Space Weather effects representation using Empirical Models

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ICTP The Abdus Salam International Centre for Theoretical Physics (ICTP)

International Colloquium on Equatorial and Low Latitude Ionosphere (ICELLI) 2022

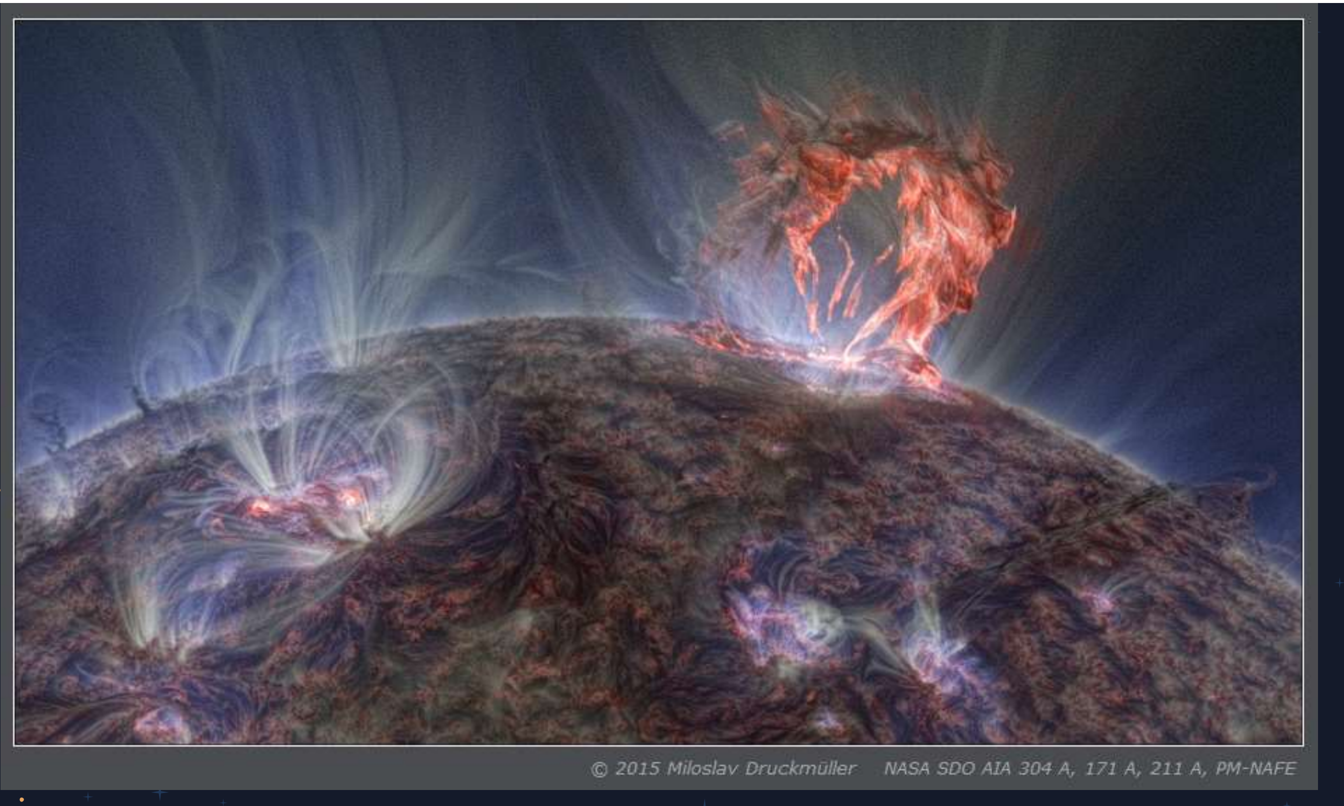
Outline

01 Space Weather & models

Sun phenomena affect the Earth magnetic field, ionosphere and thermosphere

ICMEs cause the most severe transient disturbances in the heliosphere and at the Earth

ICME-related effects can strongly influence our everyday life.



M1.7 flare, April 16, 2012

Modelling in Geophysics

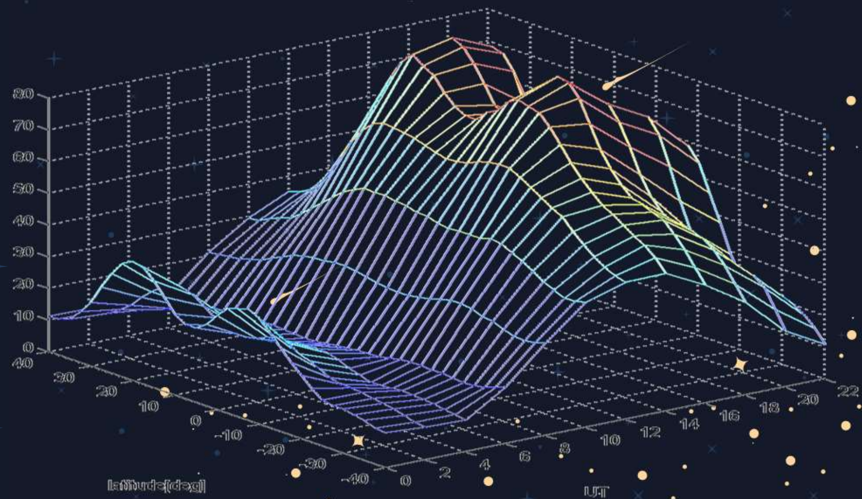
Models are invariably simpler than the real Earth phenomenon.

Any model is a mathematical expression, representing some real processes, that depends on the assumptions that are made.

Two main types of geophysical models:

Physics-based and

Empirical models.



Physics-based & Empirical models

Physics based models apply the laws of classical physics.

- They are deterministic.
- Explanation and prediction of natural phenomena are based on the mathematical representations of physical laws.

Empirical models are descriptive.

- They are based on data.
- They do not rely on the use of physics.

However…

Neither the physics-based nor
the empirical approach ignores the other.

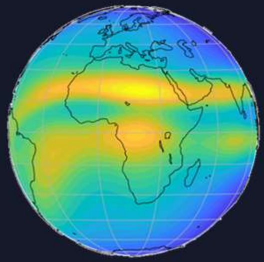
Because:

Physicists rely on observations to develop and validate physical models and estimating key quantities like initial and boundary conditions.

