Performance of a Locally Adapted NeQuick-2 Model During High Solar Activity over the Brazilian Equatorial and Low-latitude Regions

2025 Community Space Weather Modeling & Data Assimilation Workshop

UCAR Foothills Lab Campus, Boulder, Colorado

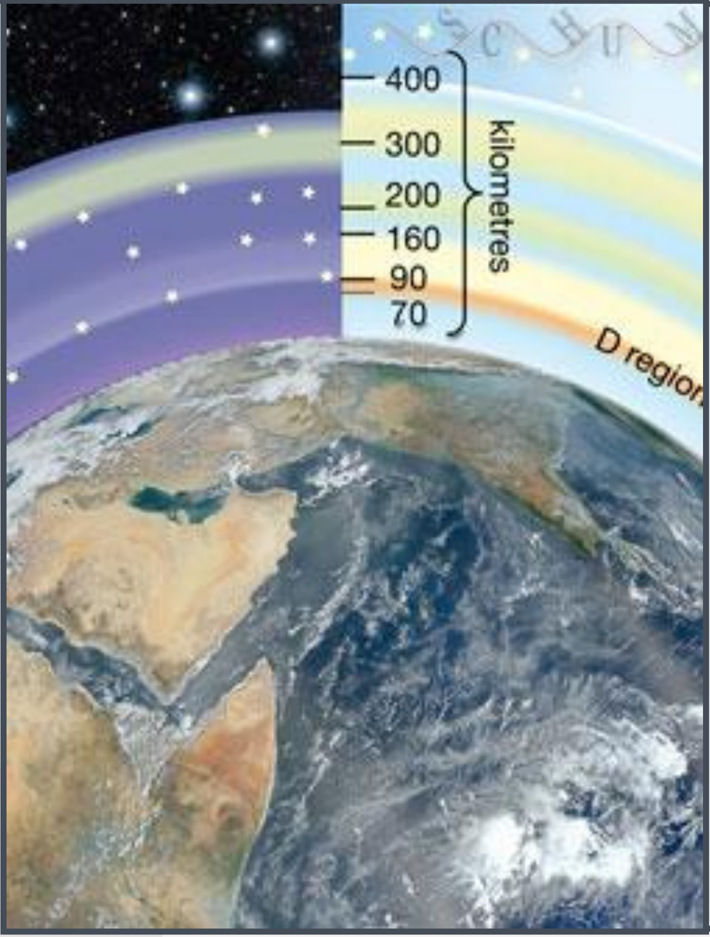
September 10-11, 2025

Taiwo Osanyin, Ph.D.

National Institute for Space Research (INPE)

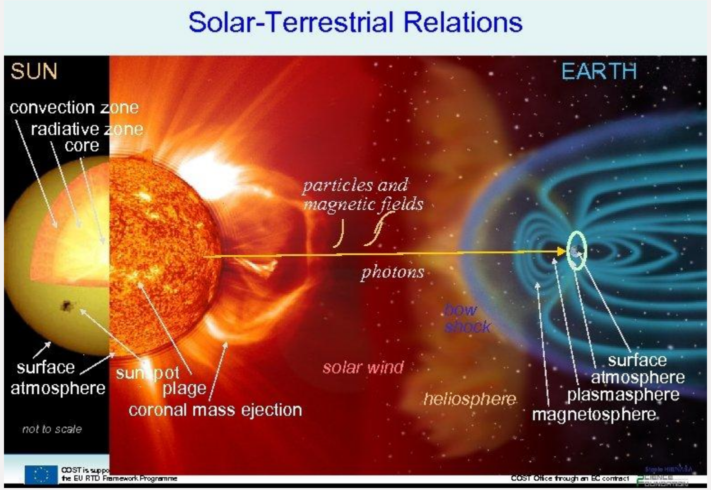
Outline of the Presentation

- Introduction
- Problem Statement
- Aim and Objectives
- Instrumentation & Methodology
- Data Analysis
- Results & Discussion
- Conclusions & Recommendation



01 Introduction

Ionospheric Response to Space Weather

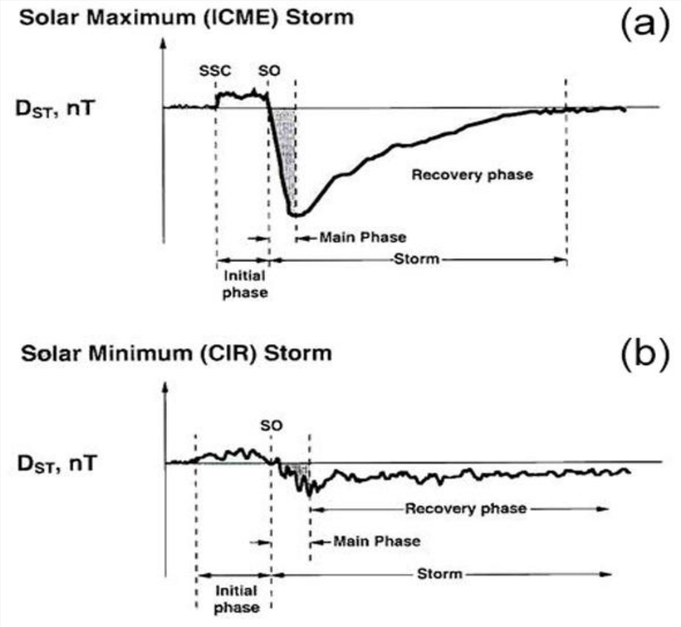


Sun-Earth Interaction:NASA.GOV

- Phases of geomagnetic storms are associated with changes in IMF & solar wind conditions.
- 90 % of HSS at solar max. are associated with ICME & in the descending phase by CIR.

The principal origin of the geomagnetic activity is the induction currents caused by solar wind electric field, $E = -V_{SW} \times B_Z$.

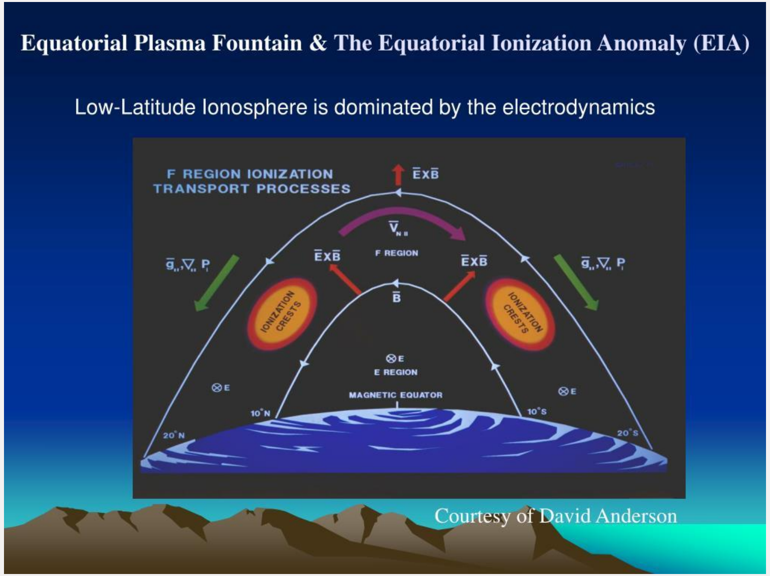
Tsurutani et al., 2019

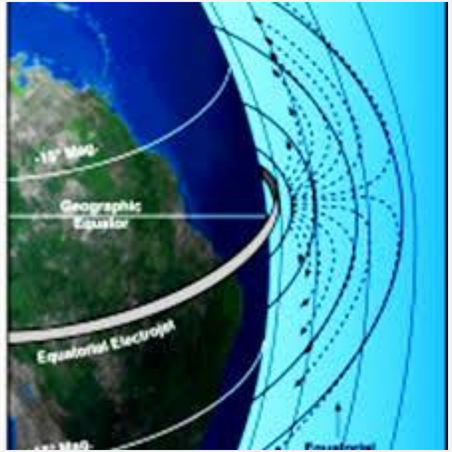


Motivation

Souza, 1999

- Low-latitude Ionosphere
- Space Weather
- Empirical models
- Data ingestion (DI)





