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Summer-winter hemisphere asymmetry of the preliminary reverse impulse of geomagnetic storm sudden commencements at midlatitudes

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[1] We present event-specific observational evidence for the prevalence of a summer-winter hemisphere asymmetry of the preliminary reverse impulse (PRI) of geomagnetic storm sudden commencements (SSCs) at midlatitudes of the local afternoon sector. The evidence is culled from the archived 10-s resolution data of midlatitude stations (geomagnetic latitude 23–46°) of the MM 210 magnetometer network. The hemisphere asymmetry is characterized by a larger peak amplitude of PRI in the summer hemisphere than in the winter hemisphere, and this feature is more prominently seen in the December solstice compared to the June solstice. In the December solstice SSC event, the amplitude of the preliminary reverse impulse, PRI (4.8 nT) at BRV (geomagnetic latitude 36.6°S) in the summer hemisphere is larger by a factor of 6 compared to that at MSR (geomagnetic latitude 37.6°N) in the winter hemisphere. The asymmetry is also apparent at lower latitudes: while the PRI assumed an amplitude of 3.7 nT at LEM (geomagnetic latitude 34.1°S), it is barely discernible at ONW (geomagnetic latitude 31.6°N) in the winter hemisphere. In the June solstice event, the PRI amplitude at RIK (geomagnetic latitude 34.7°N) in the summer hemisphere is higher by a factor of 3.44 compared to that at LEM (geomagnetic latitude 34.1°S) in the winter hemisphere. A similar behavior is also apparent in the equinox event though the hemisphere asymmetry of the preliminary reverse impulse (PRI) here is of moderate strength. In all the SSC events studied, the main impulse (MI) amplitude also exhibited the well-known summer-winter asymmetry, but the hemisphere asymmetry is more prominent with the preliminary reverse impulse (PRI) than with the main impulse (MI). Physical processes that could possibly account for the hemisphere asymmetry evidenced of the afternoon PRI at midlatitudes are discussed.

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1. Introduction

[2] The impact of fast forward interplanetary shocks on the subsolar magnetopause leads to sudden magnetospheric compression and enhancement of Chapman-Ferraro currents resulting in a step-like increase of northward magnetic field throughout the magnetosphere and on the ground. The cleanest effect of sudden magnetospheric compression is, however, commonly seen in ground level magnetic records only at low latitudes [e.g., *Russell et al.*, 1992; *Araki et al.*, 1993]. Everywhere else, the waveform of ground level (SSC) shows temporal structure, consisting of a short-lived preliminary impulse (PI) followed by the main impulse (MI), with a complex dependence of the two-pulse waveform on latitude and local time [e.g., *Nagata*, 1952, *Matsushita*, 1962, *Rastogi and Sastri*, 1974; *Araki*, 1977, 1994; *Araki et al.*, 1985; *Tsunomura*, 1998, 1999; *Kikuchi et al.*, 2001]. At high latitudes in the afternoon sector a preliminary negative impulse of about 1-min duration called the preliminary reverse impulse (PRI) often precedes the main impulse (MI) of SSC, while a positive preliminary impulse (PPI) prevails in the morning sector [e.g., *Nagata*, 1952; *Matsushita*, 1962; *Araki*, 1977]. The preliminary impulse (PI) decreases in amplitude toward the equator [*Nagata*, 1952] and is seldom seen at low geomagnetic latitudes. But the PRI reappears at the dayside magnetic equator simultaneous with that at high latitudes of the afternoon sector, with a maximum rate of occurrence around local noon [e.g., *Rastogi and Sastri*, 1974; *Araki*, 1977; *Araki et al.*, 1985]. This unique global morphology of the PRI has been explained by *Araki* [1977, 1994] in terms of the magnetic effects of a twin-vortex DP2 type ionospheric current system excited by a dusk-to-dawn electric field that is imposed on the polar ionosphere by field-aligned currents (FACs). The dusk-to-dawn electric field propagates instan-

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taneously at the speed of light through the Earth-ionosphere waveguide to the magnetic equator where it generates westward ionospheric currents to produce the PRI simultaneous with that at high latitudes. MHD simulations of the magnetospheric response to a solar wind impulse have shown the establishment of FACs and twin-vortex DP2 type current system in the high-latitude ionosphere lending substantial support to the original ideas of *Tamao* [1964a] which is the basis of Araki's physical model of SSC [*Slinker et al.*, 1999; *Fujita et al.*, 2003a, 2003b; *Chi et al.*, 2006]. The mechanism of propagation of the PRI from the high latitudes to low magnetic latitudes however has become a topic of some debate in recent times in view of the work of *Chi et al.* [2001] wherein they have shown through a case study that the PRI signal does not arrive simultaneously at different latitudes as expected from the conventional SSC model but follows a "zig-zag" latitudinal pattern which feature they interpreted in terms of propagation of MHD waves right from the point of shock impact to the ground.

