

1 Reply to Review Comments

2
3 Dear Editor,

4 Thank you very much for reviewing this manuscript, and thank the anonymous reviewer for the
5 second round of review.

6 We did our best to revise the manuscript according to the review comments. We proofread
7 our manuscript carefully, and corrected some errors of the word and grammar. We also revised
8 some confusing statements.

9
10 Our replies to the 2 detailed comments are as follows.
11

12 Comment 1

13 Lines 15-17: The text which talks about trough and crest. I suggest that the authors modify
14 the statement to “Results show a LSTID spanning at-least 60 degrees in longitude (60°
15 E-140°E) occurs as a result of possibly AGWs propagating from high to lower latitudes
16 around 09:40 UT-?? ... (here the end time should also cover the crest of the LSTID)”
17

18 Reply 1

19 Thank you very much!

20 According to this comment, the statement in the manuscript

21 “Results show that a trough of LSTID spanning at least 60° in longitude (80°E-140°E) occurs
22 and propagates from high to lower latitudes around 09:40-11:20 UT. It is followed by a crest of
23 LSTID which shows a tendency of dissipation starting from the East side.”

24 is revised to:

25 Page 3, Lines 14-17: “Results show an LSTID spanning at least 60 degrees in longitude
26 (80°E-140°E) occurs as a result of possibly AGWs propagating from high to lower latitudes
27 around 09:40-11:40 UT, and the crest of this LSTID shows a tendency of dissipation starting from
28 the East side.”

29 Correspondingly, similar statements in the Summary

30 “A trough of LSTID occurs and propagates from high to lower latitudes during 09:40-11:20
31 UT, which spans over 60° in longitude. It is followed by a crest of LSTID that characterized by a
32 clear tendency to dissipate starting from the East side.”

33 is revised to:

34 Page 13, Lines 28-30: “An LSTID occurs as a result of possibly AGWs propagating from
35 high to lower latitudes around 09:40-11:40 UT, which spans over 60° in longitude, and the crest of
36 this LSTID is characterized by a clear tendency to dissipate starting from the East side.”
37

38 Comment 2

39 Line 18, “...high frequency Doppler shift ...” , shouldn't the word “shift” be “radar” ?

40 Reply 2

1 Thank you very much!

2 In order to avoid readers' confusion about our devices and HF Radar, we did not use the term
3 "radar" in the last revised manuscript. We referred some papers concerning the HF Doppler shift
4 record, and find the "HF Doppler sounder" is more suitable here, so:

5 **The statement in the manuscript**

6 "... the recordings from 2 high-frequency Doppler shift stations and ..."

7 **is revised to**

8 **Page 3, Line 19:** "... the recordings from 2 high-frequency Doppler **sounders** and ..."

9 Similar revisions are also conducted in other contexts when necessary.

10

1 **A case study of the large-scale traveling ionospheric disturbances in the East**
2 **Asian sector during the 2015 St. Patrick's Day geomagnetic storm**

3 Jing Liu¹, Dong-He Zhang^{1*}, Anthea J. Coster², Shun-Rong Zhang², Guan-Yi Ma³, Yong-Qiang
4 Hao¹, Zuo Xiao¹.

5 1, Department of Geophysics, Peking University, Beijing, China, 100871

6 2, MIT Haystack Observatory, Westford, Massachusetts, USA

7 3, National Astronomical Observatories, Chinese Academy of Sciences, Beijing, China

8

9 **Abstract**

10 This study presents a comprehensive observation of the large-scale traveling ionospheric
11 disturbances (LSTIDs) in the East Asian sector during the 2015 St. Patrick's Day (March 17, 2015)
12 geomagnetic storm. For the first time, 3 dense networks of GPS receivers in China and Japan are
13 combined together to obtain the 2-dimensional (2D) vertical total electron content (VTEC)
14 perturbation maps in a wider longitudinal range than previous studies in this region. **Results show**
15 **an LSTID spanning at least 60 degrees in longitude (80°E-140°E) occurs as a result of possibly**
16 **AGWs propagating from high to lower latitudes around 09:40-11:40 UT, and the crest of this**
17 **LSTID shows a tendency of dissipation starting from the East side.** The manifestation of the 2D
18 VTEC perturbation maps is in good agreement with the recordings from 2 high-frequency Doppler
19 **sounders** and the iso-frequency lines from 8 ionosondes. Then, the propagation parameters of the
20 LSTIDs are estimated by applying least square fitting methods to the distinct structures in the 2D
21 VTEC perturbation plots. In general, the propagation parameters are observably longitudinal
22 dependent. For example, the propagation direction is almost due southward between 105°E-115°E,
23 while it is slightly South by West/East in the West/East side of this region. This feature is probably
24 related to the regional geomagnetic declination. The mean values of the period, trough velocity
25 (V_t), crest velocity (V_c), and wavelength of the LSTIDs in the studied longitudinal bands are
26 74.8 ± 1.4 minutes, 578 ± 16 m/s, 617 ± 23 m/s, and 2691 ± 80 km, respectively. Finally, using the
27 VTEC map data from the Madrigal database of the MIT Haystack Observatory, the characteristics
28 of the ionospheric disturbances over the European sector (30°N-70°N, 10°E-20°E) are also studied.
29 The results are very different from those in the East Asian sector in parameters like the occurrence
30 time, oscillation period, and propagation velocities.

31 **Keywords: Geomagnetic Storm; LSTID; GPS TEC.**

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1 **1. Introduction**

2 During the geomagnetic storm, the solar wind energy is impulsively or continually injected into
3 the earth polar region and making the atmospheric and ionospheric states deviate greatly from
4 their background levels [Fuller-Rowell et al., 1994]. In general, the response of the ionosphere to
5 the geomagnetic storm is classified by a variety of different features, one of which is the large
6 scale traveling ionospheric disturbance (LSTID) that is the wave-like perturbation mainly
7 propagating equatorward from high latitudes. Traveling ionospheric disturbances (TIDs) are
8 classified into LSTIDs and Medium-scale TIDs and they are considered to be the ionospheric
9 manifestation of the presence of atmospheric gravity waves (AGWs) stimulated by different
10 sources. LSTIDs are mainly caused by Joule heating or Lorenz-drag forcing in the Auroral regions
11 during geomagnetic storm period [Hines, 1960; Richmond and Roble, 1979; Hocke and Schlegel,
12 1996].

13 In earlier years, the acquisition of the continuous evolution of LSTIDs on a global scale was
14 limited by the availability of the ionospheric observations. In order to obtain the propagation
15 characteristics of LSTIDs, researchers needed to organize their findings from limited ionospheric
16 observations, for example, the foF2 data from sparsely distributed ionosondes. In the 1980s, the
17 GPS (Global Positioning System) method was introduced into the ionospheric study [Klobuchar,
18 1986; Lanyi and Roth, 1988; Coster and Gaposchkin, 1989]. With the dense and worldwide
19 distributed GPS receivers, some characteristic ionospheric phenomena, like traveling ionospheric
20 disturbances (TIDs) [Saito et al., 1998; Tsugawa et al., 2004; Ding et al., 2007], ionospheric
21 storms [Ho et al., 1996], and ionospheric responses to solar flares [Afraimovich, 2000a; Zhang
22 and Xiao, 2005] were revisited frequently and new results were obtained.

23 The propagation characteristics of LSTIDs are always topics of great research interest [Hunsucker,
24 1982; Ho et al., 1996; Balthazor and Moffett, 1999; Afraimovich et al., 1998, 2000; Shiokawa et
25 al., 2002; Tsugawa et al., 2003, 2004; Ding et al., 2008, 2014; Borries et al., 2009, 2017;
26 Habarulema et al., 2015, 2016, 2018; Zakharenkova et al., 2016; Figueiredo et al., 2017; Pederick
27 et al., 2017; Cherniak et al., 2018; Lyons et al., 2019]. Based on limited GPS stations
28 measurements, Afraimovich et al. [1998] proposed a radio interferometry method to roughly
29 estimate horizontal propagation velocities and phase front angles of TIDs. Further, the worldwide
30 or local dense distribution of the GPS receivers networks facilitates the acquisition of the global or
31 regional TEC perturbation maps with high spatial and temporal resolutions to reveal the detailed
32 propagating characteristics of TIDs [Ho et al., 1996; Saito et al., 1998; Tsugawa et al., 2004;
33 Borries et al., 2009; Ding et al., 2012]. With more than 60 GPS receivers distributed worldwide,
34 Ho et al. [1996] studied the global distribution of TEC perturbations during a magnetic storm.
35 They identified a TID propagating from the northern sub-auroral region to lower latitudes at a
36 speed of about 460 m/s. The GPS Earth Observation Network (GEONET) in Japan is one of the
37 densest GPS receiver networks on the Earth, and two-dimensional (2D) TEC perturbations over
38 Japan can be mapped with the GEONET observations. With these high-resolution TEC
39 perturbation maps, the spatial structures and temporal evolutions of a TID in the nighttime
40 mid-latitude ionosphere over Japan were revealed clearly [Saito et al., 1998]. Since then, with this
41 dense GPS network, the characteristics of LSTIDs over Japan are carefully studied through case
42 and statistical analysis, and some propagation features of TIDs in this region are revealed [Saito et
43 al., 2001; Shiokawa et al., 2002; Tsugawa et al., 2003, 2004, 2006].

