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Measurement and Comparison of Total Electron Content for Assessment of Ionospheric Models during April 7, 2000 Geomagnetic Storms

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ABSTRACT: Ionospheric modelling is a major approach to predicting the behavior of the ionosphere particularly in regions where Global Positioning Systems (GPS) are not readily available. Hence, the objective of this paper is to measure and compare Total Electron Content (TEC) for Assessment of Ionospheric Models during April 7, 2000 Geomagnetic Storms. Measured Total Electron Content (TEC) from experimental records (April 5 - 9, 2000) were compared with those predicted by the improved versions of the International Reference Ionosphere (IRI-2012 and IRI-Plas2015) and the NeQuick models. The mean values of TEC in five days of the months were plotted against the hours of the same day and the root mean square error of the models which shows their deviations from the GPS data were used to observe the diurnal variations in TEC and the performances of the ionospheric models respectively. The data obtained confirmed that TEC has their highest values during the midnight period and lowest values during the sunset period at the Australian stations and we also confirmed that European stations had their highest TEC values during the daytime and their lowest values during the night time. We affirmed that the North American station in USA had its highest TEC values during the night time and lowest values during day time. The Asian station had its highest TEC values during the day time and lowest values during the midnight period. However, NeQuick, IRIPlas2015, and NeQ-IRI produced better estimate of TEC than the IRI-2001 and IRI-2001COR at all locations during the phases of the geomagnetic storm.

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A geomagnetic storm, sometimes known as a solar storm, is a brief disruption of the Earth's magnetosphere brought on by an interaction between the magnetic fields of the Sun and the Earth. A solar Coronal Mass Ejection (CME) or a co-rotating interaction region (CIR), a fast-moving stream of solar wind emanating from a coronal hole, may be the disruption that causes the magnetic storm (Adewale *et*

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al., 2013). The solar cycle, the frequency of geomagnetic storms rises and falls. Geomagnetic storms are more frequent at solar maximum, and most of them are caused by CMEs. Although CIR storms are more numerous during solar maximum than at lowest, they are the primary cause of storms during solar minimum. The magnetosphere is initially compressed by the rise in solar wind pressure. The magnetic field of the solar wind interacts with the magnetic field of the Earth and releases more energy into the magnetosphere. Both interactions result in an increase in the electric current in the magnetosphere and ionosphere as well as an increase in the plasma mobility in the magnetosphere (caused by an increase in the magnetosphere's internal electric fields). Electric current in the magnetosphere generates a magnetic force that pushes the boundary between the magnetosphere and the solar wind during the main phase of a geomagnetic storm. On 4 April 2000, a coronal mass ejection (CME) took place close to the western limb of the Sun and the shock front of the CME hit the Earth’s magnetosphere on 6 April (Adewale *et al.,* 2011). This shows that the geomagnetic storm observed during 7 April 2000 was driven by a Corona Mass Ejection (CME). Geomagmetic storms have great influence on the earth’s ionosphere and it usually leads to changes in ionospheric density structure (Ahoua *et al*., 2015). The sharp and rapid changes in Total Electron Content (TEC) are very important conditions for eruptions of ionospheric plasma density irregularities which invariably causes scintillations in radio waves (Akala *et al*., 2013). The effects of geomagnetic storms can either increase or decrease the electron density in the ionosphere therefore making the performances of the models to vary drastically. Another phenomenon that makes the performances of empirical models to show great variations is the strong force from the lower atmosphere that coupled with the ionosphere during the geomagnetic period (Akala *et al*., 2015; Akala *et al.*, 2021; Arikan *et al*., 2008; Bidaine *et al* 2006a; Bidaine *et al* 2006b; Bilitza *et al*., 2014). The TEC values high greater in the low and equatorial latitude than the middle and high latitude so also the models deviations from the GPS data will be higher at equatorial and low latitude (Bolaji *et al.*, 2017) .The NeQuick is admired because of its improved performance in predicting the topside ionosphere, and consequently versions of the IRI model from 2007 and later have included the topside formulation of the NeQuick, and has adopted it as the most mature of the different proposals to compute the topside part of the IRI electron density profile . The NeQuick includes routines that compute the electron density along any ray-path from ground to GNSS satellite altitudes of about 20200 km, and so it is appropriate, and eases comparison with GNSS measurements (Huttunen *et al.,* 2002). NeQuick was also specifically designed to calculate the electron concentration as a function of geographic position, height, solar activity and time for trans-ionospheric applications as investigated by Karia *et al.,* 2015. Maltseva *et al.,* 2012 reported that International Reference Ionosphere (IRI) is an empirical model which is the most extensive and intensively used model. It provides many ionospheric parameters such as the ion density (O+, H+, He+, N+, NO+, O+2, Cluster ions), equatorial vertical ion drift, vertical ionospheric electron content (VTEC) e.t.c. Hence, the objective of this paper is to measure and compare of Total Electron Content (TEC) for Assessment of Ionospheric Models during April 7, 2000 Geomagnetic Storms.

MATERIALS AND METHODS

Data Collection: The data used in this research were obtained from eight GPS stations located in different regions of the world for the year 2000 in the month of April for five days (5 – 9). The GPS stations were stations located in the Low Latitude Region, Middle Latitude Region, and High Latitude Region. The year 2000 was a year of high (maximum) solar activities with severe geomagnetic storms. The year 2000 also is in solar cycle 23 with sunspot number (SSN) of 120.8, it has the most recent solar maximum activities in the solar cycle 23. The ionospheric models used in this research work are the NeQuick2, NeQuick-IRI, IRI-2001, IRI01-Cor, and IRIPlas2015. The online uniform resource locator (URL) for IRI-2012, IRI-Plas 2015 and NeQuick-2 model can be found at the National Space Science Data Center (NSSDC), USA, IONOLAB Ionospheric Research Laboratory, Turkey and International Center for Theoretical Physics (ICTP), Italy website at http://modelweb.gsfc.nasa.gov/iono/iri.html, http://ionolab.org and http://tict4d.ictp.it/nequick2/nequick-2-web-model, in that order. The two measured (experimented) TEC data used in this present research are the GOPI and IONOLAB TEC. The two sources of the measured TEC data where acquired using MATLAB software script.

Methodology: In this research work, observed data (measured) gotten from the Ionolab software script and Gopi software, were compared with data from IRI-2001, NeQuick2 and IRI-Plas2015 Models. The TEC values are calculated from these URL by querying an online interface using the call command on an operating system terminal. Both IRI-Plas2015 and NeQuick-2 have the capacity of ingesting experimental values of TEC (Maltseva, *et al.*, 2013). Corresponding monthly TEC values were obtained from the NeQuick-2 using the windows executable program created from the FORTRAN source code which was obtained from the Ionosphere Radio propagation Unit of the T/ICT4D Laboratory (https://t-ict4d.ictp.it/). (Okoh *et al.*, 2018).

To maintain consistency in the running of all the models, we make sure that no extra input option was initiated for IRI-Plas 2015. We also initiated NeQuick-2 without ingesting any observed TEC. Then, we employed all the three options of IRI-2012 model (IRI-2001, IRI-2001COR and IRI-2001NeQuick). For convenient assessments of these models with the observed GPS TEC, all the 8-station day-to-day TEC values were computed using all the models as reported by Olwendo *et al.*, 2013. Olwendo *et al.*, 2016 reported that the GPS data is in Receiver Independent Exchange (RINEX) format. RINEX is data interchange format for raw satellite navigation system data. The RINEX observation files were processed by the GPS-TEC analysis application software, developed by Gopi Seemala of the Institute for Scientific Research, Boston College, USA. The accuracy of the IRI model in a specific region and/or time period depends on the availability of reliable data for the specific region and time since it is a data-based model (Oyedokun *et al.*, 2020; Rabiu *et al.*, 2014; Salih *et al.*, 2017; Zakharenkova *et al.*, 2015).

