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Key Points:

- Ten sequential traveling atmospheric disturbances (TADs) observed over 2 days
- TADs linked to multiple Bz<0 occurrences in solar wind
- Origins involve six successive and interacting CMEs

Supporting Information:

- Figure S1

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Prolonged multiple excitation of large-scale Traveling Atmospheric Disturbances (TADs) by successive and interacting coronal mass ejections

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Abstract Successive and interacting coronal mass ejections (CMEs) directed earthward can have significant impacts throughout geospace. While considerable progress has been made in understanding their geomagnetic consequences over the past decade, elucidation of their atmospheric consequences remains a challenge. During 17–19 January 2005, a compound stream formed due to interaction of six successive halo CMEs impacted Earth's magnetosphere. In this paper, we report one atmospheric consequence of this impact, namely, the prolonged multiple excitation of large-scale (>∼1000 km) traveling atmospheric disturbances (TADs). The TADs were effectively excited in auroral regions by sudden injections of energy due to the intermittent southward magnetic fields within the stream. They propagated toward the equator at speeds near 800 m/s and produced long-duration (∼2.5 days) continuous large-scale density disturbances of order up ± 40% in the global thermosphere.

1. Introduction

Coronal mass ejections (CMEs) are violent expulsions of mass and magnetic field from the solar corona. Interactions between two or more CMEs launched in close succession have been recognized as a frequent phenomenon in interplanetary space [e.g., *Gopalswamy et al.*, 2001; *Reiner et al.*, 2003; *Shen et al.*, 2012; *Lugaz et al.*, 2012]. Interacting CMEs probably form a complex structure, being either complex ejecta with irregular intrinsic magnetic fields as defined by *Burlaga et al.* [2001, 2002] or multiple magnetic clouds (multi-MCs) as identified by *Wang et al.* [2002, 2003]. Complex structures formed en route from the Sun to the Earth can have very important geospace consequences, owing to the compressed and enhanced southward magnetic fields. Moreover, their larger physical sizes and prolonged durations (up to ∼ 4 days) can help to sustain geoeffective interplanetary conditions. When they encounter the Earth, magnetic reconnection between the intermittent southward magnetic fields and Earth's northward directed magnetopause magnetic field allows energy and momentum to be transferred into the magnetosphere from the solar wind in multiple steps, typically leading to a multiple-step geomagnetic storm and pulsating high-latitude ionospheric convection. It has long been known that sudden enhancement of ionospheric convection, and thus Joule heating and Lorentz forcing, can excite gravity waves in auroral regions [*Richmond*, 1978], and in turn give rise to traveling atmospheric disturbances (TADs) [e.g., *Mayr et al.*, 1990; *Forbes et al.*, 1995, 2005; *Bruinsma and Forbes*, 2010; *Guo et al.*, 2014, 2015]. Thus, one would theoretically expect that distinct sequential TADs can be excited over prolonged periods (>2 days) during passage of a complex structure or a compound stream.

Prior studies of TADs have mainly been performed in a thermosphere context, that is, the observation or calculation of TAD propagation based on specification of a variable source function, often as simple as correlating TAD occurrence with a sudden increase in a geomagnetic index such as *Kp*. The paper by *Bruinsma and Forbes* [2010] is a good example, wherein examination of wave-like structures in thermosphere neutral densities for days with $\delta Kp \geq 3$ provides insight into the characteristics of TADs. Recent studies of TADs suggested

