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Hemispherical and latitudinal differences in the response of geomagnetic activity to recurrent solar wind streams

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Abstract

The data-adaptive technique of Singular Spectrum Analysis isolates significant signal components from background noise in a time series. This methodology is adopted for analysis of indices of geomagnetic activity, interplanetary magnetic field (IMF) and solar wind parameters during an interval in 1974 marked by strong recurrent solar wind streams to bring out the latitudinal dependence and differences in the geomagnetic response between the northern and the southern hemispheres. The geoeffectiveness of the azimuthal component of IMF in the observed 28-day periodicity at low latitudes can be attributed to the seasonally dependent IMF polarity influence through the Russell–McPherron mechanism. In respect of the 14-day oscillation, the solar wind velocity, the variability and density which characterize the recurrent streams appear significant in their efficacy at subauroral and auroral latitudes as also in generating North–South asymmetry in the geomagnetic response. A clear difference in the response to recurrent solar wind streams, between the two hemispheres, is brought out with the southern (northern) hemisphere showing greater activity with $\sim$14-d ($\sim$28-d) periodicity. The observed responses can be interpreted in terms of the geomagnetic changes associated with the sector structure and sector boundary of IMF through the Russell–McPherron (R–M) effect.

1. Introduction

In relation to the basic question of whether magnetospheric substorms are necessary for the activation of a geomagnetic storm, one view is that the southward IMF drives the substorm and injects energetic particles into the inner magnetosphere to form the ring current; the second suggests storms and substorms can occur as independent processes (Kamide, 1992; Iyemori and Rao, 1996, and references therein). Kamide (1992) argues that the partition of energy injected into the auroral/polar ionosphere and the equatorial ring current is not always in constant proportion but no major geomagnetic storm ever occurs without associated intense substorm activity. Iyemori and Rao (1996) have, however, shown that the substorm expansive phases do not strengthen the symmetric ring current and that the Dst field decays rather than getting enhanced. Siscoe and Petscheck (1997) have attempted a reconciliation between the two opposing views by invoking an alternate scenario for the substorms responsible for magnetic storms, incorporating the growth phase also in the definition. One way of examining whether the equatorial ring current and auroral electrojet currents are modified by the energy transferred from the solar wind into the magnetosphere as a coupled system or as independent ones would be to study the response of geomagnetic activity as a function of latitude to the same causative mechanism(s) such as the IMF/solar wind fluctuations.

In this investigation, we choose an interval of time marked by strong recurrent geomagnetic activity to identify the hemispheric difference and latitude dependence of the geomagnetic response to IMF and solar wind fluctuations using the geomagnetic activity indices AE, Ap, An, As, Dst and (An–As), as also the magnetic horizontal intensity at selected observatories in both hemispheres. We show that the variability in the strength of recurrent activity at low latitudes is not exactly the same as that

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at auroral latitudes and also that individual sations in different locations in both the hemispheres have distinct response characteristics. A perceptible asymmetry in subauroral activity between the northern and the southern hemispheres is also brought out. These observed features complement excellently the recent exhaustive analysis of Mursula and Zieger (1996) and hopefully provide some useful clues to the substorm/storm activation mechanisms.

2. Data and methodology

To avoid the possibility of a mix-up between different types of solar driving forces responsible for geomagnetic activity (e.g., see Simon and Legrand, 1993), we choose the interval extending from the middle of December 1973 to the end of June 1974 marked by a recurrent pattern of high speed solar wind streams persisting over seven solar rotations. Tsurutani et al. (1995) characterize the period as "the cleanest, most unambiguous examples of recurrent streams". As the epoch under study falls in the second half of the declining phase of the even number solar cycle 20, it is also favourable for enhanced signal to noise ratio for quasi-periodic oscillations in view of the known higher activity in even number cycles (Cliver et al., 1996, and references therein). This interval was the focus of interest of Crooker and Cliver (1994) who proposed that the so-called M-regions need not be identified with only coronal holes but rather with coronal streamer — coronal hole ensembles. Over the time span of seven solar rotations utilised in the study here, they could identify some shocks, helium abundances and magnetic clouds, considered as signatures of Coronal Mass Ejections (CMEs). According to Gosling et al. (1990), interplanetary shocks driven by fast CMEs are responsible for large geomagnetic storms near solar maximum, but CMEs alone or slow CMEs not interacting with ambient solar wind are geomagnetically ineffective, and southward IMF was usually absent in such cases. Crooker and Cliver (1994) suggested that most CMEs appear to arise from the coronal streamer belt and their probability of occurrence is higher in the vicinity of a sector boundary passage; they can contribute to the strength of recurrent storms by providing a southward IMF or increasing the magnetic flux along the Parker spiral. Crooker and McAllister (1997), confirm that for the recurrent storms in solar cycle 22, the southward IMF responsible for peak activity is often associated with CMEs from the base of sector boundaries.

We use the mean daily values of the equatorial Dst index (representative of the geomagnetic activity at equatorial latitudes), AE (auroral zone index), Ap (subauroral index), An (northern hemisphere subauroral index), As (southern hemisphere subauroral index) and (An-As) (asymmetry or hemispheric difference) covering the period from 18 December 1973 – 24 June 1974 over seven solar rotations (Bartels rotation No. 1920 to No. 1926). Hourly data of IMF and solar wind parameters for the first 200 days of 1974, taken from Tsurutani et al. (1995), are depicted in Fig. 1. The $-/+$ signs on the top pertain to IMF polarity and the numbers 1 and 2 on the time profile of velocity correspond to the two sequences of corotating streams. Beyond 24 June 1974 there are some major geomagnetic storms (e.g. the one marked A in Fig. 1). The daily mean values of the activity indices Dst, Ap, AE, An, As and (An–As) for the seven solar rotations are shown in Fig. 2.

