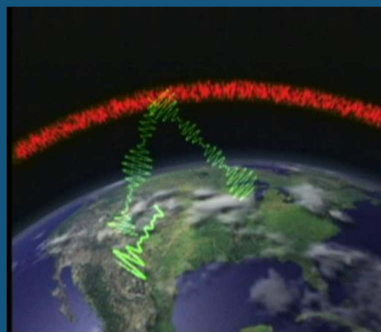



Extreme variations of the Total electron content in the course of a solar cycle – statistical analysis

L.Nikitina, R.Fiori, R.Ghoddousi-Fard

Space Climate 8

Krakow, Poland, 18-21 September 2022

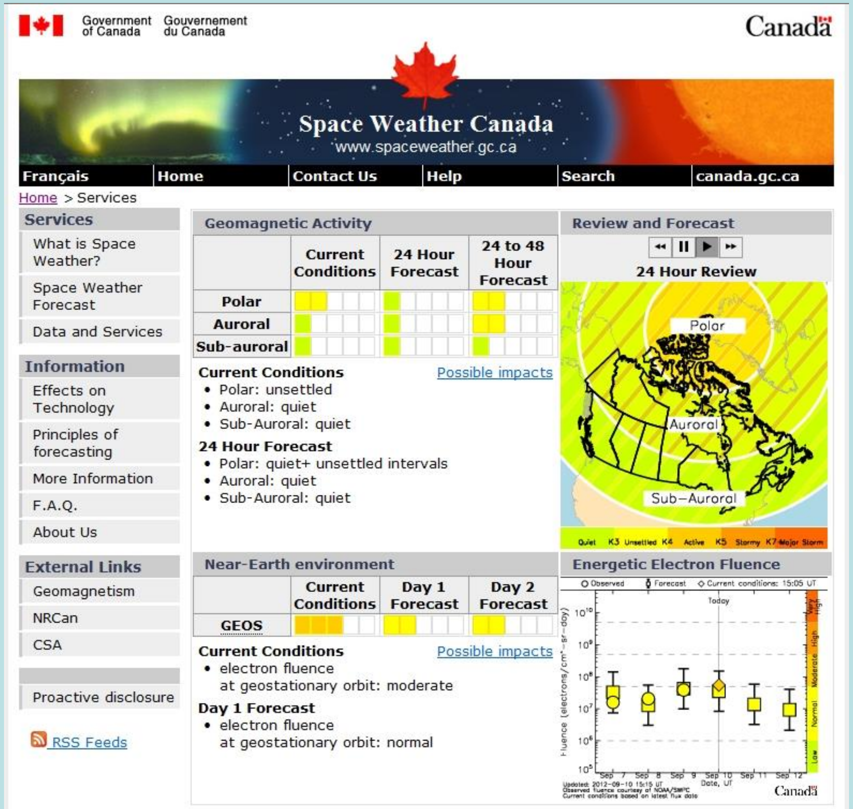
Natural Resources Canada
Ressources naturelles Canada

Canada

Benchmark model of extreme space weather event

Canadian Space Weather Forecast Centre

NRCan Canadian Hazards Information Service



Geomagnetic disturbances:

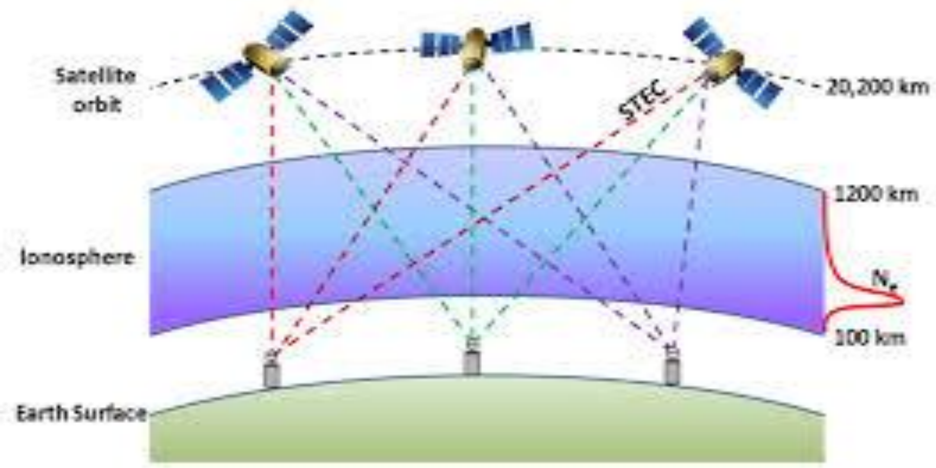
- Benchmark for one-in-100 years geomagnetic storm affecting power grids across Canada
- **geomagnetic** disturbances,
- **geoelectric** variations,
- **geomagnetically induced currents**

Ionosphere processes :

- Modeling of Extreme **Polar Cap Absorption** Event;
- Estimation of extreme values of the **Total Electron Content** in the ionosphere for one in several solar cycles event

Effects from large and extreme TEC variations on critical infrastructure

- TEC = $\int n_e(s)\,ds$, the number of electrons along the path between a transmitter and receivers;
- Disturbances of TEC caused by space weather event change the propagation of the signal between a satellite and a ground receiver providing error of navigation
- Extreme values of TEC can affect
  - ➢ Global Navigation Satellite Systems (GNSS) service,
  - ➢ high-frequency communication systems,
  - ➢ space-based remote sensing systems



https://amostech.com/TechnicalPapers/2020/Atmospherics-Space-Weather/Skone.pdf

- Assessment of large and extreme TEC values is important to mitigate risks from hazardous ionospheric conditions
- The purpose of this study is to estimate extreme TEC values with occurrences of once in several solar cycles and 1-in-100 years event