↔

The construction of statistical/empirical models is guided by physics that determines the variables and the data sets to be analyzed.

Empirical Models or profilers



- ✓ Based on a analytical description of the ionosphere with functions derived from experimental data.
- ✓ Model systematic ionospheric variation from historical data.
- ✓ Data sources are ionosondes, topside sounders, incoherent scatter radars, rockets and satellites.
- ✓ Mainly used for assessment and prediction purposes.
- ✓ Easy to use.
- ✓ Describe ionospheric climate.
- ✓ Give realistic representation of the ionosphere in the areas sufficiently covered by observations.

International Reference Ionosphere (IRI)

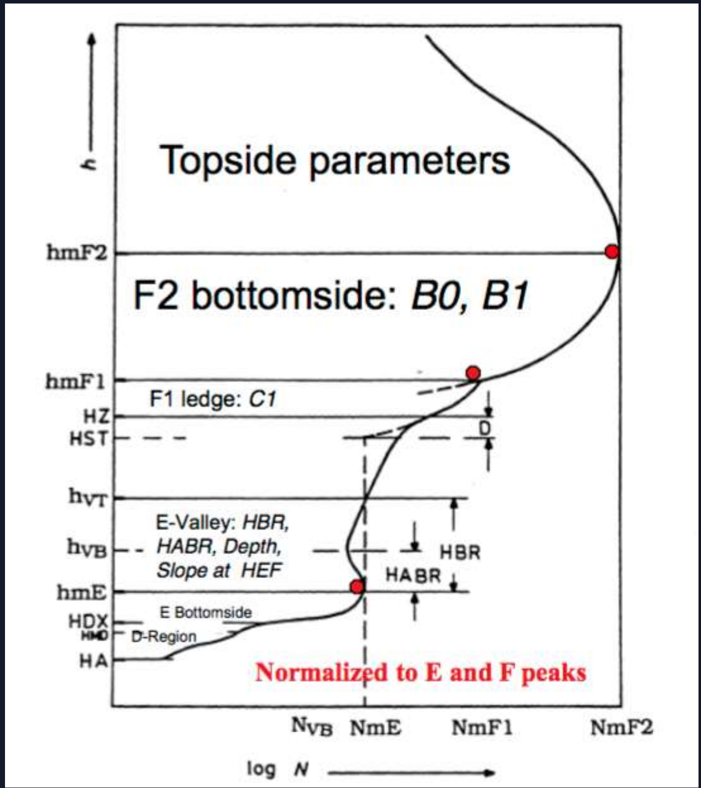
The IRI is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). These organizations formed a Working Group in the late sixties to produce an standard empirical model of the ionosphere, based on all available data sources. Several improved editions of the model have been released.

Input
Year, month, day, hour, geographic or geomagnetic coordinates, various optional input.

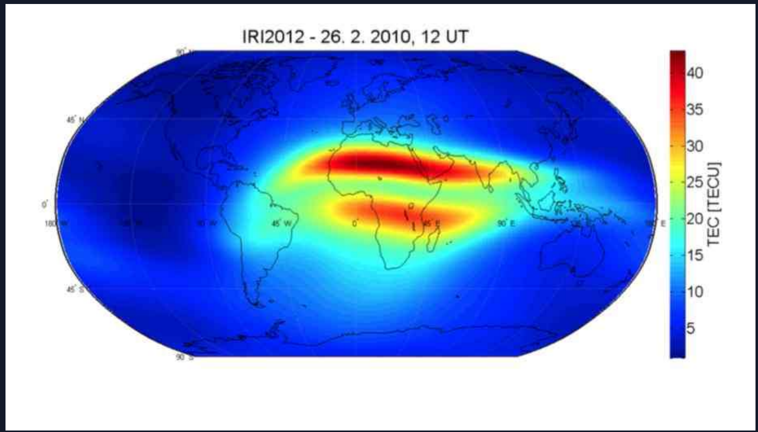
Output
Electron concentration, electron temperature, ion temperature, ion composition (O^+, H^+, He^+, NO^+, O^+_2), ion drift, ionopsheric electron content (TEC), F1 and spread-F probability

IRI Web http://irimodel.org/

International Reference Ionosphere (IRI)



Buildup of the IRI electron density profile and its separation into different regions.



From: "Mitigation of Ionospheric Threats to GNSS: an Appraisal of the Scientific and Technological Outputs of the TRANSMIT Project", Chapter 3, p. 166, InTech 2014

NeQuick

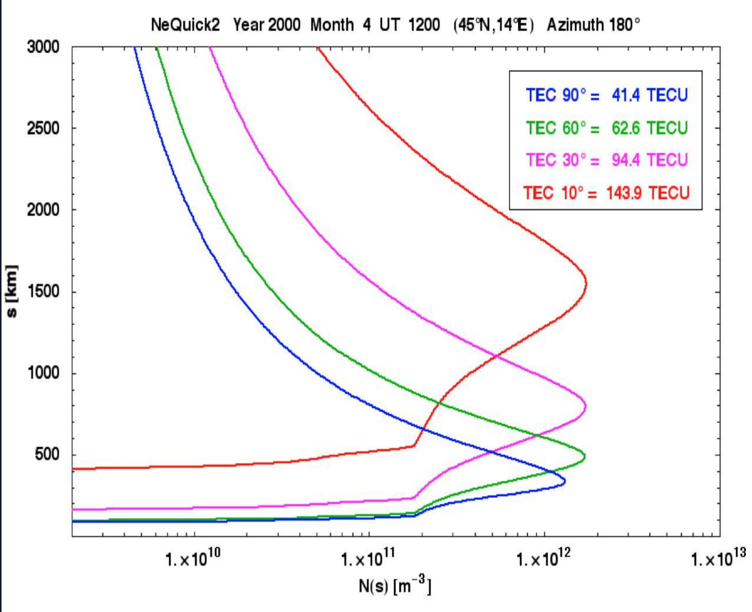
NeQuick is a 3D and time dependent ionospheric electron density model developed at the Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy and at the University of Graz, Austria. It is a quick-run model particularly tailored for trans-ionospheric applications that allows to calculate the electron density at any given location in the ionosphere and thus the total electron content (TEC) along any ground-to-satellite ray-path by means of numerical integration.