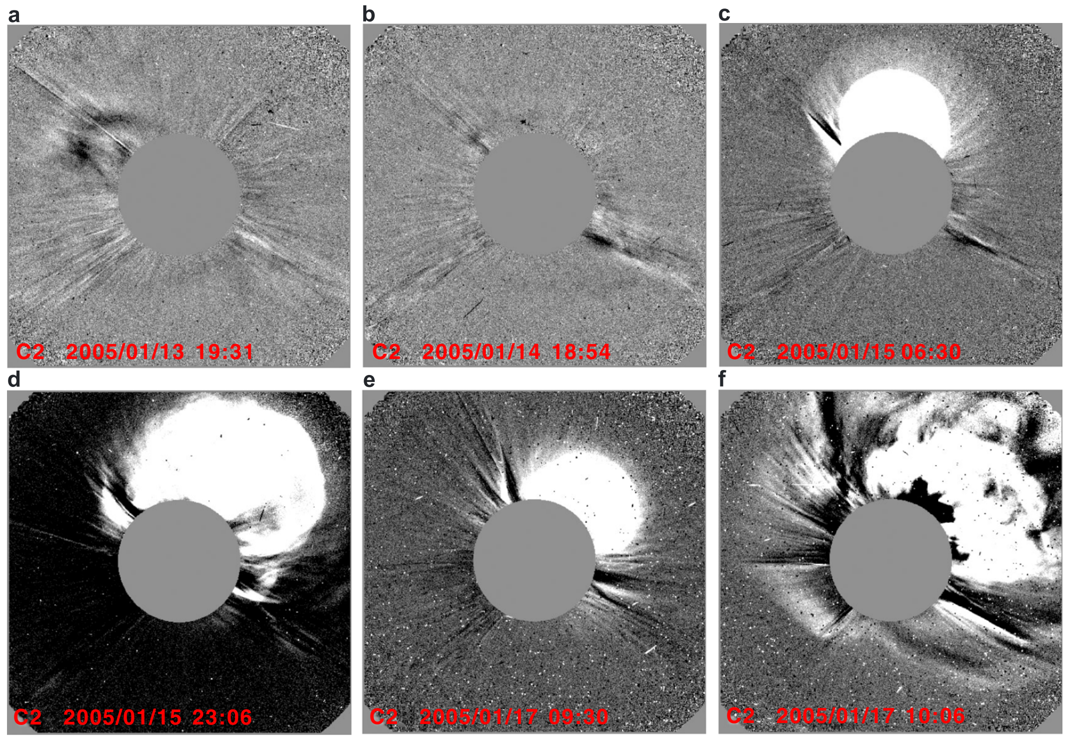

Figure 1. LASCO/C2 difference images of six full halo CMEs during 13–17 January 2005.

their excitations are clearly associated with various transient solar wind structures [*Guo et al.*, 2014, 2015]. The present paper is distinguished from prior studies in that we employ assets such as SOHO, WIND, ACE, CHAMP, and GRACE to understand linkages originating at the Sun and occurring within the solar wind, between the solar wind and magnetosphere, and between the magnetosphere and thermosphere-ionosphere, to achieve a solar-terrestrial *system* view of the origins of TADs in the thermosphere. Specifically, we report here, for the first time to our knowledge, observations of prolonged multiple large-scale (>∼1000 km) TADs excited by a compound stream formed due to interaction of six successive halo CMEs. These events occurred during the period 17–19 January 2005.

2. Observations and Analysis

During 13–17 January 2005, six successive full halo CMEs were observed by SOHO/LASCO [*Brueckner et al.*, 1995] as shown in Figure 1. The SOHO spacecraft was in a halo orbit around the Earth-Sun L1 Lagrange point with an orbital radius of ∼100 R_E. Table 1 presents each event with its first appearance in LASCO/C2, projected speed, measurement position angle (MPA), and the associated flare activity, with reference to the SOHO/LASCO catalog (http://cdaw.gsfc.nasa.gov/CME_list) [*Yashiro et al.*, 2004] and the Solar Geophysical Data listing (https://www.ngdc.noaa.gov/stp/solar/sgd.html). All six CMEs (hereinafter referred to CME1, CME2, etc.) originated from regions close to the central meridian on the visible solar disk. Overtaking and interacting between them might occur en route from the Sun to Earth. It should be noted that although all six CMEs are