Moderate and severe levels of TEC defined by ICAO (International Civil Aviation Organization)

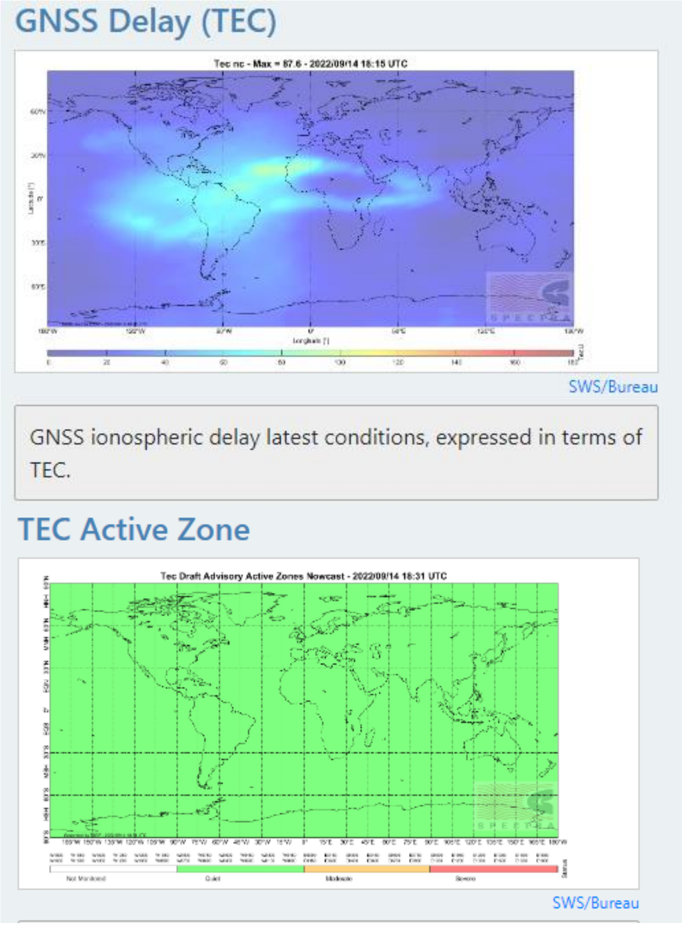
- Augmentation systems of navigation services broadcast correction messages which aims to decrease the range error of navigation services. But large variations of TEC during space weather event decrease efficiency of the augmentation systems
- The International Civil Aviation Organization (ICAO) defines two levels of TEC alerts for GNSS:

➢ Moderate – 125 TECu

➢ Severe – 175 TECu

- NRCan provides space weather advisories to ICAO as a part of ACFJ (Australia, Canada, France, Japan) Consortium
- Advisory are provided separately for high latitudes (above 60°), middle latitudes (30° - 60°) and equatorial latitudes (0° - 30°).

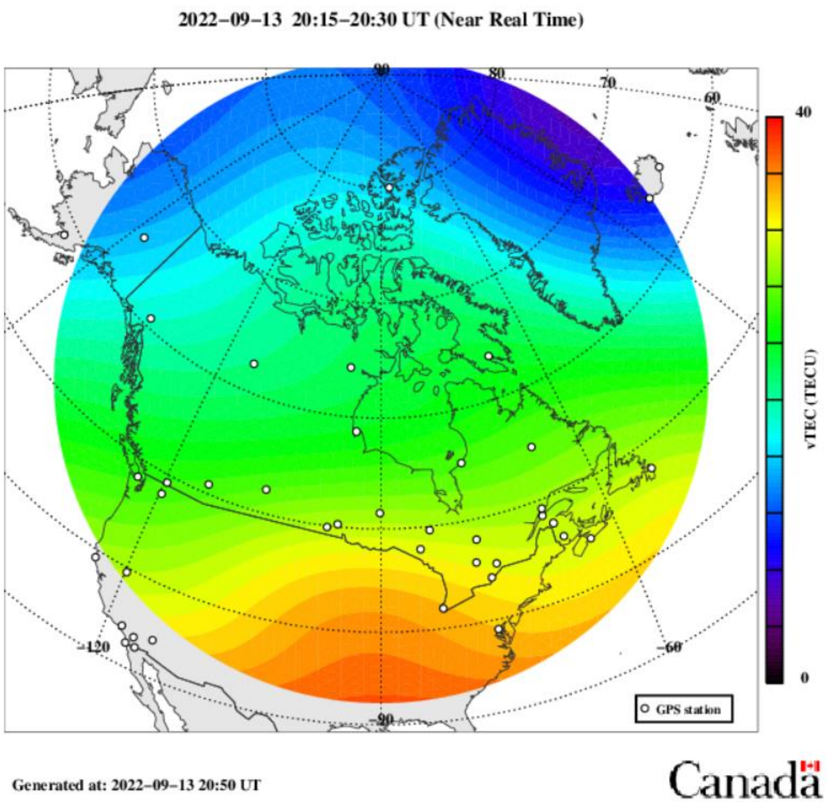
ACFJ Space Weather advisory Service



Retrieved from Bureau of Meteorology of Australia
https://www.sws.bom.gov.au/acfj/products.php?id=ionospheric_tec