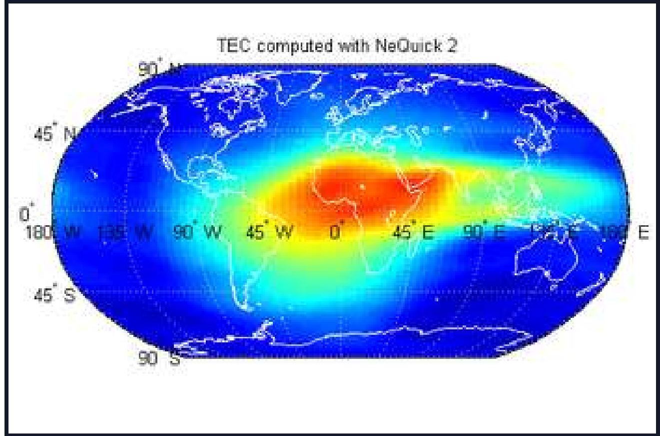
Input
Year, month, day, time, geographic coordinates of lower and higher endpoint , R12 or daily F10.7 solar flux.

Output
electron density along the path and slant TEC

NeQuick2WEB – http://t-ict4d.ictp.it/nequick2/nequick-2-web-model

NeQuick


NeQuick2 Year 2000 Month 4 UT 1200 (45°N,14°E) Azimuth 180°
TEC 90° = 41.4 TECU
TEC 60° = 62.6 TECU
TEC 30° = 94.4 TECU
TEC 10° = 143.9 TECU
s [km]
3000
2500
2000
1500
1000
500
1.×10^10
1.×10^11
1.×10^12
1.×10^13
N(s) [m^-3]


TEC computed with NeQuick 2
90° N
45° N
0°
45° S
90° S
45° W
0°
45° E
90° E

02

SW events forecasting using Empirical Models

The impact of Space Weather: from “climate” to “weather”

- Like the lower atmosphere the ionosphere exhibits both a “climate” and a “weather” variability. The ionospheric “climate” has been successfully represented by models of different types.

- The ionospheric weather variability is mostly controlled by the “Space Weather conditions”.

- The big challenge of ionospheric modelling is to take into account the impact of *varying Space Weather conditions* to reproduce the observations.

Two approaches

Systemic approach: coupled physics-based models

Data Assimilation or ingestion in models

We need to know that...

It is mandatory to have well established experimental databases that can be used to test and validate the existing models in order to generate the improvements needed.

No model is able to reproduce by itself in a satisfactory way both the “climate” and the “weather” of the Earth ionosphere.

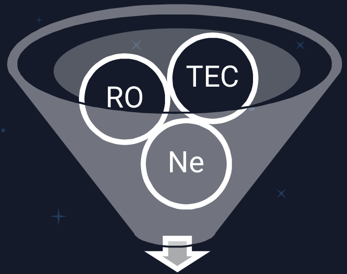
Data Assimilation

DA techniques have successfully been applied by meteorologists to improve operational weather forecasts.

Such techniques have also been introduced into ionospheric research and application.

This was possible because of the increasing availability of experimental data even in real time (solar data, ionospheric ground and space-based GNSS data, ionosonde data and radar data, RO data). These models and schemes are of different complexity and rely on different kinds of data (GAIM, IDA3D, etc).

Data Ingestion



Minimization Algorithm
| VTECexp – VTECmod |

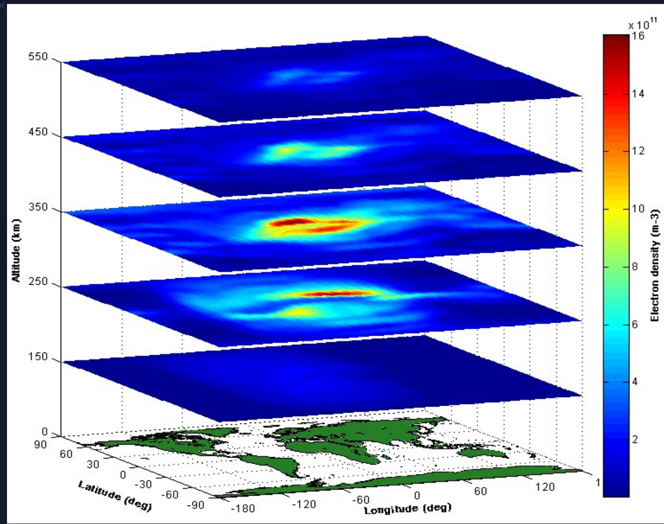
‘effective’ grids

(IG, Az)

- Calculate TEC along any ray path

3D electron density of the ionosphere that reproduces the starting source data

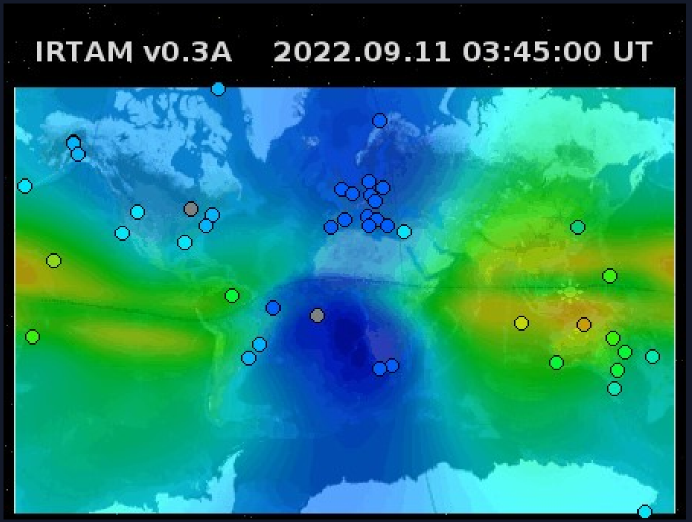
- foF2 maps
- hmF2, Nmax, etc.