Table 1. Successive Full Halo CMEs During 13–17 January 2005

ID	Date	Time	Speed (km/s)	MPA (deg)	Flare Class	Location	AR	Counterpart near 1 AU
1	2005/1/13	17:54	495	97	C4.2	S06E14	10718	MCLS1
2	2005/1/14	17:06	358	238	M1.0	S06E02	10718	MCLS2
3	2005/1/15	06:30	2049	359	M8.6	N11E06	10720	A component of Complex Ejacta
4	2005/1/15	23:06	2861	323	X2.6	N14W08	10720	A component of Complex Ejacta
5	2005/1/17	09:30	2094	334	X2.2	N13W19	10720	Ejecta
6	2005/1/17	09:54	2547	309	X3.8	N15W25	10720	MC

classified as full halo ones, not all of them are well Earth directed. From SOHO/EIT [*Delaboudinière et al.*, 1995] (not shown here) and LASCO/C2 difference images (Figures 1c–1e), one can easily recognize that CME3, CME4, and CME5 are inclined toward the north and looked more likely limb CMEs with much wider shocks. For those CMEs, their shocks and/or flanks rather their main bodies probably pass through the Earth.

Figure 2 shows the corresponding solar wind plasma (with data gap) and magnetic field observations from the WIND spacecraft and plasma composition observations from the ACE spacecraft near 1 AU for the period 16–20 January 2005. At the time of these measurements, WIND was located upstream from the Earth at about $(1.64, -0.06, 0.12) \times 10^6$ km and ACE was located upstream from the Earth at about $(1.42, -0.23, 0.14) \times 10^6$ km in GSE coordinates. On 16–17 January, two MC-like structures (MCLS1 and MCLS2), presumably in situ counterparts of CME1 and CME2 separately, can be identified by the smooth and enhanced magnetic field, low proton temperature and low proton β. In the region between MCLS1 and MCLS2, the magnetic field became less regular, proton β increased to a high level (>1.0), and solar wind speed increased slightly, indicating that interaction between MCLS1 and MCLS2 might have occurred [*Wang et al.*, 2003]. A weak shock (Shock1), driven by CME3 or CME4, was propagating into MCLS2. The proton density, temperature, and magnetic field strength within the sheath region behind Shock1 were significantly enhanced and followed by a complex ejecta, which is characterized by the complicated and enhanced magnetic field, enhanced proton density, high Fe charge state (>12) [see *Lepri and Zurbuchen*, 2004], and elevated elemental abundance ratio Fe/O. The complex ejecta are probably formed by CME3 and CME4. As mentioned above, CME3 and CME4 were not directed right toward the Earth; only their shocks and flanks encountered the Earth, and therefore, no MCs but complex ejecta were observed. Following the complex ejecta, another shock (Shock2) could be recognized by the small jumps in the density and magnetic field strength though there are data gaps in the velocity and temperature. The shock was probably driven by CME5, which was fast enough but not well observed at the Earth due to its north inclined propagation direction. After Shock2, the relatively enhanced and fluctuating magnetic field and anomalous composition signatures, such as elevated oxygen charge state ratio O^{7+}/O^{6+} (>1) [see *Henke et al.*, 2001], high Fe charge state (>12), and enhanced elemental abundance ratio Fe/O, suggest the presence of an ejection, which may be the flank of CME5. The boundary between the shock sheath and the ejecta cannot be distinguished. Following the ejecta, an MC associated with CME6 could be well defined. Its signatures include the enhanced magnetic field strength, smooth rotation of magnetic field direction, declining velocity profile, bidirectional streaming of suprathermal electrons, low proton temperature, and low proton β [*Burlaga et al.*, 1981]. According to the LASCO observations, CME3-6 are all faster than 2000 km/s, which suggest that they will arrive at 1 AU no later than 19 January, even if the deceleration of the CMEs in interplanetary space is considered. Thus, the strong enhancement in the density on 20 January was caused by another event. Overall, the in situ observations at 1 AU show a compound stream formed by six successive and interacting CMEs.