1 For the LSTID with scales of thousands of kilometers, the extensive spatial coverage of
2 ionospheric observations is undoubtedly useful for capturing its propagation features. In recent
3 years, the GPS data from densely distributed GPS stations in China were used to study LSTIDs in
4 this region [Ding et al., 2012, 2013, 2014; Song et al., 2013]. Based on the GPS data from the
5 Crustal Movement Observation Network of China (CMONOC), Ding et al. [2012] obtained
6 temporal continuous 2D imaging of ionospheric disturbances during the geomagnetic storm on
7 May 28, 2011, and find two LSTIDs moving southwestward with the front width of at least 1600
8 km during different storm stages. In addition, through the comparative climatological study of
9 LSTID over North America and China, the different time dependence of LSTID occurrence over
10 two longitudinal sectors were revealed statistically [Ding et al., 2014]. These studies further
11 emphasize the effectiveness of the large coverage, high-resolution ionospheric observations from
12 GPS networks on revealing the structures of the ionospheric disturbances.

13 The propagating direction of the LSTID during the geomagnetic storm has always been focused
14 on for the LSTID studies. From case and statistical studies about LSTIDs during geomagnetic
15 storms over East-Asia region conducted by Chinese and Japanese scientists independently, the
16 dominant propagating direction of LSTID in China and Japan is a little different. It mainly
17 propagates South by West in the Chinese region [Ding et al., 2014], while it mainly propagates
18 South by East in the Japanese region [Tsugawa et al., 2004]. Although the geomagnetic
19 declination is considered to be one of the main factors to be responsible for the propagation
20 direction of LSTID based on different LSTID studies, the LSTID studies concerning the same
21 geomagnetic storm using both Chinese and Japanese GPS networks together have not been
22 reported yet.

23 During the period of 17–18, March 2015, the strongest geomagnetic storm in the 24th solar cycle
24 occurred and LSTIDs were detected and analysed in different longitudinal sectors [Ramsingh et al.,
25 2015; Borries et al., 2016; Zakharenkova et al., 2016; Habarulema et al, 2018]. Meanwhile, two
26 high frequency (HF) Doppler sounders in Chinese mid-latitude operated by China Meridional
27 Project [Wang, 2010] recorded large ionospheric HF Doppler shifts after 10:00 UT, which seem to
28 indicate the LSTIDs in the Asian region between 09:00-12:00 UT that reported by Habarulema et
29 al. [2018]. In this study, the multi-network of densely distributed GPS receivers, the HF Doppler
30 sounder stations, and an ionosonde network are used to conduct a more comprehensive study on
31 the propagating characteristics of the disturbances in the East Asian region, especially on the
32 characteristics of the dominant propagating direction over China and Japan.

33 **2. Data and Methods**

34 Figure 1 illustrates the locations of ground-based receivers used in this study from 4 Global
35 Navigation Satellite Systems (GNSS) networks distinguished by colors. They are Chinese
36 Meteorological GNSS Network (CMGN), CMONOC, GEONET, and International GNSS Service
37 (IGS). These receivers are selected through data quality checking and regional restriction ($10^{\circ}\text{N} \sim$
38 60°N , $70^{\circ}\text{E} \sim 150^{\circ}\text{E}$), and the numbers of used stations are 259, 220, 1300, and 31 for CMGN,
39 CMONOC, GEONET, and IGS, respectively. The sample rate of all GPS data is 30 seconds.
40 Combining the carrier phase and pseudo-range measurements in two L-band frequencies of GPS,
41 the vertical TEC (VTEC) can be obtained. In the calculation, the height of the ionospheric thin
42 shell is set to be 400 km, and the cutoff elevation angle is 30 degrees. The detailed process of the

1 TEC calculation from GPS data can be found in our previous studies [Zhang et al., 2009; Zhang et
2 al., 2010].

3 Different methods were used for extracting the TEC perturbations related to LSTIDs in previous
4 researches [Wan et al., 1997; Afraimovich et al., 2000; Shiokawa et al., 2002; Nicolls et al., 2004;
5 Tsugawa et al., 2004; Ding et al., 2007]. Afraimovich et al. [2000] suggested that the LSTID
6 characteristics in TEC can be determined by removing the trend with 3 to 5 order polynomials,
7 which is introduced by the motion of satellites and background variations of ionosphere. For a
8 similar purpose, Shiokawa et al. [2002] subtracted a running average of TEC over 1 hour from the
9 raw TEC, and a series of 2D TEC perturbation maps was obtained with more than 1000 GPS
10 receivers in Japan. Ding et al. [2007] developed another method of obtaining the 2D TEC
11 perturbation maps by expressing the VTEC as a one-order function of local time and latitude.
12 According to their argument, this method is sufficient to remove background trends for continuous
13 observation of a GPS receiver-satellite pair without introducing artificial perturbations. After
14 comparing the results of these methods, a method similar to Ding et al. [2007] is conducted in this
15 study, in which the VTEC is treated as a function of universal time (UT), longitude (Lon), and
16 latitude (Lat), i.e.,

$$VTEC_0 = C_0 + C_1UT + C_2Lon + C_3Lat \quad (1)$$

$$VTECP = VTEC - VTEC_0 \quad (2)$$

17 in which $VTEC_0$ is the background change and $VTECP$ is VTEC perturbation. Then, the obtained
18 $VTECP$ data is reorganized into pixels which are bounded by $10^\circ\text{N} \sim 60^\circ\text{N}$, $70^\circ\text{E} \sim 150^\circ\text{E}$ and
19 with a spatiotemporal resolution of 1° longitude \times 1° latitude \times 10 minutes. The pixel value is the
20 average of all $VTECP$ s in this pixel. After these steps, the featured ionospheric disturbances are
21 expected to appear on a series of 2D $VTECP$ maps.

22 As a comparison, the VTEC map from Madrigal database of the MIT Haystack Observatory is
23 used to reveal the ionospheric disturbances in the European sector ($30^\circ\text{N} \sim 70^\circ\text{N}$, $10^\circ\text{E} \sim 20^\circ\text{E}$).
24 This database provides worldwide VTEC values in 1° latitude \times 1° longitude pixels with a
25 temporal resolution of 5 minutes [Rideout and Coster, 2006] and has a good data coverage in the
26 European sector. VTEC maps with such a high spatiotemporal resolution are suitable to reveal the
27 structures of traveling ionospheric disturbances [Zhang et al., 2017].

28 The Doppler shift data observed at two HF Doppler sounder stations in China are collected, which
29 are MDT (40.4°N , 116.9°E) and SZT (22.6°N , 114.1°E). The sounding system continuously
30 receives electromagnetic waves with a stabilized frequency of 10 MHz transmitted by the National
31 Time Service Center (NTSC) (35.7°N , 109.6°E) to detect the ionospheric disturbances through the
32 Doppler shifts of this standard frequency. These shifts are considered to be caused by ionospheric
33 variations mainly around the reflecting point of the electromagnetic wave in the ionosphere.
34 According to the geometrical relationships, the locations of the reflecting point for MDT and SZT
35 are (38.0°N , 113.2°E) and (29.2°N , 111.8°E), respectively. These stations are marked in Figure 1
36 with colored stars.

37 In this study, ionograms from 8 ionosonde stations in Chinese middle latitude are used to derive
38 the iso-frequency lines, which vary as a function of universal time and virtual height. The sample
39 rate of the ionograms is 15 minutes. These ionosondes belong to the China Research Institute of

1 Radio-wave Propagation (CRIRP) and their locations are marked with green triangles in Figure 1.
2 The virtual height data is manually scaled by ourselves from these ionograms with professional
3 scaling software provided by CRIRP to reduce possible errors of auto scaling [Krankowski et al.,
4 2011; Habarulema and Carelse, 2016]. During the scaling, we limited the frequency to be less than
5 7 MHz. In addition, the space environment data for this event is from OMNI dataset, which is
6 downloaded from the FTP service of the NASA Goddard Space Flight Center.

7 **3. Results**

8 **3.1 Observations**

9 Figure 2 shows the variations of (a) solar wind speed, (b) interplanetary magnetic field (IMF) B_z
10 component, (c) the SYM-H index, and (d) the AE index from the OMNI dataset, and the time
11 range is from 18:00 UT, 16 March 2015 to 06:00 UT, 18 March 2015. It should be noted that the
12 solar wind magnetic field and plasma data are time-shifted to the bow shock nose to better support
13 the solar wind-magnetosphere coupling studies. It can be seen clearly that a geomagnetic storm
14 occurred on 17 March 2015, with the sudden storm commencement (SSC) at $\sim 04:45$ UT, which is
15 characterized by a sharp increase (marked with vertical dashed lines) in the solar wind speed, B_z ,
16 and SYM-H index. The main phase of the storm can be roughly divided into two stages. The first
17 stage is from $\sim 06:00$ UT, when the IMF B_z component first turns to southward, to $\sim 12:00$ UT,
18 when the B_z turns southward again after back to northward for about 2 hours. After $\sim 12:00$ UT,
19 the B_z is southward for most of the time, until it enters the recovery phase. The SYM-H and AE
20 indices show a similar two-stage feature as the B_z . SYM-H decreases after $\sim 06:00$ UT, reaches
21 the first minimum at $\sim 09:30$ UT, and increases to a local maximum at $\sim 12:00$ UT. Then, it
22 gradually decreases with small oscillations and reaches the minimum value of -233 nT at $\sim 22:45$
23 UT. Correspondingly, the AE index exhibits the first increase period between 06:00 UT to 12:00
24 UT, with the maximum intensity of ~ 1000 nT, and the second period between 12:00 UT to 02:00
25 UT of the next day, during which the AE increases much larger with several peaks. This storm is
26 the strongest one in the 24th solar cycle [Astafyeva et al., 2015].