Data used for the analysis

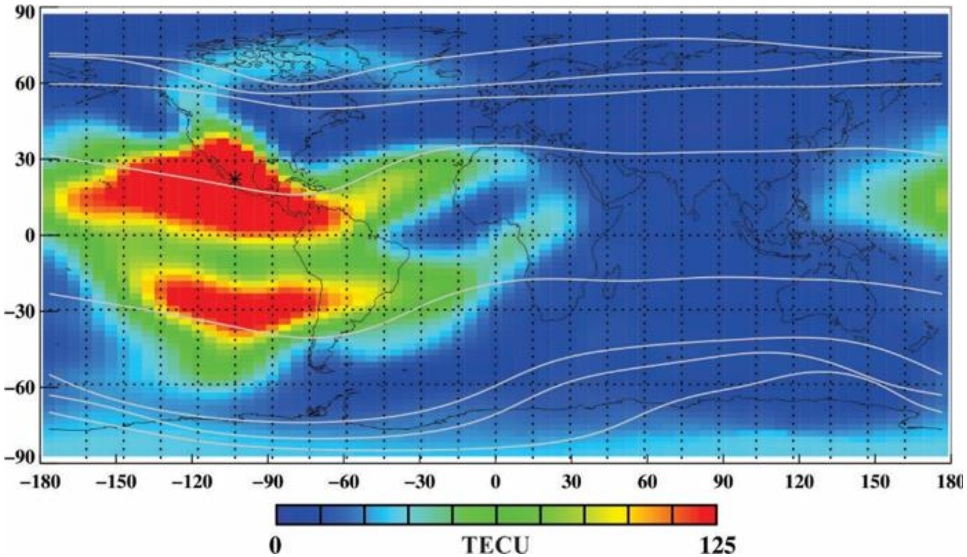
- The generation and standardization of global TEC maps has been undertaken by the International GNSS Service (IGS) from a combination of TEC maps from a number of associated analysis centers
- Canadian Geodetic Survey (NRCan) generates its daily global TEC maps using about 400 dual-frequency GNSS stations
- This map provides local TEC with use of spherical harmonics of degree and order 15



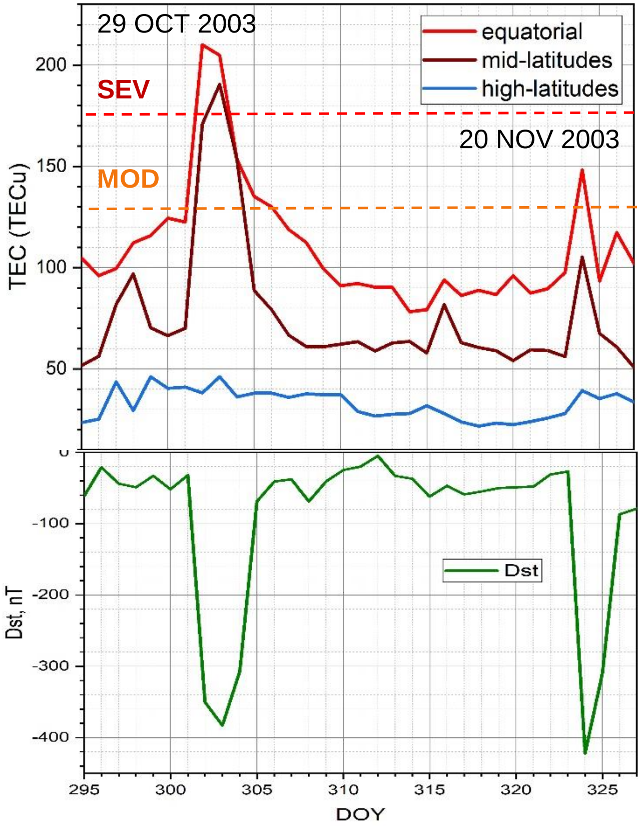
- For assessment of extreme TEC, we used the daily maximum for the global value and in three latitudinal bands: high latitudes, middle latitudes and equatorial latitudes.

TEC variation during magnetic storms

IGS Global TEC map, October 29th, 2003



Daily maximum of TEC variations, OCT-NOV 2003



- This analysis aims to assess
  - what the extreme values could be observed globally and in three bands of latitudes for once-in- several solar cycles event,
  - What is the expected time (the return period) to observe the moderate and severe TEC variations.

Extreme values statistics. Generalized Extreme Value (GEV) family.

- Extreme value analysis has been used to estimate the largest possible TEC variation
- The whole data set is separated in blocks, and the extreme distribution is applied to the maximum values of each interval

  $X(N) = max\{X_1, X_2, \cdots, X_N\}$ where *N* is large,

  and *X(N)* are independent;
- Based on the theorem of Fisher-Tippett-Gnedenko, this distribution of *X(N)* converges to one of these three forms:

Cumulative probability

$$p(M_n < x) = \exp\left\{-\left[1 + \gamma\frac{x-\mu}{\sigma}\right]^{-1/\gamma}\right\}$$

For $\gamma > 0$ Fréchet distribution;

$\gamma < 0$ Weibull distribution;

For $\gamma \to 0$ Gumbel distribution

$$p(M_n < x) = \exp\left(-\exp\left(-\frac{x-\mu}{\sigma}\right)\right).$$

x

Extreme value distribution for TEC values

Issues:

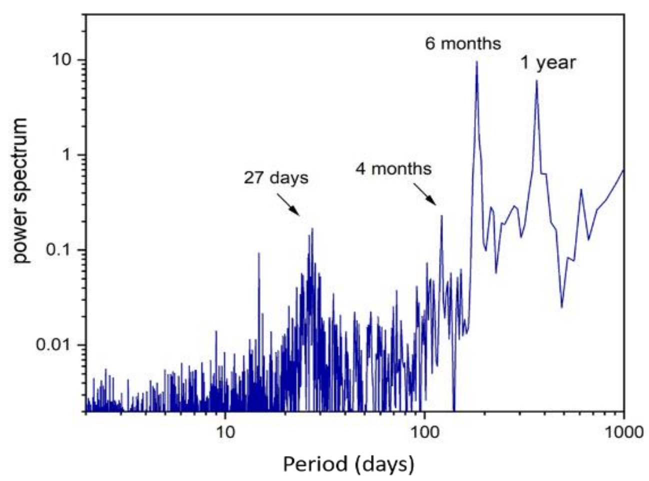
➢ **Block duration**

- TEC has a significant variability in the course of the solar cycle.

