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From solar maximum to solar minimum: a look at 11 years of global total electron content

Reza Ghoddousi-Fard

Abstract

The International GNSS Service final global maps of Total Electron Content (TEC) from 2000 to the end of 2010 have been analyzed. This period covers the last sunspot cycle, including its highest and lowest ionospheric activity periods, as well as the first year of the current cycle. Global and latitudinal statistics of TEC over this period are derived and presented. Strong correlation between daily international sunspot numbers and daily mean TEC can be seen in the data sets studied.

Introduction

Total Electron Content (TEC) maps of the ionosphere derived from Global Navigation Satellite Systems (GNSS) measurements are used for improving single frequency positioning (see e.g. Ghoddousi-Fard and Lahaye [2016]). Furthermore, these maps are among several other data sources that can be used for space weather studies in applications such as space weather nowcasts, forecasts, and empirical modeling.

It is now about 2 decades that the International GNSS Service (IGS) [Dow et al., 2009] has continuously generated global vertical TEC maps [Hernández-Pajares et al., 2009; Roma-Dollase et al., 2018] from GNSS measurements. This data set now covers periods of solar maximums and minimums. Hence, it provides valuable information for quantitative analysis of global or regional TEC variations.

In this study, 11 years of global IGS TEC maps from early 2000 to the end of 2010 have been used for a statistical analysis. This period covers most of sunspot cycle 23, including its highest and lowest ionospheric activity periods, as well as the first year of current cycle (24). Correlation between daily mean TEC and sunspot numbers is also studied over the same period. This study may help both navigation and space weather users of TEC maps have a clear quantitative insight into the TEC amounts and their variations.

Studied global TEC data

IGS provides ionospheric TEC grids in IONosphere map EXchange (IONEX) format [Schaer et al., 1998] from a combination of IONEX maps submitted by contributing analysis centres [Hernández-Pajares et al., 2009]. Each IONEX file includes 12, and more recently 13, sets of bi-hourly maps per 24 hours (TEC maps with higher temporal resolution of 1 hour or less have also been developed by some centers, including NRCan, but final IGS maps are still being generated with 2 hour temporal resolution). The maps are global, covering from -87.5 to 87.5 degree latitude. In this study 12 bi-hourly epochs per each day (from hour 1 to 23 with 2 hour intervals) are extracted from the IONEX files over the 11 years period spanning 2000 to the end of 2010.

Some unreasonably large grid TEC (and associated RMS) values were found in the IGS final TEC maps. This is likely due to the malfunctioning of the IGS combination software when large outliers exist in an individual analysis center IONEX file [Hernández-Pajares, Personal communication, 2011]. To avoid the effect of these extreme outliers in the current analysis, TEC values larger than 250 TECU (1 TECU = 10^{16} electron per m^2) are removed from the data series. Only 81 grid values out of the total of 249,903,528 detected had such unrealistic high values. Furthermore, if the maximum TEC value at a bi-hourly epoch and at a latitude band was larger than 5 times the standard deviation, the epoch was removed.

Mean and extreme TEC values over different latitudes

Figure 1 shows mean and extreme TEC values at all latitudes over bi-hourly epochs during the studied period, while figures 2 and 3 show the same for the northern and southern hemisphere respectively. Mean and extreme values for the given plots are given in Table 1 and are also plotted in figures 4 to 6 for each latitude band. These statistics computed from IGS final maps over the studied period and after removal of outliers, show absolute maximum TEC reached up to 188.60 TECU at latitude band of $10 \leq$ Lat < 30. As can be noted in figures 1 and 2 this maximum occurred during late 2003 corresponding to the well-known 2003 Halloween solar storm events. The mean of mean values in Table 1 is an indicator of average TEC for the studied period with minimum and maximum values representing the extreme variation of the mean values. Mean TEC over all latitudes (-87.5 $\leq$ Lat $\leq$ 87.5) over the studied 11 years period is 18.22 TECU. Also noted in Table 1 is that mean TEC in equatorial band varied from 8.81 to 93.02 TECU with average value of 31.09 TECU. These are highest values compared to all other latitude bands. As can be noted in Table 1, in polar regions maximum bi-hourly TEC at times can be as low as about 2 TECU while it can reach to about 80 TECU during solar maximum.

