The effect of space weather on the ionosphere at the 15° meridian during CAWSES-II

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Abstract. Space weather determines the ionospheric state, knowledge of which is especially important during disturbances. To study this state, the period March 7-17, 2012, recommended by SCOSTEP for detailed studies and called CAWSES-II, was selected. This period has a number of features of the behavior of the solar wind parameters SW and the interplanetary magnetic field IMF. In this paper, we study their relationship with the total electron content TEC and the critical frequency foF2 of the ionosphere at the meridian of 15°, near which several ionosondes are located. The correlation coefficients of TEC and foF2 with the SW and IMF parameters for the month and the selected period are determined. For foF2, the difference between the correlation coefficients for the month and March 7-17 is less than for TEC. The possibility of using TEC to determine foF2 was shown, since the response of foF2 to disturbances was very close to the response of TEC and the variations of TEC and foF2 have been occurring synchronously.

1. Introduction
In the study of the ionosphere, two branches can be distinguished: climatological features and behavior during disturbances. If climatological features can have common characteristics in different regions and in time, then the situation during disturbances is more complicated, since there is not a single repeating magnetic storm. Nevertheless, the search for certain objective laws of behavior of ionospheric parameters and relationships with space weather parameters is necessary. This is especially true for latitudinal variations. There can be various arguments for choosing geomagnetic disturbances for research. In this work, the period of March 7-17, 2012, recommended by SCOSTEP for detailed studies and called CAWSES-II (The Climate and Weather of the Sun-Earth System), was chosen. A rather large number of papers have been devoted to this period. In the paper [1], details of solar and geomagnetic conditions are presented, which are then used in other papers. Magnetic storms (MS) occurred on 7, 9, 12, and 15 March with peak SYM-H intensities of -98 nT, -148 nT, -75 nT, and -79 nT, respectively. These are called the S1, S2, S3, and S4 events. It was shown that three of the storm main phases (S1, S3, and S4) were caused by IMF Bsouth sheath fields and the S2 event was associated with a magnetic cloud. In [2], a longer period of March 5–20, 2012 was used to present a new method for detecting plasma structures in the high-latitude zone. It is shown that after each onset of southward IMF there is an enhancement of TEC. The authors detected the rapid expansion of the auroral oval during geomagnetic storms, which occurred with the onset of southward IMF polarity and rapid enhancement of auroral electrojet. For the analyzed events the equatorward boundaries of oval...
were detected at ~60 ° and ~55 ° of geomagnetic latitudes on day- and night-side, respectively. In [3], the period 7–10 March 2012 was analyzed in detail, the physical causes of the features of the TEC behavior in this period are indicated. So, the authors concluded that the interplanetary solar wind controls largely the ionospheric response, and with reference to the papers [1, 4] showed that an interplanetary shock detected at 0328UT on 7 March caused the formation of prompt penetrating electric fields in the dayside that transported plasma from the near-equatorial region to higher latitudes forming a giant plasma fountain which is part of the so-called dayside ionospheric super-fountain. The super-fountain produces an increase in TEC which is the dominant effect at middle latitudes, masking the effect of the negative storm. The dynamics of large scale traveling ionospheric disturbances linked to auroral electrojet intensification was found and modeled. In [5*], it was shown that event S4 was affected by high speed stream, which caused the extended recovery phase with increased auroral activity. Near the meridian of 15 °, there are several ionospheric stations, which allow us to trace the latitudinal dependence of the influence of space weather on the ionosphere. With higher resolution, this effect can be traced using TEC, since TEC shows the latitude of the transition from positive/negative to negative/positive phase.

2. The latitudinal dependence of the ionospheric response to disturbances in the period March 7-17, 2012

Figure 1 shows the behavior of the Dst and AE indices in March 2012, which characterizes the geomagnetic situation. Examples of latitudinal distributions of TEC along the 15 ° meridian are given in figure 2. The x-axis represents geographic latitude.

![Figure 1](image1.png)

**Figure 1.** The behavior of the indices Dst and AE in March 2012.

![Figure 2](image2.png)

**Figure 2.** The behavior of TEC in quiet conditions and during disturbances along the meridian of 15°.

The upper left drawing represents the monthly medians of TEC, whose behavior is close to the behavior in quiet conditions. The calculations were performed in 2-hour increments in accordance
with the resolution of the global JPL maps, but some curves are not shown if they are close to each other (for example, curves in UT10 and UT14, UT8 and UT18, UT6 and UT20). TEC values increase with decreasing latitude with a maximum value of ~ 50 TECU. At night, a trough is seen near 57.5°. The rest of the graphs show the latitudinal distribution on disturbed days. On March 7, 2012, it can be seen that during the daytime hours (UT10 and UT12), ionization increased strongly in the low latitude zone, which is due to the super-fountain effect according to the opinion of [1, 3-4]. In the evening hours (UT18), the trough became deeper and shifted to lower latitudes. On March 9, 2012, a large zone was formed from high to low latitudes with weak gradients, but in the daytime there is a noticeable increase even compared to the behavior of March 7 during the observation of a magnetic cloud [1]. On March 16, a negative disturbance covered all latitudes: TEC values almost halved compared to March 9. The highest TEC values are observed in UT12. The trough deepens compared with its behavior in quiet conditions and shifts to the region with lower latitudes: at UT18 it is 60°, at UT20 - 57.5°, at UT22 - 55°.

