Ionospheric Total Electron Content responses to HILDCAAs intervals

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Abstract

The High-Intensity Long-Duration and Continuous AE Activities (HILDCAA) intervals are capable of causing a global disturbance in the terrestrial ionosphere. However, the ionospheric storms' behavior due to these intervals is still not widely understood. In the current study, we seek to comprise the HILDCAAs disturbance time effects in the Total Electron Content (TEC) values with respect to the quiet days' pattern analyzing local time and seasonal dependences, and the influences of the solar wind velocity to a sample of ten intervals occurred in 2015 and 2016 years. The main results showed that the hourly distribution of the disturbance TEC may vary substantially between one HILDCAA interval and another. It was found an equinoctial anomaly since the equinoxes represent more ionospheric TEC responses than the solstices. Regarding the solar wind velocities, although HILDCAA intervals are associated with High Speed Streams, this association does not present a direct relation to TEC disturbances magnitudes in low and equatorial latitudes.

Keywords: HILDCAA, TEC, Equatorial Ionosphere

1. Introduction

As similar to geomagnetic storms, High-Intensity Long-Duration and Continuous AE Activities (HILDCAA) intervals can influence the ionosphere, leading to disturbances in the ionospheric F2-region. It is well known that these intervals can change the F2-region peak height being, generally, less intense than those observed during typical geomagnetic storm events (Sobral et al., 2006; Koga et al., 2011, Silva et al., 2017).

In fact, HILDCAAs are characterized by present some criteria: i) the AE index must reach an intensity peak greater than or equal to 1000 nT; ii) the AE index needs to be almost continuous and never drops below 200 nT for more than two hours at a time; iii) the event must have a duration of at least two days, and iv) the event occurred after the main phase of magnetic storms. However, the same physical process may occur whether one of the four criteria are not strictly followed (Tsurutani and Gonzalez, 1987; Tsurutani et al., 2004; Sobral et al., 2006, Tsurutani et al., 2006; Hajra et al., 2013, Silva et al., 2017). As the main feature is the high AE index levels, in this study we have considered drops below 200 nT for more than two hours as long as the AE index value returns in high activity for prolonged hours.

The electron density perturbation in the ionosphere during HILDCAA events is different from that one occurred during geomagnetic storms in the equatorial and low latitudes stations. Since the HILDCAA presents a weak/moderate geoeffectiveness when it compares to the other forms of space disturbances, it is expected that the ionosphere response presents a different behavior.

The Total Electron Content (TEC) is an important ionospheric parameter to several studies and technologic applications. As HILDCAAs can cause F2-region peak alterations, it can be observed the enhancements/depletions in TEC profile. In fact, the TEC response to the geomagnetic storms is a well-known issue in the space physics field (Lu et al., 2001; Kutiev et al., 2005; Mendillo, 2006; Maruyama and Nakamura, 2007; Biqiang et al., 2007). However, only few studies about TEC pattern during HILDCAAs intervals have been found in the literature (de Siqueira et al., 2011).

Ionospheric storms are manifestations of space weather events, which are caused by energy inputs in the upper atmosphere in the form of enhanced electric fields, currents, and energetic particle precipitation (Buonsanto, 1999; Mendillo, 2006). Usually, ionospheric storms are associated with ionosphere responses to geomagnetic storm events. However, in a broader way, these responses happen due to magnetospheric energy inputs to the Earth's upper atmosphere, and this can occur to all kind of geomagnetic activity form. Park (1974) pointed that ionospheric storms can be understood in terms of the superposed effects of many substorm. In view of the foregoing and considering that the development of ionospheric storms during HILDCAAs intervals has not been dealt with in depth, in the current study we have focused the TEC pattern during this kind of event.

Recently, Verkhoglyadova et al. (2013) suggested that HILDCAAs associated with High Speed Streams (HSS) can be one of the external driving TEC variabilities. Indeed, the continuous energy injection and energetic particles precipitation into the polar upper atmosphere during HILDCAA intervals could modify the dynamic and chemical coupling process of the thermosphere-ionosphere system resulting in changes in the electron density. These modifications, beyond to change the auroral electron density, can be mapped to low latitudes involving electric fields disturbances, as prompt penetration electric fields (PPEF) and disturbance dynamo (DD) (Koga et al., 2011; Silva et al., 2017; Yeeram and Paratrasri, 2019).

