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COMMENTARY

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Is the *Dst* Index Sufficient to Define All Geospace Storms?

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Key Points:

- Different storms have different mixes of ring current strength, radiation-belt enhancement, plasma sheet temperature, auroral currents, etc
- The *Dst* index is a poor identifier of high-speed-stream-driven storms and of other types of geospace storms
- A call is made to the space physics community to refine the definitions of storms and to develop criteria to identify them

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Abstract The purpose of this commentary is (1) to raise awareness about some shortcomings of the use of the *Dst* index to identify storms, to gauge storm intensity, and to represent storm time space-weather phenomena and (2) to initiate discussions about different types of storms and about improved identifiers for different types of storms.

Dst, the *H*-component perturbation on equatorial magnetometers (Mayaud, 1980), is a historical definition of a magnetic storm that goes back to von Humbolt in the early 1800's (Malin & Barraclough, 1991). The creation of the *Dst* index was initiated by Bartels who advocated for the development of an index for monitoring the equatorial ring current (Kertz, 1958, 1964; Mayaud, 1980; Sugiura, 1964). The *Dst* index represents the longitudinally averaged part of the external field measured at the geomagnetic dipole equator at the surface of the Earth (Sugiura, 1964) and is provided by the World Data Center for Geomagnetism, Kyoto. The most often used definition of a geomagnetic storm is an event wherein the minimum of the *Dst* index goes below a critical value, for example, −50 nT or −100 nT (Sugiura & Chapman, 1960). A minimum-*Dst* categorization that is often used to categorize storm intensity is (cf. Table 1 of Loewe & Prolss, 1997) a weak storm has -30 nT $> Dst > -50$ nT, a moderate storm has -50 nT $> Dst > -100$ nT, a strong storm has -100 nT $> Dst > -200$ nT, a severe storm has -200 nT $> Dst > -350$ nT, and a great storm has $Dst < 350$ nT.

Dst is primarily a measure of plasma pressure in the dipolar magnetosphere (Dessler & Parker, 1959; Greenspan & Hamilton, 2000; Sckopke, 1966); the *Dst* index is taken to be the strength of the Earth's ring current, but it also reacts to the partial ring current (Liemohn et al., 2001), the cross-tail current (Dubyagin et al., 2014; Ohtani et al., 2001; Turner et al., 2000), and the Chapman-Ferraro dayside-magnetopause current (Burton, McPherron, & Russell, 1975; Siscoe, McPherron, & Jordanova, 2005). While the *Dst* index estimates the strength of the storm time ring current, it is a poor proxy for other storm time phenomena. Ionospheric Joule heating during storms is not strongly related to the *Dst* index; it is instead parameterized by high-latitude geomagnetic indices (Baumjohann & Kamide, 1984; Chun et al., 2002). Ionospheric ion outflow is typically parameterized by *Kp* (Welling et al., 2015; Yau, Peterson, & Abe, 2011). Ionospheric models also use either solar wind-driven electric field models or the *Kp* index to evaluate the effects of geomagnetic storms (Garcia et al., 2007; Weimer, 1995). Variations in the thermospheric density (important for atmospheric drag and spacecraft reentry) vary with geomagnetic activity as parameterized by *Kp* (Rhoden, Forbes, & Marcos, 2000; Vallardo & Finkleman, 2014). The energy of auroral particle precipitation is parameterized by *Kp* (Emery et al., 2008; Hardy et al., 1987). *Dst* does not describe the dynamics of the particle populations in the radiation belts (Reeves et al., 2003). None of these quantities are well correlated with *Dst*. The evolution of the hot-plasma ions and electrons in the magnetosphere is well correlated with the *Kp* index (Denton et al., 2015; Korth et al., 1999). The storm time evolution of the cold plasma of the plasmasphere and plumes shows little correlation with *Dst* as it is determined by the time history of the convection electric field, which better correlates with the *Kp* or *AE* index (e.g., Goldstein et al., 2014; Maynard & Chen, 1975; Pierrard et al., 2009).

