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VARIABILITY OF THE INTERPLANETARY MEDIUM AT 1 a.u. OVER 24 YEARS: 1963–1986

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Abstract—A survey is presented of hourly averages of observations of the interplanetary medium, made by satellites close to the Earth (i.e. at 1 a.u.) in the years 1963–1986. This survey therefore covers two complete solar cycles (numbers 20 and 21). The distributions and solar-cycle variations of IMF field strength, B, and its northward component (in GSM coordinates), B_z, and of the solar-wind density, n, speed, v, and dynamic pressure, P, are discussed. Because of their importance to the terrestrial magnetosphere/ionosphere, particular attention is given to B_z and P. The solar-cycle variation in the magnitude and variability of B_z, previously reported for cycle 20, is also found for cycle 21. However, the solar-wind data show a number of differences between cycles 20 and 21. The average dynamic pressure is found to show a solar-cycle variation and a systematic increase over the period of the survey. The minimum of dynamic pressure at sunspot maximum is mainly due to reduced solar-wind densities in cycle 20, but lower solar-wind speed in cycle 21 is a more significant factor. The distribution of the duration of periods of stable polarity of the IMF B_z component shows that the magnetosphere could achieve steady state for only a small fraction of the time and there is some evidence for a solar-cycle variation in this fraction. It is also found that the polarity changes in the IMF B_z fall into two classes: one with an associated change in solar-wind dynamic pressure, the other without such a change. However, in only 20% of cases does the dynamic pressure change exceed 50%.

1. INTRODUCTION

Since the concept of magnetic reconnection between the interplanetary magnetic field (IMF) and the geomagnetic field was first introduced as a possible explanation of aurorae by Hoyle (1949) and as a source of magnetospheric and ionospheric convection (and associated ionospheric currents) by Dungey (1953, 1961), the importance of the North–South (B_z) component of the IMF has been increasingly recognized. This component is known to influence a great many characteristics and parameters of the terrestrial plasma environment, including: (i) the voltage placed across the magnetosphere by the solar-wind flow (mapped to the transpolar voltage across the ionospheric polar cap) (Reiff *et al.*, 1981; Doyle and Burke, 1983; Wygant *et al.*, 1983); (ii) the pattern of ionospheric flows (Heelis, 1984; Heppner and Maynard, 1987; Holt *et al.*, 1987; Etemadi *et al.*, 1988) and currents (Friis-Christensen *et al.*, 1985); (iii) the location and width of the dayside "cusp" aurora (Carbary and Meng, 1988; Newell *et al.*, 1989); (iv) the occurrence of magnetic activity (Schatten and Wilcox, 1967; Arnoldy, 1971; Baker *et al.*, 1981, 1983; Clauer *et al.*, 1981; Bargatze *et al.*, 1985), including magnetospheric substorms (Rostoker and Fälthammer, 1967); (v) the patterns of neutral thermospheric winds (Killeen *et al.*, 1985); (vi) the occurrence of characteristic particle and field signatures termed "flux transfer events" (FTEs) near the dayside magnetopause (Rijnbeek *et al.*, 1984; Berchem and Russell, 1984) and many other phenomena, too numerous to include here. Therefore the distribution of values for this component of the IMF (at the Earth) is of great interest if we are to understand the possible states and configurations of the coupled ionosphere–magnetosphere–thermosphere system.

Recently, there has been much interest in the response time of the terrestrial system to changes in B_z. In particular, two separate response times have become apparent. On the dayside, Nishida (1968a, b)

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reported that statistically the DP-2 current system responded to B_z on time-scales of a few minutes, a finding consistent with a number of case studies (Pellinen *et al.*, 1982; Nishida and Kamide, 1983; McPherron and Manka, 1985; Clauer and Kamide, 1985). Recently, Etemadi *et al.* (1988) have shown statistically that dayside ionospheric flows respond with similarly short time-scales, again in keeping with a number of case studies (Rishbeth *et al.*, 1985; Lockwood *et al.*, 1976; Todd *et al.*, 1988; Clauer and Friis-Christensen, 1988). On the nightside, however, the DP-1 ionospheric currents have been shown to respond on rather longer time-scales (typically about an hour) (Schatten and Wilcox, 1967; Arnoldy, 1971; Baker *et al.*, 1981, 1983). The presence of these two separate response times has also been inferred from studies of the response of geomagnetic indices to impulses in the IMF by the linear prediction filter technique (Clauer *et al.*, 1981, 1983; Bargatze *et al.*, 1985). Similarly, auroral substorm activity has been divided into two distinct processes termed the "directly-driven" (Rostoker *et al.*, 1987; Akasofu, 1981) and the "unloading-loading" or "storage" system (McPherron, 1972). We note, however, that Rostoker and Pascal (1990) describe both peaks in the impulse response function in terms of the directly-driven system, the more delayed response being relatively stronger when the pre-existing magnetic activity is low.

Lockwood *et al.* (1990) have discussed these observations of response times in terms of magnetic reconnection and conclude that the dayside flow and current patterns, with their short (about 10 min) response to changes in B_z are dominated by magnetic reconnection at the dayside magnetopause. The nightside flows and currents, on the other hand, are dominated by reconnection in the geomagnetic tail, with their longer (hour) response times to southward IMF turnings. Imbalances in the rate at which reconnection proceeds at these two locations are reflected as expansions and contractions in the ionospheric polar caps, as has been observed and quantitatively modelled by Holzer *et al.* (1986). A further complication is that almost immediate responses appear to be triggered in the tail by some northward turnings of the IMF (Rostoker, 1983), i.e. the reconnection rate in the tail may increase just as that at the dayside magnetopause decreases. Most models of ionospheric flows, horizontal currents and field-aligned currents assume that the system is in a steady state, i.e. that dayside and nightside reconnection rates are equal and the polar cap is constant in size. This conflicts with theories of substorms in which imbalances between these reconnection rates are inherent (Russell and McPherron, 1973; Hones, 1979). Lockwood *et al.* (1990) used the modelling by Siscoe and Huang (1985) to point out that these imbalances will fundamentally alter the patterns of flows and currents, which at no time in the cycle of polar-cap expansion and contraction will have the same form as the steady-state models.