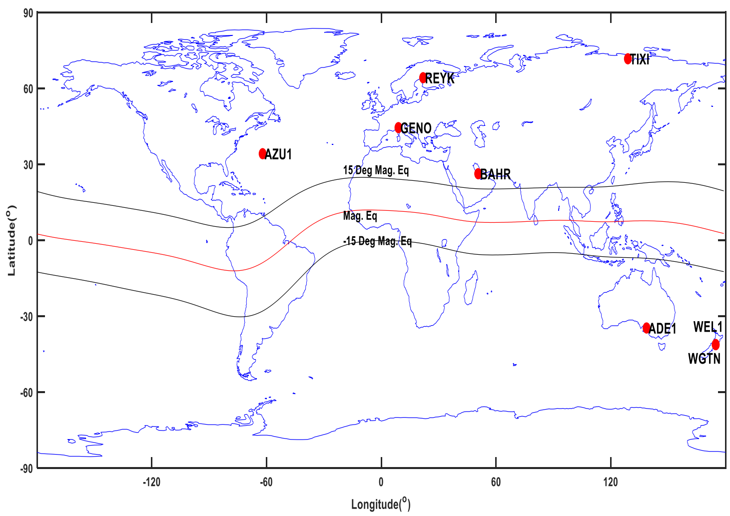

Fig 1: Map showing the study locations (From MATLAB SCRIPT developed by Dr. Daniel Okoh)

Table 1: GPS stations showing country of location, station code name, geographic and geomagnetic coordinates.

Station Code	Location	Latitude	Longitude
ADE1	Salisbury, Australia	-34.73°S	138.65°E
AZU1	Azusa, USA	34.13°N	117.92°W
BAHR	Manama, Bahrain	26.21°N	50.61°E
GENO	Genova, Italy	44.42°N	8.92°E
REYK	Reykjavik, Iceland	64.14°N	21.82°W
TIXI	Tixi, Russian Federation	71.63°N	128.87°E
WEL1	Wellington, New Zealand	-41.27°S	174.78°E
WGTN	Wellington, New Zealand	-41.32°S	174.81°E

The root-mean-square error (RMSE) has been used to quantify the performance of the models, and it can be calculated as equations 1 and 2.

$$RMSE = \sqrt{\sum_{i=1}^{N} \frac{1}{N} (TEC_{obs} - TEC_{model})^2} \quad (1)$$

where $TEC_{obs} = Observed\ TEC$ and $TEC_{model} = Model\ TEC$

$$RMSE_{average} = \frac{1}{N} \sum_{i=1}^{N} RMSE_i \quad (2)$$

where RMSE=Root Mean Square Error

RESULTS AND DISCUSSION

The plots below show the results of the observed and predicted TEC values from eight different GPS stations around the world. These GPS stations were centered at four different continents which includes Europe, Australia, North America, and Asia. The countries considered within these continents are Italy, Iceland, Russia, Australia, New Zealand, U.S.A, and Bahrain.

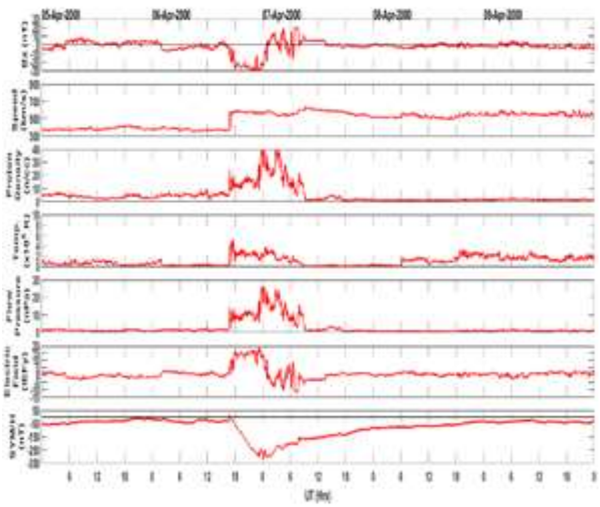

Fig. 2: Interplanetary parameters for all the phases of geomagmetic storms (a) Interplanetary Magnetic field B, IMF B_z (b) Solar wind plasma speed V_s (c) Solar wind proton density D_s (d) Solar wind plasma flow pressure P_s (e) Electric Field E_y (f) Local time storm minimum SYM/H during April 5-9, 2000.

Interplanetary Parameters Variations: From Figure 2, the interplanetary magnetic field IMF B_z experiences forward shock and decreases sporadically on April 6, 2000 with its value reaching -30 nT at 18:00 UT around the post noon period of the day (Oyedokun *et al.*, 2020). This B_z value was maintained between 18:00UT and 23:00UT of the same day. At 01:00 UT on the 7 April 2000 (the storm day), there was a sharp increase in the value of B_z from -30nT to ~ 20 nT at exactly 02:00 UT of the day. This fluctuation in IMF B_z occurred as a result of CME from the outer space. This shock was later normalized at around 08:00 UT, and was maintained till 9 April, 2000. The Solar wind plasma speed V_s maintained a uniform value of ~350 km/s from April 5, 2000 to around 17:00 UT during the sunset period of 6 April 2000. At this same time, the Solar wind plasma speed experiences a sharp increase up to ~550 km/s. This increase was followed by a slight decrease from 550 km/s to 500 km/s during the early morning hours (pre-sunrise) of 7 April, 2000. During the pre-noon period at around 09:00 UT of the same day, the value of V_s increases back to 550 km/s. A steady speed of 500 km/s was noticed at around the post noon period, which was experienced from around 00:00 UT (mid-night period) of 7 April 2000 to the same time of 9 April, 2000. Solar wind proton density D_s has a value of ~5 n/cc during the mid-night hours and attained an increase in value of D_s of about ~7n/cc at around 03:00 UT period of 5 April 2000. This increase in value of Solar wind proton density was followed by a sharp decrease to ~2 n/cc at exactly 06:00 UT hours of the same day. This minor fluctuations of the solar wind proton density continued till around 16:00UT (pre-sunset period) of 6 April, 2000. At exactly the pre-sunset period (17:00UT), of April 6 2000, there was a drastic increase in the value of D_s up to ~25n/cc and this value later decreased during the post sunset till the night period of the same day. On the 7 April 2000, the highest values of D_s was recorded, these values have two peaks at exactly 01:00UT and 03:00UT (post-midnight period) periods of the same day. The value of Solar wind proton density D_s dropped drastically to its minimum level of 0n/cc at around 09:00UT. This was followed by a slight increase around the post noon period and later decreased to the minimum. This minimum value was maintained till 9 April, 2000. The Temperature (T_s) has a value of ~1 X $10^5 K$ mid-night period till the sunset period on April 5 2000. At ~17:00UT, the temperature was observed to be the lowest which was 0K till ~23:00UT. There was a slight increase in the temperature at the post- midnight period around ~02:00UT on 6 April 2000, which was followed by a sharp drop in the temperature to 0K from ~03:00UT on the 6 of April to ~17:00UT on the same day. The highest temperature was observed to be ~5 X $10^5 K$ at the pre-sunset period of 6 April 2000, which was followed by a sharp decrease to about ~1 X $10^5 K$ at ~06:00UT (sunrise period) of the geomagnetic storm day (April 7 2000). A decrease in temperature was also observed to a 0K level at ~09:00UT on the same day which persisted till~06:00UT on 8 April 2000. The temperature increases from this time till the end of April 9 2000, At ~06:00UT of April 8 2000 till ~00:00UT of April 9 2000. The temperature was noticed to fluctuate between ~1 X $10^5 K$ and ~3 X $10^5 K$.