Dst is also often used to determine whether or not a storm occurred, to define the duration of a storm, and to distinguish between quiet and disturbed geomagnetic conditions. However, *Dst* does not identify all storms. Further, as should be expected, *Dst* is incomplete in describing storm evolution and storm phenomena. The direct relevance of *Dst* to modern space-weather phenomena is weak.

Long-duration high-speed-stream-driven (aka CIR-driven) geomagnetic storms, which lead to the strongest electron-radiation-belt radiation hazards, to the strongest plasma sheet spacecraft-charging hazards, and to the related spacecraft anomalies (Wrenn, 2009; Wrenn, Rodgers, & Ryden, 2002), have weak, short-lived *Dst* signatures (Borovsky & Denton, 2006; McPherron & Weygand, 2006) and are typically not captured in $Dst \le -50$ nT or $Dst \le -100$ nT lists of storms (Denton et al., 2009). One reason for this misidentification is

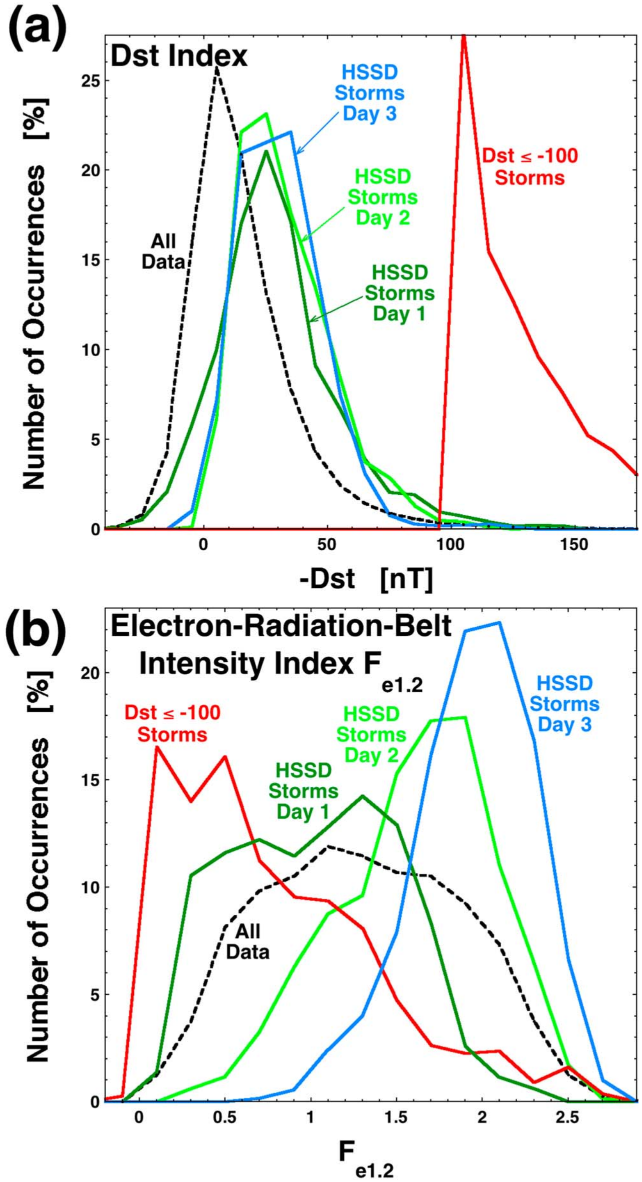

Figure 1. (a) Hourly values of $-Dst$ are binned, and (b) hourly values of the radiation-belt index $F_{e1.2}$ are plotted. In both panels the red curves are for times when $Dst \leq -100$ nT; the dark-green, light-green, and blue curves are for the first, second, and third days of high-speed-stream-driven storms; and the black dashed curve is for all times.

the fact that high-speed-stream-driven storms are characterized by a daylong increase in the solar wind ram pressure at the onset of the storm, which causes intensified Chapman-Ferraro currents to produce a positive perturbation to *Dst* that offsets the negative perturbation produced by storm convection (Borovsky & Denton, 2010). A second reason is that the ion plasma sheet is hot during a high-speed-stream-driven storm and hot ions drift azimuthally and cannot be injected close to the Earth, which makes them poor fuel for the ring current (Ebihara & Ejiri, 2000; Kozyra & Liemohn, 2003; Liemohn et al., 2001), leading to a weaker negative *Dst* signature (Lavraud et al., 2006).