Table 1- Statistics of latitudinal TEC from 2000 to 2011. Unit: TECU

Latitude band	Min			Mean			Max		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
-87.5 ≤ Lat < -70	0.10	6.56	44.80	0.80	10.91	58.96	1.50	16.97	85.00
-70 ≤ Lat < -50	0.15	5.61	39.60	1.85	12.29	55.91	4.25	22.65	101.00
-50 ≤ Lat < -30	0.20	5.86	38.80	3.83	15.86	56.41	6.80	32.64	150.30
-30 ≤ Lat < -10	0.60	7.59	38.00	5.91	24.05	77.76	9.75	51.15	161.20
-10 ≤ Lat < 10	0.50	7.87	43.30	8.81	31.09	93.02	16.30	*58.54*	165.30
10 ≤ Lat < 30	0.70	8.28	34.40	8.15	27.98	83.72	14.90	58.15	*188.60*
30 ≤ Lat < 50	0.65	7.03	28.20	6.08	17.94	57.34	9.45	37.56	170.65
50 ≤ Lat < 70	0.45	5.45	26.30	2.82	12.34	43.14	6.15	23.63	113.40
70 ≤ Lat < 87.5	0.40	6.80	26.40	1.09	10.65	40.62	2.10	16.34	77.40
Northern hemisphere	0.40	4.96	20.40	5.28	18.45	54.88	16.55	*59.41*	*188.60*
Southern hemisphere	0.10	4.75	27.20	3.83	17.87	61.87	13.90	57.54	163.70
Global	0.10	3.11	16.00	6.25	*18.22*	55.26	16.75	60.46	*188.60*

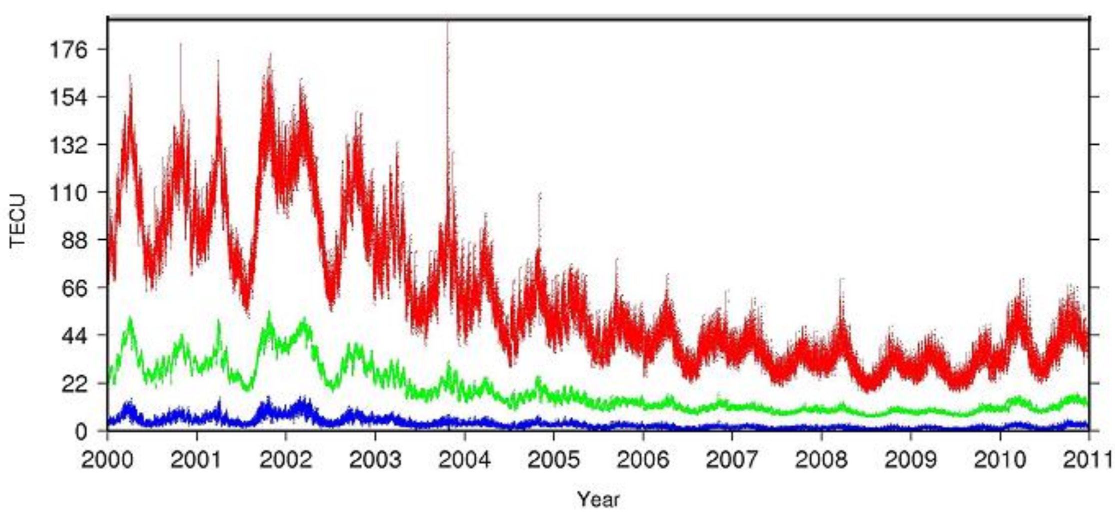

Figure 1- Min (blue), Max (red) and Mean (green) global TEC at bi-hourly epochs.