[3] In the midlatitude region (geomagnetic latitude (GML) 20–49°) of primary interest here, it is known from earlier studies that the polarity and occurrence rate of the preliminary impulse (PI) are local time-dependent. The pulse is predominantly positive (preliminary positive impulse, PPI) during the forenoon and negative (preliminary reverse impulse, PRI) in the afternoon, and the occurrence of afternoon PRI decreases rapidly with decrease of geomagnetic latitude, GML from 49.0° to 29.2° [e.g., *Nagata*, 1952; *Matsushita*, 1962; *Yamada et al.*, 1997]. The recent work of *Kikuchi et al.* [2001] showed that afternoon PPIs at midlatitudes occurred exclusively in local winter while morning PPIs exhibited no such seasonal preference. They explained the observed PPI morphology at midlatitudes in terms of the competing contributions of FACs and season-dependent ionospheric currents to ground level magnetic perturbations. On the basis of model calculations, it is suggested that the positive effects of FACs played a predominant role in the winter hemisphere when the ionospheric conductivity is relatively low leading to a preferential occurrence of PPIs in the afternoon. This interesting theroretical study also indicated that the frequent occurrence of PRIs in the afternoon at midlatitudes established by earlier statistical studies [*Matsushita*, 1962; *Yamada et al.*, 1997] could be due to the combined negative effects of Hall and Pedersen ionospheric currents swamping the positive effect of FACs.

[4] One of the early results of the 210 magnetic meridian (MM) magnetometer network project [*Yumoto et al.*, 1996a] was the finding of a frequent presence of hemispheric differences in the manifestation of SSCs at midlatitudes: the amplitude in H-component of the main impulse, MI is significantly higher in summer hemisphere compared to winter hemisphere [*Yumoto et al.*, 1996b]. The hemisphere asymmetry of MI amplitude has been attributed to the hemisphere asymmetry of the twin-vortex type of ionospheric currents driven by the disturbance of polar origin (DP field). The very recent study of *Huang and Yumoto* [2006] brought to light a noteworthy dependence of this hemisphere asymmetry of geomagnetic disturbances at midlatitudes associated with solar wind dynamic pressure enhancements, namely, SSCs and sudden impulse (SIs), on the orientation of north-south (Bz) component of interplanetary magnetic field (IMF). The hemisphere asymmetry is found to be more prominent under southward Bz conditions than for northward and fluctuating Bz conditions, and this situation prevailed for solar wind dynamic pressure enhancements of various magnitudes. *Huang and Yumoto* suggested the observed hemispheric differences are due to the tilt of the Earth's magnetic axis based on the theoretical calculations of *Russell et al.* [1994].

[5] In contrast to studies of the main impulse (MI), the hemisphere asymmetry of the preliminary reverse impulse (PRI) of SSCs at midlatitudes remained unexplored. Hemisphere asymmetry of PRI may be expected in principle because of the fact that unlike at high latitudes and at the dayside dip equator where Hall currents and Pedersen currents practically determine the characteristics of SSCs, respectively, at midlatitudes all the elements of the magnetosphere-ionosphere electric circuit, namely, FACs and ionospheric Hall and Pedersen currents contribute to the behavior of SSCs [*Yamada et al.*, 1997; *Tsunomura*, 1998, 1999; *Kikuchi et al.*, 2001; *Sastri*, 2002]. The characteristics of the midlatitude SSC waveform (polarity and amplitude of the preliminary impulse and main impulse) in individual events, therefore, depend on the relative ground magnetic effects (amplitude and polarity) of the different current systems.

[6] This paper is the first report of the presence of a noteworthy summer-winter hemisphere asymmetry in the manifestation of the preliminary reverse impulse (PRI) of SSC in the midlatitude region of the local afternoon sector. In section 2, event-based evidence is presented for the hemisphere asymmetry of the preliminary reverse impulse (PRI). In section 3, the observations are discussed in the light of current understanding of the preliminary reverse impulse (PRI) of SSCs in the subauroral region.

2. Observations

[7] We have used for this work 10-s resolution data of middle- and low-latitude stations (coverage of geomagnetic latitude, GML 20–50°) of the 210 magnetic meridian (MM) magnetometer network [*Yumoto et al.*, 1996a] archived on CD-ROMs as S-RAMP Database in Japan by the Department of Earth and Planetary Sciences, Kyushu University and Solar-Terrestrial Environmental Laboratory, Nagoya University. The stations (abbreviations) and their geomagnetic coordinates are: PTK (46.34°N, 225.91°E), MSR (37.61°N, 213.23°E), RIK (34.7°N, 210.8°E), ONW (31.65°N, 212.51°E), KAG (25.13°N, 202.24°E), DRW (23.13°S, 202.68°E), LEM (34.15°S, 185.02°E), BRV (36.58°S, 212.96°E), and CAN (45.98°S, 226.14°E). Depending on the availability of data, the conjugate (near-conjugate) station pairs are chosen for individual SSC events. Although we have used a rather low time resolution (10-s) database, the onset of the PRI is sharp enough for the PRI to be unambiguously identified in our events. Moreover, the objective of our work is to evaluate the amplitude of PRI rather than accurate timing of either its onset or arrival time (time of peak amplitude) which obviously need a higher time resolution (1-s or 3-s). We do realize that a database of 1-s or 3-s time resolution would facilitate better evaluation of the SSC waveform and its characteristics, particularly the PRI amplitude (because of its short duration

