Solar activity effects on the Earth's upper atmosphere: modeling the ionospheric storm time response to different solar wind drivers

Ioanna Tsagouri

National Observatory of Athens, Greece

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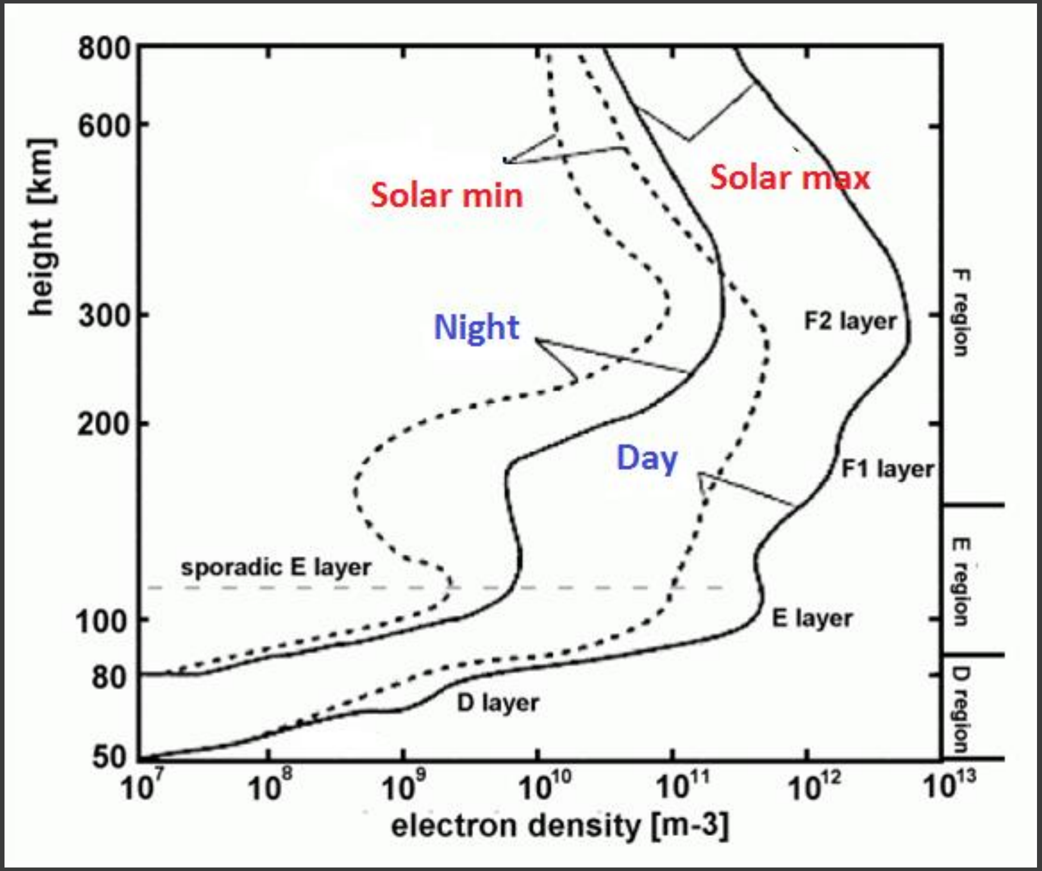
Ionospheric variability



The ionosphere is not the same every day since it is a highly coupled system: ionization production, loss and transport

$$\partial N_e / \partial t = q - l\,(N_e) - \mathrm{div}\,(N_e V)$$

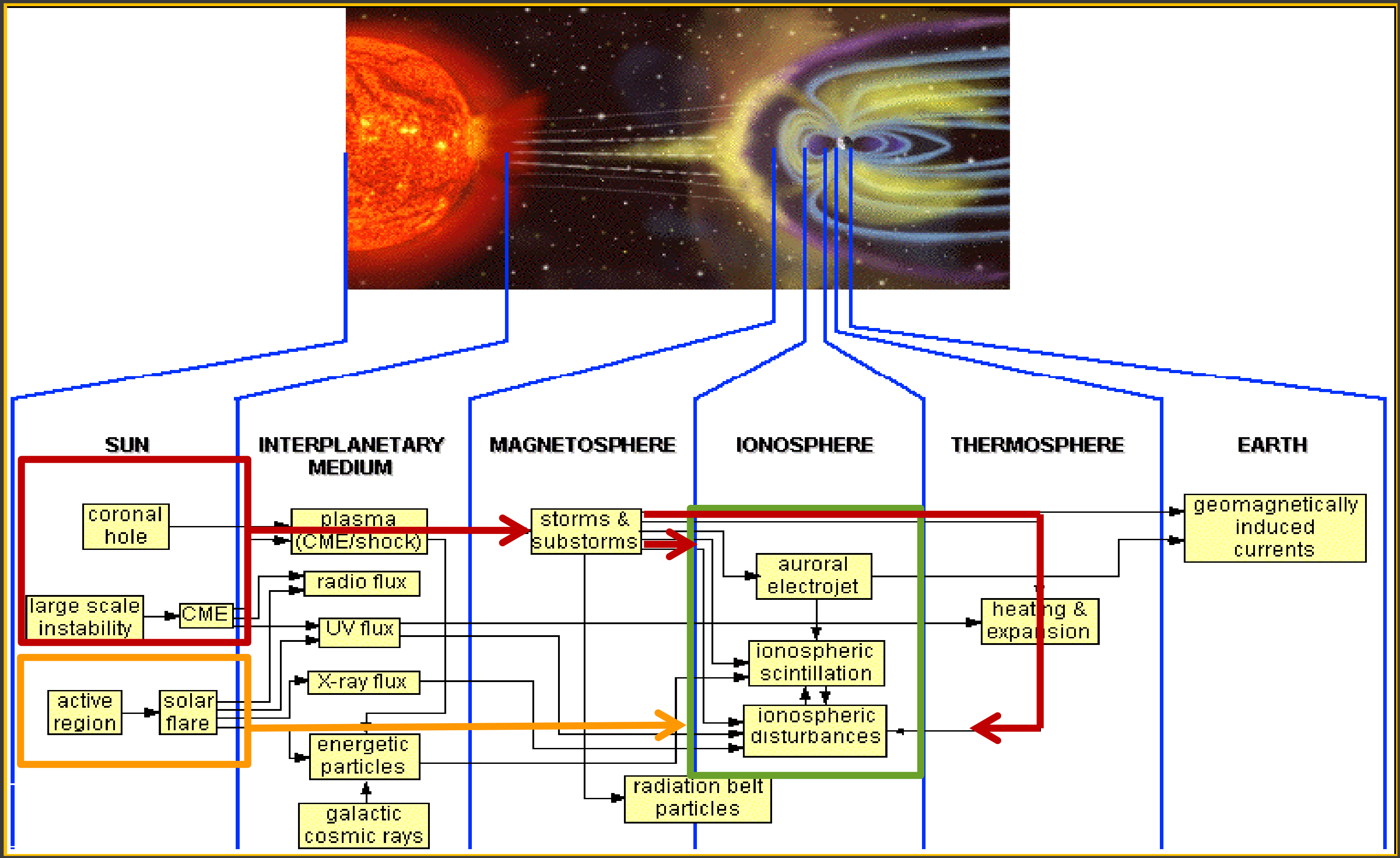
Electron density: changes over multiple timescales ranging from approximately minutes (e.g., solar flare effects) to solar cycle durations (~11 years).

Normal (e.g. diurnal, monthly, seasonal, solar cycle)

Transient (e.g. space weather effects often associated with seasonal and solar cycle timescales)