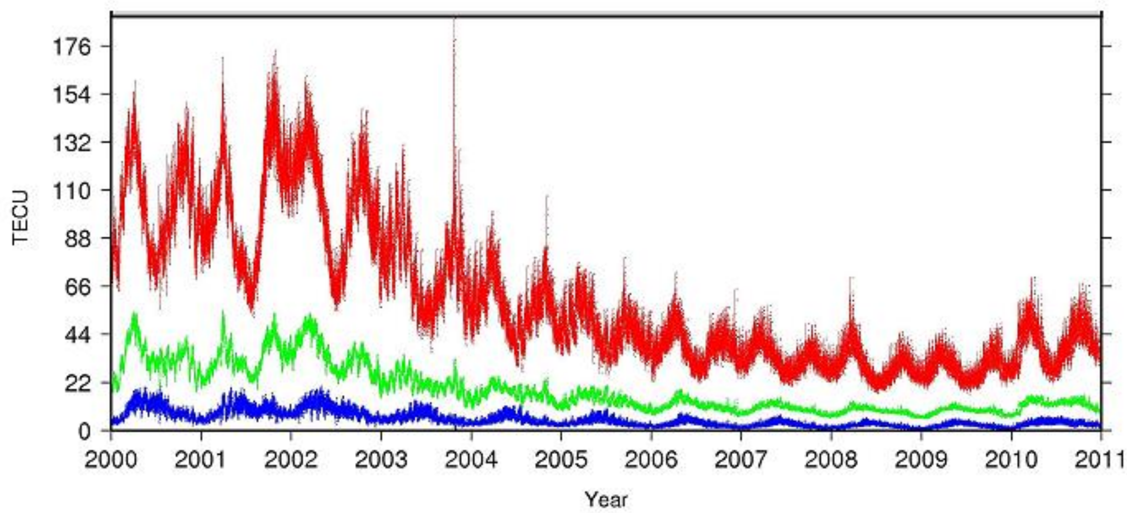

Figure 2- Min (blue), Max (red) and Mean (green) northern hemisphere TEC at bi-hourly epochs.

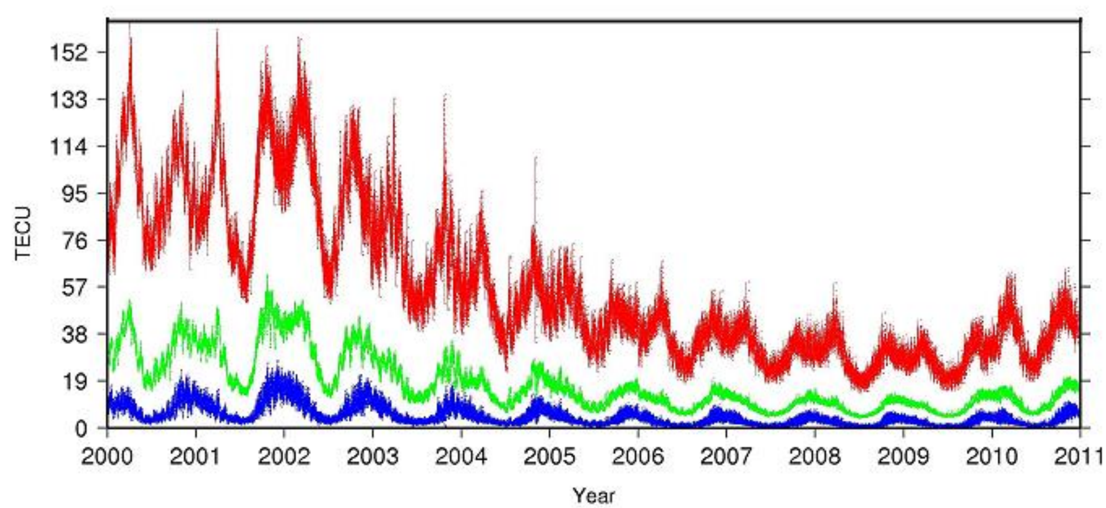

Figure 3- Min (blue), Max (red) and Mean (green) southern hemisphere TEC at bi-hourly epochs (note different vertical scale compared to figures 2 and 3).

