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How to improve our understanding of solar wind-magnetosphere interactions on the basis of the statistical evaluation of the energy budget in the magnetosheath?

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Solar wind (SW) quantities, referred to as coupling parameters (CPs), are often used in statistical studies devoted to the analysis of SW−magnetosphere−ionosphere couplings. Here, the CPs and their limitations in describing the magnetospheric response are reviewed. We argue that a better understanding of SW magnetospheric interactions could be achieved through estimations of the energy budget in the magnetosheath (MS), which is the interface region between the SW and magnetosphere. The energy budget involves the energy transfer between scales, energy transport between locations, and energy conversions between electromagnetic, kinetic, and thermal energy channels. To achieve consistency with the known multi-scale complexity in the MS, the energy terms have to be complemented with kinetic measures describing some aspects of ion−electron scale physics.

KEYWORDS

solar wind, magnetosphere, coupling parameters, turbulence, energy budget

1 Introduction

The Earth's magnetosphere represents a highly structured obstacle in the supersonic and super-Alfvénic solar wind (SW). The SW plasma carries the interplanetary magnetic field (IMF), and it is penetrated by high-energy particles. Temporal and spatial variations of plasma and field parameters or enhancements of particle fluxes in the SW generate complex responses in the near-Earth space.

1.1 Solar wind–magnetosphere coupling parameters

Both statistical and *in situ* case studies have shown that magnetic reconnection (MR) at the dayside magnetopause (MP), basically controlled by the southward-oriented IMF, plays a key role in determining how much energy, mass, and momentum enters the magnetosphere (Sibeck and Murphy, 2021). The southward-oriented IMF leads to the addition of magnetic flux to the tail, resulting in increased occurrence of many energetic magnetospheric phenomena, such as storms, substorms, and intensification of magnetospheric and ionospheric current systems (Dungey, 1961). MR can also occur during periods of weakly northward dawn–dusk magnetic field-dominated IMF or during strongly northward IMF, when the reconnection location is shifted to higher latitudes poleward of the magnetospheric cusps. The magnetospheric response to the northward IMF is much less understood. However, it is associated with complex changes in the plasma and field conditions in the polar cap (e.g., Hosokawa et al. 2020) and in the nightside magnetosphere (e.g., Fear 2021).

The challenges of understanding these couplings initiated multiple statistical studies (e.g., Borovsky, 2023) between upstream SW field and plasma parameters and their combinations (the so-called coupling parameters, CPs) and geomagnetic indices, such as AE, Dst, and Kp. Although a southward-oriented IMF is expected to be associated with enhanced levels of magnetospheric activity, the geomagnetic indices are better correlated with some combined upstream quantities. For example, the electromagnetic energy flux (ϵ_P, Poynting flux) $\epsilon_P = uB^2 sin^4(\Theta_c/2) l_0^2$ for given IMF clock angles Θ_c = arctan (By/Bz) was defined as a proxy for energy transfer to the magnetosphere (Perreault and Akasofu, 1978). Here, B is the IMF intensity, By and Bz are GSM components of $\mathbf{B}$, u is the SW velocity, and l_0 is an experimentally determined length-scale factor. The ϵ_P CP or its variants show stronger correlations with geomagnetic indices as B_Z alone. However, the substantial part of the variance is not explained (Newell et al., 2007). The upstream SW parameters do not comprise the dynamical processes that occur at the shock or in the MS, which might or might not depend on the orientation of the IMF.

To a smaller extent than MR at the MP, turbulence or fluctuations in the SW can also drive magnetospheric/ionospheric activity, leading to enhanced geomagnetic activity indices (e.g., D'Amicis et al., 2020). The multi-scale nature of turbulence in the SW is readily discernible in the power spectral densities (PSDs) of different field and plasma parameters. For example, the PSD of trace magnetic field fluctuations shows a 1/f type spectrum over energy-containing scales ($\geq 10^6$ km), a Kolmogorov-like spectrum over the inertial range (IR) of scales ($\sim 10^6$ km $\geq$ IR $\geq \sim 10^2$ km), and steeper kinetic-range scaling(s) over sub-ion, electron scales, down to a few kilometers (e.g., Bruno and Carbone (2013)). A viscous-like turbulence-driven interaction between the SW flow in the MS and magnetosphere is expected during northward-oriented IMF, when MR is not likely at the MP (Axford and Hines, 1961). However, the first statistical studies of a few northward IMF SW time intervals, when MR supposedly plays no role, indicated that only a small percentage (~1%) of the SW energy could be transferred to the magnetosphere/magnetotail through viscous interaction (Tsurutani and Gonzalez, 1995).

Borovsky and Funsten (2003) have shown that the turbulence effect on the terrestrial magnetosphere can be the result of enhanced eddy viscosity controlled by the amplitude of magnetohydrodynamic (MHD) turbulence in the upstream SW. According to these statistical results, the amplitude of SW turbulence might control the amount of viscous momentum transfer to MS and magnetosphere, accounting for approximately 150 nT variability of the auroral AE index. This study based on 3 years of data has confirmed that the viscous interaction is independent of the orientation of the IMF (Borovsky and Funsten, 2003).

A specific type of thoroughly studied viscous interaction process, occurring at both dawn–dusk flanks of the MP within the MS–MP boundary layer, is the Kelvin–Helmholtz (KH) instability. Although KH waves are more often observed for northward-oriented IMF, they also occur during any IMF orientations (Kavosi and Raeder, 2015). Within the developed KH vortices, secondary instabilities, strong gradients, reconnecting current sheets, mass transport, fast magnetosonic waves, mode conversion to kinetic Alfvén waves, and ion heating are observed (see the review paper by Masson and Nykyri, 2018). Both kinetic simulations (Nakamura et al., 2020) and spacecraft observations (Nykyri et al., 2017) indicate that fluctuations and turbulence in the MS can lead to a faster growth rate of KH instability. Comparisons of *in situ* (MP) and ground-based (auroral region) observations indicate that the KH instability-generated flux ropes are associated with field-aligned currents, which are mapped to the poleward edge of auroral regions (Hwang et al., 2022). In this way, a viscous interaction, comprising MR at the flanks of the MP and field-aligned currents reaching the auroral zones, can contribute to auroral activity during both northward/southward-oriented IMF intervals.