Table 2: Shows the Time zones for GPS stations and their corresponding period of time.

Time (Hours)	Period
01:00-05:00	Post-Midnight
06:00	Sunrise
07:00-10:00	Post-Sunrise
11:00	Pre-Noon
12:00	Noon
13:00-15:00	Post-Noon
16:00-17:00	Pre-Sunset
18:00	Sunset
19:00-20:00	Post-Sunset
21:00-22:00	Pre-Midnight
00:00	Midnight

The flow pressure (P_s) was observed to be ~2 nPa from the mid-night period of April 5 2000 to ~16:00 UT of April 6 2000. The flow pressure however started fluctuating at ~17:00 UT of April6 2000, with a flow pressure of ~15 nPa reaching its highest value at ~24:00 UT of the same day with a value of ~28 nPa. This flow pressure drops drastically to ~0 nPa at around ~09:00 UT on the 7 April 2000. This was followed by a small increase in the flow pressure to about ~3 nPa during the post noon period of the same day, and it finally comes to ~0nPa at around ~18:00 UT on the same day. This minimum flow pressure was observed till~00:00UT of April 9 2000. The Electric field (E_y) was observed to start at ~ 2 mV/m during the mid-night period of April 5 2000.

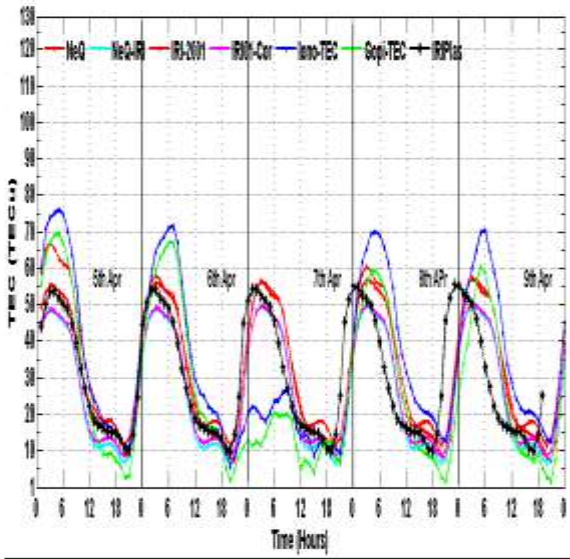

Fig 3: Diurnal variations of the observed values of TEC from Gopi and Ionolab at ADE1 along with the IRI and NeQuick predicted values.

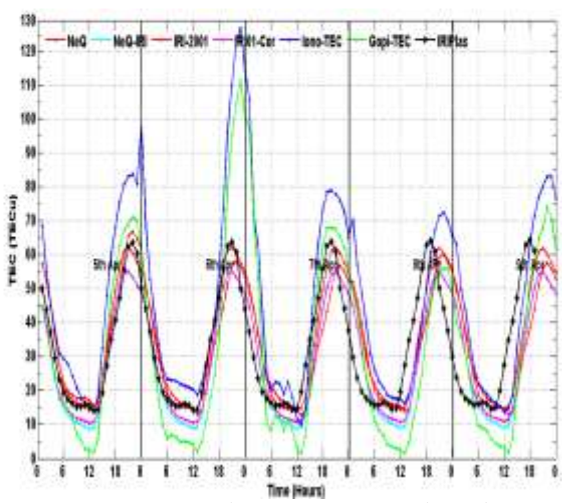

Fig 4: Diurnal variations of the observed values of TEC from Gopi and Ionolab at AZU1 along with the IRI and NeQuick predicted values.

These slight fluctuations continued in the values of the Electric field (E_y) from ~2 mV/m to ~5 mV/m and back to its minimum of ~0 mV/m was observed to persist from 5 April 2000 to 6 April 2000. There was also a sharp increase in the electric field on April 6 2000 at around ~18:00 UT during the sunset period to a value of ~15 mV/m. There was a fluctuation in the electric field between ~18:00 UT and ~00:00 UT on the same day with a value that ranges from ~15 mV/m to ~20 mV/m. There was a sharp decrease in this electric field on April 7 2000 being the day of storm at around the mid-night period with a value that ranges from ~8 mV/m to ~10 mV/m which persisted from the mid-night period to the post-sunrise period at around ~08:00 UT.

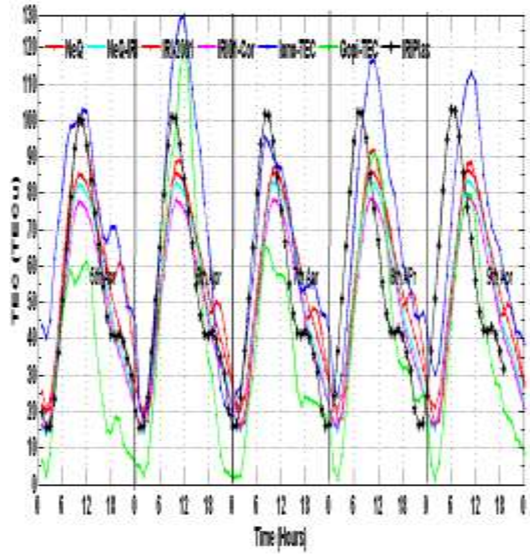

Fig 5: Diurnal variations of the observed values of TEC from Gopi and Ionolab at BAHR along with the IRI and NeQuick predicted values.

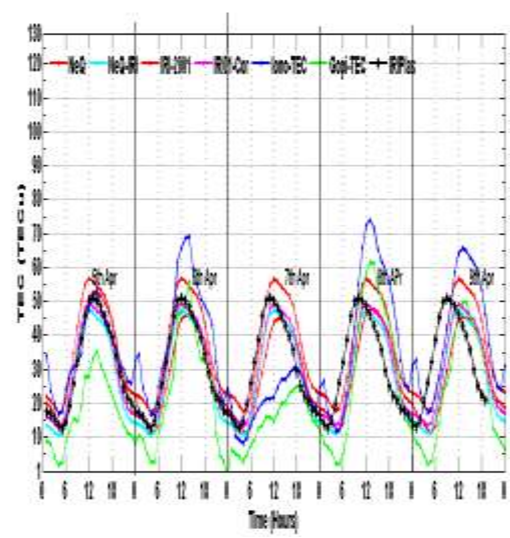

Fig 6: Diurnal variations of the observed values of TEC from Gopi and Ionolab at GENO along with the IRI and NeQuick predicted values.

A steady and slight fluctuations in the electric field was observed at around the pre-noon period on April 7 2000 till mid-night of April 9 2000. These fluctuation ranges between ~2 mV/m to ~1 mV/m. The SYM/H was observed to have attained a value of ~50 nT during the mid-night period of April 2000. This value rises steadily to about ~15nT on April 6 2000 at around ~17:00UT during the pre-sunset period. A drastic fall in the value of SYM/H was recorded from ~17:00 UT to ~23:00 UT of the same day with values of ~50 nT and ~300 nT respectively. The lowest value of SYM/H was observed to occur on 7 April 2000 at ~01:00 UT during the post-midnight period with a value of ~ -320 nT. At around ~02:00 UT, the value of SYM/H was observed to increase steadily reaching it highest value at around ~24 nT on April 9 2000 during the pre-noon period.

