Causes, Effects and Models of Ionospheric Storms

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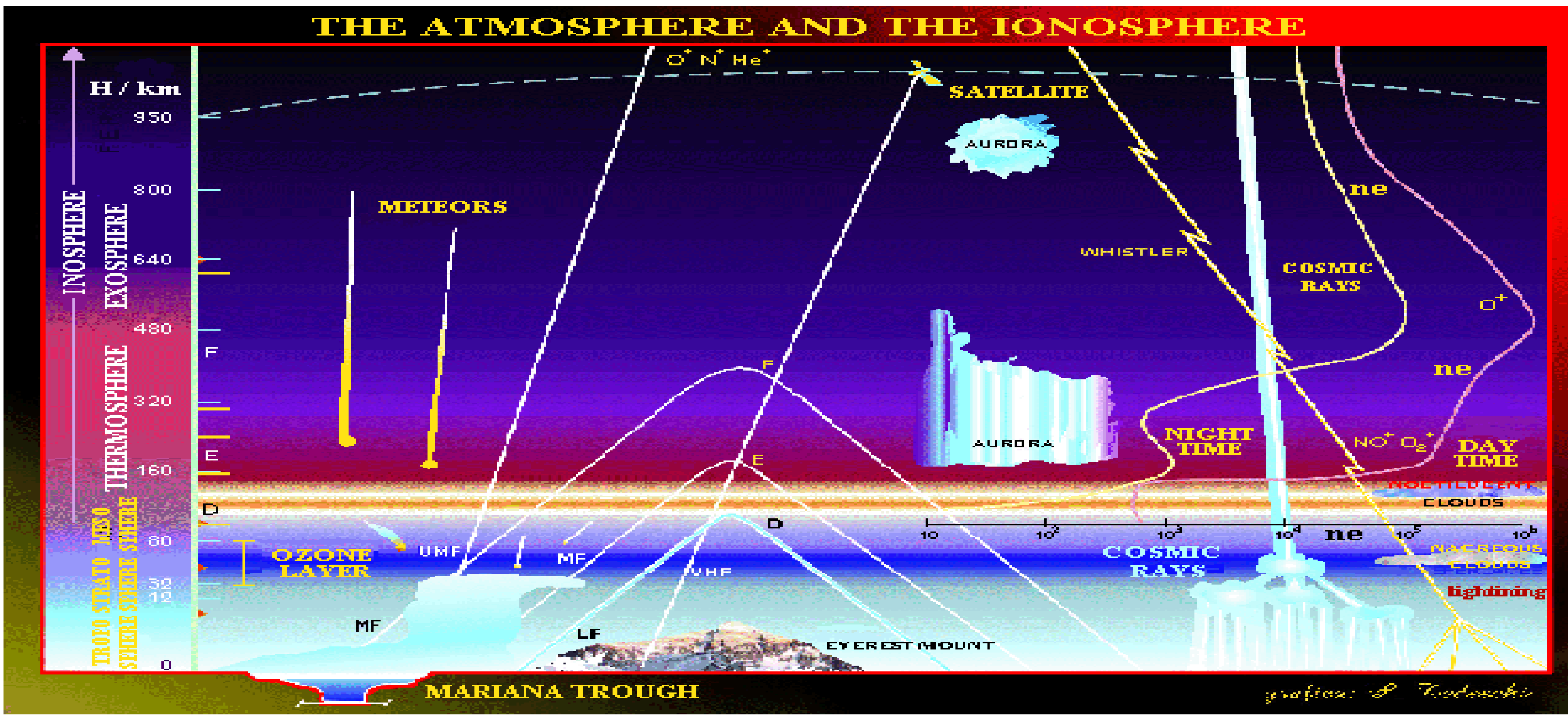
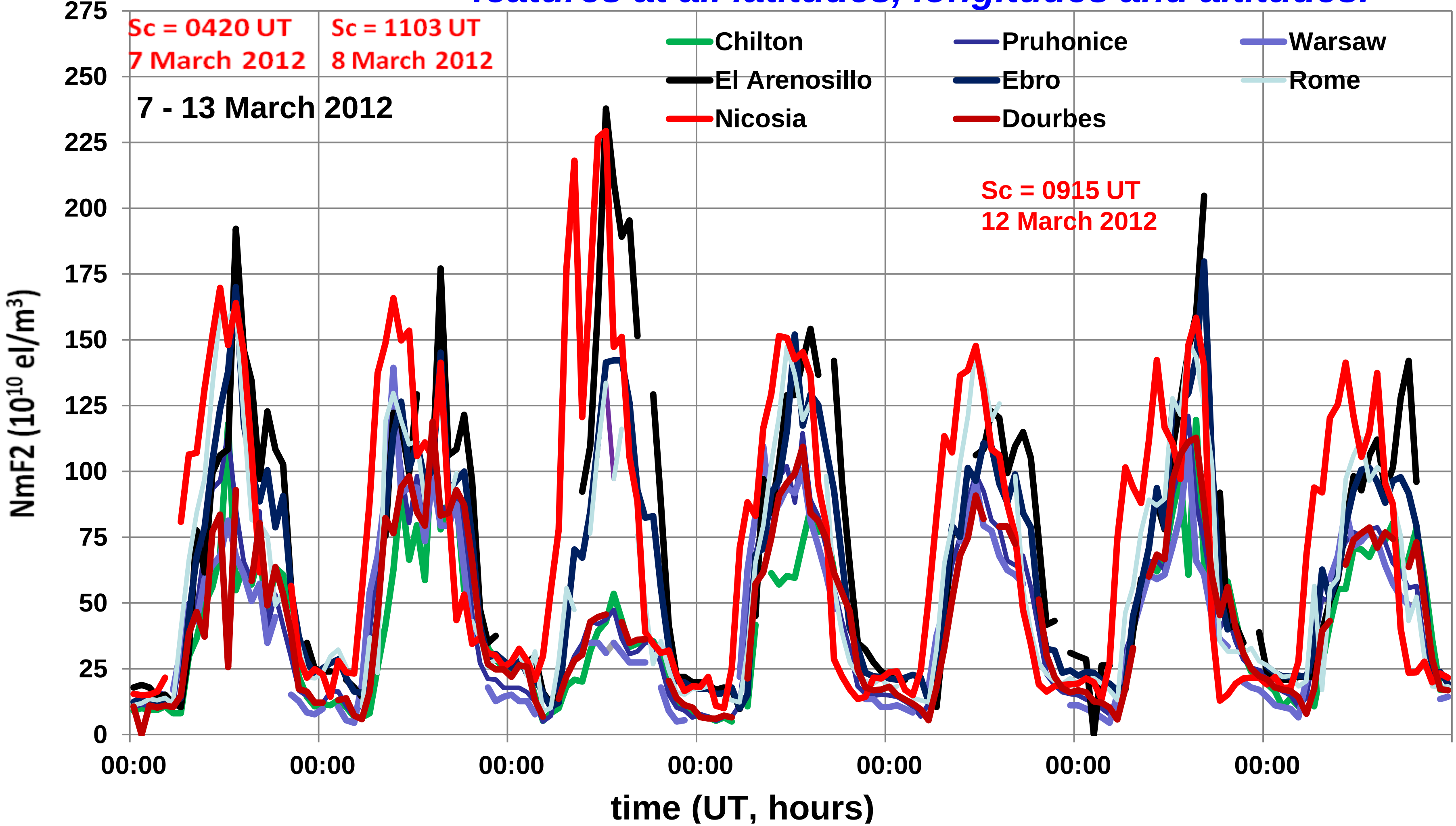
The Earth’s ionosphere is an environmental issue!

forming also an essential part of telecommunication and navigation systems; either as a medium within which they operate – use the ionosphere to function, or as a part of the degradation process – would function a lot better in its absence.



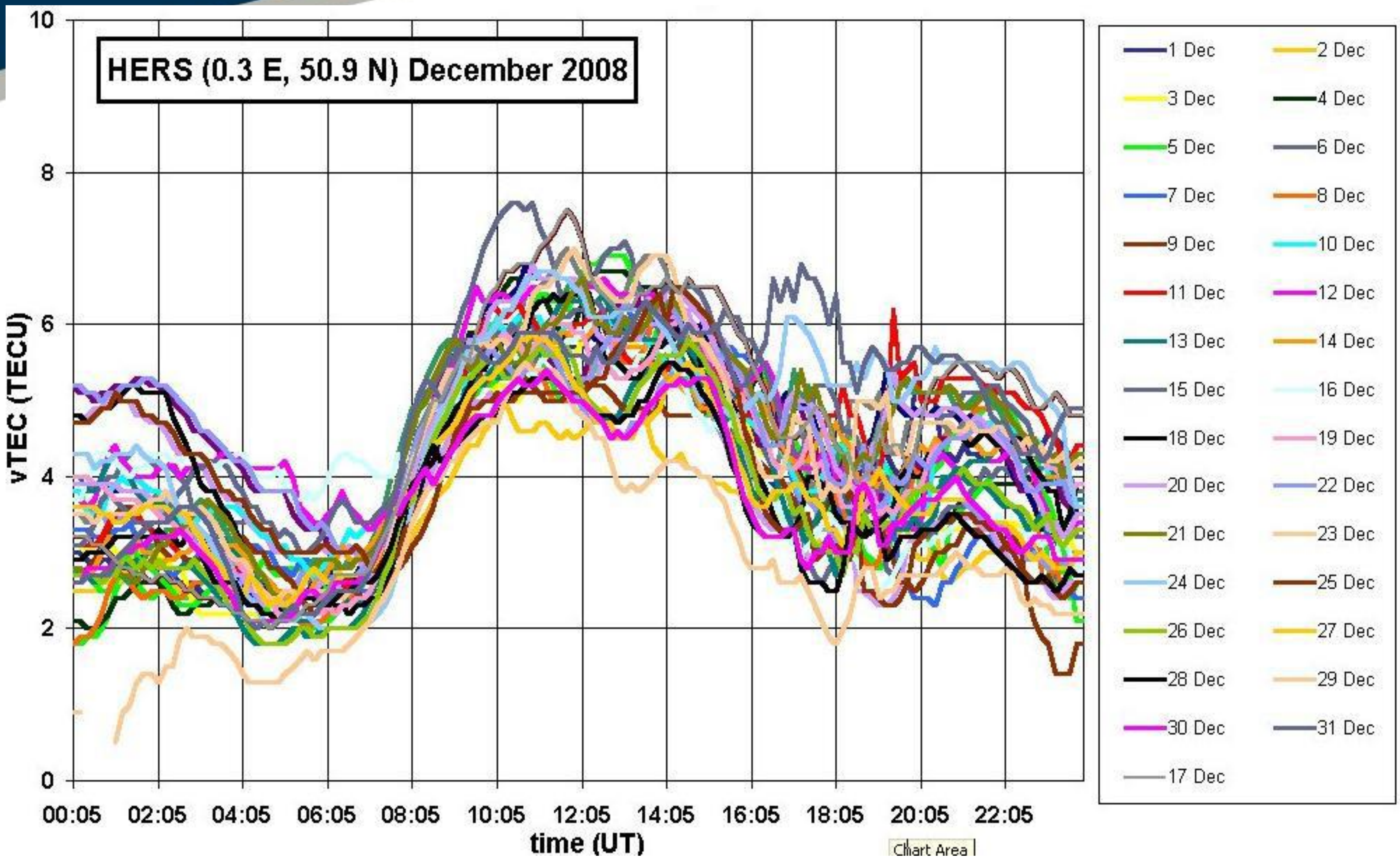
The ionosphere in space and time:

as a complex dynamic plasma medium, highly variable in space and time that exhibits climatology and weather features at all latitudes, longitudes and altitudes.



Plot of the NmF2 diurnal variations over a few mid-latitude ionosonde stations during 7-13 March 2012 storm.