It is therefore important to study how stable the IMF is in general. If the IMF usually exhibits prolonged periods of constant B_z, the system may attain a steady state (constant polar cap area) or a constant oscillation about a mean state (regular oscillations in the polar cap area). If, however, the IMF B_z component varies on time-scales comparable with, or shorter than, the response time of nightside reconnection, neither a steady state nor regular oscillations will be established. It is therefore of interest to study the persistence of a given IMF B_z to determine which of these states applies to the actual magnetosphere–ionosphere system. Because of the dependence of parameters like the transpolar voltage on the IMF B_z component, it is thought that magnetic reconnection is the dominant process for driving magnetospheric convection [see reviews by Cowley (1984) and Reiff and Luhmann (1986)]. However, the presence of some continued convection (with anti-sunward flow over the polar caps) during periods of northward IMF, when reconnection at the subsolar magnetopause is not expected to be efficient, indicates a second type of momentum transfer across the magnetopause, which is often termed a "viscous-like interaction" (Axford and Hines, 1961; Cowley, 1984; Reiff and Luhmann, 1986). Such an interaction moves closed field lines anti-sunward into the geomagnetic tail. A number of mechanisms have been proposed for this interaction including wave-driven diffusion of magnetosheath plasma across the magnetopause, "impulsive penetration" of magnetosheath plasma, "gradient drift entry" and Kelvin–Helmholtz waves (see review and discussion by Hill, 1983). Moreover, recent observations and theories have added another mechanism which would be dependent on solar-wind flow. The recent observations have shown that transient ionospheric flows can be generated by transient pulses in solar-wind dynamic pressure (Farrugia *et al.*, 1989; Sibeck *et al.*, 1989). These otherwise anomalous observations have been explained by Southwood and Kivelson (1990) and Lee (1991) and the theories have an interesting implication in that closed field lines in the ionosphere will be moved anti-sunward by both increases and decreases in solar-wind dynamic pressure. This excitation of convection by solar-wind buffeting was first suggested by Dessler (1964). The short-term variability of solar-wind dynamic pressure may also, therefore, be of importance to the general behaviour of the ionosphere–magnetosphere system. In addition, large changes in dynamic pressure have long been known to generate changes in the terrestrial magnetic field, as first suggested by Chapman and Ferraro (1931). If increased effects in field strengths precede a full geomagnetic storm they are called storm sudden commencements (SSCs): increases and decreases which are not associated with storms are termed sudden impulses (SIs). These usually also excite geomagnetic pulsations.

The location of the dayside magnetopause is known to be altered by both dynamic pressure changes and variations in reconnection rate. Increases of the former compress the magnetosphere, whereas increases of the latter "erode" the dayside magnetopause by transferring magnetic flux from the dayside into the tail (Aubry *et al.*, 1970, 1971; Holzer and Slavin, 1978).

In this paper, we investigate some of the questions about the variability of both the IMF B_z component and the solar-wind dynamic pressure using a 24-year sequence of interplanetary observations. We then discuss implications for the terrestrial coupled ionosphere–magnetosphere system. Hirshberg (1969) first suggested that the distribution of IMF values may show a solar-cycle variation. However, early studies of the interplanetary medium failed to find systematic solar-cycle dependence [see reviews by Hundhausen (1975) and Neugebauer (1975)]. As longer sequences of data became available, solar-cycle variations were found in both the solar wind (e.g. Gosling *et al.*, 1976) and the IMF (e.g. Siscoe *et al.*, 1978; Slavin *et al.*, 1986). In Section 4 of this paper we extend the earlier work by using 24 years of data to study two complete solar cycles.

Rostoker *et al.* (1988) have considered the stability of the B_z component in relation to the response times of the ionosphere–magnetosphere system. These authors used data from the *IMP*-8 satellite, averaged over 15.36 s, for a 9-month period and calculated the distribution of the intervals between times when B_z passed through zero. Hence this is an estimate of the distribution of durations for which the IMF maintained a southward or northward orientation. These authors took a typical response time of the magnetosphere to be 2 h and found that B_z was stable for longer than this for only 15% of the time. As pointed out by these authors, a problem with using these high time resolution data is that the periods of stable B_z can be interrupted by a single 15-s data point of the opposite polarity which, in reality, would almost certainly have a negligible effect on the magnetosphere–ionosphere system. Also, no account was taken of the magnitude of the swing in B_z. In this paper, we avoid these problems by considering hourly averaged data (Section 5). This is rather longer than desirable, considering that the response time is of order 2 h, but does have the advantage that the variation of the distribution (of periods of stable sense of mean B_z) over two solar cycles can be investigated. It must be noted here that a substorm cycle could be completed in a period of less than an hour, and that this could be in response to IMF changes on sub-hour timescales which may not be apparent in the hourly averages used here. However, we may still make some deductions about the likelihood of the ionosphere–magnetosphere system reaching a steady state from hourly IMF averages. This is because if the hourly averages do not maintain a constant polarity of B_z, the magnetosphere will not attain steady state: if hourly averages do maintain a constant B_z polarity, the magnetosphere may or may not attain steady state. As well as the variations in B_z polarity on sub-hour timescales discussed above, variations in the magnitude of B_z, without polarity changes, may be sufficient to prevent steady state. Therefore the fractions of time that the IMF hourly averages are of constant B_z polarity represent maxima for the fractions of time for which the magnetosphere will be in steady state. In reality, we would expect a steady magnetosphere for somewhat smaller fractions of time than those given here, which therefore represent upper limits.