The latitude dependence variation of mean TEC can be noticed in Figure 4, where it is highest around the equator and decreases with towards the poles. Variation of minimum and maximum TEC at each latitude band can be seen in figures 5 and 6.

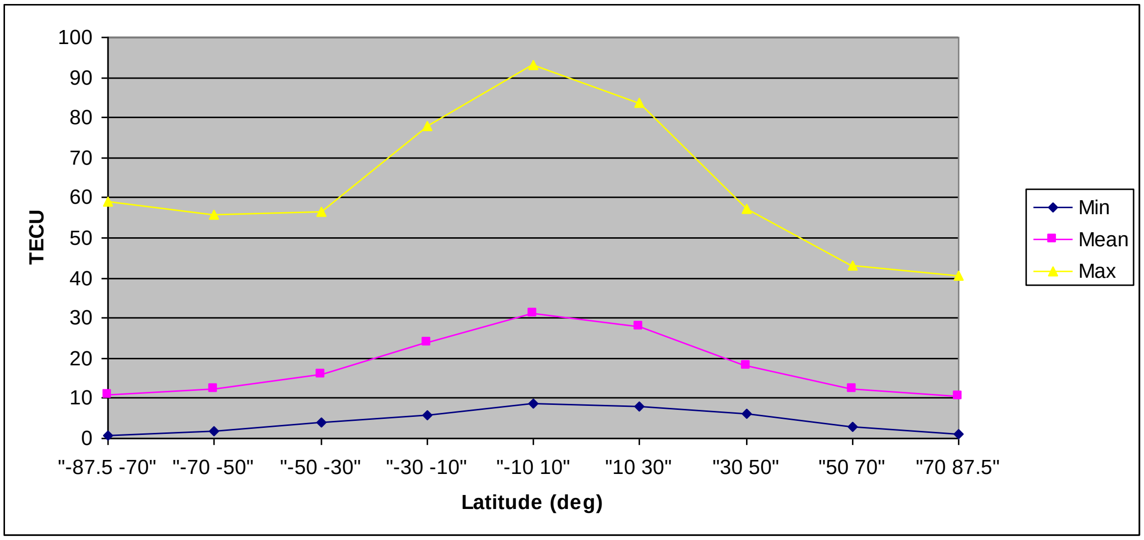

Figure 4- Statistics of mean TEC values at different latitude bands.

