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Key Points:

- We study the modification of the magnetic field direction of 82 magnetic clouds (MCs) across the bow shock and in the magnetosheath
- Their magnetic field direction varies significantly across the quasi-parallel shock, and the sign of B_z can change in the magnetosheath
- Changes in the sign of B_z are associated with a large B_y , suggesting that this component may also affect the geoeffectivity of a MC

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Statistical study of the alteration of the magnetic structure of magnetic clouds in the Earth's magnetosheath

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Abstract The magnetosheath plays a central role in the solar wind-magnetospheric coupling. Yet the effects of its crossing on solar wind structures such as magnetic clouds (MCs) are generally overlooked when assessing their geoeffectivity. Using 82 MCs observed simultaneously in the solar wind and the magnetosheath, we carry out the first statistical study of the alteration of their magnetic structure in the magnetosheath. For each event, the bow shock properties are obtained from a magnetosheath model. The comparison between the model results and observations shows that in 80% of cases, the MHD-based model captures well the magnetosheath transition; the other events are discussed separately. We find that just downstream of the bow shock the variation of the magnetic field direction shows a very good anticorrelation ($r = -0.91$) with the angle between the upstream magnetic field and the shock normal. We then focus on the magnetic field north-south component B_z because of its importance for geoeffectivity. Although the sign of B_z is generally preserved in the magnetosheath, we also find evidence of long-lasting intervals of opposite B_z signs in the solar wind and the magnetosheath during some events, with a $|B_z|$ reversal > 10 nT at the magnetopause. We find that these reversals are due to the draping of the field lines and are associated with predominant upstream B_y . In those cases, the estimated position of the regions of antiparallel fields along the magnetopause is independent of the sign of the upstream B_z . This may have strong implications in terms of reconnection.

1. Introduction

The interaction of the supersonic solar wind with the Earth's magnetosphere creates a bow shock through which the incoming flow is decelerated to subsonic speeds. The magnetosheath is the region occupied by the shocked solar wind plasma, heated, and compressed, extending from the bow shock to the magnetopause. Because it is actually the magnetosheath plasma which comes in contact with the magnetopause, its properties are crucial for the energy, plasma, and momentum transfer from the solar wind to the magnetosphere [e.g., Lopez et al., 2010; Pulkkinen et al., 2016]. The magnetosheath is a highly variable region, since its spatial and temporal plasma properties respond to the upstream solar wind state but also because of the self-generated turbulence and instabilities which arise locally. The spatial variation mostly stems from the varying bow shock parameters encountered upon entering the magnetosheath and especially the angle Θ_{Bn} between the local shock normal and the upstream magnetic field vector. The contrast between the quasi-perpendicular ($\Theta_{Bn} > 45^\circ$) and quasi-parallel ($\Theta_{Bn} < 45^\circ$) regimes gives rise to pronounced asymmetries in the magnetosheath because the processing of the plasma through the bow shock varies as a function of Θ_{Bn} [Walsh et al., 2012; Dimmock and Nykyri, 2013; Walsh et al., 2014; Dimmock et al., 2015, 2016, and references therein]. For example, because only the tangential component of the magnetic field increases through the bow shock, the magnetosheath magnetic field is stronger downstream of the quasi-perpendicular bow shock. The magnetic field lines are also distorted as they drape around the magnetosphere. Furthermore, when the magnetosheath plasma β is low, accelerated flows can be observed along the magnetopause flanks [e.g., Rosenqvist et al., 2007; Lavraud and Borovsky, 2008; Erkaev et al., 2012; Lavraud et al., 2013, and references therein]. This is due to the fact that in such conditions, the magnetic forces become predominant inside the magnetosheath. The upstream conditions for magnetopause processes, such as magnetic reconnection [Dungey, 1961] and the Kelvin-Helmholtz instability (KHI) [Hasegawa et al., 2004], are dictated by the local magnetosheath properties.

Their spatial variations can therefore influence where magnetopause processes occur, for example, favoring one flank for the KHI [Taylor *et al.*, 2012; Nykyri, 2013]. This is attributed to the lower tangential magnetic field in the quasi-parallel magnetosheath, which would increase the growth rate of the KHI.

The influence of the bow shock crossing and the subsequent convection in the magnetosheath on large-scale solar wind transients is generally overlooked. In particular, it is generally assumed that the magnetic field direction, which is central for reconnection, remains unchanged downstream of the bow shock. Consequently, the geoeffectivity of the structure is estimated based on its properties in the solar wind only. However, a number of studies convey convincing evidence that the magnetic field direction can change significantly from the solar wind to the magnetosheath, thus questioning the validity of this assumption. For example, Coleman [2005] focuses on the magnetic field clock angle, measured in the plane perpendicular to the Sun-Earth line and compares observations in the solar wind and along the magnetopause. The results show that 30% of the time, this angle varies by more than 30° from the solar wind to the magnetosheath. The author concludes that the “perfect draping approximation,” i.e., which the clock angle is preserved in the magnetosheath, is not accurate enough to estimate the magnetic field direction along the magnetopause. In Longmore *et al.* [2006], spacecraft observations in the magnetosheath are compared to the predictions of the Kobel and Flückiger [1994] field line draping model. A rotation of the clock angle ranging from 5 to 30° is found, which is attributed to field-flow coupling effects not taken into account in the Kobel and Flückiger [1994] model. We stress here that a variation of the clock angle can result in a change of the sign of the magnetic field north-south (B_z) component. The sign of B_z is fundamental for geoeffectivity because a southward B_z upstream of the magnetopause is conducive to reconnection with the Earth’s magnetic field in the subsolar region. The probability of observing different B_z signs upstream and downstream of the bow shock is investigated in Šafránková *et al.* [2009]. They find that the probability of the correct prediction of the sign of the magnetosheath B_z based on that in the solar wind is close to random coincidence for low $|B_z|$ values, and increases with $|B_z|$. Yet it does not always reach 1 even for the highest $|B_z|$. An example of such a change of the B_z sign for a predominantly southward interplanetary magnetic field (IMF) is presented in Němeček *et al.* [2015].