Periodogram demonstrates several peaks: around 27 days, 4 months, 6 months, 1 year.

The block duration of **1 year** was chosen.

Periodogram of the global TEC value, daily maximum



➢ **Selection the form of extreme value distribution**

Likelihood ratio test, H0: Gumbel distribution, γ=0 vs H1: Fréchet distribution, $\gamma \to 0$

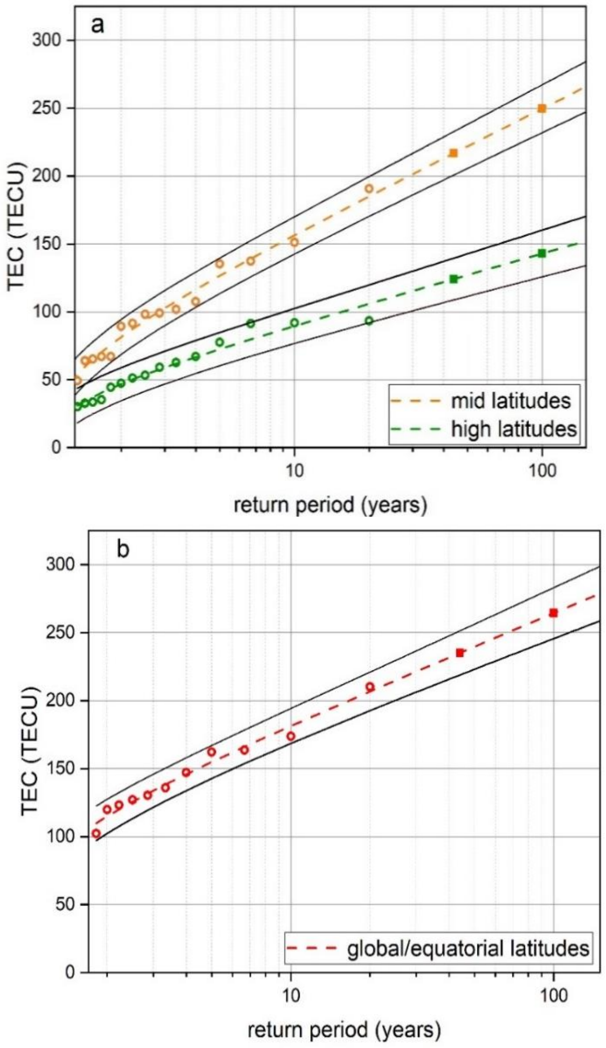
$$T_{LR} = 2 * ln \frac{\prod_{i \le n} g_{\overline{\gamma},\overline{\mu},\overline{\sigma}}(x_i)}{\prod_{i \le n} g_{0,\overline{\mu},\overline{\sigma}}(x_i)}$$

Likelihood-ratio statistics	High-latitudes	Mid-latitudes	Equat/global latitudes	χ^2_{cr}, (5%, df=1)
T_{LR}	3.40	3.66	2.96	3.84

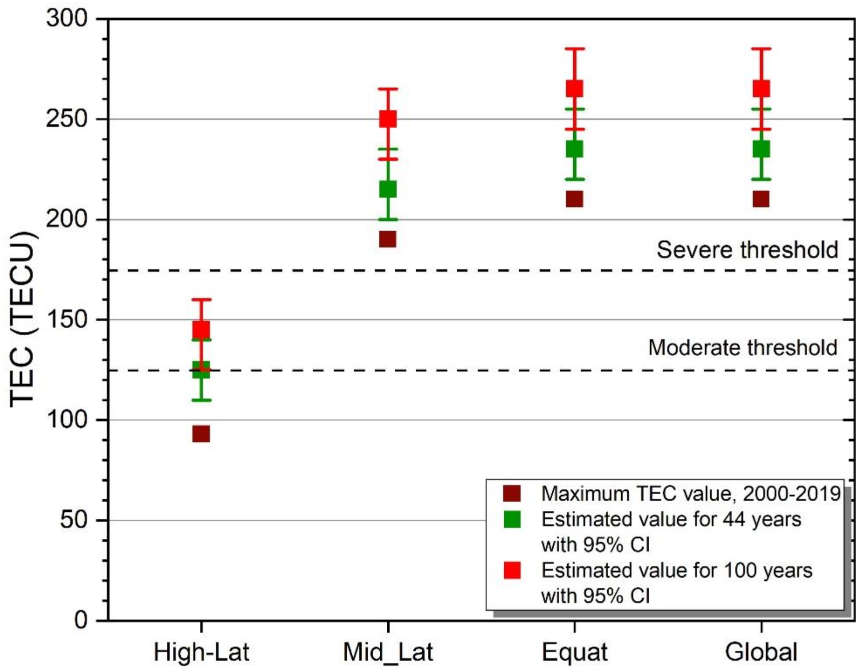
$T_{LR} < \chi^2_{cr}$(5%, df=1) in all latitudinal bands => **Gumbel distribution** has been used