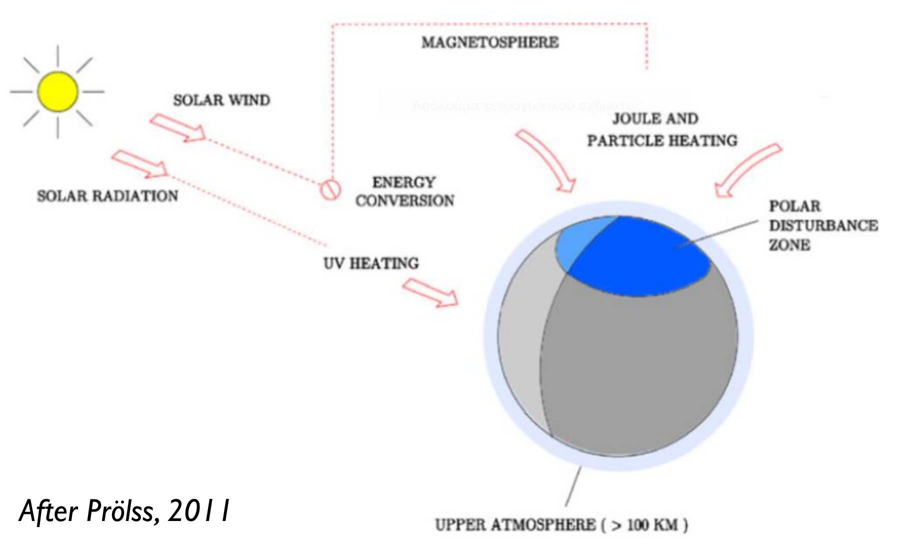
Space weather effects on the ionosphere

- Main physical processes that act on space weather *(Lathuillère et al., 2002)*



Solar wind impact

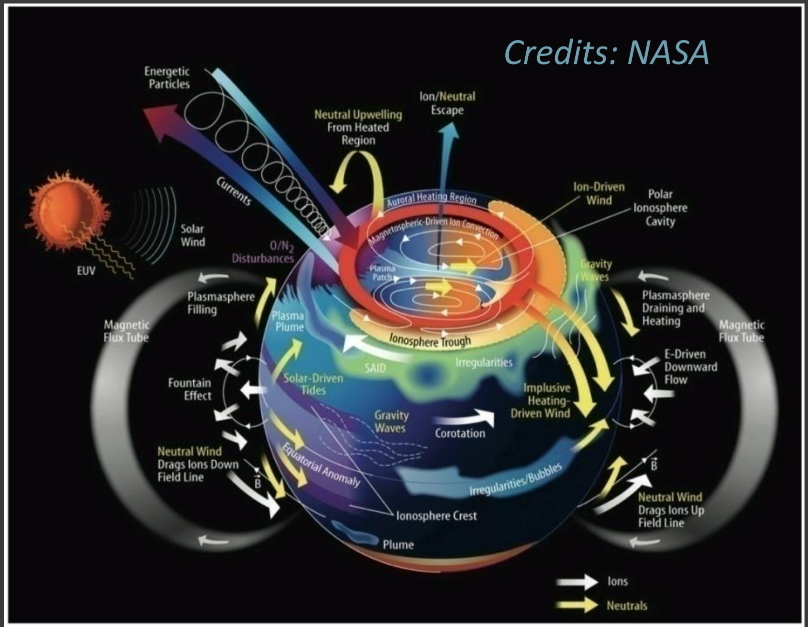
Driver: energy injection at high latitudes



After Prölss, 2011

1. Enhanced high-energy particle precipitation **[important at altitudes lower than F2 layer]**
2. Enhanced ionospheric electric currents and resulting Joule heating **[global importance]**
3. Enhanced electric fields predominantly of magnetospheric origin **[importance at higher latitude and penetrate to equatorial region]**
4. Frictional heating, primarily induced by enhanced magnetospheric convection **[importance at high latitudes]**

Thermosphere-Ionosphere –Plasmasphere interaction

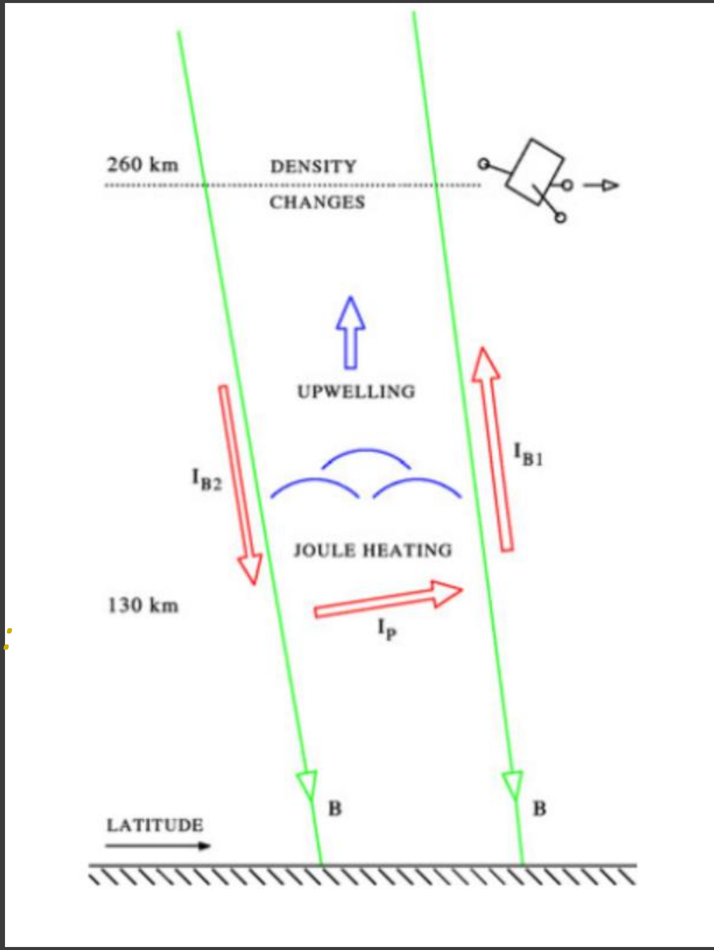


Thermodynamical, dynamical and chemical reactions such:

- Neutral composition changes
- Changes in the global wind circulation
- Travelling Atmospheric Disturbances (TADs)

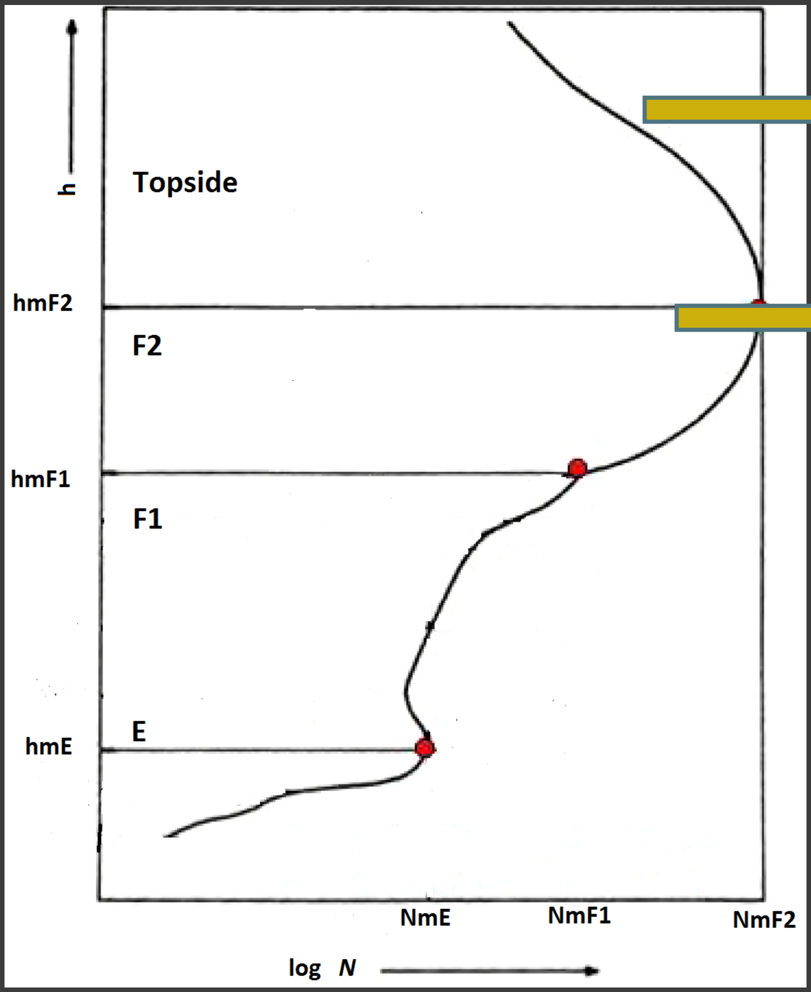
Electrodynamical processes such as:

- Penetration of electric fields of magnetospheric and interplanetary origin into the ionosphere
- Enhanced plasma fluxes from the plasmasphere



After Prölss, 2011

Relative importance with altitude



Electrodynamics: more important for changes at heights greater that the F2 layer maximum (Danilov, 2013).