SW turbulence frequently consists of non-compressive Alfvénic fluctuations, which were found to trigger high-intensity, long-duration (≥ 2 days) continuous AE activity (Tsurutani and Gonzalez, 1987). However, a statistical study has shown that Alfvénic fluctuations prevail only during solar minimum, while non-Alfvénic magnetic structures are more geoeffective during solar maximum (D'Amicis et al., 2007). A recent comprehensive statistical study (Borovsky, 2023) indicated that, during periods of low dayside MR rate, magnetic fluctuations $\Delta B/B$ are more important drivers of magnetospheric activity than Alfvénicity, $|A| = |\delta\mathbf{u} \cdot \delta\mathbf{B}/|\delta\mathbf{u}||\delta\mathbf{B}|$. Here, $\Delta B = \langle(\mathbf{B} - \langle\mathbf{B}\rangle)^2\rangle^{1/2}$, $B = \langle|\mathbf{B}|\rangle$, averaging denoted by $\langle\rangle$ is over 1 h intervals, $\delta\mathbf{u} = \mathbf{u(t + 64s)} - \mathbf{u(t - 64s)}$, and the increments $\delta\mathbf{B}$ are calculated similarly. However, finding the strongest drivers of magnetospheric/ionospheric activity is more complicated since clear correlations exist between CPs (Borovsky, 2023). For example, high Alfvénicity is correlated with SW parameters and structures such as Δv, v, ΔB, B, ϵ_P, strong current sheets, and velocity shears (Borovsky, 2023). Vertical velocity changes in the direction of the SW flow can drive flapping motions in the magnetotail (Wang et al., 2019) or even lead to sudden changes in cross-polar cap potential and comet-like disconnections of the magnetotail (Borovsky, 2012). The SW velocity shear can also trigger time-delayed MR in the magnetotail, leading to auroral activity even during northward IMF events (Vörös et al., 2014). Over time scales longer than 1h, high-speed SW also controls the temperature and plasma β in the plasma sheet, thus supporting field-aligned currents and substorms, which is clearly seen in the increased daily substorm number during episodes of fast SW (Newell et al., 2013).

The interrelationships between CPs measured locally at the upstream L1 point ($\sim 1.5 \times 10^6$ km from Earth) and the scale dependence of possibly time-delayed magnetospheric responses make it difficult to understand the SW–magnetosphere coupling. Measured quantities at L1 are frequently non-uniform over the spatial scale of the bow shock-magnetosphere, and single point measurements do not allow to properly map, for example, the IMF changing direction to the bow shock ($\sim 9 \times 10^4$ km from Earth) or MP (Kessel et al., 1999; Borovsky, 2018). As a result, the quasi-parallel ($Q_\parallel$) and quasi-perpendicular ($Q_\perp$) parts of the bow shock cannot be identified in a straightforward manner. An L1 constellation of multi-spacecraft missions (the existing ACE, WIND, DSCVR) allowing the calculation of gradients in the SW over scales comparable to the bow shock or magnetosphere could partially solve this problem (Burkholder et al., 2020). The spatial gradients or the possibly mixed spatio-temporal ΔB fluctuations calculated from 1 h averages belong to the IR of scales (Borovsky, 2023). However, PSDs of different field and plasma parameters show that downstream of the bow shock, IR turbulent scaling is usually absent and the Kolmogorov-like IR spectra re-appear near the flanks only (Huang et al., 2017; Rakhmanova et al., 2021; Rakhmanova et al., 2022). This indicates that IR fluctuations or gradients at L1 might not survive the crossing of the shock. Yet, because of the observed correlations of CPs and geomagnetic indices, the IR fluctuations at L1 influence the mass, energy, and momentum transport through the shock.

Contrary to the IR fluctuations, the sub-ion scale scalings in the MS resemble the kinetic range scalings in the SW (Huang et al., 2017). In the magnetotail plasma sheet, the kinetic scale turbulent scalings also resemble those in the SW (Vörös et al., 2007), indicating a possibly universal behavior. When the IR energy transfer toward sub-ion scales is absent, the kinetic scale turbulence should show a fast decay. By considering typical MS parameters, it takes $\sim 500\Omega_{ci}^{-1}$ (Ω_{ci} is the averaged ion cyclotron frequency) for a volume of SW plasma to move from the shock to the MP. During this time, according to kinetic, weakly compressional, collisionless plasma simulations of decaying turbulence (Yang et al., 2022), a substantial part of kinetic and magnetic energies should be converted to internal energy. This should result in changing kinetic-range scalings with increasing distances from the bow shock in the MS. However, this is not observed, indicating that at least part of the IR electromagnetic and kinetic energies available in the SW might be used for the generation of kinetic-range turbulence, plasma instabilities, coherent structures, etc. These poorly understood sub-ion-scale kinetic processes (Sahraoui et al., 2000) at the shock and in the MS might, in fact, play a role in the SW–magnetosphere coupling.

1.2 The role of dayside kinetic processes in SW–magnetosphere coupling

Some foreshock transients (e.g., Zhang et al. (2022) and references therein) such as hot flow anomalies (HFAs: low-density, hot plasma embedded in decreased magnetic field and flow deflections) and foreshock bubbles (FBs: hot, low-density core expanding rapidly in the sunward direction forming a shock) are associated with tangential and/or rotational discontinuities that interact with the bow shock or with backstreaming foreshock ions. HFAs and FBs can perturb the MP due to their locally decreased pressure, which causes the MP to locally move sunward. As a consequence, compressional fast magnetosonic waves are transmitted to the magnetosphere, ULF waves are excited, field-aligned currents to the ionosphere are generated, and auroral brightenings are triggered (Sibeck et al., 1999; Eastwood et al., 2011). We emphasize that the discontinuities that play a key role in generating HFAs and FBs could be observed at L1 as local fluctuations of $\Delta B/B$. This could partially explain the observed correlation between CPs and auroral activity.

MS high-speed jets (e.g., Plaschke et al. (2018)) originate mainly from the $Q_\parallel$ bow shock. Since jets are associated with ULF wave activity (Hietala et al., 2012) and generation of local MR through compression of current sheets (CSs) against the MP (Hietala et al., 2018), an enhanced geomagnetic response is expected. SW CPs observed at L1, such as low-cone angle, high-speed SW, and high Alfvén Mach number, can influence the probability of jet formation at the shock and their transfer through the MS (LaMoury et al., 2021). For this reason, the number of jets increases in association with large-scale structures such as stream interaction regions and high-speed SW streams (Koller et al., 2022). However, not every jet observed downstream of the bow shock has a counterpart at L1 (Koller et al., 2022). Jet sizes follow a log-normal distribution, resulting in jets as small as 0.1 R_E (Plaschke et al., 2020). The smallest jets can be related to short large-amplitude magnetic structures (SLAMS: non-linearly steepened ULF waves at the density gradients near the shock, (Giacalone et al., 1993). According to global hybrid simulations (Chen et al., 2021), during the convection of turbulence from the foreshock through the MS to the MP, SLAM-like structures can be generated with the strong $-B_Z$ component, leading to local MR at the MP. In the simulation, the IMF was initially aligned along the Sun–Earth direction with a weak northward component. Therefore, the generation of a geoeffective southward $-B_Z$ occurs entirely through local turbulent interactions.

Density gradients near the shock play an important role in the foreshock wave–particle interactions (Kis et al., 2018). Foreshock waves can modulate the magnetosonic Mach number, generating changing compression ratios downstream of the shock and fast mode waves traveling through the MS. These waves are not directly transmitted through the shock but rather generated locally downstream (Turc et al., 2021).