A glaring example of an important storm time space-weather phenomena that is not well organized by the *Dst* index is the evolution of the outer electron radiation belt. In Figure 1a the hourly values of the $-Dst$ index are binned: the red curve is the distribution of $-Dst$ values when $Dst \leq -100$ nT (*Dst*-defined storms), and the dark-green, light-green, and blue curves are the distributions of $-Dst$ values for the first day, the second day, and the third day, respectively, of 70 high-speed-stream-driven storms from the collection of Borovsky and Denton (2016). The black dashed curve is the distribution of $-Dst$ for all times. Figure 1a indicates that very few of the hours of high-speed-stream-driven storms would be categorized as a storm by the *Dst* index (less than 1% in Figure 1a). In Figure 1b the multispacecraft 1.2 MeV radiation-belt-intensity index $F_{e1.2}$ (cf. Borovsky & Yakymenko, 2017) is binned for the same events as in Figure 1a: as can be seen, the outer electron radiation belt is weak during the $Dst \leq -100$ nT storms (red) and the radiation belt is strong during high-speed-stream-driven storms, getting stronger every day while *Dst* remains weak. Statistical parameterizations of the ULF waves responsible for the inward and outward radial transport of radiation-belt particles are usually given in terms of the *Kp* index (e.g., Brautigam & Albert, 2000; Ozeke et al., 2014). VLF waves that are responsible for acceleration and loss of radiation-belt particles are also usually parameterized by *Kp* (e.g., Agapitov et al., 2015; Orlova, Shprits, & Spasojevic, 2016; Orlova, Spasojevic, & Shprits, 2014; Shprits, Meredith, & Thorne, 2007; Spasojevic, Shprits, & Orlova, 2015) or by AE/AL (Li et al., 2015; Shprits et al., 2007). The *Dst* index, however, can serve as a proxy for the adiabatic changes (Kim & Chan, 1997) of electron fluxes driven by the change in the global magnetic field; these changes result in reversible changes in the radiation environment. The behavior of the electron radiation belt is much better organized by an index such as *Kp*, which measures the strength of magnetospheric convection (Thomsen, 2004). At times of increasing electron-radiation-belt intensities the correlations of the relativistic-electron fluxes with the *Kp* index are nearly two times stronger than the correlations with the *Dst* index (Borovsky, 2017). Similarly for times when the radiation-belt flux is decaying, flux correlations with *Kp* are much stronger than flux correlations with *Dst*.

The *Dst* index is also of limited relevance to other space-weather phenomena. (1) Spacecraft charging hazards are caused by anomalously hot plasma in the magnetosphere, which is more related to *Kp* and to substorm activity. (2) Geomagnetically induced currents are caused by high-latitude currents, and this hazard is more related to the behavior of high-latitude magnetometer stations. (3) Ionospheric disturbances associated with storm time convection are more related to *Kp*. And of course the *Dst* index is irrelevant to the intensity of solar energetic particles at Earth and to solar-flare ionospheric disturbances.

There is a need to develop a methodology (A) to identify all storms or (B) to define and identify the different types of storms. *Dst* alone is not sufficient for either need.