To bring out the quasi-periodic fluctuations embedded in these time series, we use the recently developed data-adaptive method called Singular Spectrum Analysis (SSA). A complete description of the method, highlighting the advantages over conventional power spectral analysis, is given by Vautard et al. (1992). Detailed mathematical steps are provided, before its application to the equatorial Dst index, by Rangarajan and Araki (1997).

Mursula and Zieger (1996) have carried out an exhaustive analysis of the 13.5-d periodicity of the solar chromosphere, near-Earth solar wind speed, temperature and density, IMF and Kp during the last three solar cycles. Using correlation and power spectral analysis, they have been able to ascribe the observed periodicities to the tilted solar dipole model and persistent two-sector structure of the IMF. The emphasis in the present investigation is on the latitude dependence of the 14-d and 28-d oscillation in geomagnetic activity and the identification of the solar wind and IMF parameters with analogous periodicities. Thus the two analyses are expected to be complementary to each other.

3. Results and discussion

It is easily discernible from Fig. 2 that geomagnetic activity at all latitudes responds to the solar wind/IMF forcing in a recurrent fashion, but whether both the recurrent sequences 1 and 2 shown in Fig. 1, are equally geoeffective, cannot be identified easily. If both the streams trigger enhanced geomagnetic field changes, then half-a-solar-rotation periodicity ($\sim$13.5 days) should be dominant, whereas if one is less influential than the other then a $\sim$27-d periodicity should be noticed in the indices. IMF magnitude (B), solar wind speed and density show clearer recurrent patterns compared to the other parameters (see Fig. 1). To elucidate the major contributing parameters for enhanced recurrent activity, we derive the dominant principal components of 16 solar wind/IMF parameters and the geomagnetic activity indices. Table 1 gives the variance accounted for by the fundamental ($\sim$28-d), and the first two harmonics ($\sim$14-d and $\sim$9.5-d oscillations) in all these parameters.

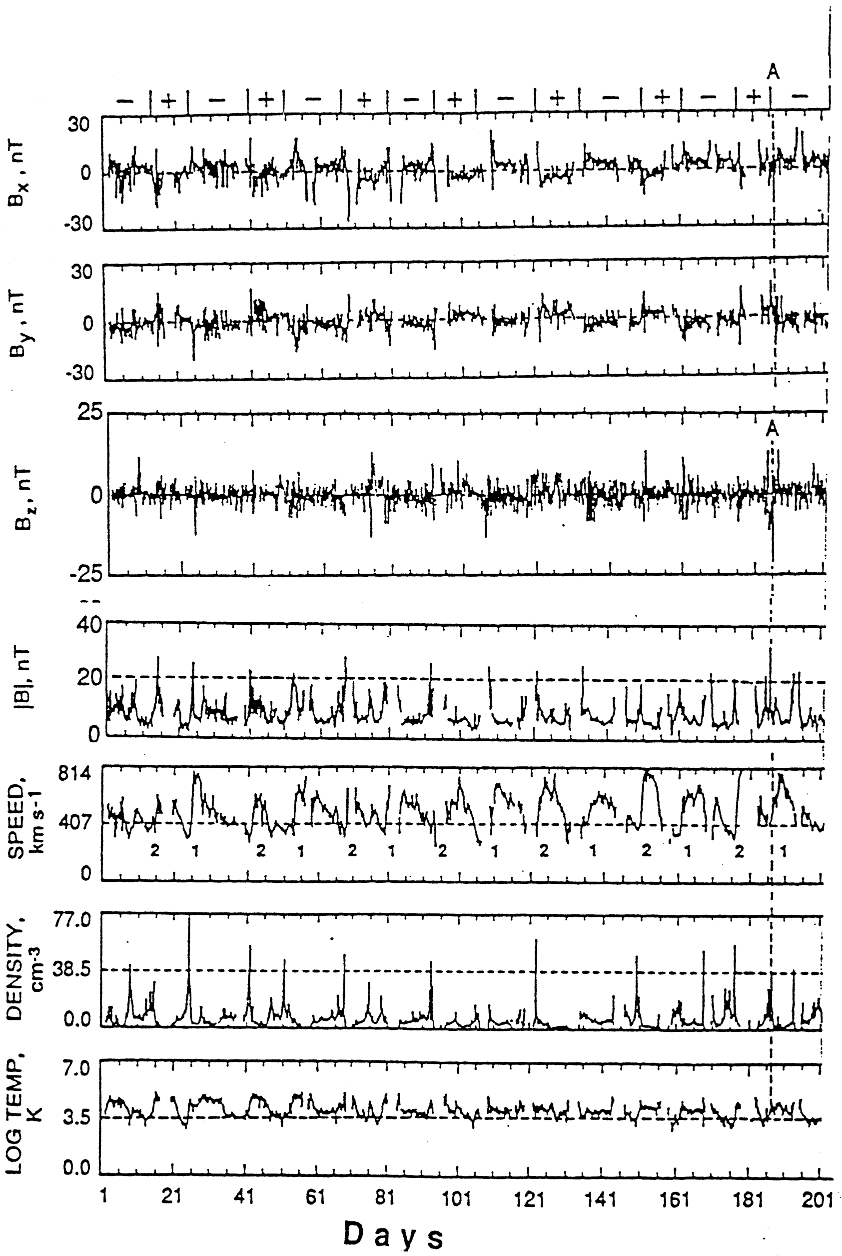

Fig. 1. Time variations in some of the IMF and solar wind parameters for the first 200 days of 1974. Symbols − and + on top indicate the polarity of IMF. Numbers 1 and 2 on the solar wind speed data indicate two distinct recurrent sequences (redrawn from Tsurutani et al., 1995).

