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Correlation Study of Solar Forcing Parameters in the Ionosphere

Illustration of different effects in the correlation of solar and ionosphere parameters in time scales of several days to months

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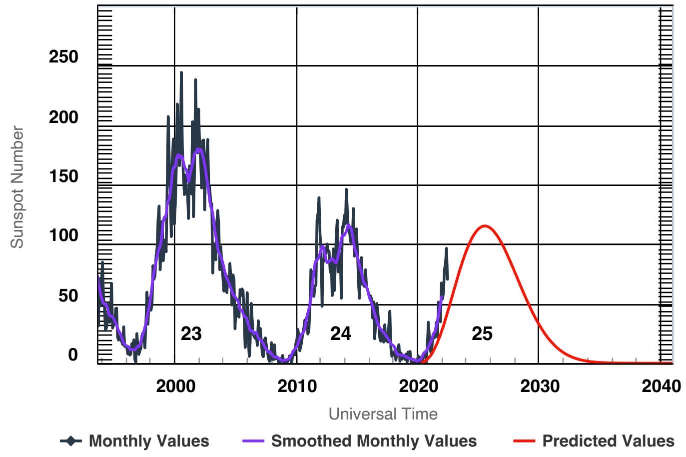
Introduction

- Space weather is strongly dependent on the activity of the Sun.
- Space weather affects technological systems in space and on Earth.
- Monitoring and understanding solar cycle and activity is crucial for predicting and mitigating its effects on Earth and in space.
- Solar flares, Coronal mass ejections (CMEs), Solar wind, Geomagnetic storms
- It has significant impact on the ionosphere and its variations.
- Ionization, Variations in electron density, Ionospheric irregularities, Total Electron Content (TEC) fluctuations



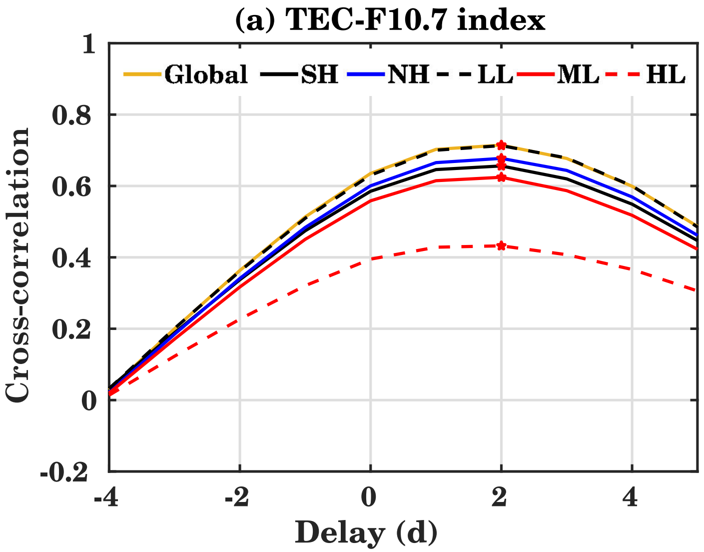
International Space Environmental Services(ISES) Solar Cycle Sunspot Number Progression. (Space Weather Prediction Center (www.swpc.noaa.gov))

Objective

- The ionospheric electron density fluctuates due to solar activity, geomagnetic storms, and atmospheric waves.
- The main objective of this thesis is to illustrate the correlation between solar forcing parameters in the ionosphere.
- Correlation analysis using Pearson correlation.
- TEC against F10.7 solar flux and solar wind speed (1998 - 2020).
- Investigates the seasonal, latitudinal, local time and solar activity dependence
- Crucial for predicting and mitigating space weather effects on our technology.

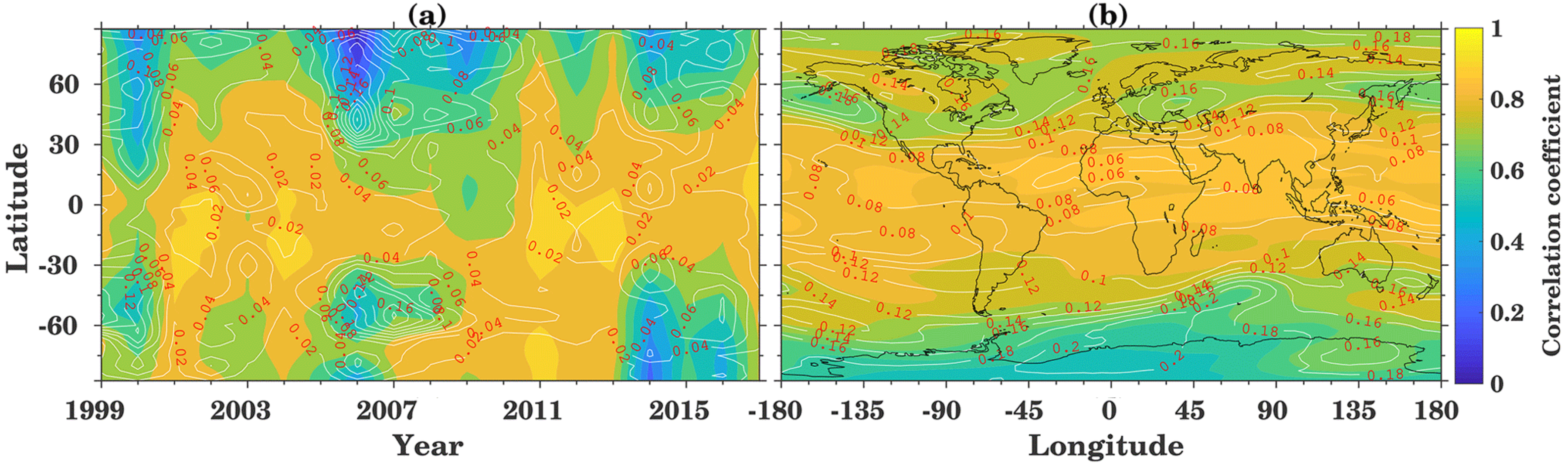
Solar variability effects in the ionosphere

- The thermosphere-ionosphere system is dynamic across solar cycles
- Transport processes may contribute to ionosphere delay, as found in Vaishnav et al.'s (2018) research.
- Findings shows an ionosphere variation delay of one to two days.
- Vaishnav et al. (2019) conducted research on the long-term variations in the ionospheric response to solar EUV.
- Global mean TEC and various solar EUV proxies to examine the temporal and spatial characteristics.
- The research covered a period of 18 years (1999-2017).
- Cross-wavelet and Lomb-Scargle periodogram (LSP).
- A stronger correlation can be detected between the variables nearer to the equator.
- Solar EUV radiation, recombination, solar zenith angles steers to the free electron concentration in the ionosphere



Cross-correlation coefficients and time delays between the global,Northern Hemisphere (NH), and Southern Hemisphere (SH) as well as low-latitude (LL,±30◦), midlatitude (ML,±(30–60◦)), and high-latitude (HL,±(60–90◦)) TEC with F10.7 during the years 1999 to 2017 for a different lag.A positive lag means that solar flux variations are heading TEC ones. The maximum correlation is indicated by a red star (Vaishnav et al., 2019).

Solar variability effects in the ionosphere



(a) Zonal mean (b) long term mean correlation coefficient betweenTEC and Mg II index for the years 1999 to 2017. The white contour lines indicate the respective standard deviations (Vaishnav et al., 2019).

- Zonal mean and long term mean correlation between TEC and and Mg II index for the years 1999 to 2017.
- At low latitudes, a maximum correlation of around 0.9.
- Correlation drops as latitude increases.
- Particle precipitation influences in the polar region.
- The ionosphere is affected by the solar wind by electrodynamic and hydro-magnetic drift.