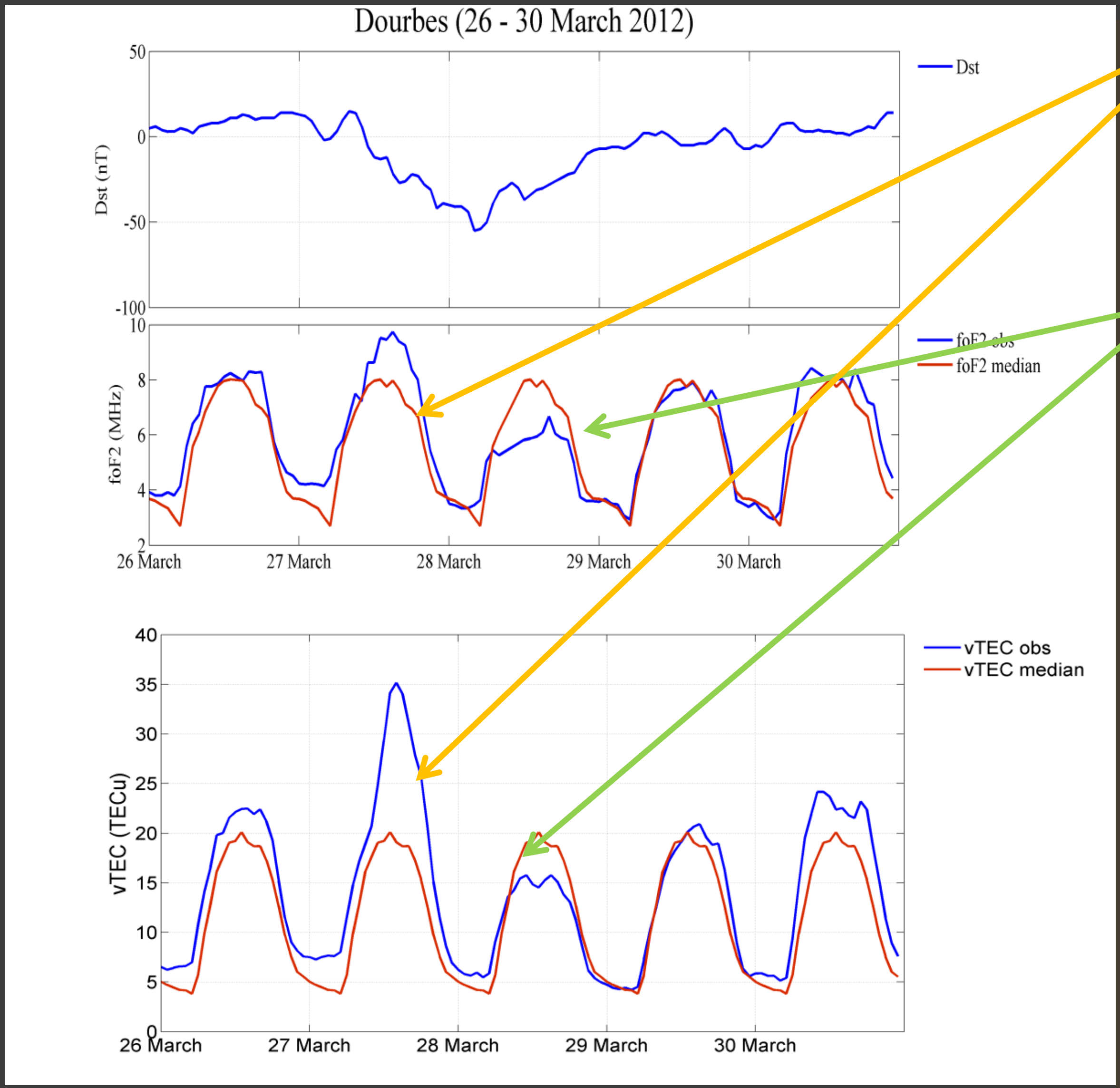
Thermodynamics: more important for changes at heights near the F2 layer maximum (Danilov, 2013).

Parameters of interest for large scale effects: NmaxF2 (or the foF2) and TEC

Total Electron Content (TEC): Integration over the entire ionospheric electron density profile.

- Maximum contribution from the F_2 layer, with approximately 2/3 of the TEC coming from regions above hmF2.
- For substantial effects in TEC, simple vertical redistributions of *F* layer plasma cannot be the main cause (Mendillo, 2006).

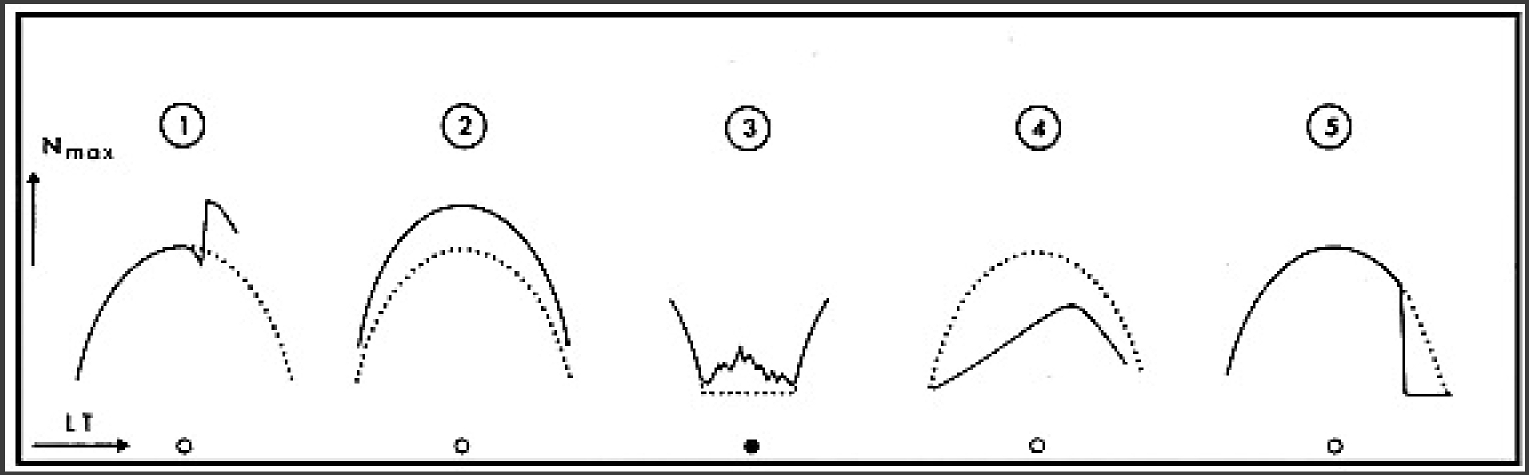
Ionospheric disturbances



Positive storm effects: increase in ionospheric ionization

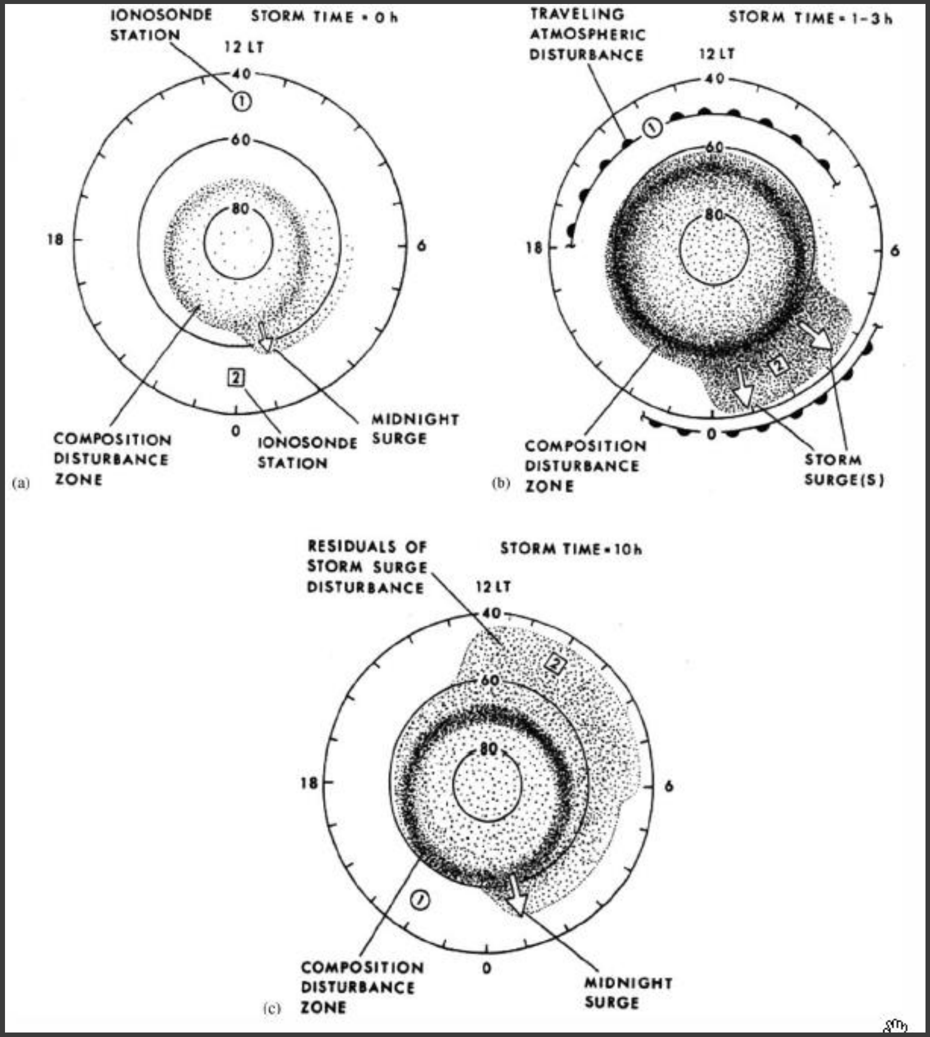
Negative storm effects: decrease in the ionospheric ionization below background conditions

Morphology of ionospheric disturbances



Types of ionospheric disturbances found during geomagnetic storms [from *Prölss*, 1995]. While intended to describe only winter storm effects in N_{max} at subauroral latitudes, this classification scheme is appropriate for the general characterization of TEC storm patterns in any season:
(1) magnetospheric convection-driven "dusk effect" in the positive phase, (2) wind-driven positive phase, (3) auroral precipitation-induced enhancement of the trough's poleward wall, (4) negative phase due to postsunrise convection effects plus longer-lived composition-induced depletions, and (5) termination of the dusk effect in item 1 via the convection-induced appearance of the trough (Mendillo, 2006).