3.1. Fine structure of the oscillations in geomagnetic activity

Figure 3(a), (b) and (c) give the time profiles of the principal components associated with periodicities of ~28, ~14 and ~9.5 days for the geomagnetic indices and (An–As). Amplitudes of the solar rotation signal and the first two harmonics derived from Fourier analysis are listed in Table 2.

The amplitudes are greater in association with the ~14-d periodic component relative to the 28-d oscillation for Ap, An and AE while, for Dst, the 28-d component has greater magnitude. This suggests that while both the sequences of the recurrent solar wind streams have been

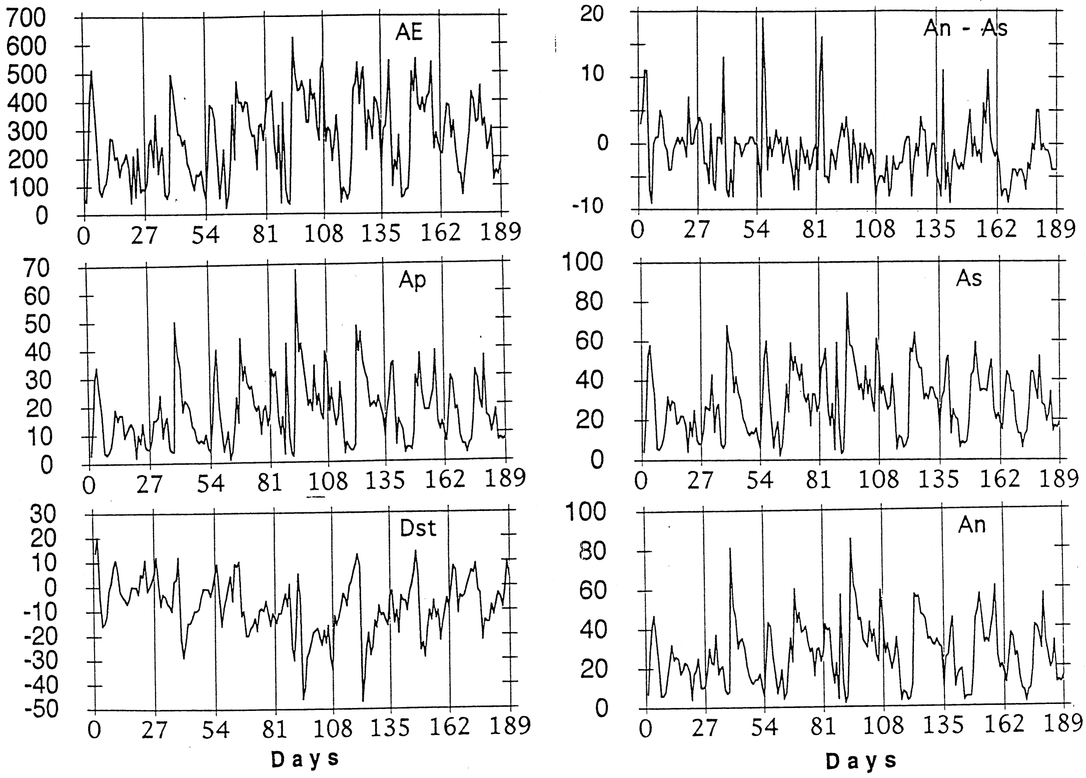

Fig. 2. Mean daily values of different indices of geomagnetic activity and hemispheric difference (An–As), covering seven solar rotations beginning 18 December 1973 and ending 24 June 1974.

equally geoeffective in the subauroral and auroral zones, the energy injection into the equatorial ring current is more for one of the two streams leading to the observed 28-day periodicity. The fact that the $\sim$14-d signal in Dst has a comparatively smaller magnitude conforms with Kamide's suggestion (1992) that the partition of the energy injected into the auroral ionosphere and the magnetosphere is not always in constant proportion. Siscoe and Petscheck (1997) also suggest that Dst is proportional to the sum of the total magnetic energy and twice the total kinetic energy, and that the entire magnetic energy need not be converted into particle energy injected into the ring current. We find that a substorm (enhanced AE) need not have associated enhanced ring current strength (enhanced negative Dst). Iyemori and Rao (1996), investigating the causal relationship between storms and substorms, find that the contribution of the substorm in the process of energy dissipation to storm-time ring current formation seems negligible and hence the two indices AE and Dst need not be expected to respond to solar wind fluctuations in a similar fashion. Our results support this viewpoint.

In their analysis of the features of the variations in AE, Dst and IMF/solar wind parameters, covering nearly the same interval, Tsurutani et al. (1995) find that the AE index remained anomalously high; this is mainly caused by chains of consecutive substorms due to the southward component of large amplitude Alfven waves within the corotating stream. AE remains relatively high even when Dst tends to recover from its peak negative value (see their schematic Fig. 12). Mursula and Zieger (1996) have, earlier, shown that the 13.5-d periodicity was much weaker in Dst than that in Kp during the past three solar cycles. They attribute this to the fact that Bz exhibits no 13.5-d periodicity whereas solar wind pressure has a clear 13.5-d oscillation. Two-stream structures do not often include two large storms during one solar rotation but only one from the hemisphere favourable for a larger R–M influence through the appropriate Bx (or By) direction. According to them, the 27-d oscillation could be due to the Alfvenic fluctuations at strong Corotating Interaction Regions (CIRs) which tend to occur only once per Carrington rotation. During the period covered in the present study, the IMF exhibits a well-defined two sector structure and hence the azimuthal and also the radial components exhibit a strong 27-day variation. Conversion