27 During the first stage of the main phase, disturbances are observed successively at MDT and SZT
28 Doppler sounder stations. Figure 3 illustrates the variations of the Doppler shift records at (a)
29 MDT and (b) SZT between 08:00 UT and 14:00 UT on 17 March 2015. It shows that two distinct
30 positive shifts occur at about 10:22 UT and 10:53 UT, respectively. Shortly after, it exhibits two
31 negative shifts but with much smaller amplitudes. Suppose these successive disturbances indicate
32 a propagating perturbation, according to the estimated locations of the reflecting points that
33 mention above and the occurrence time of the two positive peaks, the approximate speed of this
34 perturbation is about 535 m/s. This value is much larger than the speed of the movement of the
35 ionospheric negative storm that usually occurs in the middle latitude due to storm-induced
36 equatorward wind [Buonsanto, 1999], and the ionospheric storm is not serious in the Asian sector
37 during this period [Astafyeva et al., 2015]. Considering the magnitude of the speed and the time
38 interval of the positive-negative variations, the recorded perturbations probably reflect an
39 equatorward propagating LSTID in the East Asian sector.

40 To confirm this, Figure 4 presents a sequence of 2D VTECP maps between 09:40-11:40 UT on 17
41 March 2015 with the method described in section 2. The grey areas represent the nightside. The
42 raw value of VTECP has already been converted into $VTECP'$ with the equation

$$\text{VTECP}' = \text{sgn}(\text{VTECP}) * \log_{10}(\text{abs}(\text{VTECP}) + 1) \quad (3)$$

1 The raw amplitude of VTECP above 30°N is ~ 2 TECu while the raw amplitude of VTECP below
 2 30°N reaches ~ 10 TECu. So, transform (3) provides a better colormap for 2D VTECP plots by
 3 sharpening the edges between positive and negative values and reduce the differences of VTECP
 4 in middle and low latitudes. Consequently, it should be noted that the amplitude of the wavelike
 5 variation does not represent the true wave amplitude but an “artificial” one. The yellow lines
 6 illustrate the least square fitting results for all the negative pixels within certain rectangular areas
 7 bounded by longitudes and latitudes. The green lines are similar but for pixels with the bottom 5%
 8 absolute VTECP' values in selected areas (see section 3.2 for a detailed example). These lines
 9 mark the approximate locations of the wavefronts.

10 A large-scale wavelike perturbation can be seen clearly in Figure 4. The first relatively distinct
 11 wave structure emerges during the (d) 10:10-10:20 UT period, while its sign can already be
 12 observed as early as (a) 09:40-09:50 UT in the northwest part of China. During (e) 10:20-10:30
 13 UT, a negative band occurs across both the Chinese and Japanese sectors between around
 14 30°N-45°N, which gradually propagates to lower latitudes in the next tens of minutes. During (f)
 15 10:30-10:40 UT, the first clear wavefront of the positive band appears, which also shows an
 16 equatorward movement for at least half an hour. Finally, there seems to be no distinct wave
 17 structure following the positive band. Considering the spatiotemporal characteristics of this
 18 perturbation, it can be preliminarily identified as an LSTID. By the way, it is interesting to note
 19 that the positive bands do not extend to the Japanese sector in (h) and (i), and the corresponding
 20 VTECP' amplitudes seem smaller in the East side than in the West side. This may be related to the
 21 fact that the Japanese sector has already entered the nightside.

22 Both the negative and positive bands exhibit more complex variations when they enter the
 23 equatorial ionospheric anomaly (EIA) region between 20°N-30°N. On the one hand, the amplitude
 24 of VTECP' is relatively larger than those in the higher latitudes. On the other hand, it seems that
 25 the equatorward propagation of the negative band decelerates significantly in this area, which is
 26 especially shown in (Figure 4, g-l). Such complex features are probably related to the various
 27 physical processes in this region. Ding et al. [2012] suggested that LSTIDs experience severe
 28 dissipation in South China region due to viscosity and heat conductivity at low latitudes, which
 29 may account for the weakening of the equatorward propagating wavelike structures. Besides,
 30 Pradipta et al. [2016] studied the interaction of the auroral LSTIDs from opposite hemispheres
 31 near the dip equator during the 26 September 2011 geomagnetic storm. Their results show that
 32 such interaction may bring much complexity to the TEC perturbations near the dip equator.

33 Our observations of the Doppler shift and VTECP' maps are in good agreement. To show it
 34 clearly, Figure 5 shows the variations of the mean VTECP' data near the Doppler reflection points
 35 with the same time range of Figure 3. Doppler shift recordings in Figure 3 are also plotted with
 36 dashed lines for comparison. It can be seen that the troughs at around 10:20 UT in (a) and 10:50
 37 UT in (b) correspond well to the two distinct crests in Figure 3. In addition, the variations of the
 38 VTECP' between 11:00 and 14:00 are also in a good negative correlation with the Doppler shift
 39 observations for each reflecting point. It should be noted that the variation of VTECP' at the
 40 reflecting point 1 exhibits more variability than that at the reflecting point 0, especially around
 41 09:00 UT, 10:00 UT, and 12:00 UT. Considering that point 1 (29.2°N,111.8°E) is approaching the

1 EIA region, the causes for VTEC perturbations are more complicated as mentioned above. This
2 feature is consistent with the observations of the 2D VTECP' maps in Figure 4.

3 Ionospheric parameters from ionograms have been extensively used since early TID studies.
4 Recently, ionograms and iso-frequency lines with different sampling rates were used in TID
5 studies [Klausner et al, 2009; Ding et al., 2012, 2013; Pradipta et al., 2015; Ramsingh et al., 2015;
6 Habarulema et al., 2018]. Figure 6 presents the temporal variations of the virtual height for each
7 iso-frequency line. The name and location of the corresponding ionosonde stations are given in
8 each subplot. The frequency is marked on the right side for each line. On the left column, the
9 results of five stations are arranged in order from high to lower latitudes, and on the right column,
10 it shows the recordings of four stations in the same latitudinal belt. We can see clearly that a
11 distinct uplift of the virtual height occurs at 09:45 UT at Manzhouli station, and it gradually
12 moves equatorward from high to lower latitudes (Figure 6, a-e). Meanwhile, there is no clear
13 phase difference for the stations on the right column. This means that the ionospheric disturbance
14 roughly moves along the meridian line in this longitudinal sector (around 115°E), which
15 corresponds to the results of the 2D VTECP' map. Moreover, although the time resolution of 15
16 minutes is relatively low, it can still be identified that the crests in the higher iso-frequency lines
17 appear earlier than those in the lower ones. Such trends (marked with black dashed lines) indicate
18 a downward vertical phase velocity, which is one of the typical characteristics of TID and AGW
19 [Hine, 1960; Hocke and Schlegel, 1996]. It should be noted that the downward trend is not much
20 clear for certain station, especially the one in Qingdao. This may be attributed to the 15 minutes
21 sampling interval.

22 3.2 Estimating Propagation Parameters

23 As preparation for estimating the propagation parameters of this LSTID, Figure 7 shows a detailed
24 example of the wavefront fitting method with the VTECP' map in Figure 4(g) (10:40-10:50 UT).
25 The reason for choosing this period is that the structure of the wavefront is relatively clear, and the
26 boundary between the trough and crest of this LSTID can still be partly identified in the Japanese
27 sector. The green line is the least square fitting for the green dots, of which the absolute VTECP'
28 values are close to zero (bottom 5%) among all the dots in a certain region (75°E-140°E,
29 30°N-40°N). The wave propagating azimuth (marked with arrows) can be estimated with the
30 normal direction of this fitting line. The estimated azimuths are listed in Table 1 in the second
31 column.

32 It can be seen clearly that the TID moves due South around 110°E, and in the West/East region,
33 the propagation direction is slightly South by West/East. It should be noted that, although the
34 morphology of this TID is continuously changing as it moves from high to lower latitudes in the
35 studied region, the longitudinal dependences of azimuths of all fitting lines in Figure 4(e, f, g, h)
36 are similar.

37 In order to derive the phase speed, period, and wavelength of this LSTID, the time-latitude plots
38 (TLPs) of VTECP' are obtained for six longitudinal bands, which are marked with dashed
39 rectangles A-F in Figure 7. For each band, the VTECP' data is averaged along the latitude for
40 every 6 minutes, and the results as a function of UT and latitude are illustrated correspondingly in
41 Figure 8 (a-f). As mentioned above, the VTECP' variation related to EIA is rather complex.
42 Considering that EIA is mainly a low-latitudinal phenomenon, only values over 30°N are used to

1 estimate the speed. The 30°N indicates the boundary of EIA and is marked with dashed lines in
2 Figure 8.