In the bow shock foot and downstream, the steepening of ULF waves can also generate potentially reconnecting current sheets, which can convert 5%–11% of the SW energy flux (Schwartz et al., 2021). Hybrid particle-in-cell simulations indicate that the shock-driven reconnection is not strongly dependent on the shock Mach number or geometry ($Q_\parallel$ or $Q_\perp$) (Gingell et al., 2023). On the other hand, the occurrence rate of current sheets in $Q_\parallel$ MS is much higher than that in $Q_\perp$ MS (Yordanova et al., 2020), which makes the prediction of their formation based on upstream interactions even more difficult.

It is unknown how the upstream turbulence level or any other CP could control the local generation of $-B_Z$, energy conversions at the foreshock or wave generation downstream of the shock, and the propagation of these potentially geoeffective disturbances in the MS.

2 Outstanding questions

The foreshock region and the MS are unique natural laboratories for studying compressional turbulence, waves, mode conversions, and instabilities (Echim et al., 2021; Narita et al., 2021; Nykyri et al., 2021; Parks et al., 2021). In relation to the SW–magnetosphere coupling, the following focal questions can be formulated:

1. What are the relevant geoeffective CPs that can be measured at L1 (Borovsky, 2023)?
2. What is the role of potentially geoeffective, local shock MS–MP processes, which are partially or not in the least controlled by L1 CPs?
3. How can the complexity of dayside geoeffective processes, focusing on turbulence, waves, instabilities, etc., disregarding MR, be treated in a generic way, potentially leading to a better understanding of the specific processes and their role in couplings?

3 The dayside energy budget

Here, we concentrate on the aforementioned focal point 3. The question of how much energy, mass, or momentum enters the magnetosphere from the SW can be answered through a better understanding of the energy and mass transport, energy transfer between scales, and energy conversions.

3.1 Calculation of energy terms

In the SW, the energy transfer rate ϵ over the IR of scales is estimated through

$$\langle \delta z^{\mp}_{\parallel} (\delta \mathbf{z}^{\pm})^2 \rangle \ = -(4/3)\epsilon^{\pm} l. \tag{1}$$

(e.g., Marino and Sorriso-Valvo, (2023), and the references therein). Here, l is the scale, $\mathbf{z}^{\pm} = \mathbf{u} \pm \mathbf{B} / \sqrt{4\pi\rho}$ are the Elsässer variables, $\mathbf{B}$ is the magnetic field, ρ is the mass density, and $\delta\mathbf{z}^{\pm} = \mathbf{z}^{\pm}(\mathbf{r}+\mathbf{l}) - \mathbf{z}^{\pm}(\mathbf{r})$, $\delta z^{\pm}_{\parallel} = \delta\mathbf{z}^{\pm} \cdot \mathbf{l}/l$, $\epsilon^{\pm}$ is the mean pseudoenergy transfer rate, from which the average total energy transfer rate is $\epsilon = (\epsilon^{+} + \epsilon^{-})$. Since the IR is predominantly present in the flank MS, ϵ cannot be estimated downstream of the sub-solar shock (Hadid et al., 2018). The energy transfer and conversion processes can also be studied on the basis of the multispecies collisionless Vlasov equations coupled to the Maxwell equations (Yang et al., 2017; Yang et al., 2019; Matthaeus, 2021). In this formalism, the time variations of electromagnetic (ϵ^m), kinetic (ϵ^f_α), and thermal (ϵ^{th}_α) energies can be estimated from energy transport ($\nabla.()$ terms) and energy conversion (the rest terms on the right-hand sides of the Equations below) terms:

$$\partial_t \epsilon^m = -\frac{c}{4\pi}\nabla.\ (\mathbf{E}\times\mathbf{B}) - \mathbf{j}.\ \mathbf{E}, \tag{2}$$

$$\partial_t \epsilon^f_\alpha = -\nabla.\ \left(\epsilon^f_\alpha \mathbf{u}_\alpha + \mathbf{P}_\alpha.\ \mathbf{u}_\alpha\right) + \left(\mathbf{P}_\alpha.\ \nabla\right).\ \mathbf{u}_\alpha + \mathbf{j}_\alpha.\ \mathbf{E}, \tag{3}$$

$$\partial_t \epsilon^{th}_\alpha = -\nabla.\ \left(\epsilon^{th}_\alpha \mathbf{u}_\alpha + \mathbf{h}_\alpha\right) - \left(\mathbf{P}_\alpha.\ \nabla\right).\ \mathbf{u}_\alpha. \tag{4}$$

Here, the subscript α stands for species (ion and electron), c is the speed of light, $\mathbf{E},\mathbf{B}$ are the electric and magnetic fields, respectively, $\epsilon^m = (\mathbf{E}^2 + \mathbf{B}^2)/8\pi$ is the electromagnetic (Poynting) energy, $\epsilon^f_\alpha = \frac{1}{2}\rho_\alpha \mathbf{u}^2_\alpha$ is the fluid flow energy, $\epsilon^{th}_\alpha = \frac{1}{2}m_\alpha \int (\mathbf{v} - \mathbf{u}_\alpha)^2 f_\alpha(\mathbf{x},\mathbf{v},t)$ is the internal (thermal) energy, $\mathbf{j} = \Sigma_\alpha \mathbf{j}_\alpha$ with $\mathbf{j}_\alpha = n_\alpha q_\alpha \mathbf{u}_\alpha$ is the electric current density, and $\rho_\alpha = n_\alpha m_\alpha$ is the mass density; the number density (n_α), the bulk flow velocity $\mathbf{u}_\alpha$, the pressure tensor $\mathbf{P}_\alpha$, and the heat flux vector $\mathbf{h}_\alpha$ are moments of the velocity distribution function (VDF).

In stationary states ($\partial_t () \sim 0$), the transport and conversion terms balance each other out. To a first approximation, the averaged transport terms in Eqs (2–4) become zero, unless local sources are present in the integration volume, for example, the bow shock is a source region of the Poynting flux (Koskinen and Tanskanen, 2002). The SW electric field and Poynting flux are modified at the bow shock and in the MS. During time intervals of strong SW driving, both the electric field and Poynting flux decrease in the MS in the sense that enhanced values of these parameters in the SW are associated with smaller enhancements of the same parameters near the MP (Pulkkinen et al., 2016). This indicates that part of the electromagnetic energy is converted or dissipated in the MS and that the evaluation of energy terms in Eqs (1–4) can be crucial in understanding the "active" MS.