Table 1
Percentage variance accounted

Parameter	28-day component	14-day	9.5-day
IMF			
B	—	21.0	11.9
Bx	54.7	14.4	5.3
Bye	52.2	12.4	4.8
Bze	7.9	4.2	3.0
Bym	52.6	11.7	5.2
Bzm	20.8	9.4	4.2
Sig.B	—	13.4	7.2
Sig.Bx	—	12.0	3.6
Sig.Bye	—	15.1	5.6
Sig.Bze	—	14.4	—
Sig.Bym	—	15.2	5.2
Sig.Bzm	—	13.8	
SOLAR WIND			
Den.	—	25.2	10.0
Vel.	7.0	52.0	9.3
Sig.den.	—	13.1	8.6
Sig.Vel.	—	16.0	—
INDICES			
Dst	19.0	12.0	6.8
Ap	12.0	25.1	6.4
AE	19.0	24.2	8.2
An	19.8	24.0	9.0
As	12.3	29.0	9.7
An–As	14.8	20.8	5.8

Percentage variance accounted for by the solar rotation periodicity and its first two harmonics in 16 IMF solar wind parameters and indices of geomagnetic activity. The prefix Sig. indicates variability of the corresponding parameter

of a fraction of the azimuthal component through the Russell–McPherron mechanism to southward Bz can be considered the main source responsible for the enhanced geomagnetic activity at low latitudes.

Differences in the responses between AE and Dst indices can also, perhaps, be due to imperfections in the derivation of AE. Feldstein et al. (1994) suggest that, when data from subauroral locations are included to derive AE indices during magnetic disturbances, the linear relation between AE and Dst persists over a wide range. Earlier Akasofu (1981), who used the conventional IAGA-approved AE indices, had suggested that the linear relation between Dst and AE indices is valid only for quiet magnetospheric conditions. It is thus possible that, if there is a more refined AE index as proposed by Feldstein et al. (1994), its time variations may be similar to those of the Dst index. Auroral and subauroral indices are responsive to all the IMF parameters like Bx, By, Bz, solar wind speed, temperature and density together with their variabilities. Many of these parameters have more dominant 14-d fluctuations during the seven solar rotations and some perhaps throughout the last three solar cycles, as shown by Mursula and Zieger (1996). Tsurutani et al. (1995) have suggested that the sustained geomagnetic activity is due to Alfvenic fluctuations characteristic of high speed streams. As these waves have strong out-of-the-ecliptic components, independent of the sector polarity, AE may be expected to respond to coronal holes of both polarities rather than only to those having favourable orientations for the season for an effective conversion through the R–M mechanism. Though velocity and density characterize the high speed streams, the key geoeffective parameter remains the southward component. The predominance of the 14-d periodicity in AE, Ap, An, As and (An–As) and its absence in the Dst index can thus be explained. However, the observed fluctuations in (An–As) certainly requires further scrutiny.

Table 2

Period/ Index	Amplitude (nT) Dst	Ap	An	As	AE	(An–As)
28.4 d	8.1	11.2	10.8	8.7	84.1	2.72
13.5 d	3.6	18.6	12.1	14.2	104.5	2.44
9.1 d	3.7	10.6	6.7	6.8	54.8	0.81

Looking into the fine structure of the 28-d oscillation, we note that, in general, the first three solar rotations are associated with relatively weaker amplitudes. In Ap and Dst, it remains about the same in the next four rotations but there is a clear North–South asymmetry, with the northern hemisphere being more active. This feature is reflected in the (An–As) oscillation in phase with both An and As. In other words, the 28-d oscillation in subauroral activity was stronger in the northern hemisphere. For the first harmonic ($\sim$14-d), the three indices Ap, AE and As show a persistent cyclic behaviour. Dst is conspicuous with its weaker and variable amplitudes. In contrast to As, An shows more variability from cycle to cycle leading to a perceptible asymmetry, with (An–As) in anti-phase with An and As. This implies a greater amplitude for this quasi-periodic oscillation in the southern hemisphere. The southern hemisphere was more active during the initial three solar rotations compared to the latter four. The time variation of the second harmonic ($\sim$9-day periodicity), depicted in Fig. 3(c), is marked by much weaker asymmetry between the hemispheres and all the indices show the weakest signal near the middle part of the period under analysis; some amplitude modulation is also noticed.

These results suggest that while, in general, the northern hemisphere could be geomagnetically more active by about 10% (Mayaud, 1980; Rangarajan, 1991), during