3 As expected, the most distinctive structures in all panels are the pair of negative and positive
4 bands between about 10:00 UT and 12:00 UT, which correspond to the perturbations moving from
5 high to lower latitudes shown in Figure 4. The structures in the 130°E-140°E are not quite clear,
6 which may be due to the lack of data in some parts of this area, but the trough around 10:40 UT
7 can still be identified. To estimate the meridional speeds of these perturbation patterns, the linear
8 least square method is used to fit the pairs of troughs and crests. The data points for the linear
9 fitting (white dots) are the minimum/maximum values around the trough/crest. The speeds for
10 wave troughs (V_t) and crests (V_c) can be derived based on the slopes of the fitting lines. Moreover,
11 the period of the wave can be estimated through the time interval between the trough and crest in
12 TLPs. To be specific, for each longitudinal region, the averaged values of the time intervals along
13 all latitudinal bins is set to be the half period of the wave in this region. As for the estimation of
14 wavelength, note that the studied area is $\sim 20^\circ$ in latitude, which is roughly one wavelength and
15 thus make it difficult to estimate the wavelength directly from the 2D VTECP' map. So, the
16 wavelength is derived from the multiplication of speed and period.

17 However, those speed, period, and wavelength are the projections on longitudes. After adjusted by
18 the propagation azimuths that were calculated above, the final results of the estimated parameters
19 are listed in Table 1. It can be seen that these parameters show certain longitudinal dependence. It
20 should be noted that the data coverage is relatively lower in the east and west boundaries of the
21 investigated region. This may impact the accuracy of the estimation of the LSTID properties in
22 these areas. On the whole, the mean values and standard deviations of the period, V_t , V_c , and
23 wavelength are 74.8 ± 1.4 minutes, 578 ± 16 m/s, 617 ± 23 m/s, and 2691 ± 80 km, respectively. These
24 parameters are typical for an LSTID. V_t and V_c overlap, although only marginally, considering the
25 error ranges. Meanwhile, the mean V_c is slightly larger than the mean V_t , which seems like the
26 wave behind is pushing that ahead. In general, the speed of trough and crest of the LSTID should
27 be rather the same since they are induced by the same gravity wave. However, the wave properties
28 might change with time dependent on the forcing from background condition, especially for
29 LSTID covering large spatial region. This might explain the differences.

30 In addition, it is interesting to note that V_t is in reasonable agreement with the result of 535 m/s
31 derived from the Doppler recordings. To show it more specifically, we estimated the speed and
32 direction of the LSTID using the same TLP method as Figure 8 but in 111°E-114°E and
33 29°N-38°N (corresponding to the reflecting points). The results are 562 ± 59 m/s and 0.2° ,
34 respectively. In general, the LSTID velocity estimated from ground-based stations tend to be
35 larger than the actual velocity since these stations, in most cases, are not in perfect alignment with
36 the propagation direction of the LSTID [Afraimovich et al., 1998; Habarulema et al., 2013]. Such
37 good agreement between VTECP' and HF Doppler results may be attributed to the fact that the
38 reflecting points (29.2°N, 111.8°E; 38.0°N, 113.2°E) of the Doppler sounders are in a narrow
39 longitudinal band and the direction of the LSTID's propagation is also almost due south between
40 111°E-114°E.

41 As mentioned above, the VTECP' in the EIA region seems to exhibit different features compared
42 to that in the middle latitude. It can be seen from Figure 8(c) that VTECP' in the EIA region also

1 shows a periodic variation, but it seems to have longer period and time duration than the LSTID.
2 These disturbances are probably related to the complex variations of VTEC after 08:00 UT
3 (around dusk). Besides, the perturbations at 20°N around 12:00 UT and 13:00 UT show patterns of
4 poleward movement. Habarulema et al. [2018] identified TIDs in the Asian-Australian sector
5 during the same storm period. It provides clear examples of TIDs crossing the dip equator from
6 the southern hemisphere to the northern hemisphere around 09:00-12:00 UT. Their analysis shows
7 that these TIDs may not have exceeded 30°N. Such poleward feature was also detected in other
8 longitudinal sectors during this storm [Zakharenkova et al., 2016] and other storms [Pradipta et al.,
9 2016; Jonah et al., 2018]. In addition, Ding et al. [2013] studied the poleward-propagating LSTIDs
10 in southern China during a medium-scale storm in 2011. They attributed their observations to the
11 excitation of secondary LSTIDs during the dissipation of primary disturbances from the lower
12 atmosphere. Besides, the poleward-moving disturbances may also be induced by the variation of
13 the equatorial electrojet as pointed out by Chimonas [1970] and more recently by Habarulema et
14 al. [2016]. A detailed investigation of this phenomenon is not the focus of this work.

15

16 **4. Discussion**

17 Our results show that the propagation parameters of the LSTID in the East Asian sector during the
18 St. Patrick's Day storm are longitudinal dependent. Among these parameters, the longitudinal
19 dependence of the propagation azimuth of an LSTID receives much attention in previous works.
20 In general, earlier studies suggested that there are four main factors that affect the direction of a
21 polar originated LSTID, including the velocity of the background neutral wind [Hines, 1960;
22 Morton and Essex, 1978; Maeda and Handa, 1980], the structure and evolution of the source
23 region in the auroral oval [Maeda and Handa, 1980; Hunsucker, 1982; Ding et al., 2007], the
24 Coriolis force [Maeda and Handa, 1980; Balthazor and Moffett, 1999; Afraimovich et al., 2000;
25 Tsugawa et al., 2004; Ding et al., 2013], and the declination of geomagnetic field [Tsugawa et al.,
26 2004; Borries et al., 2009].

27 The Coriolis force effect is generally believed to contribute to the clockwise shift of the
28 propagation direction of the LSTIDs [Afraimovich et al., 2000; Tsugawa et al., 2004; Ding et al.,
29 2013]. The observations of the shift (10°-20° on average) are consistent with the calculation by
30 Maeda and Handa [1980] and the model simulation by Balthazor and Moffett [1999]. However, in
31 our study, the shift of the propagation direction is not systematic westward, which means the
32 variability of the LSTID azimuth in our observation cannot be attributed to the Coriolis force, at
33 least not to it alone.

34 The structure/movement of the source region for the LSTID in the auroral oval is another
35 candidate for explaining the longitudinal dependence of the propagation direction of the LSTID.
36 Previous studies suggested that the westward movement of enhanced electrojets in the auroral arc
37 is an important cause of the westward shift of the LSTID propagation direction at high latitudes
38 [Hunsucker, 1982; Ding et al., 2007]. The change of the propagation direction of LSTIDs as they
39 move from high to middle latitudes during the superstorm of 29 October 2003 over North America,
40 was explained by Ding et al. [2007] as related to a change in the position of the electrojet
41 enhancement area near the auroral oval. Nevertheless, since the structure and the evolution
42 process of the source region during storm period is complicated, more cases and modeling studies

1 are needed to find a clear connection between it and the propagation direction of LSTIDs.

2 In general, the velocity of the neutral wind is much less than that of the LSTIDs, and the
3 thermospheric wind velocity in the same latitudinal belt with a limited longitudinal extension
4 should exhibit little variance. So, the contribution of the background wind on the change of the
5 propagating direction would be limited in the absence of the geomagnetic field. However, a
6 combined effect of magnetic declination and zonal wind can cause F region electron density
7 differences between two sides of the zero declination [Zhang et al., 2011]. During storm periods,
8 the enhanced zonal winds [Fuller-Rowell et al., 1994] can intensify these differences [Thomas et
9 al, 2016]. As a result, the geomagnetic declination is considered to be an important factor that
10 affects the propagation direction of the LSTID. Some researchers studied the predominant
11 propagation direction of LSTIDs during storm periods in different longitudinal sectors, and
12 suggested that, statistically speaking, the predominant directions of LSTID in Europe, China and
13 Japan are primarily southward, South to West and South to East, respectively [Nicolls et al, 2004;
14 Tsugawa et al, 2004; Borries 2009; Ding et al, 2013]. These results are all consistent with the
15 corresponding geomagnetic declination in each sector.

16 In the longitudinal region of 70°E-150°E, the geomagnetic declination angles change from North
17 by East in the West side to North by West in the East side. This characteristic seems to show some
18 kind of consistent with the azimuth results in Table 1. To illustrate such connection quantitatively,
19 Figure 9 depicts the (a) the geomagnetic declination on the wavefront in different longitudes in
20 Figure 7 and (b) the propagation direction (azimuth-180°) of the LSTID at the same spot. The
21 connection between these two parameters is quite obvious in this event. This result manifests that
22 the propagation of LSTIDs in different longitudes is probably influenced by the orientation of the
23 geomagnetic field lines in the East Asian sector. In addition, the tendency of field-aligned
24 propagation of the LSTID indicates that it is driven by the neutral winds since the winds push the
25 plasma up and down along the magnetic field lines. There is no evidence, such as simultaneous
26 perturbations at all latitudes in other cases [Borries et al., 2016; Zakharenkova et al., 2016], to
27 show that the LSTID in the Chinese/Japanese sector is affected by prompt penetration electric
28 field (PPEF) during the same period. Besides, considering the relatively low data coverage in the
29 East/West side of the studied region, it should be noted that our speculation needs to be verified
30 with more observational data and numerical simulation to reduce uncertainty in our propagation
31 estimation and to figure out the detailed physical processes.