From a solar wind-driver point of view there are two types of storms: CME-driven (shock, sheath, and ejecta) storms and high-speed-stream-driven (CIR then stream) storms. The widely available *Kp* index could be used to identify both the CME-driven and the high-speed-stream-driven storms, although a *Kp* index with a time resolution much faster than the currently available 3 h would be needed to determine storm onset times. The NOAA geomagnetic-storm scale (http://www.swpc.noaa.gov/sites/default/files/images/NOAAscales.pdf) is based on the instantaneous value of *Kp*. Focusing specifically on high-speed-stream-driven storms where storm duration impacts the radiation-belt intensity, a running average or time integral of *Kp* would better serve to identify the occurrence of those storms and a time integral of *Kp* could describe the evolution of the electron radiation belt. Another way to specifically identify high-speed-stream-driven storms could be via temporal increases in the intensity of the outer electron radiation belt (cf. Figure 1b) that bring the intensity levels to above-average values. A current limitation of the *Kp* index is that it saturates at $Kp = 9$ and cannot be used to compare the strengths of superstorms for which *Kp* reaches the maximum allowed value of 9. The discrete values at which *Kp* is given (e.g., 0, 0+, 1, 1−, and 1+) complicate the systematic analysis of this index. The *Ap* or the *am* indices (Mayaud, 1980) may be much more appropriate for gauging storm intensity and for statistical studies.

From a geospace-response point of view there are several types of geospace storms. Focusing on the ring current and the associated low-latitude magnetic disturbances, "geomagnetic storms" as characterized by *Dst* are important. Focusing on intensifications of relativistic electrons, what might be called "trapped radiation storms" could be characterized by radiation-belt fluxes or by the time integral of a *Kp*-like index (e.g., Baker, Kanekal, & Blake, 2004; Borovsky & Yakymenko, 2017; Rochel et al., 2016). Focusing on high-latitude currents, "high-latitude electrical storms" could be characterized by dB/dt or the temporal Fourier transforms from ground-based magnetometers (e.g., Marshall et al., 2011; Wintoft, Wik, & Viljanen, 2015). Focusing on ionospheric disturbances associated with convection, "ionospheric storms" could be characterized by f_oF_2 or total electron content (TEC) (e.g., Blagoveshchenskii, 2013; Nishioka et al., 2017). Focusing on spacecraft-charging hazards, "hot-plasma storms" could be characterized by *Kp* (e.g., Denton et al., 2016; Thomsen, Henderson, & Jordanova, 2013). There are of course overlaps of the various types of geospace storms, just as a thunderstorm can be a rainstorm, a lightning storm, a hailstorm, and/or a windstorm.

From a system-science point of view, a "state vector" composed of several measures would provide a superior indication of the intensity of global geospace activity (Luo, 2010; Vassiliadis, 2006). Storm occurrence and storm severity could be indicated (a) by the nature of the vector, (b) by the magnitude of the vector, or (c) by the dot product of the vector with some indicator of storm properties. Components of such a state vector might be measurements of critical magnetospheric properties such as the amount of open flux, the strength of convection, the intensity of the ring current ions, the density of the cold plasma population, the intensity of the electron radiation belt, the substorm-occurrence rate, the intensity of the substorm-injected energetic-particle population, the plasma sheet density and temperature, indices of ULF wave activity, ionospheric global TEC, and f_oF_2 indices. Geomagnetic indices such as *Dst*, *Kp*, *AL*, and *PCI* should also be components of the state vector.

An approach could be to specifically catalog different types of storms separately using different definitions and different criteria. With the state-vector approach it might involve taking the dot product of the magnetospheric state vector with different reference vectors to highlight properties that are characteristic of the different types of storms.

The *Dst* index alone is not an appropriate indicator for identifying all geospace storms, for the comparison of the evolution during different storms, for performing superposed epoch analysis, or for determining the onset and end of a storm.

The physical processes operating during storms are much better understood now than they were when von Humbolt originally defined a magnetic storm and when the indices were first created by Bartels, Kertz, and Sugiura. Many studies choose *Dst* as a proxy for storms simply because of its continuous scale, its high cadence, and its simple interpretation; however, as argued in this commentary such use of this index may often be inappropriate or not optimal for identification of geomagnetic storms and representation of storms and their effects. We as a community should consider a better set of criteria.

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