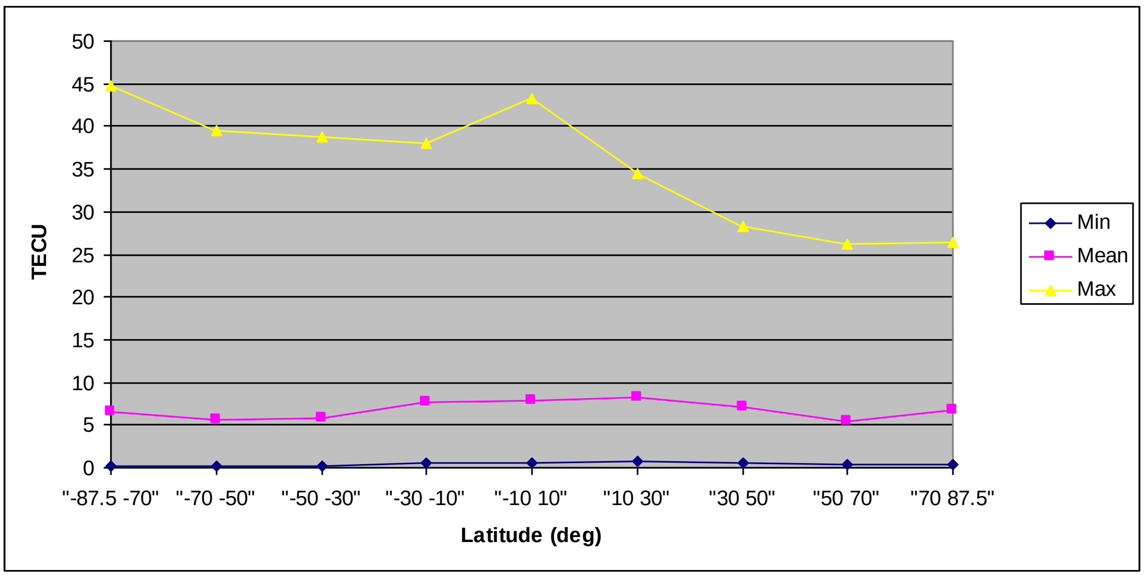

Figure 5- Statistics of minimum TEC values at different latitude bands.

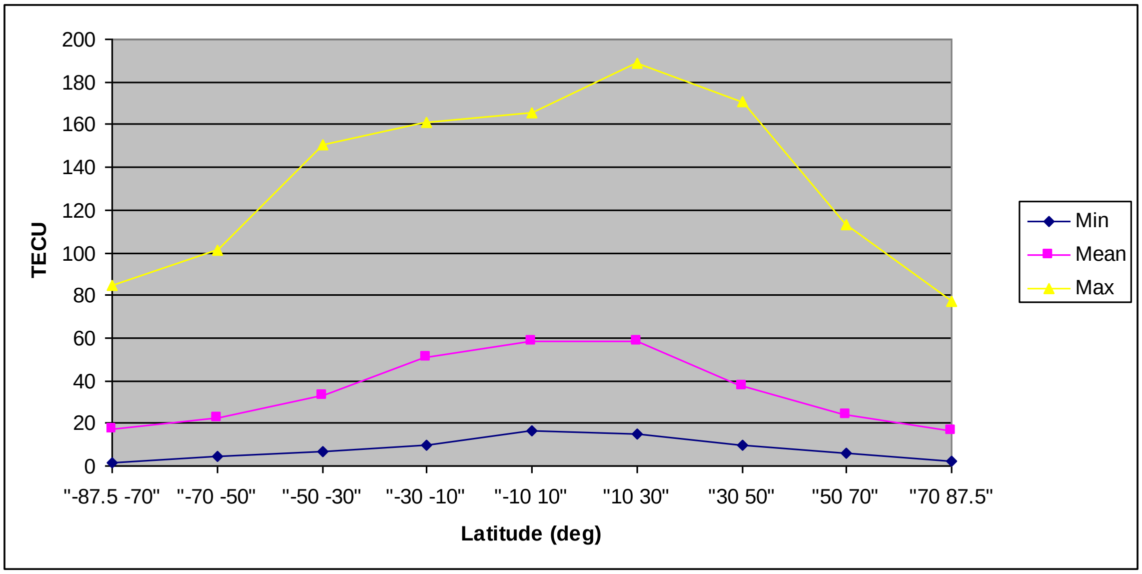

Figure 6- Statistics of maximum TEC values at different latitude bands.

Figure 7a shows global daily mean TEC. As it can be seen the maximum global daily mean TEC reached to about 50 TECU at some epochs during 2000 to early 2002. Figures 7b and 7c show daily mean TEC for the northern and southern hemisphere respectively. Comparing figures 7b and 7c shows that mean daily TEC reaches its annual maximum during late spring to early summer at each hemisphere. However, there are other mean daily peak values during high solar activity period of 2000 to 2003.