The energy transfer rate ϵ (Eq. (1)) has been estimated in the SW (Sorriso-Valvo et al., 2007; Sorriso-Valvo et al., 2018). On the basis of Cluster and THEMIS measurements, Hadid et al. (2018) estimated ϵ when the IR was present in PSDs in the MS. The electromagnetic energy conversion term $\mathbf{j}.\mathbf{E}$ (Eqs 2,3) has been estimated in numerous papers on MR at the MP (e.g., Burch et al. (2016), and references therein), downstream of the bow shock (Schwartz et al., 2021), at (reconnecting) current sheets in the MS (Chasapis et al., 2015; Vörös et al., 2016; Vörös et al., 2017; Yordanova et al., 2016; Phan et al., 2018), by considering also non-ideal electric-field terms (Vörös et al., 2019; Stawarz et al., 2021). In these papers, the current density was calculated from plasma distributions or using tetrahedron measurements. Chasapis et al. (2018) have shown that the so-called pressure–strain terms $(\mathbf{P}_\alpha.\nabla).\mathbf{u}_\alpha$ (Eq. 3; Eq. 4), which are important in describing conversions between fluid flow and thermal energies, can be estimated using MMS tetrahedron measurements. To make observations and interpretations possible, the pressure tensor was decomposed into scalar and deviatoric parts, and the velocity gradient tensor was decomposed into symmetric and antisymmetric parts (strain rate and rotation rate tensors) (Yang et al., 2017; Chasapis et al., 2018). The pressure–strain terms can also be used as measures of energy conversion in reconnection regions at the MP or in the MS (Bandyopadhyay et al., 2021). Numerical simulations indicate (Yang et al., 2022) that when the IR is absent and ϵ cannot be calculated from Eq. 1, the pressure–strain terms near ion and sub-ion scales can still be used to estimate the energy content of the turbulent cascade.

We also mention here some fluid model alternatives, which might be needed in the MS. In comparison to the SW, the high plasma β in MS can lead to faster growth rates of pressure anisotropy-associated instabilities (Artemyev et al., 2022). Compressions or the tailward expansion of MS volumes can be associated with the generation of field-aligned and field-perpendicular pressure (gyrotropic) anisotropy

(Artemyev et al., 2022) through the conservation of the double-adiabatic Chew–Goldberger–Low (CGL) invariants (Chew et al., 1956). However, a superimposed sheared velocity field can additionally generate non-gyrotropic pressure anisotropy in the plane perpendicular to the magnetic field (Del Sarto et al., 2016). With regard to fluid model alternatives (CGL or non-gyrotropic), for the sake of simplicity, Eqs (**1**–**4**) can be kept for describing the energy budget in MS, complemented by estimations of the pressure anisotropy or non-gyrotropy directly obtained from the data (e.g., Vörös et al. (2017)).

3.2 Multi-scale and multi-dimensional physics

Kinetic simulations and data analysis show that the energy transfer and conversion terms ϵ, $\mathbf{j}.\mathbf{E}$, and $(\mathbf{P}_\alpha.\nabla).\mathbf{u}_\alpha$ have two rather different features: a) their volume-integrated scale-filtered versions show a smooth turbulent cascade-like evolution over magnetohydrodynamic and electron fluid scales (Matthaeus et al., 2020), and b) they are concentrated into regionally correlated narrow coherent structures (Yang et al., 2019; Yordanova et al., 2021). These features predetermine feasible methodologies for multi-scale analysis of turbulence in MS. In both cases a) and b), the energy terms provide a generic description as they can describe the energy budget of various specific physical processes, provided that the free energy is supplied by the fluid-scale cascade or by wave–particle interactions (Eqs **1**–**4**). However, over the sub-ion scales, which is also a domain of electron fluid description, dual real- and velocity-space anisotropic cascades of ion-entropy fluctuations can co-exist, having an impact on turbulent fluctuations and dissipation (Cerri et al., 2018). According to 3D hybrid simulations, the phase-space cascade is also anisotropic due to linear phase mixing along the magnetic field lines, especially above the ion gyroradius, while a non-linear phase mixing is acting at perpendicular scales below the ion gyroradius. Accounting for phase mixings results in scalings consistent with intermittent dissipation at coherent structures (Cerri et al., 2018). The pressure anisotropy-driven instabilities (e.g., mirror, firehose), which, in their non-linear phase, do not obey CGL invariance, can be associated with the sub-ion scale cascade matching the expectations for kinetic-Alfvén-wave (KAW) turbulence (Kunz et al., 2014). KAWs and ion Bernstein waves can also be responsible for the reduction in intermittency over sub-ion scales (Roberts et al., 2020).

The aforementioned examples demonstrate the fluid-kinetic-scale complexity of specific processes in collisionless plasmas. We believe the best strategy to handle this complexity is to use the aforementioned introduced energy terms and estimate the other parameters, such as gyrotropic and non-gyrotropic pressure anisotropies (e.g., Vörös et al. (2017)) or deviations from Maxwellian VDFs (Cerri et al., 2018; Perri et al., 2020; Graham et al., 2021; Pezzi et al., 2021) directly from the data. The energy transfer or wave damping mechanisms can also be revealed from the fine structure of the velocity space by using a single-point field–particle correlation technique (Chen et al. (2019); Klein et al. (2020), and references therein). Since the energy terms are enhanced at coherent structures, their relation to locally estimated anisotropy measures or VDF structures can be studied using conditional statistics (e.g., Vörös et al. (2019)). For example, the dependence of deviations from a Maxwellian (kinetic description) on the amount of free energy over fluid scales (Eq **1**, Eq. **4**) can be studied locally through conditional statistics. Although this approach is suitable for studying the multi-scale aspects of specific physical processes, the same method considering local fluid kinetic descriptions at coherent structures is not sufficient for investigations of the global energy budget or correlations with CPs or geomagnetic response. For that, volume-integrated quantities would be needed.

Obviously, instead of volume integrations, one can use statistical ensembles of quantities summed up along spacecraft trajectories only. Since the energy terms in (Eq. **1**, Eq. **4**) are not sign-definite, the net trajectory-integrated changes can cancel each other out. Therefore, the non-sign-definite energy measures have to be integrated separately, summing up their positive or negative parts. For j.E, the signs indicate energy conversions between waves and particles, or *vice versa*. The signs of other energy terms indicate the direction of the cascade in Fourier space (Matthaeus, 2021), whether the energy at a given scale is transferred toward smaller or larger scales. The kinetic level description, for example, deviations or the fine structure of particle VDFs at coherent structures, can be associated with given time intervals as a normalized frequency of occurrence ($\mathcal{FO}_{kinetic,i}$) of kinetic measures ($i = 1{:}N$). In this way, the variations of normalized amounts of trajectory-integrated fluid scale energy terms ($\mathcal{E}_{fluid,j}$, $j = 1{:}M$, Eqs **1**-**4**) can be associated with the corresponding variations of the normalized frequencies of occurrences in the kinetic response. The first step in statistical analysis is to construct time- and location-dependent sets of normalized parameters $\{MS\} \in \{\mathcal{E}_{fluid,j}, \mathcal{FO}_{kinetic,i}, \mathcal{E}_{fluid,j} = F(\mathcal{FO}_{kinetic,i}), \mathcal{FO}_{kinetic,i} = G(\mathcal{E}_{fluid,j})\}$, where $\{MS\}$ stands for MS sets of these combined parameters, and F and G are possible functional expressions for statistical dependencies between fluid kinetic scales and *vice versa*. $\{MS\}$ can be complemented with averages of local plasma parameters such as plasma β, compressibility, and Alfvénicity, or with the normalized frequency of occurrences of other structures such as jets, SLAMS, and waves. In the next step of statistical analysis, the sets of CPs $\{CP\}$ and indices or measures of magnetospheric response $\{Mag\}$ could be compared, where $\{Mag\}$ stands for various sets of geomagnetic indices, cross-polar cap potential, magnetospheric ULF waves (when available), etc. The final step would be an extended statistical comparison between $\{CP\} \rightarrow \{MS\} \rightarrow \{Mag\}$ sets. The right arrows indicate all possible interrelations between the different sets. Technically, from these sets of data, a multi-dimensional parameter space of varying dimensionality can be constructed, where pattern recognition techniques can be used. The dimensionality refers to different subsets of data. Since correlations can exist between the various parameters (Borovsky, 2023), the dimensionality of parameter space can presumably be reduced through principal component analysis (e.g., Härdle and Simar, 2019). As for pattern recognition, 'closeness' criteria for finding data clusters in parameter spaces could be used (e.g., Härdle and Simar, 2019).