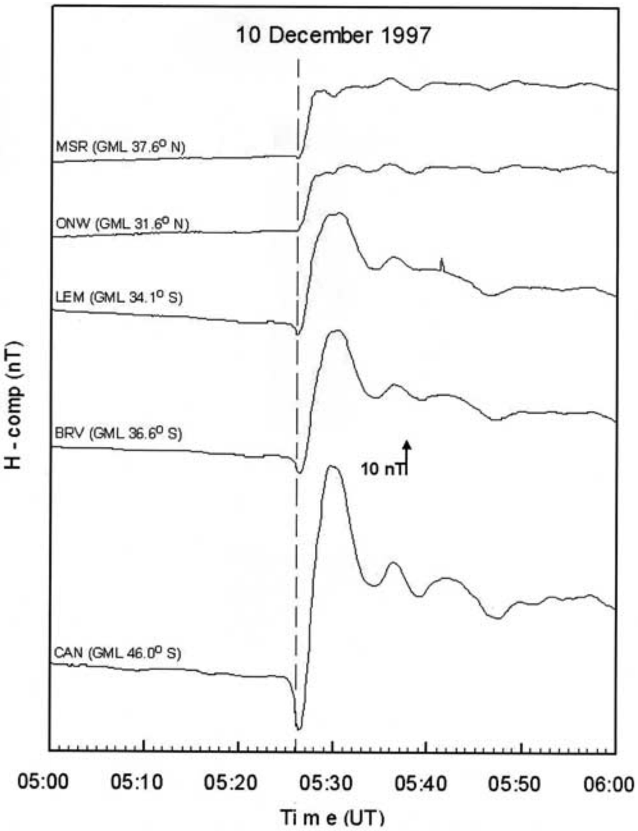

Figure 1. Waveform of the storm sudden commencement (SSC) in H-component at middle- and low-latitude stations of the 210 magnetic meridian magnetometer network in the afternoon sector (0526 UT; 1426 MLT) on 10 December 1997. The geomagnetic latitude (GML) of each station is given in brackets by the side of the station code. Note the significantly larger amplitude of the preliminary reverse impulse (PRI) at BRV corresponding to the summer hemisphere compared to MSR of the winter hemisphere.

of about 1-min), but we believe that the primary objective of the our work, namely, demonstration of the hemisphere asymmetry of PRI amplitude would not be significantly impacted by the 10 s database we relied on here.

2.1. Event of 10 December 1997

[8] This is a well-studied SSC event from the view point of its interplanetary and solar origin. It was reported to be due to an interplanetary shock at 0433 UT as observed by ACE satellite which, in turn, was assessed to be associated with the partially Halo solar coronal mass ejection (CME) that left the Sun at 1027 UT on 6 December 1997 with an initial speed of 397 km/s [*Cane and Richardson*, 2003; *Kim et al.*, 2007]. We have consulted the 1-min resolution (OMNI) data sets of solar wind plasma and magnetic field at the Earth's bow shock nose, prepared by Joe King and Natalia Papitashvili and made available in the public domain through CDAWeb (http://cdaweb.gsfc.nasa.gov), for ascertaining the solar wind conditions relevant to the SSC. The sudden increase in solar wind dynamic pressure, Pd characterizing the shock responsible of the SSC was from 1.63 nPa to 4.23 nPa (an increase of 2.6 nPa or 159 percent from the ambient). The interplanetary magnetic field (IMF) was mildly northward (2–4 nT) for an hour prior to the event and it swung southward across the Pd enhancement and maintained that orientation after the shock.