During the Earth passage of this compound stream, the intermittent southward magnetic field (Figure 3a) led to multiple momentum and energy injections into geospace from the solar wind via magnetic reconnection at the magnetopause, and in turn gave rise to a multiple-step geomagnetic storm (Figure 3b) and impulsive auroral electrojet intensifications (Figure 3c). Sudden increases in Lorentz force and/or Joule heating are known to excite gravity waves in auroral regions, as well as large-scale TADs (each consisting of packets of gravity waves). Figure 3d illustrates the TADs excited within the present study interval, as revealed in thermosphere neutral densities near 400 km and near 0800/2000 local time derived from CHAMP accelerometer measurements (for details of CHAMP measurements and data processing refer to *Sutton* [2011]). It is surprising to note that the TADs are continuously present throughout the compound stream interval on both the dawn and dusk sides; i.e., before one TAD is dissipated, another one or more TADs are generated. In the form of density maxima progressing equatorward with time (magenta arrows), a series of TADs are seen to be launched from northern and southern auroral regions, to the equator, and often penetrating into the opposite hemisphere and sometimes the opposite polar region (Note that the orbit-by-orbit 90 min sampling makes it difficult to distinguish the more wavelike disturbances underlying the TADs and thus to unambiguously track them). It seems that these TADs are associated with 10 (from the second to the eleventh, as indicated in Figure 3) impulsive auroral electrojet intensifications, implying prolonged multiple excitation of large-scale TADs by pulsating ionospheric convection (auroral electrojet) associated with intermittent southward magnetic fields within the stream.

A filtering procedure is applied to densities measured along the orbit to elucidate the propagation characteristics of large-scale TADs. Specifically, we calculate 250 and 1510 s running means and then subtract 1510 s