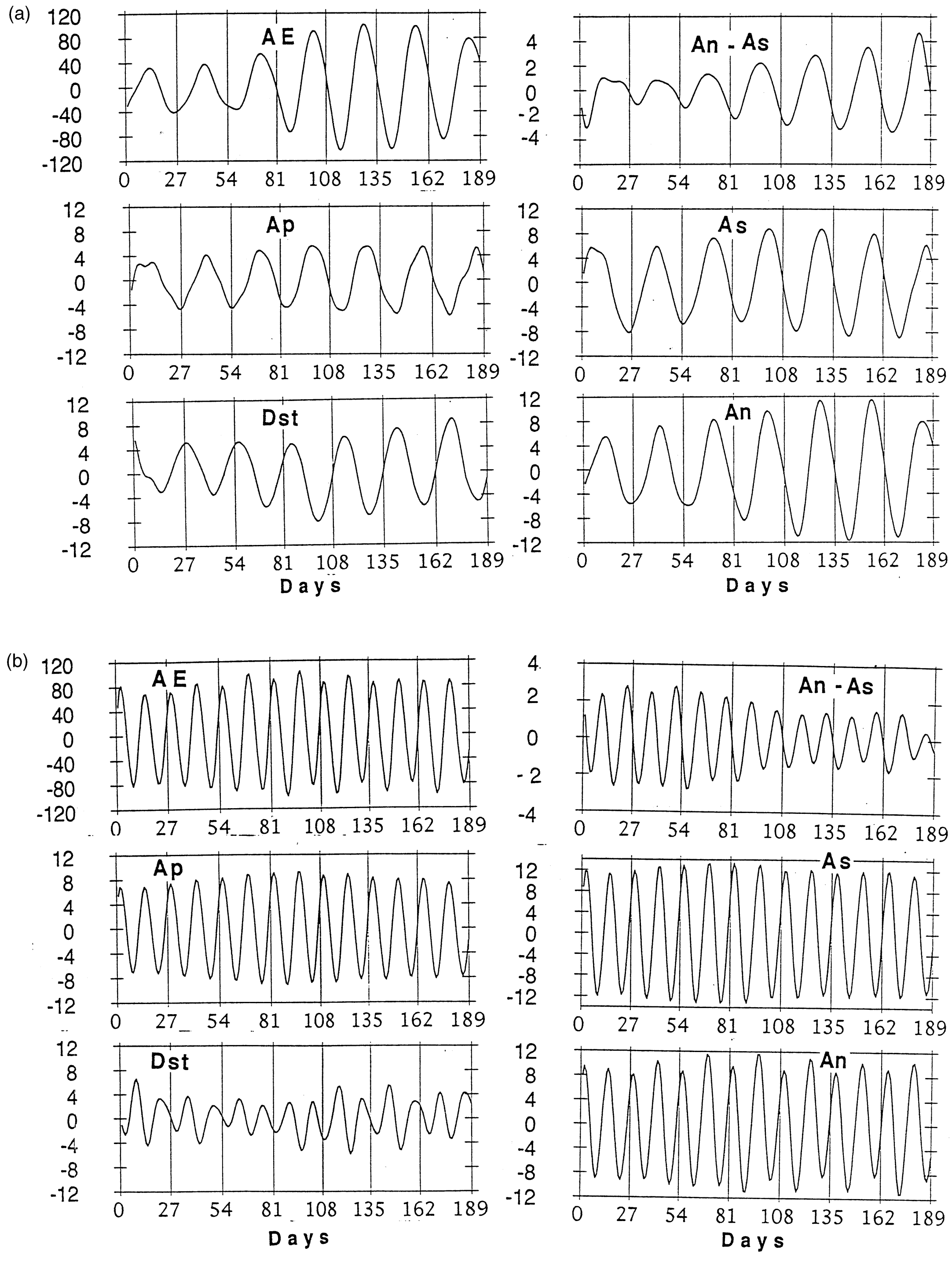

Fig. 3. (a) Principal component corresponding to the 28-day oscillation in different indices of geomagnetic activity derived from Singular Spectrum Analysis of the time series of mean daily values; (b) Same as (a), but for the 14-day oscillation; (c) Same as (a), but for the 9.5-day oscillation.

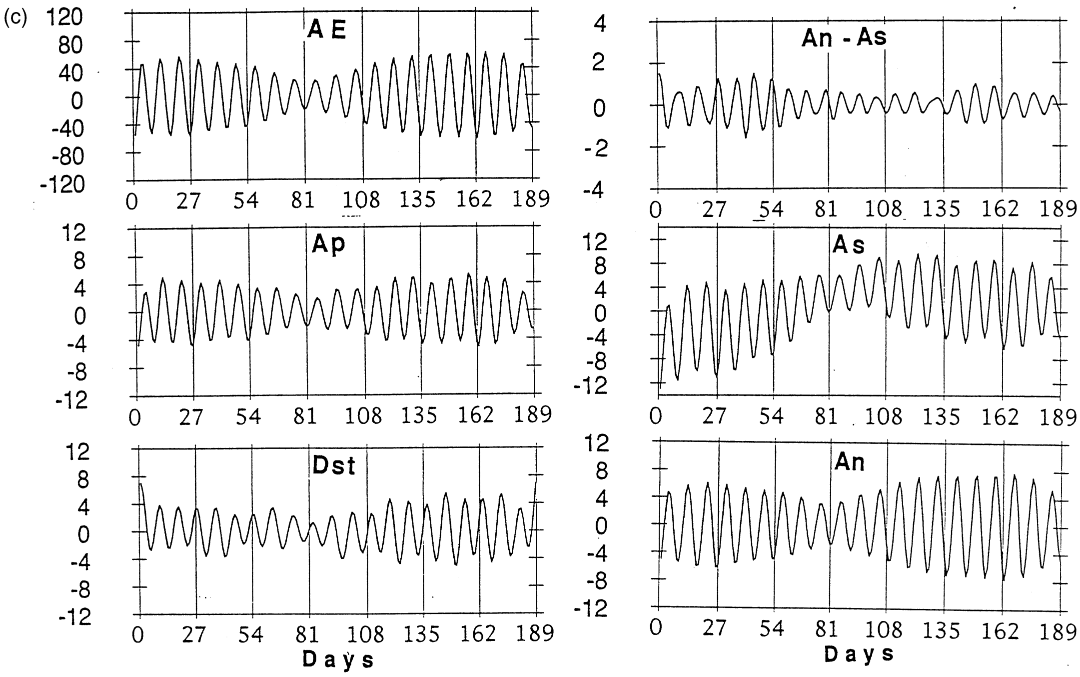

Fig. 3. (c).

individual sequences of recurrent solar wind streams, and consequent enhanced activity, either hemisphere can be more selectively affected. Based on Yoshizawa (1984), solar wind velocity and the North–South component (Bz) should also play a part, as the asymmetry appears only when Bz is directed southward and increases with increased magnitude of the southward component and solar wind velocity. In Fig. 1, a variability in the length of the individual sectors, with longer durations for the negative sectors, can be noticed. Since the polarity of the IMF dictates which hemisphere is more favourably linked to the southward component, the observed variability in (An–As) oscillations can be attributed to this.

3.2. Field oscillations at individual stations

The indices of activity are derived by averaging the field intensity over an appropriate network of magnetic observatories and the local time-dependent component is largely eliminated in the process. In particular, an intermediate standardisation procedure to give due weight for enhanced nighttime activity is part of the scheme to derive Kp (Menvielle and Berthelier, 1991). To highlight the latitude dependence of the geomagnetic field fluctuations at individual locations, we next analyse the mean daily values of horizontal intensity at ten selected stations well distributed in latitude, five in each hemisphere. The station coordinates are given in Table 3.