[9] Figure 1 shows the variation of H-component at the stations MSR (GML 37.61°N), ONW (GML 31.65°N), LEM (GML 34.15°S), BSV/BRV (GML 36.58°S) and CAN (GML 45.98°S) over the interval 0500–0600 UT on 10 December 1997 encompassing the SSC at 0526 UT (1426 MLT). It is quite evident from Figure 1 that a distinctive preliminary reverse impulse (PRI) preceded the main impulse (MI) at all the stations (except at the low-latitude location, ONW in the Northern Hemisphere where it is hardly visible). More importantly, there are obvious hemisphere differences in the behavior of both the PRI and MI at the magnetic conjugate stations. The PRI started at 0525:20 UT at BRV, LEM, and MSR and attained its maximum by 0526:10 UT at MSR and LEM, and by 0526:30 UT at BRV. The ratio of PRI amplitude at BRV (4.8 nT) in the summer hemisphere to that at MSR (0.8 nT) in the winter hemisphere is 6. Such a hemisphere difference is also evident at the lower-latitude station pair, LEM and ONW in that while the PRI amplitude at LEM in the summer hemisphere is 3.7 nT, the PRI is not apparent at the winter hemisphere station, ONW where the step-like increase in H-component characterizing the MI started at 0526:20 UT when, as already mentioned, the PRI either attained or approaching its peak value at BRV, LEM, and MSR. It is to be noted, however, that the geomagnetic longitudes of LEM and ONW differ by as much as 28°. And so the difference in the manifestation of the PRI at the two stations could also have a possible contribution from a magnetic local time dependence of the PRI amplitude. There is precious little information on how the equatorial PRI varies with magnetic longitude (magnetic local time) from simultaneous observations along the magnetic equator, excepting the recent effort of *Sastri et al.* [2001]. The largest amplitude of PRI (16.3 nT) is seen at the high-midlatitude location, CAN (GML 45.98°S) in the summer hemisphere, but we could not ascertain the hemisphere asymmetry at this latitude due to nonavailability of data of the conjugate station, PTK. It is pertinent and worthwhile to mention here that PRI is clearly seen with an amplitude of 6 nT in the normal run magnetograms at the dip equatorial location, Kodaikanal (dip 4°N), India in the forenoon sector (not shown here). According to the conventional understanding, such an occurrence of PRI at the forenoon dip equator simultaneous with that at higher latitudes in the afternoon is the characteristic feature of the global pattern of PRI [*Araki*, 1977, 1994].

[10] The summer-winter hemisphere dependence is also seen clearly in the manifestation of the main impulse (MI) of this SSC event as can be expected from the earlier work of *Yumoto et al.* [1996b] and *Huang and Yumoto* [2006]. The ratio of MI amplitude at BRV (39.0 nT) in the summer hemisphere to that at MSR (24.3 nT) in the winter hemisphere is 1.6 and the corresponding ratio for the stations, LEM and ONW is 1.71. The MI amplitude is reckoned from the H-component value prior to the event. These magnitudes of the amplitude ratio are compatible with the values reported earlier in the literature [*Yumoto et al.*, 1996b; *Huang and Yumoto*, 2006]. On the basis of the established

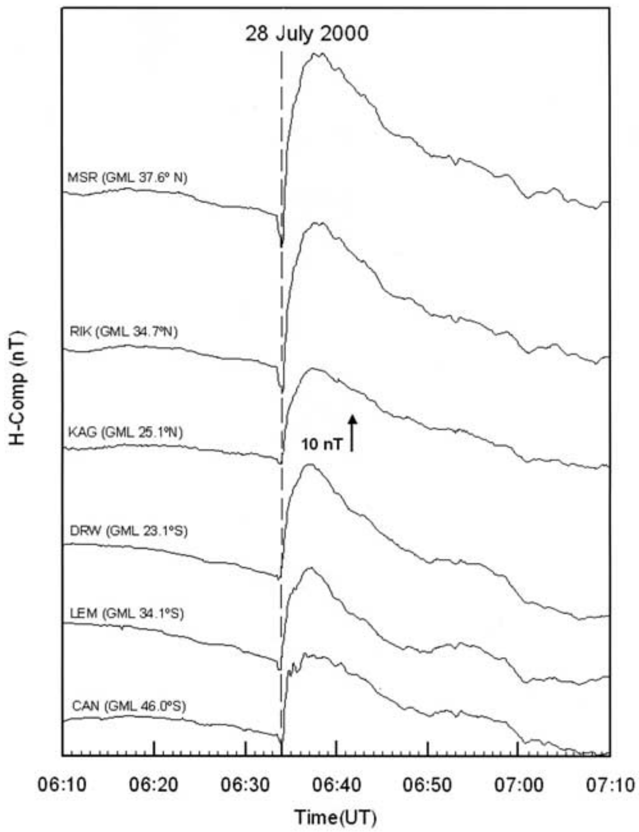

Figure 2. Same as in Figure 1 but for the SSC event at 0634 UT (1534 MLT) on 28 July 2000. Note the conspicuous difference in the manifestation of the PRI at the summer hemisphere stations, RIK and KAG, compared to their conjugate stations LEM and DRW, respectively.

empirical relationship between the change in the square root of Pd and the amplitude of ground level geomagnetic disturbances at low latitudes [*Russell et al.*, 1992; *Araki et al.*, 1993, *Huang and Yumoto*, 2006], we can expect a MI of 14.3 nT at all the stations (with GML in the range 20–40°) whose data are displayed in Figure 1. The amplitude of the main impulse (MI) at the various stations (20–39 nT) is higher than the expected (14.3 nT) and the hemisphere asymmetry of MI, though not as prominent as that of PRI, increases toward lower latitudes (compare the ratios of station pairs BRV-MSR and LEM-ONW). These observations are consistent with the prevailing view that the main impulse of SSC at middle and low latitudes receives contributions from not only FACs and ionospheric Hall and Pedersen currents associated with the twin-vortex polar current system but also the fundamental effect of magnetospheric compression that predominates at low latitudes (DL field) and while the effect of FACs decreases toward the lower latitudes that of DL field gains prominence.