Therefore, in the current study we have focused the TEC pattern during HILDCAAs intervals, taking into account local time dependence, seasonal dependence and high/slow speed streams influences in the equatorial and low latitude ionosphere. This paper is structured as followed: in the next section we present the HILDCAA intervals chosen to support this study as well as the GNSS receivers locations over the Brazilian region. In section 3 we show the results and discussion of the analysis and the conclusions are presented in the last section.

2. Data and Methodology

In this study was possible to construct an overall perception of the ionospheric storms occurred during HILDCAA disturbance time intervals that affect the TEC values with respect to the expected behavior for quiet days. The features studied are local time and seasonal dependences, and solar wind velocity influences.

We have selected ten HILDCAA intervals occurred during the 2015 – 2016 period. These intervals are listed in Table 1, where the two columns present the identification and the data range of each interval. The geomagnetic indices and interplanetary data used to classify the HILDCAA events were obtained from OMNIWeb Plus data and service. The Kp index data were obtained from the World Data Center for Geomagnetism, Kyoto, Japan. In this work it was used the daily Kp sum value.

The TEC mean was initially processed by a program developed at the Institute for Space Research, Boston College, USA (Krishna, 2017). The mean values of vertical TEC (VTEC) were obtained from two Brazilian GNSS stations, São Luís (SL) (2.59 S; 44.21 W) and Cachoeira Paulista (CP) (22.68 S; 44.98 W), representing the station closest to the equator and the low latitude station, respectively. The Rinex files used in this study were obtained from Brazilian Network for Continuous Monitoring of the

GNSS-RBMC Systems (RBMC). Besides that, the TEC data during HILDCAA events were analyzed and then compared with a set of three days average belonging to a quiet period, in which it refers to the three days less disturbed (ΣKp <24) of the month of the occurrence of each HILDCAA interval.

Figure 1 shows a map with the location of each GNSS station, which is represented by a red triangle. The dashed line represents the magnetic equator. The TEC data obtained during the HILDCAA intervals were analyzed and then compared to the TEC data during the selected quiet days, resulting in dTEC (dTEC = TEC mean – TEC quiet days). All the analyses done in this work took into account the dTEC values.

3. Results and Discussions

In this section, we will present the ionospheric TEC responses observed during ten HILDCAA intervals focusing on local time dependence and seasonal features and the solar wind velocity influences.

3.1 Local time dependence

A common feature of ionospheric storms is to be associated with dependence on local time, mainly when they are caused by geomagnetic storms (Titheridge and Buonsanto, 1988; Pedatella et al., 2010). However, to the best of the authors' knowledge, no study has been found analyzing this aspect when regarding HILDCAA intervals.

Figures 2 and 3 show the mean dTEC hourly values related to all HILDCAA intervals for São Luís and Cachoeira Paulista, respectively. Each panel represents a single interval from the bottom (H01) to the top (H10). The x axis is given in the Universal

Time (LT = UT – 3) and the color scale represents the dTEC values in TEC units (TECu).

Notice that the dTEC values have a greater magnitude for the low latitude GNSS station to the detriment of the closer equatorial GNSS station. The minimum and maximum values are, respectively, -16.00 TECu and 27.40 TECu for São Luís, and -37.60 TECu and 48.80 TECu for Cachoeira Paulista. These values were considered to perform the TEC hourly distribution, i. e., for each specific GNSS station, the maximum and minimum TEC values were used to analyze all HILDCAAs in the same range. This fact explains why some intervals appear too close to the quiet time pattern. We believed that since the HILDCAA events has low/moderate geoeffectiveness it was not expected high values of the dTEC.