4 Discussion

In hydrodynamic turbulence, dissipation occurs at small scales, which are characterized by velocity derivatives (e.g., Batchelor (1967)). Due to non-linearities, vorticity structures are tilted and folded together with a build-up of a strain field. The dynamical properties of 3D turbulence are largely determined by the interaction between vorticity and the rate of the stress tensor. Direct measurements of velocity derivatives in atmospheric surface layer turbulence have shown that vorticity, strain, and interaction terms are concentrated at intermittent coherent structures (e.g., Tsinober, 2004).

Yang et al. (2017) and Matthaeus et al. (2020) have shown that the pressure–strain interaction terms are also needed to understand the dynamics of turbulent collisionless space plasmas. If turbulent processes in the MS play a role in SW–magnetosphere coupling, Eqs **1**–**4** containing the generic energy transfer, conversion, and transport terms cannot be circumvented. Although some energy terms have been estimated locally in the MS (e.g., Chasapis et al., 2015; Chasapis et al., 2018; Hadid et al., 2018; Vörös et al., 2019; Bandyopadhyay et al., 2021; Wang et al., 2021), a thorough statistical analysis is still missing. To treat the fluid kinetic scale complexity as simply as possible, we propose to complement the energy terms with '*ad hoc*' parameters, such as measures of anisotropy, non-gyrotropy, deformations, and fine structures of VDFs, which can be estimated directly from the data. In addition, the $\{MS\}$ database can incorporate the frequency of occurrence of waves and mesoscale structures such as jets, SLAMS, or other transients.

In summary, we expect a considerable advance in the understanding of the SW–magnetosphere coupling through statistical studies of $\{CP\}\{MS\}$ and $\{Mag\}$ datasets, which also involve modern pattern recognition techniques and dimensionality reduction. Contrary to similar statistical approaches, particular attention is devoted to the turbulent energy budget in MS. The essential novelty lies in the fact that from tetrahedron measurements of MMS and Cluster missions, and potentially from multi-point measurements of the planned Helioswarm mission (Klein et al., 2019, also: https://eos.unh.edu/helioswarm), one can estimate gradients and calculate the energy terms in Eqs **2**–**4**. Local estimations of the energy terms combined with conditional statistics allow comparisons with kinetic measures not available in the fluid description. The integrated energy terms along spacecraft trajectories can also be compared to the frequency of the occurrence of kinetic measures, wave activities, or transient events.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Artemyev, A., Shi, C., Lin, Y., Nishimura, Y., Gonzalez, C., Verniero, J., et al. (2022). Ion kinetics of plasma flows: Earths magnetosheath versus solar wind. *Astrophys. J.* 939, 85. doi:10.3847/1538-4357/ac96e4

Axford, W., and Hines, C. (1961). A unifying theory of high-latitude geophysical phenomena and geomagnetic storms. *Can. J. Phys.* 39, 1433–1464. doi:10.1139/p61-172

Bandyopadhyay, R., Chasapis, A., Matthaeus, W. H., Parashar, T. N., Haggerty, C. C., Shay, M. A., et al. (2021). Energy dissipation in turbulent reconnection. *Phys. Plasmas* 28, 112305. doi:10.1063/5.0071015

Batchelor, G. (1967). *An introduction to fluid dynamics*. Cambridge: Cambridge University Press.

Borovsky, J., and Funsten, H. (2003). Role of solar wind turbulence in the coupling of the solar wind to the Earth's magnetosphere. *J. Geophys. Res.* 108, 1246. doi:10.1029/2002JA009601

Borovsky, J. (2023). Further investigation of the effect of upstream solar-wind fluctuations on solar-wind/magnetosphere coupling: Is the effect real? *Front. Astron. Space Sci.* 9, 975135. doi:10.3389/fspas.2022.975135

Borovsky, J. (2012). The effect of sudden wind shear on the Earth's magnetosphere: Statistics of wind shear events and ccmc simulations of magnetotail disconnections. *J. Geophys. Res.* 117, A06224. doi:10.1029/2012JA017623

Borovsky, J. (2018). The spatial structure of the oncoming solar wind at Earth and the shortcomings of a solar-wind monitor at l1. *J. Atmosp. Sol. Terr. Phys.* 177, 2–11. doi:10.1016/j.jastp.2017.03.014

Bruno, R., and Carbone, V. (2013). The solar wind as a turbulence laboratory. *Living Rev. Sol. Phys.* 10, 2. doi:10.12942/lrsp-2013-2

Burch, J., Torbert, R. B., Phan, T. D., Chen, L.-J., Moore, T. E., Ergun, R. E., et al. (2016). Electron-scale measurements of magnetic reconnection in space. *Science* 352, aaf2939. doi:10.1126/science.aaf2939

Burkholder, B. L., Nykyri, K., and Ma, X. (2020). Use of the l1 constellation as a multispacecraft solar wind monitor. *J. Geophys. Res. Space Phys.* 125, e2020JA027978. doi:10.1029/2020JA027978

Cerri, S., Kunz, M., and Califano, F. (2018). Dual phase-space cascades in 3d hybrid-vlasov–Maxwell turbulence. *Astroph. J. Lett.* 856, L13. doi:10.3847/2041-8213/aab557

Chasapis, A., Retinó, A., Sahraoui, F., Vaivads, A., Khotyaintsev, Y., Sundkvist, D., et al. (2015). Thin current sheets and associated electron heating in turbulent space plasma. *Astrophys. J. Lett.* 804, L1. doi:10.1088/2041-8205/804/1/L1

Chasapis, A., Yang, Y., Matthaeus, W., Parashar, T., Haggerty, C. C., Burch, J. L., et al. (2018). Energy conversion and collisionless plasma dissipation channels in the turbulent magnetosheath observed by the magnetospheric multiscale mission. *Astrophys. J.* 862, 32. doi:10.3847/1538-4357/aac775

Chen, C., Klein, K., and Howes, G. (2019). Evidence for electron landau damping in space plasma turbulence. *Nat. Comm.* 10, 740. doi:10.1038/s41467-019-08435-3