32 During the 2015 St. Patrick's Day storm, LSTIDs in the European-African, American and
33 Asian-Australian sectors were detected and analysed with TEC observations [Borries et al., 2016;
34 Zakharenkova et al., 2016; Habarulema et al., 2018]. It shows clearly in their results that the
35 European sector also exhibits LSTIDs around 11:00 UT. As a comparison, we also analysed these
36 LSTIDs but with VTEC data from the Madrigal database of the MIT Haystack Observatory. To
37 derive the VTECP, a narrow longitudinal band (10°E-20°E, 30°N-70°N) is selected and the VTEC
38 data with the same latitude at the same time is averaged. At each latitude bin, the averaged VTEC
39 forms a time series and the temporal resolution is set to 12 minutes with bin averaging. Then, a
40 running mean with a 1.5-hours window is conducted for each time series and their difference is
41 taken as the VTECP. The result is plotted in Figure 10 as a TLP. The fitting lines are obtained with
42 the same method as those in Figure 8.

1 Figure 10 is basically consistent with previous results [Borries et al., 2016; Zakharenkova et al.,
2 2016], such as the synchronous perturbations around 04:45 UT and 09:15 UT, and the LSTID
3 structures between 10:00 UT and 17:00 UT. Moreover, our result shows that the VTECP'
4 behavior between 60°N and 70°N is quite different from that between 30°N and 60°N. The pattern
5 around 10:00 UT seems to represent a TID with smaller speed. Considering that the physical
6 processes are more complex in such high latitudes [Foster et al., 2014], we only focus on the
7 perturbations below 60°N. The speeds estimated from the most distinct crest and trough are ~
8 500 ± 51 m/s and ~ 427 ± 55 m/s, respectively, and the estimated period is ~ 4.0 ± 0.2 hours. It is clear
9 that the appearances of the LSTIDs are different in the European and East Asian sectors during the
10 same period for the same storm event. Borries et al. [2016] presented a detailed study on the
11 LSTID in Europe during this storm. It is suggested that the perturbation occurring around 11:00
12 UT is special since it is impacted by PPEF and wind at the same time. Comparatively, the LSTID
13 in the Chinese/Japanese sector seems only driven by winds. This may partly account for the
14 difference of LSTIDs between the East Asian and European sectors. Besides, such difference may
15 also be related to the location or structure of the Joule heating source in the auroral oval or the
16 difference of the background TEC in the two sectors. For better understanding this difference,
17 more studies on the Joule heating source are needed.

18

19 5. Summary

20 Using data from 4 GPS receiver networks (CMGN, CMONOC, GEONET, IGS), together with
21 recordings of 2 HF Doppler sounders and 8 ionosondes, we provide comprehensive and detailed
22 observation results of the LSTIDs in the East Asian sector during the 2015 St. Patrick's Day storm.
23 The GPS receiver networks in China and Japan are combined together to produce 2D VTEC
24 perturbation maps in order to give a wider image of the LSTID structures in the East Asia. As a
25 comparison, the ionospheric disturbances in the European sector are also studied with VTEC data
26 from the Madrigal database. The propagation parameters of the LSTIDs are estimated. Main
27 results can be summarized as follows:

28 (1) An LSTID occurs as a result of possibly AGWs propagating from high to lower latitudes
29 around 09:40-11:40 UT, which spans over 60° in longitude, and the crest of this LSTID is
30 characterized by a clear tendency to dissipate starting from the East side. These features are in
31 good agreement with observations by HF Doppler sounders and ionosondes.

32 (2) The propagation orientation is almost due southward around 105°E-115°E, and it tends to
33 slightly shift westward/eastward in the West/East part of the studied area. This is suggested to be
34 influenced by the regional declination of the geomagnetic field lines.

35 (3) The propagation parameters in different longitudinal bands are estimated. These parameters
36 show certain longitudinal differences. On the whole, the mean values and standard deviations of
37 the period, V_t , V_c , and wavelength are 74.8 ± 1.4 minutes, 578 ± 16 m/s, 617 ± 23 m/s, and 2691 ± 80
38 km, respectively.

39 It should be noted that our results show certain consistency with previous researches focusing on
40 the Chinese or Japanese sector for different LSTID events. Nevertheless, the longitudinal
41 dependence shown in our results should be examined further with more case studies based on

1 large longitudinal and high-resolution coverage of GPS data.

2

3

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1 **Captions of Table and Figures**

2 **Table 1.** The estimated propagation parameters of the LSTID and the corresponding standard
3 errors. The second column contains the propagation directions, which are measured clockwise
4 from the South. V_t/V_c represents the speed estimated with certain wave trough/crest.

5 **Figure 1.** Locations of the GPS stations of different networks (colored dots), the HF Doppler
6 sounder stations (green stars), the National Time Service Center of China (grey stars), and the
7 ionosonde stations (green triangles) that used in this study.

8 **Figure 2.** Temporal variations of (a) the solar wind speed (V_{sw}), (b) the IMF Bz component, (c)
9 the SYM-H index, and (d) the AE index between 18:00 UT, 16 March 2015 and 06:00 UT, 18
10 March 2015. The occurrence of SSC is shown with vertical dashed lines.

11 **Figure 3.** Temporal variations of the HF Doppler shift records from (a) MDT and (b) SZT
12 between 08:00 UT and 14:00 UT, 17 March 2015.

13 **Figure 4.** A series of 2D VTECP' maps over the East Asian sector from the period of 09:40-09:50
14 UT to 11:30-11:40 UT on 17 March 2015. The grey areas represent the nightside. The colorbar
15 represents the VTECP' (units: TECu), which is transformed from the original VTECP value with
16 equation (3) for a more viewer-friendly colormap. The green and yellow lines illustrate the least
17 square fittings (order 2) for wavefronts.

18 **Figure 5.** Temporal variations of mean VTECP' near the Doppler reflection points between 08:00
19 UT and 14:00 UT, 17 March 2015. Doppler shift recordings in Figure 3 are plotted with dashed
20 lines for comparison.

21 **Figure 6.** Temporal variations of the virtual height for iso-frequency lines from 8 ionosondes
22 between 08:00 UT and 12:00 UT, 17 March 2015. Frequencies are depicted on each iso-frequency
23 line. The time resolution is 15 min for all stations. The black dashed lines indicate the downward
24 phase change.

25 **Figure 7.** A detailed example of the wavefront fitting method. Green dots indicate the data points
26 for least square fitting. Green arrows depict the propagation orientations in different longitudes.
27 Dashed black rectangles mark the areas for generating TLPs in Figure 8.

28 **Figure 8.** TLPs of VTECP' for different longitudinal bands between 07:00-14:00 UT. White dots
29 give the data points for linear fitting, and the fitting results are marked with white lines. 30°N in
30 (b-d, f) is marked with black dashed lines which indicate the boundary of EIA. 40°N is marked in
31 (f).

32 **Figure 9.** The sketch of (upper) the geomagnetic declination angels and (lower) the propagation
33 directions in different longitudes on the wavefront fitted in Figure 7. The propagation directions
34 are measured clockwise from the South.

35 **Figure 10.** The TLP of VTECP' for the European sector (10°E-20°E, 30°N-70°N) between
36 01:00-23:00 UT. White lines and dots are similar to those in Figure 8. The black dashed line
37 depicts 60°N.

