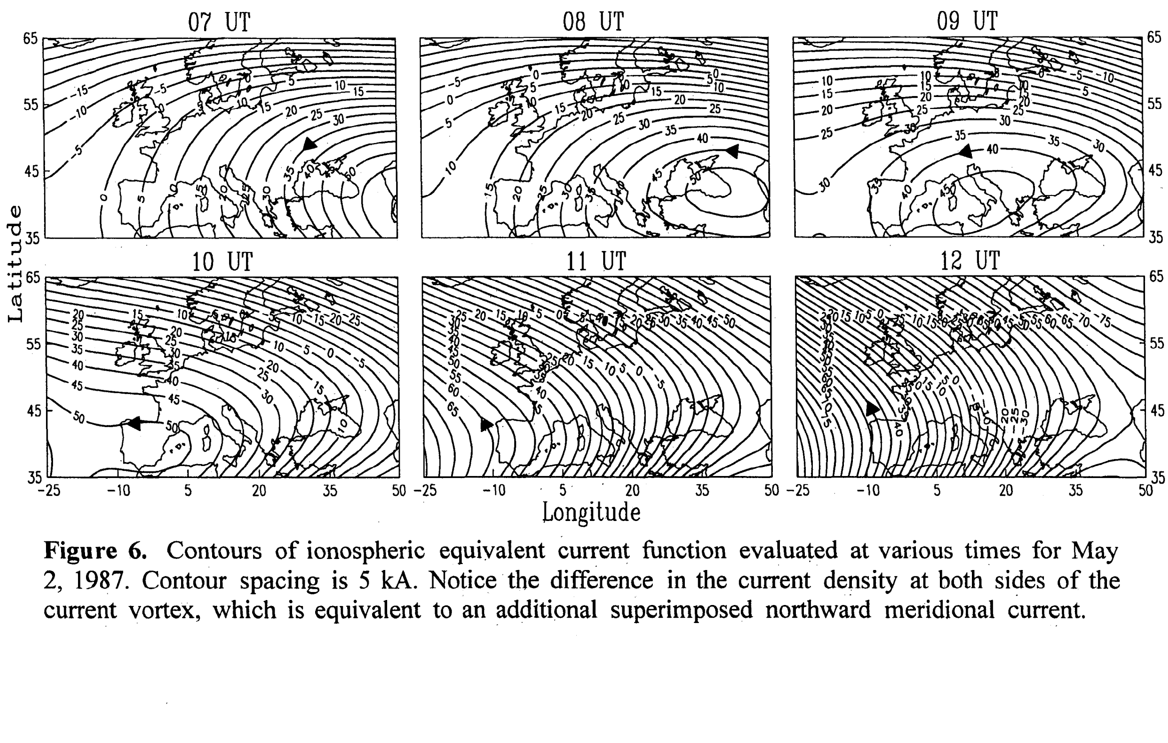

Figure 6. Contours of ionospheric equivalent current function evaluated at various times for May 2, 1987. Contour spacing is 5 kA. Notice the difference in the current density at both sides of the current vortex, which is equivalent to an additional superimposed northward meridional current.