Chen, L., Wang, S., Ng, J., Bessho, N., Tang, J., Fung, S., et al. (2021). Solitary magnetic structures at quasi-parallel collisionless shocks: Formation. *Geophys. Res. Lett.* 48, e2020JA027978. doi:10.1029/2020GL090800

Chew, G., Goldberger, M., and Low, F. E. (1956). The Boltzmann equation and the one-fluid hydromagnetic equations in the absence of particle collisions. *Proc. R. Soc. A* 236, 112. doi:10.1098/rspa.1956.0116

D'Amicis, R., Bruno, R., and Bavassano, B. (2007). Is geomagnetic activity driven by solar wind turbulence? *Geophys. Res. Lett.* 34, e2006GL028896. doi:10.1029/2006GL028896

D'Amicis, R., Telloni, D., and Bruno, R. (2020). The effect of solar wind turbulence on magnetospheric activity. *Front. Phys.* 8, 604857. doi:10.3389/fphy.2020.604857

Del Sarto, D., Pegoraro, F., and Califano, F. (2016). Pressure anisotropy and small spatial scales induced by velocity shear. *Phys. Rev. E* 93, 053203. doi:10.1103/PhysRevE.93.053203

Dungey, J. W. (1961). Interplanetary magnetic field and the auroral zones. *Phys. Rev. Lett.* 6, 47–48. doi:10.1103/physrevlett.6.47

Eastwood, J., Schwartz, S., Horbury, T., Carr, C., Glassmeier, K., Richter, I., et al. (2011). Transient pc3 wave activity generated by a hot flow anomaly: Cluster, rosetta, and ground-based observations. *J. Geophys. Res. Space Phys.* 116, A08224. doi:10.1029/2011JA016467

Echim, M., Chang, T., Kovacs, P., Wawrzaszek, A., Yordanova, Y., Narita, E., et al. (2021). "Turbulence and complexity of magnetospheric plasmas," in *Space physics and aeronomy: Magnetospheres in the solar system*. Editors R. Maggiolo, N. André, H. Hasegawa, and D. Welling (New York, United States: American Geophysical Union, John Wiley Sons, Inc.). doi:10.1002/9781119815624.ch5

Fear, R. (2021). "The northward imf magnetosphere," in *Space physics and aeronomy: Magnetospheres in the solar system*. Editors R. Maggiolo, N. André, H. Hasegawa, and D. Welling (New York, United States: American Geophysical Union, John Wiley Sons, Inc.). doi:10.1002/9781119815624.ch19

Giacalone, J., Schwartz, S., and Burgess, D. (1993). Observations of suprathermal ions in association with slams. *Geophys. Res. Lett.* 20, 149–152. doi:10.1029/93gl00067

Gingell, I., Schwartz, S. J., Kucharek, H., Farrugia, C. J., Fryer, L. J., Plank, J., et al. (2023). Hybrid simulations of the decay of reconnected structures downstream of the bow shock. *Phys. Plasmas* 30, 012902. doi:10.1063/5.0129084

Graham, D., Khotyaintsev, Y. V., André, M., Vaivads, A., Chasapis, A., Matthaeus, W., et al. (2021). Non-maxwellianity of electron distributions near Earth's magnetopause. *J. Geophys. Res. Space Phys.* 126, e2021JA029260. doi:10.1029/2021JA029260

Hadid, L., Sahraoui, F., Galtier, S., and Huang, S. (2018). Compressible magnetohydrodynamic turbulence in the Earth's magnetosheath: Estimation of the energy cascade rate using *in situ* spacecraft data. *Phys. Rev. Lett.* 120, 055102. doi:10.1103/PhysRevLett.120.055102

Härdle, W., and Simar, L. (2019). *Applied multivariate statistical analysis*. Gewerbestrasse: Springer Nature Switzerland.

Hietala, H., Partamies, N., Laitinen, T., Clausen, L. B. N., Facskó, G., Vaivads, A., et al. (2012). Supermagnetosonic subsolar magnetosheath jets and their effects: From the solar wind to the ionospheric convection. *Ann. Geophys.* 30, 33–48. doi:10.5194/angeo-30-33-2012

Hietala, H., Phan, T., Angelopoulos, V., Oieroset, M., Archer, M., Karlsson, T., et al. (2018). *In situ* observations of a magnetosheath high-speed jet triggering magnetopause reconnection. *Geophys. Res. Lett.* 45, 1732–1740. doi:10.1002/2017GL076525

Hosokawa, K., Kullen, M. S., Reidy, J., Zou, Y., Frey, H., Maggiolo, R., et al. (2020). Aurora in the polar cap: A review. *Space Sci. Rev.* 216, 15. doi:10.1007/s11214-020-0637-3

Huang, S. Y., Hadid, L. Z., Sahraoui, F., Yuan, Z. G., and Deng, X. H. (2017). On the existence of the Kolmogorov inertial range in the terrestrial magnetosheath turbulence. *Astrophys. J. Lett.* 836, L10. doi:10.3847/2041-8213/836/1/L10

Hwang, K.-J., Weygand, J., Sibeck, D., Burch, J., Goldstein, M., Escoubet, C., et al. (2022). Kelvin-helmholtz vortices as an interplay of magnetosphere-ionosphere coupling. *Front. Astron. Space Sci.* 9, 895514. doi:10.3389/fspas.2022.895514

Kavosi, S., and Raeder, J. (2015). Ubiquity of kelvin-helmholtz waves at Earth's magnetopause. *Nat. Comm.* 6, 7019. doi:10.1038/ncomms8019

Kessel, R., Quintana, E., and Peredo, M. (1999). Local variations of interplanetary magnetic field at Earth's bow shock. *J. Geophys. Res.* 104, 24869–24878. doi:10.1029/1999ja900230

Kis, A., Matsukiyo, S., Otsuka, F., Hada, T., Lemperger, I., Dandouras, I., et al. (2018). Effect of upstream ulf waves on the energetic ion diffusion at the Earth's foreshock. ii. observations. *Astrophys. J.* 863, 136. doi:10.3847/1538-4357/aad08c

Klein, K., Alexandrova, O., Bookbinder, J., Caprioli, D., Case, A., Chandran, B., et al. (2019). *Multipoint measurements of the solar wind: A proposed advance for studying magnetized turbulence*. Ithaca, NY: Cornell University. arXiv 1903. 05470v2.