Lastly, in Section 5.3, we consider the changes of the solar-wind dynamic pressure which accompany polarity changes in the B_z component of the IMF, given their possible role in the excitation of ionospheric flows. Such flows may be transients due to these discrete changes in dynamic pressure (Sibeck, 1990). However, we also discuss the possibility that large scale, quasi-steady convection is generated by continuous buffeting of the magnetosphere by the solar wind.

2. DATA SOURCES

The data used in this work have been taken from a compilation of solar wind plasma and IMF data prepared by the US National Space Science Data Center (NSSDC), using data supplied by a number of experimental groups. This data product, known as the Omnitape, contains hourly averages of all solar wind plasma and IMF data available to the NSSDC (Couzens and King, 1986). The data were recorded on a number of spacecraft: *IMP*-1, *IMP*-3 to -8, *AIMP*-1 and -2, *OGO*-5, *HEOS*, *VELA*-2 to -6, *ISEE*-1 to -3. The Omnitape dataset is updated as new data become available from experimenters.

The dataset available to us covers the period 2

November 1963–31 May 1987. Within this period we have examined only those cases for which both plasma and magnetic field data are available simultaneously. This restricts our analysis to the period 27 November 1963 to 4 April 1986. Within this period there are 101,558 hourly values available out of a total 195,960 hours possible (an average availability of 52%). Data coverage is limited for a number of reasons. The two most important of these are: (i) the limited availability of telemetry stations to receive data from the spacecraft that monitored the solar wind and IMF; and (ii) all these spacecraft, with the exception of *ISEE*-3, spent only part of each orbit in the solar wind.

The coordinate system used to present the magnetic field data is the geocentric–solar–magnetospheric (GSM) system (Russell, 1971). This was chosen as it makes the IMF B_z component nearly parallel to the magnetic dipole axis of the Earth. Thus it is a good representation of B_z for studies of IMF–magnetosphere coupling by magnetic reconnection.

The data used in this study were read off magnetic tape and stored on-line in a number of databases which operate under a formal database management system called R-EXEC (Read, 1986). This system was developed at the Rutherford Appleton Laboratory for the manipulation of scientific data and has proved invaluable in this work, as it facilitated the implementation of many different analyses.

3. DISTRIBUTIONS OF IMF AND SOLAR-WIND PARAMETERS

Figure 1 shows the distributions of observed solar wind and IMF parameters derived from the dataset described above. The distributions are drawn between the largest and the smallest of the hourly averaged values observed during the 24-year period. Figure 1a shows the distribution of solar-wind speed, v, which ranged between 250 and 950 km s^{-1}, with a mode value of 370 km s^{-1}. This is broadly consistent with results from surveys of smaller solar-wind datasets (e.g. Gosling *et al.*, 1971; Gosling, 1972). Figure 1b shows the distribution of solar-wind densities which ranged up to 83 cm^{-3}, with a mode value of 6 cm^{-3}. The upstream solar-wind dynamic pressure is $P = nmv^2$. Taking the mean mass of the solar wind, m, to be 1 a.m.u. (i.e. the solar wind is assumed to be predominantly protons and electrons), P is found to have ranged up to 28 nPa, with a mode value of 3 nPa (Fig. 1c). All these solar wind distributions are considerably skewed. Figure 1d shows that the magnitude of the IMF varied between 0 and 85 nT. (Note that one hourly mean was zero—which means that on one occasion, the average total field was less than 0.1 nT.) The mode value is 6 nT, about which the distribution is much less skewed than in Fig. 1a–c. This IMF field strength distribution is very similar to those for 1967–1974, as presented by King (1976).

Figure 1e shows the distribution of B_z values in GSM coordinates. Values ranged between -31 and 27 nT, but the distribution is almost completely symmetrical about a mode value of zero. (The calculated mean value is 0.014 nT, with a standard deviation of 3.3 nT.) This indicates that, over the two solar cycles examined, the values of B_z are normally distributed and northward and southward fields occur with equal frequency.

As in the case of the solar wind parameters, these IMF distributions are very similar to those reported from smaller datasets (e.g. Siscoe *et al.*, 1978).

4. SOLAR-CYCLE VARIATIONS

Because of their importance to the terrestrial magnetosphere–ionosphere system, we here investigate the solar-cycle variation in IMF B_z and solar-wind dynamic pressure, P. The variation of the magnitude of the IMF has been studied for cycles 20 and 21 by Slavin *et al.* (1986). For the IMF study we have followed the method Siscoe *et al.* (1978) employed for cycle 20: for each calendar year we took all hourly values of the magnitude of B_z and then calculated the mean of these values, $\langle |B_z| \rangle$, and the standard deviation associated with that mean, σ_{B_z}. These annual means and standard deviations are plotted as solid lines in the upper two panels of Fig. 2. The dashed lines give the corresponding variations of IMF field strength, i.e. $\langle |B| \rangle$ and σ_B. For comparison the annual mean sunspot number, $\langle R \rangle$, is plotted in the bottom panel. There is a clear solar-cycle variation in both the mean magnitude of B_z and in its standard deviation, as reported by Siscoe *et al.* (1978) for a single solar cycle. Our results extend their work and show that these solar-cycle variations in the characteristic properties of B_z also occurred in cycle 21. The amplitude of these variations was larger in cycle 21 than in cycle 20; this behaviour is similar to that for $\langle R \rangle$ and other solar indices such as the solar radio flux. It can be seen that the variation in B_z largely reflects that in B, i.e. there is no detectable variation in the elevation angle of the IMF.