The detailed effect of space weather on TEC behavior can be represented using latitudinal profiles for several hours during a selected period. The results for UT0, UT6, UT12, UT20 are given in figure 3. For each day, a latitudinal dependence is given, similar to that shown in figure 2.

![Figure 3](image)

**Figure 3.** Dynamics of TEC disturbances in the period of March 6-17, 2012.

The behavior of TEC on March 6 is close to the median, but at high latitudes in UT0 there is a slight increase in TEC associated with the behavior of the Dst index. In UT6, there is a slight decrease in TEC over the entire latitude range. In UT12 and UT18, the situation is close to quiet conditions, as on March 7 in UT0 and UT6. Only at high latitudes, a negative disturbance is observed. In UT12, with the development of the main phase of MS (S1), a negative response is visible at high latitudes and a positive response in the rest of the zone. The latitude of the change in the perturbation sign is 60°. In UT20, the latitude for changing the perturbation sign is 50°. On March 8, despite a positive surge in the Dst-index, the behavior of the TEC is close to quiet. On March 9, the strongest disturbance S2 occurred during this period with a longer recovery phase (March 10-12). In UT0 and UT6, until MS started, there is no disturbance in TEC. In UT12, the strongest response was observed with a change in the perturbation sign from plus to minus at a latitude of 45°, which is less than on March 7. In UT20, in the recovery phase, a negative disturbance covers the entire region and lasts until the first half of March 10. March 11 was a quiet day. The same can be said about the following days (March 12-14), with the exception of ionization enhancements at the lower boundary of the zone in UT0. Another magnetic storm was observed on March 15 (S4). The main phase occurred in the evening, therefore, the change in the perturbation sign occurred in UT20. In the trough latitude zone in the range 67.5° – 52.5°, the TEC values coincide, and the sign changes at the ends of the trough. On March 16, as was
seen in figure 1, in the recovery phase, a strong negative perturbation was observed in the entire region. On March 17, recovery occurred only in the UT20.

Thus, the following general features of the three MSs of the period March 7–17 can be distinguished: (1) in the main phase of the MS, the ionosphere response is negative at high latitudes and positive in the rest of the zone, (2) if the main phase occurs during the day, then the perturbation sign is changing on a smaller latitude (45 °) for a stronger MS, i.e. a wider zone of negative disturbance is observed; in the evening, the zone of negative perturbation is smaller, (3) the fundamental fact of the disturbed state is confirmed: the shift of the trough to lower latitudes and its deepening, (4) nightly amplification of TEC in the region of low latitudes on quieter days.

3. Interconnection of TEC and foF2 ionospheric parameters during disturbances

TEC characterizes the distribution of ionization from the beginning of the ionosphere to the height of measurement. In our case, this is the height of the GPS satellites (~ 20,000 km). The main characteristic of the ionosphere is the maximum plasma density $N_{mF2}$ (or/and the critical frequency $f_{oF2}$ associated with it). These values are interconnected by the equivalent slab thickness $\tau = \frac{\text{TEC}}{N_{mF2}}$ of the ionosphere. The determination of $f_{oF2}$ using TEC and $\tau$ is an important method due to the high correlation of these parameters [6]. It is believed that correlation may worsen during disturbances. For the selected study period and the 15 ° meridian, it is possible to estimate the relationship between the TEC and $f_{oF2}$ parameters according to several ionosonde data: Longyearbyen (78.2 ° N, 15.9 ° E), Juliusruh (54.6 ° N, 13.4 ° E), Rome (41.9 ° N, 12.5 ° E). The results are shown in figure 4. The first graph shows the TEC values together with the medians, the second graph, in addition to the experimental values of $f_{oF2}(\text{obs})$ and their medians, shows the frequencies $f_{oF2}(\text{rec})$ reconstructed using the TEC and $\tau(\text{med})$ by the method [7]. The third graph represents the relative deviations $\delta\text{TEC}$ and $\delta f_{oF2}$ in%.