In this study, we focus on a specific type of large-scale solar wind transients called magnetic clouds (MCs). MCs are a subset of coronal mass ejections which possess a well-defined magnetic structure in the interplanetary space. They are characterized by an enhanced and smoothly rotating magnetic field, generally accompanied by a depressed proton temperature [Burlaga *et al.*, 1981]. MCs are the drivers of the most intense geomagnetic storms [Huttunen *et al.*, 2005; Echer *et al.*, 2008; Yermolaev *et al.*, 2012]. Understanding how they interact with the Earth’s environment is thus crucial for space weather forecasting. Many studies [e.g., Gopalswamy *et al.*, 2008; Ji *et al.*, 2010; Hidalgo *et al.*, 2011, and references therein] focus on establishing linear correlations between one or a combination of the MC’s parameters with the level of geomagnetic activity as estimated from ground-based indices, in order to predict the geoeffectivity of upcoming events. Yet the correlation coefficients obtained in these kind of studies rarely reach 0.9 [Gopalswamy *et al.*, 2008] but are generally lower [e.g., Borovsky, 2013]. Moreover, a very large scatter of the parameters is observed for the most extreme values. The linear correlation thus tends to decline for the strongest events. Therefore, a closer scrutiny of the processes at play when MCs interact with the Earth’s environment is needed.

The first steps of this interaction are the crossing of the terrestrial bow shock and the propagation into the magnetosheath. The MCs’ properties, and in particular their magnetic field direction, are expected to be significantly altered through these regions, as is the case for the regular solar wind. Furthermore, we note that MCs are characterized by a low Alfvén Mach number (M_A), generally below 5 [Lavraud and Borovsky, 2008; Turc *et al.*, 2016]. These low M_A conditions in the solar wind alter the volume of the magnetosheath, which becomes much larger than usual as the bow shock moves outward, but also how energy is processed at the bow shock [e.g., Treumann, 2009], the magnetosheath flows [Lavraud *et al.*, 2007; Farrugia *et al.*, 2013], the current systems in the Earth’s environment [Lopez *et al.*, 2011], and more generally, the solar wind-magnetospheric coupling during MC events [Lopez *et al.*, 2004; Lavraud and Borovsky, 2008; Farrugia *et al.*, 2013; Myllys *et al.*, 2016]. Because MCs correspond to atypical conditions, it is particularly interesting to investigate how they evolve across the bow shock and into the magnetosheath. Eastwood *et al.* [2002] used combined spacecraft observations in the solar wind and the magnetosheath to study the evolution of a small-scale flux rope across the bow shock. They showed that the bow shock crossing causes a rotation of the flux rope axis. More recently, a few case studies of MCs observed simultaneously in the solar wind and the magnetosheath were presented

in *Turc et al.* [2014a]. The results, supported by modeling and numerical simulations [*Turc et al.*, 2014b, 2015], suggest that the modification of the magnetic field direction across the bow shock is directly controlled by the angle Θ_{Bn} .

The aim of the present paper is to extend the results of the *Turc et al.* [2014a] case studies through a comprehensive statistical study. In particular, we will examine the relationship between Θ_{Bn} and the variation of the magnetic field direction, and attempt to establish an empirical relationship linking these two parameters. We will also investigate how this variation is distributed on the different magnetic field components and especially how B_z is affected. We will focus on the cases when B_z has a different sign upstream and downstream of the bow shock and look for conditions when this take place. Finally, this statistical study will also allow us to test the performances of the magnetosheath model introduced in *Turc et al.* [2014b] on a large number of events. The paper is structured as follows: in section 2, we describe the data sets, the magnetosheath model, and the methodology used in the study. In section 3 the main results of this work are presented. Section 4 analyzes the events which were not correctly modeled and discusses the limitations of the magnetosheath model. Finally, section 5 provides a summary and a discussion of our main findings.

2. Data Set and Methodology

This study is based on the MC catalog introduced in *Turc et al.* [2016], which lists the MCs observed near the Sun-Earth L_1 libration point from 2000 to 2014. For each of these MCs, our list also indicates in which region (i.e., solar wind, magnetosheath or magnetosphere) the following spacecraft can be found: Cluster [*Escoubert et al.*, 2001], the Time History of Events and Macroscale Interactions during Substorms (THEMIS) [*Angelopoulos*, 2008], the Geomagnetic Tail Lab (GEOTAIL) [*Nishida*, 1994], Interball-Tail [*Galeev et al.*, 1996], and Double-Star TC1 [*Liu et al.*, 2005]. Note that the identification of the different geophysical regions is not based on models of their boundaries but on the inspection of the actual spacecraft data for each MC. This facilitates the selection process for all kind of studies focusing on the interaction of MCs and of their sheath regions with the near-Earth space.

Here we select the MCs during which spacecraft observations are available in the dayside magnetosheath, with at least 1 h of continuous sampling of this region. We find 82 suitable MCs, out of which 32 (39%) even have two spacecraft or more in the dayside magnetosheath during the same MC, though not necessarily simultaneously. This yields a total of 129 sets of magnetosheath measurements during a MC (hereafter referred to as "events"), when taking into account separately the contribution of the different spacecraft. Note that the Cluster fleet is considered as a single spacecraft as the spacecraft separations are much smaller than the scales of interest. Likewise, the different THEMIS satellites are only included if the interspacecraft separation exceeds $2 R_E$. This study is drawn upon magnetic field measurements from the fluxgate magnetometers aboard Cluster [*Balogh et al.*, 1997], THEMIS [*Auster et al.*, 2008], and Double-Star [*Carr et al.*, 2005]; the magnetic field experiment [*Kokubun et al.*, 1994] aboard GEOTAIL and from the FM-3I; and the multicomponent investigations of fluctuations magnetometers [*Nozdrachev et al.*, 1995; *Klimov et al.*, 1997] aboard Interball-Tail. Note that all vector quantities will be given in the Geocentric Solar Ecliptic (GSE) coordinate system throughout this paper.