Figure 3 shows the solar-cycle variation in solar-wind dynamic pressure, and the factors which contribute to it. Again the variation of mean sunspot number is plotted at the base of the figure for comparison [part (f)]. Figure 3a shows the mean solar-wind density, $\langle n \rangle$. For cycle 20 there appeared to be a clear anti-correlation of $\langle n \rangle$ with sunspot number.

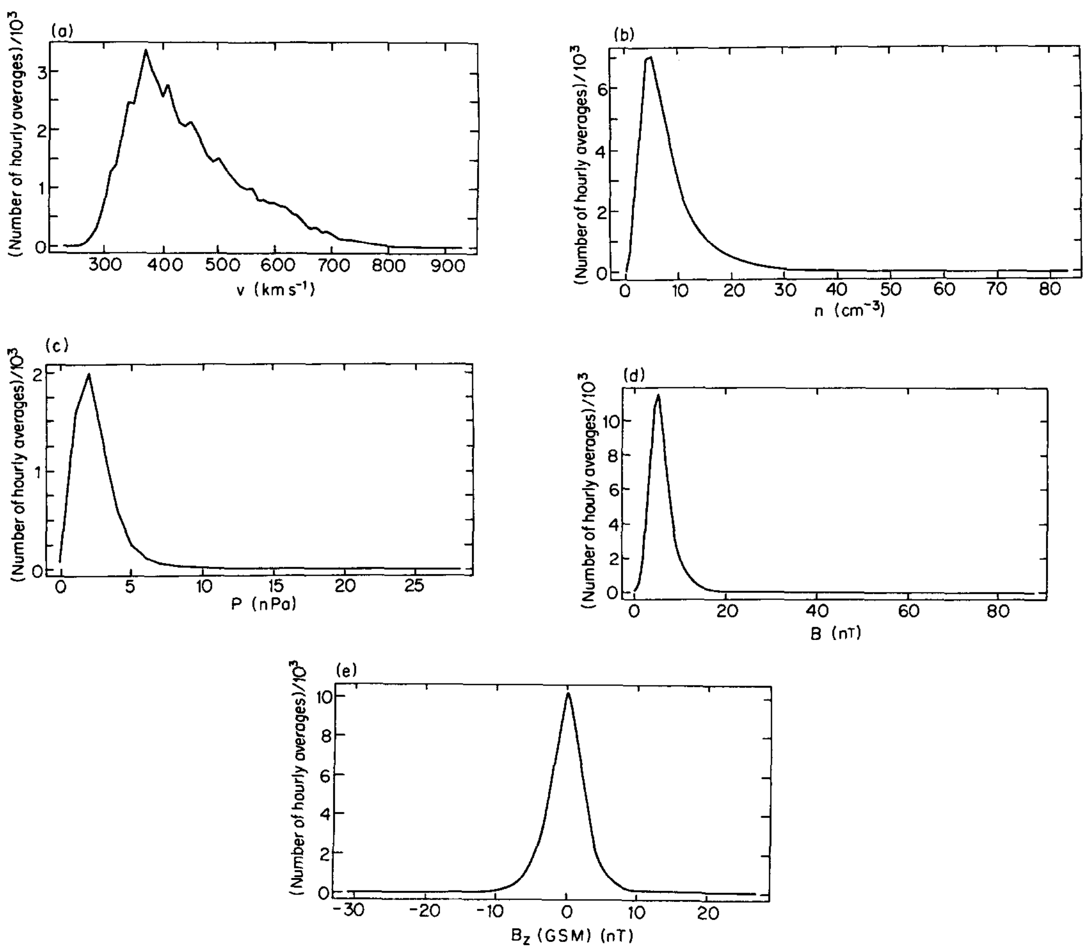

FIG. 1. DISTRIBUTIONS OF IMF AND SOLAR-WIND VALUES FOR THE WHOLE DATASET.
(a) The solar-wind speed, v; (b) the solar-wind density, n; (c) the solar-wind dynamic pressure, P; (d) the IMF field strength, B; and (e) the northward component of the IMF (GSM coordinates) B_z.

This anti-correlation was noted in data for part of this cycle by Diodato *et al.* (1974) (see also Neugebauer, 1975). However, this anti-correlation cannot be seen for cycle 21, despite this cycle giving much larger $\langle R \rangle$. Rather, after about 1972 there is a gradual increase in $\langle n \rangle$. Part (b) shows the corresponding annual means of the standard deviations of the hourly mean values, $\langle \sigma_n \rangle$. This can be seen to follow the density quite closely, again indicating an anti-correlation with $\langle R \rangle$ during cycle 20, but a gradual increase during cycle 21.