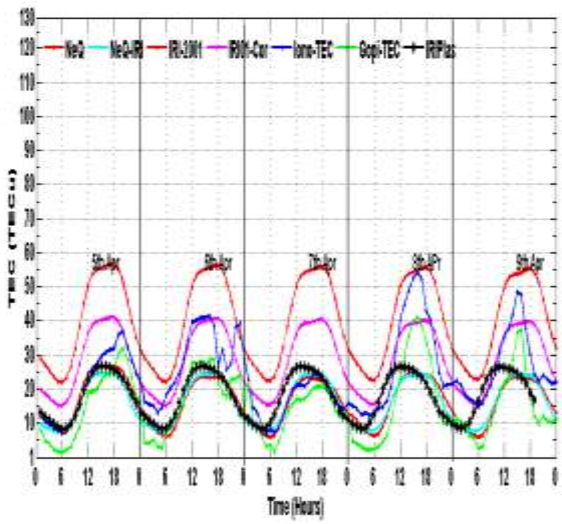

Fig 7: Diurnal variations of the observed values of TEC from Gopi and Ionolab at REYK along with the IRI and NeQuick predicted values.

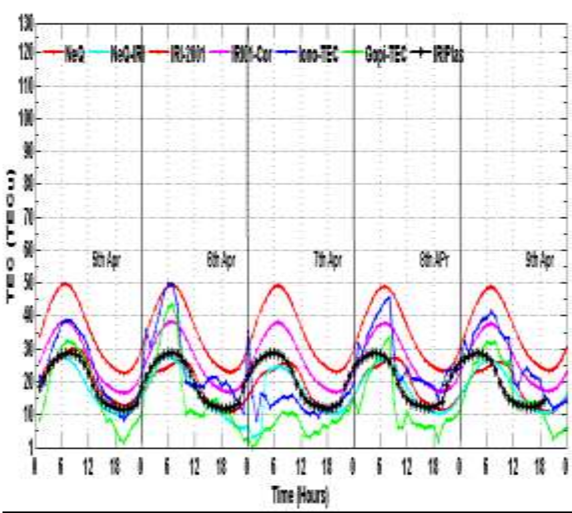

Fig 8: Diurnal variations of the observed values of TEC from Gopi and Ionolab at TIXI along with the IRI and NeQuick predicted values.

*Diurnal Variations in TEC***:** Figure 3 shows the diurnal variations of the VTEC values for five days in the month of April for station ADE1 which is located at Salisbury in Australia with geographical location of Lat -34.73 ^{O}S, Long 138.65 ^{O}E**.** In thi**s** GPS station, The Observed data has their highest values on the first day (5th of April 2000) of the variation with Ionolab-TEC and the Gopi-TEC to be ~75 TECu and ~70 TECu respectively. On the second day, the peak values of the TEC were seen to be ~71 TECu in the Ionolab which is observed data and was seen to be ~03 TECu in the Gopi Observed data. It was also seen that the predicted data has its lowest value around ~58 TECu in the IRI-2001 model while the lowest TEC value from the predicted data was also seen in the same model. On the third day, the highest value of the predicted TEC data is seen to be ~58 TECu in the IRI-2001 model while the lowest TEC value was seen to be ~05 TECu in the TEC value from Gopi. On the fourth day, the peak value of the TEC was seen to be ~70 TECu in the observed data from the Ionolab while the lowest value of the TEC drastically to ~ 02 TECu in the predicted data from the Gopi. On the last day in this GPS station, almost the same effect was observed in the value of the TEC from the both the observed data from Gopi and Ionolab, and the predicted values from the rest of the models. Figure 4 shows the diurnal variations of the VTEC values for five days in the month of April for station AZU1 which is located at Azusa in USA with geographical location of Lat 34.13 ^{O}N**,** Long 117.92 ^{O}W. Here, on the first day the highest value of the TEC was seen in the observed data from the Ionolab at exactly 97 TECu while the lowest TEC value was ~02 TECu in the predicted data from the Gopi. On the second day, a very high variation was observed in the value of the TEC. The peak value of the TEC was found to be ~128 TECu which was observed data from the Ionolab while the lowest value of the TEC data was ~02 TECu from the Gopi. On the third day, the value of the TEC from the Ionolab in the day two decreased from ~128 TECu to ~110 TECu in the second day, making it the peak of the TEC in day three which was the observed data from Ionolab while the lowest value still remains ~02 TECu. On the fourth day, the observed TEC value from Ionolab decreased to ~71 TECu making it the highest value on that day while the lowest value of the TEC remained constant from the Gopi observed data. On the last day, the value of the TEC increased again to ~84 TECu from the Ionolab data which was the peak value of the TEC recorded that day while the lowest value still remained ~ 02 TECu from the Gopi observed data.

Figure 5 shows the diurnal variations of the VTEC values for five days in the month of April for station BAHR which is located at Manama in Bahrain with geographical location of Lat 26.2 ^{O}N**,** Long 50.6 ^{O}E. In this station on the first day, the highest value of TEC was found to be ~101 TECu from the Ionolab observed data while the least value was ~01 TECu from the Gopi observed data. On the second day, there was a very tremendous increase in the value of the TEC from ~101 TECu to ~130 TECu which was the highest TEC value recorded that day which was from the Ionolab observed data while the lowest data recorded was the same as the first day from the Gopi. On the third day, the TEC value from the IRIPlas2015 predicted data became the highest value that was recorded which was seen to be ~100 TECu while the lowest value was still recorded as ~02 TECu from the Gopi observed data. On the fourth day, the value of TEC of the observed data from Ionolab increased to ~116 TECu which was the highest data recorded that day while the observed TEC value from the Gopi remained the lowest value recorded. On the last day, a decrease in the value of the observed data from ~116 TECu to ~114 TECu was recorded from the Ionolab data which was still the highest value recorded while the lowest value still remain constant as was seen in the other days.

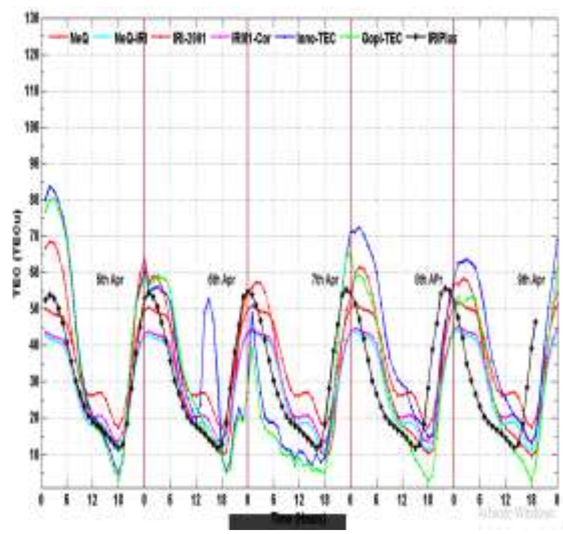

Fig 9: Diurnal variations of the observed values of TEC from Gopi and Ionolab at WEL1 along with the IRI and NeQuick predicted values.

Figure 6 shows the diurnal variations of the VTEC values for five days in the month of April for station GENO which is located at Genova in Italy with geographical location of Lat 44.42 ^{O}N**,** Long 8.92 ^{O}E. On first day, the highest TEC value recorded here was predicted data from IRI-2001 model at exactly ~56TECu while the lowest values were recorded to be ~02 TECu for the observed data from Gopi. On the second day, an increased in the observed TEC data from Ionolab was recorded from ~35 TECu to ~70 TECu which was the peak value of the TEC on this day while the lowest value of the TEC still maintain its constant variations as recorded on the other days from the Gopi observed data. On the third day, the predicted data from IRI-2001 model was recorded to have the highest value of TEC but it still maintained it maximum value of ~56 TECu while the minimum value still remained the same as recorded in other days. On the fourth day, an increased in the value of the observed data from Ionolab was recorded which amount to about ~75 TECu on this day, and it was the highest recorded while the lowest still remained ~02 TECu. On the last day, a decrease in the observed data from Ionolab was recorded from ~75 TECu to ~67 TECu which was the highest recorded on this day while the lowest value recorded was the same as those of the other days (~02 TECu).