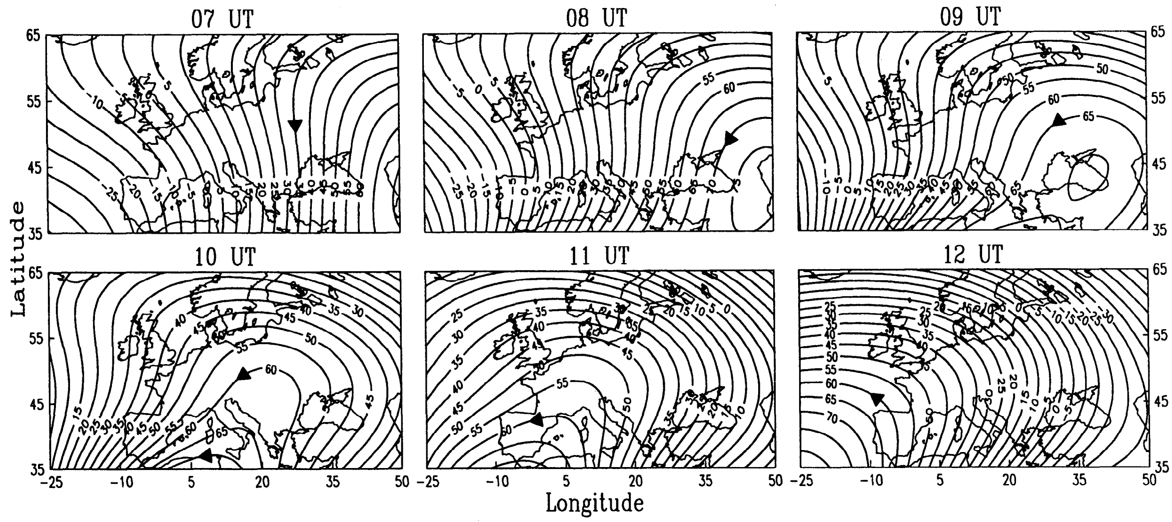

Figure 7. Contours of ionospheric equivalent current function evaluated at various times for April 21, 1987. Contour spacing is 5 kA. Notice that in the central part of the system the vortex is misshapen.

solstitial character. We have also discarded the parenthetical days of Table 1 in the seasonal averages, since we believe, as described above, that they are biased by magnetospheric current influences.

The evolution of the focus position in each season is shown by Figure 8, in which the point of maximum current function is plotted every 15 min. During winter the weak

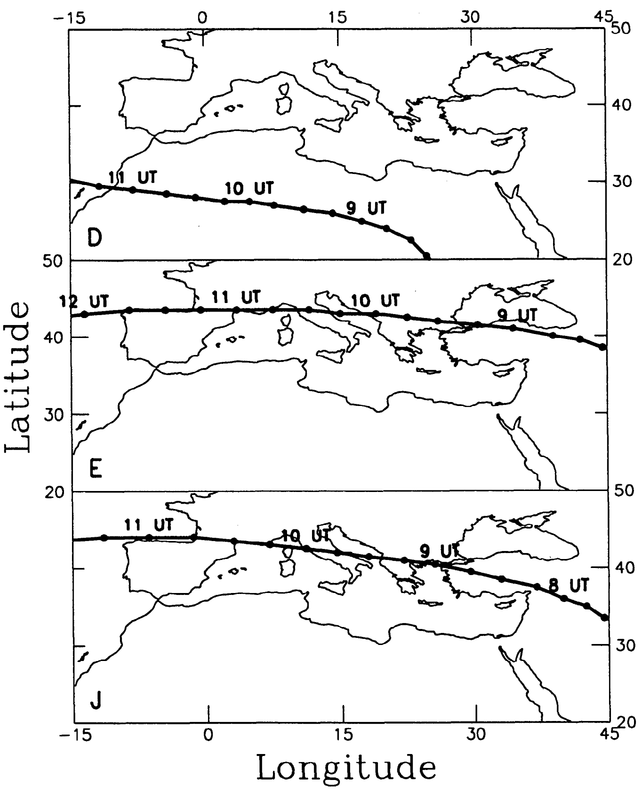

Figure 8. Seasonal evolution of the focus position of the external current system for the averages of quiet days of 1987. The positions are shown at every 15 min, upper labels indicate the positions at universal time hours.

counterclockwise vortex moves most equatorward. Being its central position far south from the area with measurements and thus difficult to be estimated, the hour of maximum counterclockwise current appears to us as a bit uncertain. However, it seems to appear closer to noon in summer and equinoxes than in winter. In general, it occurs from about half an hour to 2 hours before noon and, normally, earlier in summer and closer to noon in the equinoxes. It is also during the equinoxes when it shifts to its highest latitudes. These features are somewhat coincident with the results of an study from data of Ebre Observatory during the last 30 years [*Curto et al.*, 1994], in which the *Sq* current focus has been analyzed at the time of occurrence of solar flare effects (sfe). The only discrepancy is found in the time of occurrence of such maximum current which, as expected by the theory of *Fukushima* [1994] on the interhemispheric field-aligned currents, should appear in an earlier local time in the summer, while in a later local time in the winter. In some occasions, the point of maximum current seems to move at a not constant velocity, as it would be expected. This unrealistic fact can be due to the scarcity of stations in the Mediterranean area and, specially, the null coverage in the Mediterranean North African coast, which could result in a poor delineation of the lower part of the current foci.