The distribution of the dTEC effects hour-to-hour during HILDCAA intervals shows a substantial variability from one event to another. Habarulema et al. (2013) found that the negative storms effects are observed during geomagnetic storms recovery phases over equatorial latitudes. However, since HILDCAAs intervals are characterized by a long continuous phase of Dst index recovery, this does not apply. The HILDCAA intervals present the positive dTEC predominance. 60% (70%) of all intervals present a positive dTEC response during the whole event for São Luís (Cachoeira Paulista). In a more simplified definition, HILDCAA means an interval where there is always energy injection (Søraas et al., 2004; Sandanger et al., 2005). Silva et al. (2017) observed that during HILDCAA intervals it was seen the uplift of the equatorial F2 region peak height, probably due to prompt penetration electric fields. One of the main mechanisms of TEC enhancements is the rise of the ionosphere to higher altitudes where the recombination rates are small. Besides that, our results are in agreement with the results found by de Siqueira et al. (2017). They did a study comparing the TEC responses between two magnetic storms and two HILDCAAs intervals following by them, and found a great TEC variability pattern from one to another event. Hereupon, it was not possible to find a response pattern to the HILDCAA effects in the equatorial and low latitude TEC considering only the local time. There is great variability, and it is important to consider the day-to-day ionospheric variabilities as well as the separate effect of each electric fields disturbance (PPEF/DD).

Comparing both stations, Cachoeira Paulista GNSS station presented higher values both to positive as negative ionospheric storms. During the daytime hours, the latitude is responsible for the different ionospheric responses due to the presence of photoionization. This probably explains the dTEC higher sensibility to low latitude station in detriment of the closer equatorial latitude station.

Analyzing the hourly behavior of each interval from Figures 2 and 3, we observed more intensity in TEC disturbances, both for positive and negative storms, during some specific intervals. This aspect led us to make a seasonal analysis, which will be presented in the next section.

3.2 Seasonal Dependence

It is well known for geomagnetic storms that the influence of the season entails on positive/negative ionospheric storms is more pronounced in winter/summer than in equinox months (Matsushita, 1959; Prölss and Najita, 1975; Mendillo, 2006, among others). However, has not yet been established whether the occurrence of HILDCAA interval in different seasons can do different TEC disturbances.

In a recent study involving more than one hundred HILDCAA events, Hajra et al. (2013) reported no seasonal dependence, in what regards to predominant occurrence rate in any specific epoch of the year due to the solar cycle influences. They announced the HILDCAAs may occur during any month and any year, with increases in the numbers of events occurring during the solar cycle descending phase. In the current study, it was considered as seasonal dependence feature the TEC disturbances responses at HILDCAA intervals already classified in a seasonal way. The years 2015 and 2016 years comprise the descending phase of the 24th solar cycle, which made it possible to catalog an expressive number of HILDCAAs events in a short time. Among the ten intervals chosen for this study, we have separated eight ones to represent the seasonal variability, being two events for each season, taking into account the month of occurrence of each interval, and considering the seasons as they occur in South Hemisphere. The intervals are distributed according to the Table 2.

Figure 4 shows the disturbed TEC according to the seasonal classification which the blue and coral colors refer to São Luís and Cachoeira Paulista, respectively. The solid lines show an estimate of the central tendency for all values, minute-to-minute, for all days of the events belongs to the season, while the shaded area represents the confidence interval for that estimate. While the positive storms are more pronounced in the winter for geomagnetic storms, to HILDCAA intervals this season presents less geoeffectiveness, or almost none. Our results show that the equinoxes represent more ionospheric TEC responses during HILDCAA intervals than the solstices. Both equatorial and low latitude stations present positive storms during the autumn, while the spring presents a negative behavior, mainly. This equinoctial anomaly may be originated from the equinoctial differences in neutral winds, thermospheric composition, and electric fields. Additional studies are necessary to quantify how each factor can play an important role in HILDCAA seasonal TEC disturbances.

3.3 Solar wind velocities analysis

During the solar cycle descending phase, polar coronal holes migrate to lower latitudes emanating intense magnetic fields. When HSS from these low latitudinal coronal holes interact with slow speed streams (SSS) a region called Corotating Interaction Regions (CIR) is formed and it is well characterized by compressions of the magnetic field and plasma.

There are considerable works that show how HILDCAA is well associate with HSS and CIRs (Tsurutani et al., 2006; Verkhoglyadova et al., 2013). However, to be associated not necessarily means that the degree of geoeffectiveness is directly related to high speeds. Including, Yeeram (2019) suggest that Alfvén waves present during HILDCAA interval are more dominant than CIR-storms, revealing that both are controlled by different interplanetary drivers.

