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Climatology of the Traveling Ionospheric Disturbances over Europe

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Abstract

Using more than 1000 GPS receivers' estimated detrended total electron content (dTEC) data, we studied the climatology of the traveling ionospheric disturbances (TIDs) during high (2014), medium (2016), and low (2020) solar activity years over Europe. We found diurnal, seasonal, and solar activity dependency on the occurrence and propagation directions of the TIDs. Some of our results are in agreement with earlier investigations from other locations of the globe. We found a significant number MSTIDs occurrence in March 2020 a low solar activity year, for the first time. More interestingly, the present results show that the solar activity dependency of the MSTIDs occurrence varies based on the local time, that is, the post-midnight MSTIDs show a positive solar dependency and the daytime and pre-midnight MSTIDs occurrence shows negative solar dependency.

1. Introduction

Traveling ionospheric disturbances (TIDs) are wave-like undulations in the ionospheric plasma density, which are caused by atmospheric gravity waves (AGWs) originating through the forcing from the lower atmosphere and geomagnetic disturbances. The TIDs are classified into large and medium scale (LS and MS) based on their characteristics such as horizontal wavelengths, phase speed, and period. LSTIDs have horizontal wavelengths longer than 1000 km, a phase speed of 400–1000 m/s, and a period ranging from 30 min to 3 h [1]. The horizontal wavelength, phase speed, and period of MSTIDs are several hundred kilometres, 250–1000 m/s, and 15 min to 1 h, respectively. The wave-like effects of the MSTIDs are one of the main obstacles for accurate interpolation of ionospheric corrections in a medium-scale reference of the Global Positioning System (GPS) networks as the ionospheric delay is almost proportional to Total Electron Content (TEC) along the signal path and inversely proportional to the frequency squared.

It is well understood that LSTIDs are mostly generated during geomagnetically disturbed conditions [2]. On the other hand, it has been believed that MSTIDs are generated in association with AGWs originating in the lower/middle atmosphere. MSTIDs are observed both in the daytime and in the nighttime, but the causative mechanism of daytime and nighttime MSTIDs is different [3]. Investigations suggested that daytime MSTIDs are generated in association with primary and/or secondary GWs [4] mainly originating in the lower and middle atmosphere, respectively. On the other hand, the nighttime MSTID is caused by the electrodynamical processes i.e. Perkins instability associated with E- and F-region coupling [5].

An additional challenge is the proven dependence of climatology with longitude. The local time dependency and source of the daytime MSTID occurrence is reported by [4] and argued that polar atmospheric processes particularly polar vortex variabilities, and stratospheric winds are primarily responsible for controlling the occurrence of high-latitude and mid-latitude winter daytime MSTIDs. In general, daytime MSTID activity is higher during winter irrespective of longitudes [6]. Nighttime MSTIDs show seasonal and longitudinal variations over mid-latitudes. For example, 630 nm airglow and GPS TEC observations showed the occurrence of MSTIDs with two distinct peaks: a primary peak during summer and a secondary peak in winter over the Japanese sector [7]. At the same time, the semiannual variation of nighttime MSTIDs shows maxima during solstices and minima during equinoxes over North America [8] and Europe [9]. Es layers and interhemispheric coupling are proposed as possible generation mechanisms of nighttime MSTIDs and for their semiannual variation [8].

Previously, using the GPS TEC data [9] studied the statistical characteristics of occurrence rate and propagation direction of day and nighttime MSTIDs over Europe in 2008. However, the long-term climatology and solar activity dependency of the MSTIDs over European sector has not been explored well. Thus, in this study using dTEC keograms we propose a new methodology to investigate the MSTIDs and present occurrence and propagation characteristics in varying solar conditions. Data analysis and methodology is presented in section 2, results and discussions are provided in section 3 and finally summary and conclusion of the present study in given in section 4.

2. Data and Methodology

The TEC maps were derived from Global Navigation Satellite System (GNSS) observation data in Receiver

INdependent EXchange format and obtained from the regional GNSS receiver network over Europe. Maps are provided through https://stdb2.isee.nagoya-u.ac.jp/GPS/GPS-TEC/ and a list of GNSS data providers can be found at https://stdb2.isee.nagoya-u.ac.jp/GPS/GPS-TEC/gnss_provider_list.html. The temporal and spatial resolution of the TEC data is 30 seconds and the Latitude-Longitude grid is 0.25° × 0.25°, respectively.