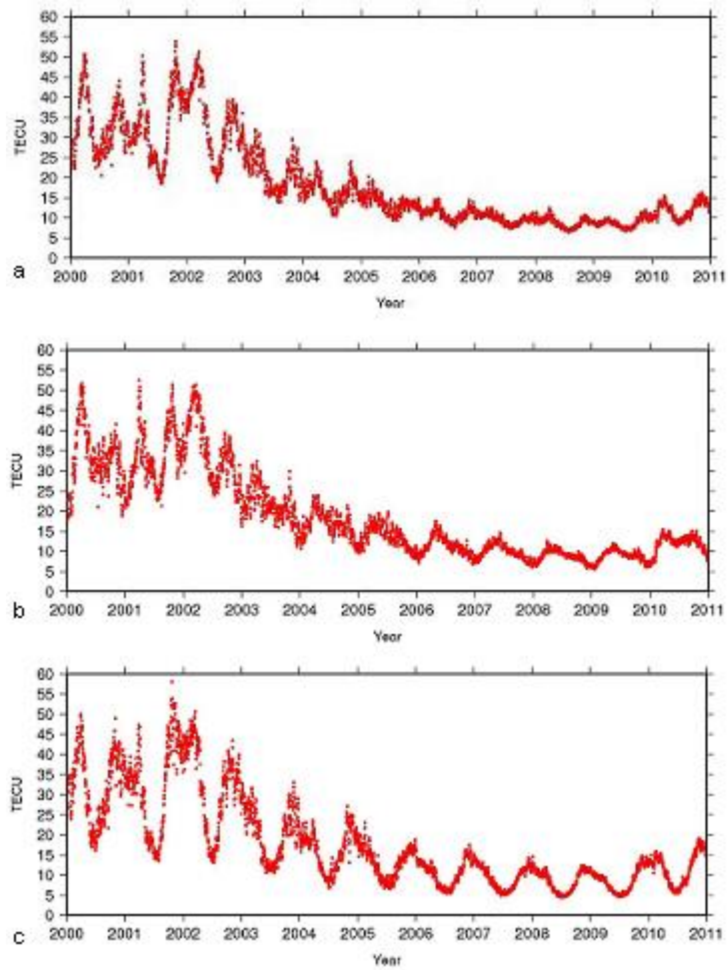

Figure 7- Daily mean TEC: a) Global b) Northern hemisphere c) Southern hemisphere.

Figure 8 shows daily mean variation of TEC globally and for each hemisphere. It can be seen that daily mean TEC variation rarely exceeded 5 TECU over the studied period, whether over all latitudes or for each hemisphere. The higher variations mainly occurred during years of high solar activity.

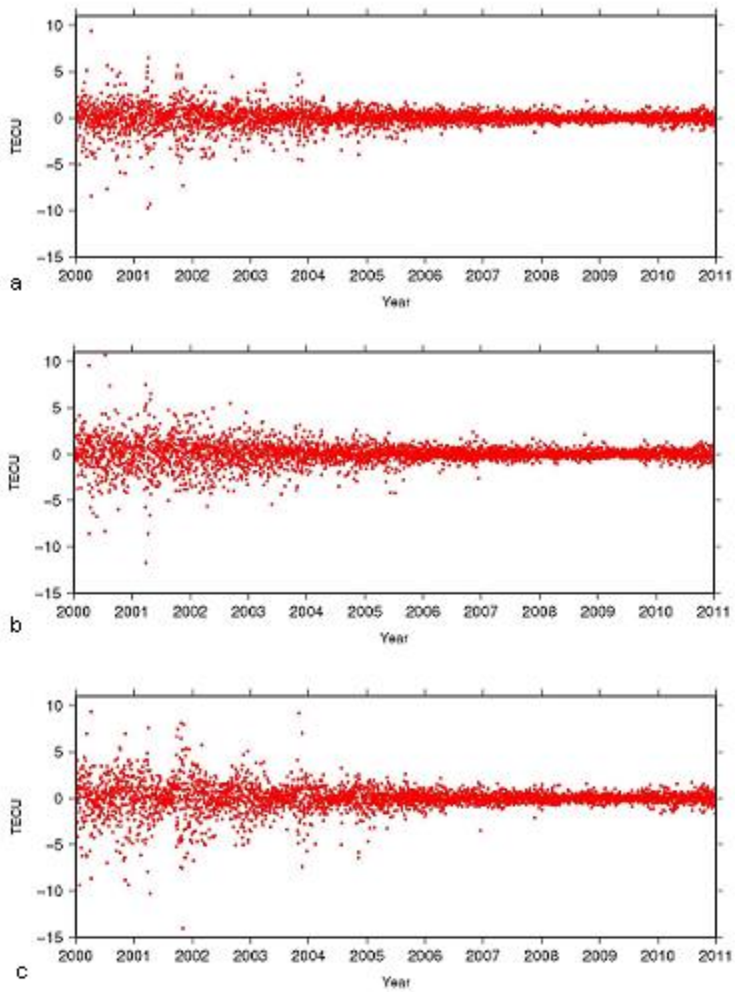

Figure 8- Daily mean TEC variation: a) Global b) Northern hemisphere c) Southern hemisphere.