The principal components associated with the first two harmonics for the ten stations are shown in Fig. 4(a) and (b). At almost all the stations, the influence of the two recurrent streams is definitely weaker during the initial three solar rotations. The 28-d variation is clearly noticed throughout the interval at the northern low latitude stations — Guam, Alibag and Kanoya. These time profiles are also comparable with that of the Dst index, shown in Fig. 3(a). Apia, in the southern hemisphere, also depicts this systematic change. At Tananarive, located at nearly the same geographic latitude as Alibag, but in the southern hemisphere, the time variations are distinctly different with hardly any signal over the first three solar rotations in the first harmonic. Similarly, at the high latitude station of Sanae, both the 28-d and the 14-d, signals are distorted. Boulder, a subauroral station, mimics the features seen for Ap or An fairly well. In most of the ten individual stations, the time variations are only grossly comparable to the corresponding changes in the appropriate indices (Dst for low latitudes, Ap, An or As for subauroral station or AE for Sanae).

At low and auroral latitudes, the disturbance field should be enhanced in the dusk-dawn MLT sector as compared to the daylight hemisphere due to the additional contributions from both the partial ring current and the stronger westward auroral electrojet current. The distortions seen in the time profiles at individual observatories, in contrast to the smoother profiles noticed for the indices, may be largely due to the influence of the local time-dependent currents. Also, a significant part

Table 3

Station	Station Code	Geographic Lat.	Geographic Long.	Geomagnetic Lat.	Geomagnetic Long.
Boulder	BOU	40.13	254.77	48.88	319.04
Memambetsu	MMB	43.90	144.20	34.61	210.23
Kanoya	KNY	31.42	130.88	21.12	199.85
Alibag	ABG	18.63	72.87	9.64	145.39
Guam	GUA	13.58	144.87	4.57	214.76
Apia	API	−13.80	188.22	−15.61	261.99
Tananarive	TAN	−18.92	47.55	−23.89	113.96
Hermanus	HER	−34.42	19.23	−33.73	82.67
Amberley	AML	−43.15	172.72	−47.16	254.00
Sanae	SNA	−70.30	357.65	−64.23	46.20

(about 30%) of the magnetic field variations observed at the surface is caused by the currents due to electromagnetic induction within the conducting interior beneath the station and, hence, some of the observed differences can be attributed to the lateral conductivity contrast and subsurface geology of the station concerned. Despite these differences, the influence of the two recurrent streams is definitely weaker all over the globe in the first three solar rotations.

In recent years, it has been emphasized that quasi-periodic fluctuations in the winds in the mesosphere or stratosphere can generate ionospheric currents to produce appropriate geomagnetic signatures (Pei Ren Chen, 1992; Olsen, 1994; Rangarajan, 1994). A class of waves, termed planetary waves, are identified as free oscillations in the atmosphere with periodicities in the range of 5–21 days. Enhanced power densities close to the planetary wave periodicities have indeed been observed in An index as also in the ionospheric parameters foE, foF2 and the sunspot number (Altadill, 1996). These waves travel exclusively westward (Kosheik et al., 1995). If in the observed 14-d or 9-d waves in the geomagnetic field fluctuations were caused by these planetary waves, they could be identified from the progressive change in the phase at a network of stations with different longitudes. The observed H variations in the 14-day or 9.5-day bands do not show any phase difference whenever the signals are strong. Thus we may rule out the possibility of ionospheric/mesospheric contributions to these quasi-periodic fluctuations and attribute them solely to solar causes.

3.3. Quasi-periodic fluctuations in IMF and solar wind parameters

We have given, in Table 1, the fractions of the total variance accounted for by the solar rotation periodicity (∼28-d) and its first two harmonics in terms of percentages. From this table it becomes clear that: (1) not all the 16 listed solar wind/IMF parameters are geoeffective, and (2) the cumulative percentage of the total variance does not exceed 60, indicating that the remaining part is due to non-recurrent sources and the day-to-day variability in the quiet magnetosphere. In the list, we have included the IMF components in both the GSEQ and GSM coordinate systems (Russell, 1971) because IMF is ordered in the solar-equatorial plane whereas its interaction with the Earth's magnetosphere is ordered in the solar-magnetosphere coordinate system (Russell and McPherron, 1973).

Figure 5(a) and (b) give the time variations of 28-d and 14-d components in the solar wind/IMF parameters which have significant contributions to the total variance. Though the southward component of the IMF is identified as a crucial parameter for both substorms and storm activities, it has a very minor role in its geoeffectiveness during the period under study. Solar wind velocity is certainly seen to be a crucial parameter, particularly for the 14-d oscillatory trend with a nearly constant amplitude of about 100–120 km/sec throughout the interval (Fig. 4 of Mursula and Zeiger, 1996, may also be seen). Solar wind density too exhibits a similar structure anti-phase with the velocity, as would be expected (Fig. 5(b). For the 28-d or 9.5-d components, these two parameters are not significant, suggestive of the unambiguous recurrence every 14 days.