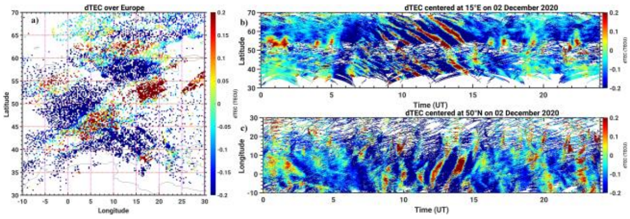

Figure 1. Presents a) A sample dTEC map over Europe at 15:00 UT, b) NS keogram, and c) EW keogram on 02 December 2020.

We estimated dTEC by subtracting 1-hr running averages from the original TEC for each pair of satellites and receivers [9]. This allows us for the investigation of TEC variations caused by MSTIDs. An example dTEC map on 02 December 2020 at 13:00 UT over Europe is shown in Figure 1a, which represents the northeast to southwest aligned blue and red bands. In this map, a vertical (horizontal) magenta (red) dotted line denotes every 5° along these lines ±0.5° averaged data is used for constructing the north-south (NS) and east-west (EW) keograms at different longitudes and latitudes, respectively.

Table 1. Identification of propagation direction using the keograms

Label	Direction	Characteristics of phase front in EW and NS keogram
1	North	EWK-aligned; NSK-progression towards north
2	East	EWK-progression towards east; NSK-aligned
3	South	EWK-aligned; NSK-progression towards south
4	West	EWK-progression towards west; NSK-aligned
5	Northeast	EWK-progression towards east; NSK-progression towards north
6	Southeast	EWK-progression towards east; NSK-progression towards south
7	Southwest	EWK-progression towards west; NSK-progression towards south
8	Northwest	EWK-progression towards west; NSK-progression towards north

The keogram is an effective tool to visualize the temporal and spatial evolution of the TIDs. Thus, it can provide more information about the TIDs characteristics as well as latitude and longitude variation of TIDs occurrence and propagations. The NS and EW keogram of dTEC on 02 December 2020 is given in Figures 1b, and 1c, respectively. The EW keogram can provide information about the east or west propagation as well as the EW-alignment of the TIDs. For example, in the present case, a periodic TEC perturbation with more than 0.2 TECU was observed between 08:00 to 17:00 UT, and in all the latitudes, the perturbation is progressing from west to east. On the other hand, the NS keogram provides us the information about the propagation in the north-south direction and NS alignment of the perturbation. By combining both EW and NS keogram observation, we can conclude that on 02 December 2020, the daytime MSTIDs are propagating towards the southeast. Based on the orientation of the phase fronts in the EW and NS keograms, we classified eight possible propagation directions that are listed in Table 2. Through visual inspections, we identified the occurrence and the direction of propagation of MSTIDs for the climatology.

3. Results and Discussion

To study the diurnal, seasonal, and solar activity dependency of the MSTIDs occurrence and propagation characteristics, we analyze three years of data in varying solar conditions viz. 2014 (solar maximum), 2016 (moderate solar activity), and 2020 (solar minimum) and for four seasons i.e., March (spring equinox), June (summer solstice), September (fall equinox), and December (winter solstice), respectively. The obtained results are presented in the following subsections.

3.1 Diurnal, and seasonal dependency of MSTIDs occurrence over Europe

We estimate the occurrence characteristics of the MSTIDs using the dTEC keogram analysis. Diurnal, and seasonal (Solstice and equinox) variations of the MSTIDs in different solar activity years over Europe are shown in Figure 2. Based on the occurrence characteristics, we classify the MSTIDs in to four categories namely, post-midnight (00-04 UT), early morning (05-08 UT), daytime (09-16 UT), and pre-midnight (19-23 UT).