As demonstrated in previous studies [e.g., *Turc et al.*, 2014a], the modification of the properties of MCs from the solar wind to the magnetosheath is strongly controlled by the bow shock configuration. To interpret the observations, it is therefore necessary to know the local value of Θ_{Bn} associated with each of our magnetosheath samples. Since we cannot directly measure this angle, we use a magnetosheath model [*Turc et al.*, 2014b] to estimate where the streamline passing through the spacecraft in the magnetosheath intersects the bow shock and what is the corresponding Θ_{Bn} value. The inputs of the model are the solar wind parameters, which are primarily taken from the magnetic field experiment (MAG) [*Smith et al.*, 1998] and the Solar Wind Proton, Electron and Alpha Monitor [*McComas et al.*, 1998] aboard the Advanced Composition Explorer (ACE) [*Stone et al.*, 1998] spacecraft. Alternatively, the OMNI data set propagated to the Earth's bow shock, or the Magnetic Field Investigation [*Lepping et al.*, 1995], and the Solar Wind Experiment [*Ogilvie et al.*, 1995] measurements from the Wind spacecraft [*Acuña et al.*, 1995] are used when there are large gaps in ACE data. Each event is divided into 5 min intervals, over which the data are averaged, as was done in *Turc et al.* [2016]. This is necessary because the magnetosheath model requires quasi-steady upstream parameters as inputs in order to ensure that the flow pattern in the magnetosheath remains nearly steady while the plasma propagates from the bow shock to the spacecraft. Averaging the data also reduces the errors due to the time shift of the

solar wind measurements from L_1 to Earth. On the other hand, it is also important not to degrade excessively the resolution of the data because the bow shock and the magnetosheath properties would respond rather quickly, i.e., in a matter of minutes, to changes in the upstream state and our samples need to be representative of the simultaneous upstream and downstream conditions. The 5 min windows were therefore selected as a trade-off between a good time resolution and the requirements of the magnetosheath model.

In order to perform this statistical study, some modifications were made in the magnetosheath model in order to optimize its results. First, the compression ratio is now calculated using the formula established by *Borovsky* [2013], which provided a better agreement between model and observations than the formula of *Landau and Lifshitz* [1959]. Second, the bow shock model of *Jeřáb et al.* [2005] employed in the initial version of the model was chosen because of its better performance in the low- M_A range [*Turc et al.*, 2013], but not all MCs are associated with low- M_A conditions. We have thus implemented a second bow shock model [*Měrka et al.*, 2005] into the magnetosheath model in order to better describe the events with higher M_A . On these events, the magnetosheath model was run with each of the bow shock models and we selected whichever model provided the best estimates of the observed magnetosheath magnetic field. When $M_A > 5$, the *Měrka et al.* [2005] generally gave better results than the *Jeřáb et al.* [2005] model.

To validate the results of the magnetosheath model, we compare its prediction of the magnetic field direction at the spacecraft position with the actual measurements. A first selection was done by visual inspection: if the model visibly failed to globally predict the magnetic field orientation and its overall temporal variations, the event was discarded (criterion 1). Among the retained events, we then calculated the angle between modeled and observed magnetosheath magnetic fields and selected only those 5 min samples for which the model correctly estimates the magnetic field direction in the magnetosheath within 10° (criterion 2). The model satisfactorily reproduces the observations for 103/129 events (80%) (selected with criterion 1), which yield a total of > 5900 samples satisfying criterion 2. Note that our selection method allows for isolated samples to be selected, for which criterion 2 may in some cases be satisfied accidentally. We estimate that our data set contains 3% of isolated samples, which should not affect the results of our analysis. The events we completely discarded will be further examined in the discussion. To each magnetosheath sample are associated a number of parameters determined from the magnetosheath model, in particular the angle Θ_{Bn} encountered upon entering the magnetosheath and the fractional distance inside the magnetosheath:

$$F = (r - r_{mp}) / (r_{bs} - r_{mp}) \quad (1)$$

[*Soucek and Escoubet*, 2012, and references therein], where r , r_{bs} , and r_{mp} are the geocentric distances of the spacecraft, the bow shock, and the magnetopause, respectively (along the Earth-spacecraft direction).

Figure 1 displays the position of the magnetosheath samples, color coded according to the spacecraft from which the measurements were taken. In Figure 1 (left), the position of the data points is normalized in order to illustrate their distribution relative to the magnetosheath boundaries. The average bow shock and magnetopause positions (dashed black lines) were obtained from the *Jeřáb et al.* [2005] and *Shue et al.* [1998] models, respectively, with the average MC parameters as the input ($n = 6.5 \text{ cm}^{-3}$, $V = 482 \text{ km s}^{-1}$, $B = 12.4 \text{ nT}$, $B_z = 0$; see *Turc et al.* [2016]). Each data point is then plotted inside this “average magnetosheath,” its position being determined by its solar zenith angle and its fractional distance F between the magnetosheath boundaries as determined with the magnetosheath model. Figure 1 (right) shows the position of our samples in the GSE YZ plane, where the dashed black line corresponds to the bow shock position in the terminator plane. Our data set is mostly concentrated near the equatorial plane because of the orbits of the spacecraft sampling the magnetosheath. Only Cluster (blue) and Interball-Tail (brown) probe the higher latitudes, thus providing some data points beyond $|Z| = 10 R_E$. However, as shown in Figure 1 (left), we have a very good coverage of the relative distances between the bow shock and the magnetopause, and of the angular distance from the Sun-Earth line, except very close to the subsolar point. Our data set thus covers most of the low-latitude dayside magnetosheath.

3. Results

3.1. Magnetic Field Direction

We first investigate the variation of the magnetic field direction across the bow shock. In order to quantify its modification, we define ψ as the angle between the magnetic field vector in the solar wind and that in the magnetosheath. Figure 2 shows a scatter plot of this angle ψ as a function of the Θ_{Bn} value encountered at

Figure 1. (left) Position of the magnetosheath samples relative to the magnetosheath boundaries (see text for more detail) and (right) in the GSE YZ plane. The colors indicate from which spacecraft the data were obtained (Cluster: blue; Interball-Tail: orange; GEOTAIL: green; Double-Star-TC1: red; THEMIS: purple). The dashed lines correspond to modeled bow shock and magnetopause (Figure 1, left, only) for average MC conditions, in the equatorial plane (Figure 1, left), and in the terminator plane (Figure 1, right).

the bow shock, estimated from the magnetosheath model, for each of the 5 min magnetosheath samples. There is a clear tendency for ψ to increase as the shock configuration becomes more parallel. The color scale indicates the fractional distance inside the magnetosheath (as defined in equation 1). The light blue points correspond to observations near the magnetopause, while the magenta points are located just downstream of the bow shock. We find that the observations near the bow shock are clustered in a rather narrow range, while most of the scatter is due to the measurements in the vicinity of the magnetopause.

The solid black line shows a linear fit of the entire data set, with the equation of the best fit line being the following: $\psi = 64.8^\circ - 0.659\Theta_{Bn}$, associated with a fairly good anticorrelation ($r = -0.76$). If we restrict to the data points in the first 30% of the magnetosheath from the bow shock inward, i.e., at a fractional distance $F > 0.7$, the correlation coefficient increases to 0.91. The equation of the line is then

$$\psi = 60.3^\circ - 0.647\Theta_{Bn} \quad (2)$$

The slope of the line does not vary significantly, but it comes closer to $\psi = 0^\circ$ for $\Theta_{Bn} = 90^\circ$ with the reduced data set, which is what we would expect from Rankine-Hugoniot equations. The goodness of both linear fits is also illustrated by the very narrow 99% confidence intervals (green lines). The larger scatter of the samples for the entire data set most likely stems from the fact that other processes such as field line draping come into play when moving deeper into the magnetosheath. Also, wave activity increases closer to the magnetopause, which can augment the spread of the data.