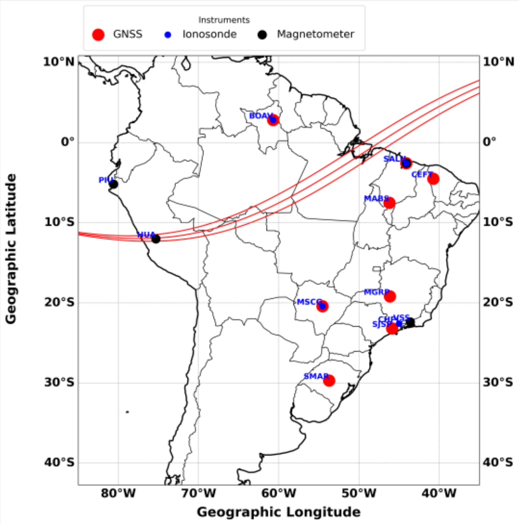
Instrumentation

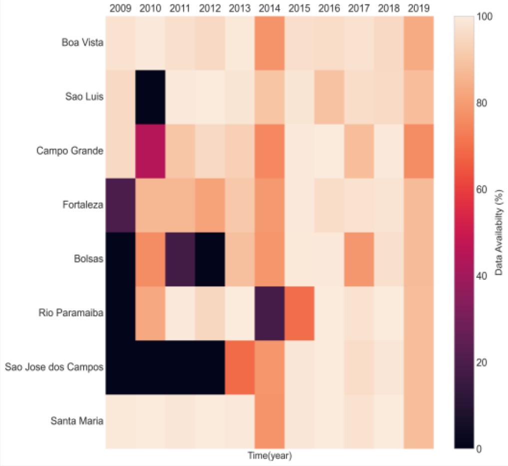
Methodology

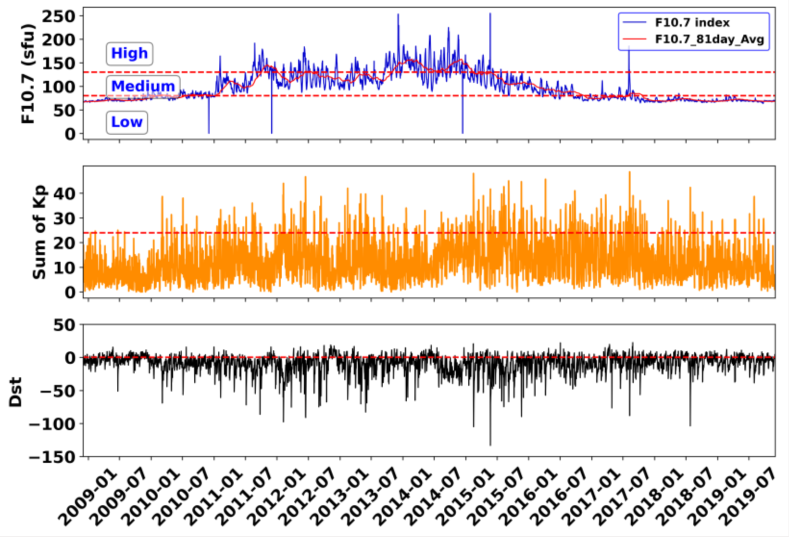
- **Intruments** — GNSS, Ionosonde
- **Models** — NeQuick 2 & IRI
- **Analysis** — TEC calibration software, SAO Explorer software, MAD, statistical analysis
- **Data Ingestion** — Local Model, Binary search algorithm, Fortran 77 language.

Experimental Dataset

- vTEC from 8 ground-based receivers.
- GPS data from 2009 to 2019, covering the previous solar cycle (SC 24).
- Only magnetically quiet days ($\sum kp \leq 24$).

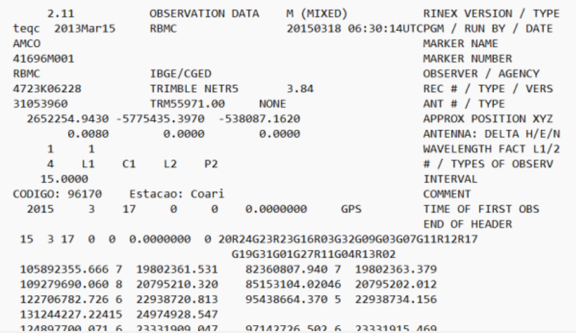






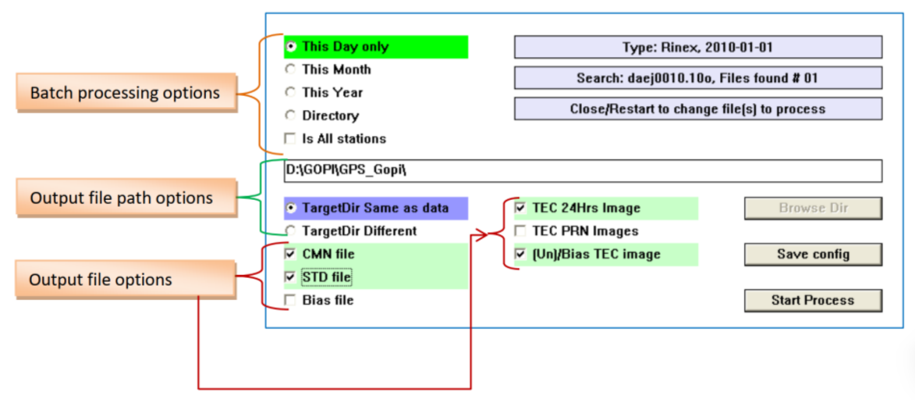
- Variation of both solar and geomagnetic activity indices during the study period

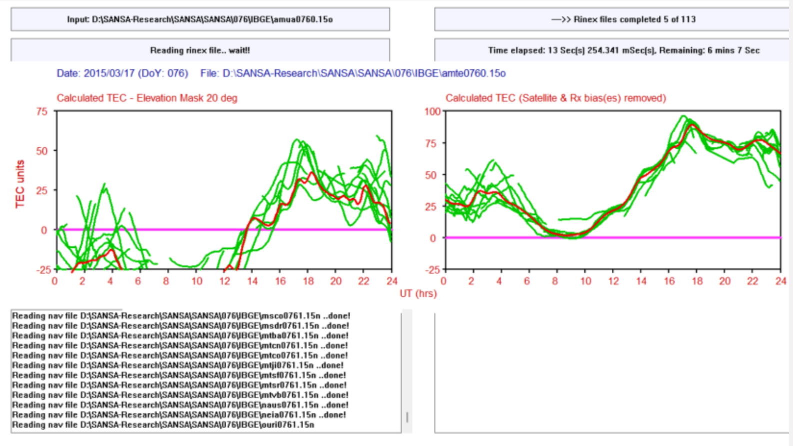
Extracting TEC data from GPS RINEX format



```
     2.11           OBSERVATION DATA    M (MIXED)           RINEX VERSION / TYPE
teqc  2013Mar15     RBMC                20150318 06:30:14UTCPGM / RUN BY / DATE
AMCO                                                        MARKER NAME
41696M001                                                   MARKER NUMBER
RBMC                IBGE/CGED                               OBSERVER / AGENCY
4723K06228          TRIMBLE NETR5       3.84                REC # / TYPE / VERS
31053960            TRM55971.00     NONE                    ANT # / TYPE
  2652254.9430 -5775435.3970  -538087.1620                  APPROX POSITION XYZ
        0.0080        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
     4    L1    C1    L2    P2                              # / TYPES OF OBSERV
    15.0000                                                 INTERVAL
CODIGO: 96170       Estacao: Coari                          COMMENT
  2015     3    17     0     0    0.0000000     GPS         TIME OF FIRST OBS
                                                            END OF HEADER
 15  3 17  0  0  0.0000000  0 20R24G23R23G16R03G32G09G03G07G11R12R17
                                  G19G31G01G27R11G04R13R02
 105892355.666 7  19802361.531    82360807.940 7  19802363.379
 109279690.060 8  20795210.320    85153104.02046  20795202.012
 122706782.726 6  22938720.813    95438664.370 5  22938734.156
 131244227.22415  24974928.547
```

- RINEX stands for Receiver Independent Exchange format.
- The RINEX observation file, navigation file, and DCB files are required during pre-processing.
- Median Average Deviation (MAD) technique