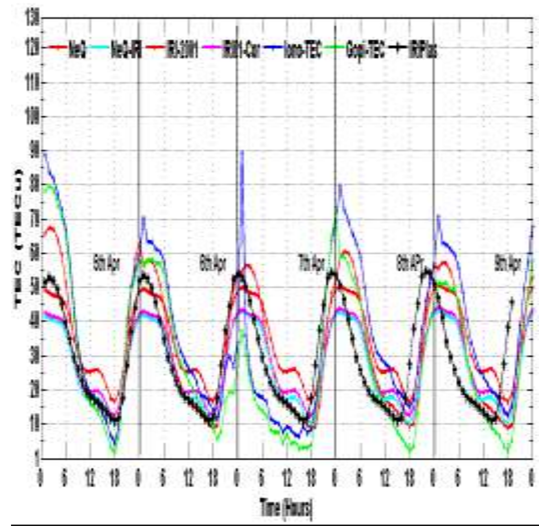

Fig 10: Diurnal variations of the observed values of TEC from Gopi and Ionolab at WGTN along with the IRI and NeQuick predicted values.

Figure 7 shows the diurnal variations of the VTEC values for five days in the month of April for station REYK which is located at Reykjavik in Iceland with geographical location of Lat 64.14 ^{O}N**,** Long 21.82 ^{O}W. In this GPS station, the maximum value of TEC recorded was the predicted data from NeQuick model at exactly ~57 TECu all through the five days of the variations. On day one and three, the predicted data from the IRI01-Cor was found to have the high values after the NeQuick model while on day four and five, the observed data from the Ionolab was found to have high values after the NeQuick model. On the second day, the peak value of the predicted data from IRI01-Cor was observed to almost coincide with that of the observed TEC value from Ionolab data while the minimum TEC values was ~ 02 TECu which was the same throughout the five days.

Figure 8 shows the diurnal variations of the VTEC values for five days in the month of April for station TIXI which is located at Tixi in Russian Federation with geographical location of Lat 71.63 ^{O}N, Long 128.87 ^{O}E. In this station, similar variations were observed as that of the Reyk. The maximum value of the TEC that was predicted data recorded as ~50 TECu from the NeQuick model. The minimum value of the TEC recorded was ~02 TECu all through the five days of the variations except for days three and five which were observed to have their lowest as ~1 TECu and ~3 TECu respectively for their observed data from Gopi. Figure 9 shows the diurnal variations of the VTEC values for five days in the month of April for station WEL1 which is located at Wellington in New Zealand with geographical location of Lat -41.27 ^{O}S, Long174.78 ^{O}E**.** The variations here show that the highest value of TEC recorded was at exactly ~84 TECu for observed data from Ionolab while the lowest value was found to be ~3 TECu from Gopi observed data on the first day. On the second day, the maximum value of the TEC was found to be exactly ~60 TECu from the NeQuick model while the minimum value was found to be exactly ~05 TECu which is the position where the two observed data source (Ionolab and Gopi) coincided. On the third day, the maximum value of TEC recorded was ~57 TECu from NeQuick model while the minimum was ~04 TECu from the observed data Gopi. On the fourth day, the maximum values of the observed TEC data (Ionolab) was found to increase from ~49 TECu (day3) to ~73 TECu while the minimum value was found to be 02 TECu. On the last day, the maximum value of the TEC increased from ~64 TECu to ~69 TECu for observed data from Ionolab while the minimum was recorded to be ~2.5 TECu for the observed value from Gopi. Figure 10 shows the diurnal variations of the VTEC values for five days in the month of April for station WGTN which is located at Wellington in New Zealand with geographical location of Lat -41.32 ^{O}S, Long 174.81 ^{O}E. In this GPS station, the maximum values of the TEC were the observed data from the Ionolab while the minimum values were also observed data from Gopi throughout the five days during the diurnal variations. On the first day, the maximum TEC value recorded was ~89 TECu while the lowest was found to be ~1.5 TECu. On the second day, the maximum value of TEC decreased from ~89 TECu to ~70 TECu while minimum increased to ~07 TECu. On the third day, the maximum value of TEC increased sharply to ~ 90 TECu while the minimum value decreased to ~03 TECu. On fourth day, the maximum TEC value decreased to ~80 TECu while the minimum also followed the same pattern and decreased to ~02 TECu. On the last day, the maximum value of the TEC decreased to ~70 TECu while the minimum value maintained the same level as the fourth day.

Longitudinal Variations in TEC: GPS station like Azu1 and Bahr closer to the Greenwich Meridian and also close to the magnetic equator or exactly on it will experience a high value of TEC because of the high amount of solar energy and ionospheric plasma will easily flow from the equator down to the station because of the proximity while other GPS stations (Ade1, Geno, Reyk, Tixi, Wel1, and Wgtn) closed to the poles and farther from the Greenwich Meridian and magnetic equator will receive less ionospheric plasma flow but will still receive some solar proton and electron deposits from the outer space reaching the poles. The E x B electric field effects will have much effects on Azu1 and Bahr because of the interactions of the plasma bubbles with the earth’s magnetic field.

Latitudinal Variations in TEC: In figure 3 -10 Ade1 and Azu1 are low latitude station which makes them closer to the magnetic equator they received high solar radiations from the sun which makes them record a high TEC values during the all the phases of the storm. The highest peak value of TEC recorded in Ade1 from the Iono-TEC was ~75 TECu around the sunrise hours of April 5 (Initial phase) while the highest peak value of TEC from Azu1 was ~128 TECu also from Iono-TEC around the mid-night hours of April 6. For Bahr which is equatorial low latitude stations receives the highest solar radiations from the sun than even Ade1 and Azu1 because of its proximity to the equator. The highest peak value at this station was recorded as ~132 TECu from the Iono-TEC around the period of April 6 (Initial phase). The middle latitude stations `Geno had its highest peak TEC values to be ~75 TEC at around post noon of 6 April while Wel1 and Wgtn had their highest peak values of ~85 TECu and ~90 TECu around the post-midnight of April 5. The Wgtn had exactly the same peak value on the main phase of storm (April 7) as was recorded on the 5 April (Initial storm phase). For high latitude region, Reyk and Tixi recorded the lowest values of TEC at all the phases of the storm days because of they are farther than all other GPS stations from the equator, they recorded their highest peak value values of TEC to be ~57 TECu and ~50 TECu at around the sunset and sunrise hours respectively during all the phases of the storm from the IRI-2001 option.