Local-time dependence: Prölss phenomenological model (1993)



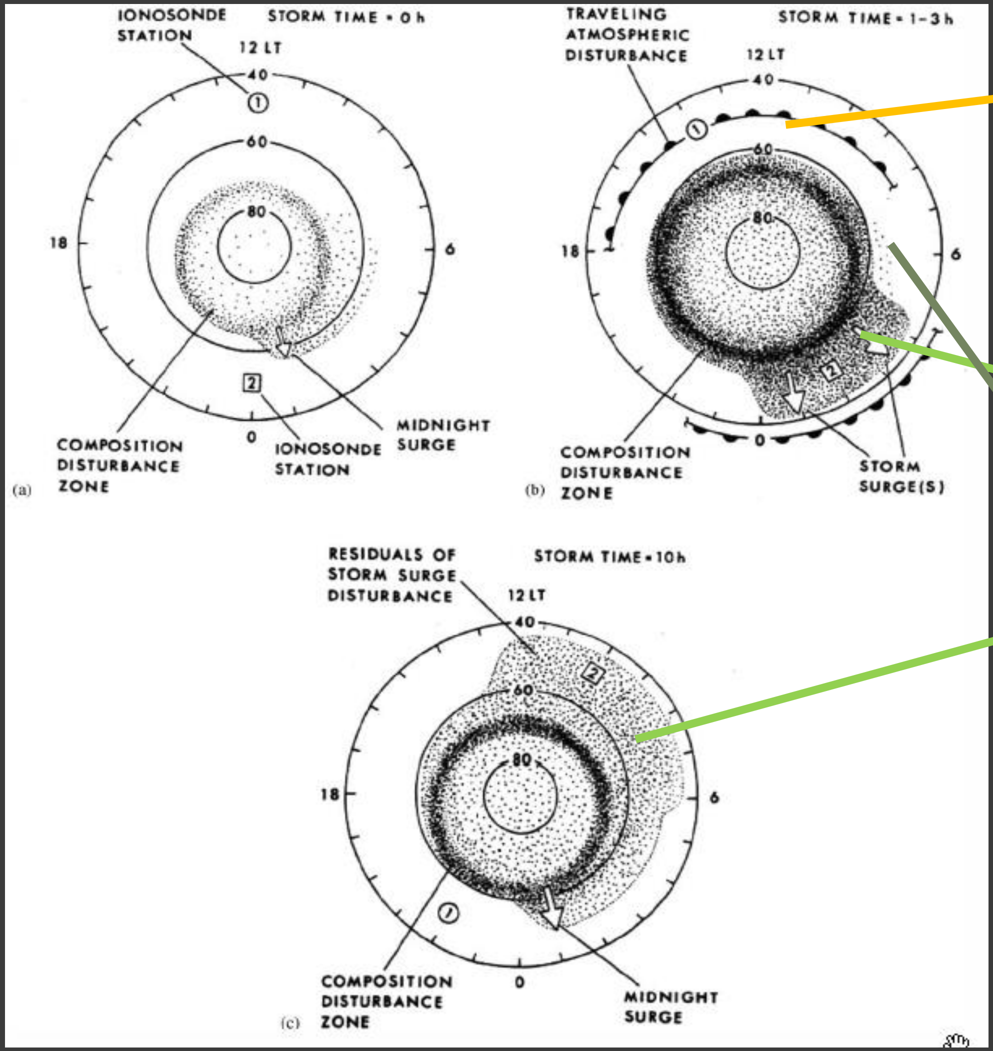
Negative storm effects:

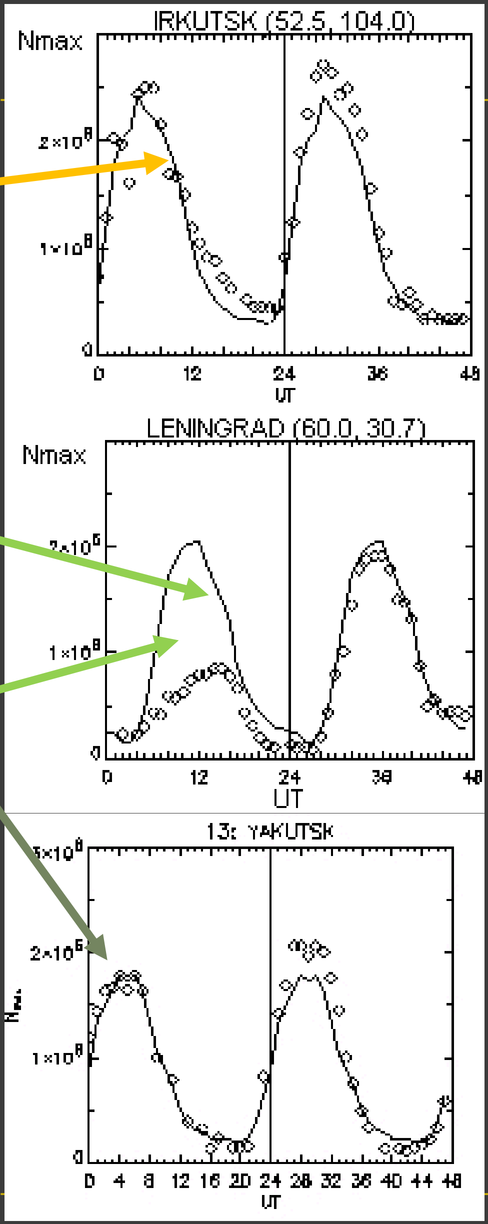
The negative phase is attributed to changes in the neutral gas composition due to heating of the thermosphere.

Positive storm effects:

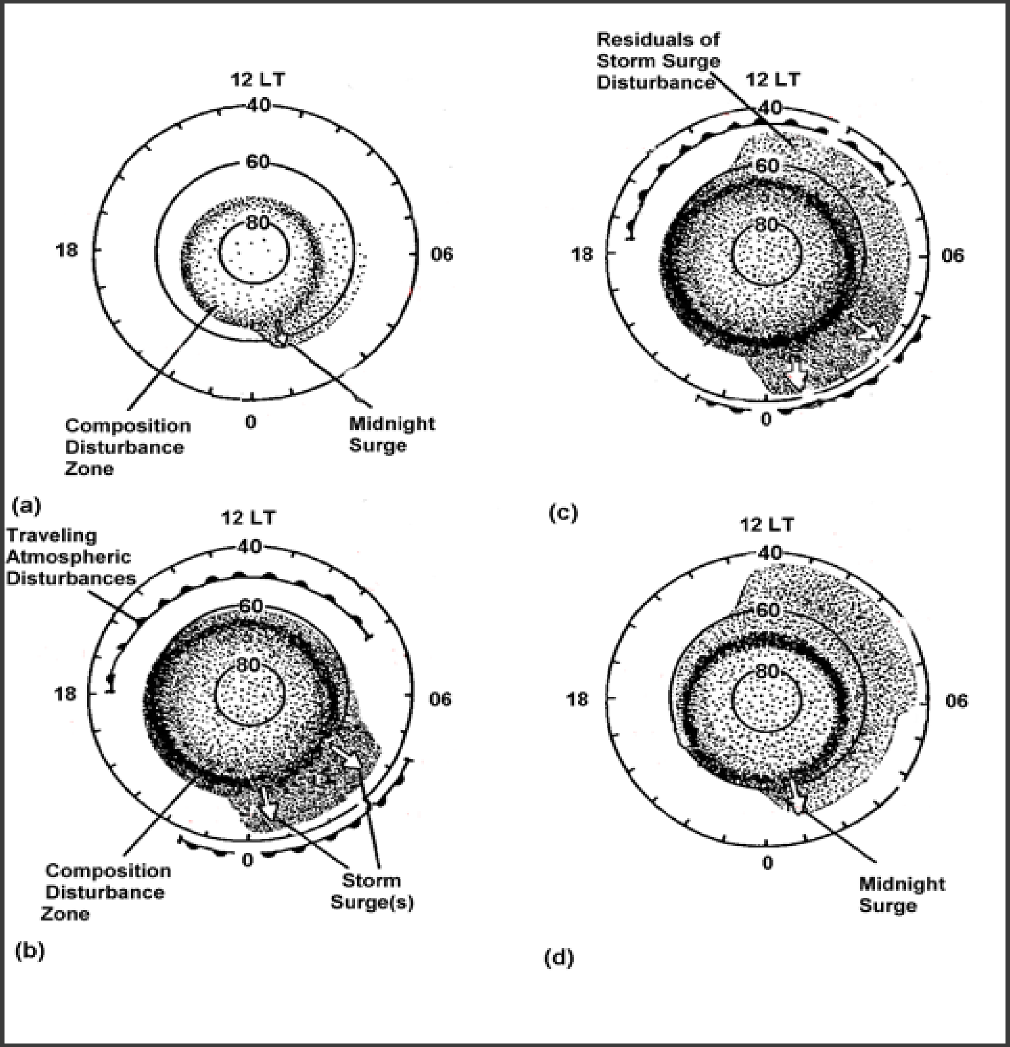
During the day TADs (Travelling Atmospheric disturbances) propagate from auroral zone to lower latitudes. The ionization is pushed upward along geomagnetic field lines. This results in an increase of hmF2 and an increase of NmF2 due to lower electron loss rate at higher altitudes. At night lack of ionization production diminishes their formation.