![Figure 4. Behavior of the ionosphere parameters during the CAWSESII period.](image-url)
comparison with the median shows that they reflect the nature of the disturbance. There are not \( \delta \text{foF2} \) values on the corresponding plot owing to the absence of \( \text{foF2(} \text{obs)} \). When values of both parameters are available, a fairly good agreement is seen. On the mid-latitude station Juliusruh, daytime TEC amplification on March 7, 8, 12, and 14 was observed (UT12). In figure 3 on March 7, the change in the perturbation sign was at a latitude of 60 °, i.e. the station fell into the region of positive perturbation. On March 16, a strong negative disturbance was observed, which continued on March 17 until recovery in UT20. All \( \text{foF2} \) values were available for this station, and a good agreement between the nature of the disturbance in TEC and \( \text{foF2} \) is seen. The values of \( \text{foF2(rec)} \) are somewhat overestimated in comparison with observations, but clearly give an idea of disturbances in comparison with the median. The deviation graph indicates the synchronism of variations. The Rome station has the lowest latitude, so for it the TEC amplifications are more pronounced. The correspondence between \( \text{foF2(} \text{obs)} \) and \( \text{foF2(rec)} \) is better than for the rest of the stations. Variations of TEC and \( \text{foF2} \) occur synchronously. Thus, at all stations, the response of the ionospheric parameters to disturbances is visible. If we compare the response magnitude, then for the first MS it is greatest at high latitudes, decreases at mid latitudes and changes sign at low latitudes. For the second MS, the greatest response was at the Juliusruh station and the smallest at the Rome station. The fourth MS caused the greatest response at Rome station. This corresponds to the latitudinal dependence of TEC. Thus, TEC can be used to assess the nature of disturbances, and \( \text{foF2(rec)} \) to assess the state of the ionosphere, including in those zones where there are no ionosonde.

4. Connection of TEC with space weather parameters
This section mainly includes an assessment of the correlation coefficients between TEC and space weather parameters. As the parameters of space weather, the average daily values of the solar radiation index F10.7, the geomagnetic activity indices Dst and Kp, the total interplanetary magnetic field strength IMF, and the density of solar wind protons Np are used. In figure 5, the corresponding coefficients \( \rho(\text{TEC-foF2}) \), \( \rho(\text{TEC-F10.7}) \), \( \rho(\text{TEC-Dst}) \), \( \rho(\text{TEC-Np}) \) for the four stations considered are given.

![Figure 5](image.jpg)

**Figure 5.** Connection of TEC with various parameters for four stations during the month and the disturbed period.

The monthly average values of the coefficients in the diurnal course and the coefficients calculated for the disturbance period of March 7-17, 2012 are shown in figure 5. The \( \rho(\text{TEC-Kp}) \) coefficients are not given, since they are an almost complete mirror reflection of the \( \rho(\text{TEC-Dst}) \) coefficients with respect to the x axis, and \( \rho(\text{TEC-IMF}) \), since they are smaller than \( \rho(\text{TEC-Np}) \).
The coefficients ρ(TEC-foF2) show that, with rare exceptions, a high correlation between these parameters is confirmed. Only for the evening hours for the Longyearbyen station and the morning hours for the Juliusruh station, the correlation during the periods of disturbances is weakened compared with the monthly average values. The remaining coefficients have a daily cycle. For the correlation coefficients ρ(TEC-F10.7), an unexpected result was obtained in the form of negative values of the coefficients, but the same results were obtained for foF2 with the exception of the Juliusruh station, where all monthly values are positive and quite high. High daily values ρ(TEC-F10.7) during periods of disturbances indicate the joint role of these two parameters. The monthly average values ρ(TEC-Dst) decrease with decreasing latitude. The coefficients ρ(foF2-Dst) behave similarly. One can see the absence of any definite dependence of the coefficients on the time of day, which indicates that with an increase/decrease in the Dst index, the TEC values can both increase and decrease. For the parameter Np, there is a slight decrease in the correlation between the TEC and Np during disturbances, most pronounced for the Juliusruh station.

5. Conclusion
A study of the behavior of TEC during disturbances and the relationship with the parameters of SW and IMF in the period March 7-17, 2012 was performed. In previous publications, the unusual behavior of the parameters of SW and IMF was found. In this paper, such features of TEC behavior were confirmed in this period as: an increase of TEC during the southern direction of IMF, expansion of the zone of the equatorial anomaly due to the effect of super-fountain. The new results are the TEC latitudinal dependences for various UTs, showing the transition from the positive to the negative phase and vice versa compared to the median. The correlation coefficients of the TEC with the SW and IMF parameters did not reveal the prevailing factor for all time of the day. The prevalence is possible for specific hours, different for different stations, and, consequently, latitudinal zones. For practical applications, it is important to use TEC to determine foF2, especially when there are data gaps. It was shown that during disturbances there is a high correlation between TEC and foF2, which indicates the possibility of using TEC.

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