2.2. Event of 28 July 2000

[11] This SSC event at 1638 UT also owes its origin to a Halo solar coronal mass ejection (CME) that left the Sun at 0330 UT on 25 July 2000 with an initial velocity of 528 km/s; the consequent interplanetary shock was detected by ACE satellite at 0542 UT on 28 July 2000 [*Cane and Richardson*, 2003; *Kim et al.*, 2007]. Consultation of the OMNI solar wind data at the Earth's bow shock nose showed that the SSC is due to a sharp enhancement of solar wind dynamic pressure (Pd) from 1.41 nPa to 4.36 nPa, an increase by 2.95 nPa (209% from the ambient level). The Bz component of IMF was steadily southward (about 7 nT) for more than an hour prior to the Pd enhancement and became more southward and oscillatory in its wake.

[12] Figure 2 shows the H-component variation at the 210MM stations from 0610 UT to 0710 UT of 28 July 2000 encompassing the SSC at 0634 UT (1534 MLT). We have included data of the stations CAN (GML 45.98°S) and MSR (GML 37.61°N) in the figure although data of the magnetic conjugate stations, namely, PTK and BRV, respectively, were not available for this event. This is done primarily to illustrate that the striking hemisphere asymmetry stands out even in these observations. It is quite evident from Figure 2 that a PRI preceded the main impulse (MI) at the midlatitude and low-latitude locations in both the hemispheres, with a general decrease in amplitude toward lower latitudes. But the more interesting point of relevance here is the significant difference in PRI amplitude between the magnetic conjugate station pairs: RIK-LEM and KAG-DRW. Like in the December solstice case, the PRI amplitude is higher in the summer hemisphere than in the winter hemisphere. The ratio of PRI amplitude at RIK (8.6 nT) to that at LEM (2.5 nT) is 3.44 while that for the station pair KAG-DRW, the corresponding value is 1.7. The impressive hemisphere asymmetry can also be gauged from the fact that the PRI amplitude (10.0 nT) at MSR (GML 37.6°N) in the summer hemisphere is higher than its value (4.9 nT) at CAN (GML 45.98°S), and keeping in mind that, in any hemisphere, the PRI in general gains in amplitude and becomes more prominent as one moves from middle to high midlatitude locations on the same meridian. This behavior can clearly be seen in the PRI signature at the various stations depicted in Figure 2. The PRI is also evidenced (not shown here) at the dip equatorial stations on the dayside, CEB (geomagnetic coordinates 0.50°N, 209.69°E) and DAV (geomagnetic coordinates 1.32°S, 196.79°E) of the Circum-pan Pacific Magnetometer Network (CPMN) corresponding to the magnetic local time (MLT) interval 1453–1459 h.

[13] As can be expected, the hemisphere asymmetry of the main impulse (MI) is also seen in this SSC event. The amplitude of MI at RIK (44.4 nT) is larger than at LEM (28.8 nT) by a factor of 1.54. Though the stations MSR and CAN are not exactly a magnetic conjugate pair, the MI amplitude is substantially higher at MSR (49.9 nT) when compared to CAN (24.3 nT), a station at a higher magnetic latitude than MSR but in the opposite hemisphere. The summer-winter hemisphere asymmetry of the MI is, however, not apparent at the low-latitude station pair KAG-DRW where, in fact, the MI is larger in the winter hemisphere at DRW (34.3 nT) than at KAG (27.6 nT) in the summer hemisphere, and the amplitude ratio (KAG/DRW) is 0.8. Much like for the December solstice event, the MI amplitude at the various stations are also higher than the value of 16.6 nT expected for this SSC event, based on the well-known empirical relationship between the change in the square root of Pd and the magnitude of low latitude