Figure 5 shows the solar wind velocities (V_{SW}) during each HILDCAA interval. As the Figure 4, the blue and coral colors refer to São Luís and Cachoeira Paulista, respectively. The diameter of the bubble is related to the velocity. The results showed great variability from one interval to another, even considering the intervals that occurred in the same year. In our first analysis (not shown here) we did not find a direct association or cross-correlation between the V_{SW} magnitude and the dTEC in the equatorial and low latitude GNSS stations. Kim (2007) indicated that HILDCAA intervals can be accompanied by HSS as well as SSS. It is possible to see in our results that the dTEC responses to some intervals present similar behavior to both HSS and SSS (e.g. H03, H07 and H08). This means that HILDCAA intervals can affect the ionospheric TEC, but not in a direct correlation.

4. Conclusions

For this work, the ionospheric TEC response to a sample of ten HILDCAA intervals has been studied. We have used two GNSS stations from RBMC network representing equatorial and low latitude locations. As HILDCAA can affect the equatorial ionospheric F2 region, some disturbed TEC from its quiet time pattern is found. Addressing how the ionospheric storms behave during the HILDCAA intervals is our main goal.

In summary, HILDCAAs geoeffectiveness in Earth is mainly associated with CIRs, for this reason, the HILDCAA occurrence is more recurrent in the solar cycle descending phase since CIRs play a major role during this phase. Their effects occur during magnetic reconnection due to association with southward z component of the interplanetary magnetic field and Alfvén waves present in it (Tsurutani et al., 2004). These long-lasting intervals are due to continuous injection of energy and precipitation of particles, which disturb the high latitude ionosphere. The mainly disturbs are changes in thermospheric neutral composition, temperature, winds and electric fields. Similar to geomagnetic storms, theses disturbs can be mapped to low and equatorial latitude and alter the quiet time ionosphere. However, generally, they are less intense because in one astronomical unit the CIRs are not fully developed. In this study we seek to understand the behavior of the ionospheric storm during HILDCAA intervals. The main results are highlighted below:

- The hourly distribution of the dTEC during HILDCAAs intervals may vary substantially between low and equatorial latitude. Probably, the photoionization associated with latitude is responsible for these variations;
- Despite the geomagnetic storms recovery phase presents negative ionospheric storms, this pattern do not occur during HILDCAA intervals. There is great variability from one interval to another, but, predominantly, occurs positive phase;

- Regarding seasonal features, while the positive storms are more pronounced in the winter for geomagnetic storms, this season present less geoeffectiveness, or almost none to HILDCAA intervals. The equinoxes represent more ionospheric responses to HILDCAA intervals presenting positive/negative phase predominance during the autumn/spring;
- A well-known HILDCAA feature is its association with HSS present in the solar wind. However, this association does not present a direct relation regards to TEC disturbances in low and equatorial latitudes.

To conclude, the upshot of this study is the possibility to understand how ionospheric storms behave during some HILDCAA intervals and to contribute to improving the discussions about this issue.

Data availability

The data used in this work are made publicly available on the following sites: https://omniweb.gsfc.nasa.gov/ow.html , http://wdc.kugi.kyoto-u.ac.jp/kp/index.html, and https://www.ibge.gov.br/en/geosciences/geodetic-positioning/geodetic-networks/20079-brazilian-network-for-continuous-monitoring-of-the-gnss-systems-2?=&t=o-que-e . The GPS-TEC program used in this work is available in http://seemala.blogspot.com/

Author contributions

R. P. Silva conceived the study, designed the data analysis, discussed the results and leaded writing this manuscript.

C. M. Denardini assisted to conceive the study, to design the GNSS data analysis and discuss the final results.

M. S. Marques assisted with the GNSS data analysis and with designing the figures.

L. C. A. Resende assisted to design the study and discuss the results of the study.

J. Moro assisted to design the study and discuss the results of the study.

G. A. S. Picanço assisted to discuss the results of the study and review the manuscript.

G. L. Borba assisted to discuss the results of the study and review the manuscript.

M. A. F. Santos assisted to discuss the results of the study and review the manuscript.

All the authors helped to write and to revise the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Special issue statement

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Figure captions

FIGURE 1 – Map showing the locations of the GNSS stations used in the present study. Both stations are localized in the Brazilian region and are marked by a red triangle, where SL and CP are, respectively, São Luís and Cachoeira Paulista.

FIGURE 2 – dTEC hourly values to all HILDCAA intervals to São Luís (equatorial station).