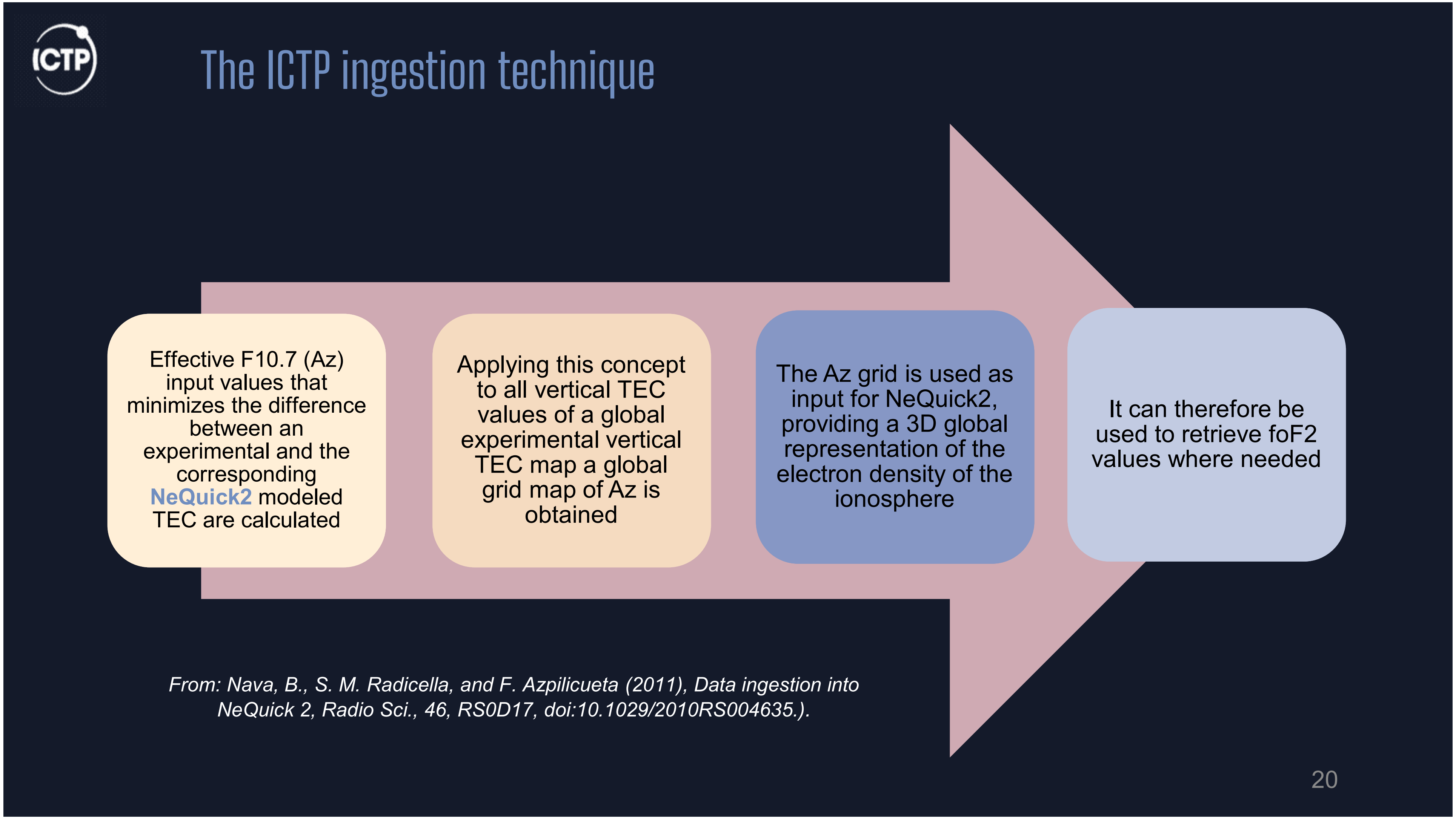
- Is one of the earliest and most simplistic approaches to data assimilation.
- The model states are directly replaced with the observations.

IRTAM

- IRI Real-Time Assimilative Modelling (IRTAM) system assimilates digisonde data from the Global Ionospheric Radio Observatory (GIRO) network into the IRI model.
- The IRTAM approach is based on the ITU-R models for the F2 peak plasma frequency foF2 and the propagation factor M(3000)F2 that are being used in IRI.
- IRTAM uses the CCIR set of functions to describe the global and spatial variation of the difference between the digisonde measurement and the IRI prediction of foF2.



Galkin, I. A., B. W. Reinisch, X. Huang, and D. Bilitza (2012), Assimilation of GIRO data into a real-time IRI, Radio Sci., 47, RS0L07, doi:10.1029/2011RS004952.