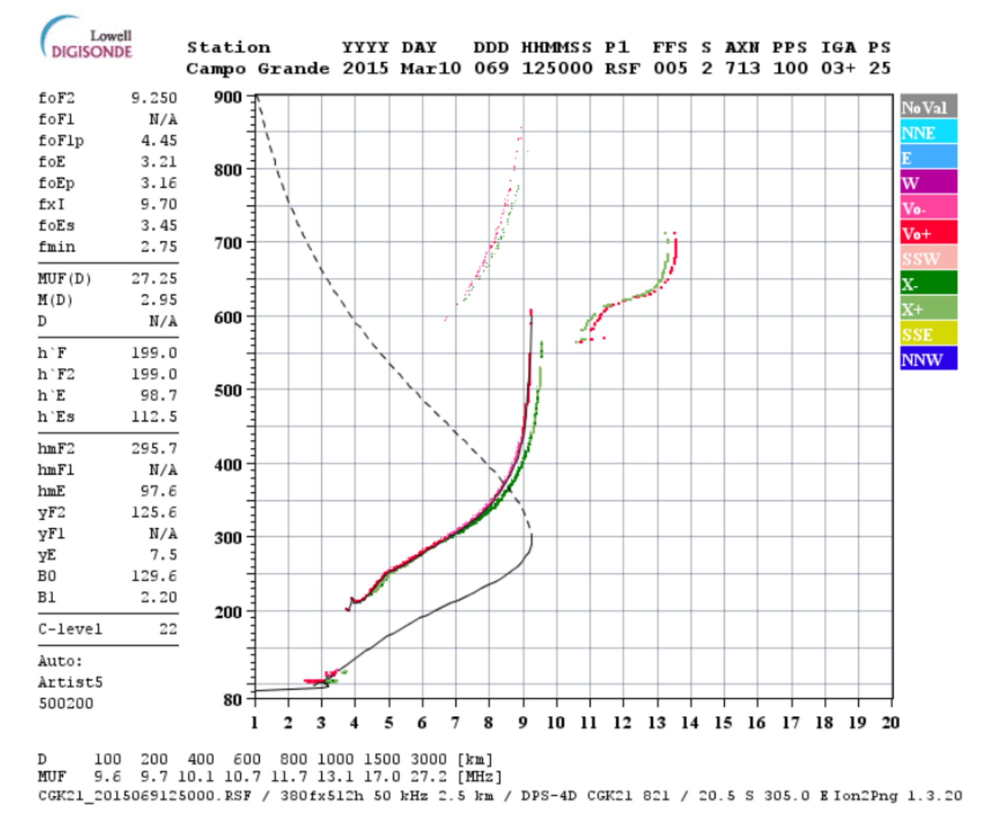




Digisonde data and Ionogram Scaling

- Sao Explorer software (https://ulcar.uml.edu/SAO-X/SAO-X.html).
- Ionogram plot displaying virtual height versus frequency.
- F2 layer frequency (foF2) has been used for model's validation.

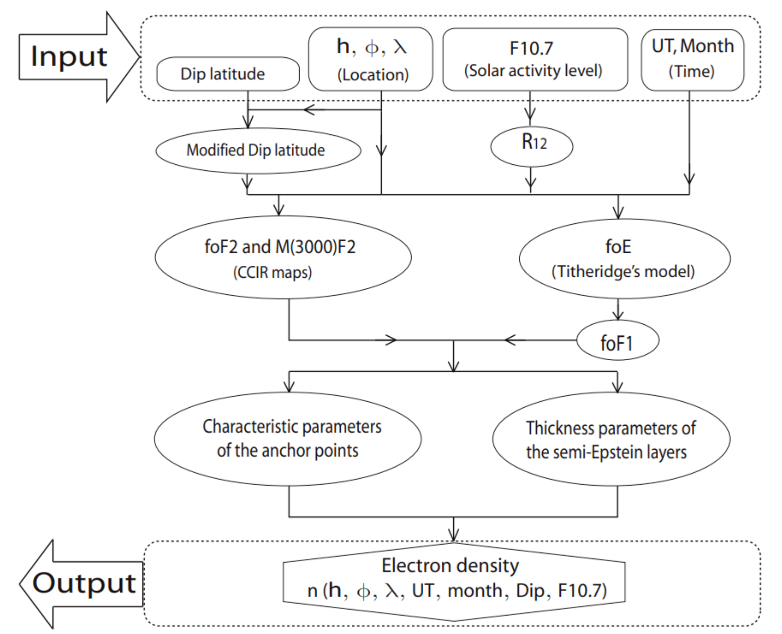
$$N_mF_2 = 1.24 \times 10^4\ (f_oF_2)^2$$



NeQuick 2 Model

NeQuick 2 model is based on empirical climatological representation of the ionosphere.

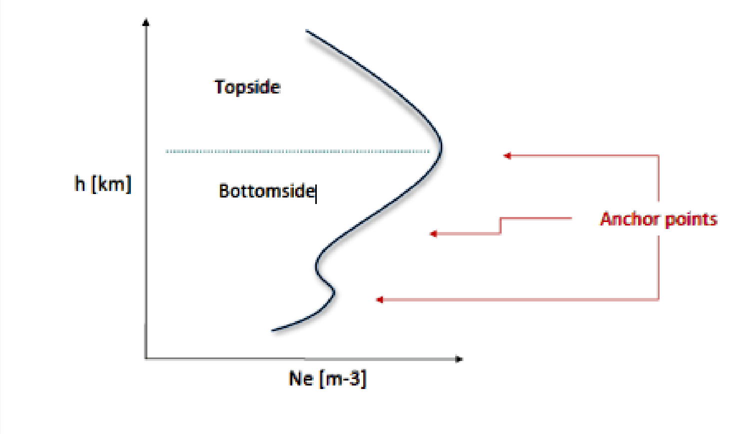
Memarzadeh, 2009



$$N_{bot}(h) = N_E(h) + N_{F1}(h) + N_{F2}(h)$$

$$N_{F2}(h) = \frac{4N_mF2}{\left(1 + exp\left(\frac{h - h_mF2}{B2}\right)\right)^2} exp\left(\frac{h - h_mF2}{B2}\right)$$

$$N_{top}(h) = \frac{4N_mF2}{(1 + \exp(z))^2} exp(z), \qquad z = \frac{h - h_mF2}{H}$$

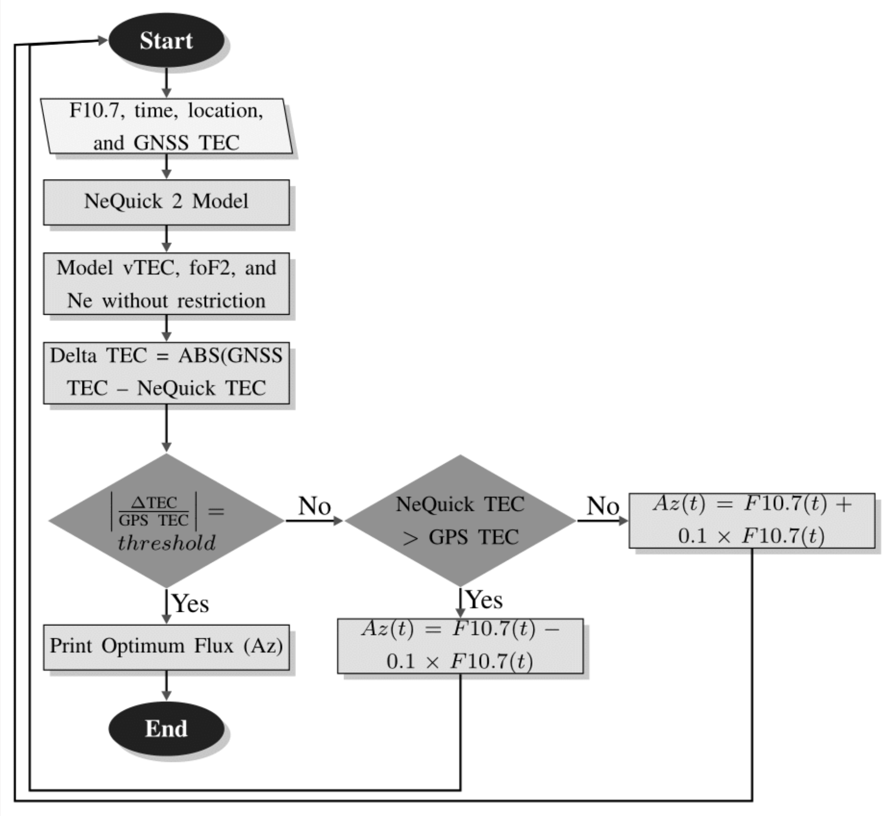


Adaptation of NeQuick to GNSS TEC data

- Ingestion of vTEC measured by GNSS receivers (Osanyin et al., 2023; Osanyin et al., 2025 (manuscript in print))
- Binary search algorithm
- Threshold falls within acceptable GPS range error of ±5 TECu.