Estimated values for extreme TEC

Fitting of annual maximum values to Gumbel distribution



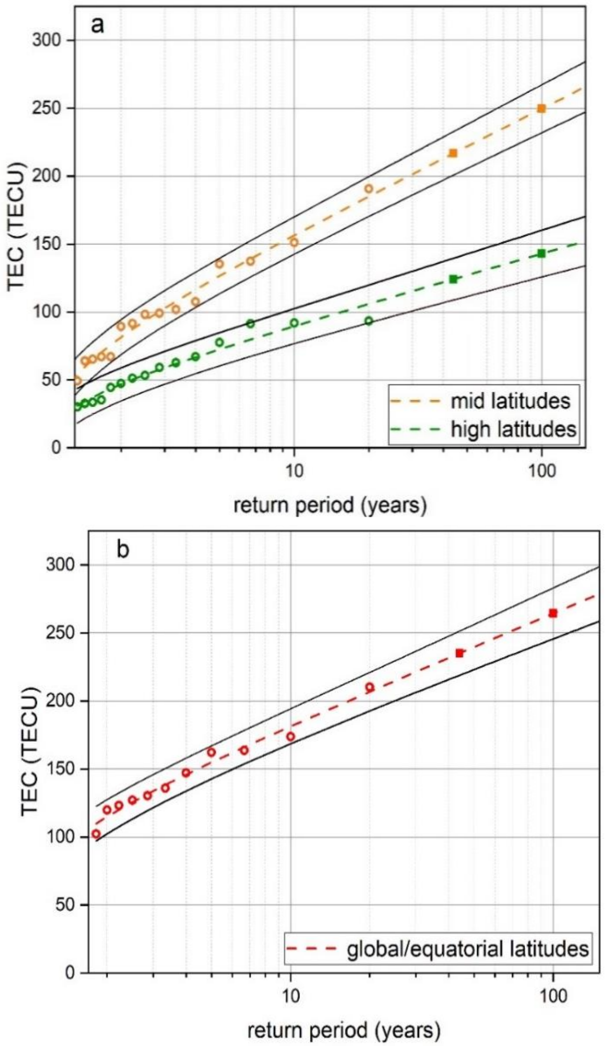
Estimated values for once-in-4 solar cycles and one in 100 years TEC



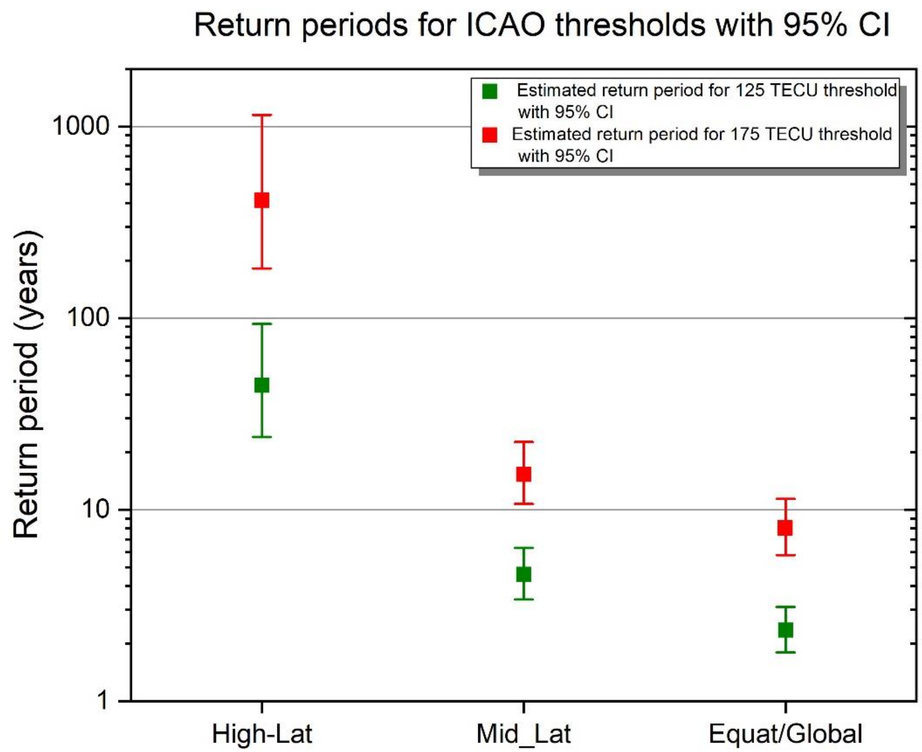
Region	Maximum in 2000-2019, TECU	44 years, 95% CI, TECU	100 years, 95% CI, TECU
High Latitudes	93.3	125 [110, 140]	145 [125, 160]
Mid-latitudes	190.6	215 [200, 235]	250 [230, 265]
Global and equatorial latitudes	210.1	235 [220, 255]	265 [245, 285]

Estimated values for extreme TEC

Fitting of annual maximum values to Gumbel distribution



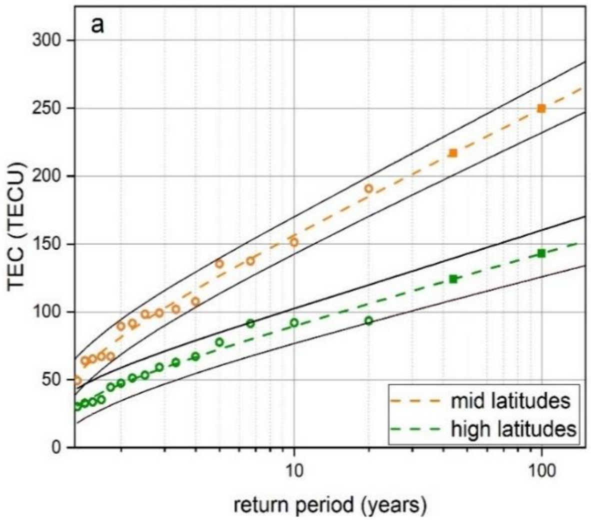
Return periods for the moderate (125 TEC) and severe (175 TEC) thresholds