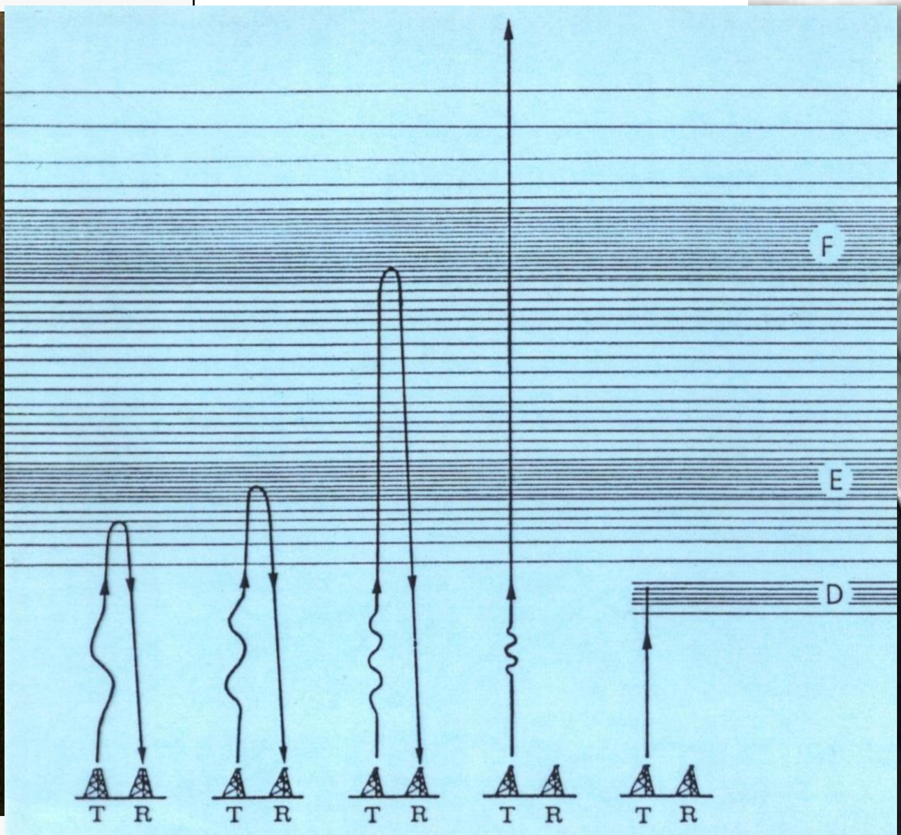
The ionosphere in time:



Plot of the vTEC diurnal variations over a mid-latitude ground-based GPS receiver at HERS, UK during absolute solar minimum in December 2008 when Ri=0.8.

Ionospheric

vertical sounding ***uses basic radar tecniques to detect electron density of ionospheric plasma as a function of the height by scanning the trasmitting frequency from 1 to 20 MHz and measuring the time delay of any echoes.***

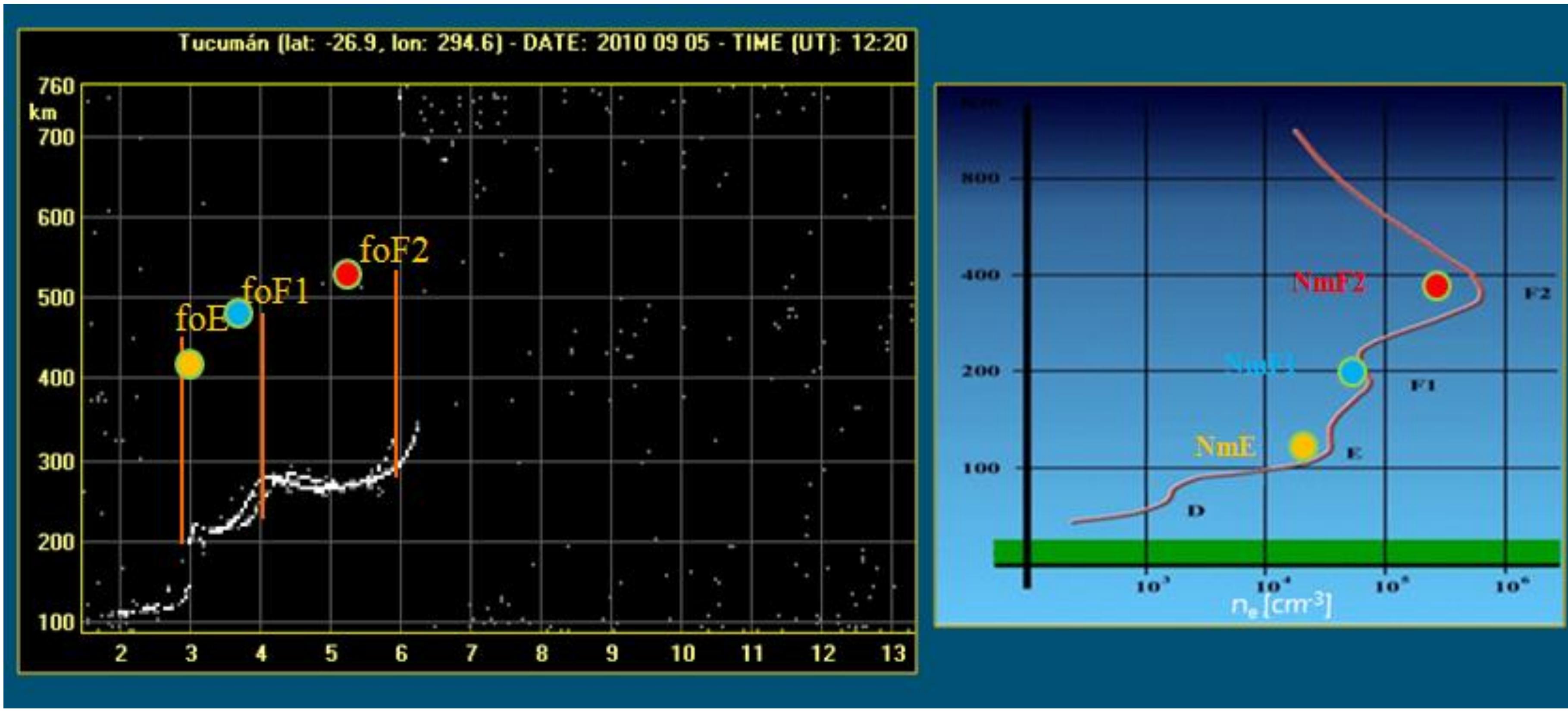


Guglielmo Marconi, *the Nobel prize in 1909 for contribution to the development of wireless telegraphy, realizing on 12th December 1901.*

Edward V. Appleton, *the Nobel Prize in 1947 for describing the vertical structure of the Earth's ionosphere by the systematic experiments and theoretical studies.*

A Ionogram:

the following ionospheric characteristics can be found: the critical frequencies, minimum virtual heights and propagation factors of the E, F1 and F2 layers.



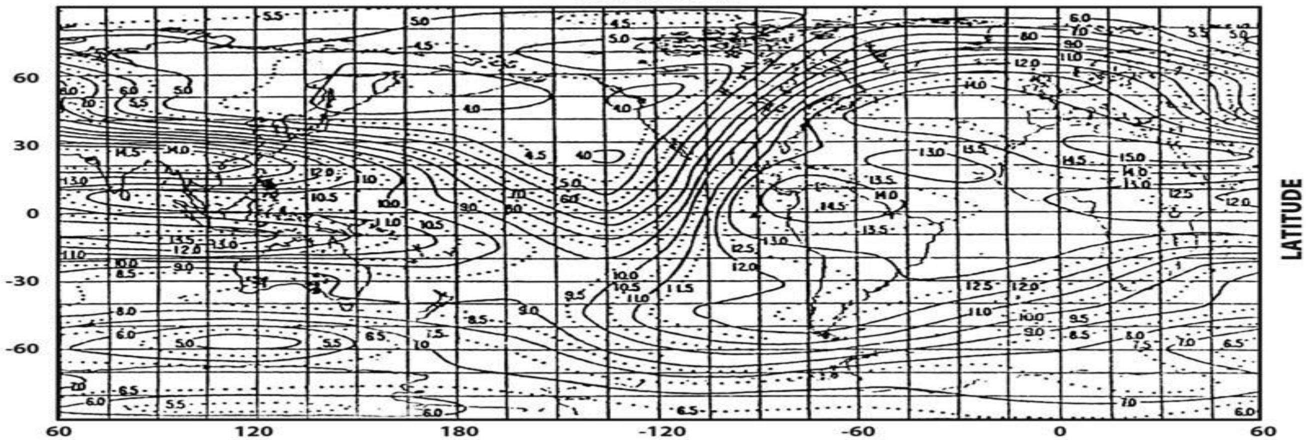
The maximum electron density N_M corresponds to the maximum reflected incidence frequency called the critical frequency fo

$$N_M = 1.24\ 10^{10}\ fo^2$$

where N_M and fo are expressed in el/m3 and in MHz, respectively.

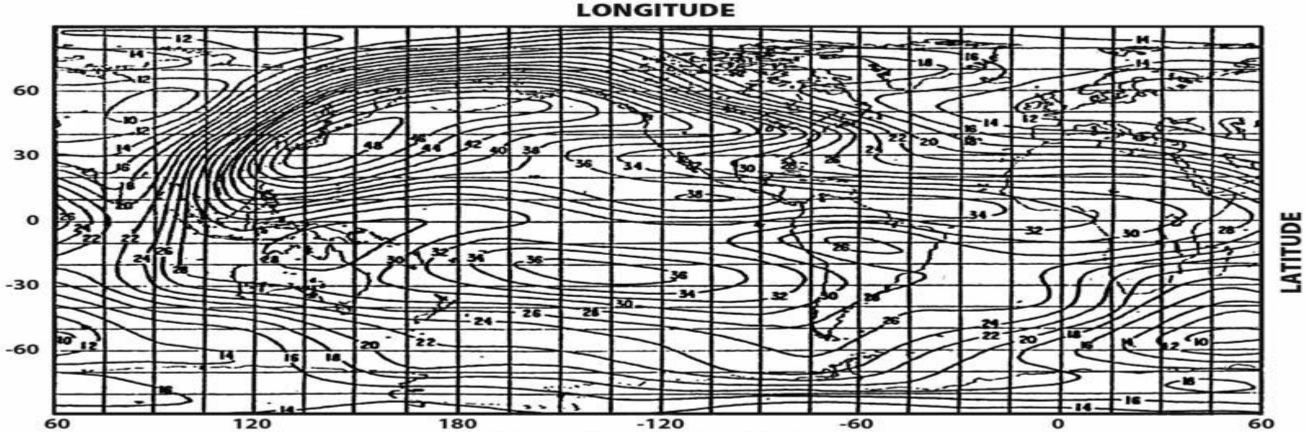
The CCIR (International Radio Consultative Committee), currently ITU (International Telecommunication Union) Atlas, 1967. IRI INPUT:

LONGITUDE



MEDIAN F2-ZERO-MUF (Mc/s)

LONGITUDE



MEDIAN F2-4000-MUF (Mc/s)

An example of ITU hourly maps of MUF(0) and MUF(4000) in MHz.

Global Ionospheric Radio Observatory (GIRO):

With Real-Time and retrospective HF Ionospheric Radio Sounding data from Lowell DIDBase (http://giro.uml.edu/).