Observations and solar parameters

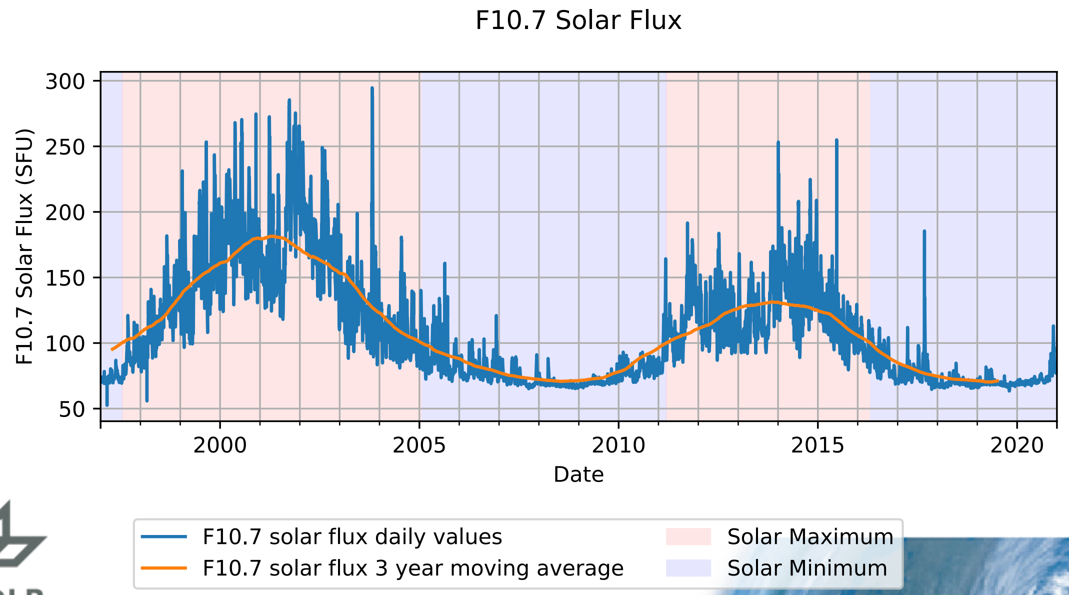
F10.7 Solar Flux

Solar Wind Speed

Total Electron content (TEC)

F10.7 Solar Flux

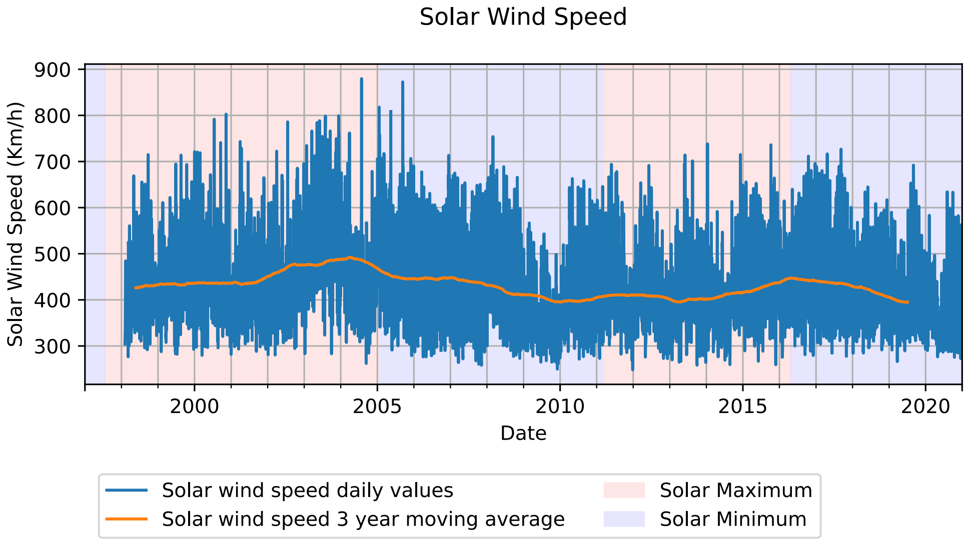
- Important parameter for characterizing solar activity and its effects
- Measure of the solar radio flux density at a wavelength of 10.7 cm.
- Measured by ground-based radio telescopes; radio emissions from the Sun at a frequency of 2800 MHz
- F10.7 solar flux typically increases during high solar activity and decreases during low solar activity
- Indicator of the potential for geomagnetic storms and other space weather events.
- Natural Resources Canada provides daily values of the F10.7 solar flux.
- The adjust value from the data source is used in this study for further analysis
- January 2005 to March 2011 and April 2016 to December 2020 - solar minimum
- January 1998 to January 2005 and March 2011 to April 2016 - solar maximum



F10.7 Solar flux values from 1998 to 2020. The blue line rep-resents the daily adjusted F10.7 solar flux readings provided by DominionRadio Astrophysical Observatory and Natural Resources Canada, while the orange line represents the three-year moving average value. Red and blue shading represent the solar maximum and solar minimum, respectively.

Solar wind speed

- Solar wind speed is the speed at which the charged particles moving away from the Sun.
- Vary widely depending on the activity of the Sun
- Important parameter for understanding the behaviour of the Earth's magnetosphere.
- Key parameter for space weather forecasting
- Affects Earth's magnetosphere and ionosphere, as well as increased auroral activity.
- The Solar Wind Electron Proton Alpha Monitor (SWEPAM) instrument of Advanced Composition Explorer (ACE) provides solar wind information.
- SWEPAM level 2 data consists of ion data and electron data which include proton density, proton temperature, proton speed.
- In this analysis, the solar wind speed is represented by the proton speed (V p),which is given in kilometers per second.

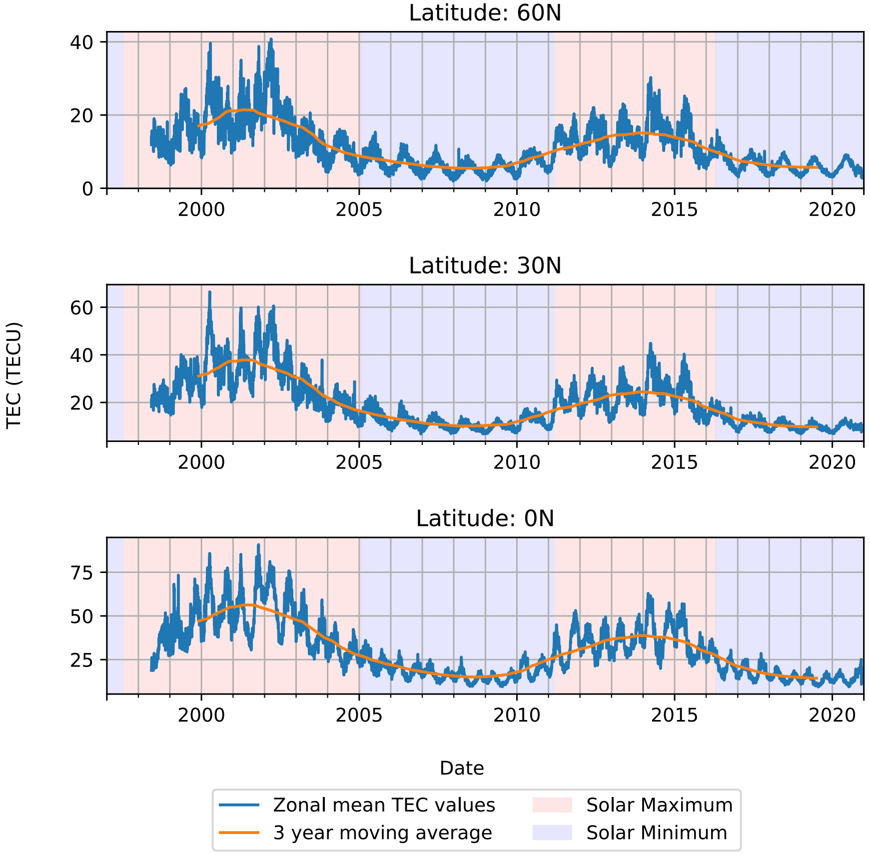


Solar Wind Speed values from 1998 to 2020. The blue line represent the SWEPAM daily averaged solar wind speed data from ACE spacecraft, while the orange line represents the three-year moving average value. Red and blue shading represent the solar maximum and solar minimum, respectively.