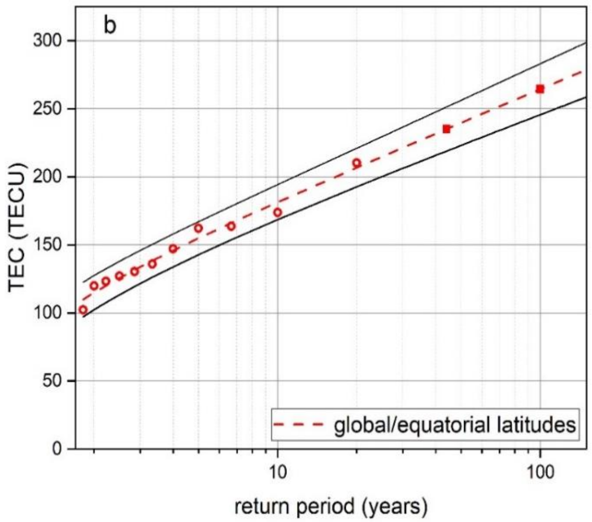


Return period for exceedance of a threshold	Moderate threshold 125 TECU with 95% CI, years	Severe threshold 175 TECU with 95% CI, years
High-latitudes	44.0 [24, 93]	N/A
Mid latitudes	4.6 [3.4, 6.3]	15.3 [10.7, 22.6]
Global and equatorial latitudes	2.3 [1.8, 3.1]	8.0 [5.8, 11.4]

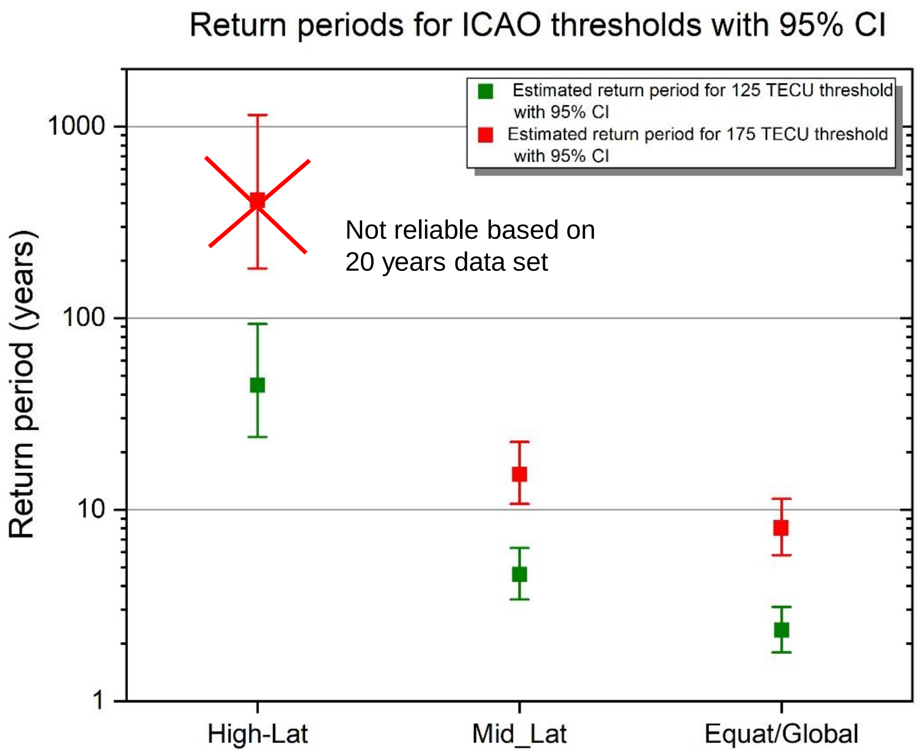
Estimated values for extreme TEC

Fitting of annual maximum values to Gumbel distribution



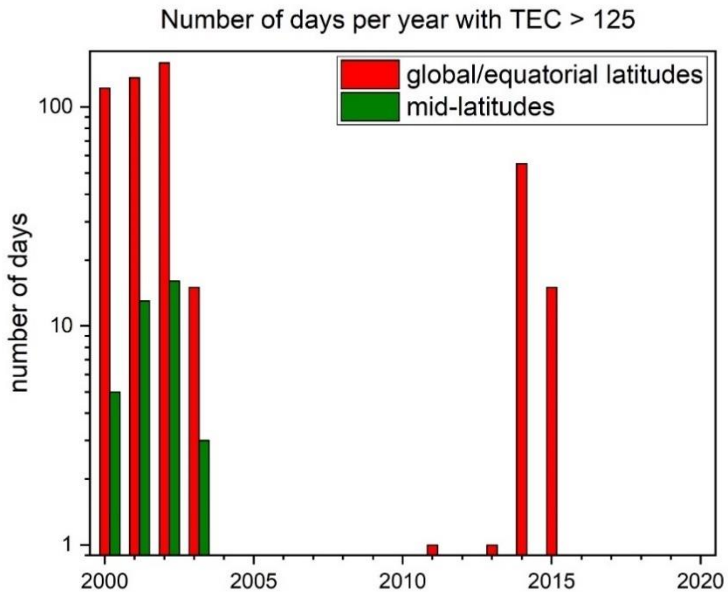


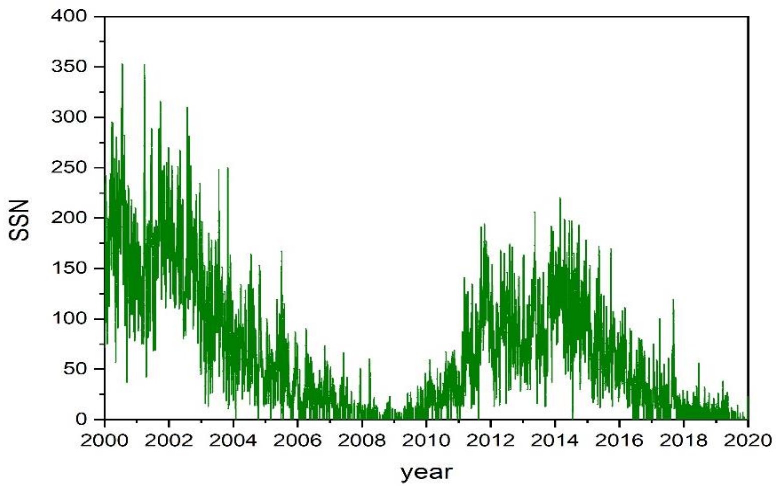
Return periods for the moderate (125 TEC) and severe (175 TEC) thresholds