We now compare our data with MHD predictions, in order to illustrate the expected behavior of ψ as a function of Θ_{Bn} just downstream of the bow shock. Since the solar wind parameters are relatively steady during MCs, and we consider 5 min averaged data both upstream and downstream of the shock; Rankine-Hugoniot relations can be applied to our data sets to describe the bow shock crossing. From the equations of Rankine-Hugoniot and assuming that magnetic coplanarity is satisfied and that the tangential velocity is

Figure 2. Scatter plot: Θ_{Bn} as a function of the angle ψ between the magnetic field vectors in the solar wind and the magnetosheath, color coded as a function of the fractional distance inside the magnetosheath. Both angles are schematized on the figure. Black curves: linear fit of the entire data set (solid line), of the reduced data set ($F > 0.7$; dashed line), fit based on MHD equations (see text) of the entire data set (dotted line) and of the reduced data set (dash-dotted line). The green lines show the 99% confidence intervals for both linear fits.

conserved across the bow shock (see Génot *et al.* [2011] for a discussion of this last assumption), the relationship between Θ_{Bn} and ψ can be written as

$$\psi = \arctan(R \tan(\Theta_{Bn})) - \Theta_{Bn} \quad (3)$$

where R is the bow shock compression ratio, i.e., the ratio of downstream to upstream density. At the Earth's bow shock, this parameter usually ranges between 3 and 4 and varies as a function of the upstream conditions, in particular the magnetosonic Mach number. According to MHD theory [Farris and Russell, 1994; Borovsky, 2013], R tends toward 4 when the Mach number tends to infinity (assuming that the ratio of specific heats $\gamma = 5/3$ in the formula of Farris and Russell [1994]). The only free parameter being the compression ratio, we perform a least squares fitting of the entire data set (dotted line in Figure 2) and of the reduced data set ($F > 0.7$; dash-dotted line). Because the magnetosheath model employed to calculate Θ_{Bn} is based on the assumptions listed above, equation (3) should be verified in the outer parts of the magnetosheath, i.e., just behind the shock. However Rankine-Hugoniot relations may not be obeyed for some cases as they are not valid inside the shock transition nor when the shock is not stationary. The values obtained for the compression ratio both exceed the upper limit given by the MHD. We interpret this as the consequence of the pileup of the field lines in front of the magnetopause. We checked that if only the samples very close to the bow shock ($F > 0.9$) are considered, we obtain $R = 3.6$, which is consistent with the MHD predictions. As illustrated by the dotted line being above the dash-dotted line in Figure 2, a larger compression results in a larger ψ for a given Θ_{Bn} . Since the compression ratios obtained from the fits are above 4, this means that overall the propagation in the magnetosheath further increases ψ .

Interestingly, for $\Theta_{Bn} \leq 25^\circ$, the MHD description predicts a decrease of ψ when Θ_{Bn} tends toward zero. However, no conclusive evidence of this decrease can be found in our data set because of the scarcity of our samples for the lowest Θ_{Bn} values and their scatter. Two factors contribute to the poor coverage of the lowest Θ_{Bn} values ($\Theta_{Bn} < 30^\circ$, hereafter termed "strongly parallel"). First, this configuration is less frequently observed than the quasi-perpendicular geometry on the dayside bow shock during MCs [Turc *et al.*, 2016]. Second, we only retained here the samples for which we had a good agreement between model and observations. Yet the MHD description used in the model is not sufficient to capture all the features of the quasi-parallel shock configuration, where kinetic processes dominate. Hence, the complete absence of data points below $\Theta_{Bn} = 10^\circ$

and the sparse observations below 30° . Moreover, equation (3) is only valid just downstream of the bow shock, which may also explain why we do not observe the decrease of ψ at low Θ_{Bn} . It is therefore difficult to draw any firm conclusion for the strongly parallel regime.

At higher Θ_{Bn} values, the functions derived from MHD are approximately linear. We use the sum of the squared residuals to compare the quality of the different fittings. We find that the fit quality is relatively insensitive to employing either the linear fitting or the function derived from MHD, but that using the data set restricted to $F > 0.7$ significantly improves it. Therefore, we conclude that equations (2) and (3), despite the assumptions required to apply the latter, both provide a simple and fairly reliable way of estimating ψ in the outer magnetosheath. Deeper in the magnetosheath, as data becomes more scattered, the fit quality is lower but remains acceptable. Overall, we find that for $\Theta_{Bn} > 30^\circ$, ψ increases linearly as Θ_{Bn} decreases.

However, ψ only gives us information about the overall variation of the magnetic field orientation but not which components will be affected by those changes. We now investigate how the magnetic field cone angle $\theta_{Bx} = \cos^{-1}(B_x/B)$ and clock angle $\phi_c = \cos^{-1}(B_z/\sqrt{B_y^2 + B_z^2})$ are modified from the solar wind (sw) to the magnetosheath (Msheath). Figure 3a displays the variation of the cone angle $\Delta\theta_{Bx} = \theta_{Bx}^{\text{Msheath}} - \theta_{Bx}^{\text{sw}}$ as a function of the ψ angle. The data points are visibly clustered around $\Delta\theta_{Bx} = \pm\psi$, thus revealing that most of the variation of the magnetic field direction translates into a change of the cone angle. The positive $\Delta\theta_{Bx}$ are associated with $\theta_{Bx}^{\text{sw}} < 90^\circ$, while negative values are obtained when $\theta_{Bx}^{\text{sw}} > 90^\circ$. This shows that the field lines tend to rotate away from the Sun-Earth line, consistent with their draping around the dayside magnetopause. As expected from Figure 3a, Figure 3b shows that $\Delta\phi_c$ is much smaller than $\Delta\theta_{Bx}$ and remains generally below 20° .