The ICTP ingestion technique
Effective F10.7 (Az) input values that minimizes the difference between an experimental and the corresponding NeQuick2 modeled TEC are calculated
Applying this concept to all vertical TEC values of a global experimental vertical TEC map a global grid map of Az is obtained
The Az grid is used as input for NeQuick2, providing a 3D global representation of the electron density of the ionosphere
It can therefore be used to retrieve foF2 values where needed
From: Nava, B., S. M. Radicella, and F. Azpilicueta (2011), Data ingestion into NeQuick 2, Radio Sci., 46, RS0D17, doi:10.1029/2010RS004635.).
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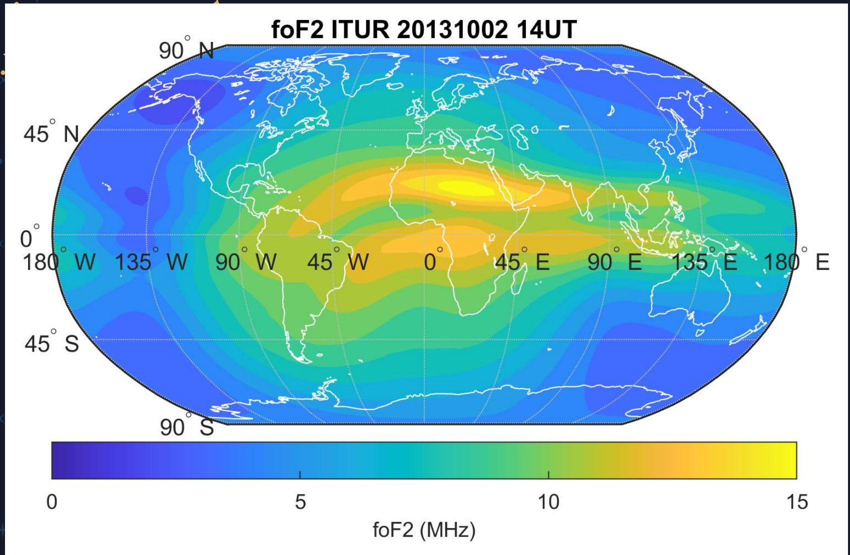
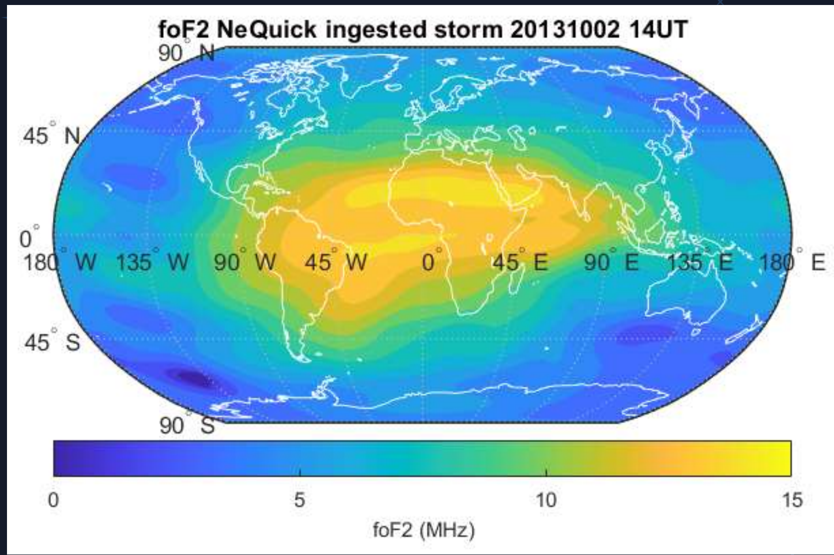
Examples

DI application



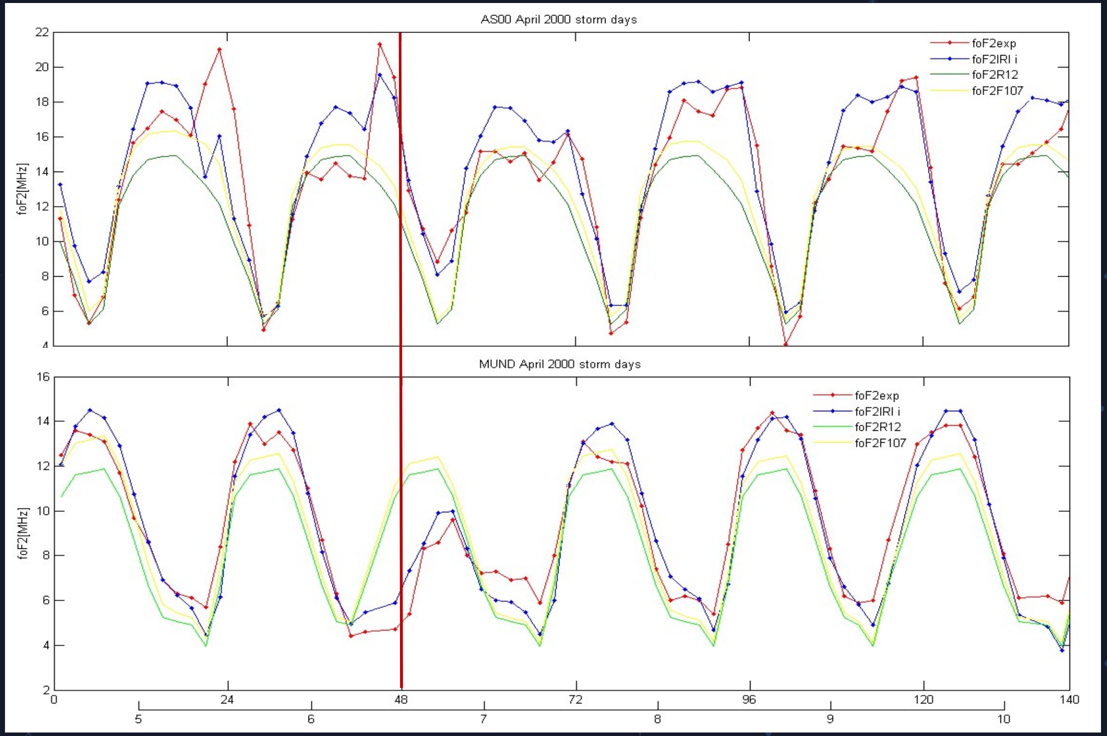


ITU-R foF2 map computed with daily F10.7 for 2nd October 2013 (left) and global map of foF2 for 2nd October 2013 obtained after the CODE GIM VTEC ingestion into the NeQuick model (right).

Radicella and Migoya-Orué, 2021, Elsevier Book GPS and GNSS Technology in Geoscience, Chapter 11.