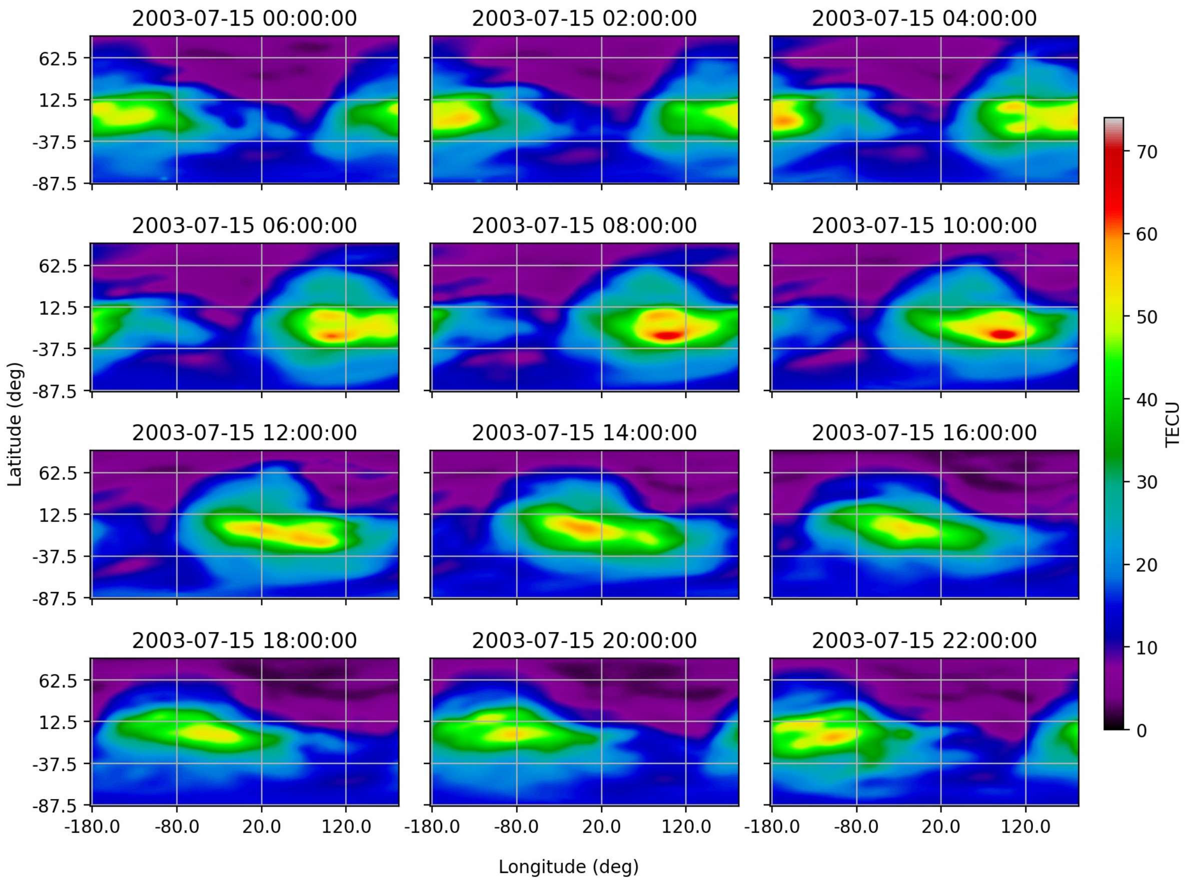
Total Electron Content (TEC)

- TEC refers to the total number of free electrons present ionosphere.
- TEC is an important parameter for studying ionospheric behavior.
- Estimated by measuring the time delay of radio signals passing through the ionosphere.
- TEC is affected by solar activity, geomagnetic activity, and local time.
- High solar activity leading to higher TEC values.
- TEC are higher during daytime hours and lower during nighttime hours.
- Ionosphere can be disturbed during periods of geomagnetic activity,
- The Crustal Dynamics Data Information System (CDDIS) is a NASA data center distributes TEC data.
- Data available in three temporal resolution, namely 15 minutes, 1 hour, and 2 hours.

Total Electron Content (TEC)



Zonal mean TEC values in the ionosphere at latitude 60N, 30N and 0N from 1998 to 2020. Red and blue shading represent the solar maximum and solar minimum, respectively.



A 2-hour resolution TEC map for 2003-07-15 created using data from the IGS Ionosphere Group.

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Methodology

Data Collection and Preprocessing

Mathematical Background of the Correlation Analysis

Software tool

Data Collection and Preprocessing

- Makes the data easier to analyze by preliminary processing.
- Removes gaps or duplicates in the data
- Data available in a variety of file formats, including CSV, text files, and other forms.
- Data files are read and then transformed to a binary file format known as the Hierarchical Data Format HDF.
- The F10.7solar flux data and solar wind speed data is structured as a time series having frequency of daily values and the data is indexed with date.
- TEC data is structured and indexed with date and time, having a resolution of 2.5º, 5º and 1 hour respectively.
- The method of linear interpolation is used to replace data gaps.
- A smoothing of data points was performed on the three data sets by taking a 27-day moving average.
- Relative difference is computed to determine the percentage of actual values to the 27 days mean.
- The relative difference of the data set is computed in order to remove the long-term effects of the solar cycle.

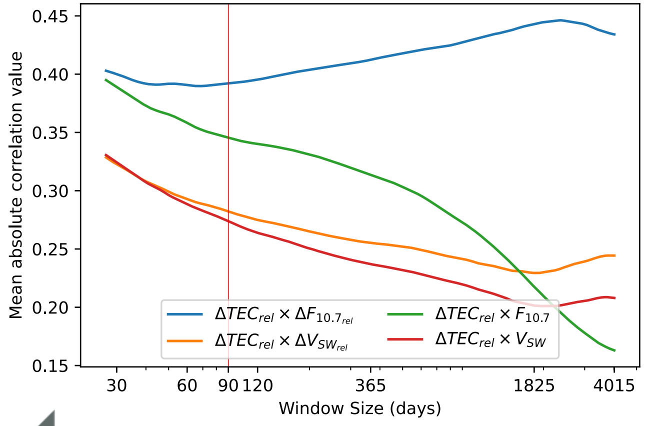
Correlation Analysis

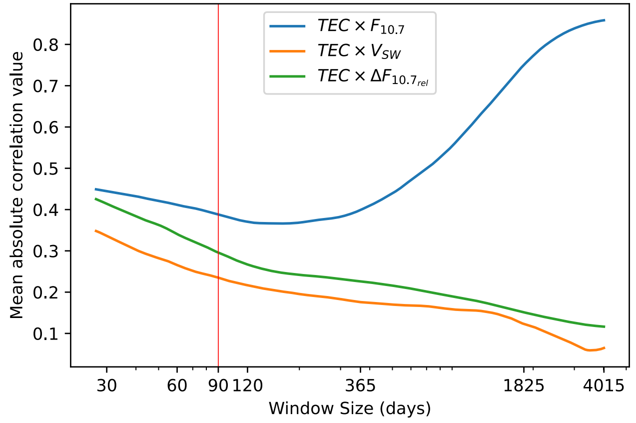
- Correlation analysis is a statistical technique that measures the degree to which two or more variables are related.
- Pearson correlation is a measure of the linear association between two variables.

$$R = \frac{n(\sum XY) - (\sum X) * (\sum Y)}{\sqrt{n(\sum X^2) - (\sum X)^2} * \sqrt{n(\sum Y^2) - (\sum Y)^2}}$$

n is the number of observations, *X* is the measure of variable 1 and *Y* is the measure variable 2

- Calculations carried out using a box window of 90 days.
- Window size should be small enough to detect the seasonal effects and large enough to have a sufficient number of values to correlate.
- The window size was checked by finding the mean absolute correlation between ΔTEC_{rel}, TEC, ΔV_{SWrel}, V_{SW}, $\Delta F10.7_{rel}$, F10.7.