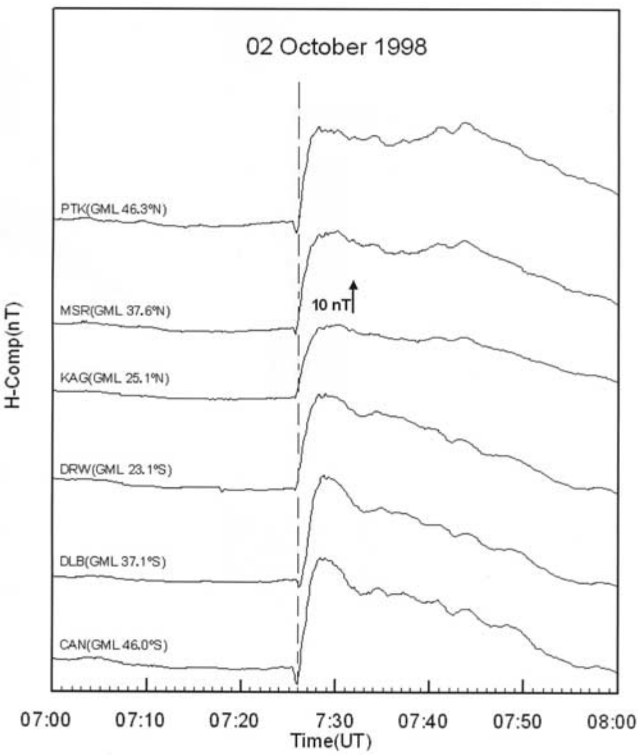

Figure 3. Same as in Figure 1 but for the SSC event at 0726 UT (1626 MLT) on 2 October 1998. The north-south asymmetry of moderate strength may be seen in the PRI amplitude at the magnetic conjugate station pairs: PTK-MSR, MSR-BRV, and KAG-DRW.

ground level geomagnetic disturbance [*Russell et al.*, 1992; *Araki et al.*, 1993].

2.3. Event of 2 October 1998

[14] From a scrutiny of OMNI solar wind data corresponding to the nose of Earth's bow shock, we associate this equinox SSC event with a sudden increase in solar wind dynamic pressure, Pd by 3.02 nPa (enhancement by 196 percent from the preevent level). The IMF Bz component fluctuated around low values at and around the Pd enhancement. Fortunately for this SSC event, data of all the three magnetic conjugate station pairs, PTK-CAN, MSR-DLB and KAG-DRW are available, and these are graphed in Figure 3 in the same format as of Figures 1 and 2, for a 1-h interval encompassing the SSC at 0726 UT. The presence of a hemisphere asymmetry in the amplitude of both the PRI and MI is quite evident in Figure 3 but it is only of moderate strength (for both PRI and MI) when compared to the solstice events presented earlier. To give the details, the PRI amplitude is 5.7 nT at the southern hemisphere station, CAN and this is larger by a factor of 1.22 than the value of 4.4 nT at the magnetic conjugate station, PTK in the northern hemisphere. The corresponding value of the amplitude ratio for the stations DLB/MSR and DRW/KAG is 1.22 and 3.0, respectively. The high value of the ratio for the station pair DRW-KAG is, however, to be treated with some caution because of the small value of PRI amplitude at the two stations (see Figure 3) and the low time resolution (10-s) of our database. For the sake of completeness, we record here that the PRI was also evidenced (not shown here) at the dip equatorial stations, CEB (geomagnetic coordinates 0.85°N, 195.27°E), DAV (geomagnetic coordinates 1.32°S, 196.79°E) and YAP (geomagnetic coordinates 0.5°N, 209.69°E) of the Circum-pan Pacific Magnetometer Network (CPMN) covering the magnetic local time (MLT) interval from 1544 h to 1642 h. The main impulse (MI) of this equinox event also exhibited a hemisphere asymmetry with higher amplitude at southern hemisphere locations compared to their magnetic conjugate locations in the northern hemisphere. The amplitude ratio for the three station pairs varied in the range 1.11–1.33 for the main impulse. We have documented this event primarily to emphasize that the hemisphere asymmetry of PRI is not exclusive to the solstices though it seems to be only of moderate strength at the equinox.

3. Discussion and Conclusions

[15] We have presented 210MM magnetometer network observations to show that the preliminary reverse impulse (PRI) of ground level SSC at middle latitudes of the afternoon sector manifests with a significantly larger amplitude in the summer hemisphere than in the winter hemisphere. This hemisphere asymmetry of PRI is seen in all seasons (solstices and equinox) and is essentially of the same nature as that of the main impulse (MI) which is well-known. The hemisphere asymmetry is seen however more prominently with the preliminary reverse impulse (PRI) than with the main impulse in individual events of the present study.

[16] The sudden magnetospheric compression induced by the sharp increase of solar wind dynamic pressure launches compressional waves which during their passage in the inhomogenous magnetosphere generate shear Alfven waves that drive field-aligned currents (FACs) into the polar ionosphere. The FACs are directed inward on the dusk side and outward on the dawn side at latitudes around 70°. According to the phenomenological SSC model developed by *Araki* [1977, 1994] based on the original ideas of *Tamao* [1964a] and synthesis of extensive observational results, the global characteristics of the PRI (marked local time and latitude dependence of polarity and amplitude) are the outcome of the generation of FACs and the dusk-to-dawn magetospheric electric field which they map on to the polar ionosphere where it excites a global twin-vortex type ionospheric current system. The current vortex is counterclockwise in the forenoon and clockwise in the afternoon, causing thereby an increase and decrease, respectively, in ground level H-component at high latitudes in the Northern Hemisphere, as observed. The study of *Lukianova* [2003] showed that sudden increases of solar wind dynamic pressure lead to an initial negative spike before the main increase in the polar cap (PC) index which is a measure of the magnetic disturbance caused by the transpolar portion of the ionospheric currents related to global convection.