In March, three dominant peaks are noted that is post-midnight (20%), daytime (60%), and pre-midnight (40%) in 2020. However, in 2016 and 2014 only post-midnight MSTIDs were observed with occurrence percentages of 30 and 50, respectively. An interesting point is that post-midnight MSTIDs occurrence is higher in 2014 than in 2016 and 2020. In September, MSTIDs occurrence is below 10% in 2016 and 2020. On the other hand, nearly 60% of post-midnight and 15-20% of pre-midnight MSTIDs were noted in 2014. Compared to all the other months the post-midnight MSTIDs occurrence is high in September 2014. Earlier investigations showed that MSITDs occurrence presents a minima in the equinoxial months [11]. In contradiction with earlier observations present study shows a significant number of post-midnight MSTIDs occurrences in equinox with a positive solar activity dependency. In addition, we also found 60% and 30% day and pre-midnight MSTIDs in March 2020.

In June, pre- (10-40%) and post-midnight (30-60%) MSTIDs were observed in all the years with maximum occurrence in 2014 and minimum in 2020. To be specific similar to the March in June also the post-midnight MSTIDs occurrence shows a clear positive variation with the solar activity. Interestingly, we have observed ~60%

of early morning MSTIDs in June 2020, however in 2014 and 2016 occurrence is less than 5%.

The daytime MSTIDs occurrence is higher in December than in any other month. These results are in good agreement with the earlier studies [3, 6, 9]. Furthermore, we also observed a negative solar activity dependency of the daytime MSTIDs occurrence with its occurrence being slightly higher during low solar activity than the high solar activity condition which is also in agreement with a recent investigation [7]. We found 20-50% of post-midnight MSTIDs are observed in the June and December solstice. Contrary to the June solstice post-midnight MSTIDs occurrence is more in 2016 and 2020 than in 2014 in December.

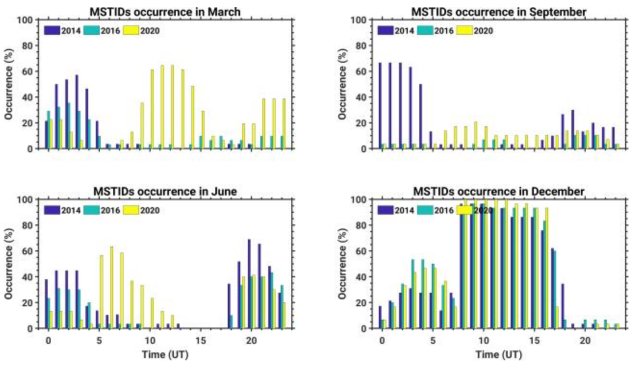

Figure 2. Shows occurrence characteristics of the MSTIDs over Europe, extracted from dTEC keograms, during equinoxes (March and September) and solstices (June and December) in high, moderate, and low solar activity years of 2014 (high), 2016 (moderate), and 2020 (low).

As mentioned earlier, the pre-midnight MSTID occurrence is high on June solstice. This result is in contradiction with [9], where they used one-year dTEC data over Europe and found the maximum nighttime MSTID occurrence in December solstice. However, the present result is in agreement with the results from the Japanese sector [10]. More surprisingly, the nighttime MSTIDs occurrence shows a positive solar activity dependency maximum occurrence in 2014 for the June solstice. However, during March 2020 ~40% of nighttime MSITD were observed and it decreased to 10% in 2016 but in 2014 no MSTID were found.

In a nutshell, the daytime MSTID occurrence is high in December. The pre-midnight MSTID occurrence is higher in June and post-midnight MSTID occurrence is higher in March, September (only 2020), and June. Both the pre and post-midnight MSTID occurrence presents a positive variation with the solar activity (except March 2020 pre-midnight).

3.2 Propagation characteristics of the MSTID using dTEC keograms

Using the keogram analysis we investigate the direction of propagation of the MSTIDs. In Figure 3, top, middle, and bottom panels represent the years of 2014, 2016, and 2020, respectively, for March, June, September, and December.

As mentioned in the previous section in March 2020, we observed a significant number of daytime and nighttime MSTIDs, all propagating southwest. In 2016, the post-midnight MSTIDs preferably propagated either southwest or west and the evening and pre-midnight hours MSTIDs mostly propagated towards south. In 2014, post-midnight MSTIDs are showing random directions such as south, west, and southwest, etc.