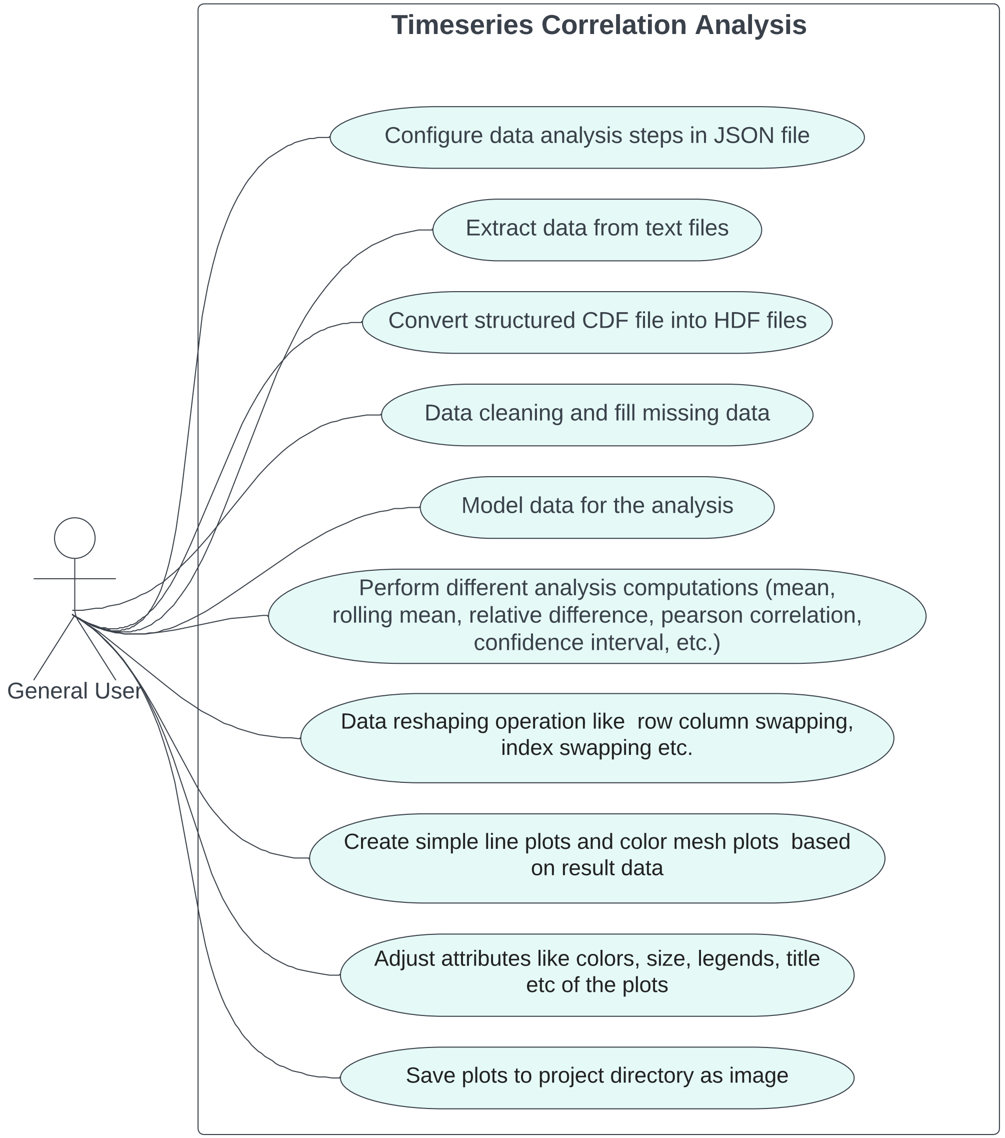




Window size test with mean absolute correlation between ΔTEC_{rel}, TEC, ΔV_{SWrel}, V_{SW}, $\Delta F10.7_{rel}$, F10.7 at location 12.5N 0E. Red vertical line indicates 90 days window size.

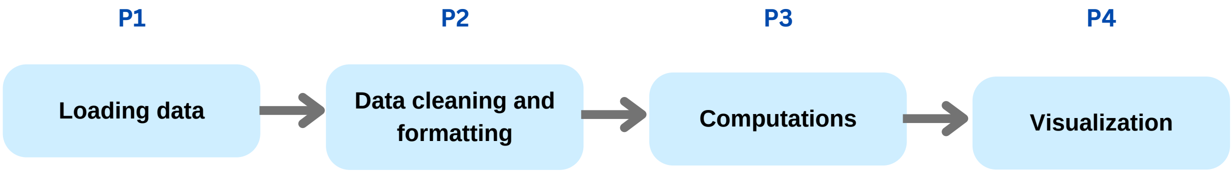
Software Tool

- Development of a software tool for the analysis using Python.
- File format, loading time, the structure of the data, and the computation complexity are taken into account for the software.
- Manages multiple computation operations and to independently manage the flow of the computations and results.



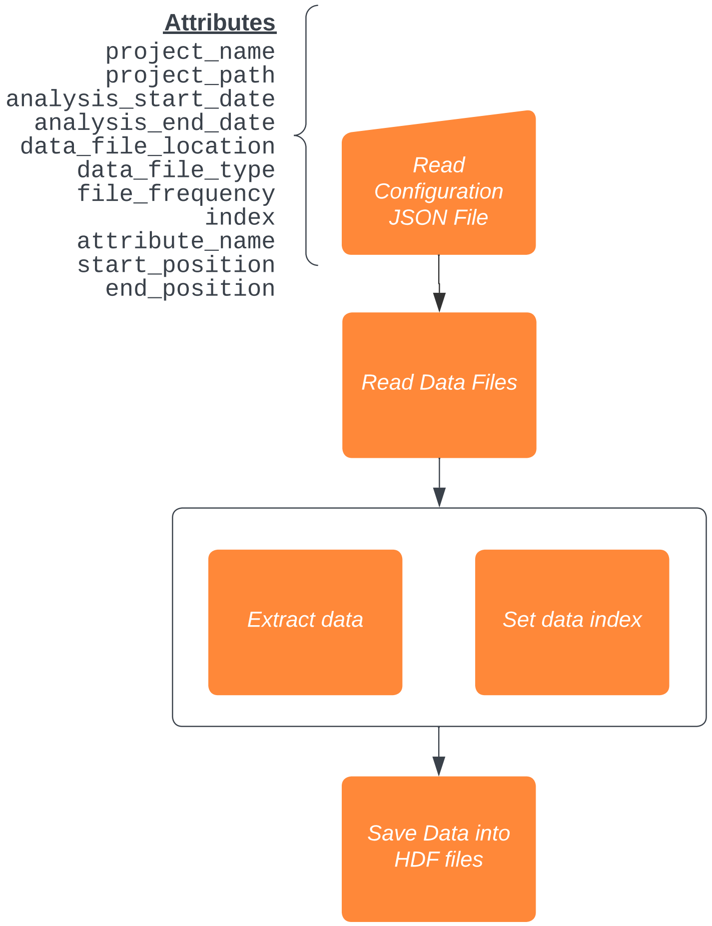
Software Tool

- The software system is separated into four distinct modules.



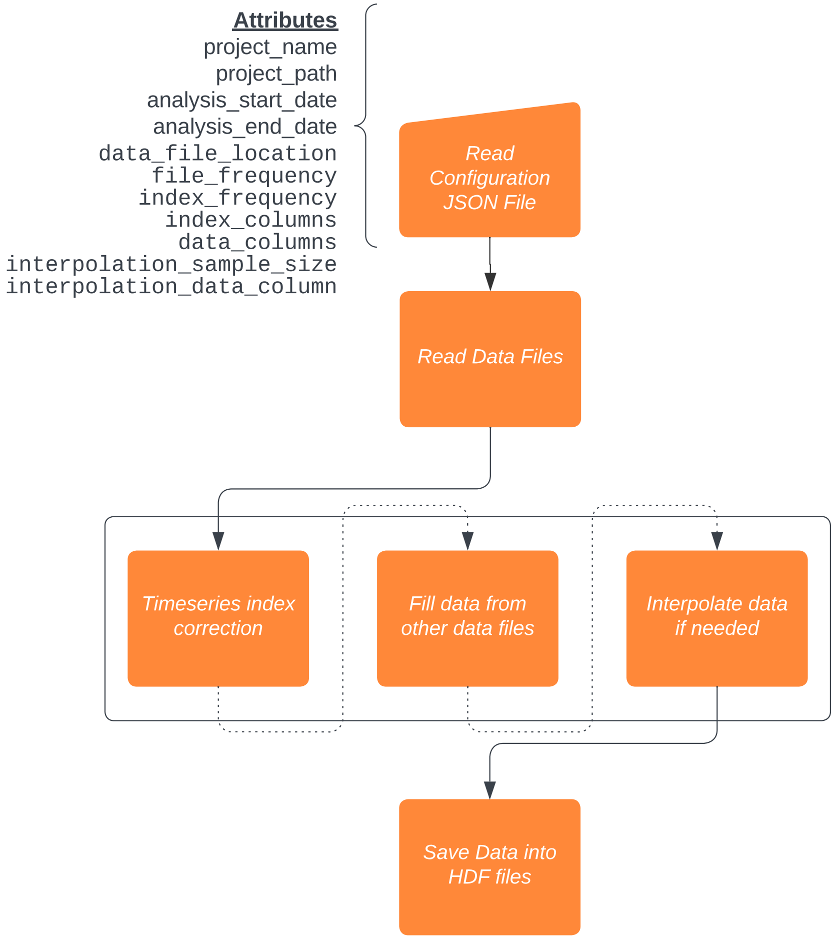
- Setting up the project and loading the data (P1)
- Data cleaning and formatting (P2)
- Computations (P3)
- Visualization (P4)