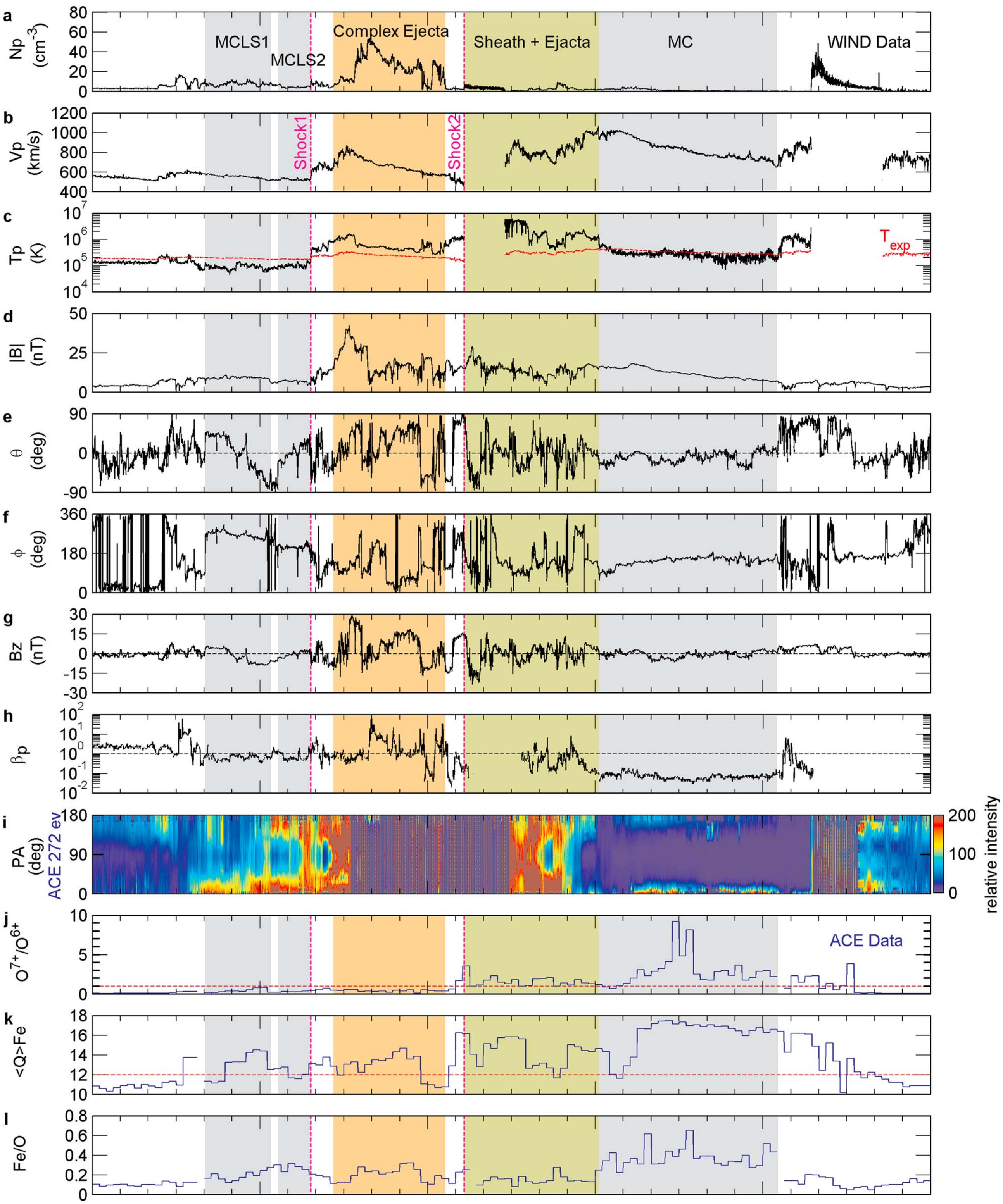

Figure 2. Solar wind parameters observed by WIND and ACE during 16–20 January 2005. From top to bottom: (a) proton density, (b) bulk speed, (c) proton temperature overlaid with the expected temperature (dotted curve) from the observed speed, (d) magnetic field strength, (e) elevation and (f) azimuthal angles of field direction in GSE coordinates, (g) Bz component in GSM coordinates, (h) proton β, (i) electron pitch angle, (j) oxygen charge state ratio, (k) average iron charge state, and (l) elemental abundance ratio Fe/O. The shaded regions indicate the ejecta and complex ejecta intervals, and the vertical dashed lines mark the associated shocks.