The variation of the mean solar-wind speed, $\langle v \rangle$, is shown in part (c) and the mean of the hourly standard deviation of speeds, $\langle \sigma_v \rangle$, is shown in (d). The mean speed appears to be somewhat elevated in the falling phase of the cycle: the only exception to this is for 1963, for which the data are very sparse. The variability of speeds also peaks when $\langle R \rangle$ is falling: this occurred early in the falling phase in cycle 21 but somewhat later in cycle 20. This effect was not noted in early surveys of this variation (e.g. Gosling *et al.*, 1971; Diodato *et al.*, 1984; Neugebauer, 1975), probably because they did not have much data from this phase of the cycle. These earlier surveys tended to show high-speed streams to be most common at the peak of cycle 20 (e.g. Intriligator, 1974) and this may be the cause of the small peak in $\langle v \rangle$ for 1968; however, no such effect is seen for solar maximum years of cycle 21. However, Gosling *et al.* (1976) did find mean flow speeds to be greater in sunspot minimum and declining phase years 1962, 1973 and 1974, and the spread of the distribution of speeds also to be considerably greater for these years. This is consistent with the peak in $\langle v \rangle$ and $\langle \sigma_v \rangle$ for these years in Fig. 3. Gosling *et al.* ascribe the larger mean

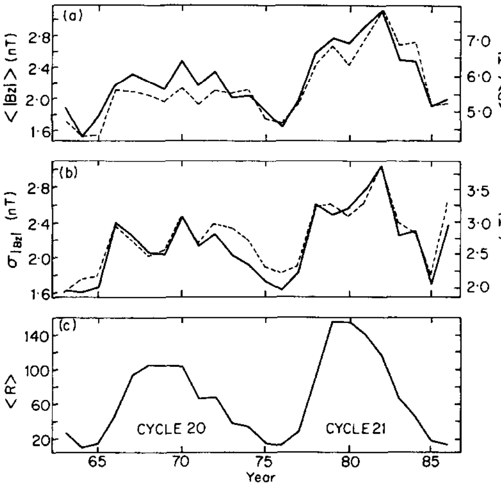

FIG. 2. SOLAR-CYCLE VARIATIONS IN OUT-OF-ECLIPTIC COMPONENT OF THE IMF (GSM COORDINATES).
The solid lines and left-hand scales are for annual values of (a) the mean magnitude of B_z and (b) the standard deviation of the magnitude of B_z. The dashed lines and the right-hand scales are the equivalent variations for the IMF strength, B. The lowest panel (c) gives the mean international sunspot number, R.

and spread of the distribution to extremely high-speed flow streams, as observed in minimum and declining phase years by Bame *et al.* (1976).

Figure 3 shows that annual means of n vary by a factor of about 2 and that $\langle\sigma_n\rangle/\langle n\rangle$ is roughly constant and of order 0.1. By contrast, $\langle v\rangle$ varies by a factor of only about 1.3 and $\langle\sigma_v\rangle/\langle v\rangle$ is about 0.02. Even allowing for the square-law dependence on velocity, we find that most of the variability in solar-wind dynamic pressure on sub-hour time-scales originates from the variability in solar-wind density. On yearly time-scales variations in both density and velocity contribute to dynamic pressure variability.

The variation of annual means of hourly dynamic pressure values is given in Fig. 3e. The data appear to show a long-term trend over the 24 years, with values typically 50% higher at the end of the period than at the beginning. Superposed on this is a solar cycle variation, with lower dynamic pressure at sunspot maximum for both cycles. Interestingly, however, parts (a) and (c) show that the minimum at the peak of cycle 20 arises mainly from lower values of the mean solar-wind density, whereas that at the peak of cycle 21 arises more from lower solar-wind speeds.

5. SOUTHWARD AND NORTHWARD TURNINGS OF THE IMF

5.1. *Definition of "events"*

The main objective of this investigation was to examine major reversals of B_z, the North–South component of the interplanetary magnetic field. These reversals are important events which should cause significant changes in the terrestrial magnetosphere. We therefore identified "events" as times when there was a reversal of the polarity of B_z between adjacent hourly mean values. As a secondary condition, we required that the magnitude of B_z was greater than 1 nT for both hourly values.

The magnetic-field data were analysed using a computer program which searched for events using the criteria defined above. A total of 6018 events were found for the 24-year period.

5.2. *Duration of stable IMF* $\mathbf{B}_z$ *conditions*

To estimate the duration of stable IMF conditions, we determined the interval following each event for which B_z maintained the same polarity. Cases in which data gaps occurred before B_z changed sign were excluded from this analysis. Figure 4 shows the number of occasions that a particular interval of stable B_z sign occurred in the dataset. Note that the minimum

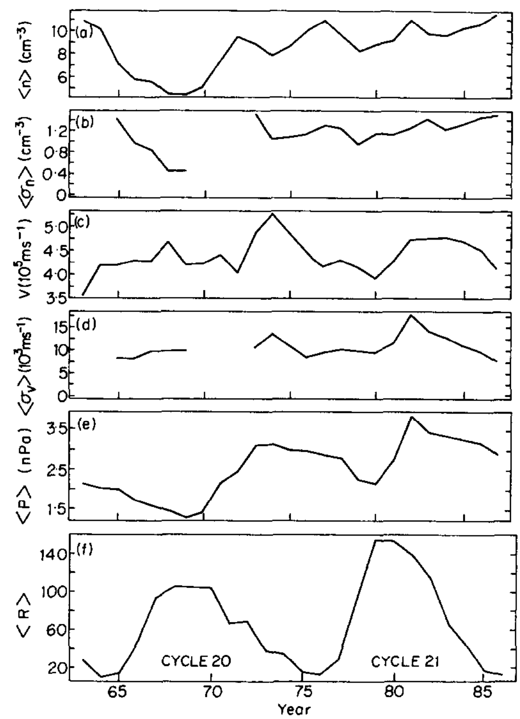

FIG. 3. SOLAR-CYCLE VARIATIONS IN THE SOLAR WIND.
Annual means of: (a) the solar-wind density, n; (b) the hourly standard deviation of n values, σ_n; (c) the solar-wind speed, v; (d) the hourly standard deviation of v values, σ_v; (e) the dynamic pressure, P; and (f) the international sunspot number, R.