Setting up the project and loading the data



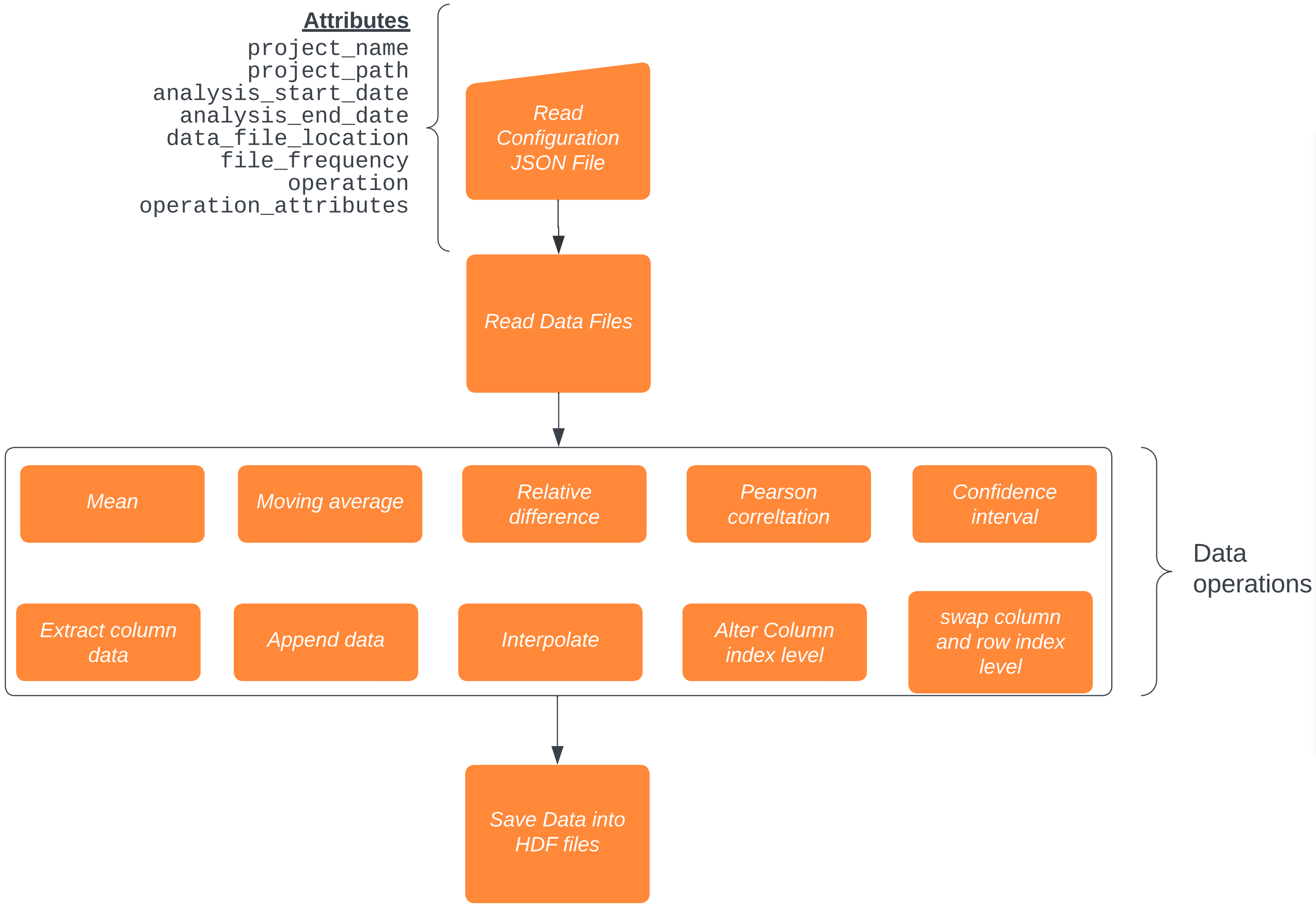
workflow of data load module (P1)

Data cleaning and formatting



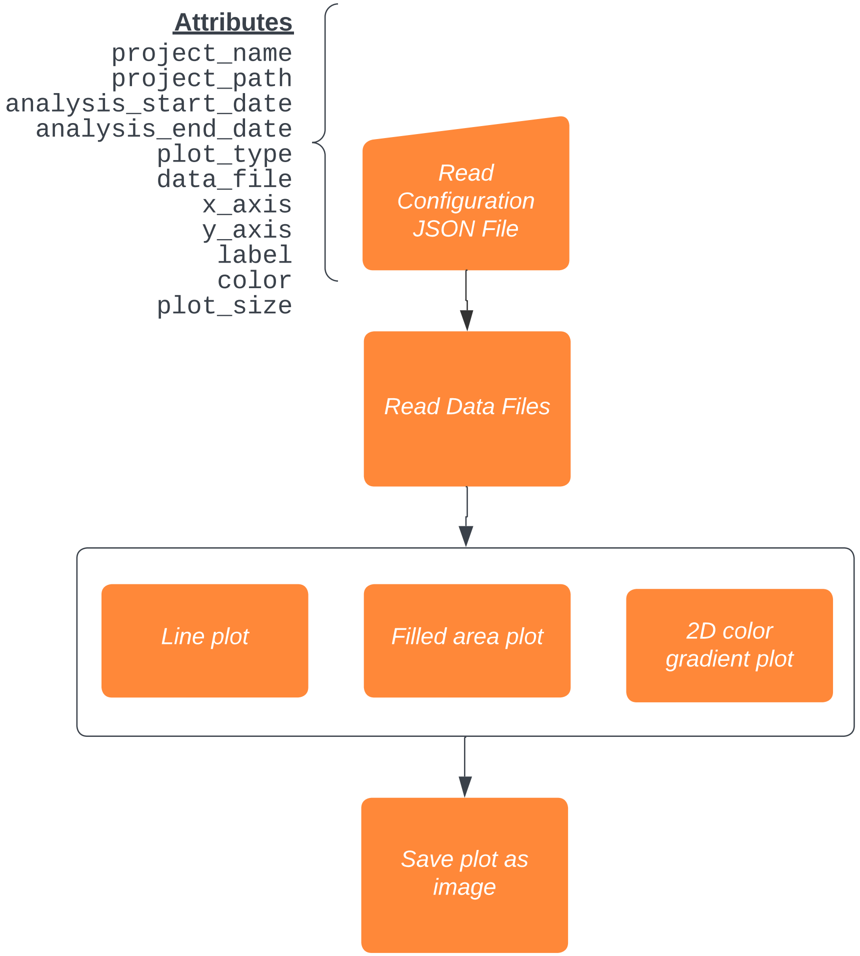
workflow of data cleaning & formatting module (P2)

Computations



Workflow of computation module (P3)

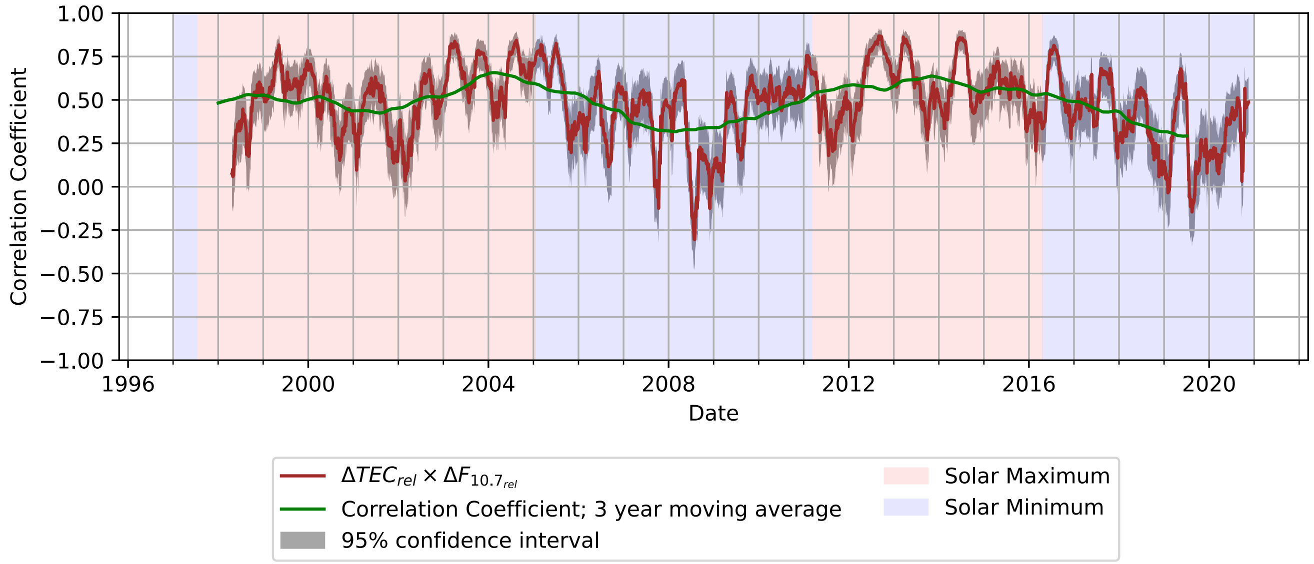
Visualization



workflow of visualisation module (P4)