We propose the following interpretation for the distribution of the variation on θ_{Bx} and ϕ_c . At the bow shock nose, the normal direction is aligned with the Sun-Earth line. We have thus $B_x = B_n$, and the GSE YZ plane corresponds to the bow shock tangential plane. This configuration is illustrated schematically in the lower left part (1) of Figure 3d, where the dark purple surface is the bow shock. The tangential vectors t_1 and t_2 are contained in the GSE YZ plane, materialized by the lilac rectangle. (u) denotes the values upstream, and (d) the values downstream of the bow shock. Because of magnetic coplanarity, which is assumed to hold here, the tangential components (here B_y and B_z) have the same direction across the shock [Treumann, 2009], as shown in Figure 3d by the vectors $B_t(u)$ (yellow) and $B_t(d)$ (green). Therefore, ϕ_c is preserved at the crossing of the subsolar bow shock, while θ_{Bx} varies as the IMF is rotated away from the shock normal. When moving toward the dawn-dusk terminator (at any latitude), the plane tangential to the shock's surface departs progressively from the GSE YZ plane. This is illustrated in the upper right part (2) of Figure 3d, where the shock tangential plane, shown by the dark blue rectangle, is no longer parallel to the GSE YZ plane. The variation of ϕ_c should therefore increase with increasing distance from the subsolar point. This is confirmed by Figure 3c, which shows the variation of ϕ_c just downstream of the bow shock. Each sample is color coded according to the solar zenith angle. In the subsolar region (dark blue points), ϕ_c remains roughly unchanged at the bow shock's crossing, while further on the flanks (green points) its variation can reach up to 40° . The propagation inside the magnetosheath causes a further variation of ϕ_c , independently of the solar zenith angle but which remains relatively modest, below 10° in 85% of the cases (not shown). On the contrary, the draping of the field lines affects θ_{Bx} more prominently so that the field lines progressively become tangential to the magnetopause. The combination of these different mechanisms causes the large variation of θ_{Bx} , while ϕ_c shows only minor deviations.

In terms of the magnetic field components, this implies that near the equatorial plane, the traversal of the magnetosheath will mostly change the relative importance and possibly the signs of B_x and B_y , while in the noon-midnight meridian plane, it will essentially affect B_x and B_z . Note that the magnitude of all components will also be modified due to the magnetic compression at the bow shock's crossing and the piling up of the field lines at the magnetopause.

3.2. B_z Component

We now concentrate on the B_z component of the magnetic field because of its pivotal role for geoeffectivity. In Figure 4a we have plotted the B_z component measured inside the magnetosheath as a function of that in the upstream solar wind. Each data point is color coded according to the fractional distance inside the magnetosheath. Contrary to the ψ angle whose values are more scattered deeper into the magnetosheath (see section 3.1), the spread of the magnetosheath B_z does not increase when approaching the magnetopause.

Figure 3. Scatter plots of the variation of (a) the cone angle and (b) the clock angle from the solar wind to the magnetosheath, as a function of ψ . The color code indicates the Θ_{Bn} associated with each of the samples. (c) Variation of the clock angle from the solar wind to the immediate downstream of the bow shock, as a function of Θ_{Bn} . The color code shows the zenith angle, measured from the Sun-Earth line. (d) Schematic of the modification of the magnetic field direction across the bow shock (dark purple surface) at the bow shock nose (1) and farther on the flanks (2). (u) Denotes the upstream vectors (yellow) and (d) the downstream vectors (green). The reference frames in black are aligned with the GSE frame, while the reference frames in blue are the local frames defined by the shock normal direction (n) and the plane tangential to the shock surface (t_1 and t_2). B_t refers to the projection of the magnetic field in the tangential plane while B_n is the magnetic field normal component, which is preserved across the bow shock. The magnetic field cone angles θ_{Bx} are indicated by black curves in (1). The magnetic field clock angles ϕ_c are indicated by purple curves.

The distribution of the points in Figure 4 suggests that there is a linear relation between B_z in the solar wind and in the magnetosheath, which is particularly prominent for $|B_z^{sw}| < 15$ nT. At larger $|B_z|$, the lack of data points and their scattering make it difficult to assess whether this linear relationship persists. The equation of the best fit line obtained from the linear least-squares regression of the whole data set is: $B_z^{msheath} = 3.19 \times B_z^{sw} - 0.07$, associated with an excellent correlation coefficient ($r = 0.95$) and a narrow 99% confidence interval (green lines). For the subset of the data points in the vicinity of the bow shock ($F > 0.7$), the correlation coefficient is 0.97. We only find a slightly lower value for the slope (2.87) when $F > 0.7$, while its value increases to 3.35 if we restrict to the points where $F < 0.3$. In other words, B_z is about three times stronger in the magnetosheath than in the solar wind, and it only marginally increases when nearing the magnetopause.

Figure 4b presents a close-up of the central part of Figure 4a, with a different color code: red indicates that the sign of B_z is the same in the solar wind and the magnetosheath, while the samples drawn in blue have opposite B_z signs. We find that in a number of cases, a southward B_z can turn north in the magnetosheath, and vice versa. However, the change of the B_z sign is only significant if its sign can be reliably determined both in the solar wind and the magnetosheath. For a given sample, which corresponds to 5 min averaged measurements, we consider that B_z is significantly positive (negative) if $B_z - \sigma(B_z + \sigma)$ is also positive (negative). σ is the standard deviation of B_z during the considered 5 min interval. This criterion is applied to B_z in the solar wind and in the magnetosheath. Those samples for which the sign of B_z is reliable and which have different B_z signs in the solar wind and the magnetosheath are indicated by the large blue crosses in Figure 4b. Hereafter, the term “ B_z reversals” will refer to the intervals or samples for which the sign of B_z in the magnetosheath

Figure 4. (a) Magnetic field B_z component in the magnetosheath plotted against that in the solar wind. Each data point is colored according to its fractional distance inside the magnetosheath. The black dashed line shows the linear fit of the data set and the green lines the 99% confidence interval. Note that the green lines are overlapping the black line in the central part of the plot. (b) Magnified section of the central part of Figure 4a, with a different color code. The sign of B_z is the same in the solar wind and the magnetosheath for the red samples, and changes for the blue samples. (c) Scatter plot of the angle ψ as a function of the angle between the upstream magnetic field vector and the Z axis. Same color code as Figure 4b.

Figure 5. ACE (time shifted) (black) and Cluster (blue) observations during the MC starting on 29 November 2006. The vertical lines indicate the leading and trailing edges of the MC. The area highlighted in green shows when Cluster is inside the magnetosphere. From top to bottom: magnetic field strength, B_x , B_y , B_z , and magnified section of B_z in the interval highlighted in grey.

differs from that in the solar wind. Such reversals are observed in 1.4% of our magnetosheath samples. The occurrence rate of the B_z reversals will be further discussed in section 5. Although most of these data points are rather isolated (4 or less per MC), we also find three events with half an hour or more of uninterrupted observations of a reversed B_z . Therefore, the sign of the B_z component of the magnetic field in a region of the magnetosheath can differ from that in the solar wind during extended intervals.