38

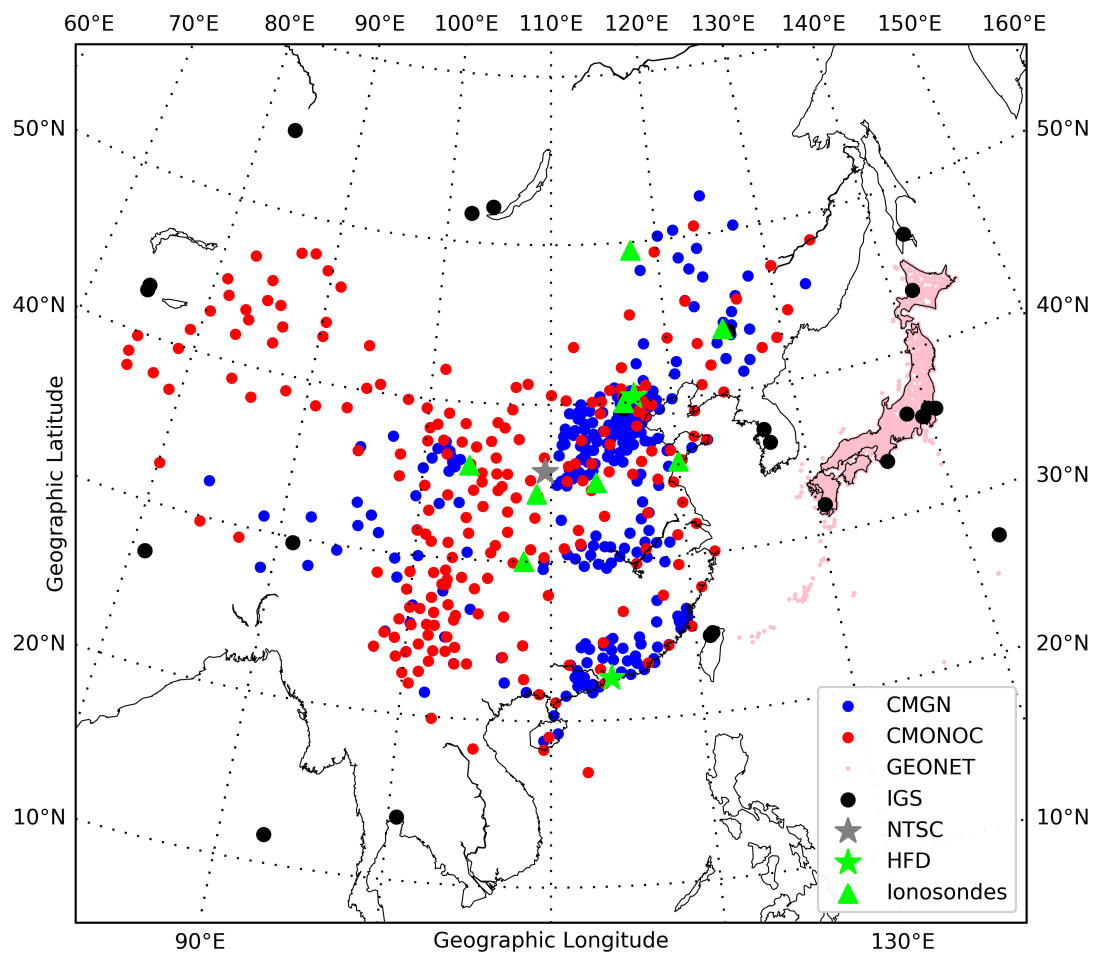
1 **Table 1.**

Lon. (°E)	Dir. (°)	Period (min)	Vt (m/s)	Vc (m/s)	Wavelength (km)
80-90	-11.2	81.1±3.4	500±40	542±31	2536±163
90-100	-7.1	77.6±5.2	552±22	670±44	2845±222
100-110	-2.9	58.8±1.5	587±47	638±76	2160±167
110-120	1.3	62.4±2.0	605±27	562±25	2184±99
120-130	7.9	94.2±1.3	647±39	673±63	3731±216

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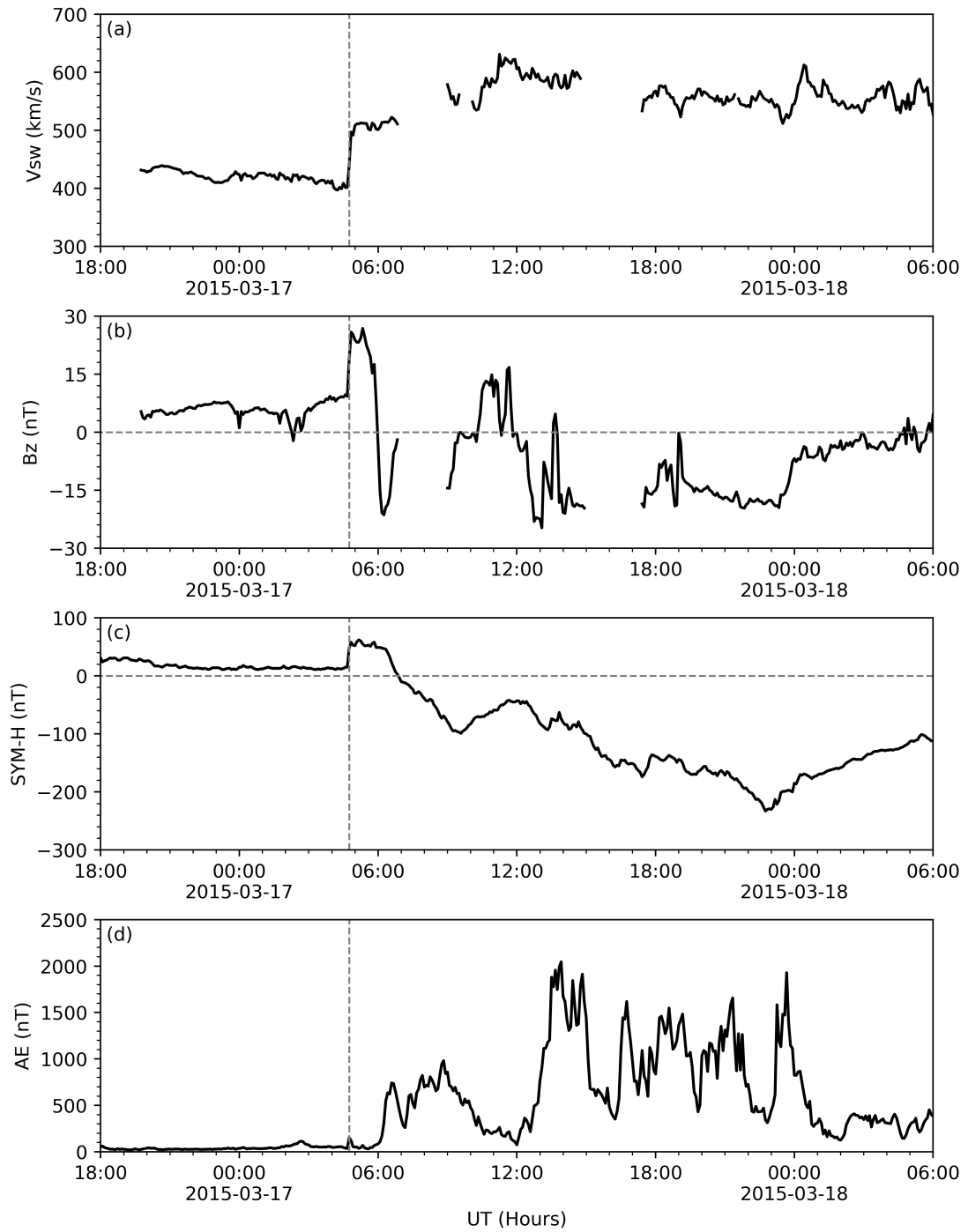
1 Figure 1.



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1 Figure 2.

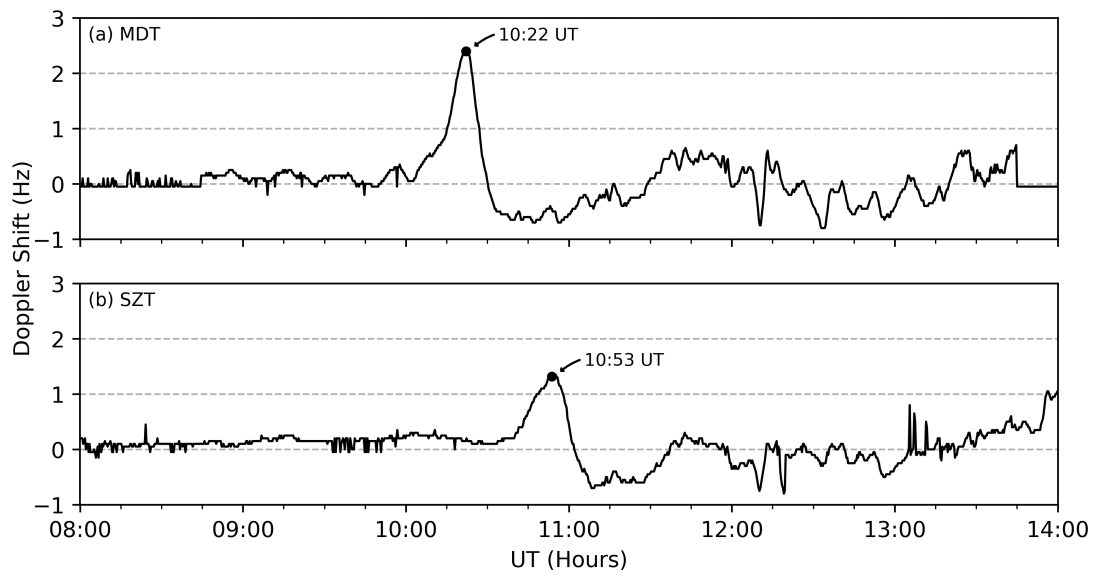


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1 Figure 3.