GNSS derived TEC ingestion into IRI

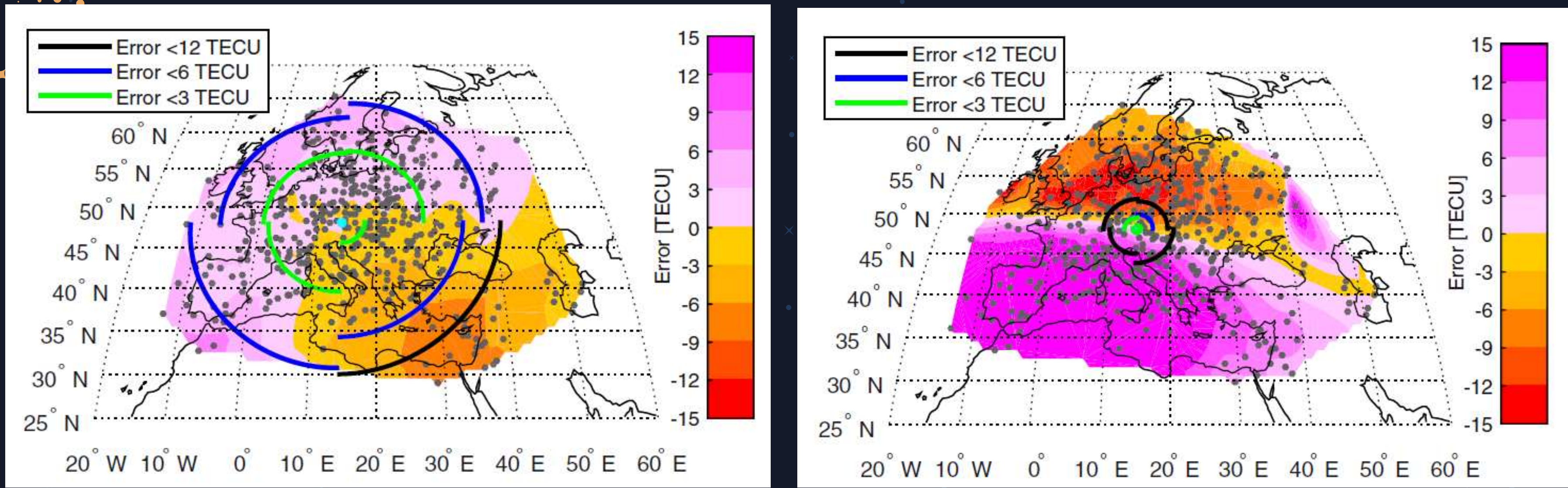
Migoya-Orue et al., 2015, Adv. Space Research



foF2 comparison during storm days April 2000

Locally Adapted NeQuick

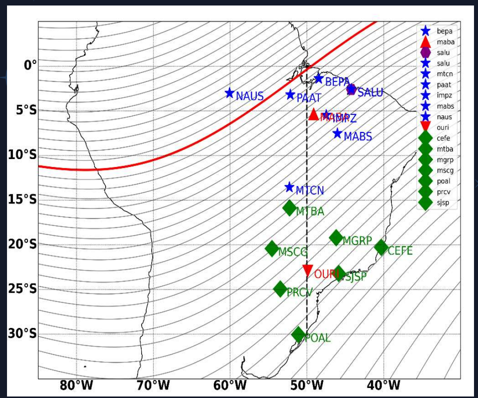
Vuković and Kos, 2017, Adv. Space Research



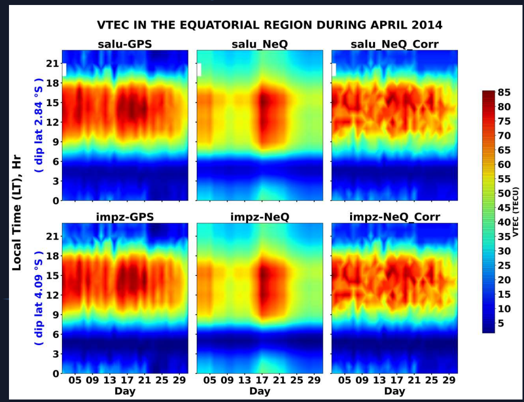
Locally adapted NeQuick maps performance 3 days before (left) and during St. Patrick Storm 2015 (right).

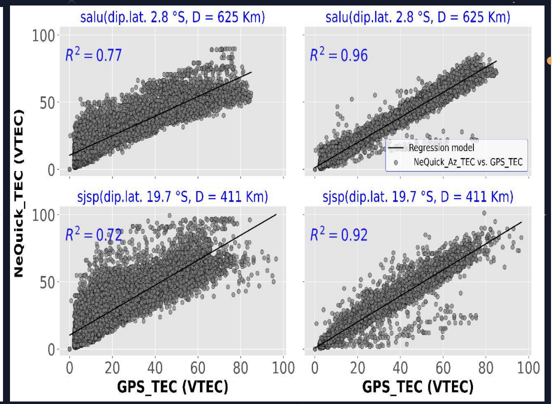
Locally Adapted NeQuick

Osanyin et al., in preparation

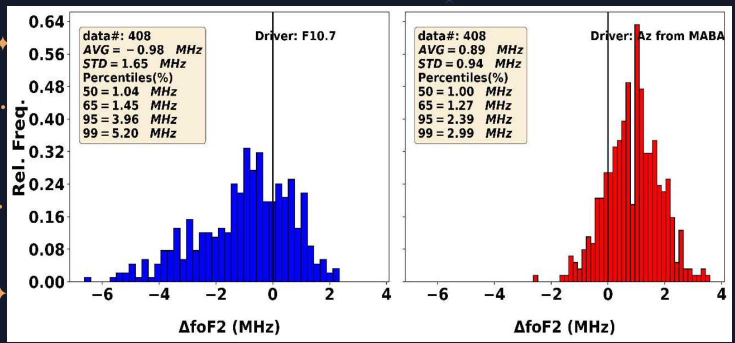


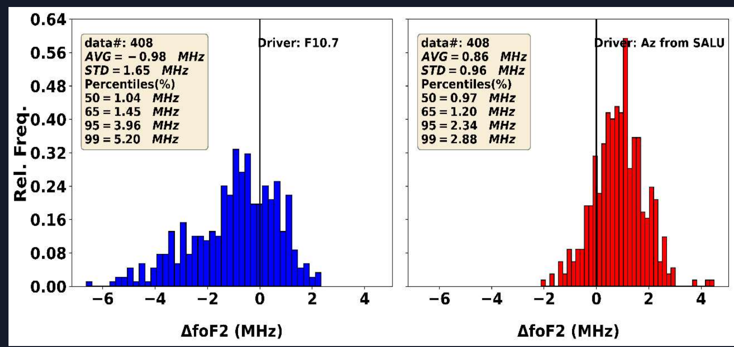
GPS and ionosonde stations used in the study