$$\Delta t = \frac{40.3 * TEC}{f^2}$$

$$RMSE = \sqrt{\sum_{i=1}^{N}\left\{\frac{\left(vTEC_m(Az)_i - vTEC_{o_i}\right)^2}{N}\right\}}$$



Data binning & Statistics

- Solar activity binning
  - Low solar activity → F10.7 ≤ 80 s.f.u
  - Medium solar activity → 130 ≥ F10.7 ≥ 80 s.f.u
  - High solar activity → F10.7 ≥ 130 s.f.u
- Seasonal binning
  - Autumnal equinox (Feb, Mar, April)
  - June solstice (May, June, July)
  - Vernal equinox (Aug, Sept, Oct)
  - December solstice (Nov, Dec, Jan)

- Percentage Improvement

$$\frac{RMS_{SN} - RMS_{AN}}{RMS_{SN}} \times 100$$

- Relative Deviation

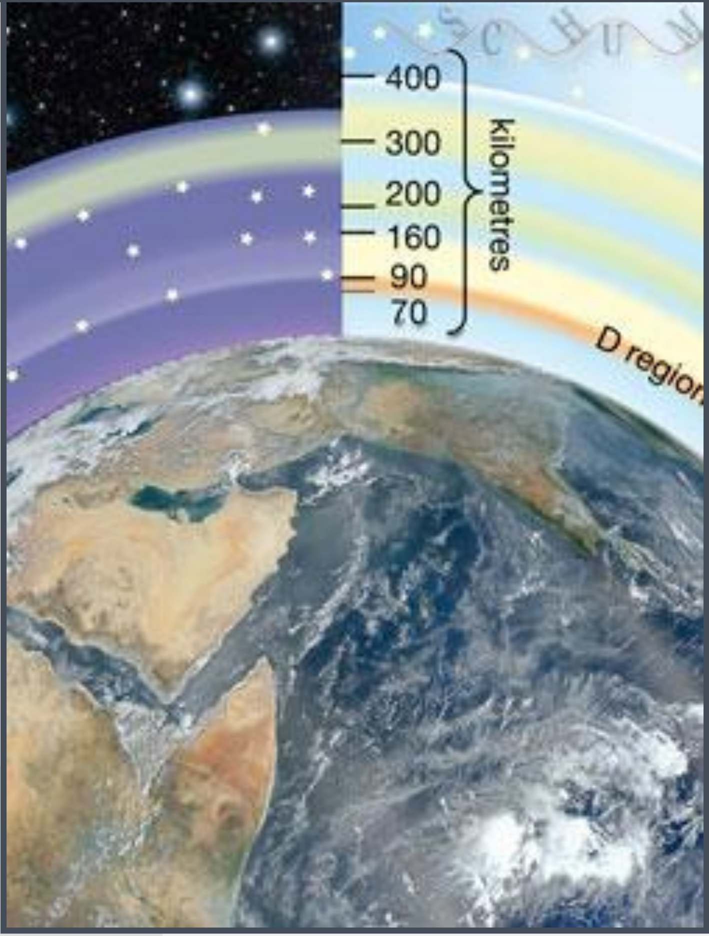
$$RD\ (\%) = \left(\sum_{i=1}^{N} \left\{ \frac{(vTEC_m(Az)_i - vTEC_{o_i})}{vTEC_{o_i}} \right\} \right) * 100$$