FIGURE 3 – dTEC hourly values to all HILDCAA intervals to Cachoeira Paulista (low latitude station).

FIGURE 4 – Seasonal dTEC response to HILDCAA intervals. The blue and coral lines refer to São Luís and Cachoeira Paulista, respectively.

FIGURE 5 – Solar wind velocities analysis during HILDCAA intervals. The blue and coral colors refer to São Luís and Cachoeira Paulista stations, respectively, while the bubble diameter is related to velocity (km/s).

Table captions

TABLE 1 – The date range for HILDCAA intervals identified during 2015 – 2016 years

TABLE 2 – Seasonal classification of HILDCAA intervals (according to the seasons in the Southern hemisphere).

FIGURE 1 –

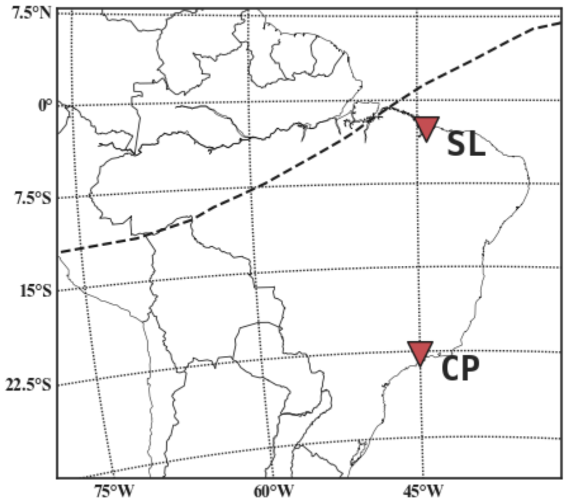
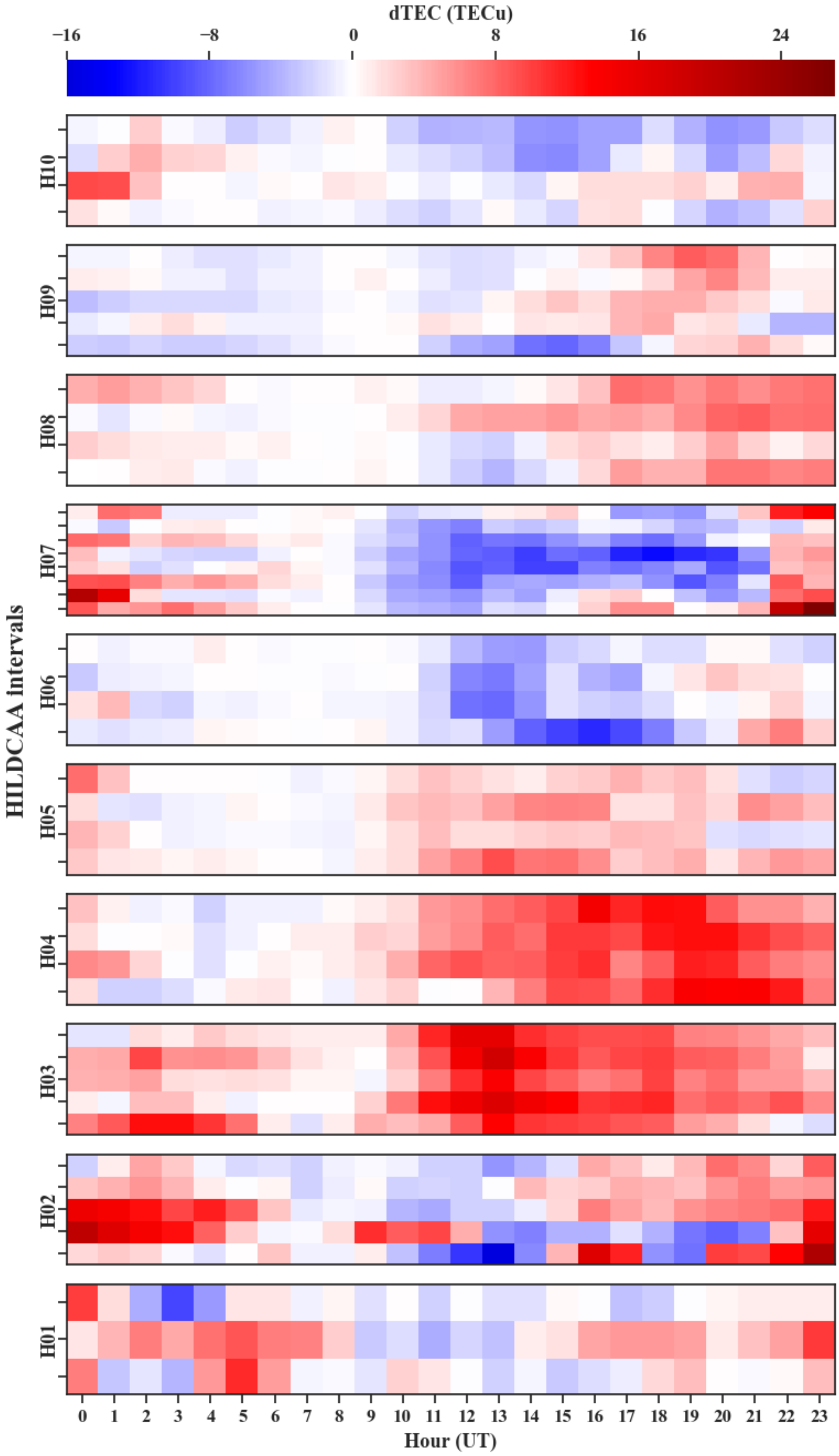