Daily mean TEC and sunspot numbers

Sunspots are magnetic regions with a strong magnetic field that appear darker than surrounding regions on the surface of the Sun. These are the longest recorded features of solar evolution. The so-called international sunspot number is produced by the Solar Influence Data Analysis Center, World Data Center for the Sunspot Index at the Royal Observatory of Belgium. Daily international sunspot numbers are accessible from 1818 until present through National Oceanic and Atmospheric Administration's National Geophysical Data Center web site [NGDC, 2011] and are plotted in Figure 9 to the end of 2010. A closer view of sunspot numbers from 2000 to the end of 2010 is plotted in Figure 10.

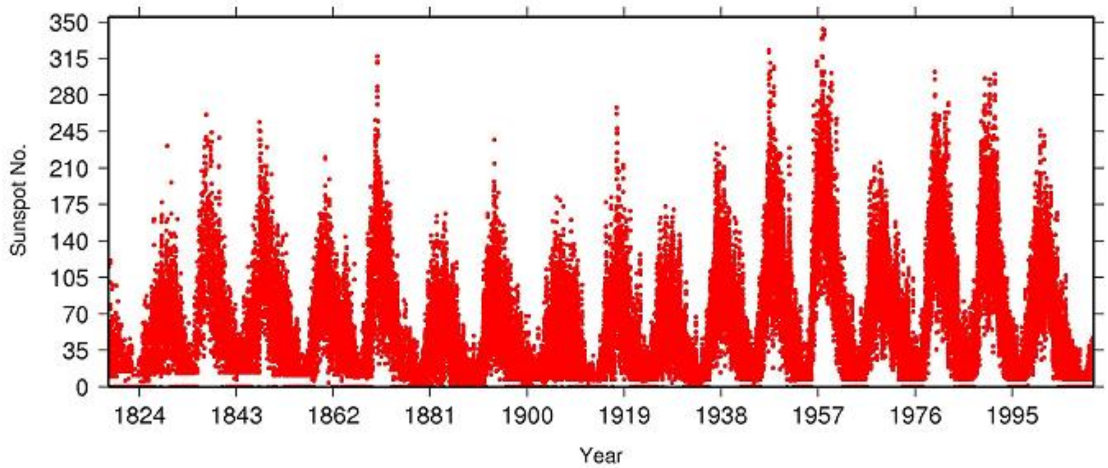

Figure 9- The International sunspot number (1818 - 2011).