We then investigate in which conditions these B_z reversals occur. We find no clear ordering of our samples with the shock configuration or the position inside the magnetosheath (not shown), though these parameters were central for the overall variation of the magnetic field direction (see section 3.1). The reversals do not tend to be associated with higher- or lower-latitude spacecraft observations. No relationship with the upstream solar wind parameters can be established either, except with the upstream magnetic field orientation. This is illustrated by Figure 4c, which shows ψ plotted against the angle $\theta_{sw} = \arccos(B_z/B)$ in the solar wind. The color code is the same as in Figure 4b, with the data points in blue having different B_z signs in the solar wind and in the magnetosheath and the large blue crosses indicating the significant B_z reversals. We note that all blue samples are clustered near $\theta_{sw} = 90^\circ (\pm 10^\circ)$, which corresponds to a magnetic field lying close to the equatorial plane, where $B_z = 0$. Therefore, we observe a change of the B_z sign when a limited rotation of the upstream magnetic field direction is sufficient to move from one side of the equatorial plane to the other. The reversal of the B_z component is, however, independent of the total change of the magnetic field direction across the bow shock, as evidenced by the distribution of the blue data points across all the ψ values.

As an example, Cluster and ACE magnetic field observations from 04:00 UT on 29 November 2006 to 04:00 UT the next day are shown in Figure 5. This interval encompasses a MC, whose front and rear boundaries are marked by vertical dashed lines. ACE data are lagged by 58 min to account for the offset of ACE being in L_1 . Cluster is located in the magnetosheath during most of the event, until around 22:50 UT when it crosses the magnetopause. ACE magnetic field measurements are magnified by a factor of 3 to facilitate the comparison with Cluster observations. ACE data are displayed at 16 s resolution and Cluster's at spin (~ 4 s) resolution. The green area in Figure 5 indicates when Cluster is in the magnetosphere. A magnified section of Figure 5 (fourth panel) is shown in the inset, corresponding to the interval highlighted in grey, just before Cluster enters the magnetosphere. During this period, the prevailing magnetic field components in the solar wind are B_x and B_y (Figure 5, second panel, and Figure 5, (third panel), respectively), while B_z is much weaker (Figure 5, fourth panel, and inset). Pointing initially northward, B_z turns south shortly after 21:30 UT and remains negative until the end of the event. In the magnetosheath, however, Cluster measures a steadily northward magnetic field throughout. The southward fields after 22:30 UT are magnetospheric fields. The spacecraft thus observes a

Figure 6. Maps of the dayside magnetopause projected onto a plane, with the subsolar point at the center and the radial distance from the center proportional to the zenithal angle. B_z component along the magnetopause during the B_z reversals observed on (a) 29 November 2006 and (b) 22 January 2012. (c and d) Shear angle along the magnetopause for the same intervals. The asterisks on Figures 4a and 4b show the position of Cluster and THEMIS A, respectively.

reversed B_z in the close vicinity of the magnetopause, which may affect the reconnection in this region provided this reversal is observed in a sizable area. One can also note that the sign of B_x measured by Cluster is opposite to the sign sampled by ACE (Figure 5, second panel), consistent with the expected orientation of the draped IMF, as Cluster is located in the duskside magnetosheath.

Using the magnetosheath model [Turc *et al.*, 2014b], we calculate the magnetosheath magnetic field along the dayside magnetopause. The solar wind parameters averaged between 21:45 UT and 22:30 UT on 29 November 2006 are employed as the input. This interval will be hereafter referred to as Event 1. Figure 6a displays the dayside magnetopause surface as seen from the Sun, color coded according to the value of the magnetic field B_z component on the outer side of the boundary. The distance from the center of the plot is proportional to the zenith angle, relative to the Sun-Earth line, ranging here from 0 to 90°, while the azimuthal direction is the angle in the plane perpendicular to the Sun-Earth line. The black star indicates Cluster's position. As expected from the southward orientation of the upstream magnetic field, B_z is negative along most of the magnetopause (in blue). However, the model also predicts that there are two regions where B_z is positive (in red) and that Cluster is located in the largest of them. Figure 6b shows another example of a B_z reversal, observed by THEMIS A on 22 January 2012 around 14:00 UT (hereafter Event 2). The format is the same as in Figure 6a. In this second example, the upstream B_z is oriented northward. It turns south in two regions of the magnetosheath, one of them encompassing the position of THEMIS A. We find that the maximum reversed B_z (in absolute value) are 11 nT in Event 1 and −19 nT in Event 2. We calculate that 19% of the dayside magnetopause encounters a reversed B_z in Event 1 and 22% in Event 2.

We then compute the shear angle between the magnetosheath and magnetospheric magnetic fields along the magnetopause during both events. The magnetospheric magnetic field at the Shue *et al.* [1998] magnetopause is obtained from the T96 model [Tsyganenko, 1995], as done for example in Trattner *et al.* [2012, and references therein]. The results for Events 1 and 2 are displayed in Figures 6c and 6d, respectively. The shear angle maps for these two events are roughly mirror images of each other. This is due to the oppositely directed

Table 1. Summary of the Sources of Discrepancies Between Model and Observations

Category	Source of Discrepancies	Number of Events
(i)a	Bow shock position	4
(i)b	Magnetopause position	2
(i)c	Boundary position	3
(ii)a	Quasi-parallel configuration	9
(ii)b	Spacecraft skimming the magnetopause	8

magnetic fields in the YZ plane, with B_y and B_z respectively, positive and negative in Event 1 and vice versa in Event 2. Note that B_x is positive in both cases. For both events, we find two regions of antiparallel magnetic fields (in red), i.e., favorable to reconnection, the largest being in the Southern Hemisphere, on the dawn (Event 1) or dusk (Event 2) flank.