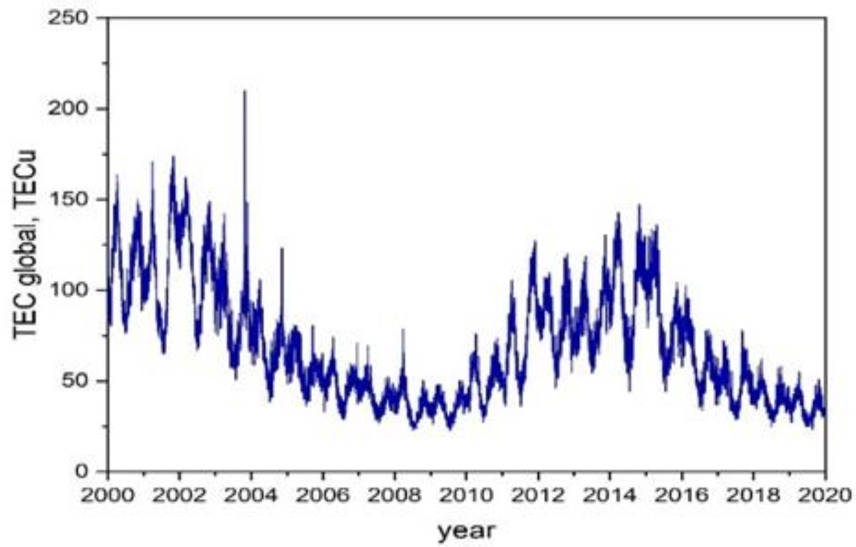
Return period for exceedance of a threshold	Moderate threshold 125 TECU with 95% CI, years	Severe threshold 175 TECU with 95% CI, years
High-latitudes	44.0 [24, 93]	N/A
Mid latitudes	4.6 [3.4, 6.3]	15.3 [10.7, 22.6]
Global and equatorial latitudes	2.3 [1.8, 3.1]	8.0 [5.8, 11.4]

Variability of TEC during the solar cycle. Analysis of extremes for solar maximum and mimimum



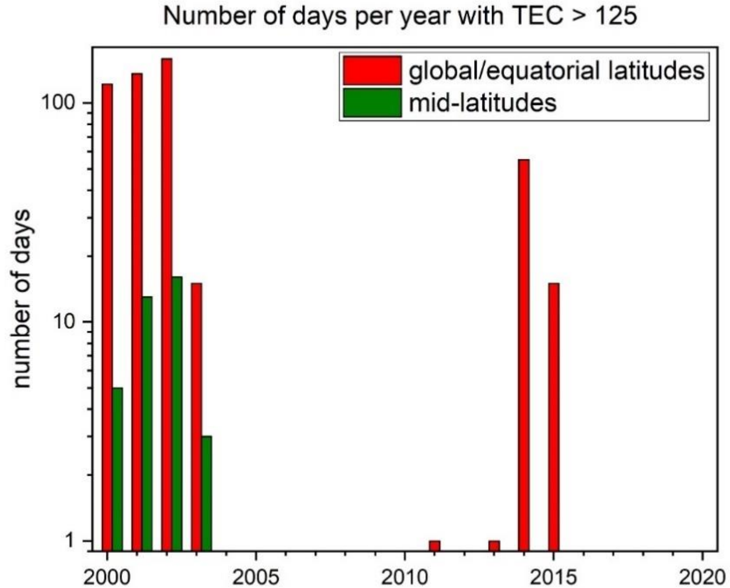


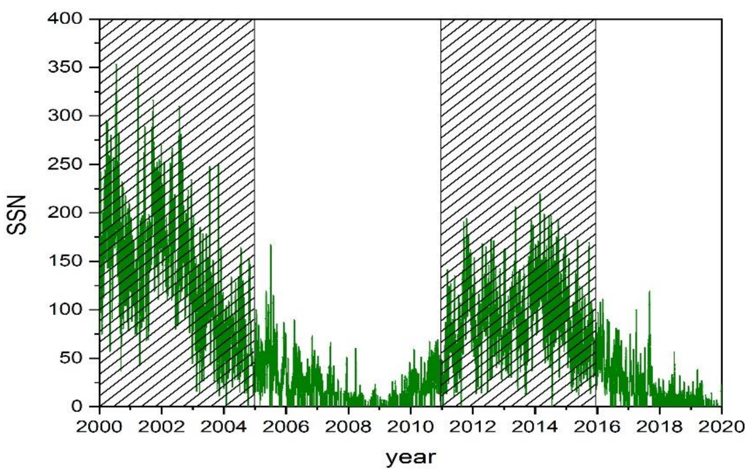
Global TEC value, daily maximum 2000-2019