- Quiet-time reference

$$\Delta\chi = \left(\frac{\chi - \chi_m}{\chi_m}\right) x100$$

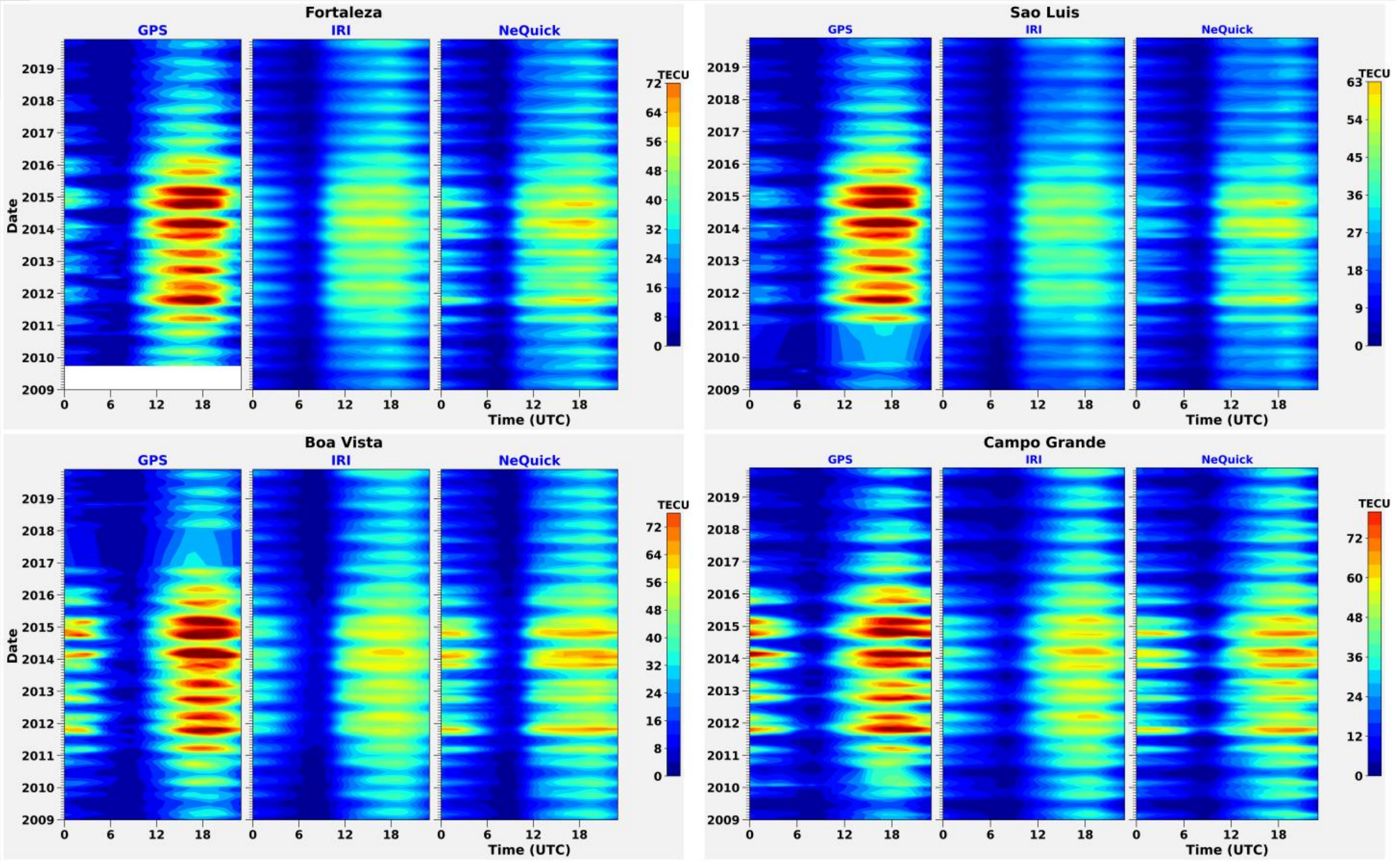
- Local Time

$$LT = UT + {}^{longitude}/_{15^o}$$



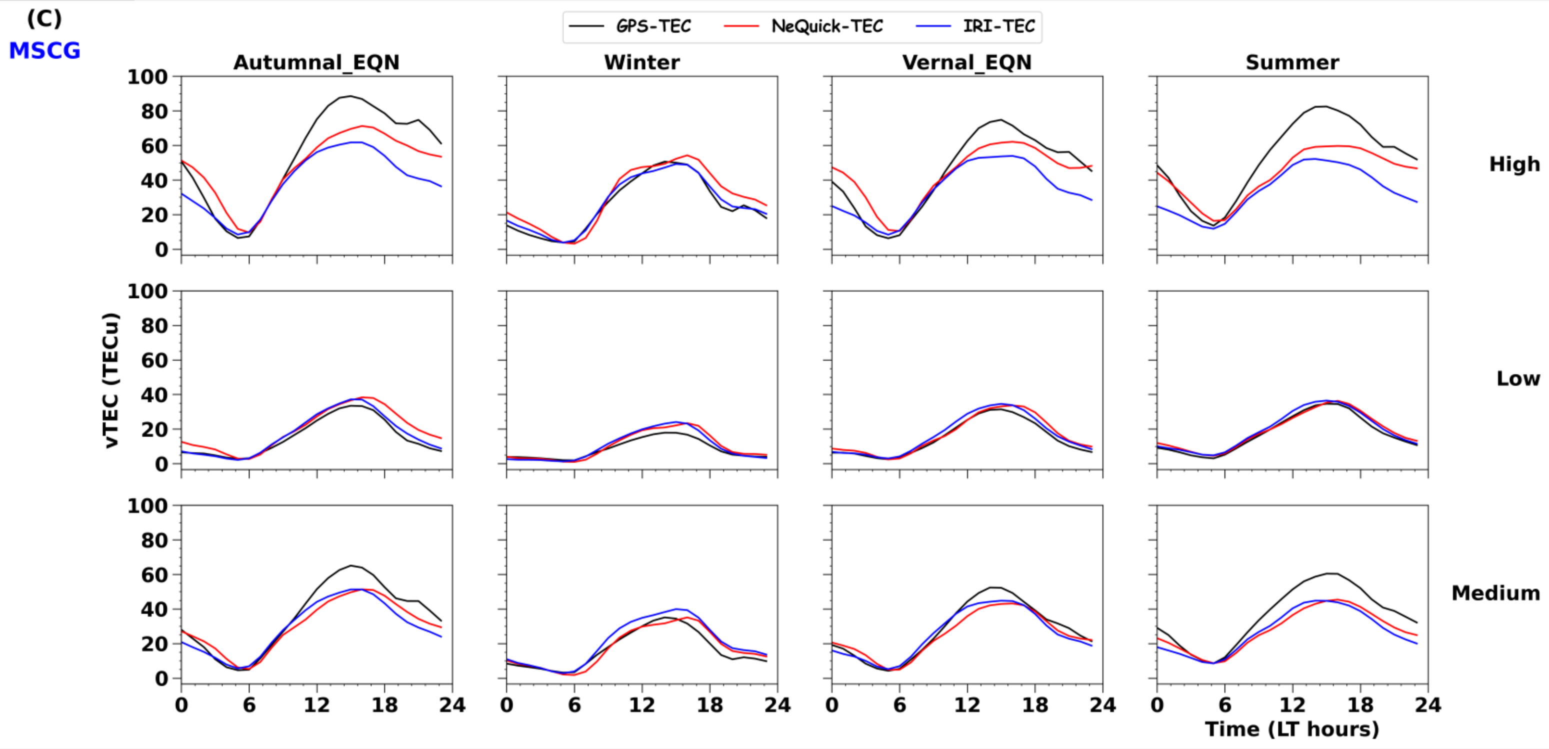
07
Results & Discussion

Contours of monthly averaged TEC



- Underestimation during HSA
- Appleton Anomaly
- Diurnal variation
- LT=UT-3

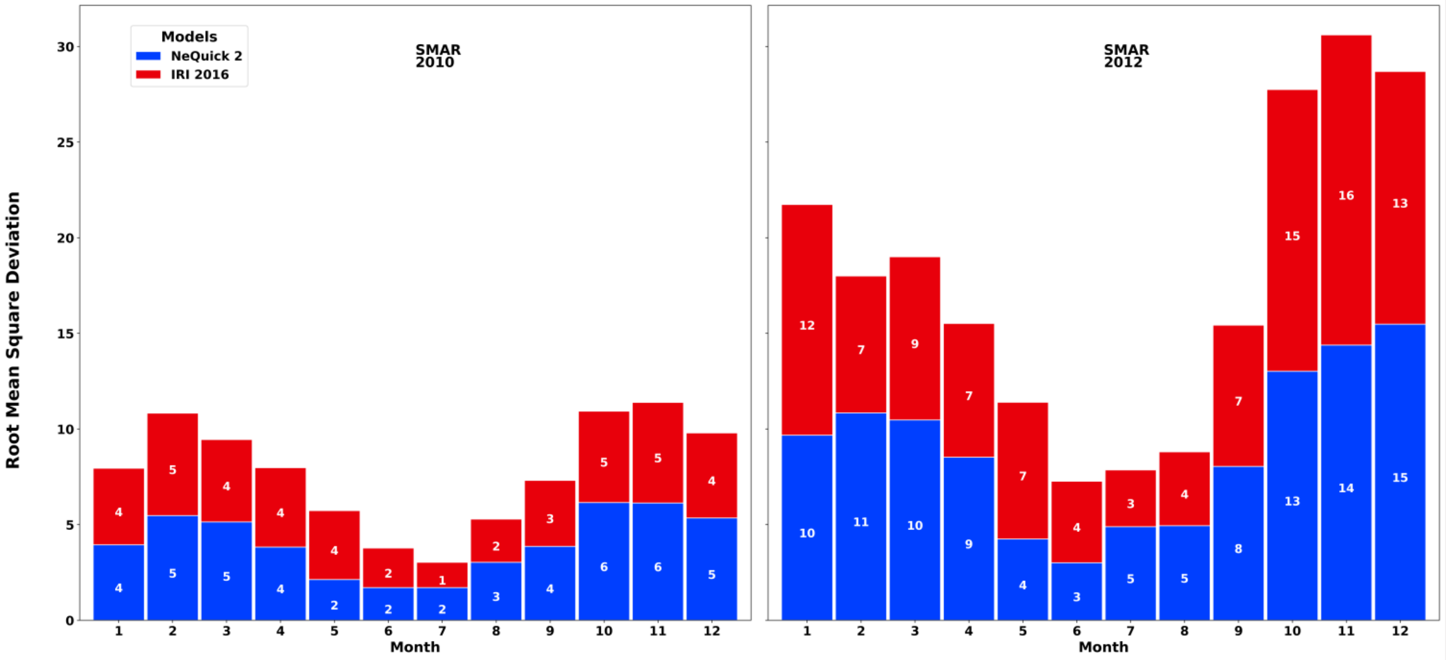
Seasonal & Solar Activity Variation of TEC



- TEC strongly depends on SA.
- Equinoctial asymmetry.
- Good performace of models during winter

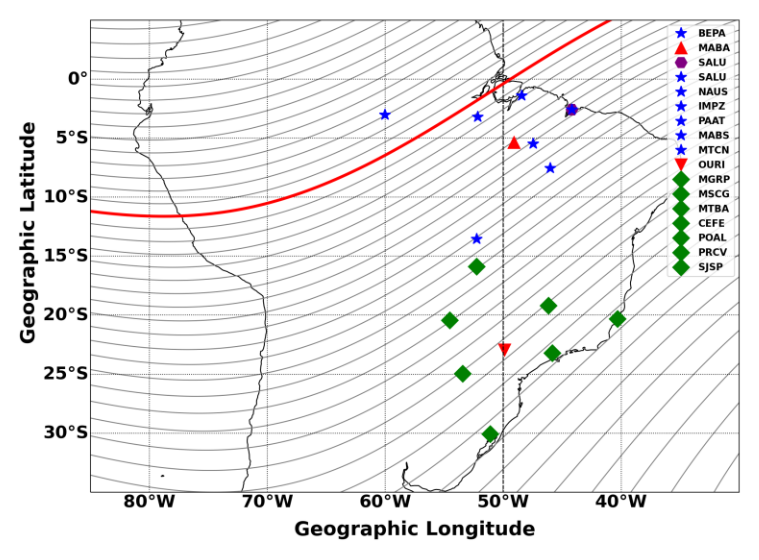
Root Mean Square Deviation (RMSD)

Ascending Phase
SAMA region

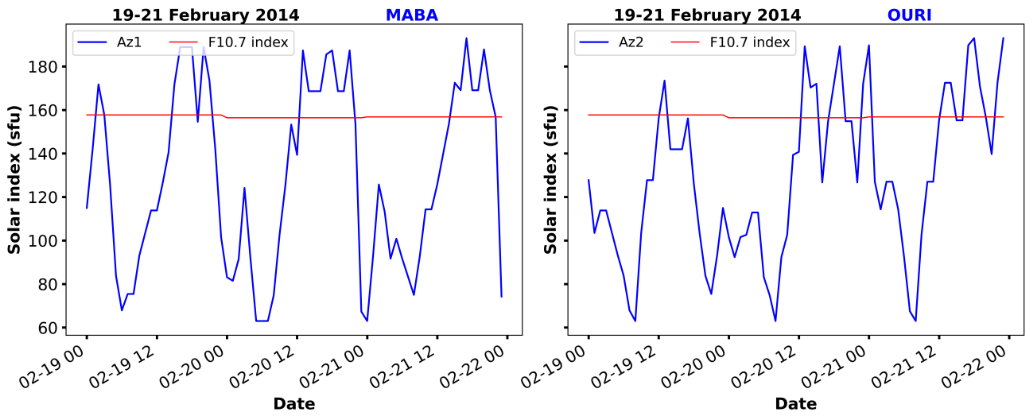


- Seasonal variability.
- Larger RMSD at equinoxes and summer.