FIGURE 2 –


dTEC (TECu)
−16
−8
0
8
16
24
HILDCAA intervals
H10
H09
H08
H07
H06
H05
H04
H03
H02
H01
0
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2
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5
6
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14
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17
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20
21
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23
Hour (UT)

FIGURE 3 –

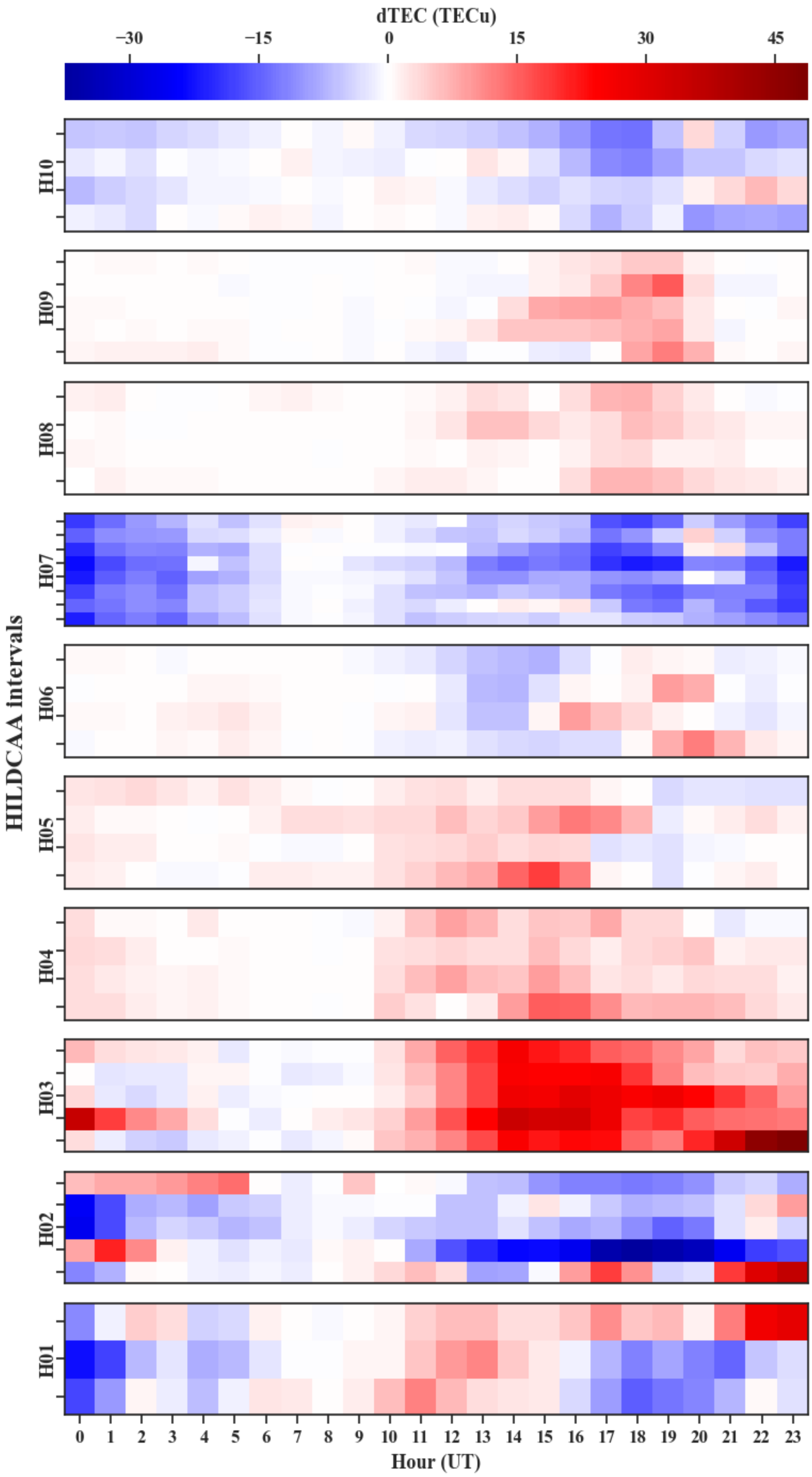
dTEC (TECu)
−30
−15
0
15
30
45
H10
H09
H08
H07
H06
H05
H04
H03
H02
H01
HILDCAA intervals
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Hour (UT)