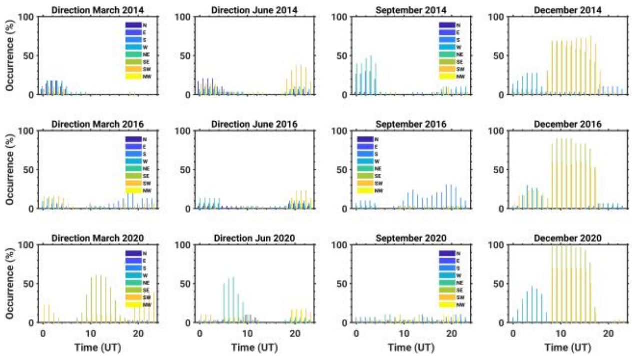

Figure 3. Diurnal, seasonal, and solar activity dependency of the propagation directions of the MSTIDs.

In June, southwest propagating MSTIDs are predominant in all the years during the pre-midnight hours, additionally, a notable number of northwest propagating MSTIDs is also observed. Furthermore, occasionally (less than 10 %) southward and westward propagating pre-midnight MSTIDs also present in all the years. In June 2020, early morning and 2016 post-midnight MSTIDs are mostly propagating in the northeast direction. The post-midnight MSTIDs during June 2014 show three major propagation directions viz south, southwest, and northeast.
In September 2016, most of the time MSTIDs show southward propagation, in 2014 northeast and southward propagation during the post-midnight hours. In September 2020, MSTIDs propagation is random (south, southwest, northwest, northeast, etc.) there is no preferable direction.
The daytime MSTIDs show two preferable directions of southeast and southwest in December for all three years. Southeast-propagating MSTIDs were more than southwest-propagating MSTIDs in the years 2016 and 2020 but in 2014 SW and SE-propagating MSTIDs were almost equal SW propagating MSTIDs were more than SE in the afternoon hours. In December, the pre-midnight and early morning MSTIDs propagated towards the west in 2020 while in 2014 and 2016 their propagation was most often either west or southwest.

3.3 Solar activity dependency of MSTID occurrence over Europe

To investigate the solar activity dependence we combined all four-month data for each year and the results are shown in Figure 4. Interestingly, post-midnight MSTIDs occurrence shows a positive solar activity dependency of highest occurrence in 2014 and lowest in 2020. On the contrary, the day and pre-midnight MSTIDs occurrence show a negative solar activity dependency of maximum occurrence in 2020 and it decreases in 2014 and 2016. This suggests that the pre-midnight MSTIDs are caused by the Perkins instability, in which the growth rate is anti-correlated with the solar activity. Similarly, the anti-correlation in the daytime MSTIDs suggests that they could be caused by secondary gravity waves [7].

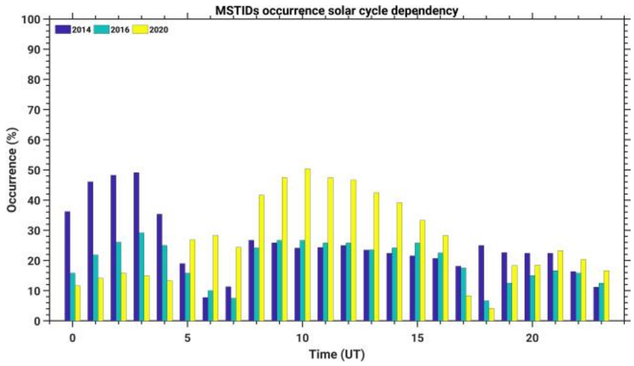

Figure 4. MSTIDs occurrence in high (2014), moderate (2016) and low (2020) solar activity years.

4. Conclusions

Using the dTEC data during high, moderate, and low solar activity conditions, we studied the climatology of diurnal seasonal and solar dependency of the MSTIDs occurrence over Europe. Our investigation reveals that MSTIDs occurrence shows four peaks of post-midnight, early morning, day, and pre-midnight based on the season and solar activity. We found a significant number MSTIDs occurrence in March 2020 a low solar activity year, for the first time. More interestingly, the present results show that the solar activity dependency of the MSTIDs occurrence varies based on the local time that is the post-midnight MSTIDs show a positive solar dependency, and daytime and pre-midnight MSTIDs occurrence shows negative solar dependency.

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