These maps are consistent with the reconnection pattern inferred by Němeček *et al.* [2003] from multispacecraft observations during horizontal IMF conditions (i.e., with very small B_z component), with the reconnection regions located on opposite sides of the cusps in opposite hemispheres. They are also very similar to those obtained in Trattner *et al.* [2007a, 2007b, 2012] for a southward IMF with a large B_y component (i.e., with a clock angle around 90° or 270°). However, we remind the reader that in Event 2 the IMF B_z is actually oriented northward. Interestingly, the high shear regions are located in the same quadrants of the magnetopause as the southward turnings of the magnetic field. The B_z reversal may therefore explain why the shear angle distribution at the magnetopause in Event 2 mirrors that of Event 1. To confirm this, we calculate the shear angle along the magnetopause for the same upstream conditions but with an opposite B_z sign (not shown). For each event, we find very similar shear angle patterns for both positive and negative B_z . This suggests that the sign of B_z does not, or only marginally, affect the solar wind-magnetospheric coupling when B_z is small compared to B_y . Although we are here focusing on MC events, the maps shown in Figure 6 would be roughly the same for typical solar wind with the same IMF orientation. Our conclusions thus also hold for regular solar wind conditions.

4. Discussion: Limitations of the Magnetosheath Model

We now examine the 26 sets of spacecraft observations inside the magnetosheath during a MC's passage which are not satisfactorily reproduced by the magnetosheath model. We find that they can be divided into two categories, as the discrepancies between model and observations are either due to (i) an incorrect prediction of the position of the magnetosheath boundaries (9 events) or (ii) the limitations of the ideal MHD description employed in the model (17 events). Some of the events in Category (i) are associated with extremely low (~ 1) M_A conditions, which are at the limit of applicability of the bow shock models. Others are visibly due to an inaccurate estimate of the magnetopause position, as the model predicts the spacecraft to remain inside the magnetosphere, while its measurements show that it actually samples the magnetosheath. The remainder of the Category (i) events show an overestimation or underestimation of the magnetic field draping, which can be caused by an erroneous prediction of the position of any or both of the magnetosheath boundaries. Events in Category (ii) are either found (a) downstream of the quasi-parallel region of the bow shock or (b) when the spacecraft is skimming the magnetopause. In both regions, nonideal MHD processes can come into play, which cannot be described by the magnetosheath model. Close to the magnetopause, the magnetosheath magnetic field can be for example disturbed by reconnection, linear/nonlinear Kelvin-Helmholtz waves or turbulent flows [Coleman, 2005]. Near the quasi-parallel bow shock, the enhanced wave activity and the high level of turbulence both in the foreshock and the magnetosheath can alter the magnetic field direction [Walsh *et al.*, 2014, and references therein]. The sources of discrepancies between model and observations are summarized in Table 1.

However, it is worth noting that the model yields satisfactory results also in the quasi-parallel regime, as illustrated by the samples at $\Theta_{Bn} < 45^\circ$ in Figure 2. We have in particular 13 events where the average Θ_{Bn} is below 45° and 16 where at least one third of the samples are associated with quasi-parallel conditions. However, the discarded events in Category ((ii)a) appear to be all “strongly” quasi-parallel cases. In these events, more than 60% of the magnetosheath samples are associated with quasi-parallel conditions, and the average Θ_{Bn} per event is generally lower than in the events for which model and observations agree well. In a few case studies,

Turc et al. [2014a] showed that when $\Theta_{Bn} < 30^\circ$, the smooth rotation of the MC's magnetic field is blurred by large-amplitude fluctuations. Since such fluctuations are not included in the magnetosheath model, this may explain why no good agreement between model and observations can be obtained for very low Θ_{Bn} values. Another reason could be that magnetic coplanarity may be violated during these intervals, due to the wave activity or the nonstationarity of the bow shock [Treumann, 2009]. This may explain why we sometimes find that the model correctly predicts the overall magnetic field variation across the bow shock but not in which direction this change takes place. Note that we assume here that the Θ_{Bn} values provided by the model are reliable. The bow shock shape may depart locally from the model's predictions, due to, e.g., ripples [see, e.g., Hietala et al., 2009, and references therein], but overall, the model should provide a reasonable estimate of Θ_{Bn} in that region.

In section 3.1, we have noted that the magnetic field clock angle was only marginally modified across the bow shock. As discussed in the section 1, the deviation from "perfect draping" (i.e., no variation of the clock angle) in the magnetosheath was also investigated by Coleman [2005] using GEOTAIL and Interball-Tail data for 36 magnetopause crossings during non-MC conditions. This study shows that near the magnetopause, the deviation of the clock angle is below 30° in 70% of the cases. In the present work, however, we find that 98% of our samples are within 30° of the perfect draping. One of the reasons for that may be that the MC's magnetic field generally lies close to the plane perpendicular to the Sun-Earth line; i.e., B_x is typically small [Turc et al., 2016]. It was shown by Coleman [2005] that such upstream conditions tend to decrease the deviation from perfect draping. Yet even when restricting our data set to low cone angle values, we still find a very small variation of the clock angle. The small B_x component inside MCs is therefore not sufficient to explain the discrepancies between our results and the findings of Coleman [2005]. We note, however, that in 8 of the 9 discarded events when the bow shock is in quasi-parallel configuration, a large ($\geq 30^\circ$) modification of the clock angle is observed. This implies that the largest deviations from perfect draping are actually discarded from our data set. This also suggests that the crossing of the quasi-parallel bow shock can result in a significant variation of the clock angle. In those cases, the magnetosheath model fails to reproduce such large changes of the clock angle but generally gives a reasonable estimate of the ψ angle. In other words, the overall variation is correctly predicted but not in which direction the magnetic field vector rotates. Therefore, the discrepancies between model and observations might be caused by magnetic coplanarity not being satisfied across the bow shock.

Interestingly, in three of the events with a large variation of the clock angle, long-duration (1 to 3 h) reversals of the B_z component are observed. Two events are similar to those discussed in section 3.2, with $\theta_{sw} \sim 90^\circ$. In the other, however, the upstream magnetic field direction lies up to about 30° from the equatorial plane ($\theta_{sw} \sim 120^\circ$), while most of the blue samples in Figure 4c were found within 10° of this plane. The large variation of the clock angle thus allows B_z to reverse in that case. The magnetosheath B_z is also higher, up to 20 nT, than the other reversed B_z (see the blue data points in Figure 4b). This B_z reversal is observed downstream of a strongly parallel shock ($\Theta_{Bn} \sim 20\text{--}30^\circ$). This suggests that our results based on the magnetosheath model provide a lower limit of the extent and occurrence rate of the B_z reversal but that there may be more significant changes in B_z when the shock is strongly parallel.