Hemispherical Variations in TEC: The earth has two hemispheres, they are the Northern and Southern hemisphere. The GPS stations close to the poles of the earth (Northern and Southern Poles) behaves differently from the ones at the center of the earth. These behaviors could be attributed to the interactions of the northern and southern poles of the earth with solar protons and electrons and other high energetic particles released from space to the earth. It was observed that the Northern hemisphere GPS stations (GENO, REYK, TIXI) has a low TEC values as compared to the Southern hemisphere GPS station (WEL1 and WGTN) despite the fact that they all receive energetic particles from outer space. This is because the Southern hemisphere stations are closer to Southern Atlantic and the Indian Oceans where the ocean currents have major impact on the TEC recorded in all the GPS stations (Arikan *et al.,* 2008). From Figure 3, it was observed that the NeQ, NeQ-IRI, IRI2001, IRI01-Cor, and IRIPlas2015 were all underestimated from 00:00 at midnight to 14:00 during the post-noon period where they were later observed to be overestimated in comparison with the Gopi-TEC from 15:00 post-noon hour to 22:00 at pre-midnight time and later back to the normal estimation from 23:00 to 00:00 on the same day. On the second day (6th of April 2000), the plot shows that the highest values of Ionolab-TEC and the Gopi-TEC was observed to be ~71TECu and ~69TECu .It was later observed that the NeQ, NeQ-IRI, IRI-2001, IRI01-Cor, and IRI-Plas2015 were underestimated until 19:00 during the night where they were overestimated till the day comes to an end. On the third day (7th of April 2000), the prediction was worst because the models were overestimated compared to the observed data from Ionolab-TEC and the Gopi-TEC this was because of large electron concentration which implies very high variability reported by Olwendo *et al,*.2013. This high in the value of the plot can also as a result extreme ultraviolet flux from the sun since year 2000 itself is a year of high solar activity. On the fourth day (8th of April 2000), the TEC values from the models were underestimated. The IRIPlas2015 model gave the lowest value of TEC in the prediction from 06:00 to 11:00 of the day and later had a better prediction at from 12:00 to 19:00. During the night hour at around 20:00 to 24:00, all the models had the best predictions except for the IRIPlas2015 model which was observed to be overestimated during that period of time. This may occur as a result of the plasmapheric content in the atmosphere as reported by Maltseva *et al.,* 2013. On the fifth day (9th of April 2000), the predictions were better with all the models except for the IRIPlas2015 which was observed to be underestimated from pre-sunrise hour (5:00) up till the noon time where its prediction was now better with other models. At exactly 19:00, it was observed that the IRIPlas2015 model had no data till the pre-midnight hours, this occurs as a result of equipment failure (Bolaji, *et al.,* 2017).

From Figure 4 on the first day (5th of April 2000), the plot shows that the predictions were good from the midnight to the pre-sunrise period until it was observed that the TEC values were underestimated in comparison with the observed values from the Ionolab-TEC from the pre-sunrise period (05:00) to the noon time (12:00) and was overestimated for the Gopi-TEC observed data from the post sunrise period (08:00) to the post-noon period (13:00). This occurs as a result of the geomagnetic activities and the local atmospheric conditions in that area. On the second day (6th of April 2000), the predictions were worst throughout the day because the TEC values were overestimated in comparison with the observed data from Gopi during the post-midnight period at around 04:00 to the sunset period of the day (18:00). It was also observed that the TEC values were underestimated in comparison with both the observed data from Gopi-TEC and the Ionolab-TEC in which the Ionolab-TEC data was observed to have its highest value at around ~128 TECu and the Gopi-TEC data having its highest value at ~110 TECu. This very high values of the TEC were due to the equipment failure during the daily recording of the GPS-TEC values. On the third day (7th of April 2000), the TEC values was underestimated during the midnight period to the pre-sunrise time, but the predictions were good at around 12:00 (noon period) till the end of the day except for the underestimation that was observed in comparison with the Ionolab-TEC data from sunrise (6:00) to pre-noon time (11:00) and overestimation in comparison with the Gopi-TEC data from the pre-sunrise period (05:00) to post noon period (14:00) of the day. On the fourth day (8th of April 2000), it was observed that the TEC values from the Ionolab-TEC was very high (the NeQ, NeQ-IRI, IRI2001, IRI01-Cor, and IRIPlas2015 were underestimated when compared with the Ionolab-TEC) from the midnight period to the noon time, while the TEC values from the Gopi TEC were observed to be the lowest from the pre-sunrise up till the sunset period around 18:00 of the day. On this day, it was also observed that there is agreement among all the models except for IRIPlas2015 model which was observed to deviates from the midnight hour to early morning or the pre-sunrise period of the day, and later was found to agree with all the models from 6:00 to the noon time (12:00). At exactly after noon time, the IRIPlas2015 model became higher than the rest of the models up till the sunset period and later fall back all through the night hour of the day. On the last day (9th of April 2000), the same phenomenon was observed as on the fourth day (8th of April 2000), but it was also observed that at exactly 19:00 (post sunset period), there was no data found for the IRIPlas2015 model till the end of the day. This occurs as a result of equipment failure during the period when the recording of the data was done (Salih *et al.,* 2017). From Figure 5 on the first day (5th of April 2000), it can be seen from the plot that the performances of the models were very poor because they were underestimated in comparison with the Ionolab-TEC values from the midnight period to almost the noon period, while they were overestimated in comparison with the values from Gopi-TEC from the pre-sunrise period to (00:00) midnight period till the end of the day. These large variations were due to the effect of outflow of plasma from the ionosphere which in turn varies according to the level of geomagnetic activity (Cherniak *et al.*, 2014). On the second day (6th of April 2000), it was observed that the predictions were good in comparison with the TEC values from Ionolab during the midnight hours up to the post-sunrise hour around 8:00 of the day until a sudden rise occurred in the Ionolab predicted data at exactly 9:00 from 100 TECu to 130 TECu and later dropped down to 50 TECu at around post sunset period of the day (20:00).Almost the same variations was observed also for the values from the Gopi model, but it was also observed that the prediction was poor in comparison with the values from Gopi-TEC model due to their overestimation at around the sunset period (18:00) till the end of the day, but the prediction was generally good at around the pre-sunrise period (05:00) of the day to the post-sunrise hours of the day (07:00). On the third day (7th of April 2000), almost the same effect was observed, the TEC values from IRIPlas2015 model was over estimated in comparison with the observed data from Gopi and Ionolab-TEC where the peak of its value was at 100 TECu followed by the Ionolab-TEC observed GPS value with its peak at around ~96 TECu. On the fourth day (8th of April 2000), the same effect was observed as in the second day but here, the IRIPlas2015 model has a poor prediction during the midnight and the day time period but was a little better at the night period. Also, the models were underestimated in comparison with values from the Ionolab-TEC almost throughout the day but a little better at night time. On the fifth day (9th of April 2000), the same effect was observed as seen in the fourth day but here, the model performed poorly in comparison with the GPS TEC values from Gopi from 12:00 noon time till midnight 00:00 of the day. It was also observed that at exactly (19:00) post-sunset hours of the day, there was no data recorded for the IRIPlas2015 model, this might be due to errors during the recording process or equipment failure as reported by (Bolaji *et al.*, 2017).

From Figure 6, it was observed in this station that the TEC values were very low for all the five days. The GPS TEC values from the Ionolab TEC observed value had the highest value with its peak at around ~75 TECu on 8th of April 2000. It was observed on the 6th, 8th and 9th, the values of the TEC data from the models were underestimated in comparison with the observed values from Ionolab-TEC. On the first day, the performance of the models was very good in comparison with the observed data from the Ionolab TEC but the performance was very poor in performance in comparison with the observed GPS data from Gopi. On 7th of April 2000, the performance of the models was very good during the midnight to sunrise hours (00:00 to 06:00) and very poor during the night time. It was also observed that the performance of the models in comparison with observed GPS TEC value from Gopi was always good during the day time and worst during the midnight time except for on the 5th and 7th were the performance was significantly poor during the day time. On the 9th, it was observed that there was no data recorded in the IRIPlas2015 model from the post-sunset period (19:00) till the midnight period (00:00), this might have occurred as a result of error in the equipment during the recording process or epileptic power supply (Bolaji *et al.*, 2017).