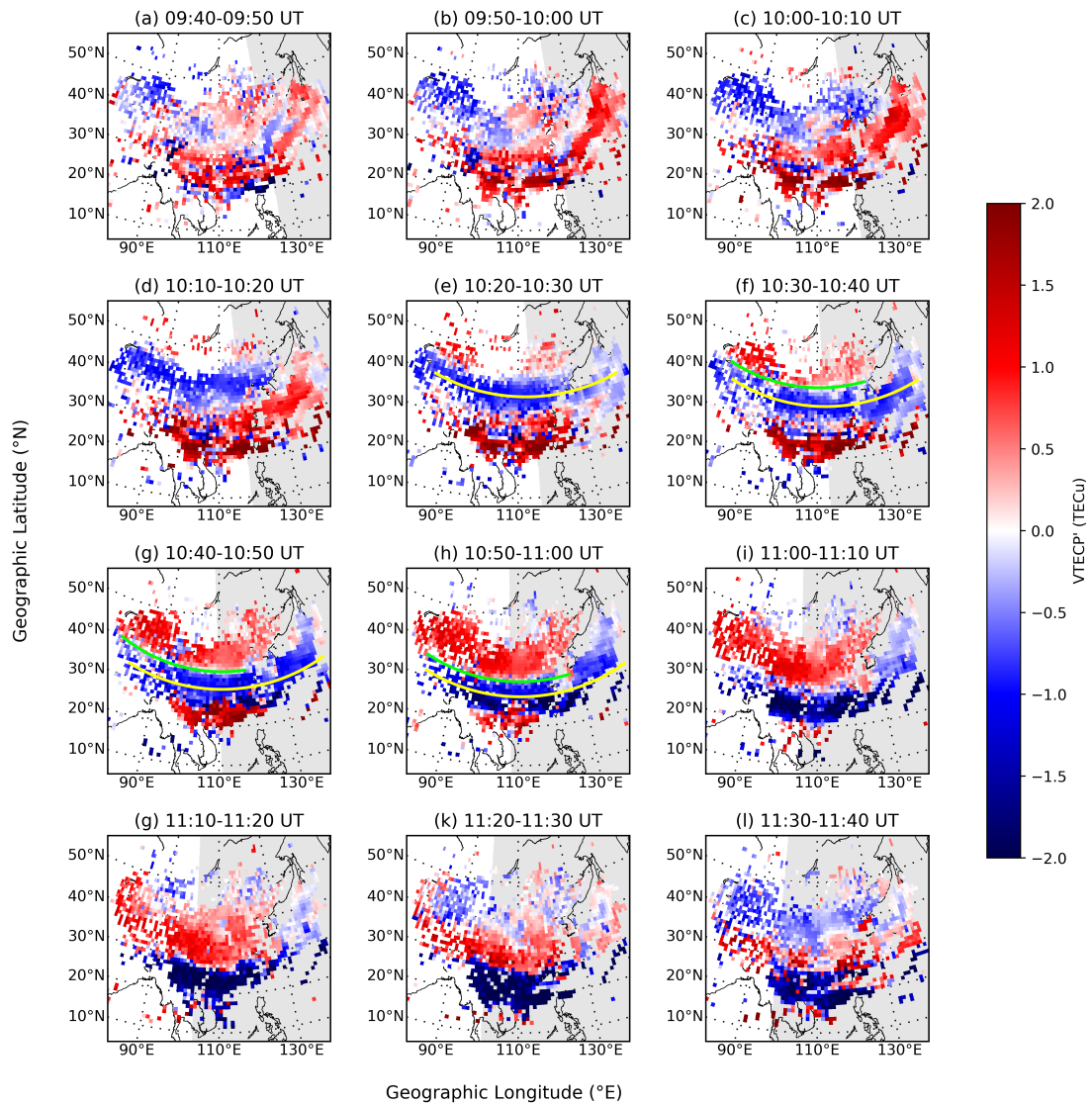
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1 Figure 4.

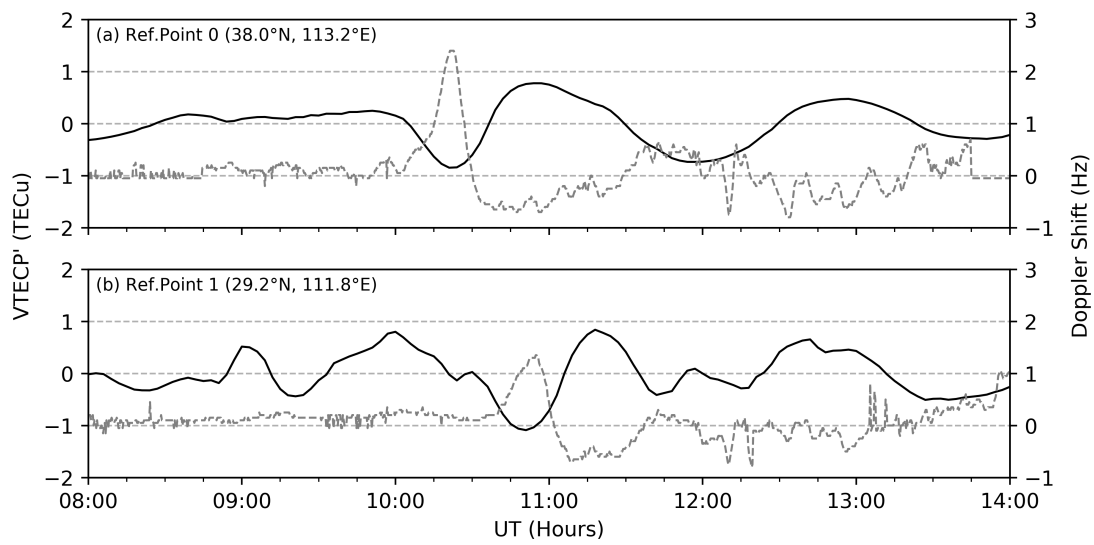


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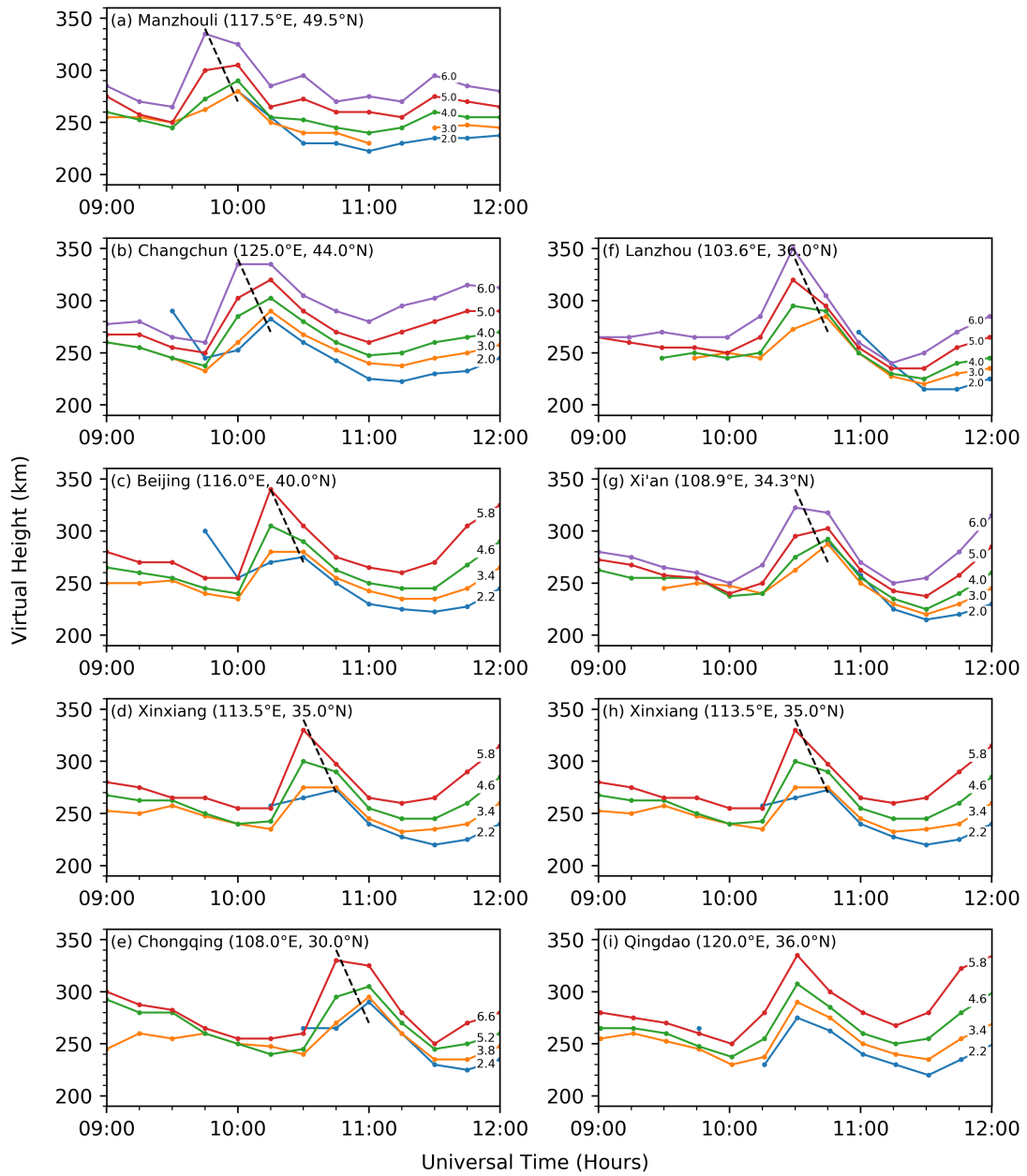
1 Figure 5.