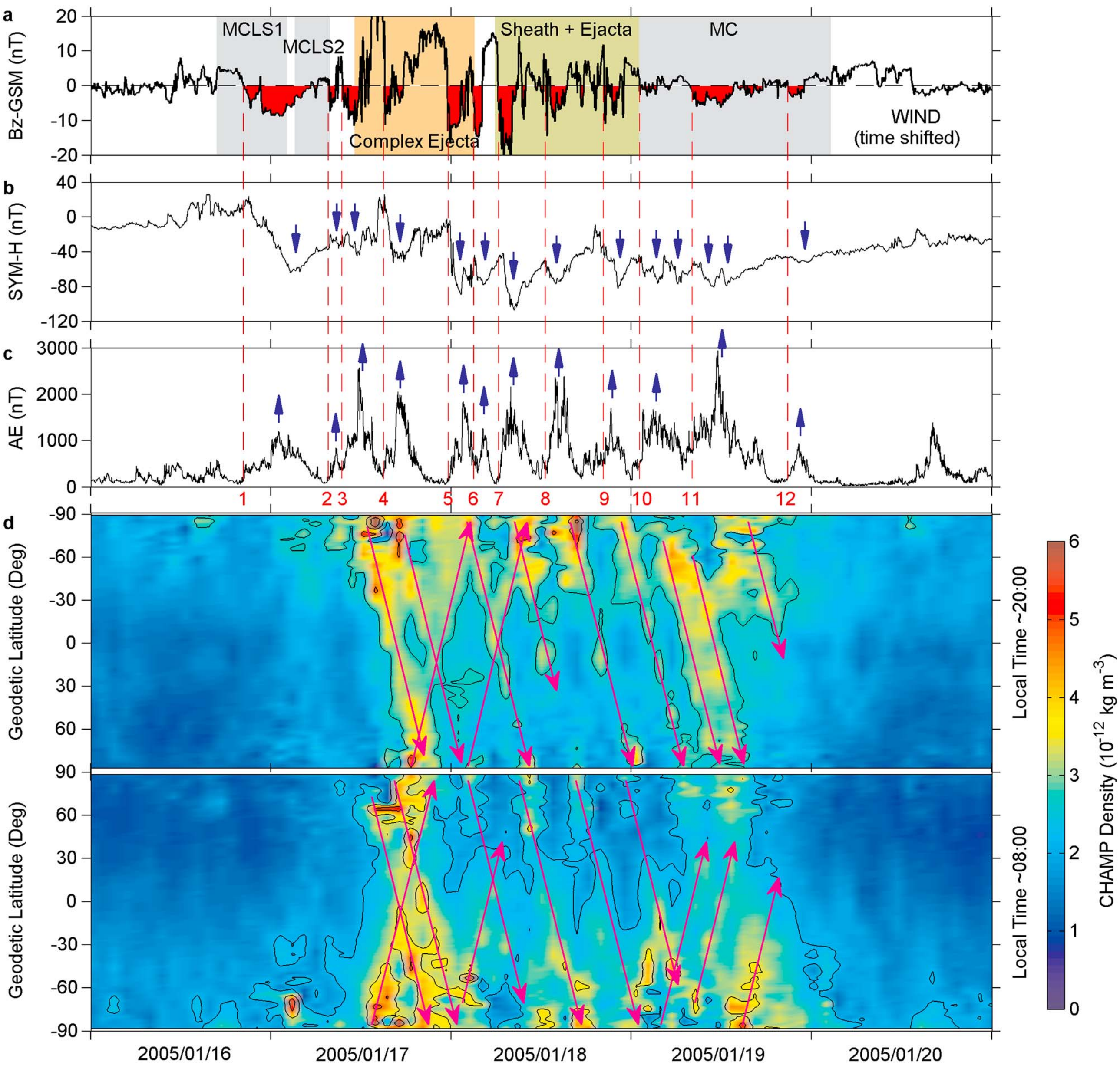

Figure 3. Variations of (a) WIND magnetic field Bz component (shifted 35 min to the nose of the magnetopause) in GSM coordinates, (b) ring current index SYM-H, (c) auroral activity index AE, and (d) CHAMP neutral density at 400 km and near (top) 2000 LT (latitude axes in reversed order) and (bottom) 0800 LT during 16–20 January 2005. The shaded regions in Figure 3a correspond to the identified ejecta and complex ejecta intervals. The dashed vertical lines show the one-to-one correspondence between Bz southward intervals (red shaded regions), SYM-H decreases (one or two major dips indicated by downward arrows), and AE increases (indicated by upward arrows). The magenta arrows in Figure 3d show large-scale density disturbances propagating from the auroral sources to the equator and into the opposite hemisphere.

running means from 250 s running means, effectively performing a band-pass filter. Given an approximate satellite velocity of 7.5 km/s, this procedure effectively isolates horizontal scales between about 1000 and 6000 km [see *Bruinsma and Forbes*, 2010 and *Guo et al.*, 2014, for more details]. The relative density variations obtained from the above procedure are displayed in Figure 4. The positive density enhancements progressing equatorward with time, marked by the magenta arrows, indicate the presence of large-scale TADs. It is important to note that the alternation of density enhancements and depressions often served as a signature of gravity waves or TADs were not unambiguously tracked on consecutive orbits due to the limited temporal sampling, approximately 93 min. Long-duration (~2.5 days) continuous large-scale TAD activity is clearly evident, as expected from Figure 3. These TADs propagated toward the equator at speeds near 800 m/s and produced large-scale density disturbances of order up ± 40% in the global thermosphere. Their propagation