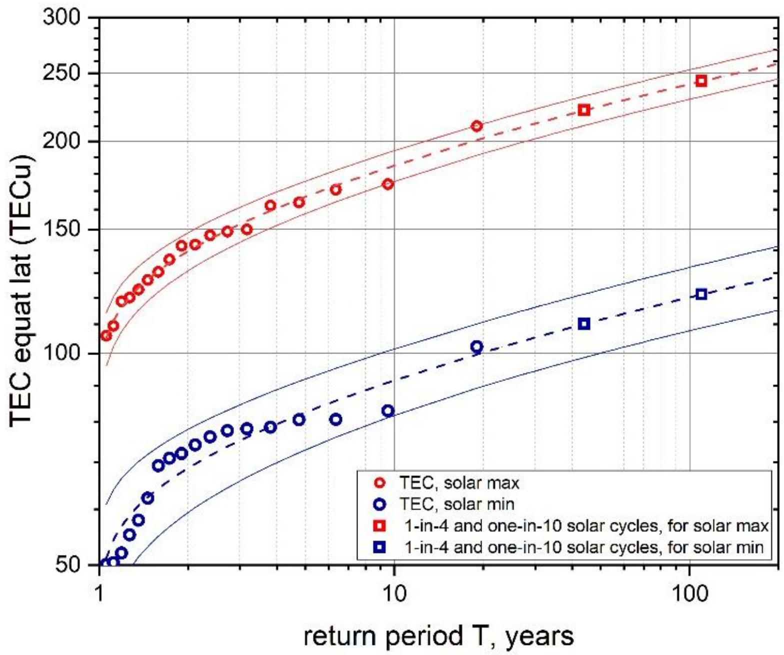
- All the data were separated between the maximum and the minimum of solar activity.

Variability of TEC during the solar cycle.
Analysis of extremes for solar maximum and mimimum



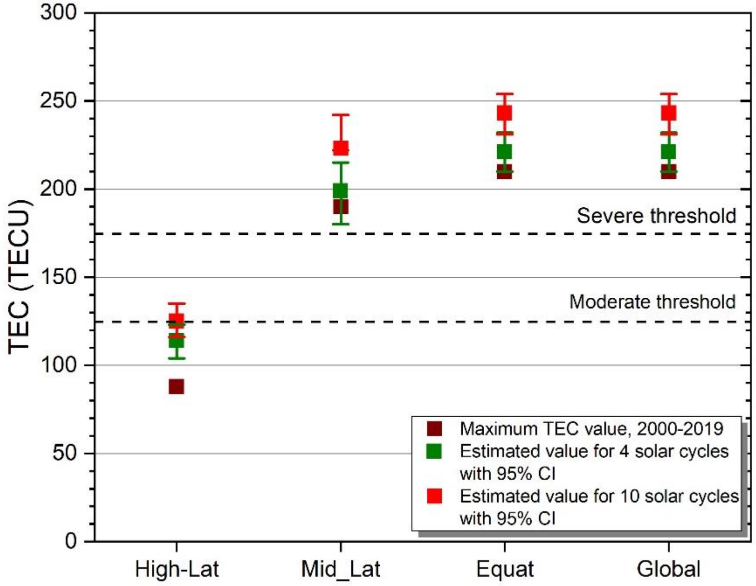


Fitting of equatorial TEC data from the solar minimum and the solar maximum to Gumbel distribution, Estimation for one in4 solar cycles and one in 10 solar cycles:

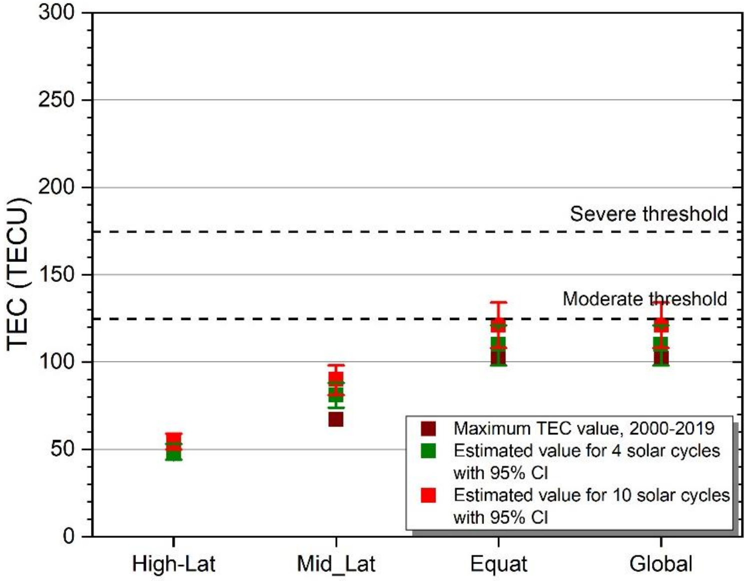


Estimated extreme values for one in 4 and one in 10 solar cycles

Solar maximum



Solar minimum



CONCLUSION

- Extreme value analysis has been applied to the daily maximum values of TEC to estimate the largest possible TEC for one in several solar cycles space weather event;
- This analysis has been made separately for high-latitude, mid-latitude and equatorial latitude bands;
- Due to variability of TEC in the course of the solar cycle, estimation of extreme values of TEC has been made separately for the periods of maximum and minimum solar activity;
- It was shown that **for the solar maximum**:

  the largest possible values for one-in-4 solar cycles event is about

  105-125 TECu in high-latitudes, 210-230 TECu in mid-latitudes and about

  180-215 TECu in equatorial latitudes;
- It was shown that **for the solar minimum** the largest possible values for 4 solar cycles:

  44-53 TECu in high-latitudes, 74-88 TECu in mid-latitudes, and about

  100-120 TECu in the equatorial latitudes;
- Overall estimation of TEC extremes for the solar maximum is approximately

  2-2.7 times as large as estimations for the solar minimum.