[17] The negative spike (duration about 3 min) in PC index indicates a rapid response of convection to abrupt changes in solar wind dynamic pressure due to development of short-lived current vortices in the ionosphere near noon.

[18] The dusk-to-dawn large scale electric field imposed on the polar ionosphere penetrates instantaneously to the dayside dip equator at the speed of light in the Earth-ionosphere waveguide and, though suffering geometrical attenuation with decrease of latitude, generates appreciable westward ionospheric currents at the dayside dip equator due to enhanced Cowling conductivity that prevails there [*Kikuchi et al.*, 1978; *Kikuchi and Araki*, 1979]. This conventional interpretation of the PRI is supported by HF Doppler observations of ionospheric vertical plasma motions (proxy of zonal electric fields) at midlatitudes and at the dip equator [*Kikuchi et al.*, 1985; *Kikuchi*, 1986; *Sastri et al.*, 1993]. The most recent study of (near) simultaneous SSC waveform at ground level and by Oersted satellite (above the ionosphere) provided further evidence for the presence of a westward ionospheric current at the dayside dip equator at the time of PRI [*Han et al.*, 2007].

[19] As mentioned in the introduction section, the propagation mechanism of PRI from high to low latitudes has become a subject of some debate in recent times [*Kikuchi and Araki*, 2002; *Chi et al.*, 2002]. This situation arose following the work of *Chi et al.* [2001] wherein they found in a case study that the travel time (time of peak amplitude) of the PRI is not exactly the same at all latitudes as can be expected from the conventional SSC model [*Araki*, 1977, 1994] but follows a "zig-zag" latitudinal pattern. These authors interpreted the differentiation of the travel time of PRI with latitude, especially the sharp jump in travel time across the plasmapause latitude as the direct effect of MHD wave propagating right from the source point in the subsolar magnetopause to the ground locations at different latitudes, based on model calculations of the MHD travel time following the ideas of *Tamao* [1964b]. *Chi et al.* [2001] therefore opined that there is no need to invoke the Earth-ionosphere waveguide mode for the low latitude propagation of the PRI. This work had been commented upon by *Kikuchi and Araki* [2002] and replied to by *Chi et al.* [2002].

[20] The recent MHD simulations of *Chi et al.* [2006] of the propagation of the sudden impulse (SI) signal in the three-dimensional magnetosphere do show the development of short-lived twin-vortex type ionospheric current system at high latitudes as originally proposed by *Tamao* [1964a], and a latitude-dependent travel time as observed by *Chi et al.* [2001] as well as a latitude-independent onset time of the sudden impulse as observed in many earlier studies [see *Araki*, 1977, 1994]. This rendered the MHD wave propagation model as an alternative to the conventional SSC model for the low-latitude PRI. Since *Chi et al.* [2001] could not make an assessment of the efficacy of MHD wave propagation in producing the equatorial PRI due to unavailability of equatorial data for the SSC event studied by them, they expressed the need to explore further whether the equatorial PRI and the low-latitude counterparts as evidenced in their case study share the same MHD propagation mechanism or not. We are not aware of any subsequent results in the literature bearing on this question.

[21] Against the backdrop of the currently unsettled status of the origin of the preliminary reverse impulse (PRI) at low latitudes, we hold the view that the conventional paradigm of invoking the electric circuit comprising of FACs and ionospheric currents offers a possible explanation, though highly qualitative, of the summer-winter hemisphere asymmetry of afternoon PRI at midlatitudes. *Kikuchi et al.* [2001] calculated the ground magnetic effects of stationary FACs and ionospheric currents incorporating realistic representations of ionospheric conductivity including its north-south (seasonal) asymmetry using the numerical model of *Tsunomura* [1999]. Their results showed that at midlatitudes (GML 35°) the net effect of FACs and ionospheric currents is positive during most of the daytime in the winter hemisphere, while it is positive only in the forenoon in the summer hemisphere. This provided an explanation for their statistical result derived from a study of 46 well-defined preliminary positive impulses (PPIs) at Memambetsu (GML 34.93°N) in the Japanese sector, namely, the exclusive occurrence of afternoon PPIs in local winter, with no such seasonal dependence in the occurrence of morning PPIs. On the other hand, the earlier statistical study of the preliminary impulse (PI) at Fredericksburg, FRD (GML 49.0°N) in the American sector based on 462 SSC events spread over the period 1957–1975 showed that (1) the preliminary impulse manifests predominantly (about 70 percent of the time) as PPI in the forenoon and as PRI in the afternoon and this local time pattern of the polarity of the preliminary impulse persists in all the seasons and (2) the local time pattern of PI occurrence is symmetric around noon while the model calculations of the effect of the stationary current systems predict an asymmetric distribution of PI occurrence around noon [*Yamada et al.*, 1997]. These robust statistical results and their disagreement with the predictions based on the conventional paradigm raised questions about the validity of the concept of stationary current systems and ignoring of the induction electric fields associated with rapidly varying ionospheric current systems in explaining the characteristics of midlatitude PRI. The most recent study of *Takeda* [2008], in fact, demonstrated that the induction electric field affects the ionospheric current system driven by FACs of magnetospheric origin on timescales less than 4 min as is the case with the PRI of SSC and renders the ionospheric current system symmetric with noon, a result that is consistent with the local time variation of the preliminary impulse (PI) at midlatitudes derived by *Yamada et al.* [1997]. The inadequacy of the conventional SSC model is also apparent in the noteworthy difference between the observed amplitude of ground level vertical electric field and that predicted by the model, as highlighted by *Yamada et al.* [1997] and *Chi et al.* [2001, 2002].