Mursula and Zieger (1996) using a more extensive data base, have earlier identified a sharp spectral peak close to the 14-d period in solar wind speed. They also find that IMF Bz (in GSM coordinates) has some power around 27 days but the first harmonic is quite weak. The 'sector component' of the IMF — obtained by rotating the radial IMF by 44 degrees off the x-axis — showed a dominant 27-d periodicity over the entire interval of 1964–1994; a

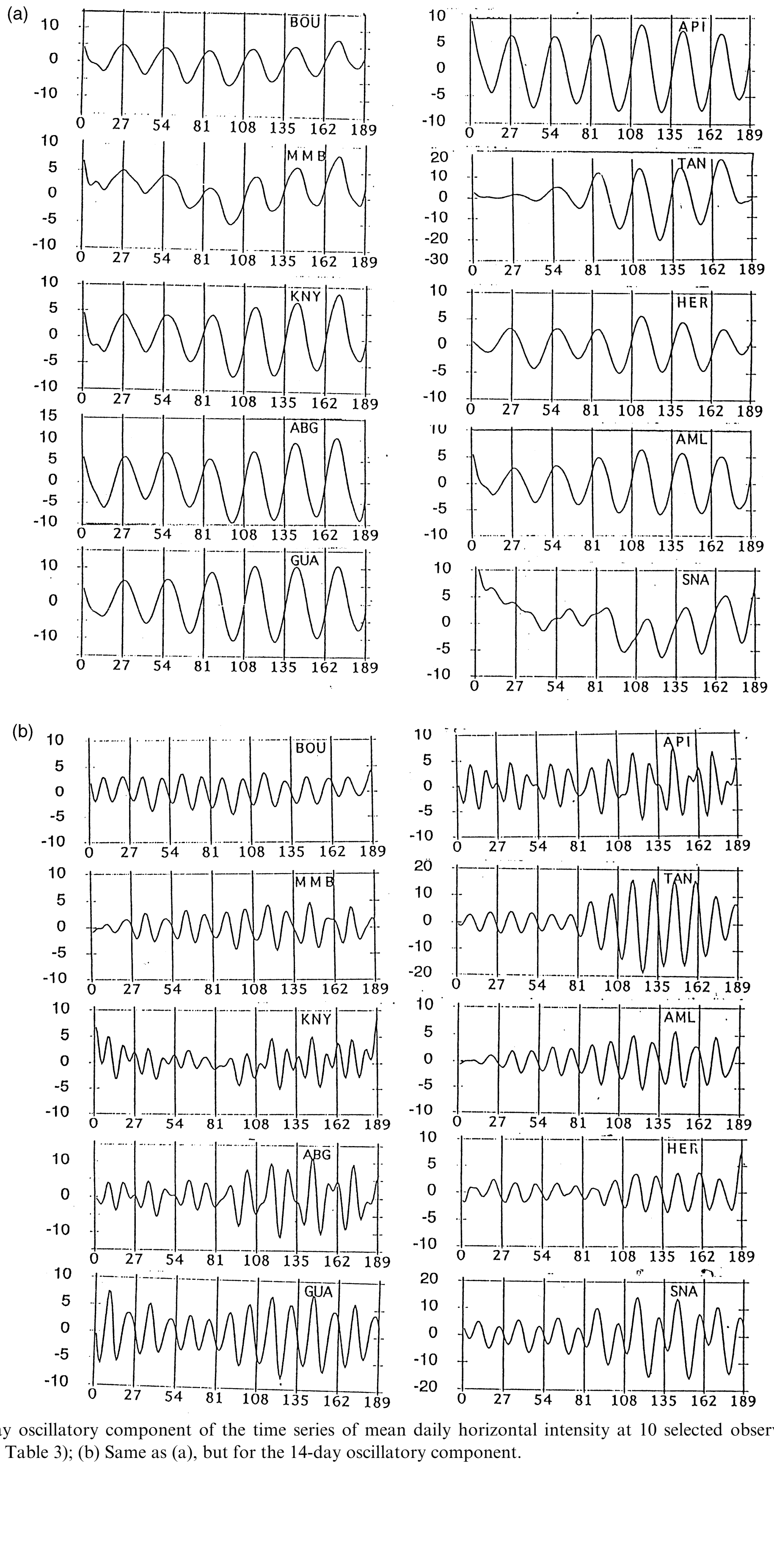

Fig. 4. (a) 28-day oscillatory component of the time series of mean daily horizontal intensity at 10 selected observatories in both hemispheres (see Table 3); (b) Same as (a), but for the 14-day oscillatory component.