4. Discussion

The major characteristics of the quiettime daily field variations and their associated current functions found in this study are similar to those expected from earlier studies: The amplitudes of *Sq* were largest in summer and smallest in winter. The apparent penetration of the southern system into the northern hemisphere is a characteristic behavior of the winter solstice. Foci paths are very changeable month-to-month. The focus was located most equatorward in winter and most poleward in equinoxes. The point of maximum current is apparently closer to noon in summer and equinoxes than in winter.

This seasonal behavior significantly coincides with that found by *Curto et al.* [1994], but it is difficult to compare with other results over Europe [e.g., *Matsushita*, 1965; *Gupta*, 1973; *Suzuki*, 1973; *Campbell and Schiffmacher*, 1985] since, as already stated by *Stening* [1971], there is a wide disparity in the observed focus positions by different authors, because different methods and day-selection criteria are used to determine those positions. Therefore a special effort was devoted to the selection of the appropriate quiet periods of magnetic activity. The difficulty in finding extremely quiet solar-terrestrial activity conditions limited the number of suitable days in some months, even though a year of minimum activity, 1987, had been selected. This, of course, can prejudice the representativeness of a monthly behavior, being obtained by the average of few individual recordings. It is thus advisable for future analyses the use of selected days from more than a single year.

For the explanation of the above mentioned behaviors of the quiet day ionospheric current system in the European region several possibilities have been studied. As in the region investigated in this paper, there are many places where continent alternates with sea, it could be assumed that the complexities differing from the standard *Sq* current behavior are due to nonmigrating tides. Nonmigrating tides appear at the boundary between land (continents) and sea [*Kato*, 1980, 1989; *Tsuda and Kato*, 1985; *Yagai*, 1989]. However, the amplitude of nonmigrating tides can be neglected above 40 km as compared to that of migrating tides, the former having amplitudes of 0.1-1 m/s [*Tsuda and Kato*, 1985], but the latter amplitudes of some tens of meters per second, both referred to the height range between 0 and 90 km.

Another possibility put forward for the explanation of the behavior of the *Sq* current system can be the effect of the returning part of the auroral electrojet at the high-latitude part of the *Sq* current system [*Fesen et al.*, 1991]. If the days, for which the *Sq* current system is constructed, are carefully selected, as it has been done in this case, the influence of the auroral electrojet can be excluded.

Similarly, another source of the complexities could be the equatorial electrojet. However, the region of the equatorial electrojet is located at latitudes more than 30° south of the region under study [*Onwumechilli*, 1967]. Nevertheless, as shown by *Rastogi* [1994] for the Indian region, it would be interesting to look at the midlatitudinal effects associated with counterelectrojet events which are mainly detected during the afternoon. In this study, however, we have specially focused our attention at the interval in which the current focus crosses Europe (approximately between 0700 and 1200 UT), because it represents the most characteristic and well-delineated feature of the system.

A further source of the deviation of the quiet day ionospheric current system from the standard morphology could be the change of the height of the current system due to the change in the distribution of the electrical conductivity with height within the dynamo region of the ionosphere [*Kirchhoff and Carpenter*, 1975]. However, the height of the maximum of the Hall conductivity does not change on quiet days, only the magnitude shows the usual daily variation because of the daily variation of the electron density. The latter is included in the morphology of the *Sq* current system, the current density being more intense on the dayside than on the nightside.

Considering now the different examples shown in the paper, the development of the current system from month to month shown in Figure 4 seems to be irregular. It is an open question why the geomagnetic variation in the equinoctial seasons may indicate a greater amplitude in comparison with the average of two solstitial seasons (this fact was already discussed by *Fukushima* [1991]), because if we take into account the variation of the electron density in the *E* region (maximum in summer, minimum in winter), the current density is maximum in the summer solstice. (However, the strength of the winds driving the dynamo is also significant in determining the strength of the current system.) The most poleward position of the focus in the equinoxes is also remarkable because, taking into account the change of the electron density with latitude (it varies according to the solar zenith angle), it might be expected to be located most poleward again in the summer solstice. Instead of this, the position of the focus in April and June, disregarding May, can be anomalous with the focus located in April too northward, in June too southward. (As stated before, the patterns of May and October cannot be taken as representative.) In Figure 6 an entirely irregular variation of the current system is presented, where the speed of the focus of the day-current system seems to be greater than that of the regular vortex; that is, the current system is shifted westward. In Figure 7 a similar case can be seen; however, here this process is inhibited till 1000 UT by the nighttime vortex.