FIGURE 4 –

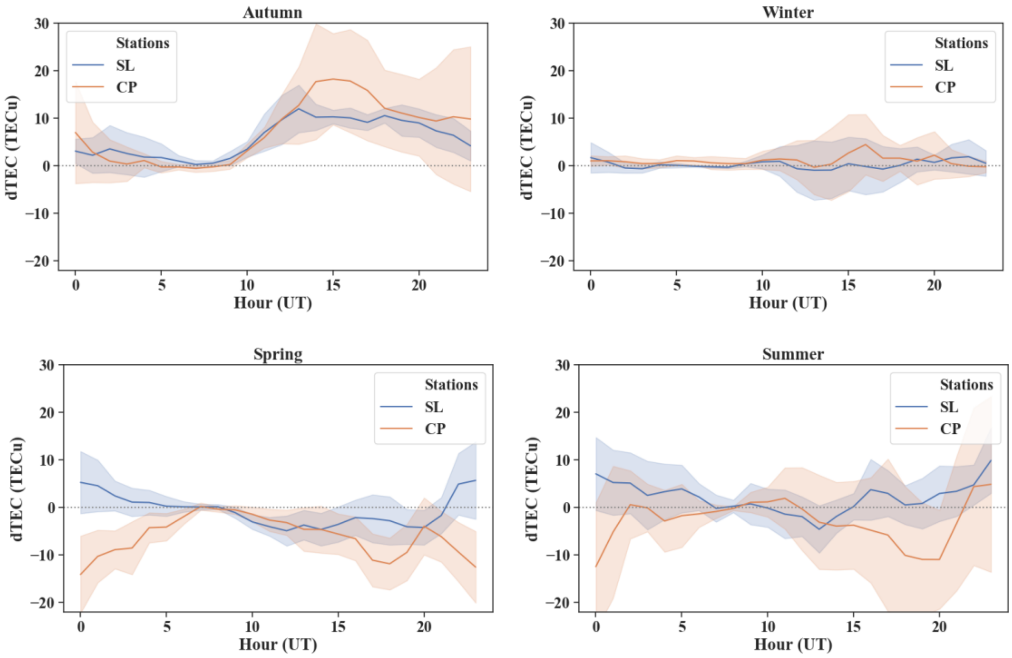
Autumn
Winter
Spring
Summer
Stations
SL
CP
dTEC (TECu)
Hour (UT)