From Figure 7, it was also observed in this station that the TEC values were very low even compared with those observed at Genova in Italy. The highest TEC values was observed in the IRI-2001 model with its peak value at ~59 TECu throughout the five days. The models had a better performance on the 5th and 7th and had a poor performance on the 8th and 9th but had the worst performance on 6th during the night time, early morning hour, post sunset and night time. It was observed on the 6th that the Ionolab-TEC data was seen to almost assume a sinusoidal pattern with sudden rise and immediate drop in the value of the TEC during the post sunset till the night period for almost six hours. The explanation for this observation is as a result of the dramatic variation of solar activity in the year 2000, it has the most recent solar maximum activities in the solar cycle 23. On the 9th, the there was no data available or recorded for the IRIPlas2015 model from the post-sunset period (19:00) till the midnight period (00:00) as it was observed at Genova in Italy. Almost similar features were observed on the 8th and 9th this is because the geomagnetic activities like the wind flow during those disturb times and the local atmospheric conditions have almost the same effect on these days as reported by Karia *et al.*, 2015.

From Figure 8, it was observed in this GPS station that the observed GPS-TEC values from the Gopi and Ionolab can be seen exhibit a very large variation from what was expected, this is because the geomagnetic effect, the plasmapheric content and ionospheric disturbances have too much effect in the data during their measurement and recording. The best performance of these models in this particular stations was observed on the first day (5th April 2000). It was observed that all the predicted data (IRI-2001, IRIPlas2015, NeQ and the IRI01-Cor) models gave better sinusoidal pattern except the NeQ-IRI model which gave different pattern of plot throughout the five days.

From Figure 9 on the first day (5th of April 2000), the performances of the models were good during the pre-sunrise time, sunrise time to the noon time and the night time, and they had a poor performance at the midnight period and the post sunrise period of the day.

Table 3: The Root Mean Square Error for the comparison of the 5 models with the data from Gopi for five days in the month of April year 2000.

Date	Station ID	Gopi_NeQ	Gopi_IRI _Plas2015	Gopi_NeQ _IRI	Gopi_IRI _2001	Gopi_IRI01 _Cor
4/5/2000	ade1	5.98282744	9.52565375	11.66089762	8.966822991	11.4145238
4/6/2000	ade1	9.18506093	9.066108212	13.20281151	10.92072632	12.79486198
4/7/2000	ade1	22.8939319	22.23508342	18.42435885	23.34358897	18.76410079
4/8/2000	ade1	5.93807484	5.168021095	7.071922398	7.475364448	7.036251864
4/9/2000	ade1	6.91944302	6.847278911	6.292287652	8.540620436	6.532482311
4/5/2000	azu1	9.72185299	9.221760348	8.747278682	7.913288326	9.166676639
4/6/2000	azu1	22.0903934	18.57841021	22.56104465	21.60135161	22.8067718
4/7/2000	azu1	16.4220382	15.70909521	16.09545755	14.10595326	16.37571591
4/8/2000	azu1	8.44748489	8.625754614	6.1273341	10.51989884	6.742762836
4/9/2000	azu1	10.2442045	9.259827836	8.610020581	9.265576249	9.094359044
4/5/2000	Bahr	33.752319	26.07270005	22.3994579	25.7036799	19.52993291
4/6/2000	Bahr	21.4279808	16.37035254	19.26344554	20.92737672	20.49480063
4/7/2000	Bahr	20.6661325	23.23504306	18.6777346	21.99270923	15.74277802
4/8/2000	Bahr	14.1687978	11.00556377	10.39124604	13.37694492	9.817651366
4/9/2000	Bahr	19.296339	19.73874121	16.59068508	20.20385408	14.27866827
4/5/2000	Geno	16.5308266	14.25500408	12.090683	19.7143618	13.90608368
4/6/2000	Geno	8.94834372	8.738867812	7.815840827	14.25998723	9.33038907
4/7/2000	Geno	15.4184458	18.82772648	16.7356097	23.86244928	18.33375551
4/8/2000	Geno	8.18361205	7.626418483	8.326731916	10.23222292	8.408402698
4/9/2000	Geno	6.87523112	7.901686805	6.209875313	13.17329865	7.923347182
4/5/2000	Reyk	5.75659159	5.895377448	5.838178361	25.71889173	14.28947056
4/6/2000	Reyk	4.41832077	4.529006623	4.457119369	23.6553038	12.11682135
4/7/2000	Reyk	4.05539855	5.838728974	4.887667854	27.94376587	16.15888073
4/8/2000	Reyk	7.86057051	7.831640908	7.703085058	23.76369043	13.08103698
4/9/2000	Reyk	5.89928027	6.455667991	5.866599373	26.15793322	14.81462331
4/5/2000	Tixi	6.37631349	5.160425426	5.505621117	18.42746948	10.41480669
4/6/2000	Tixi	9.56157255	8.728146762	7.138361661	18.74041472	11.57338777
4/7/2000	Tixi	12.6762466	14.79446617	9.882493326	29.55014107	21.0015316
4/8/2000	Tixi	9.07545521	9.311336209	7.034861165	22.5641499	14.33394221
4/9/2000	Tixi	5.27105304	4.945607791	4.913832123	17.93075703	9.846381753
4/5/2000	wel1	7.9516037	15.62879507	20.04694151	16.42579715	19.35928759
4/6/2000	wel1	11.2815606	9.632404362	12.08968433	12.29921358	11.80155701
4/7/2000	wel1	18.6276638	18.2420719	15.65650247	20.28597511	16.49006078
4/8/2000	wel1	5.31905882	4.888282461	8.07546278	9.895814972	8.314567191
4/9/2000	wel1	3.83812647	4.656177854	7.878809411	9.203990844	7.973430764
4/5/2000	wgtn	7.79625199	15.21432036	19.65268119	16.34143308	19.02430504
4/6/2000	wgtn	11.0194824	9.391503619	11.9871141	11.8112102	11.60240452
4/7/2000	wgtn	18.8645435	18.28830331	16.40318271	20.9753333	17.27116737
4/8/2000	wgtn	5.2718171	4.843552057	8.073107124	9.956185453	8.314104374
4/9/2000	wgtn	4.00633101	4.690662271	7.251386435	9.611190354	7.571084493
Average rmse		11.2	11.2	11.2	16.9	13.1

On the 6th, the observed GPS TEC data from Ionolab was seen to have a sudden sharp increase follow by immediate decrease from 12:00 to 18:00 of the day which can be seen as the noon bite out explained in the research work of Akala *et al*., 2013. It was observed that the performances of the models in this station was highly affected by storm due to its geographical location and the effect of the magnetic equator (Cherniak *et al.*, 2014). The IRI-2001 model showed consistent noon bite out effect and the IRIPlas2015 model showed a very good plot pattern as seen in other stations throughout the five days. It was also observed here that the IRIPlas2015 model had no data around the post-sunset period (19:00) till the midnight period around (00:00). On the 7th , the storm effect on the observed GPS TEC data from the Ionolab was very high. The effect of the storm was the day time bite out from the sunrise period (06:00) to the sunset period (18:00).

From Figure 10 on the first day (5th of April 2000), the models were observed to have a better performance except for the midnight period which was observed to have some slight deviations. On the second day (6th of April 2000), the performance models were also good except for midnight bite out that was observed at around 01:00 and also a pre midnight bite out at around 23:00. On the third day, (7th of April 2000), there was a tremendous increase in the GPS TEC data from the Ionolab from ~35 TECu to ~90 TECu, this sudden rise can be attributed to the equipment failure and other physical factors. On this same day, the GPS TEC data from the Ionolab and Gopi was observed to have a continuous bite out (midnight and midday bite out) from 01:00 to around 18:00. The performance of the models here was relatively poor due to over estimation from the midnight period till the sunset period. It was observed this day that performance of the models was very good during the night time. During this night time, the recombination of the ions is very high and ionization is very low, invariably leading to low amount of electrons (Akala *et al*., 2015).On the 8th and 9th, almost the same effect was observed, as it can be seen on both days that the performance of the model was relatively good from noon time period till the night time except for the IRIPlas2015 model which shows a slight variation.