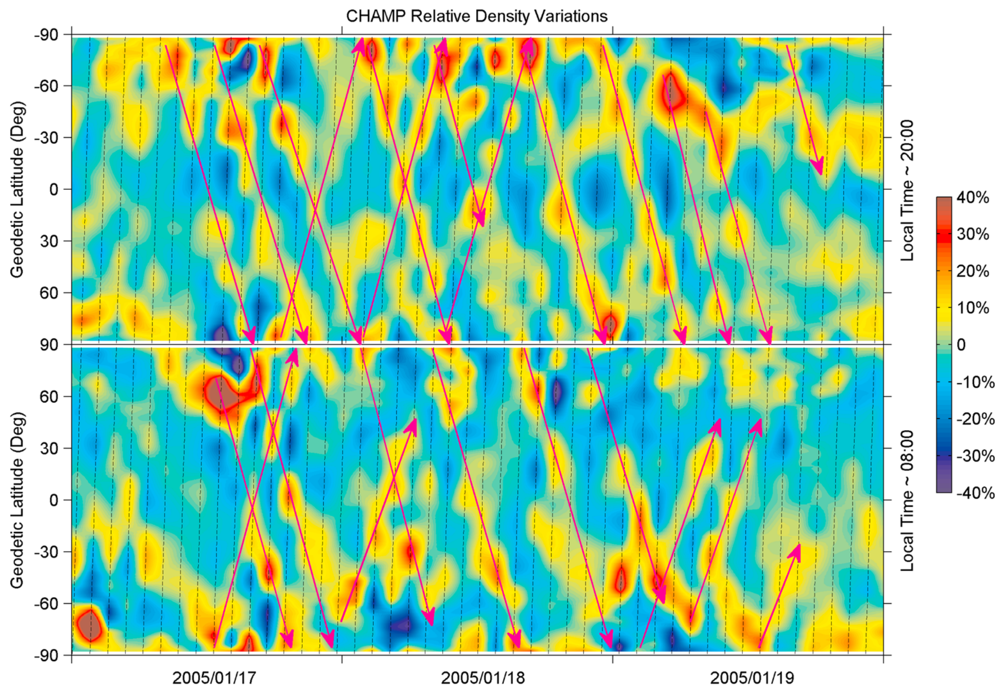

Figure 4. Latitude versus time variations of the filtered relative density at 400 km and near (top) 2000 LT (latitude axes in reversed order) and (bottom) 0800 LT during 17–19 January 2005. The parallel dashed lines represent the orbital track of the CHAMP satellite. The measurements are confined to the orbital tracks, and the interorbital density structures arise from linear interpolation. The magenta arrows show the large-scale TADs propagating to the equator and into the opposite hemisphere (see the details in the text).

shows no noticeable differences between dawnside and duskside. Note that several assumptions have been made in estimating the phase speeds: (1) The TADs propagate toward the equator with a ring-like longitudinal extension; (2) The satellite tracks are normal to the phase fronts of the TADs; and (3) The phase speeds are independent of longitude sampling of the satellite. According to *Bruinsma and Forbes* [2010], these assumptions tend to either underestimate or overestimate the phase speeds up to ± 10%. The large-scale TADs are generally believed to consist of large-scale gravity waves [e.g., *Hedin and Mayr*, 1987; *Mayr et al.*, 1990; *Forbes et al.*, 1995, 2005], which propagate quasi-horizontally in the thermosphere at velocities close to the sound speed and are influenced by the Coriolis force [*Maeda and Handa*, 1980]. These large-scale waves can propagate over large distances in the thermosphere [see *Guo et al.*, 2015] before being dissipated by molecular viscosity, thermal conduction, ion drag, nonlinear saturation, and radiative damping.

The long-duration continuous large-scale TAD activity was simultaneously detected by the GRACE-A and GRACE-B satellites, which were in near-polar 0630/1830 local time orbital plane, i.e., 1.5 h apart from CHAMP orbital plane. The propagation characteristics inferred from GRACE observations, including phase speeds, amplitudes and horizontal distances traveled, are very close to those inferred from CHAMP observations. To avoid repetition, the GRACE observations are not displayed here but are included in an auxiliary file.

3. Conclusions

We have presented the observations of long-duration (~2.5 days) continuous large-scale TAD activity during the Earth passage of a compound stream formed by interaction of six successive halo CMEs. The TADs were effectively excited in auroral regions by sequential sudden increases ionospheric convection (and thus Joule heating and Lorentz forcing) associated with intermittent southward magnetic fields within the stream. After being launched at auroral regions, they propagated toward the equator at speeds near 800 m/s and penetrated into the opposite hemisphere, giving rise to large-scale traveling density disturbances of order up ± 40% in the global thermosphere. Some TADs reached auroral/polar regions in the opposite hemisphere. This example represents the first recognized instance of prolonged multiple excitation of large-scale TADs by successive and interacting CMEs. The results enrich our understanding of the pathways through which the thermosphere responds to successive and interacting CMEs.

Acknowledgments
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