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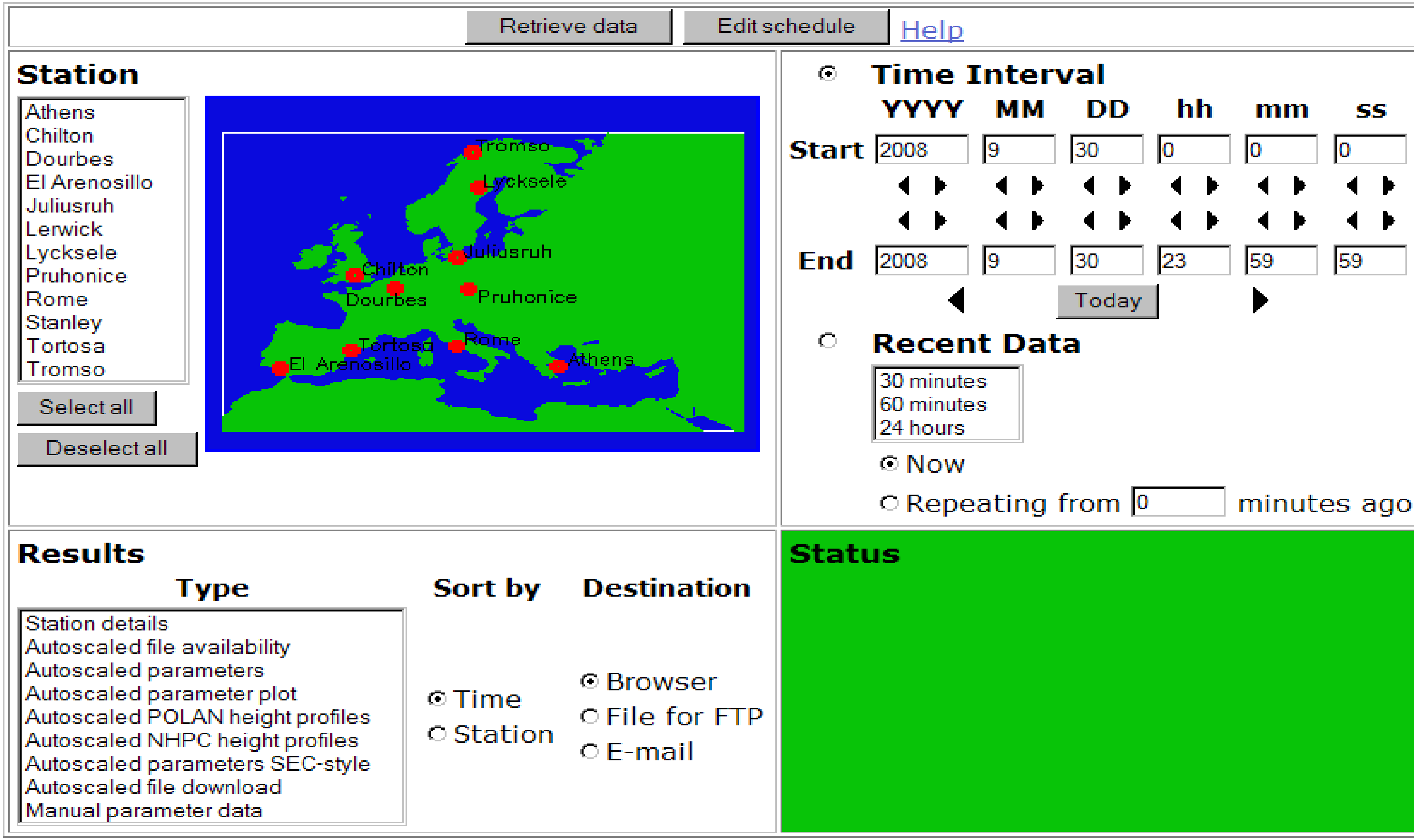
Ionospheric COST271 Action:



Prompt Ionospheric Database
(http://www.ukssdc.ac.uk/wdcc1/ionosondes/cost_help.html).

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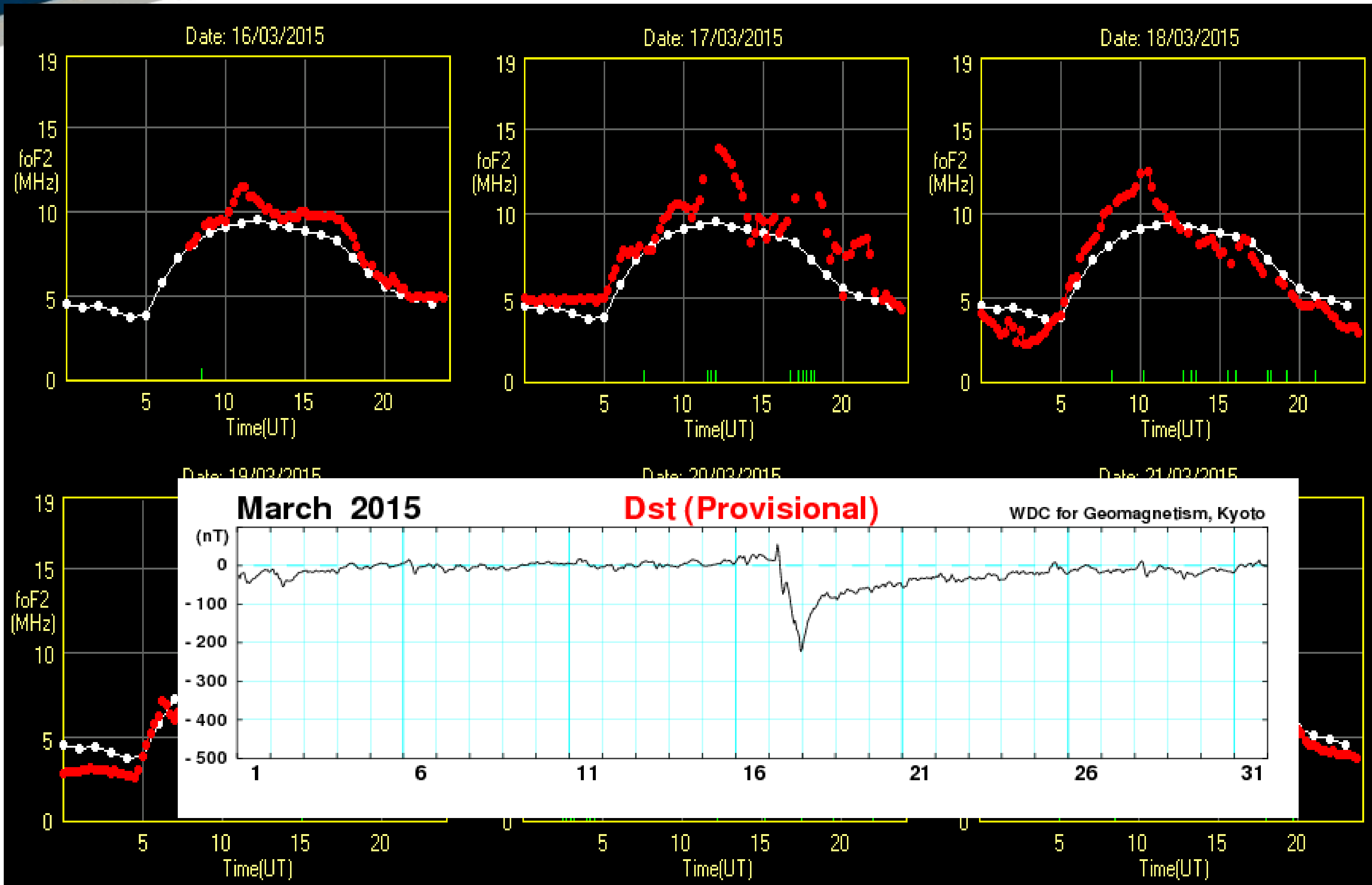
These ionosonde data are absolutely essential for monitoring the Earth's ionospheric plasma in real-time and understanding of the ionospheric storms.



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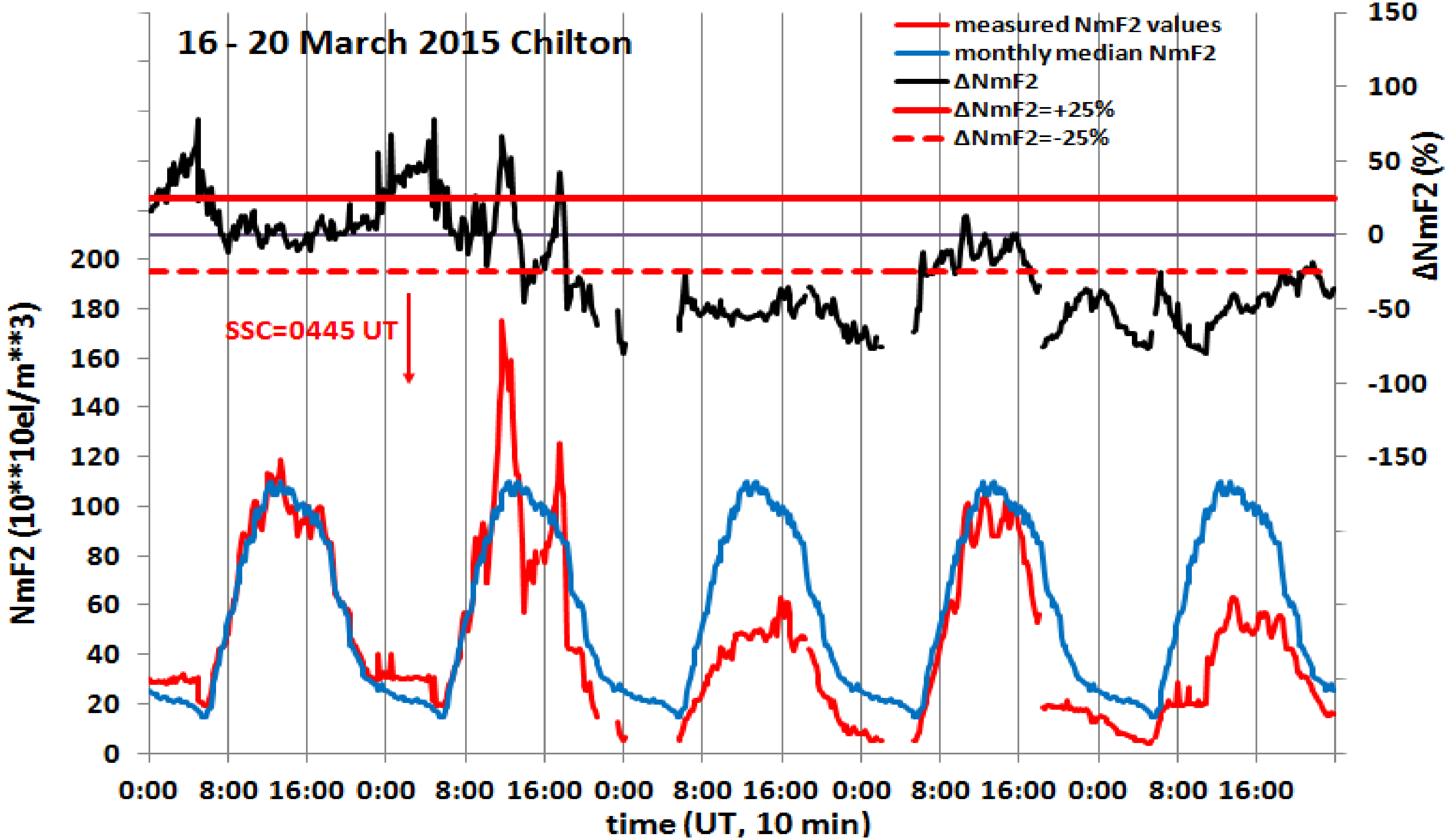
NmF2 example of the ionospheric storm:



NmF2 values and their percentage changes from the monthly median ΔNmF2 for Chilton (358.67° E, 51.70° N) ionosonde station.