Single station data ingestion into NeQuick 2

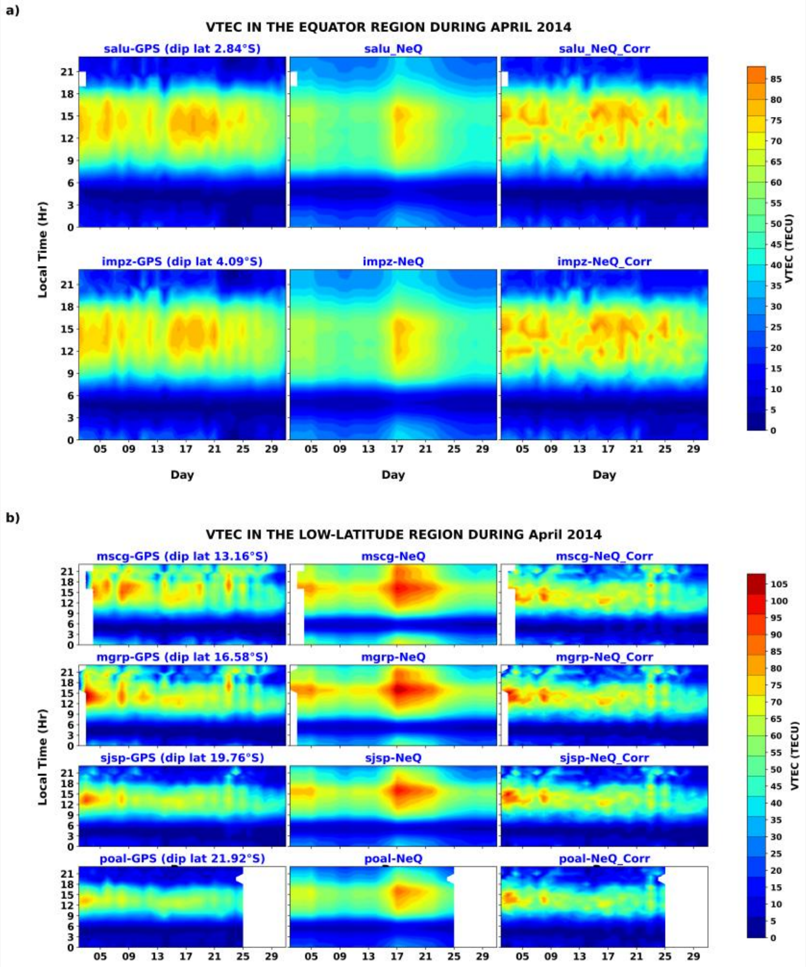


- The red markers signify the stations whose GPS data are used for data ingestion.
- Variation of the standard and adjusted solar radio flux during 19-21 February 2014 geomagnetic storm.



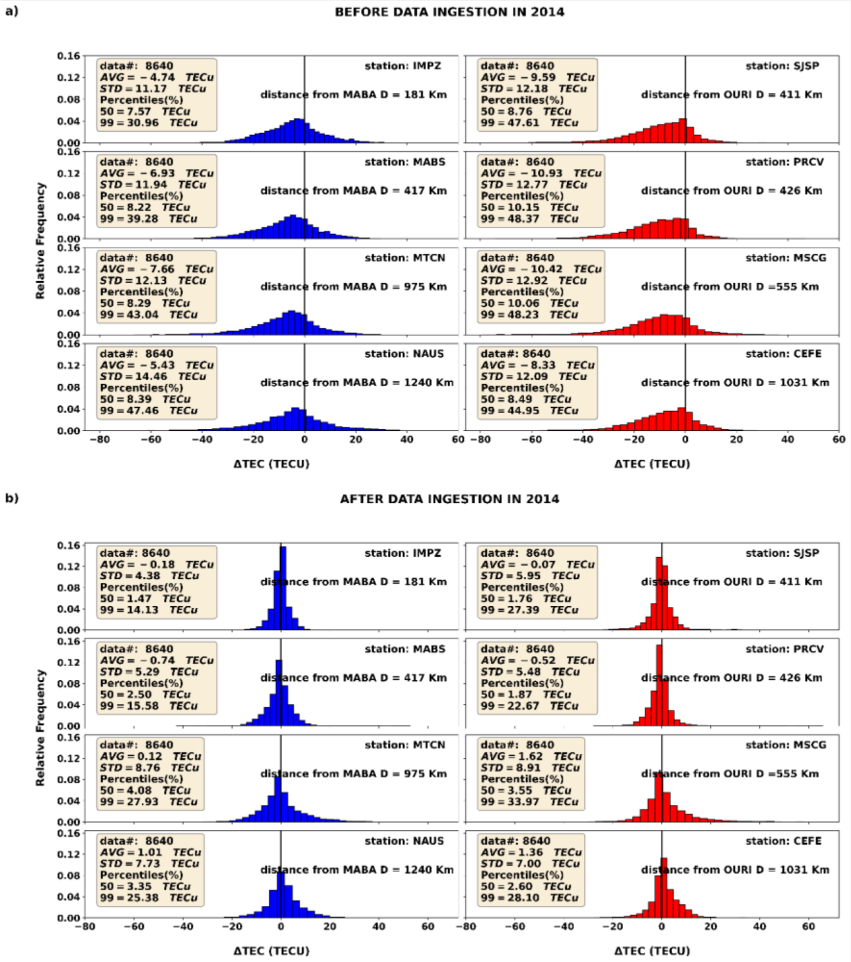
TEC Variability in April

- EIA crest shows higher TEC variation.
- Poor performance by the standard NeQuick.
- Great improvement after data ingestion



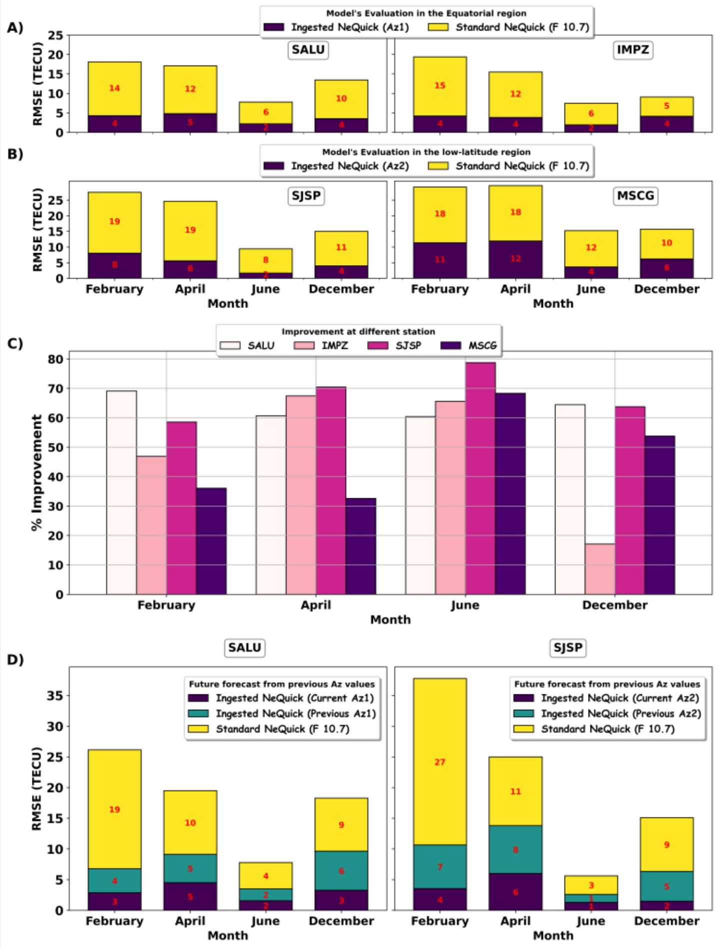
Relative Error

- Reduction in spread of error after DI.
- Reduced error in the North-South direction.
- Error increases with latitude.