Summarizing, on the basis of the anomalous behavior of the examples shown, it can be established that the process causing the anomalous behavior could be the displacement of the current system, in one case northward, or southward, in other cases westward, or eastward. Considering the dynamo theory, thus it remains one possibility yet according to the circumstances mentioned above. This possibility would be the change of the dynamical conditions in the lower thermosphere. It should not be forgotten that besides atmospheric tides, prevailing winds play a not negligible role in this part of the atmosphere [e.g., *Manson et al.*, 1985, 1989; *Forbes*, 1985; *Killeen et al.*, 1992]. It is well known that the prevailing wind in the lower thermosphere shows a seasonal variation [*Manson et al.*, 1990]. The zonal mean wind at dynamo altitudes in our range of latitudes is westward in winter and eastward in both the summer and equinoctial months, but in the equinoxes the wind speed decreases to relatively small values. Considering the mean meridional component of the prevailing wind, it is generally southward both in winter and in summer. In the equinoctial months it is mostly northward. On the other hand, these zonal and meridional predominant senses depending on the season are also subject to variation from day-to-day. The consideration of whether the prevailing wind can contribute to the explanation of the anomalous behavior of the *Sq* current system in the European region, that is, if the prevailing wind sometimes being commensurable with the tidal wind can influence the development of the *Sq* current system is an hypothesis whose study is in progress.

The effect of the day-to-day variability of the diurnal and semidiurnal tides must also not be disregarded, since the amplitude of these changes can also be often significant from the point of view of the shaping of the *Sq* current system [*Takeda and Araki*, 1984]. *Forbes and Lindzen* [1976] have suggested that diurnal and semidiurnal tidal modes seem to be responsible for the magnetic variations at ground level and the most part of the variability is ascribed to the variability of those modes themselves. Evidences of changes in the wind patterns, even during the course of a day have been also previously encountered [e.g., *Schlapp*, 1973; *Kane*, 1976].

The symptoms of northward superimposed meridional currents that have been encountered could have a three-dimensional structure, the closure of them being attributed to field-aligned currents resulting from interhemispherical asymmetries, as first suggested by *van Sabben* [1966]. These features are coincident with those of the meridional currents found by *Mazaudier and Venkateswaran* [1985] over Saint-Santin. *Stening* [1989] could explain these currents by the role played by semidiurnal antisymmetric tides. These modes may also explain other particular features of the ionospheric current systems, as the apparent invasions of one hemisphere's current pattern by that of the opposite hemisphere.

Finally, the existence of some dynamical phenomena can also contribute to the distortion of the tidal waves producing the *Sq* current system, besides the prevailing wind or the semidiurnal antisymmetric tides. It is to be noted that according to the investigation of *Teitelbaum and Vial* [1991], two secondary waves are generated by the nonlinear interaction of tidal waves with planetary waves in the lower thermosphere. The frequencies of these secondary waves are the sum and the difference of the frequencies of the primary waves. The secondary waves beating with the tidal wave modulate the amplitude of the tidal wave with the period of the planetary wave. It has also been shown [*Miyahara and Forbes*, 1994] that the interaction between diurnal tides and breaking gravity waves in the lower thermosphere can suppress the diurnal tide by convective instability (the diurnal tide itself is convectively stable, but the wind field due to the superposition of the diurnal tide and gravity wave is unstable). The results of other investigations [*Phillips and Briggs*, 1991] seem to support the establishment that long period variations of the tidal waves are related to the variations of the source exciting the tides or to that of the propagation conditions (wave-wave interactions) in the middle atmosphere, while short period fluctuations may be attributed to local perturbations [*Bernard*, 1981].

Thus, on the basis of the above described circumstances the conclusion might be drawn that, in the development of the variability of the *Sq* current system, the variability of the tidal and prevailing winds in the lower thermosphere can play as important role as the geomagnetic disturbances. This situation raises difficulties for the determination of a mean *Sq* current system behavior. A systematic study with the addition of North African and mid-Atlantic records would help to clarify even more the characteristics of the northern hemisphere ionospheric current system over the European-African sector. Further, interesting results for the understanding of the apparent distortions of some of our equivalent current systems from the expected *Sq* currents are envisaged by the addition of contemporary information from tidal and prevailing winds, and from interactions with atmospheric gravity or planetary waves.

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