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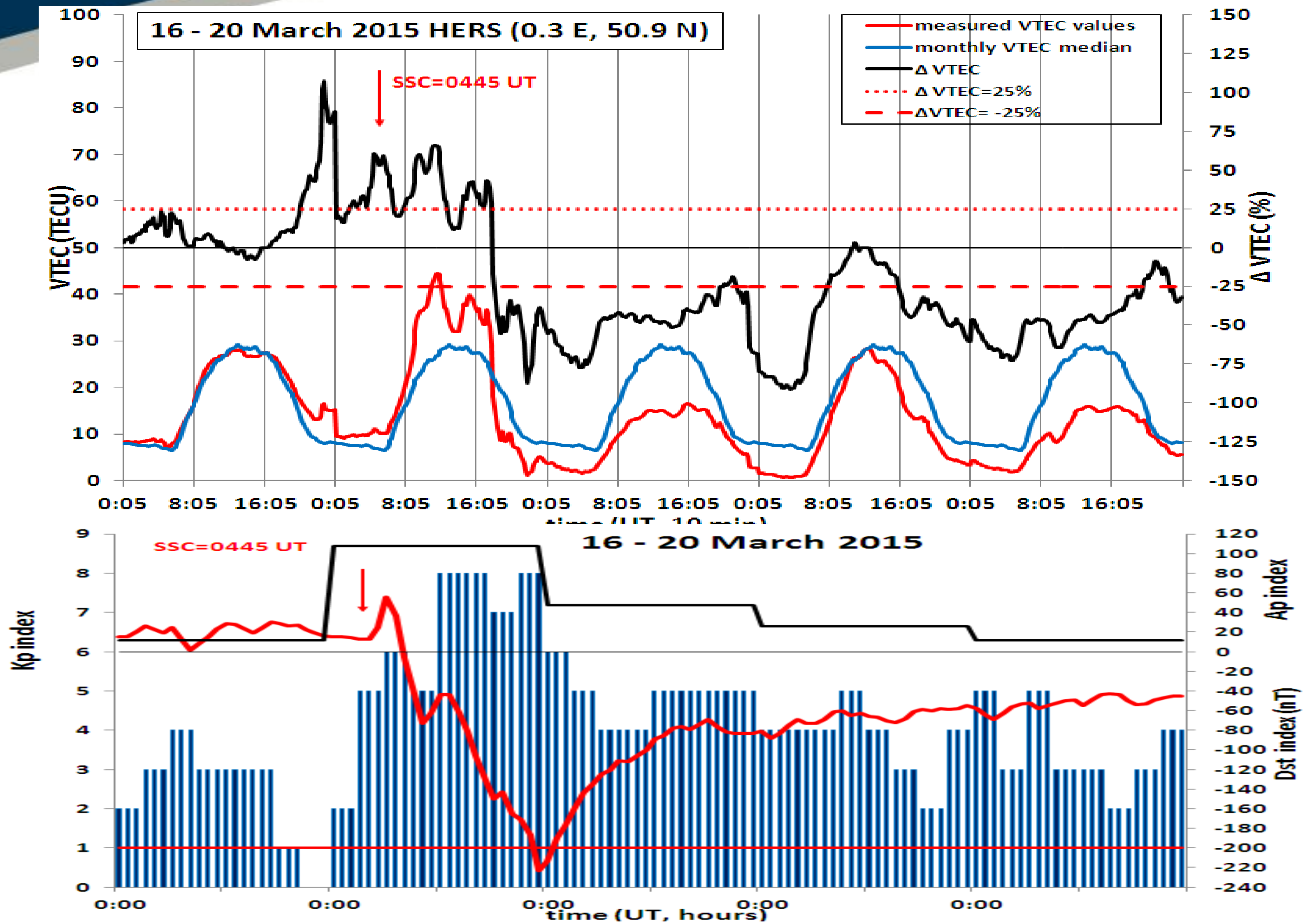
VTEC example of the ionospheric storm:



VTEC values and their percentage changes from the monthly median ΔVTEC for HERS (0.3° E, 50.9° N) GPS station with Kp, Ap and Dst variations.

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Milestone Papers and Review Articles:

AUTOR	*COMMENT*
Martyn, Proc R. Soc. London, 1953	*First comprehensive analysis of ≈100 storms at midlatitudes with ionosonde data.*
Sato, J.Geomagn, geoelectr.,1957	*First set of global morphology for storms with ionosonde data.*
Matsushita, JGR, 1959	*First to assess storm effects versus the strength of the geomagnetic storm with ionosonde data.*
Matura, Space Sci. Rev., 1972	*Second major review article on ionospheric storms.*
Prölss, Handbook of Atmos. Electrodyn., 1995	*Third major review article on ionospheric storms.*

Milestone Papers and Review Articles:

AUTOR	COMMENT
Obayashi, 1964	First true review article on ionospheric storms for both E and F layers and TEC effects.
Mendillo, Nature, 1971	Second major review article on ionospheric storms with TEC data.
Mendillo and Klobuchar, Tech. Rep., 1974	An atlas of the ionospheric storms with TEC data.
Jakowski, in Modern Ionospheric Science, 1996	Major review article on TEC monitoring.
Mendillo, Rev. Of Geophys., 2006	Major review article on ionospheric storms with TEC data.

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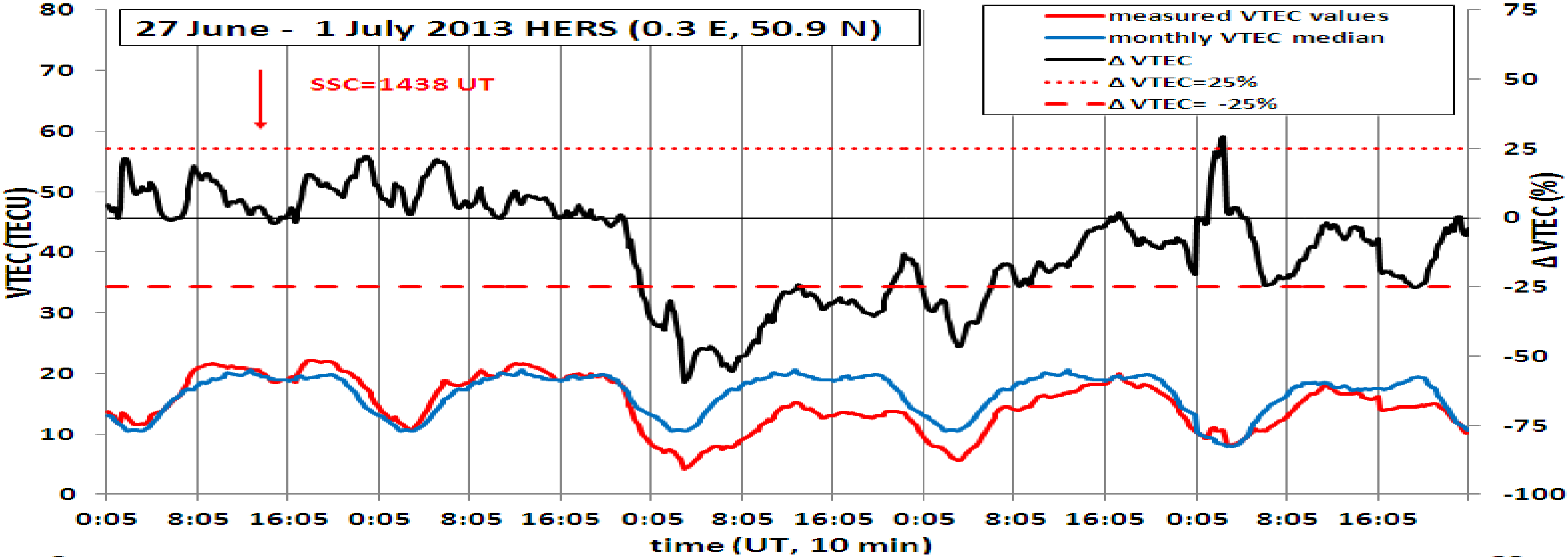
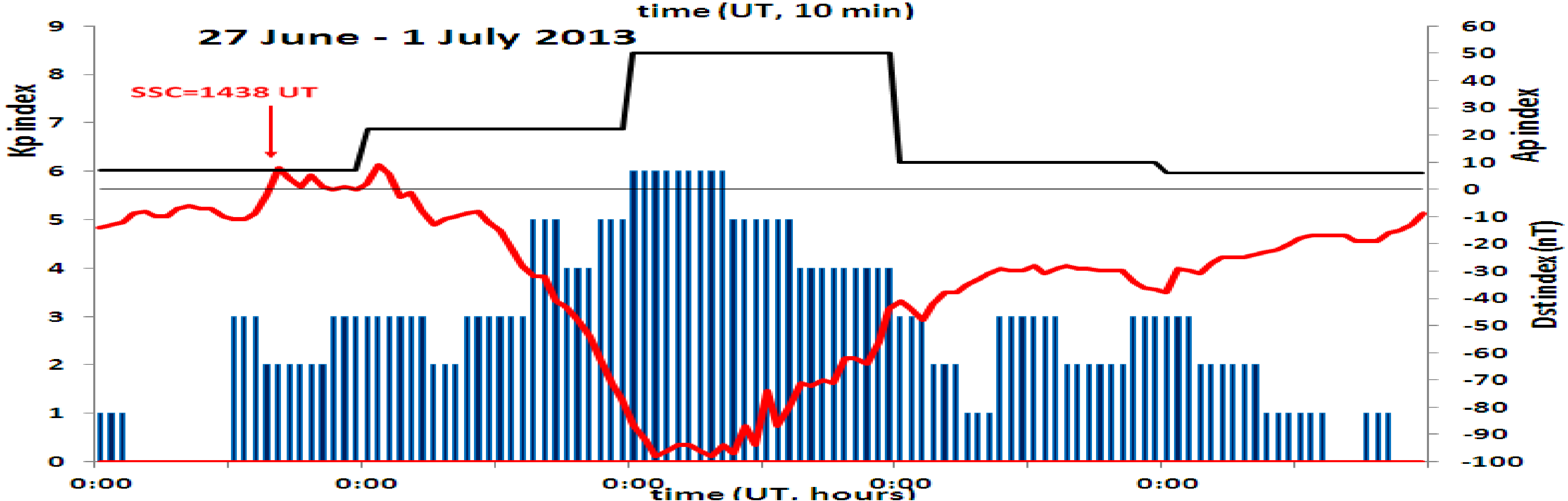
Negative ionospheric storm's phases are more pronounced in summer:





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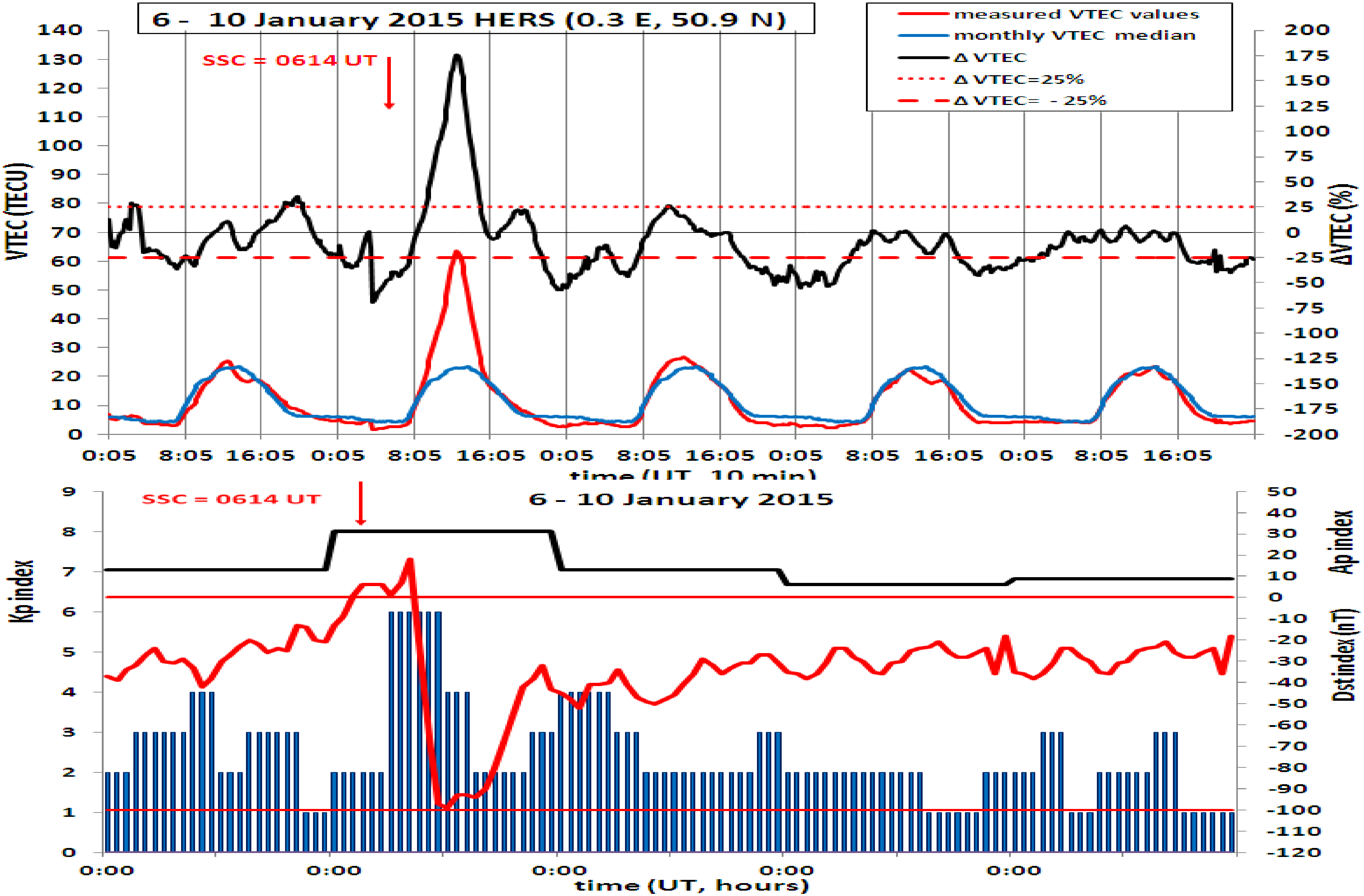
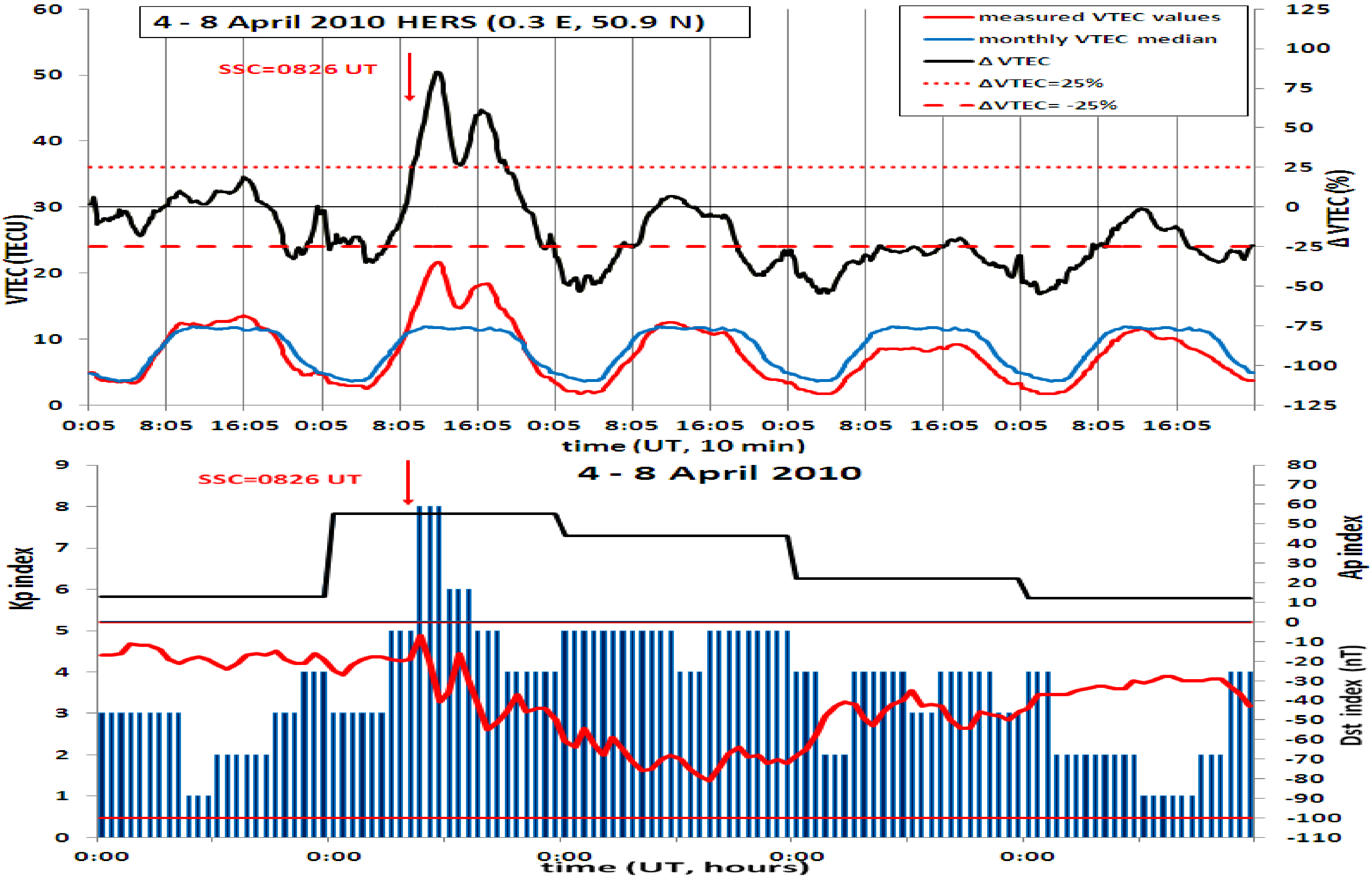
Positive ionospheric storm's phases are more pronounced in winter:



The positive phase with double peaks followed by a prolonged negative phsse:



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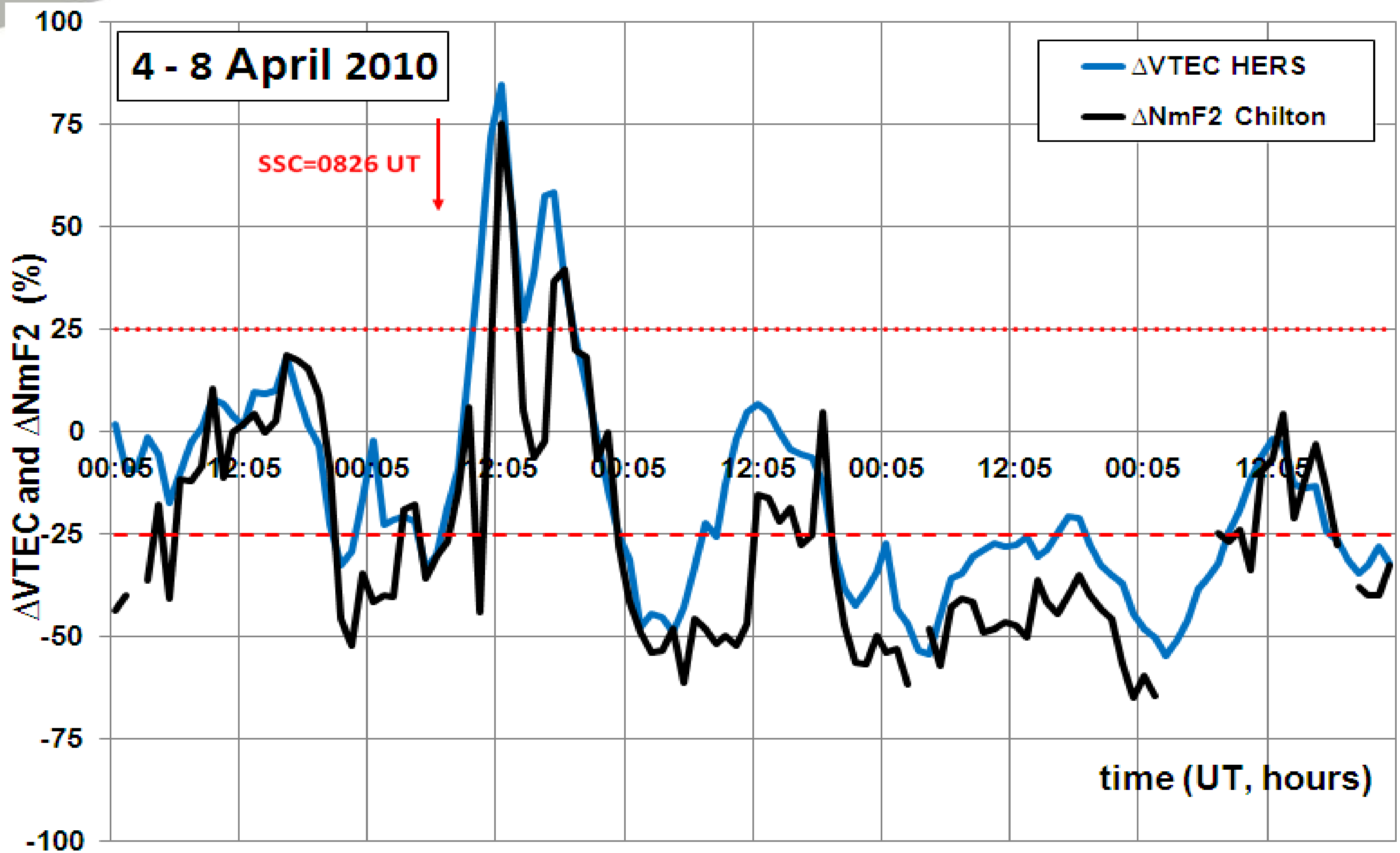
NmF2/VTEC correlation:



Daily values of Δ vTEC and Δ NmF2 at mid-latitude HERS GPS and Chilton ionosonde stations during 4 – 8 April 2010 storm.

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Common features in NmF2/VTEC response:

(1) For the typical storm events, the amplitude level of the NmF2/VTEC variations tend to increase (positive phase) during the first 24 hours of the geomagnetic storm, and then decrease below its quiet time reference level (negative phase) with recovery in one or two days later;

(2) During a negative phase of the NmF2/VTEC variations the perturbation amplitudes of NmF2/VTEC show a remarkable reduction in summer compared to in winter;

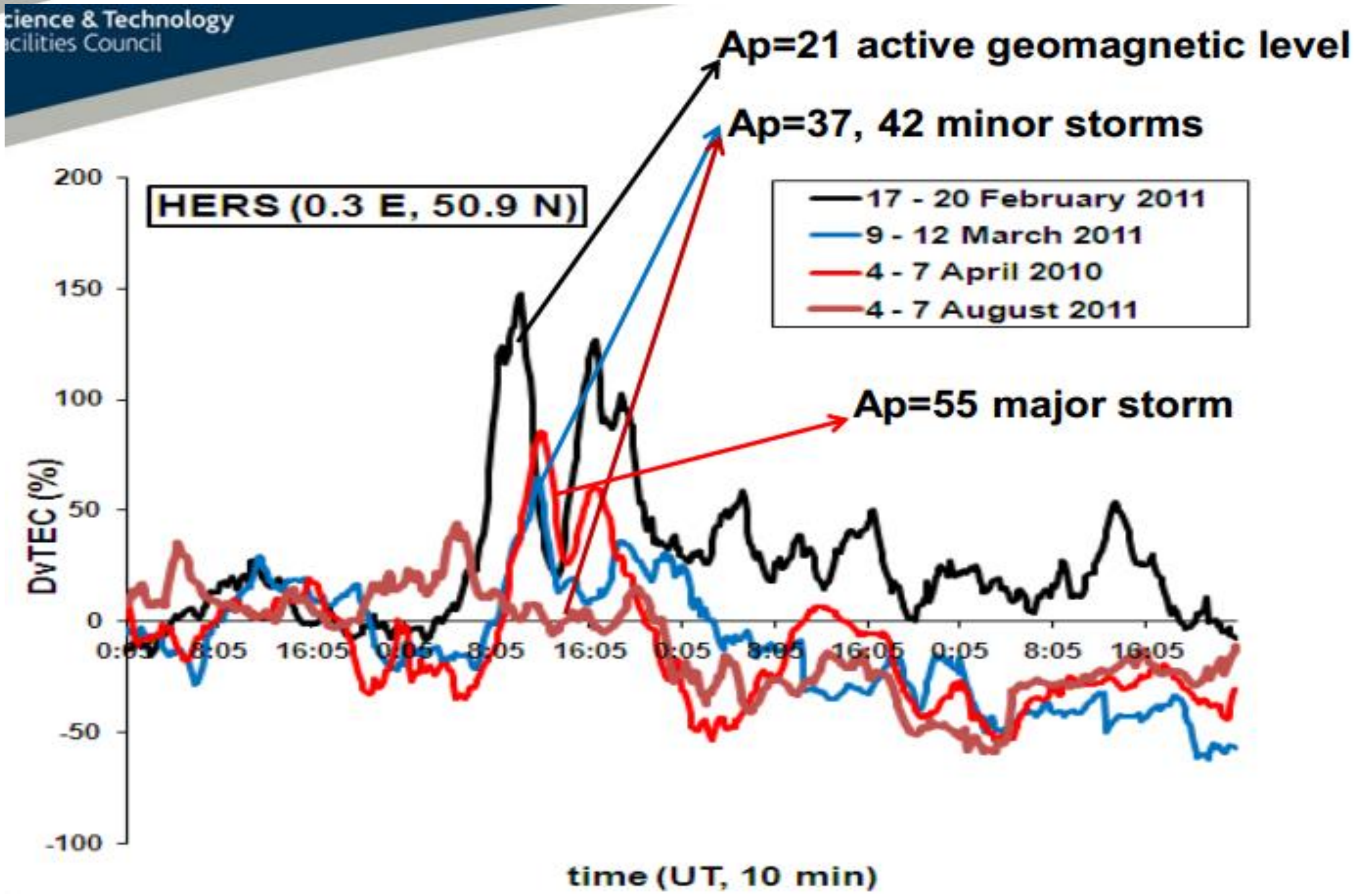
(3) NmF2/VTEC positive phase is often at low and mid-latitudes in the daytime;

(4) NmF2/VTEC negative phase is often at high latitudes and around the geomagnetic equator in the daytime;

(5) There is a north-south asymmetry in the positive response as the northern hemispheric response appeared to be more pronounced.