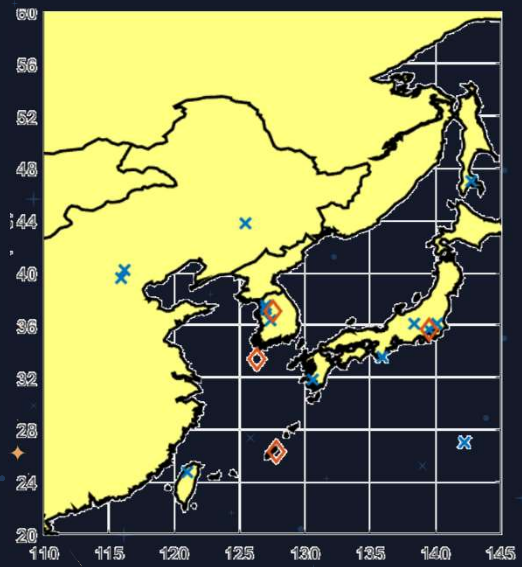


Histograms of foF2 differences – SALU July 2014





Data Assimilation into NeQuick through KF technique



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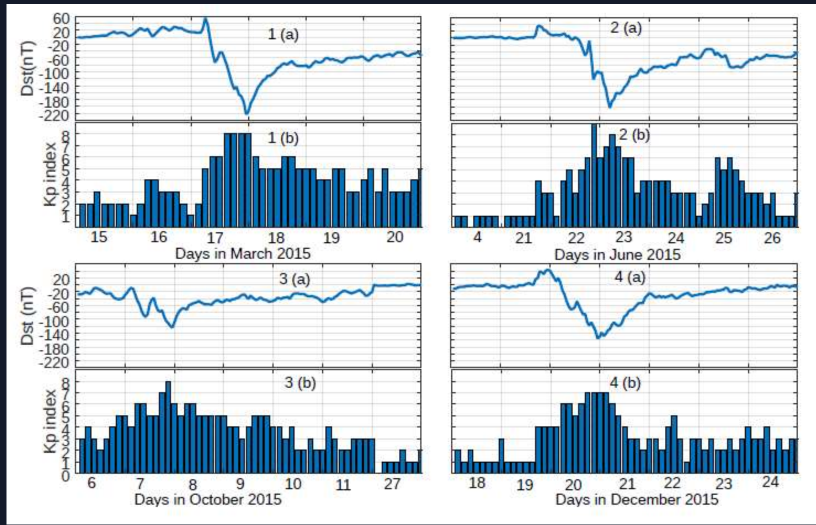


$$y = Hx_b + w$$

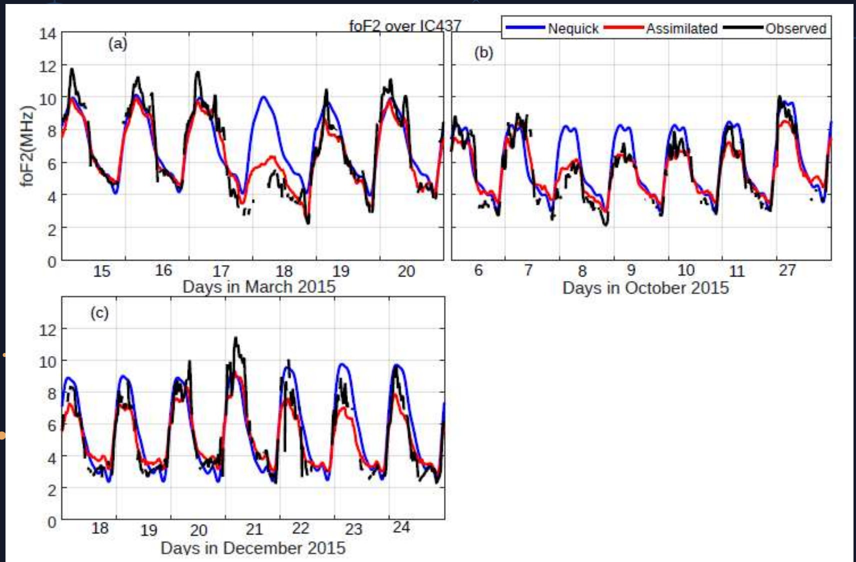
$$x_a = x_b + K(y - Hx_b)$$

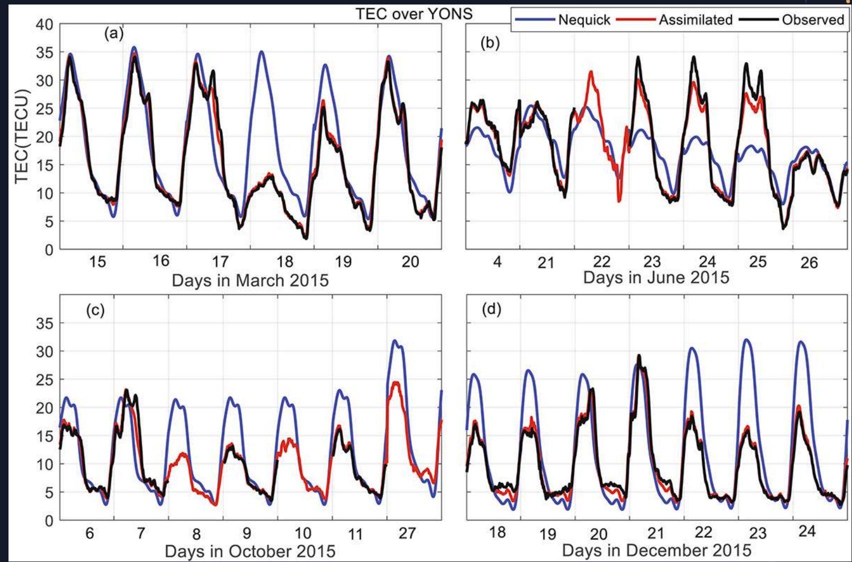
$$K = BH^T(HBH^T + R)^{-1}$$

$$\begin{pmatrix} x_a^1 \\ x_a^2 \\ . \\ . \\ . \\ x_a^n \end{pmatrix} = \begin{pmatrix} x_b^1 \\ x_b^2 \\ . \\ . \\ . \\ .x_b^n \end{pmatrix} + K\left(\begin{pmatrix} y_1 \\ y_2 \\ . \\ . \\ . \\ y_n \end{pmatrix} - H\begin{pmatrix} x_b^1 \\ x_b^2 \\ . \\ . \\ . \\ x_b^n \end{pmatrix}\right)$$