LT time dependence of ionospheric storm effects

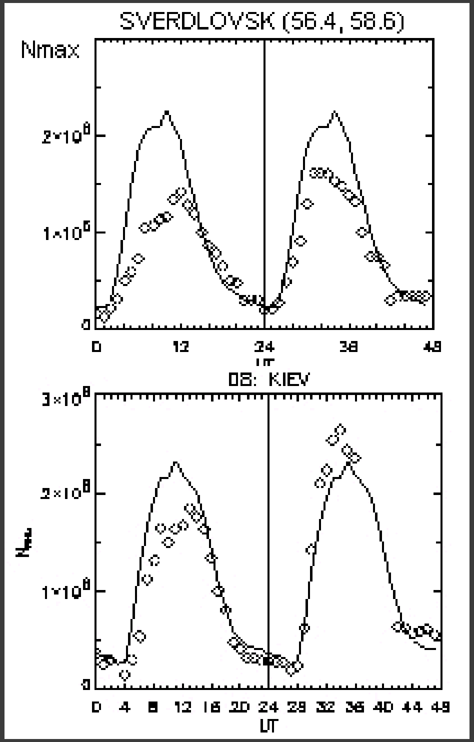




Successive storm events

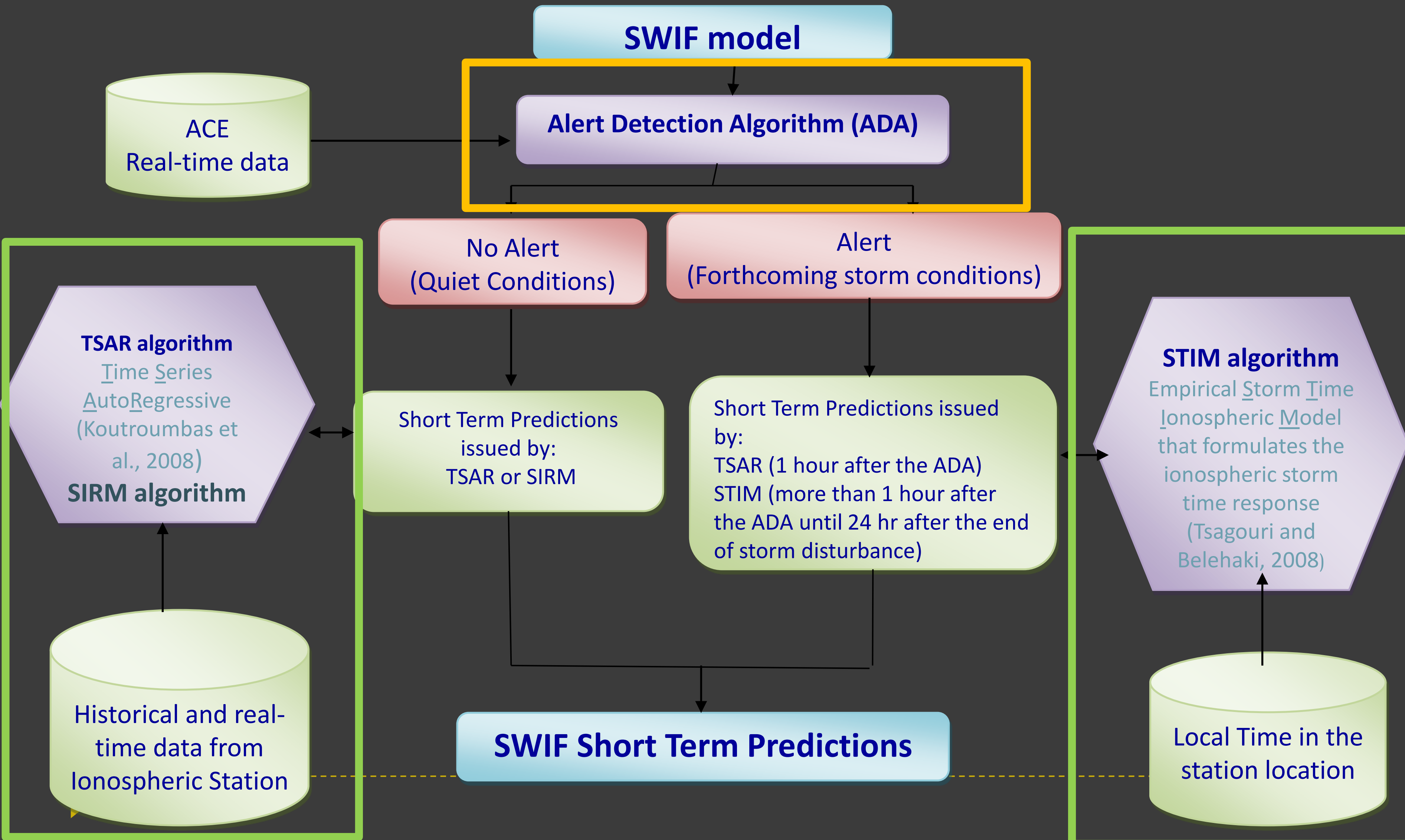


<u>Tsagouri et al.,</u> Positive and negative ionospheric disturbances at middle latitudes during geomagnetic storms,GRL, 2000



The Solar Wind driven autoregression model for Ionospheric short term Forecast (SWIF)

(Tsagouri et al., 2009; Tsagouri & Belehaki, 2008)

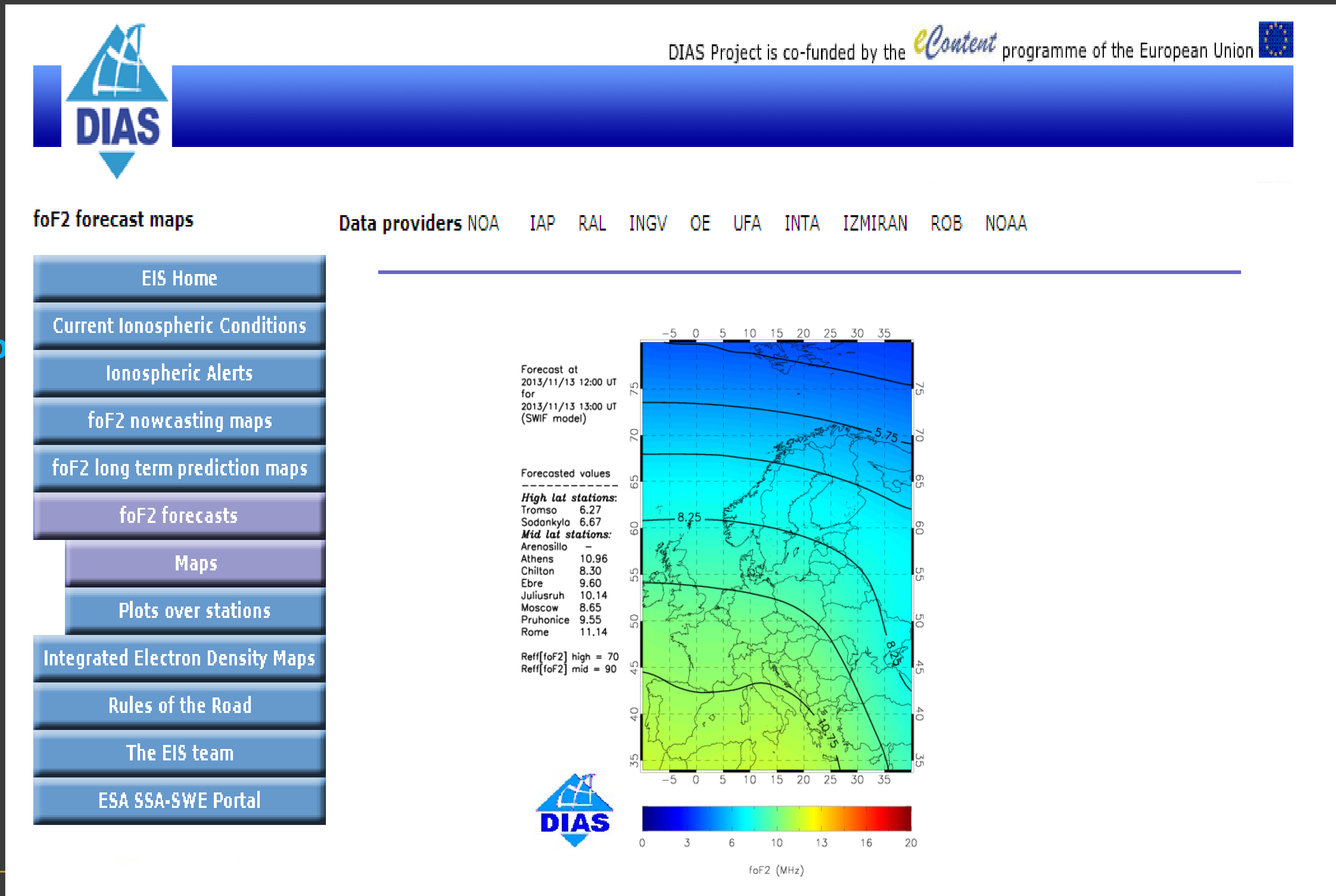


SWIF is implemented in DIAS (http://dias.space.noa.gr) to provide ionospheric forecasting services for DIAS and ESA/SSA (http://swe.ssa.esa.int/web/) users