HOWEVER …

a number of questions remain, e.g. solar-terrestrial circumstances and prior storm ionospheric condition necessary for these phases to occur.



Daily values of DvTEC at HERS during 4-7 April 2010, 17–20 February 2011, 9-12 March 2011 and 4-7 August 2011 storms.

Common couses in NmF2/VTEC response:

(1) It is long-established that at mid-latitudes thermospheric winds and electromagnetic fields are the main drivers of ionospheric storms producing electron density changes beyond a climatological level;

(2)The origin of negative phase has been attributed to changes in the neutral gas composition of the upper atmosphere. It results from enhanced ionospheric chemical loss driven by the storm induced modifications to thermospheric circulations. As the relaxation time of the thermosphere is not quick thus the longevity of most negative phase storm effects;

(3) Positive phase is considered to be caused by upward transport of ionospheric electron density but the question of two main drivers, that are thermospheric winds and electromagnetic fields, dominate role is under consideration . Results suggest that thermospheric heating and resulting circulation need to be critically examined to quantify the actual Joule heating enhancement and test whether it is sufficient to overwhelm the prevailing winds.

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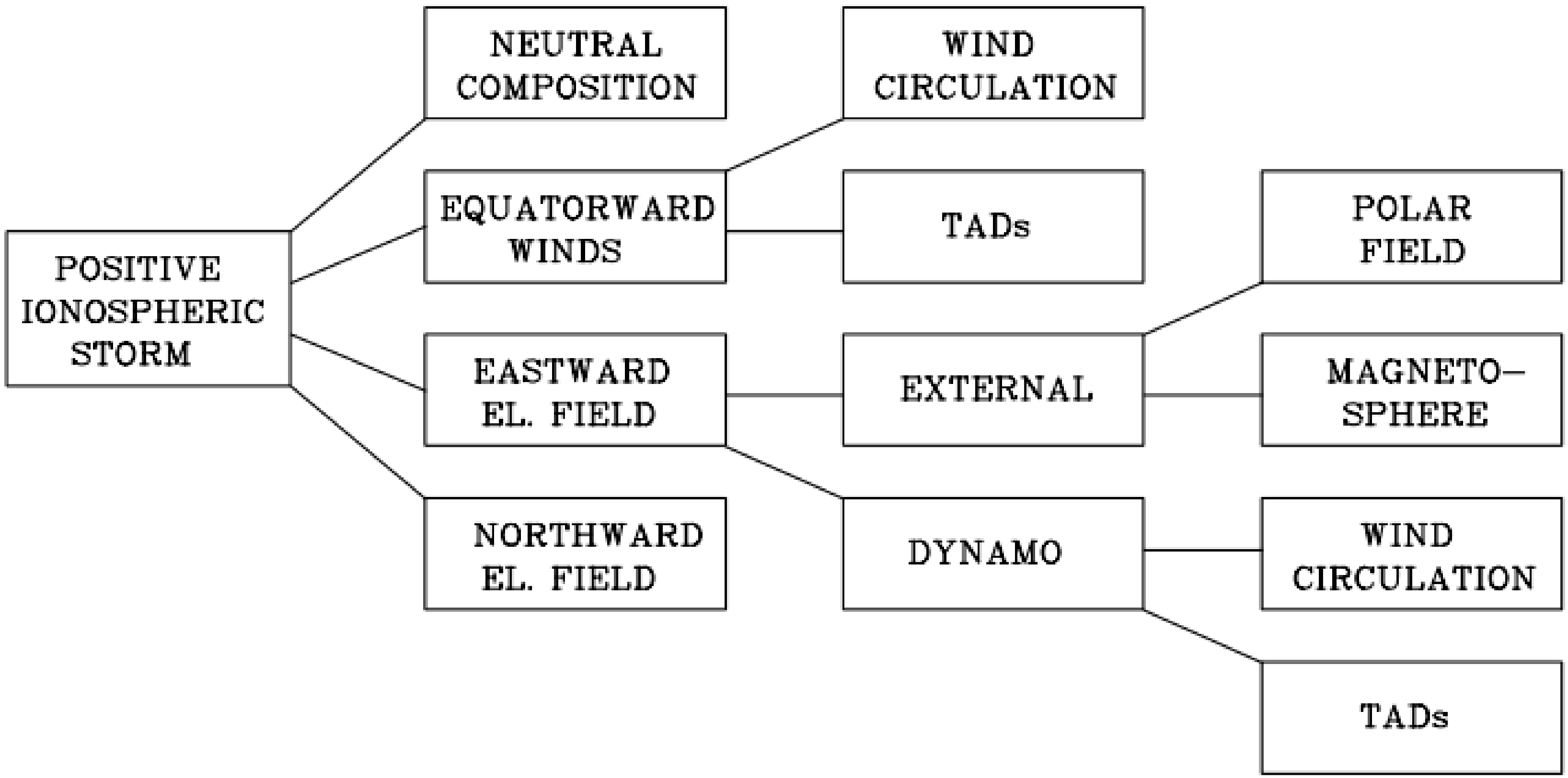
Mechanisms contributing to the positive phase of ionospheric storms at middle latitudes:



Prölss, G.W. (2006) Ionospheric F-region Storms: Unsolved Problems. In Characterising the Ionosphere (pp. 10-1 – 10-20). Meeting Proceedings RTO-MP-IST-056, Paper 10. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

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Modeling and Nowcasting Ionospheric Storms:

- ***Since ionospheric and geomagnetic storms have very different drivers, the ionospheric storm onset is not necessarily correlated with the geomagnetic storm main phase;***

- ***Massive movements of ionization during geomagnetic storms followed by global changes in thermospheric winds and chemistry leading to a complex behaviour from the initial to the recovery phases indicate that the disturbed ionosphere is even more complex than results presented here suggest;***

- ***This raises the first questions about the persistence and consequently predictability of ionosphric storms. The second aspect of predictability is the problem of forecasting the disturbed geomagnetic field.***

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STORM TIME EMPIRICAL IONOSPHERIC CORRECTION MODEL:

- *It is the first empirical model of the response of the ionosphere to a geomagnetic storm that has demonstrated a consistent and measurable improvement over climatology.*

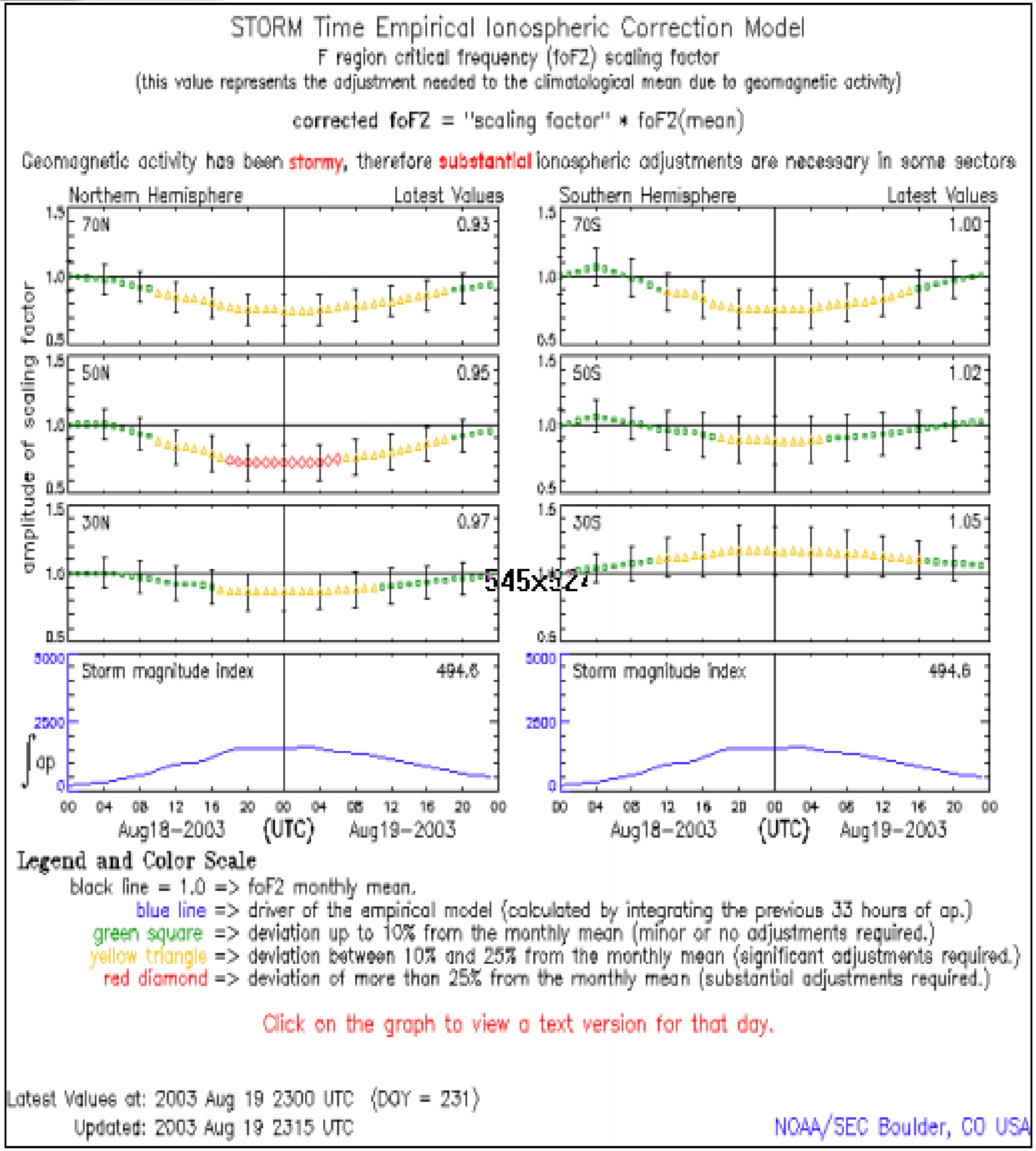
- *Based solely on an analysis of an extensive database of ionosonde observations, but the algorithms and data sorting procedure has been guided by numerical simulations from a coupled thermosphere ionosphere model.*

- *The intensity of the storm is characterized by a new index derived from filtering the previous 33 hours of ap.*