FIGURE 5 –

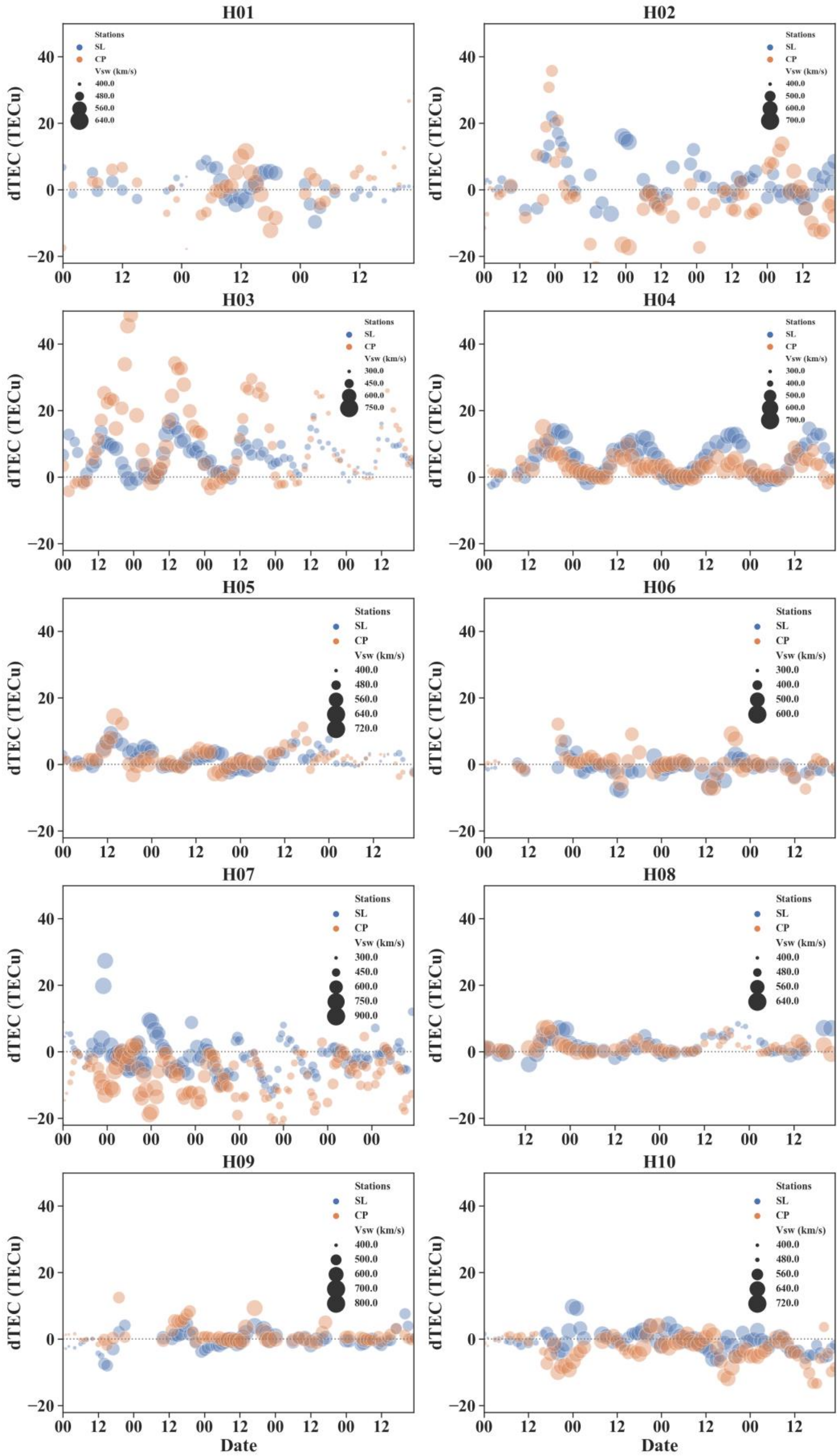
H01
H02
H03
H04
H05
H06
H07
H08
H09
H10
Stations
SL
CP
Vsw (km/s)
dTEC (TECu)
Date

TABLE 1 –

ID	Date range
H01	2015/03/01 – 03
H02	2015/03/17 – 21
H03	2015/04/16 – 20
H04	2015/06/08 – 11
H05	2015/07/11 – 14
H06	2015/08/15 – 18
H07	2015/10/07 – 14
H08	2016/07/09 – 12
H09	2016/08/03 – 07
H10	2016/12/08 – 11

TABLE 2 –

Season	HILDCAA Intervals
Autumn	H03 and H04
Winter	H05 and H06
Spring	H07 and H10
Summer	H01 and H02