[22] The calculations of *Kikuchi et al.* [2001] indicate a hemisphere dependence of the polarity of the preliminary impulse in the afternoon sector at midlatitudes: it is to be a positive impulse (PPI) in the winter hemisphere and a negative impulse (PRI) in the summer hemisphere. In contrast, what is evidenced in the case studies presented here is that the preliminary impulse manifests as a PRI in both the hemispheres but with a larger amplitude in the summer hemisphere than in the winter hemisphere. This behavior in deviation to the model prediction is perhaps a moderate form of the hemisphere asymmetry suggested by the work of *Kikuchi et al.* [2001], in that the combined negative effect of Hall and Pedersen currents is able to overcome the positive effect of FACs to result in a PRI in

both the hemispheres but more effectively so in the summer hemisphere than in the winter hemisphere, leading to the hemisphere asymmetry. If the magnetospheric current source is a voltage generator instead of a current generator [*Tsunomura*, 1999], then, the higher conductivity in the summer hemisphere would enable the ionospheric currents to oppose the effect of FACs more effectively in that hemisphere than in the winter hemisphere, thereby leading to the hemisphere asymmetry of the PRI.

[23] The hemisphere asymmetry of PRI may also be understood in terms of the MHD wave propagation model. The current resulting from the electric field associated with the MHD waves is stronger when the ionospheric conductivity is higher as it would be the case in the summer hemisphere compared to the winter hemisphere, resulting in a hemisphere asymmetry of PRI amplitude as observed. It is worth mentioning in this context that *Han et al.* [2007] also opined that the westward ionospheric current during the period of the PRI at the dayside dip equator can be explained in terms of both the conventional SSC model and the MHD wave propagation model. It is appropriate to mention here that there are other factors that may also contribute to the observed hemisphere differences in PRI amplitude at midlatitudes. The first one is the tilt of the discontinuity in solar wind dynamic pressure with reference to the normal of the X-direction. If the location of impact of the solar wind discontinuity is off the equator because of its tilt, then the PRI signal would be stronger in that hemisphere of the impact. The second factor is the ground conductivity which may play a role because the ground level manifestation of the PRI signal is the magnetic induction of ionospheric currents. If there are to be significant differences in the ground conductivity between conjugate locations, this would reflect in the PRI signal amplitude in the two hemispheres. It is imperative that further work is necessary to assess the efficacy of the possible physical mechanisms and factors mentioned and gain an improved understanding of the characteristics of preliminary reverse impulse (PRI) of storm sudden commencements (SSC) in the subauroral region in their entirety.

[24] It also remains to be assessed whether the summer-winter hemisphere asymmetry of the preliminary reverse impulse (PRI) reported for the first time here represents the typical or atypical behavior of midlatitude SSCs in the afternoon sector through a systematic study of the extensive database of MM210 magnetometer network. It is worth mentioning in this context (pending the outcome of a specific search) that we did come across in the MM210 magnetometer network database some midlatitude SSC events of the afternoon sector with a noteworthy summer-winter hemisphere asymmetry of its preliminary reverse impulse (PRI). Good examples are the SSC events at 0638 UT (1538 MLT) on 10 July 2000, at 0716 UT (1616 MLT) on 3 August 2001, and at 0531 UT (1431 MLT) on 28 November 2000. Moreover, it is fortuitous indeed that both of the solstice SSC events discussed here as well as the event of 10 July 2000 are due to interplanetary shocks driven by Halo solar coronal mass ejections (CME). This raises the interesting query whether the characteristics of ground level SSCs in the subauroral region bear any systematic relationship to the solar origin of the causative IP shocks. This new and interesting dimension deserves to be probed.

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