5. Summary and Conclusions

Using 82 MCs with simultaneous observations in the solar wind and the magnetosheath, we have carried out a statistical study of the modification of their magnetic structure across the bow shock. Our main results are the following:

1. We have confirmed statistically that the angle measured between the solar wind and magnetosheath magnetic field direction is controlled by two processes: the bow shock crossing and the draping of the field lines. Far enough from the magnetopause, where the draping effects are not predominant, that is, in the first 30% of the magnetosheath, we empirically find that the relationship between the local change in the magnetic field orientation and the angle Θ_{Bn} encountered at the bow shock's crossing is approximately linear for $\Theta_{Bn} > 30^\circ$. This linear relationship is in good agreement with MHD predictions for this range of Θ_{Bn} (see Figure 2).
2. The variation of the magnetic field direction takes place essentially through a modification of its cone angle. Large rotations of the magnetic field clock angle are observed only in a few cases. They all appear to be associated with strongly quasi-parallel shock configurations. However, those events are

generally not satisfactorily reproduced by the magnetosheath model and are therefore excluded from our statistical analysis.

3. The sign of the solar wind B_z is not always preserved in the magnetosheath. We find evidence of opposite B_z signs on either sides of the bow shock. In particular, during three events, the B_z reversal lasts half an hour or more. We find that such reversals occur when the upstream magnetic field lies close to the equatorial plane.
4. Using a magnetosheath model, we estimate the extent of the region where B_z reverses. We find that it affects a significant ($\sim 20\%$) part of the magnetopause. Maps of the shear angle along the magnetopause reveal that the regions favorable to reconnection follow the patterns expected for B_y -dominated conditions, independently of the sign of B_z in the upstream medium. This suggests that if the predominant IMF component is B_y , positive and negative B_z could be equally geoeffective.
5. The comparison of the results of the *Turc et al.* [2014b] magnetosheath model with spacecraft observations for 129 events shows that this model reproduces well the magnetic field direction inside the magnetosheath in most cases (80%). This implies that MHD is in general sufficient to capture the transition through the bow shock and the magnetosheath during MCs. This may be due to the bow shock being mostly quasi-perpendicular in MC conditions [*Turc et al.*, 2016].
6. We also establish the limits of applicability of the *Turc et al.* [2014b] magnetosheath model. The model's outputs are mostly reliable (i.e., the differences between model and observations are within 10° for most of the samples, and the overall temporal variations are correctly reproduced by the model) when the shock is not strongly parallel ($\Theta_{bn} \geq 20^\circ$), the spacecraft is not skimming the magnetopause and the Alfvén Mach number is not approaching 1. This is consistent with the ideal MHD description on which the model is based. Within its limits of applicability, i.e. excluding the nine strongly parallel events ((ii)a), the eight events in the vicinity of the magnetopause ((ii)b) and the four events with dramatically low M_A ((i)a), the model provides reliable predictions of the magnetosheath magnetic field direction for 95% of the events (103/108).

In some instances, the position of the magnetosheath boundaries is not properly described by the models employed here [*Shue et al.*, 1998; *Jeřáb et al.*, 2005; *Měrka et al.*, 2005], thus leading to incorrect results of the magnetosheath model. The performances of the *Shue et al.* [1998] magnetopause model have been investigated by *Case and Wild* [2013], who showed that this model tends to overestimate the magnetopause position. The authors suggest that this may be due to the data set on which the model was build. As regards the bow shock models, the sources of the discrepancies are not clear, except for the very low M_A conditions, and identifying them lies beyond the scope of this paper. Improved bow shock and magnetopause models could solve this issue and would therefore allow for more events to be properly modeled. Overall, the *Turc et al.* [2014b] magnetosheath model performs well for the majority of events.

Though the present study shows evidence of B_z changing sign from the solar wind to the magnetosheath, it does not, however, allow us to estimate reliably the occurrence rate of the B_z reversals, for the following reasons. (1) The B_z reversals only take place in a limited (though significant, $\sim 20\%$ in the examples given here) part of the magnetosheath for a given IMF configuration. Furthermore, most spacecraft orbit close to the equatorial plane, while the B_z reversals generally occur at higher latitudes (see Figures 6a and 6b). The reversal of B_z may therefore be missed in a number of events due to the limited coverage provided by spacecraft observations. (2) Our selection criteria for our magnetosheath samples require a good agreement between the modeled and observed magnetic fields, but B_z reversals can also occur when ideal MHD is not satisfied. In particular, significant B_z reversals are observed when the shock is strongly parallel, but the magnetosheath model is not valid in such conditions, as discussed in section 4. These events are thus not taken into account in the results shown in section 3.2. We also note that the probability of observation of a change of the B_z sign is lower in our data set than in the results of *Šafránková et al.* [2009]. This may stem from the higher magnetic field strength during MCs, since *Šafránková et al.* [2009] showed that this probability decreases with increasing magnetic field magnitude; (2) can also contribute to this lower probability. Furthermore, we only retained those samples where B_z and $B_z \pm \sigma$ have identical signs, to ensure that the B_z reversal is significant. No such criterion was applied to the *Šafránková et al.* [2009] data set. Finally, although the B_z reversals are observed only in a limited number of events, their spatial and temporal extent suggests that they may affect the interaction of these MCs with the magnetosphere.

To conclude, there is clear evidence that the magnetic field direction inside MCs can be significantly modified downstream of the Earth's bow shock and that the largest changes are associated with the quasi-parallel shock configuration. This should also hold for regular solar wind conditions, but it is more apparent during MCs as the upstream magnetic field direction varies but slowly over extended intervals. These changes of the

magnetic field orientation may have strong implications in terms of reconnection at the magnetopause. As a consequence, the effects of MCs on the magnetosphere may sometimes differ from what could be expected from the sole analysis of their properties near L_1 . We also stress the importance of not only taking into account the B_z component when assessing the possible geoeffectivity of a MC. This is exemplified by the fact that northward and southward B_z both lead to similar shear angle patterns at the magnetopause when B_y is predominant. The modification of B_z inside the magnetosheath when B_y is predominant may also affect the duration of the geoeffective part of the MC, in particular during the so-called bipolar MCs [Mulligan *et al.*, 1998]. In the central part of such MCs, B_y is predominant while B_z turns progressively either from positive to negative or from negative to positive. Only the rear part of the former or the front part of the latter is expected to be geoeffective. However, if B_z changes sign at different times in the magnetosheath and in the solar wind, this may affect the onset or end time of geomagnetic activity. Taking this into account may contribute to improve space weather forecasting. Further work is still required to quantify the influence of the bow shock and the magnetosheath on the geoeffectivity of MCs and thus refine our understanding of the interaction of MCs with the Earth's environment.

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