Klein, K., Howes, G., TenBarge, J., and Valentini, F. (2020). Diagnosing collisionless energy transfer using field-particle correlations: Alfvén-ion cyclotron turbulence. *J. Plasma Phys.* 86, 905860402. doi:10.1017/S0022377820000689

Koller, F., Temmer, M., Preisser, L., Plaschke, F., Geyer, P., Jian, L., et al. (2022). Magnetosheath jet occurrence rate in relation to cmes and sirs. *J. Geophys. Res. Space Phys.* 127, e2021JA030124. doi:10.1029/2021JA030124

Koskinen, H., and Tanskanen, E. (2002). Magnetospheric energy budget and the epsilon parameter. *J. Geophys. Res.* 107, 1415. doi:10.1029/2002JA009283

Kunz, M., Schekochihin, A., and Stone, J. (2014). Firehose and mirror instabilities in a collisionless shearing plasma. *Phys. Rev. Lett.* 112, 205003. doi:10.1103/PhysRevLett.112.205003

LaMoury, A., Hietala, H., Plaschke, F., Vuorinen, L., and Eastwood, J. (2021). Solar wind control of magnetosheath jet formation and propagation to the magnetopause. *J. Geophys. Res. Space Phys.* 126, JA029592. doi:10.1029/2021/JA029592

Marino, R., and Sorriso-Valvo, L. (2023). Scaling laws for the energy transfer in space plasma turbulence. *Phys. Rep.* 1006, 1–144. doi:10.1016/j.physrep.2022.12.001

Masson, A., and Nykyri, K. (2018). Kelvin-helmholtz instability: Lessons learned and ways forward. *Space Sci. Rev.* 214, 71. doi:10.1007/s11214-018-0505-6

Matthaeus, W. (2021). Turbulence in space plasmas: Who needs it? *Phys. Plasmas* 28, 032306. doi:10.1063/5.0041540

Matthaeus, W., Yang, Y., Wan, M., Parashar, T., Bandyopadhyay, R., Chasapis, A., et al. (2020). Pathways to dissipation in weakly collisional plasmas. *Astrophys. J.* 891, 101. doi:10.3847/1538-4357/ab6d6a

Nakamura, T. K. M., Stawarz, J. E., Hasegawa, H., Narita, Y., Franci, F., Wilder, L., et al. (2020). Effects of fluctuating magnetic field on the growth of the kelvin-helmholtz instability at the earth's magnetopause. *J. Geophys. Res. Space Phys.* 125, e2019JA027515. doi:10.1029/2019JA027515

Narita, Y., Plaschke, F., and Vörös, Z. (2021). "The magnetosheath," in *Space physics and aeronomy: Magnetospheres in the solar system*. Editors R. Maggiolo, N. André, H. Hasegawa, and D. Welling (New York, United States: American Geophysical Union, John Wiley Sons, Inc.). doi:10.1002/9781119815624.ch9

Newell, P. T., Gjerloev, J. W., and Mitchell, E. J. (2013). Space climate implications from substorm frequency. *J. Geophys. Res. Space Phys.* 118, 6254–6265. doi:10.1002/jgra.50597

Newell, P. T., Sotirelis, T., Liou, K., Meng, C. I., and Rich, F. J. (2007). A nearly universal solar wind-magnetosphere coupling function inferred from 10 magnetospheric state variables. *J. Geophys. Res.* 112, e2006JA012015. doi:10.1029/2006JA012015

Nykyri, K., Ma, X., Dimmock, C., andFoullon, A., Otto, A., and Osmane, A. (2017). Influence of velocity fluctuations on the kelvin-helmholtz instability and its associatedmass transport. *J. Geophys. Res. Space Phys.* 122, 9489–9512. doi:10.1002/2017JA024374

Nykyri, K., Ma, X., and Johnson, J. (2021). "Cross-scale energy transport in space plasmas: Applications to the magnetopause boundary," in *Space physics and aeronomy: Magnetospheres in the solar system*. Editors R. Maggiolo, N. André, H. Hasegawa, and D. Welling (New York, United States: American Geophysical Union, John Wiley Sons, Inc.). doi:10.1002/9781119815624.ch7

Parks, G., Lee, E., Yang, Z., Lin, N., Fu, S., and Liu, Y. (2021). "Solar wind interaction with Earth's bow shock," in *Space physics and aeronomy: Magnetospheres in the solar system*. Editors R. Maggiolo, N. André, H. Hasegawa, and D. Welling (New York, United States: American Geophysical Union, John Wiley Sons, Inc.). doi:10.1002/9781119815624.ch8

Perreault, P., and Akasofu, S.-I. (1978). A study of geomagnetic storms. *Geophys. J. R. Astronomical Soc.* 54, 547–573. doi:10.1111/j.1365-246X.1978.tb05494.x

Perri, S., Perrone, D., Yordanova, E., Sorriso-Valvo, L., Paterson, W. R., Gershman, D. J., et al. (2020). On the deviation from maxwellian of the ion velocity distribution functions in the turbulent magnetosheath. *J. Plasma Phys.* 86, 905860108. doi:10.1017/S0022377820000021

Pezzi, O., Liang, H., Juno, J. L., Cassak, P. A., Vásconez, C. L., Sorriso-Valvo, L., et al. (2021). Dissipation measures in weakly collisional plasmas. *Mon. Not. R. Astron. Soc.* 505, stab1516. doi:10.1093/mnras/stab1516

Phan, T., Eastwood, J. P., Shay, M. A., Drake, J. F., Sonnerup, B. U. Ö., Fujimoto, M., et al. (2018). Electron magnetic reconnection without ion coupling in Earth's turbulent magnetosheath. *Nature* 557, 202–206. doi:10.1038/s41586-018-0091-5

Plaschke, F., Hietala, H., Archer, M., Blanco-Cano, X., Kajdi, P., Karlsson, T., et al. (2018). Jets downstream of collisionless shocks. *Space Sci. Rev.* 214, 81. doi:10.1007/s11214-018-0516-3

Plaschke, F., Hietala, H., and Vörös, Z. (2020). Scale sizes of magnetosheath jets. *J. Geophys. Res. Space Phys.* 125, e2020JA027962. doi:10.1029/2020JA027962

Pulkkinen, T. I., Dimmock, A., Lakka, A., Osmane, A., Kilpua, E., Myllys, M., et al. (2016). Magnetosheath control of solar wind–magnetosphere coupling efficiency. *J. Geophys. Res. Space Phys.* 121, 8728–8739. doi:10.1002/2016JA023011

Rakhmanova, L., Riazantseva, M., and Zastenker, G. (2021). Plasma and magnetic field turbulence in the Earth's magnetosheath at ion scales. *Front. Astron. Space Sci.* 7, 616635. doi:10.3389/fspas.2020.616635

Rakhmanova, L., Riazantseva, M., Zastenker, G., and Yermolaev, Y. (2022). Large-scale solar wind phenomena affecting the turbulent cascade evolution behind the quasi-perpendicular bow shock. *Universe* 8, 611. doi:10.3390/universe8120611

Roberts, O., Verscharen, D., Narita, Y., Nakamura, R., Vörös, Z., and Plaschke, F. (2020). Possible coexistence of kinetic alfvén and ion bernstein modes in sub-ion scale compressive turbulence in the solar wind. *Phys. Rev. Res.* 2, 043253. doi:10.1103/PhysRevResearch.2.043253

Sahraoui, F., Hadid, L., and Huang, S. (2020). Magnetohydrodynamic and kinetic scale turbulence in the near Earth space plasmas: a (short) biased review. *Rev. Modern Plasma Phys.* 4. doi:10.1007/s41614-020-0040-2