Results

Temporal changes of the Correlation between TEC and F10.7 Solar Flux

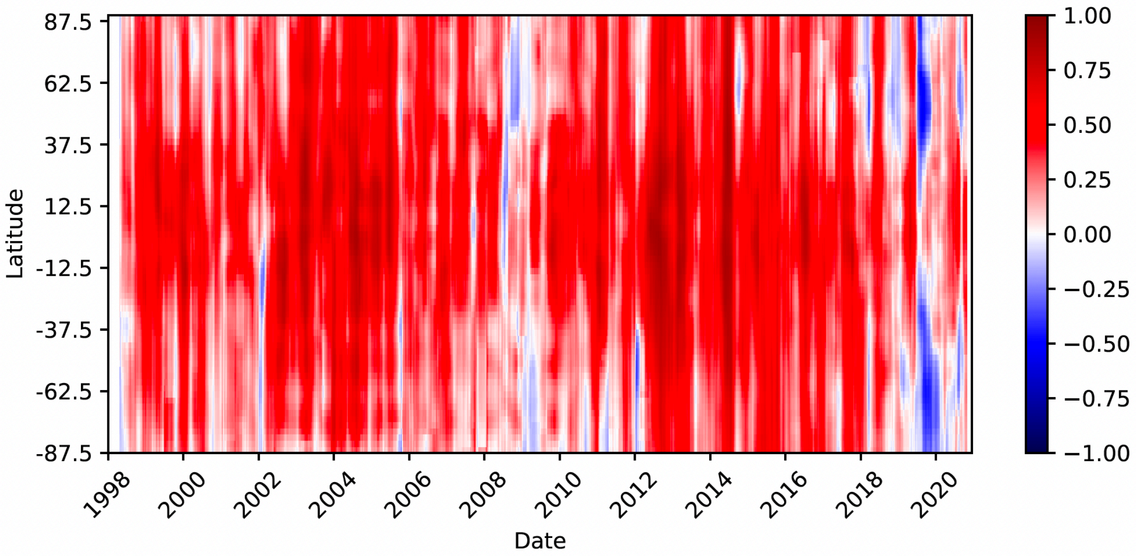


Correlation between $\Delta F10.7_{rel}$ and ΔTEC_{rel} with a 90 days window at 12.5 N latitude from 1998 to 2020. The red line represents the Pearson correlation coefficient values, and the green line represents the 3-year moving average of the correlation result. Red and blue shading represent the solar maximum and solar minimum periods, respectively.

- A significant positive correlation between TEC and F10.7 solar flux, particularly during periods of high solar activity.
- Correlation values vary from 0.8 to -0.4
- The strength of the correlation can vary depending on season, the latitude, and the level of geomagnetic activity.

Latitudinal dependency of the Correlation between TEC and F10.7 Solar Flux

A



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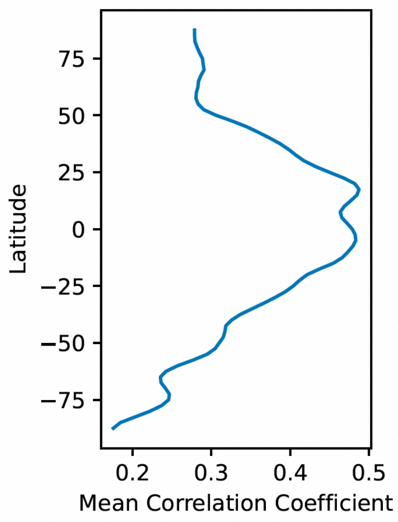
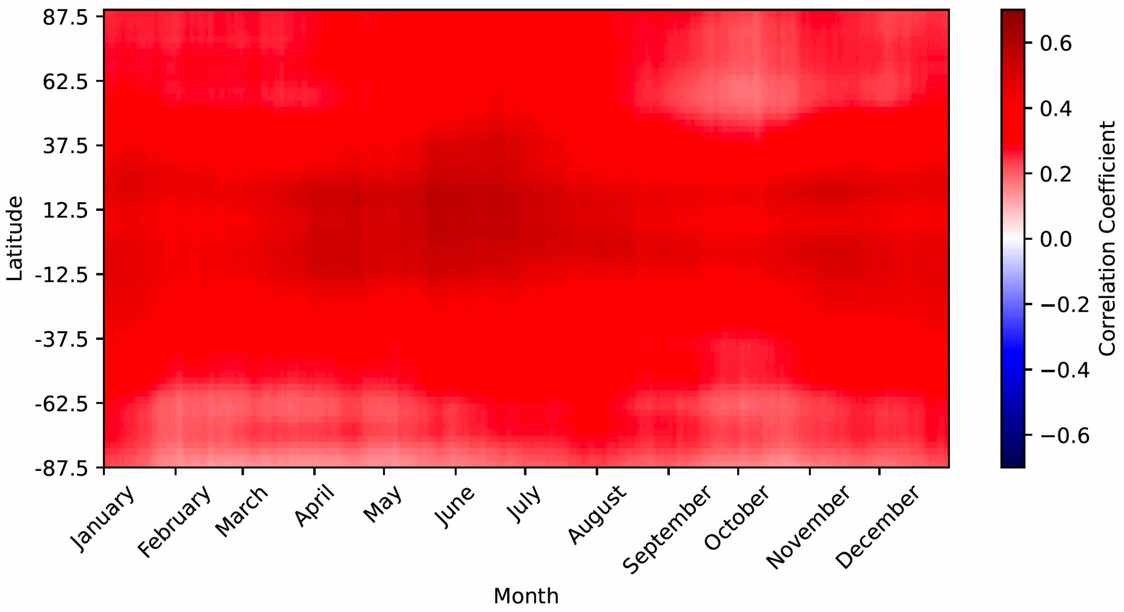


A: Latitudinal variation of correlation coefficient between $\Delta F10.7_{rel}$ and zonal mean ΔTEC_{rel} with 90 days box window from 1998 to2020. Red gradient represents magnitude of positive correlation coefficient and blue gradient represents negative correlation coefficient values.

B: Latitude mean correlation coefficient $\Delta F10.7_{rel}$ and ΔTEC_{rel} from 1998 to2020.

- Significant positive correlation trend across all latitudes during the study period.
- The correlation coefficients are stronger at lower latitudes than at higher latitudes.
- Higher correlation values at the equator generate a structure with two crests at the equator between -20 and+20 degrees latitude.