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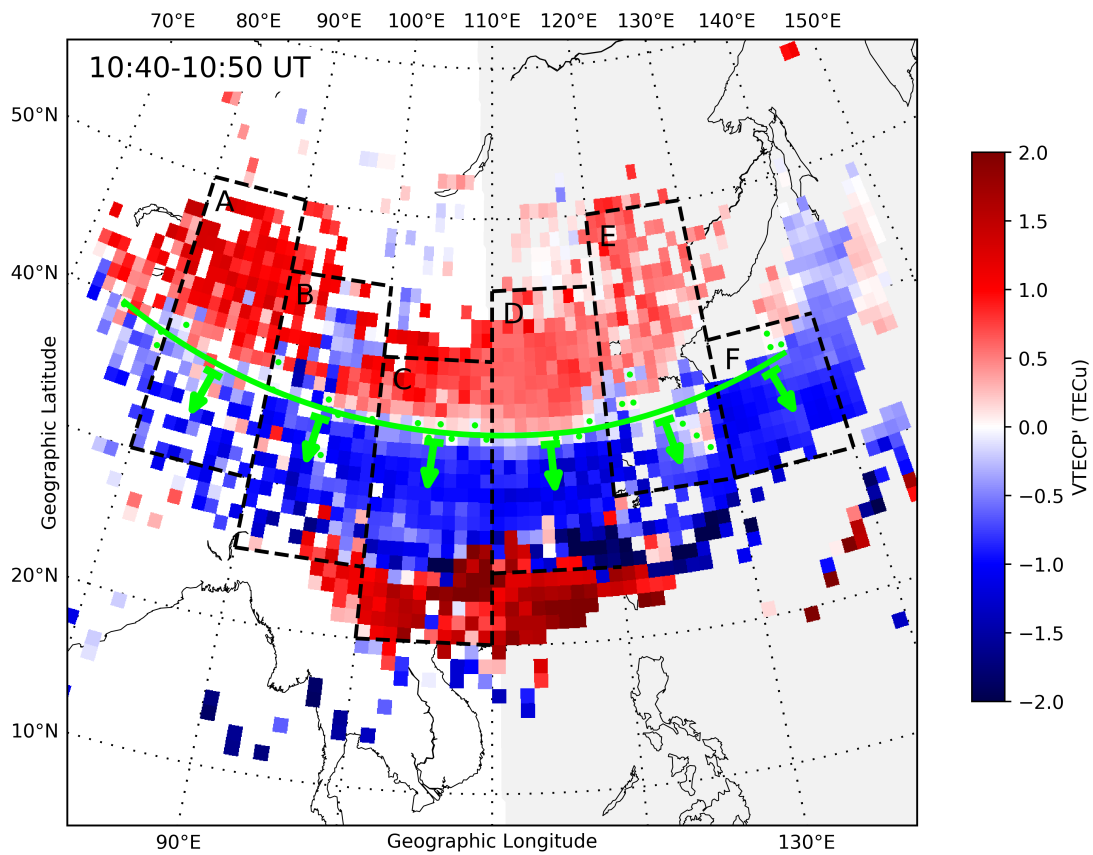
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1 Figure 6.



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1 Figure 7.



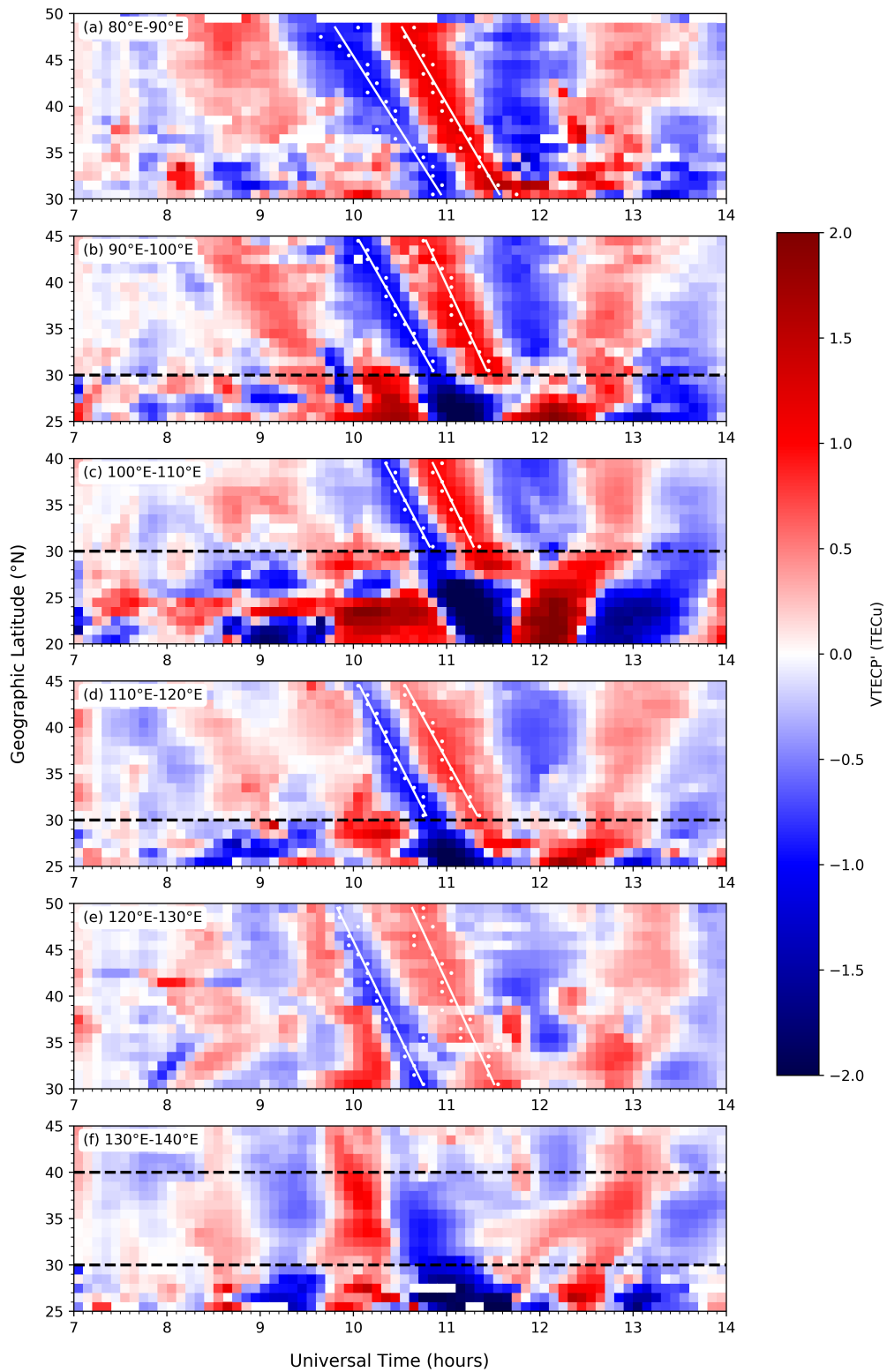
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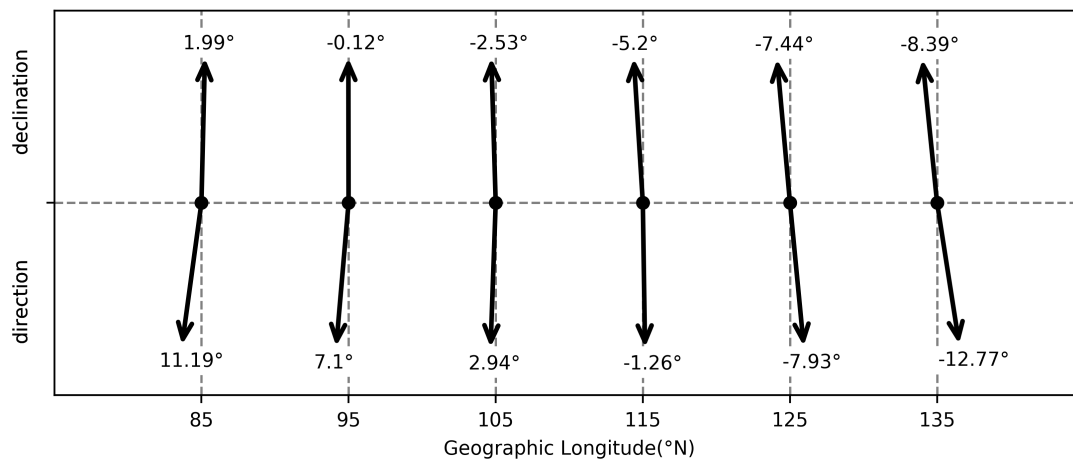
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1 Figure 8.



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1 Figure 9.

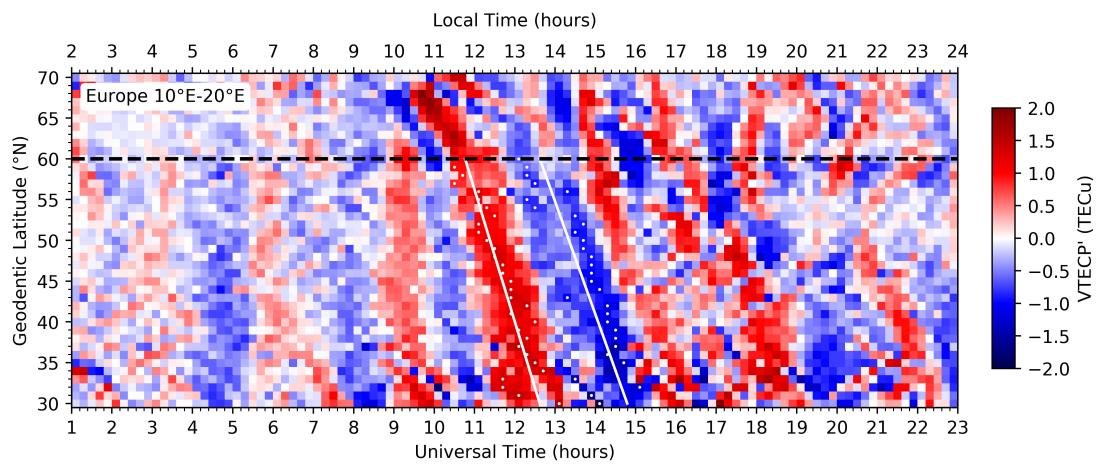


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1 Figure 10.



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