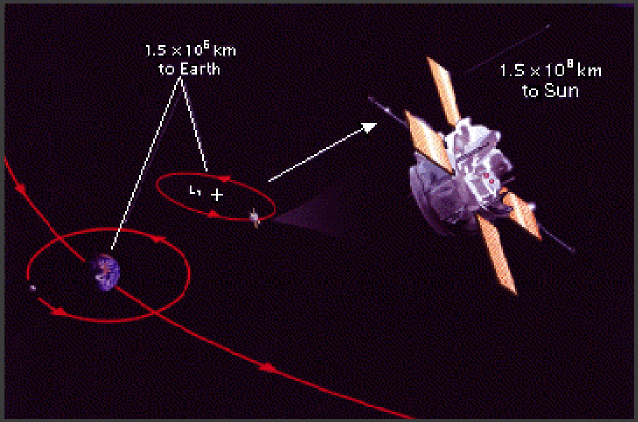
Alerts & Warnings

Single Site Forecasts (up to 24 ho ahead)

Regional maps for the whole Europe



SWIF's Storm component



The idea:

Use of IMF (Interplanetary Magnetic Field) parameters at L1 as proxy of the ionospheric activity level

Rate of the solar wind energy input into the magnetosphere (i.e., the energy coupling function between the solar wind and the magnetosphere) (Perreault and Akasofu, 1978):

$$\varepsilon = V B^2 \sin^4(\theta/2) l_0^2,$$

where l_0 is 7 R_E , B is the magnitude of the IMF, and θ is the IMF clock angle defined as

$$\begin{aligned} \theta &= \tan^{-1}(|By/Bz|) & \text{for} \quad Bz > 0 \\ \theta &= 180° - \tan^{-1}(|By/Bz|) & \text{for} \quad Bz < 0. \end{aligned}$$

SWIF's Storm component

IMF-B and Bz good indicators of the solar wind energy input in the magnetosphere.

- **Alert Detection Algorithm**

  Quantitative criteria to

  IMF-B (Total magnitude and rate of change)

  IMF-Bz component

The criteria were determined through empirical tests (superimposed epoch analysis) and literature investigation. Emphasis in intense F region storm conditions.

- **STIM's formulation of the ionospheric storm time response:** empirical expressions to provide a correction factor to the background variation based on the latitude of the observation point and its local time at the storm onset at L1 point (superposed epoch analysis):

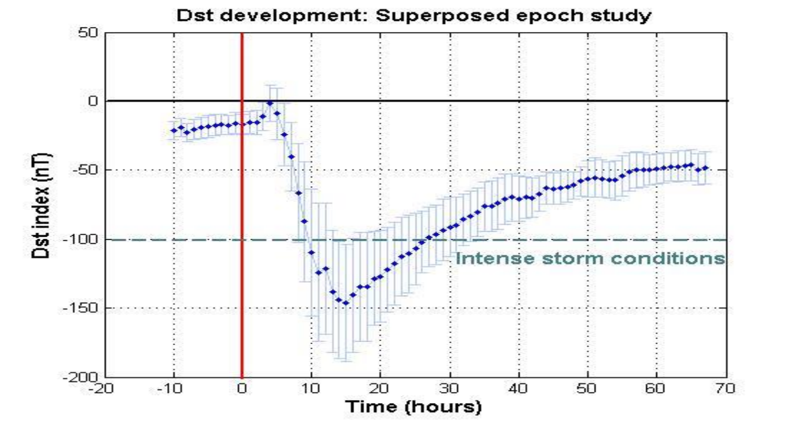
  - Two latitudinal (middle latitude) zones (greater or less than 45°)
  - Four local time sectors: Morning (02 – 06 LT); Prenoon (06 – 12 LT); Afternoon (12 – 18 LT); Evening (18 – 02LT)

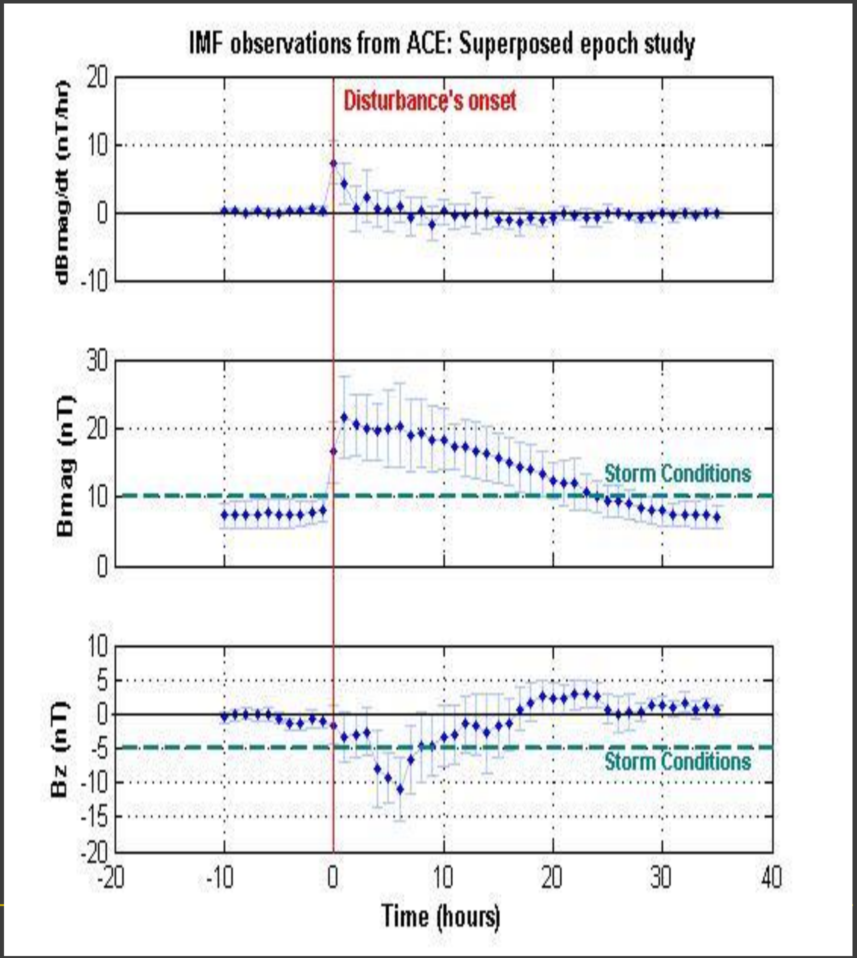
SWIF’s alert

(i) The IMF–B should record either a rapid increase denoted by time derivative values greater than 3.8 nT/h or absolute values greater than 13nT.