The Root Mean Square Error: The tables below show the root mean square of all models in the 8 stations in comparison with the observed data from Gopi and Ionolab for 5 days in the month of April in year 2001. In studies on meteorology, air quality, and climate, the root mean square error (RMSE) has been employed as a common statistical indicator to assess model performance. The most prevalent issue with using this statistic is its sensitivity to outliers (Adewale *et al.*, 2011).

Table 4: The Root Mean Square Error for the comparison of the 5 models with the data from Ionolab for five days in the month of April year 2000.

Date	Station ID	Iono _NeQ	Iono_IRI _Plas2015	Iono_NeQ _IRI	Iono_IRI _2001	Iono_IRI01 _Cor
4/5/2000	ade1	5.77812934	13.43389556	17.00252891	11.73576884	16.26971142
4/6/2000	ade1	10.3546593	11.3551448	15.64456509	11.54555673	14.95656576
4/7/2000	ade1	18.6739866	17.88521539	14.58664134	19.0252649	14.73904118
4/8/2000	ade1	7.65253671	10.26429004	14.71712408	9.043052293	13.75243953
4/9/2000	ade1	8.12522514	8.587594807	13.06868677	7.425996423	12.07941135
4/5/2000	azu1	14.2483795	15.70861186	20.5561506	15.60082966	20.41173816
4/6/2000	azu1	28.6435091	24.27445198	30.52475173	26.36129111	30.40256597
4/7/2000	azu1	21.7170812	20.21213848	22.30212754	17.9378609	22.23675363
4/8/2000	azu1	8.77472123	8.573863438	12.86670292	7.823175651	12.51024987
4/9/2000	azu1	15.3719275	12.58979209	16.23201984	11.39472276	16.07424692
4/5/2000	bahr	14.9614	21.97385793	23.38345871	19.77704223	26.0177816
4/6/2000	bahr	24.4712047	21.8378176	25.02690523	23.40642534	28.12060235
4/7/2000	bahr	12.408006	12.87581671	13.87950431	10.73982577	16.20212906
4/8/2000	bahr	16.3276334	16.15161838	20.45080794	17.32654907	23.62935455
4/9/2000	bahr	17.2775059	14.8833063	18.78135181	15.44232831	21.80617863
4/5/2000	geno	5.36371356	5.622552238	8.751744634	6.595977081	7.19917034
4/6/2000	geno	12.8108994	10.88809421	13.43263483	6.606713451	11.55097363
4/7/2000	geno	10.4648321	13.70704719	12.34686338	18.46920777	13.50067858
4/8/2000	geno	14.1291695	13.05563104	15.64676582	9.225324812	13.9753892
4/9/2000	geno	13.3519591	10.76249912	13.60456548	6.25945256	11.65914931
4/5/2000	reyk	5.06382731	5.744358969	7.269476617	19.71850542	8.548941253
4/6/2000	reyk	13.6861456	12.0511231	13.65217846	13.74510865	6.060878305
4/7/2000	reyk	3.03140407	3.228847894	3.427273703	24.55624809	12.80279375
4/8/2000	reyk	14.5478145	13.68296863	14.87126724	12.79824518	6.656552161
4/9/2000	reyk	12.1607363	10.32626197	11.84975039	14.99947939	5.937627653
4/5/2000	Tixi	5.00416976	5.676068697	7.455611845	12.1844504	5.064056352
4/6/2000	Tixi	11.5530545	10.81300882	11.09572765	11.52244452	7.132149874
4/7/2000	Tixi	7.45360684	9.041954897	6.326506252	23.61601056	15.20448145
4/8/2000	Tixi	9.71057356	9.238983396	10.0649774	10.07712332	5.03144451
4/9/2000	Tixi	9.16504165	8.071683887	9.303035686	9.945714602	4.036879602
4/5/2000	wel1	8.82910515	16.86151249	21.37839636	17.29418064	20.60087224
4/6/2000	wel1	16.8751871	15.22743053	15.98394587	14.18004763	15.19811844
4/7/2000	wel1	16.3738356	15.65642854	14.12067647	17.97031768	14.77145898
4/8/2000	wel1	8.66681032	11.45626622	15.82434065	10.14507321	14.63115737
4/9/2000	wel1	8.54670797	8.994130185	13.76068028	8.338647545	12.6044429
4/5/2000	wgtn	8.61170473	17.34095008	21.2402374	17.15144605	20.45394065
4/6/2000	wgtn	10.1903257	10.37713664	13.20318114	9.794343816	12.21785601
4/7/2000	wgtn	16.4906903	17.44369333	14.31455055	18.0741037	14.94559266
4/8/2000	wgtn	8.84554972	12.24610529	15.95143075	10.14196121	14.70148763
4/9/2000	wgtn	8.54998159	9.46983932	13.78202657	8.304013469	12.58746063
Average rmse		12.1	12.7	14.9	13.9	14.4

Table 3 and Table 4 shows the (Root Mean Square Average) RMSE values obtained for the five models in comparison with the observed data from Gopi and Ionolab respectively. In Table 3, during the comparisons of the five models with the observed data from Gopi, we observed that the NeQuick2, IRIPlas2015, and NeQ-IRI models had the best performance while the IRI01_Cor model had a better performance but the IRI-2001 model had the worst performance. From Table 4, we can also deduce that during the comparison of the five models with the observed data from the Ionolab, we observed that NeQuick2 model had the best performance followed by the IRIplas2015 model, the IRI-2001 model had a better performance followed by the IRI01-Cor model while NeQuick-IRI model had the worst performance.

*Conclusions***:** In this study, the diurnal variations of VTEC over Europe, Australia, North America, and Asia have been reported, using data from eight GPS receivers. The major work carried out in this research work was that the predicted TEC data NeQuick2, IRI-2012 (NeQuick-IRI, IRI-2001, IRI01-Cor), and IRIPlas2015 were separately compared with the observed GPS data from Gopi and Ionolab. The results showed that VTEC has their highest values during the midnight period and lowest values during the sunset period at the Australian stations except for Salisbury (ADE1) that had its highest values during the early morning hours around 06:00 and lowest values during the night period. The European stations had their highest VTEC values during the daytime and their lowest values during the night time except for REYK that had its highest VTEC values during the night period and its lowest values during the early morning hour at around 06:00. The North American station (ADE1) in USA had its highest VTEC values during the night time and lowest values during day time. The Asian station (BAHR) in Bahrain had its highest VTEC values during the day time at around the noon period (12:00) and lowest values during the post-midnight period at around 02:00. TEC values generally increased from 18:00 in all Australian stations and during the five days reaching its maximum values during 02:00 to 06:00. Also in the North American station, TEC values generally increased from 13:00 across the five days to reaching its maximum values during 19:00 to 24:00. It was also observed in the Asian station that the TEC values generally increased from 02:00 across the five days reaching its maximum values during 07:00 to 12:00. In the European stations except for the station located at Russia, TEC values generally increased from 06:00 across the five days reaching its maximum values during 12:00 to 14:00 (See Figures 3-10). This research has proven that interplanetary parameters facilitate and enhance geomagnetic storm effects (See figure 2). From figure 3 to 10, it has clearly shown that geomagnetic storm has little or no effect on the performances of all the models during April 7 2000 geomagnetic storm period. It can be deduced from the table of the root mean square error (RMSE) that the ionospheric models in decreasing order of performance are NeQuick, IRIPlas2015, and NeQ-IRI models in their comparison with Gopi-TEC data during phases of geomagnetic storm. It can be seen from the above mathematical computations of the root mean square error (RMSE) that the ionospheric models with the least RMSE had the best performances while the ones with high RMSE value had the worse poor performance (See Table 3 and Table 4).

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