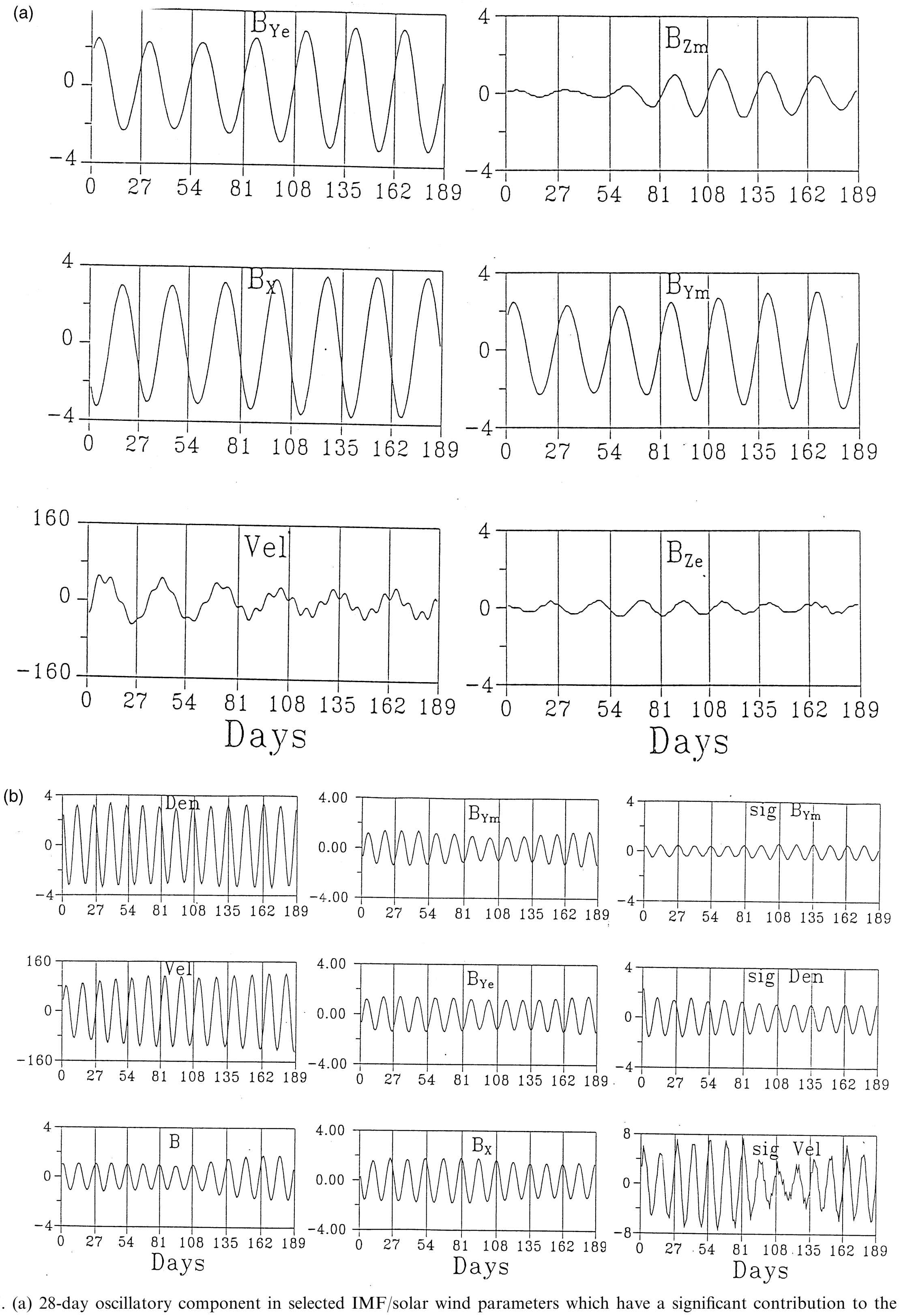

Fig. 5. (a) 28-day oscillatory component in selected IMF/solar wind parameters which have a significant contribution to the total variance in the corresponding time series (see Table 1); (b) Same as (a), but for the 14-day oscillatory component.

similar feature has been noted by us for Bx, Bye and Bzm. This implies that, while a 14-d periodic component in the solar wind velocity is a near-permanent feature, that in IMF Bz could undergo amplitude modulation over different solar cycles.

Variability in the solar wind velocity (Sig.vel.) was also identified as a possible source for geomagnetic activity earlier (Garrett et al., 1974) and we find Sig.vel. and Sig.den. (variability in the solar wind density) are the two parameters with fairly large amplitude in the two sequences of recurrent streams. IMF and solar wind variability do not depict the 28-d oscillation sequence, unlike indices of geomagnetic activity. The strong solar rotation signal observed in Bx, Bye and Bym (Fig. 5(a)) is a clear indication that the sector polarity of IMF, and consequently the azimuthal component of the IMF, are the main sources for the observed oscillation with 28-d periodicity in the geomagnetic activity indices and the North–South asymmetry. As seen from Fig. 1, during the first half of 1974, the number of days with IMF polarity directed toward the Sun was substantially more and hence the geoeffectiveness of the Russell–McPherron effect is also expected to be greater due to the favourable IMF orientation. Crooker and Cliver (1994) found that the peak activity in Dst followed the passage of a sector boundary in 1974 and suggested that the sustained activity which follows the peak was due to solar wind speed rather than due to southward IMF. Thus, it is likely that when both the recurrent streams are geoeffective, particularly at the subauroral and auroral latitudes, it is mainly through the solar wind speed oscillations, whereas when one of the streams is more geoeffective, as observed in the equatorial latitudes, the IMF direction in the heliospheric equatorial plane is the main responsible mechanism.

Crooker et al. (1977) found that solar wind velocity, during solar cycle 20, was highly correlated with Ap index, when six-month averages are utilized and that as the averaging interval is increased, the significance of the southward component of IMF in controlling geomagnetic activity diminishes whereas the velocity continues to be essential for geoeffectiveness. Feldstein et al. (1984) also find that the solar wind velocity must be an important input in the modelling of the equatorial Dst field during a geomagnetic storm in contrast to the earlier suggestion of Burton et al. (1975) who placed greater emphasis on the southward component of IMF and the electric field, VBs. Concurrent solar wind velocity and geomagnetic activity (Ap) oscillations with a periodicity of 1.3 years were recently reported by Paularena et al. (1995). Thus, over a large range of frequencies, the fluctuating solar wind velocity appears to be an important driving force for solar wind-magnetosphere interaction. This is confirmed from the present analysis that the solar wind velocity is one of the major causative sources for the observed 14-day oscillation in geomagnetic activity and its North–South asymmetry.

Field variations in the period-range of 9–28 days at individual magnetic observatories exhibit intermittency of amplitude variations, but these are not discernible in the solar wind parameters. This implies that not all the energy transferred into the magnetosphere is deposited in the auroral zone or into the ring current, in conformity with the suggestion of Kamide (1992). This inference is also borne out by the lower cumulative percentages, accounting for three major components of oscillations (see Table 1). In addition, we emphasize that the relative contribution differs between the two hemispheres and as a function of latitude. A possible cause for the observed differences in the two hemispheres is the relative location of the centre of the substorm current wedge. Wu et al. (1991) find that the substorm westward electrojet flows at a higher latitude in the winter hemisphere, caused by the effect of the magnetic dipole tilt on the location of the closed hemisphere. Similarly, the average latitude of the ring current swings northward (southward) in winter (summer) (Malin and Isikara, 1976) which can lead to a North–South asymmetry even at low latitudes, as a function of season.

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