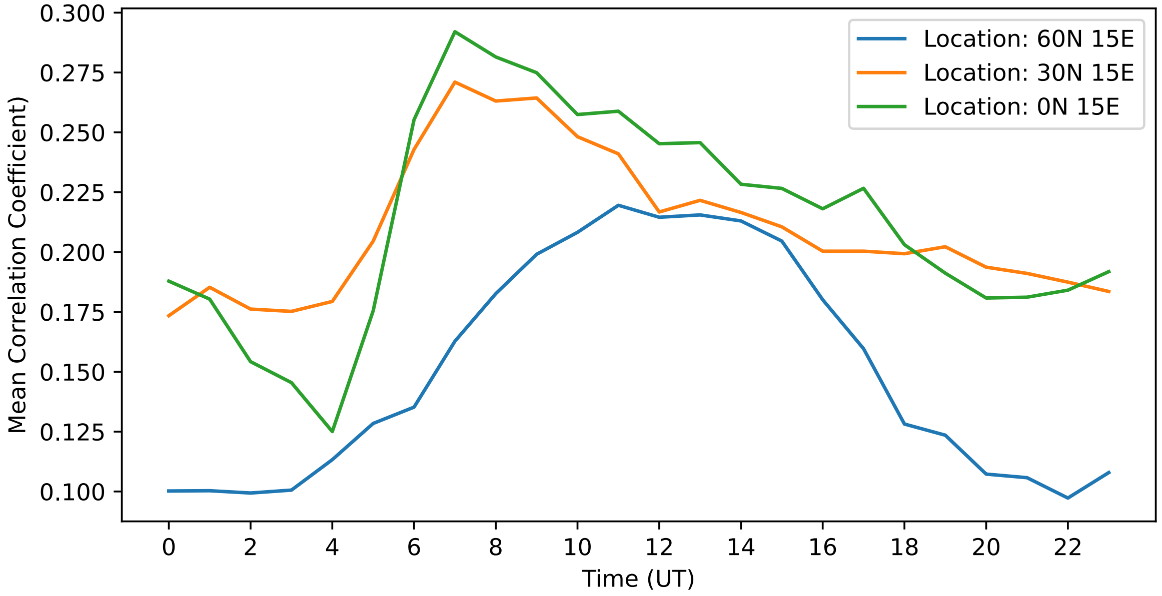
Latitudinal dependency of the Correlation between TEC and F10.7 Solar Flux



The correlation computation between $\Delta F10.7_{rel}$ and ΔTEC_{rel} averaged over the course of the year in the period 1998 to 2020. Red gradient represents magnitude of positive correlation coefficient and blue gradient rep-resents negative correlation coefficient values.

- The $\Delta F10.7_{rel}$ and ΔTEC_{rel} have been shown to have a positive correlation.
- There is no distinguishable pattern of seasonal dependence, however, there are small shifts in the degree to which a positive correlation exists between the months of summer and winter.
- Correlation values shows a significant positive correlation close to the equator, but it decreases as it moves to the polar regions.

Local time dependency of the Correlation between TEC and F10.7 Solar Flux



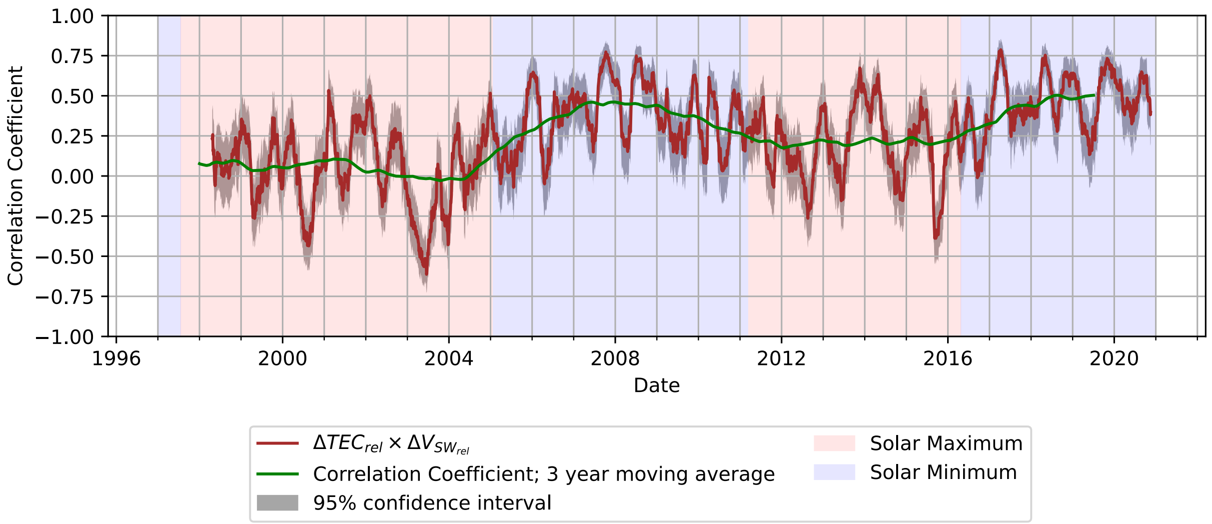
Local time variation computed by superposition of correlation between $\Delta F10.7_{rel}$ and ΔTEC_{rel} at each UT during the period 1998–2020. Locations 60N/15E, 30N/15E and 0N/15E are represented using colours blue, orange and green respectively.

- Magnitude of correlation values is highest during the daytime hours
- Correlation values are lowest during the nighttime hours.
- From 6:00 UT to 16:00 UT, the correlation values are high.
- Local time dependency becomes more pronounced as it gets closer to the equator.
- At high latitude regions, the amplitude of the correlation is greatest during the day, while the time period gets shorter.

Discussion of TEC and F10.7 Solar Flux Correlation

- Significant positive correlation between the TEC and F10.7 solar flux what is in good agreement with common knowledge.
- The correlation is particularly strong in the equatorial region, as shown in e.g. Vaishnav et al. (2019).
- The ionization efficiency depends on the solar zenith angle.
- The correlation coefficient values becomes much weaker with increasing latitude.
- Due to the EIA, higher correlation values at the equator generate a structure with two crests between -20 and +20 degrees magnetic latitude.
- A high level of solar activity is characterized by a rise in the number of sunspots as well as an increase in the magnitude of solar irradiance.
- The findings of this investigation are clearly consistent with the statement made by Hamzah and Homam (2015).
- Correlation between the two variables is significantly higher during the summer months than winter months.
- Winter months have also demonstrated a second maximum of positive correlation because of winter anomaly.
- X-ray and UV light from the Sun mainly impacts the production term of the continuity equation. This impact is only during daytime hours.

Temporal changes of the Correlation between TEC and Solar Wind Speed

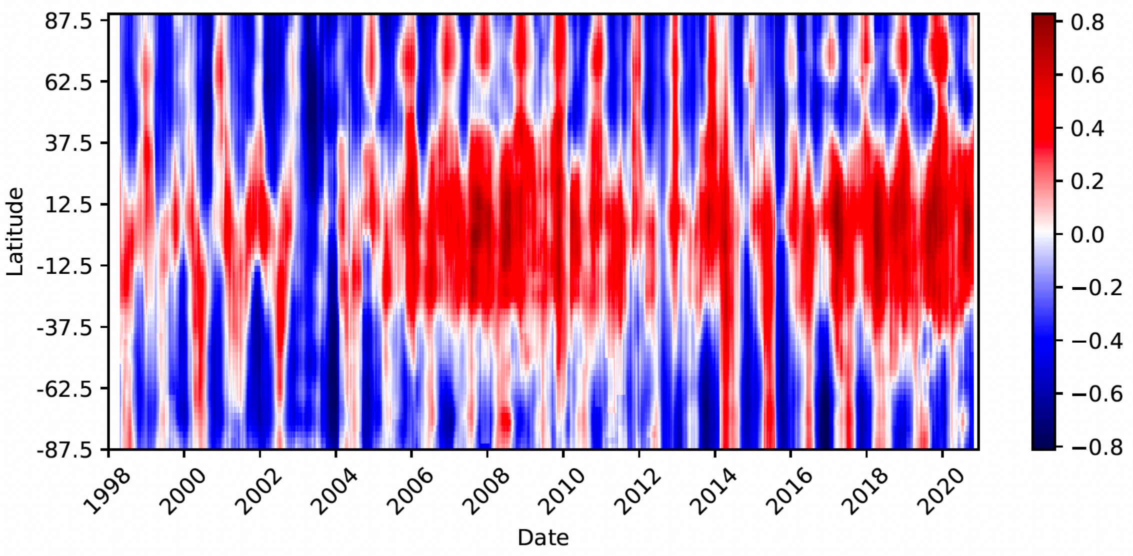


Correlation between ΔV_{SWrel} and ΔTEC_{rel} with a 90 days win-dow at 12.5 N latitude from 1998 to 2020. The red line represents the Pearson correlation coefficient values, and the green line represents the 3-year moving average of the correlation result. Red and blue shading represent the solar maximum and solar minimum periods, respectively.

- The correlation coefficient shows a pattern with variations in the solar cycle.
- Correlation becomes very low and often negative during solar maximum conditions near the equator region and correlation coefficient values increases when solar conditions are minimum.
- Strength of correlation is higher in solar cycle 23 compared to cycle 24.