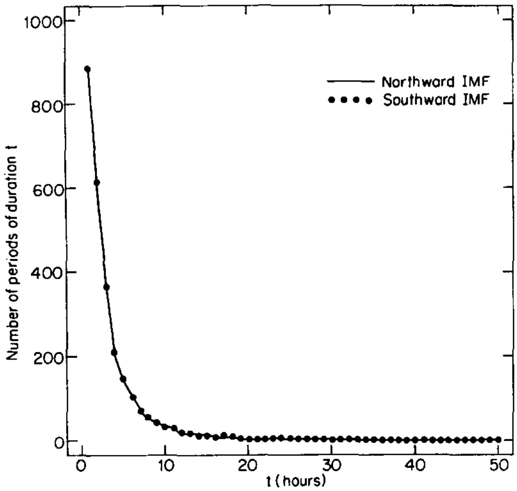

FIG. 4. THE STABILITY OF THE IMF.
(a) The number of B_z polarity changes for which B_z subsequently had a constant sense for a time t, as a function of t.

interval shown in the figure is 1 h. This is the case that B_z changes sign again at the hourly value immediately following the event and so B_z has constant sign for only 1 h at most.

The intervals following northward and southward turnings of B_z are shown separately in Fig. 4, as a solid line and data points, respectively. The two distributions are almost identical. Thus we can conclude that the stability of the IMF is independent of the sign of B_z.

To quantify the stability of B_z, we have determined the number of cases for which the sign of B_z is stable for 2 h or more. For the total dataset we found that this number was 2007 out of a total of 5277 cases in which the period of stability could be measured. This amounts to 38% of all cases. The total duration of these periods (during which the polarity of B_z does not alter for more than 2 h) is 12,369 h, which is 12.2% of the total number of hours in the study. This result is similar to the equivalent fraction of 15% reported by Rostoker *et al.* (1988). However, a number of factors should be noted. Rostoker *et al.* employed 15-s IMF values, giving much greater time resolution, but meaning that periods of stable IMF could be interrupted by a single data point giving B_z of opposite polarity—this will tend to have reduced this percentage. On the other hand, some periods of stable IMF B_z polarity will have been lost in our study because they did not start with a 2 nT change in B_z or because they were interrupted by a data gap.

In this paper, we wish to investigate the solar-cycle dependence of the stability of IMF B_z. Therefore we have also calculated the number of cases for which the B_z polarity is stable for more than 3 h for each year. The results are shown as a fraction of the total number of cases in the upper panel of Fig. 5. For comparison, the annual sunspot numbers are shown in the lower panel. There is considerable variation in this fraction between about 10 and 40%. There is some evidence for a solar-cycle variation, with clear and deep minima of this fraction occurring around the 1965 and 1986 minima in $\langle R \rangle$. There is also a minimum around the 1976 sunspot minimum, but it is much less marked (at around 27%) and is not significant, when compared, for example, with the minimum observed at the 1968 solar maximum.

Hence it seems there may well be a solar-cycle variation in the stability of the polarity of the IMF B_z, but the minimum between cycles 20 and 21 was not as clear cut as might have been expected. This could even indicate an underlying 22-year cycle, rather than the 11-year cycle, although why variability of B_z should be different for one polarity of the solar field from that for the other is unclear. However, there is certainly great variability in the fraction of time that the IMF is stable, evaluated on an annual basis. It is important to continue to monitor the IMF and extend this study of the variability of B_z over cycles 22 and 23, in order to establish that there is indeed a 22-year cycle in its stability of polarity.

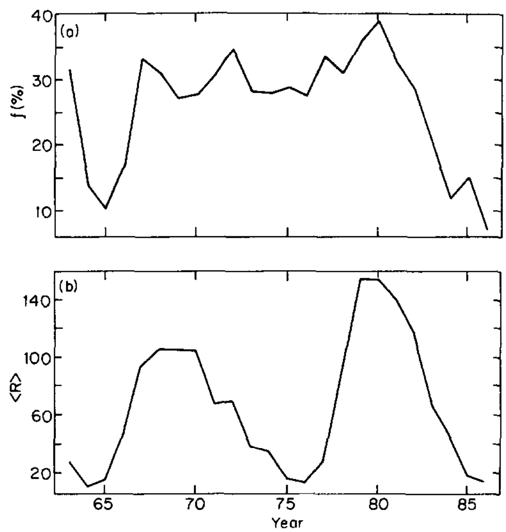

FIG. 5. (a) ANNUAL FRACTION OF CASES FOR WHICH B_z HAD A CONSTANT SIGN FOR THREE OR MORE HOURS FOLLOWING A MAJOR REVERSAL OF THE B_z SIGN (UPPER PANEL).
The fraction is given as a percentage. For comparison, annual sunspot numbers are shown in (b).

5.3. *Changes in solar wind dynamic pressure*

We have also investigated whether there is any possible link between B_z polarity changes and variations in the dynamic pressure of the solar wind on the hour-to-hour time-scales discussed above. We have calculated the pressure changes and changes in B_z for the 6018 events defined in Section 4.1. To look for any relationship between these two datasets we used the 3-D histogram shown in Fig. 6 (a traditional scatter plot was unsatisfactory because the large numbers of points obscured detail). This plot shows the number of events along the vertical axis, bins also being colour-coded by this parameter, according to the given colour scale. The two horizontal axes show the change in IMF B_z in the events, ΔB_z, and the percentage change in the hourly mean of the solar-wind dynamic pressure, $\Delta P/P$, where P is the value before the event. The histogram suggests that there are two populations of events:

(a) events in which there is no significant pressure change associated with the change in the sign of B_z. These events are represented by the prominent ridge at zero pressure change;

(b) events in which there is a pressure change coincident with the change in B_z sign. These are represented by the broader distribution.