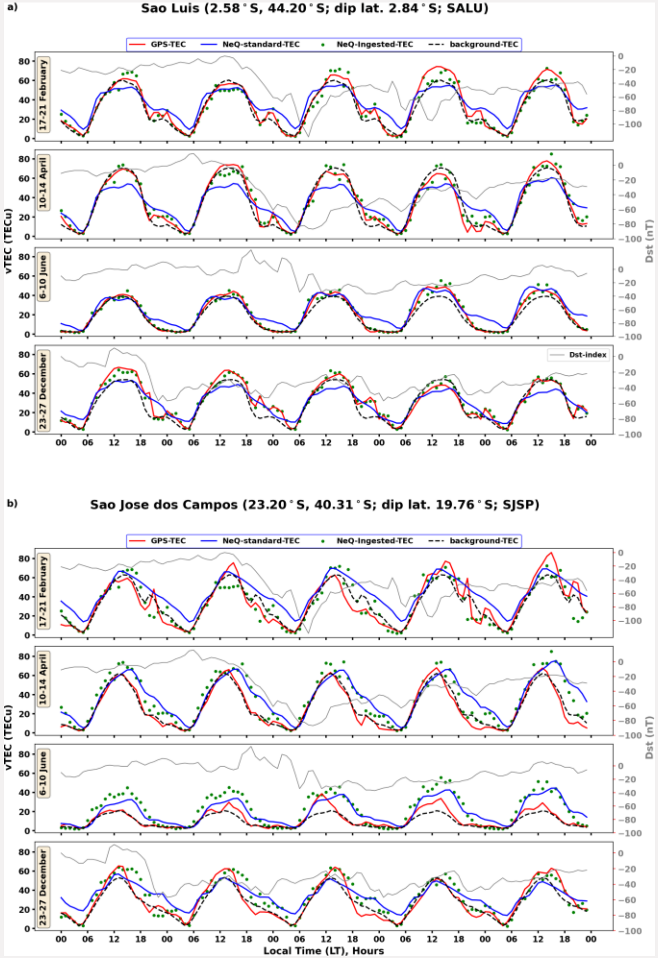
Improvement & Forecasting Test

- Higher RMSE values in February & April.
- Highest improvement in June at SJSP (South crest of EIA).
- Successful forecast with reduced error compared to the standard results.



Variation of vTEC during Geomagnetic Storms

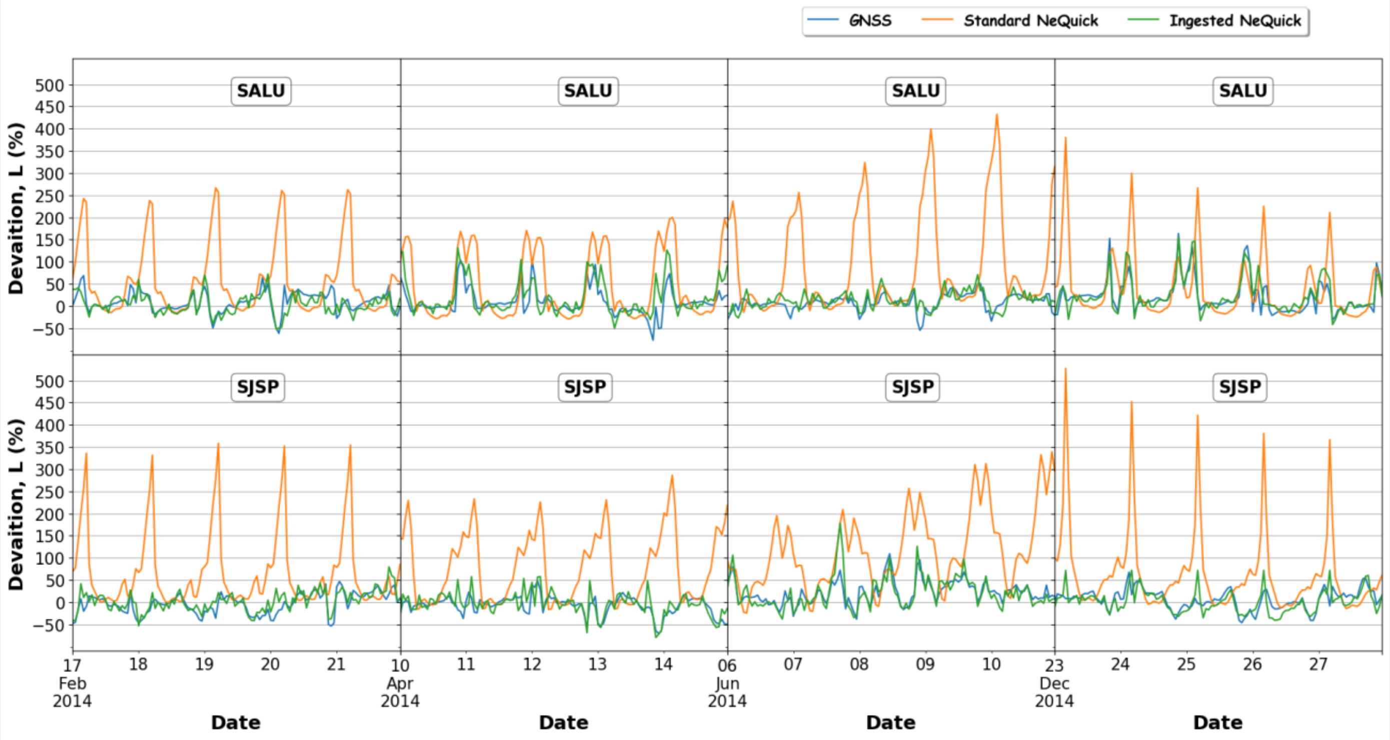
- Closer values after Data Ingestion at SALU during the storm periods.
- Poor performance during the recovery phase at SJSP.
- The improvement in NeQuick ranges from 56 to 61 % in the equator and 69 to 83 % in the EIA crest.



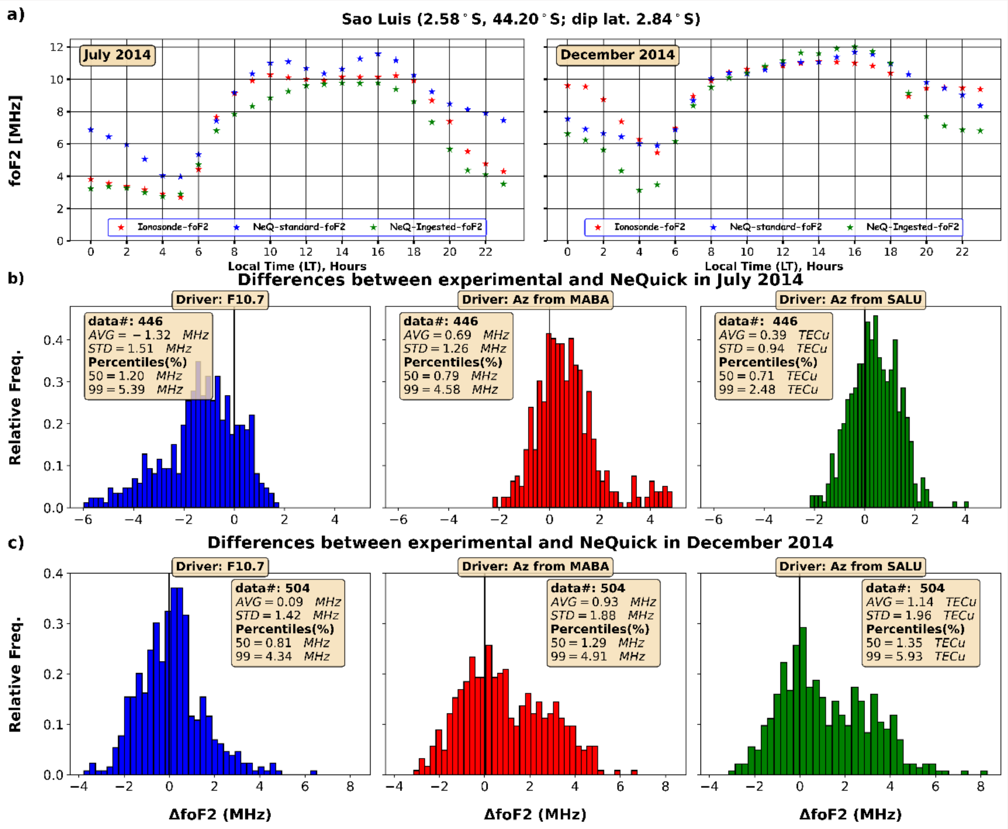
NeQuick 2- Response to Geomagnetic Storms