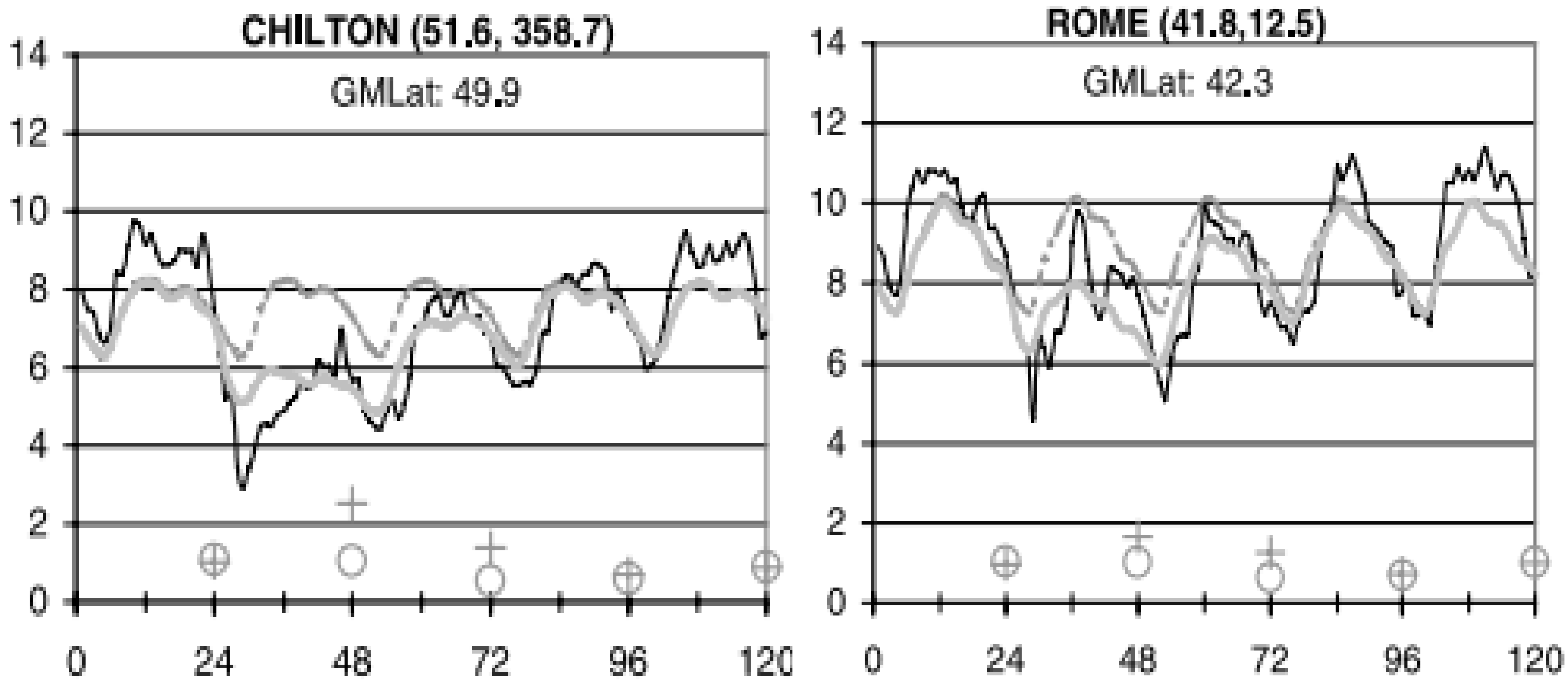
- *The first characterization of STORM has been designed to adjust the F-region peak critical frequency (foF2) as function of geomagnetic latitude, season, and intensity of the storm.*

E. A. Araujo-Pradere, T. J. Fuller-Rowell, and M. V. Codrescu, STORM: An empirical storm-time ionospheric correction model, RADIO SCIENCE, VOL. 37, DOI 10.1029/2001RS002467, 2002

STORM MODEL:


STORM Time Empirical Ionospheric Correction Model
F region critical frequency (foF2) scaling factor
(this value represents the adjustment needed to the climatological mean due to geomagnetic activity)
corrected foF2 = "scaling factor" * foF2(mean)
Geomagnetic activity has been stormy, therefore substantial ionospheric adjustments are necessary in some sectors
Northern Hemisphere
Latest Values
Southern Hemisphere
Latest Values
70N
0.93
70S
1.00
50N
0.95
50S
1.02
30N
0.97
30S
1.05
amplitude of scaling factor
Storm magnitude index
494.6
∫ap
Aug18-2003
(UTC)
Aug19-2003
Legend and Color Scale
black line = 1.0 => foF2 monthly mean.
blue line => driver of the empirical model (calculated by integrating the previous 33 hours of ap.)
green square => deviation up to 10% from the monthly mean (minor or no adjustments required.)
yellow triangle => deviation between 10% and 25% from the monthly mean (significant adjustments required.)
red diamond => deviation of more than 25% from the monthly mean (substantial adjustments required.)
Click on the graph to view a text version for that day.
Latest Values at: 2003 Aug 19 2300 UTC (DOY = 231)
Updated: 2003 Aug 19 2315 UTC
NOAA/SEC Boulder, CO USA

Validation of the STORM response in IRI2000:



Data and output of the IRI95 and IRI2000 models at two different locations for the 23 - 27 May 2000 storm. The dashed shaded line shows IRI95, the solid line is the observation, and the solid shaded line shows IRI2000.

Araujo-Pradere, E. A., T. J. Fuller-Rowell, and D. Bilitza, Validation of the STORM response in IRI2000, J. Geophys. Res., 108(A3), 1120, doi:10.1029/2002JA009720, 2003.

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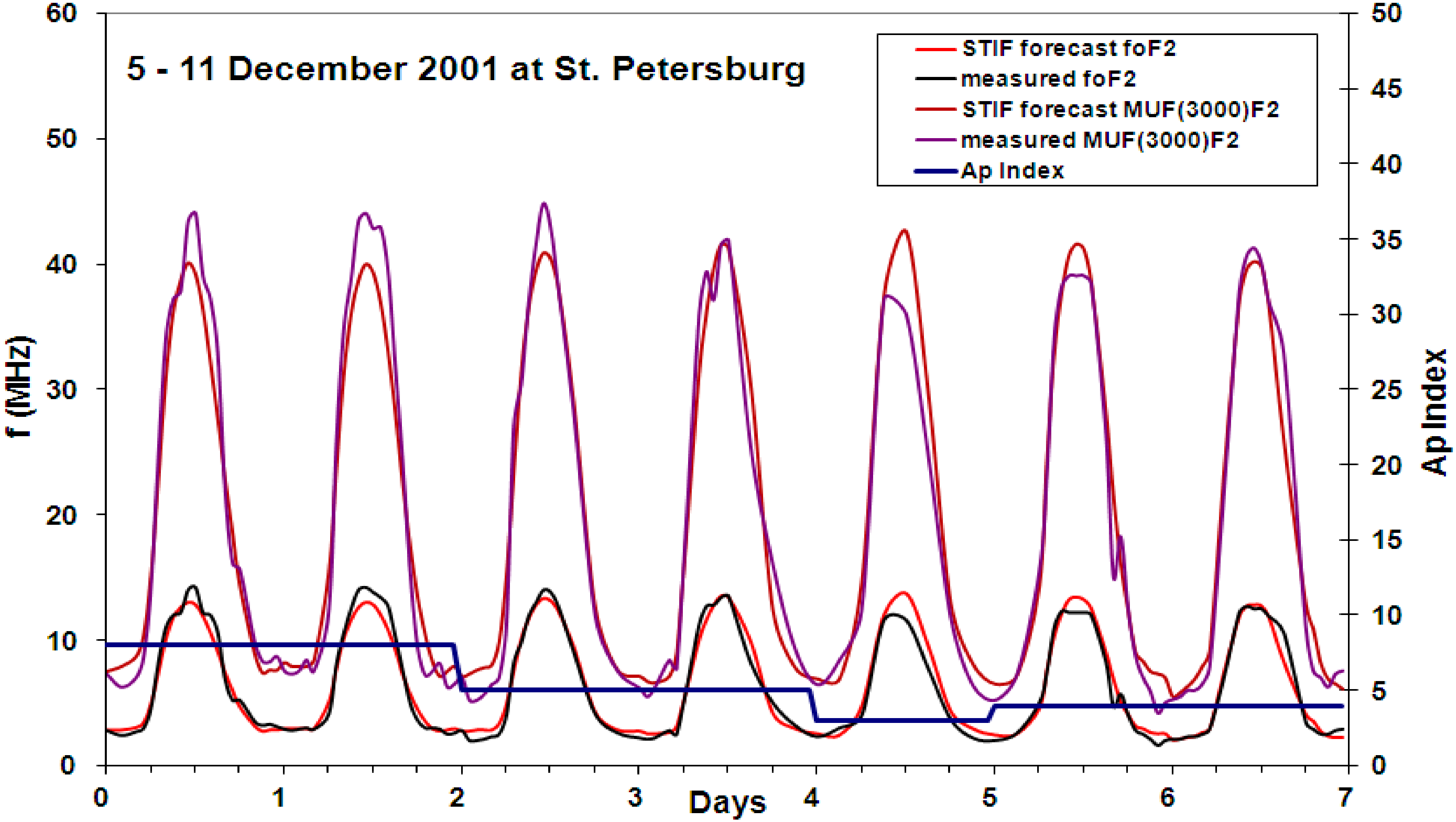
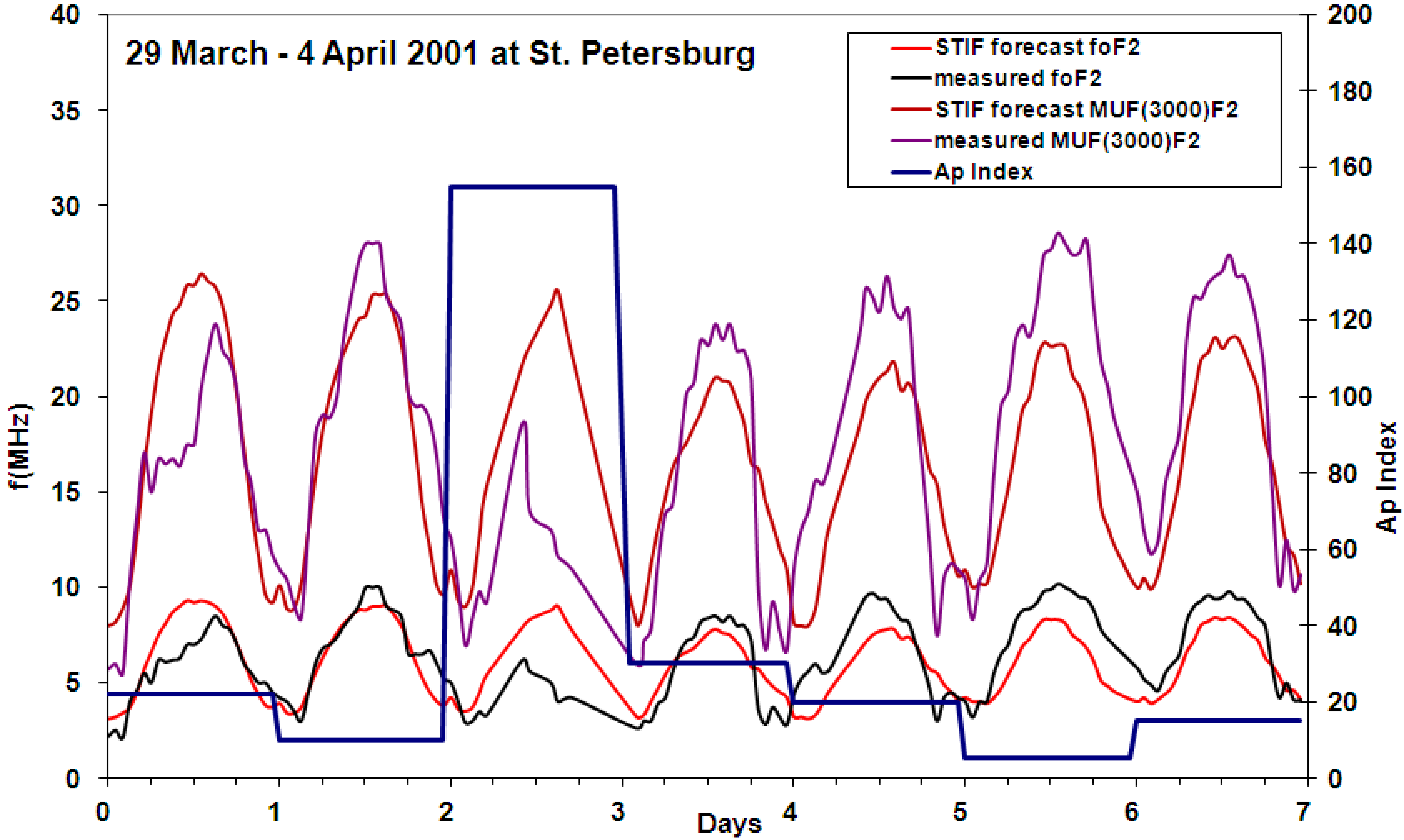
STIF (Short-Term Ionospheric Forecasting) 24- hours ahead:



Typical STIF foF2and MUF(3000)F2 results and measurements at the St Petersburg (59.9° N, 30.7° E) ionosonde station during quiet geomagnetic conditions.