Note that there are no events for $|\Delta B_z| < 2$ nT, because of the definition of events employed (as given in Section 5.1). It is of interest to note that for the class (a) events (i.e. $\Delta P \approx 0$) the mode value of $|\Delta B_z|$ is 3 nT, i.e. there are more events (by a factor of about 2) for which B_z changes by 3 nT than when it changes by 2 nT; this is true for both northward and southward turnings. For class (b) events, the pressure change may not be causally associated with the IMF change, but the two could just occur at the same time by a chance occurrence. The importance of class (b) events is that it would be difficult to distinguish between the causes of any terrestrial disturbances.

The distributions are roughly symmetric about the central ridge, showing that when southward and northward turnings are accompanied by a pressure change, it is as likely to be a rise in dynamic pressure ($\Delta P > 0$), as a fall ($\Delta P < 0$). This is true for both northward and southward turnings. There is some asymmetry at large $\Delta P/P$ because P tends to be larger for falls in dynamic pressure (relating as it does to the conditions before the event). Although the most common events are ones for which there is no pressure change ($\Delta P/P = 0$), this only makes up 12% of the total events. However, in 38% of events $|\Delta P/P|$ is less than 5% and for 58% of events it is less than 10%. We conclude that most southward/northward turnings are not accompanied by significant (>10%) changes in dynamic pressure. Only 2% of southward and northward turnings are accompanied by dynamic pressure changes exceeding 50%.

6. DISCUSSION AND CONCLUSIONS

We find the distributions of solar-wind and IMF parameters from this survey over two solar cycles to be much the same as the corresponding distributions that were presented from data for all or part of cycle 20 (Gosling *et al.*, 1971, 1976; Neugebauer, 1975; Diodato *et al.*, 1984; King, 1976). However, on examination of the solar-cycle variations we find a number of differences between solar cycles 20 and 21. The most notable of these is that the clear anti-correlation of annual means of solar-wind density and sunspot numbers, as reported previously for cycle 20 (Diodata *et al.*, 1974; Neugebauer, 1975), is hardly evident at all in cycle 21. Like Gosling *et al.* (1976), we would ascribe the increase in the mean and spread of the distribution of solar-wind speeds in the declining and minimum phase of the solar cycle to increased occurrence of high-speed streams, as noted by Bame *et al.* (1976). However, we find in cycle 20 that these peaks were just 2 years before sunspot minimum, whereas for cycle 21 they were 4 years before the minimum for $\langle\sigma_v\rangle$ and 3 years before for $\langle v\rangle$. The solar-cycle variation of $\langle|B_z|\rangle$ and $\langle\sigma_z\rangle$, reported for cycle 20 by Siscoe *et al.* (1978), is repeated in cycle 21 and both parameters reflect the larger maximum of the later solar cycle. The reappearance of a secondary minimum in both these values at sunspot maximum suggests that this is a real effect.

The solar-cycle variation in $|B_z|$ shows that there is a larger mean magnitude of the out-of-ecliptic IMF component at sunspot maximum and that the spread of values is also greater then. (Note that values are given here in GSM coordinates, but the differences tend to average out and the same statement is true in GSE coordinates.) Taken in isolation, this larger variability in $|B_z|$ would suggest that the stability of the polarity of B_z (quantified here as the fraction, f, of polarity changes for which B_z subsequently retains the same sense in two hourly averages) would be smaller at sunspot maximum. In fact, we find that, if anything, f is larger at sunspot maximum—showing deep minima near the solar minima of 1964 and 1986, and a weak minimum near 1976. There is considerable variability in f, ranging between 10 and 40%.

The significance of the fraction f is that it is a maximum estimate of the likelihood that the terrestrial ionosphere–magnetosphere system attains a steady state. As discussed in the Introduction, if f is