Solar Maximum-2014

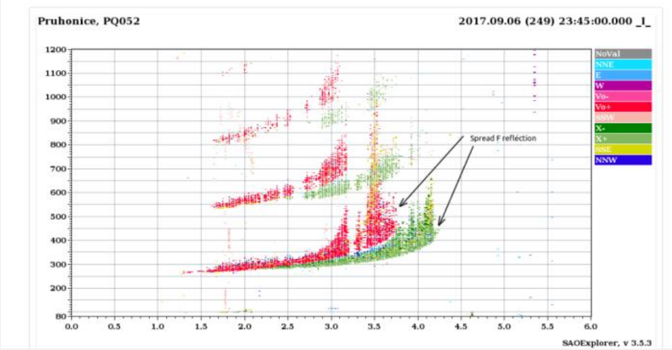
- 17-21, Feb., Dst min=-119 nT.
- 10-14, Apr., Dst min= -86 nT.
- 6-10, Jun., Dst min = -37 nT.
- 23-27 Dec., Dst = -57 nT.



External Test: F2 layer critical frequency



- July & December 2014 solstices.
- The closer the ingested station to the test station, the higher the performance of the model in July.



Conclusions

- The climatologic behavior of the ionospheric TEC at the Equator, Northern crest, Southern crest, and SAMA region for quiet geomagnetic conditions has been investigated. The features of diurnal, seasonal, and solar activity have been observed;

- The study showed that both the NeQuick 2 and IRI 2016 models need to be improved during high solar activity, especially in equinoxes and summer;

- The Az parameter depends strongly on local time, season, latitude, and geomagnetic activity. A single station data ingestion technique showed improvement of (56-61) % in the equator and (69-83) % in the EIA crest during the storm periods analyzed in this study;

- The effective ionization parameter (Az) based on the ingestion of GNSS TEC data allowed reconstruction of the critical frequency of the F2 layer (foF2) in July.

- The corrected version of the NeQuick is capable of forecasting ionospheric conditions for about three days using the Az values from the previous day.

Recommendation

- Based on the conclusion drawn from this study, there is a need to continue the objective of transitioning empirical models from climatological to weather-like specifications.

- Further improvement of the background model is essential to achieve better accuracy of data ingestion and data assimilation techniques. During their construction, climatological models rely on availability of good quality data and ionospheric variations maybe misrepresented where data are not available. We recommend the deployment of more observational data especially ionosonde which are sparsely distributed globally.

- One of the challenges faced by empirical models is their difficulties in identifying and tracking ionospheric irregularities, as well as providing realistic ionospheric behavior during geomagnetic storms. It is therefore important to take into consideration the parameters and physics required to combat such problems when constructing new models.

Data Statement & Source

- GPS TEC data: Instituto Brasileiro de Geografia e Estatistica (IBGE), website (http://www.ibge.gov.br)

- Quiet and disturbed days: World Data Center (WDC) Kyoto, Japan website (http://swdc.kugi.kyoto-u.ac.jp).

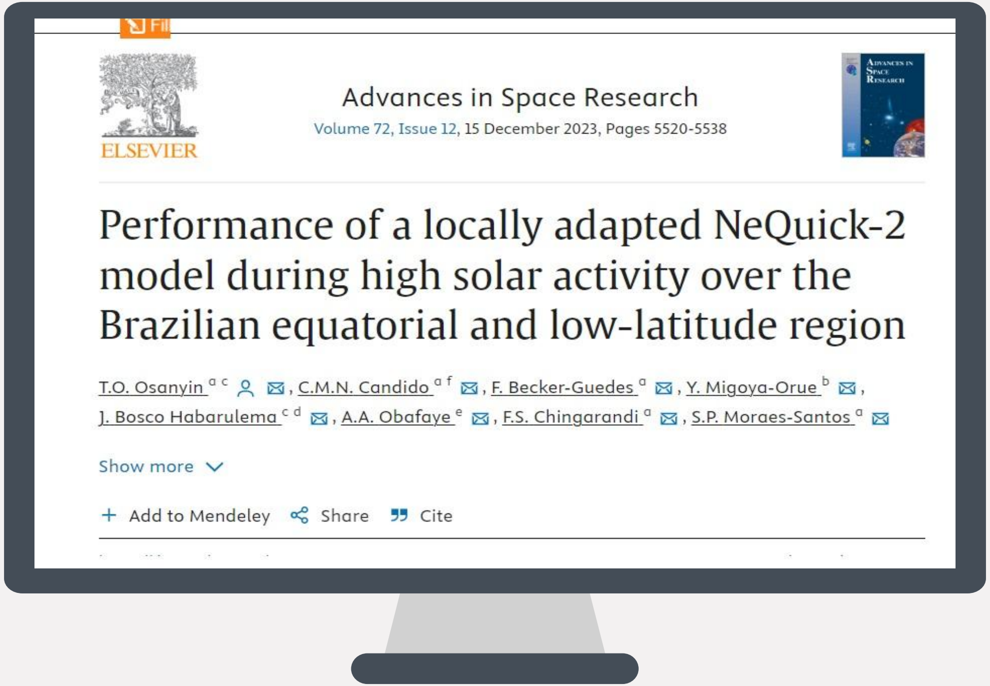
- Solar parameters and geomagnetic indices: Space Weather prediction Prediction Centre of the National Oceanic and Atmospheric Administration Centre (NOAA) website (https://omniweb.gsfc.nasa.gov/)

- Digisonde data: The EMBRACE (Brazilian Study and Monitoring of Space Weather) website (https://www2.inpe.br/climaespacial/)

Bibliographical references

- Bilitza, D., Pezzopane, M., Truhlik, V., Altadill, D., Reinisch, B. W., & Pignalberi, A. (2022). The International Reference Ionosphere model: A review and description of an ionospheric benchmark. *Reviews of Geophysics*, *60*(4), e2022RG000792.
- Goodman, J. M. (1999). Ionospheric Characteristics and Models. *Wiley Encyclopedia of Electrical and Electronics Engineering*, 1-40.Surname, A. (YEAR). *Name of the source*. Publisher
- Jursa, A. S. (1985). *Handbook of geophysics and the space environment* (Vol. 1). Springfield: Air Force Geophysics Laboratory, Air Force Systems Command, United States Air Force.
- Kos, T., & Najman, P. (2014). Chapter Performance Analysis of Empirical Ionosphere Models by Comparison with CODE Vertical TEC Maps.
- Seemala, G. K., & Valladares, C. E. (2011). Statistics of total electron content depletions observed over the South American continent for the year 2008. *Radio Science, 46*, RS5019. doi:10.1029/2011RS004722.
- Souza, J. R. D. (1999). Modelagem ionosférica em baixas latitudes no Brasil. *Revista Brasileira de Geofísica*, *17*, 98-99.
- Osanyin et al. (2023). Performance of a Locally Adapted NeQuick-2 Model During High Solar Activity over Brazilian Equatorial and Low-latitude Regions. *Advances in Space Research*, *72(12)*, 5520-5538.

Publication



ELSEVIER
Advances in Space Research
Volume 72, Issue 12, 15 December 2023, Pages 5520-5538

Performance of a locally adapted NeQuick-2 model during high solar activity over the Brazilian equatorial and low-latitude region

T.O. Osanyin [a c], C.M.N. Candido [a f], F. Becker-Guedes [a], Y. Migoya-Orue [b], J. Bosco Habarulema [c d], A.A. Obafaye [e], F.S. Chingarandi [a], S.P. Moraes-Santos [a]

Show more

+ Add to Mendeley   Share   Cite


THANK
YOU