Schwartz, S., Kucharek, H., Farrugia, C. J., Trattner, K., Gingell, I., Ergun, R., et al. (2021). Energy conversion within current sheets in the Earth's quasi-parallel magnetosheath. *Geophys. Res. Lett.* 48, e2020GL091859. doi:10.1029/2020GL091859

Sibeck, D., Borodkova, N., Schwartz, S., Owen, C., Kessel, R., Kokubun, S., et al. (1999). Comprehensive study of the magnetospheric response to a hot flow anomaly. *J. Geophys. Res. Space Phys.* 104, 4577–4593. doi:10.1029/1998JA900021

Sibeck, D., and Murphy, K. (2021). "Large scale structure and dynamics of the magnetosphere," in *Space physics and aeronomy: Magnetospheres in the solar system*. Editors R. Maggiolo, N. André, H. Hasegawa, and D. Welling (New York, United States: American Geophysical Union, John Wiley Sons, Inc.). doi:10.1002/9781119815624.ch2

Sorriso-Valvo, L., Carbone, F., Perri, S., Greco, A., Marino, R., and Bruno, R. (2018). On the statistical properties of turbulent energy transfer rate in the inner heliosphere. *Sol. Phys.* 293, 10. doi:10.1007/s11207-017-1229-6

Sorriso-Valvo, L., Marino, R., Carbone, V., Noullez, A., Lepreti, F., Veltri, P., et al. (2007). Observation of inertial energy cascade in interplanetary space plasma. *Phys. Rev. Lett.* 99, 115001. doi:10.1103/PhysRevLett.99.115001

Stawarz, J., Matteini, L., Parashar, T. N., Franci, L., Eastwood, J. P., Gonzalez, C. A., et al. (2021). Comparative analysis of the various generalized ohm's law terms in magnetosheath turbulence as observed by magnetospheric multiscale. *J. Geophys. Res. Space Phys.* 126, e2020JA028447. doi:10.1029/2020JA028447

Tsinober, A. (2004). *An informal introduction to turbulence*. Dordrecht, Netherlands: Kluwer Academic Publishers.

Tsurutani, B., and Gonzalez, W. (1987). The cause of high-intensity long-duration continuous ae activity (hildcaas): Interplanetary alfvén wave trains. *Planet. Space Sci.* 35, 405–412. doi:10.1016/0032-0633(87)90097-3

Tsurutani, B., and Gonzalez, W. (1995). The efficiency of viscous interaction between the solar wind and the magnetosphere during intense northward imf events. *Geophys. Res. Lett.* 22, 663–666. doi:10.1029/95gl00205

Turc, L., Roberts, O., Verscharen, D., Dimmock, A., Kajdič, P., Palmroth, M., et al. (2021). Transmission of foreshock waves through Earth's bow shock. *Nat. Phys.* 19, 78–86. doi:10.1038/s41567-022-01837-z

Vörös, Z., Baumjohann, W., Nakamura, R., Runov, A., Volwerk, M., Asano, Y., et al. (2007). Spectral scaling in the turbulent Earth's plasma sheet revisited. *Nonlin. Proc. Geophys.* 14, 535–541. doi:10.5194/npg-14-535-2007

Vörös, Z., Facskó, G., Khodachenko, M., Honkonen, I., Janhunen, P., and Palmroth, M. (2014). Windsock memory conditioned ram (co-ram) pressure effect: Forced reconnection in the Earth's magnetotail. *J. Geophys. Res. Space Phys.* 119, 6273–6293. doi:10.1002/2014JA019857

Vörös, Z., Yordanova, E., Echim, M., Consolini, G., and Narita, N. (2016). Turbulence-generated proton-scale structures in the terrestrial magnetosheath. *Astrophys. J. Lett.* 819, L15. doi:10.3847/2041-8205/819/1/L15

Vörös, Z., Yordanova, E., Khotyaintsev, Y. V., Varsani, A., and Narita, Y. (2019). Energy conversion at kinetic scales in the turbulent magnetosheath. *Front. Astron. Space Sci.* 6, 00060. doi:10.3389/fspas.2019.00060

Vörös, Z., Yordanova, E., Varsani, A., Genestreti, K. J., Khotyaintsev, Y. V., Li, W., et al. (2017). Mms observation of magnetic reconnection in the turbulent magnetosheath. *J. Geophys. Res. Space Phys.* 122, e2017JA024535. doi:10.1002/2017JA024535

Wang, G., Thang, T., Wu, M., Schmid, D., Cao, J., and Volwerk, M. (2019). Solar wind directional change triggering flapping motions of the current sheet: Mms observations. *Geophys. Res. Lett.* 46, 64–70. doi:10.1029/2018GL080023

Wang, Y., Bandyopadhyay, R., Chhiber, R., Matthaeus, W. H., Chasapis, A., Yang, Y., et al. (2021). A preliminary study of magnetosphere-ionosphere-thermosphere coupling at jupiter: Juno multi-instrument measurements and modeling tools. *J. Geophys. Res. Space Phys.* 126, e2021JA029469. doi:10.1029/2021JA029469

Yang, Y., Matthaeus, W., Parashar, T., Haggerty, C., Roytershteyn, W., Daughton, W., et al. (2017). Energy transfer, pressure tensor and heating of kinetic plasma. *Phys. Plasmas* 24, 072306. doi:10.1063/1.4990421

Yang, Y., Matthaeus, W., Roy, S., Roytershteyn, V., Parashar, B. R., Wan, M., et al. (2022). Pressure–strain interaction as the energy dissipation estimate in collisionless plasma. *Astrophys. J.* 929, 142. doi:10.3847/1538-4357/ac5d3e

Yang, Y., Wan, M., Matthaeus, W., Sorriso-Valvo, L., Parashar, L. Q., Shi, Y., et al. (2019). Scale dependence of energy transfer in turbulent plasma. *Mon. Not. R. Astron. Soc.* 482, 4933–4940. doi:10.1093/mnras/sty2977

Yordanova, E., Vörös, Z., Raptis, S., and Karlsson, T. (2020). Current sheet statistics in the magnetosheath. *Front. Astron. Space Sci.* 7, 2. doi:10.3389/fspas.2020.00002

Yordanova, E., Vörös, Z., Sorriso-Valvo, L., Dimmock, A., and Kilpua, E. (2021). A possible link between turbulence and plasma heating. *Astrophys. J.* 921, 65. doi:10.3847/1538-4357/ac1942

Yordanova, E., Vörös, Z., Varsani, A., Graham, D. B., Norgren, C., Khotyaintsev, Y. V., et al. (2016). Electron scale structures and magnetic reconnection signatures in the turbulent magnetosheath. *Geophys. Res. Lett.* 43, 5969–5978. doi:10.1002/2016GL069191

Zhang, H., Zong, Q., Connor, H., Delamere, P., Facskó, G., Han, D., et al. (2022). Dayside transient phenomena and their impact on the magnetosphere and ionosphere. *Space Sci. Rev.* 218, 40. doi:10.1007/s11214-021-00865-0