Latitudinal dependency of the Correlation between TEC and Solar Wind Speed

A



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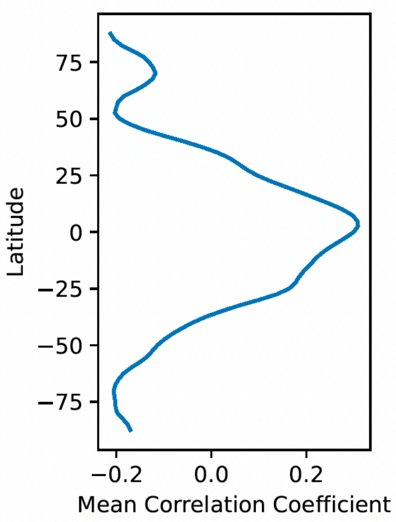
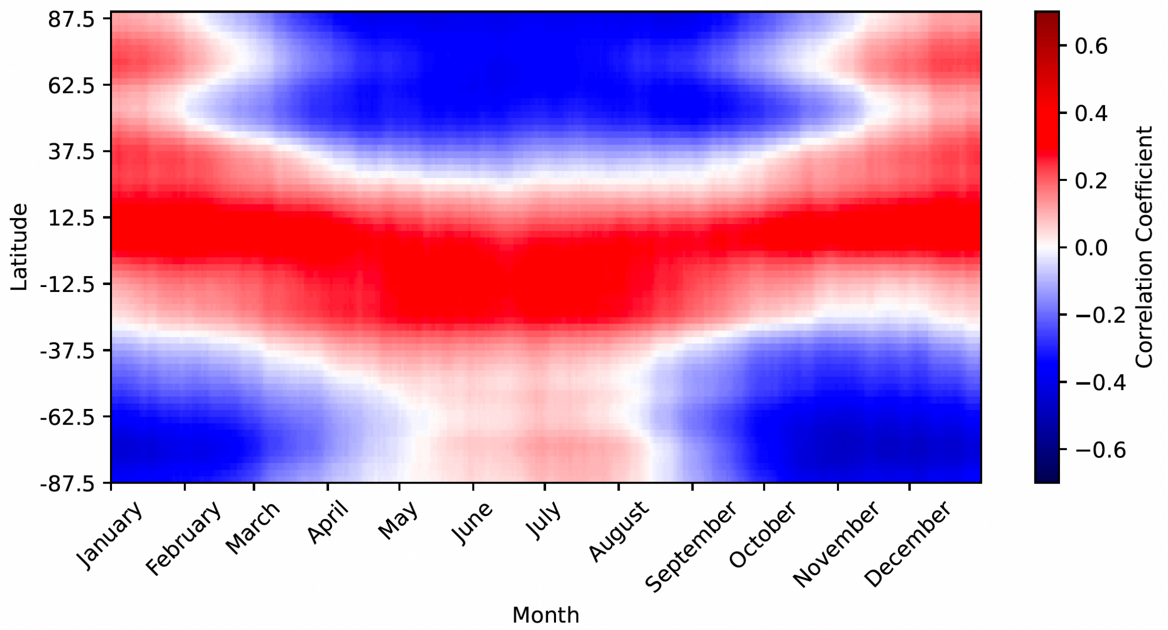


A: Latitudinal variation of correlation coefficient between ΔV_{SWrel} and ΔTEC_{rel} with 90 days box window from 1998 to 2020. Red gradient represents magnitude of positive correlation coefficient and blue gradient represents negative correlation coefficient values.

B: Latitude mean correlation coefficient ΔV_{SWrel} and ΔTEC_{rel} from 1998 to 2020.

- The correlation coefficient values range from as low as -0.775 to as high as0.778.
- A strong positive correlation is more prevalent closer to the equator, negative correlation is more prevalent in high latitudes.
- Correlation values at the equator are higher during the period of solar minimum,
- Correlation coefficient values drop to negative values during the solar maximum.
- In the polar regions, there is a significant negative correlation that exists during the summer months of the years.

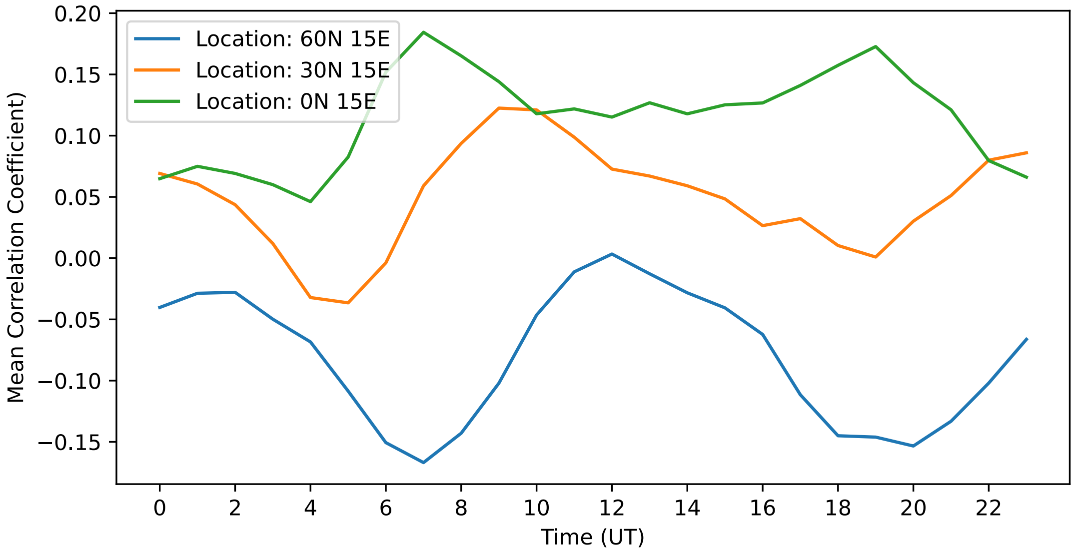
Latitudinal dependency of the Correlation between TEC and Solar Wind Speed



The correlation computation between ΔV_{SWrel} and ΔTEC_{rel} averaged over the course of the year in the period 1998 to 2020. Red color represents magnitude of positive correlation coefficient and blue color represents negative correlation coefficient values.

- There is a positive correlation that exists around the equator during all season.
- During the winter, the positive correlation at the polar region extends to the North Pole, while the southern polar region is having a negative correlation influence.
- During the summer, a positive correlation persists in the southern polar region, while a negative correlation exists in the northern polar regions.

Local time dependency of the Correlation between TEC and Solar Wind Speed



Local time variation computed by superposition of correlation between ΔV_{SWrel} and ΔTEC_{rel} at each UT during the period 1998–2020. Locations 60N/15E, 30N/15E and 0N/15E are represented using colours blue, orange and green respectively.

- At the equator, correlation values increase throughout the day and decrease during the night.
- As it goes to the higher latitudes, the magnitude of mean correlation decreases as well as the period also decreases.

Discussion of TEC and Solar Wind Speed Correlation

- Higher positive correlation between TEC and solar wind speed is visible during the solar minimum.
- When solar irradiance decreases, the effect of solar wind on TEC variations becomes more visible.
- In the winter, there is a significant positive correlation, whereas in the summer, there is a significant negative correlation in the mid and high latitude regions.
- Variations in correlation coefficients are likely to be caused by the combined action of the solar wind imposing an electric field onto the regular ionosphere electric fields.
- The equatorial region exhibits a positive correlation, whereas the mid-latitudes and polar regions frequently exhibit a negative correlation.
- A clear seasonal dependency in the correlation between ΔV_{SWrel} and ΔTEC_{rel} can be observe.
- Solar wind disturbances can drive ionospheric convection, which can transport plasma to different regions of the ionosphere and alter its density.
- Solar wind disturbances can also directly transport plasma into the ionosphere, increasing TEC in high-latitude ionosphere.

Summary and Conclusion

- The aim of this thesis was to illustrate and characterize correlation between the solar forcing parameters in the ionosphere at time scales of several days to months.
- Temporal, latitudinal, seasonal, and local time variations were investigated.
- Based on quantitative evaluation, there is a significant relationship between solar forcing parameters in terms of time, latitude, and season with the TEC.
- TEC and F10.7 solar flux correlation result indicates that, there exist a significant positive correlation in the equatorial region.
- High solar zenith angle in the equatorial region, which leads to high ionization rates.
- Other factors like atmosphere variability and geomagnetic activity, which contribute to the TEC variability.
- The results presented here show that in the time scale of days, solar wind is obviously impacting TEC.
- It can be assumed that the solar wind modify electric fields in the ionosphere, which modify the plasma transport and ionosphere currents.
- Studies with numerical models can generate further insight into the coupling processes.

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Thank you for your attention

Questions, comments and discussion.