STIF (Short-Term Ionospheric Forecasting) 24- hours ahead:



Typical STIF foF2and MUF(3000)F2 results and measurements at the St Petersburg (59.9° N, 30.7° E) ionosonde station during disturbed geomagnetic conditions.

$$RE = \frac{1}{N}\sum_{i=1}^{N}\frac{abs(y_i - x_i)}{y_i}.100\%$$

$$RE = \frac{1}{N}\sum_{i=1}^{N}\frac{abs(y_i - x_i)}{y_i}.100\%$$

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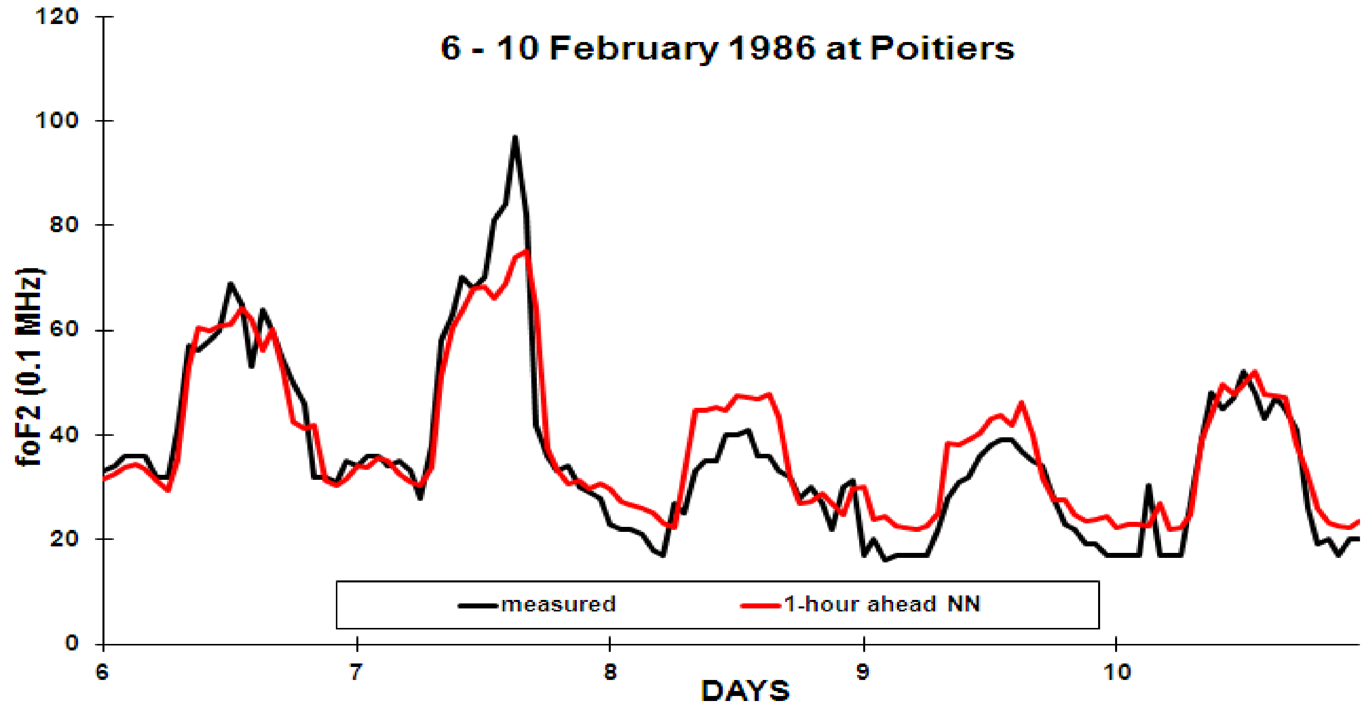
Ionospheric forecasting over a storm period by NN:

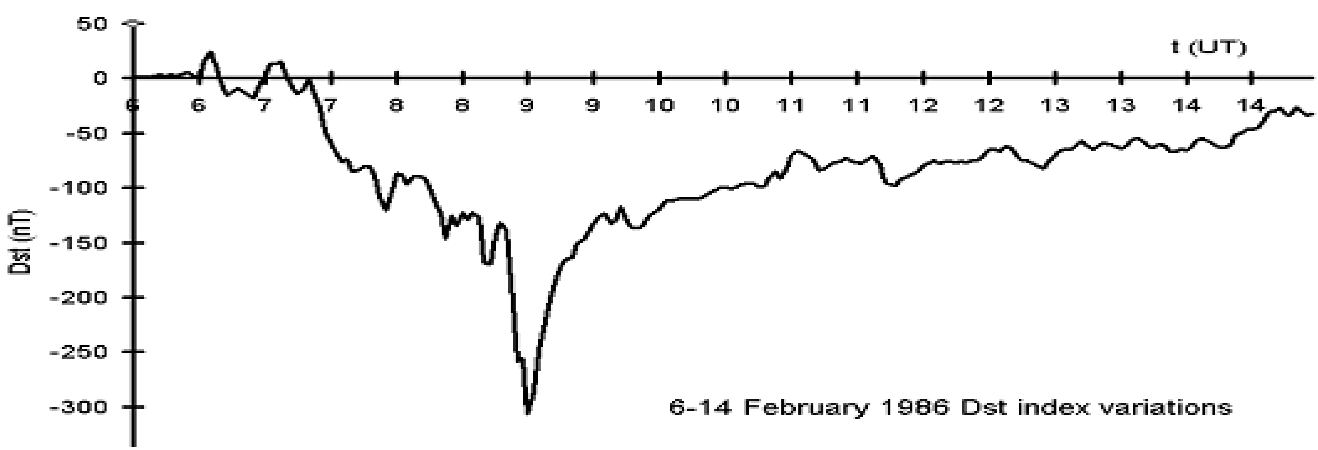
Measured and 1-hour ahead forecast foF2 values for 6 - 10 February 1986 at Poitiers ionosonde station (46.6° N, 0.3° E).

RMSE=0.45 MHz
NRMSE=0.32

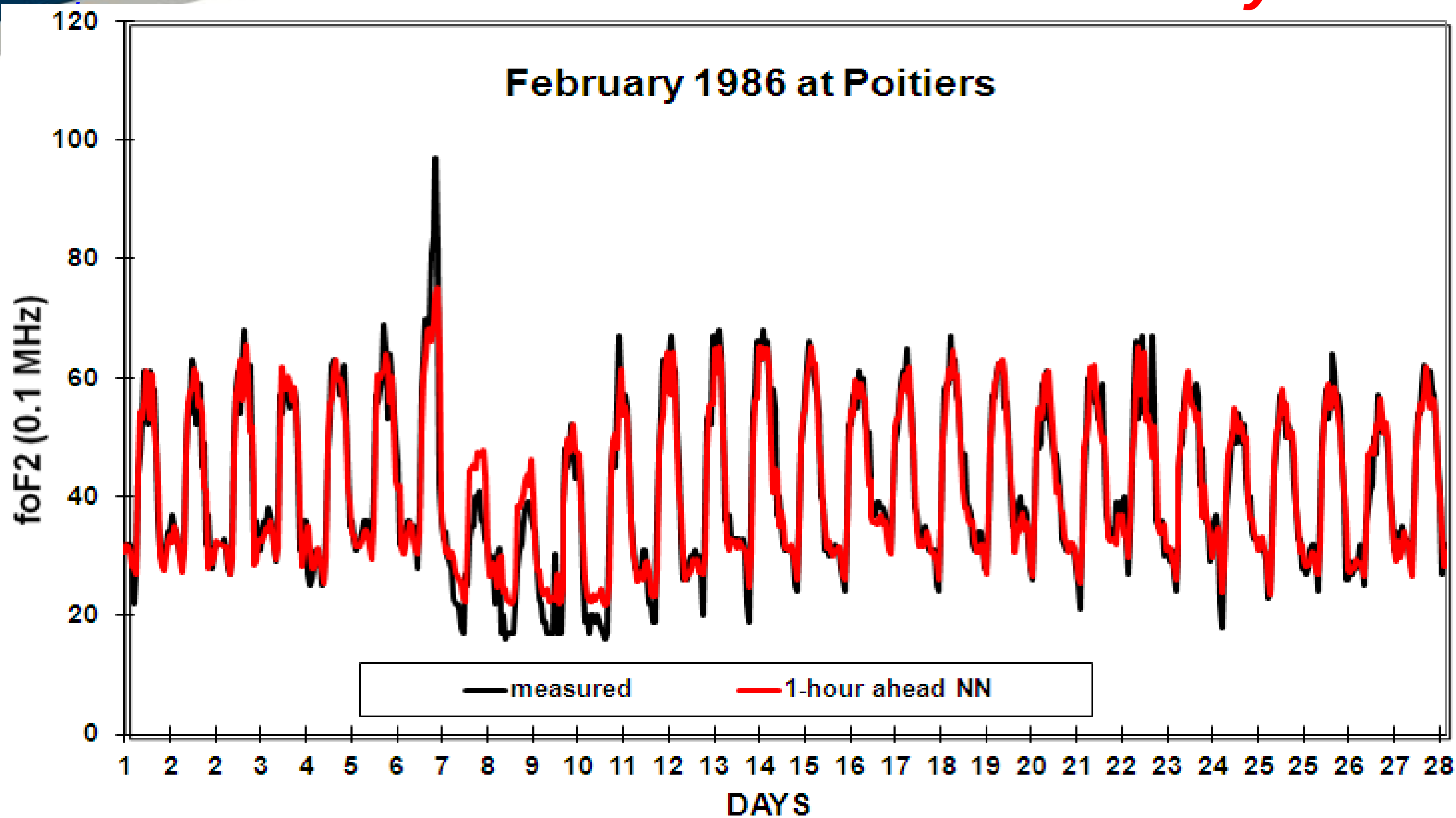
$$RE = \frac{1}{N}\sum_{i=1}^{N}\frac{abs(y_i - x_i)}{y_i}.100\%$$

STATION/ INPUT PARAMETERS	PT046 RE (%)
foF2 only	*9.14*
foF2 + Ri + Ap	*8.63*
foF2 + Ri + Dst	*8.89*
foF2 + Ri + Ap + Dst	***8.60***





Ionospheric forecasting over a month by NN:



Measured and 1-hour ahead forecast foF2 values at Poitiers (46.6° N, 0.3° E) ionosonde station in February 1986.

Zolesi, B., Cander, LjR, Ionospheric Prediction and Forecasting, Springer-Verlag, Berlin Heidelberg, 2014.

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CONCLUSSIONS (1):

•.

• The ionosphere's response to geomagnetic storms has been studied since the earliest days of terrestrial space physics. Ionospheric storms were discovered more than 85 years ago (Hafstad and Tuve, Proc. Inst. Radio Eng., 17, 1513-1522, 1929);

• In terms of temporal coverage, the largest data sets used have been from the global network of ground-based ionosonde measurements. Nowadays this is the case with TEC data;

• Most previous studies examined the behaviour of the F-region's maximum electron density contrasting the difference seen between storms that occur during solar maximum/minimum years and between;

• The overall results show consistency in characteristic patterns of an ionospheric storm: a short positive phase that occurs during the daytime hours on the first day of a storm, with a prolonged negative phase on subsequent days. Statistical differences occur in the overall magnitudes and longevities of storm patterns;

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CONCLUSSIONS (2):

•.

- ***Short-timescale dynamical mechanisms driving the storms (electrodynamical and thermospheric) dominate the positive phase, while longer-timescale composition changes the negative phase;***

NEEDED WORK: Modelling of multiday ionospheric storm time behaviour. In particular:

1. ***Duration and magnitude of the negative and/or positive phase versus latitude, local time, season, and phase of solar cycle as well as between different solar cycles;***
2. ***Temporal relationships between characteristics of the geomagnetic storm and the development of the ionospheric storm in real-time;***
3. ***Differences in NmF2 and TEC ability to characterize the overall ionosphere during storms, although the physical causes for their storm time variations are the same;***

AND SO ON… AD INFINITUM