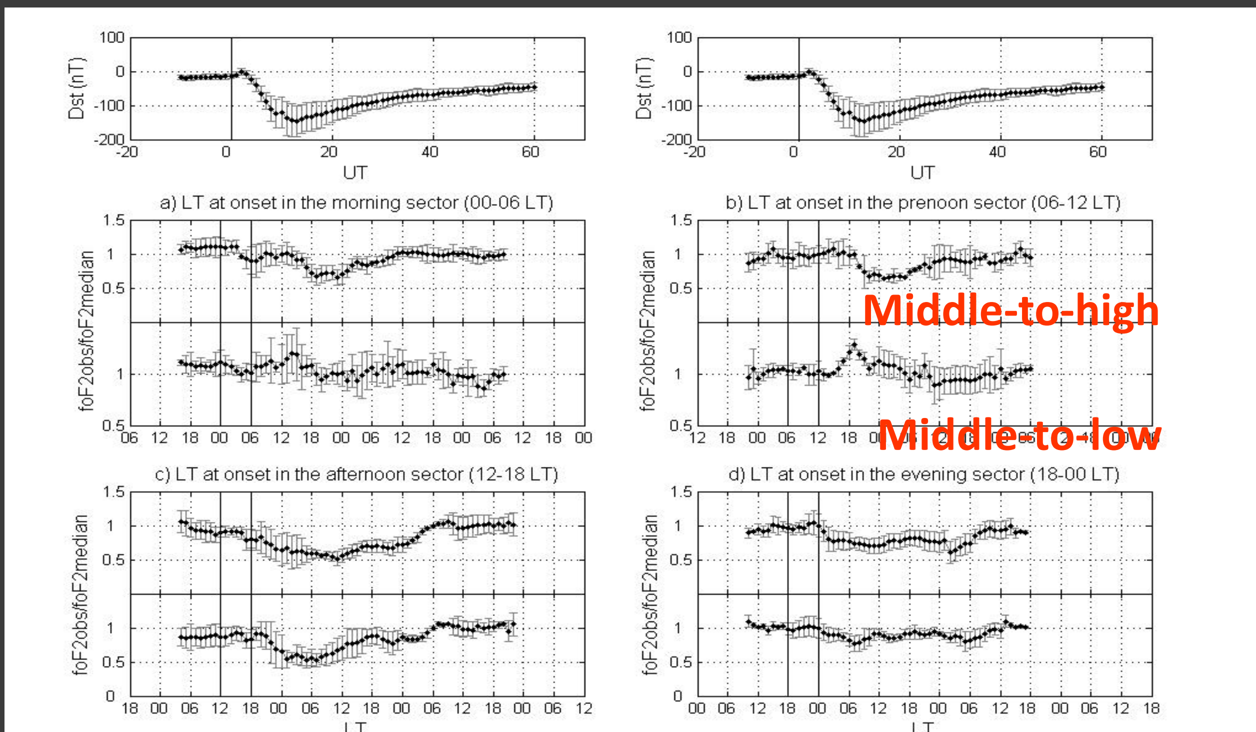
(ii) The IMF–Bz component should be southward directed either simultaneously or a few hours later. Intense storm conditions (Bz<-10nT for at least 3h)

(e.g. Gonzalez and Tsurutani, 1987; Tsurutani and Gonzalez, 1995)





SWIF: ionospheric storm time response

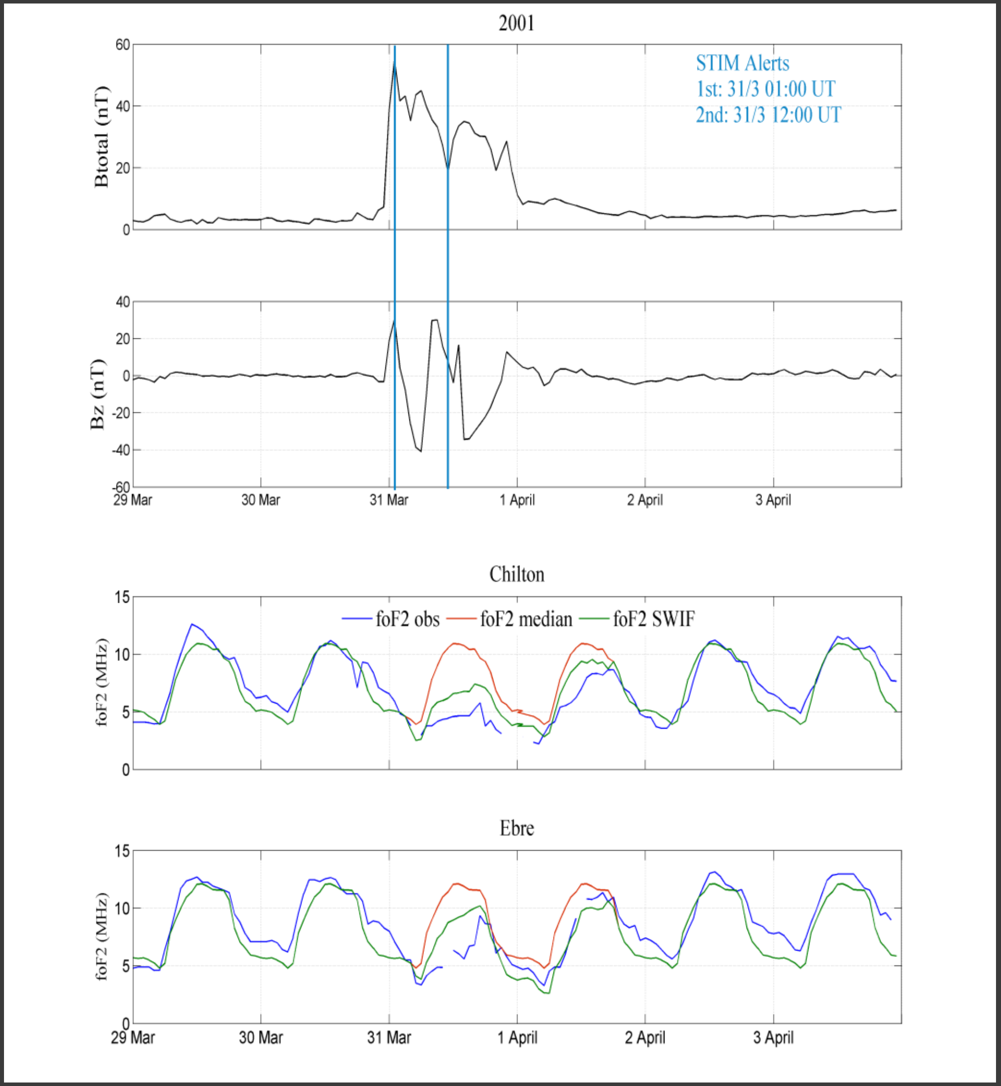


Ionospheric response to the storm events: consistent with Prölls phenomenological scenario [Prölls (1993)]

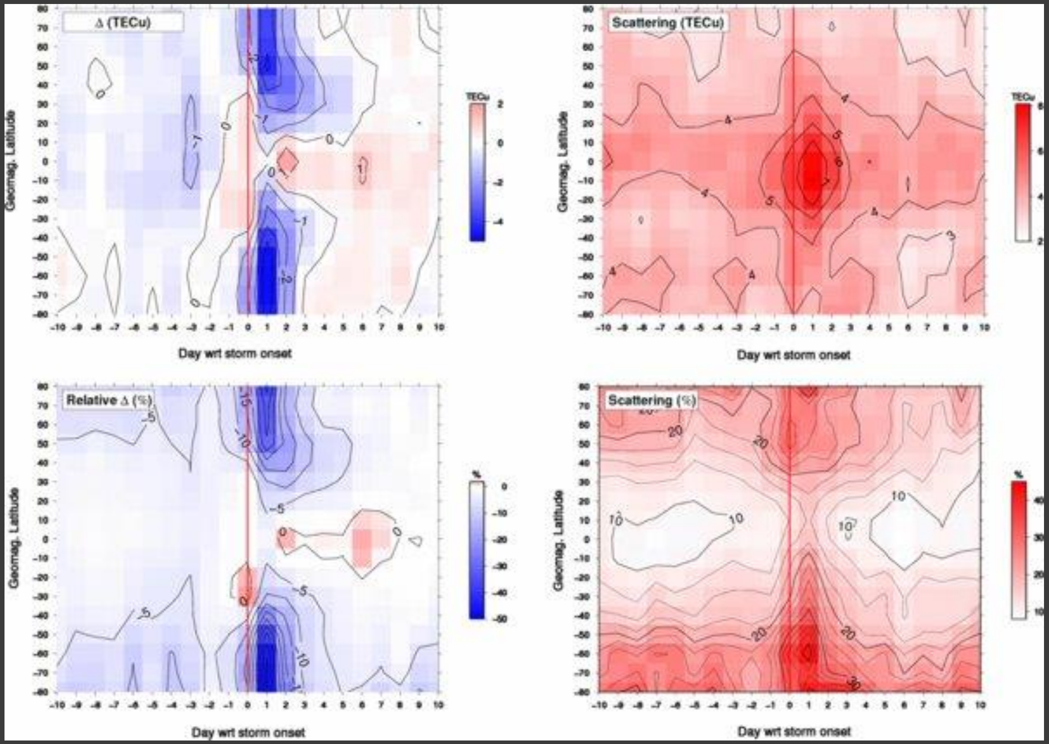
High and Middle to High latitudes: negative storm effects

Middle to Low latitudes: negative storm effects in the night-side hemisphere and positive storm effects for daytime.