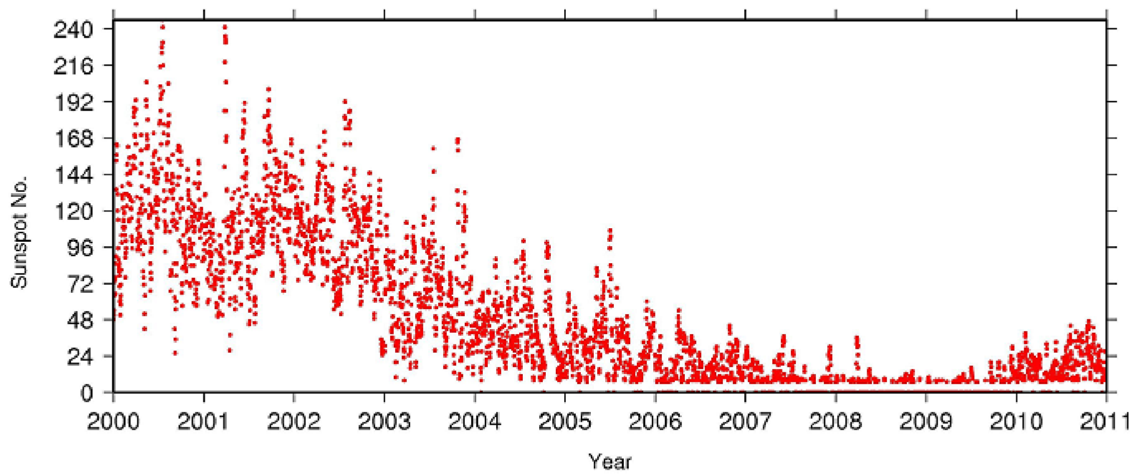

Figure 10- The International sunspot number (2000 – 2011).

Our daily mean TEC over all latitudes, northern hemisphere and southern hemisphere are plotted in Figure 11 against the daily international sunspot numbers. Correlation coefficient of the two data series are also given in the plots. It can be seen that there is a high correlation of 0.85 between the global daily mean TEC and sunspot numbers. The correlation is slightly higher when only the northern hemisphere is considered (0.87) and it is less (0.77) for the southern hemisphere daily mean TEC values.

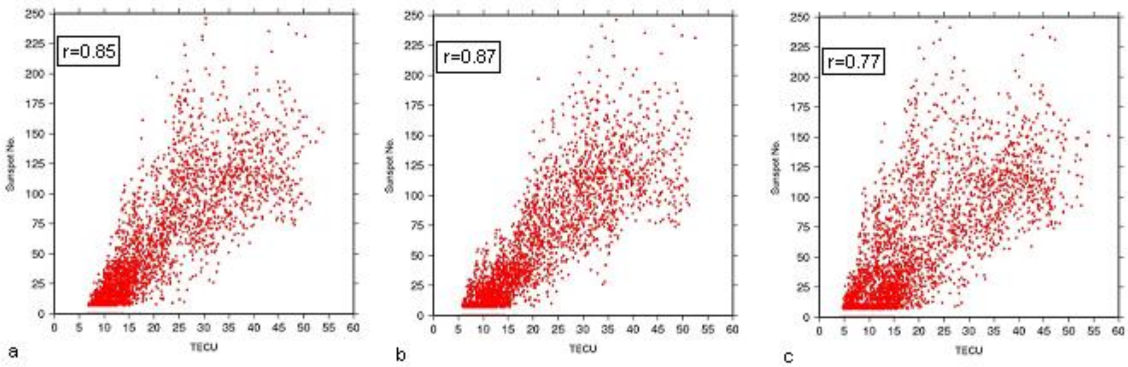

Figure 11- International sunspot number vs. daily mean TEC (2000 – 2011): a) Global b) Northern hemisphere c) Southern hemisphere.

Summary and conclusion

A statistical look at 11 years of IGS final global TEC maps revealed mean and extreme TEC values over this period. After removing the outliers based on criteria used in this study the global mean vertical TEC was 18.22 TECU while absolute maximum vertical TEC over the studied period reached about 188.6 TECU. This maximum value is equal to about 30.55 meters on L1 GPS frequency. Day to day variations of global mean TEC rarely exceed 5 TECU which may be the case during high solar activity periods. The highest mean TEC can be seen in the equatorial band while it decreases toward the poles. However absolute maximum TEC at polar regions reached up to about 80 TECU. One can observe smaller mean and extreme TEC values in the current solar cycle as it is the smallest cycle in over 100 years with its maximum already reached in April 2014 [MSFC, 2018].

Daily mean TEC averaged globally or over the northern hemisphere shows high correlation with daily international sunspot numbers. The correlation is slightly decreased when TEC is averaged only over the southern hemisphere. It is worth mentioning that accuracy of global TEC maps is expected to be a function of the number of contributing GNSS stations which is significantly less over southern hemisphere and absent over the oceans. Longer period of global TEC maps with enhanced quality as a result of increased number of ground and space based GNSS measurement, will provide promising additional data sources for studying solar cycles and other space weather events.

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