Mungufeni et al., J. Space Weather Space Clim. 2022

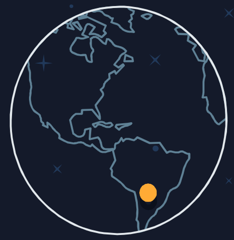
TEC Assimilation into NeQuick through Kalman filtering technique





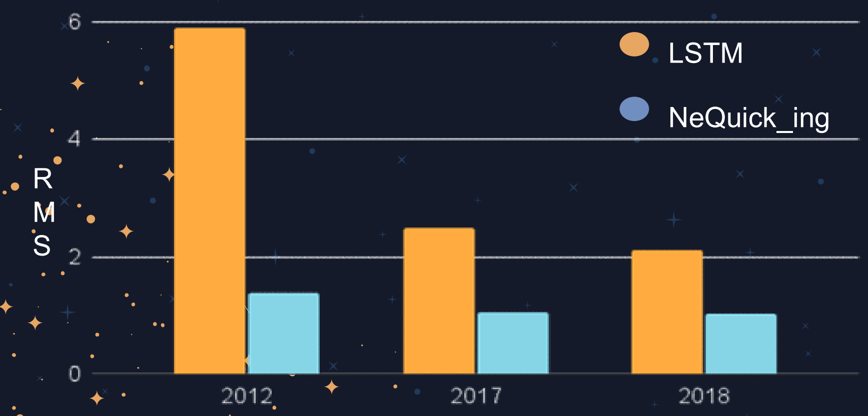
Mungufeni et al., J. Space Weather Space Clim. 2022

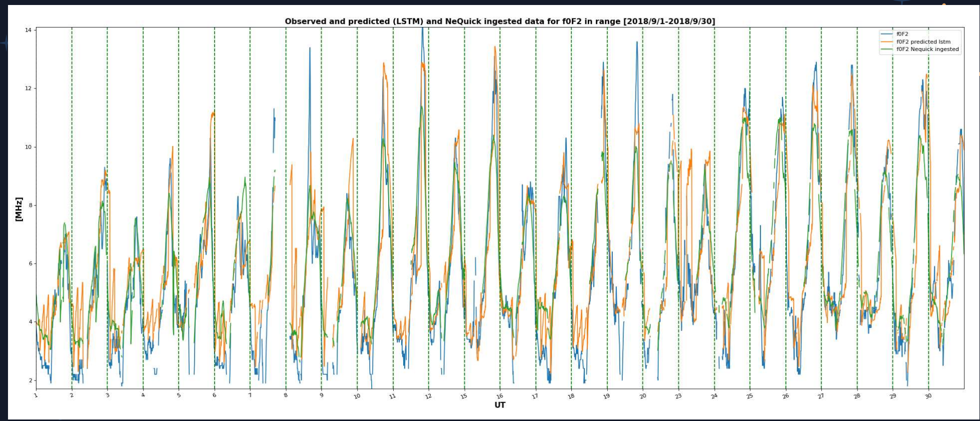
LSTM vs NeQuick ingested model



Namour et al, in preparation

Long-Short Term Memory are a special kind of RNN, capable of learning long-term dependencies.





Observed vs LSTM – NeQuick/ing models (Tucumán, September 2018)

- 1 hidden layer, 5 neurons
- Training Data range: 01/01/2017 to 30/08/2017
- Missing data: % 16.1
- Data Split: %70 training (%20 validation), %30 test

04

Conclusions & Useful Info

CONCLUSIONS

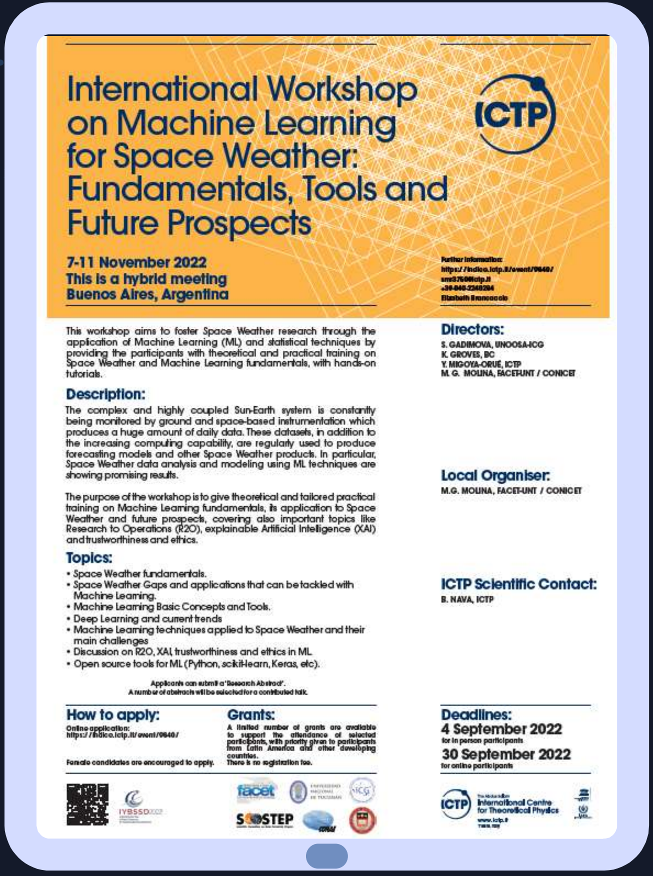
- The assimilation/ingestion of ionospheric data into empirical models allows to provide global and regional 3D specification of the electron density of the ionosphere and is able to improve the challenge that represents the reproduction of the 'weather' variability of ionospheric parameters during SW events.

- It has been showed examples of the prediction of TEC, Ne and foF2 with NeQuick and IRI by ingesting different ionospheric data series and some comparisons with experimental values and other models.

CONCLUSIONS

- The models performance show a dependence on geomagnetic activity with RMS errors increasing with increasing geomagnetic activity.
- The models performance show also a complex dependence with latitude.
- The models faced a real challenge in their ability to forecast and nowcast local and global ionospheric effects of Space Weather events.
- Statistical and ML techniques application to SW have received a significant boost in the recent years.

ICTP International Workshop on ML for SW



https://www.ictp.it

Thanks!

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