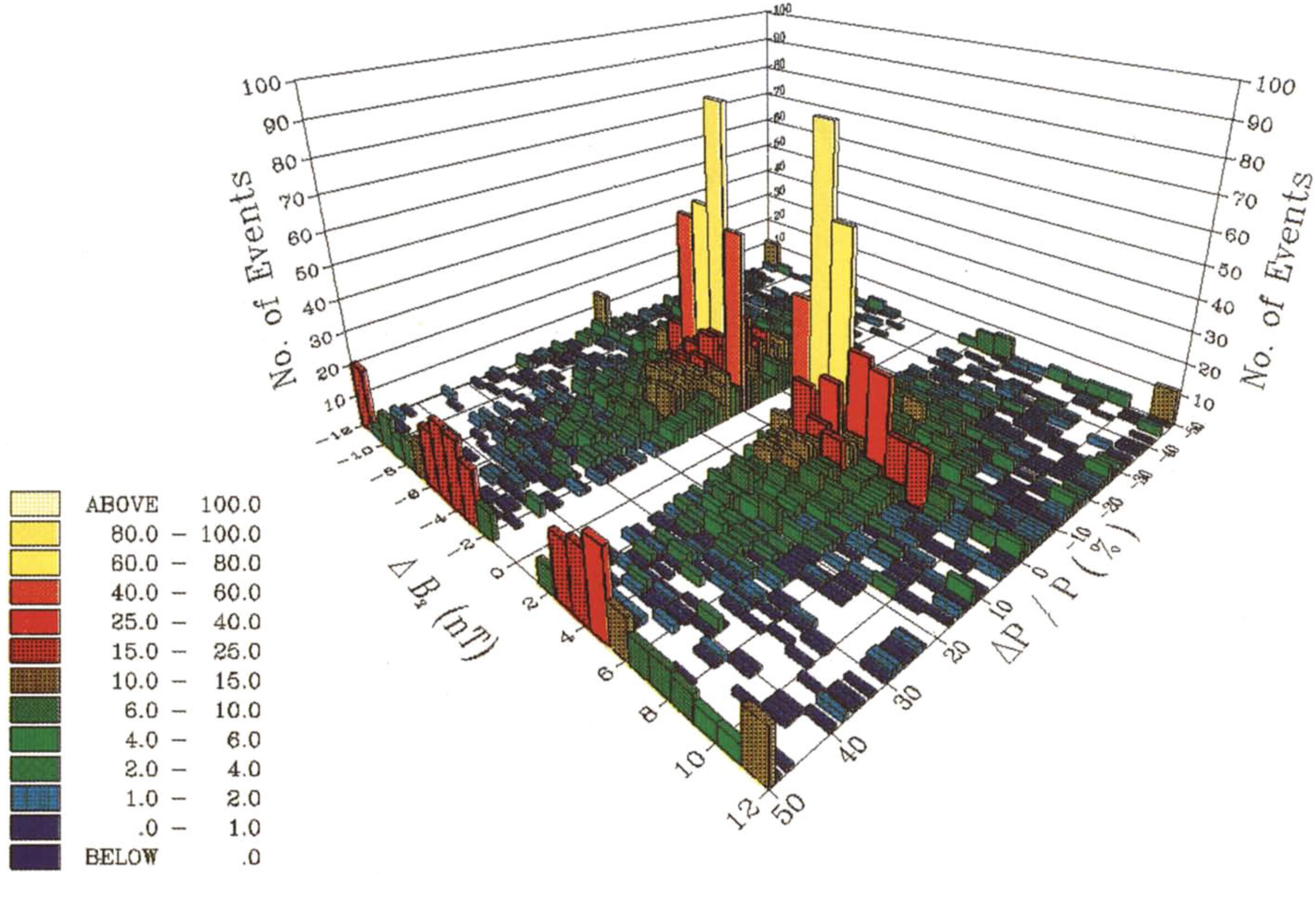

FIG. 6. THREE-DIMENSIONAL HISTOGRAM SHOWING THE RELATIONSHIP BETWEEN B_z CHANGES AND FRACTIONAL DYNAMIC-PRESSURE CHANGES AT MAJOR REVERSALS IN B_z POLARITY.

The empty band aligned along the $\Delta B_z = 0$ axis arises from the definition of major events, i.e. $|B_z| > 1$ nT before and after the event. The high counts at the edges of the plot arise because extreme values outside the ranges given by the horizontal axes, have been accumulated and plotted there.

large we would expect the terrestrial system to attain a steady state often, or show regular oscillations—although we must also remember it may show non-steady responses to any variations in B_z on time-scales of less than the 1-h resolution of the data used here. In fact we find for all years f is less than 40 % (and for some years it is as low as 10%) indicating that more often changes in polarity occur before a steady-state situation can be achieved. Allowing for responses to sub-hour variations, the terrestrial system will, in reality, achieve steady state for even smaller fractions of time than the values of f given above. We conclude, as did Rostoker *et al.* (1988), that steady-state convection in the ionosphere–magnetosphere system will rarely, if ever, be achieved. We also note that the steady state may be particularly rare at every second solar minimum, although more data are required to confirm this 22-year cycle.

We find northward and southward IMF orientations to be equally common and that the distribution lifetimes of periods of constant orientation are the same for northward and southward pointing fields.

To investigate the implications for the terrestrial magnetosphere–ionosphere system of these findings concerning the solar wind, we have evaluated the solar-cycle variation of solar-wind dynamic pressure. We find a clear solar-cycle oscillation superposed on a long-term trend throughout the period studied. The trend appears to show a 50% increase in solar-wind dynamic pressure over the 24-year period. The cause of this trend is not apparent, and it may be related to the larger solar activity observed during cycle 21. The solar-cycle variation shows dynamic pressure is a maximum in solar minimum years, and vice versa. However, the variation is more complex than the means of P suggest, as in cycle 20 the variation of solar-wind density dominates, whereas in cycle 21 the variations in both speed and density are important. As a result, the magnetopause will be compressed to locations nearer the Earth, on average, during sunspot minimum years. Using the equations given by Schield (1969) (see also Farrugia *et al.*, 1989) we estimate the magnitude of both the gradual change and solar cycle variation in the location of the magnetopause to be about 1 R_E.

We also found that neither southward nor northward turnings of the IMF are accompanied by major dynamic-pressure changes (only 2% show fractional changes in P exceeding 50%). Hence there is little likelihood that phenomena attributed to reconnection (for example erosion of the dayside magnetopause or onset of enhanced convection following a southward turning of the IMF) were really caused by a concurrent change in solar-wind dynamic pressure. It should be noted that we have only studied changes in the hourly means of the dynamic pressure. To evaluate the likely effect of shorter-term solar-wind dynamic pressure variations, and the proposed buffeting effect as a driving mechanism for convection, we must study the standard deviation associated with the hourly means of P, σ_P. Because the solar-wind density, n, is not uncorrelated with the solar-wind speed, v, we cannot use the equivalent standard deviations, σ_n and σ_v, to compute σ_P. Rather, to evaluate σ_P we must return to the 1-min data from which the hourly means were computed. This study is currently being undertaken and will be reported elsewhere. However, we note that the fractional variability in n (σ_n/n) is much greater on sub-hour time-scales than that in v (σ_v/v) and hence the former is the dominant contributor to the variability of P on these time-scales.

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