29 March – 3 April 2001



SWIF for TEC storm time response (solar cycle 23)

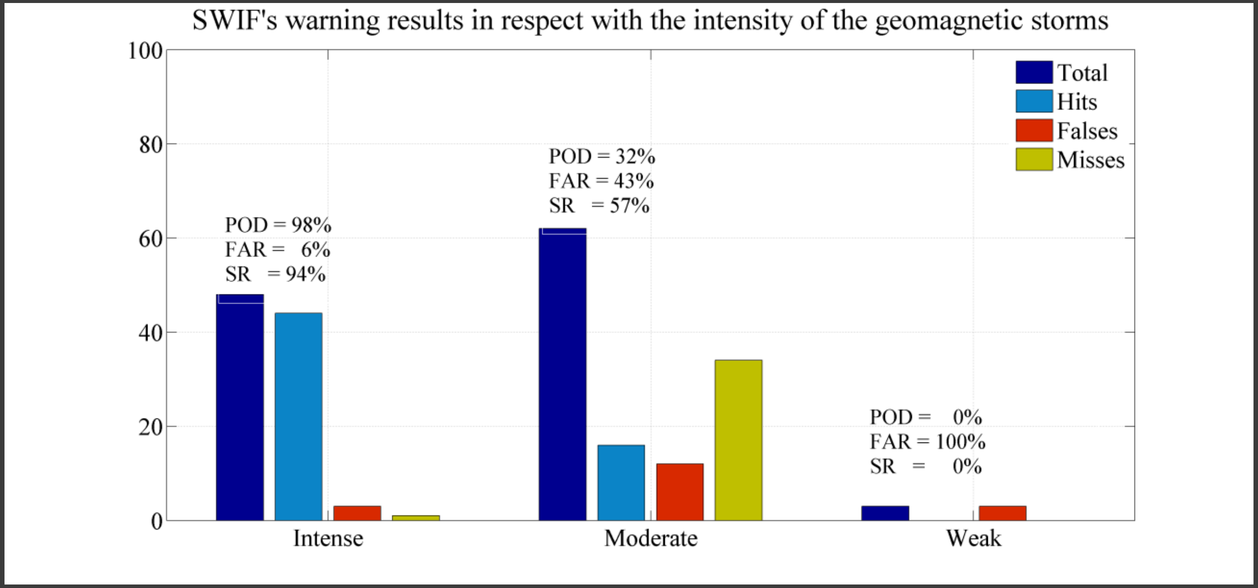


The storms significantly affect the TEC mainly at high latitudes, with a loss of ionization with respect to the climatological model. The peak of the ionization depletion is detected one day after the onset, which becomes negligible 3–4 days after the onset. A slight increase in the TEC with respect to climatology is observed at low latitudes (Bergeot et al., 2013).

Mean effect of geomagnetic storms on climatological TEC for a period of 20 days around the onset. *Top left*: mean differences (Δ) between the modelled and observed LDM-TEC in TECu. *Top right*: scattering of the differences. *Bottom left*: mean relative differences (scaled by the observed) in percentage. *Bottom right*: scattering of the relative differences. The red line is day of the detected onset of the storms.

Validation tests: SWIF 's prediction efficiency

(Tsagouri, 2011; Tsagouri and Belehaki, 2015)



Intense storm events (min Dst < - 100 nT) are successfully predicted by SWIF

Poorer performance is recorded under the occurrence of moderate storm events

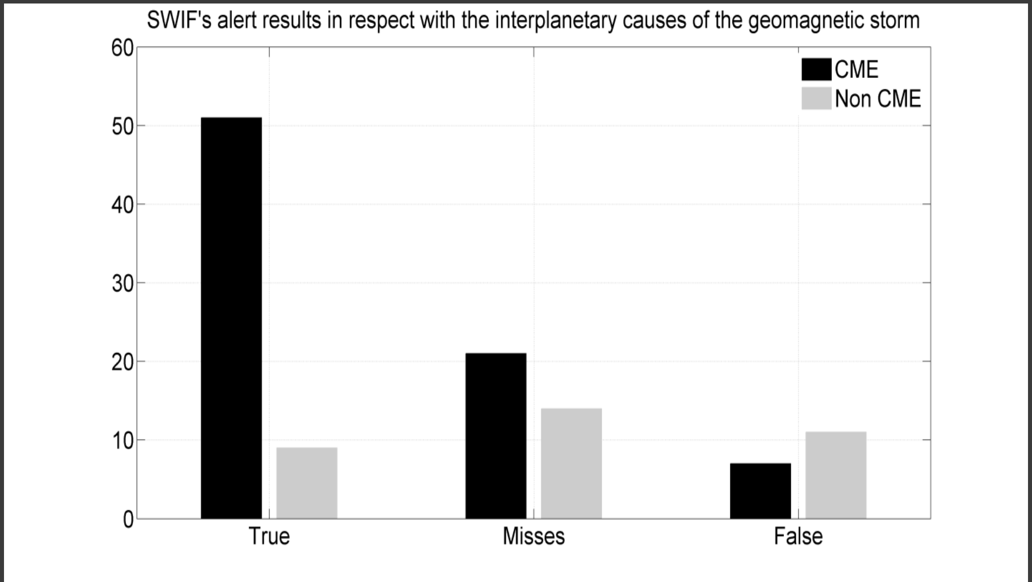
Metrics:

- *Probability of Detection: POD = A / (A + C)*
- *False Alarm Rate: FAR = B / (A + B)*
- *Success Ratio: SR = A / (A+B)*

where: A the number of true alerts or hits (ionospheric storm time disturbances over Europe were forecast and did occur) ; B the number of false alarms (ionospheric storm time disturbances over Europe were forecast but not occurred); and C the number of missed events (ionospheric storm time disturbances were not predicted but did occur).

Validation tests: SWIF 's prediction efficiency

(Tsagouri, 2011; Tsagouri and Belehaki, 2015)



The results show that the majority of **hits or true alerts** are received under the occurrence of storms related with **interplanetary CME** signatures (usually intense storms). **False alarms** tend to be related with **non-CME structures**, while such structures are related also with a significant number of **misses** (usually storms of moderate intensity).

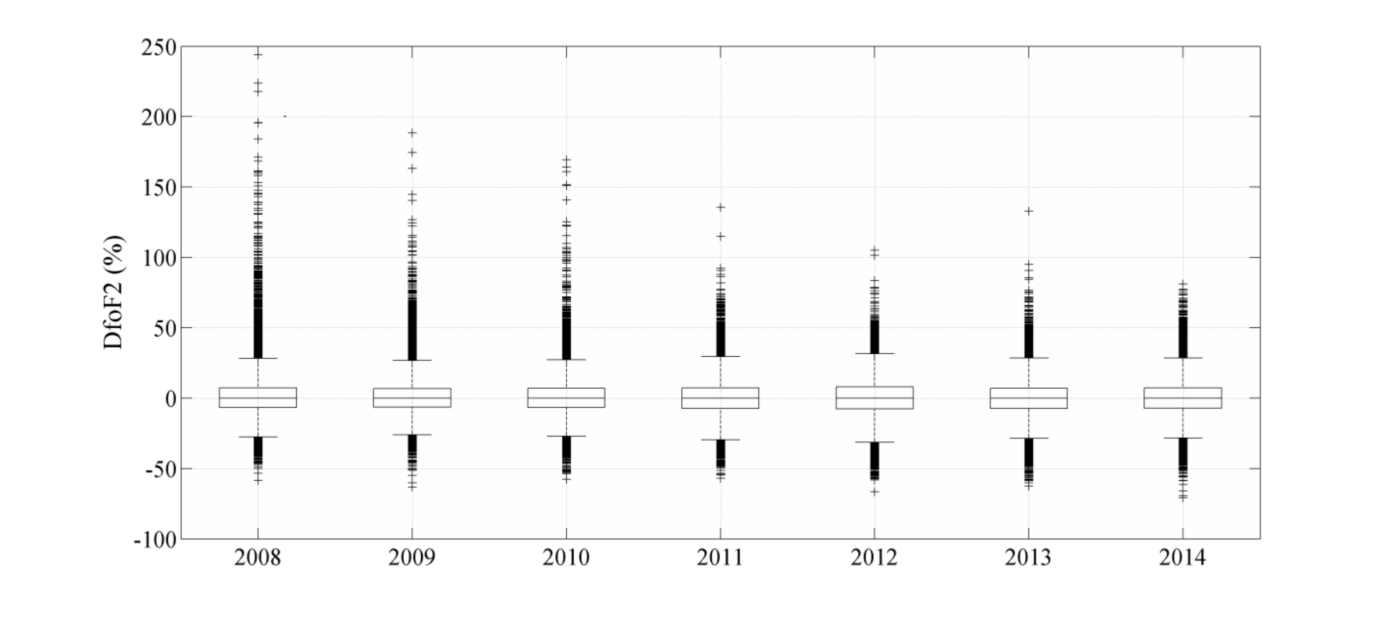
This result indicates that the ionospheric effects for storms of different interplanetary cause should be studied separately for ionospheric forecasting purposes

CME: *Storms related to CME-associated solar wind flows (e.g., sheath fields or the ejecta itself) in the near-Earth solar wind*

Non CME: *storms not related to such structures. The latter may be associated to other sources of disturbances, e.g., Corotating Interaction Regions (CIRs) and pure High Speed Streams (HSSs).*

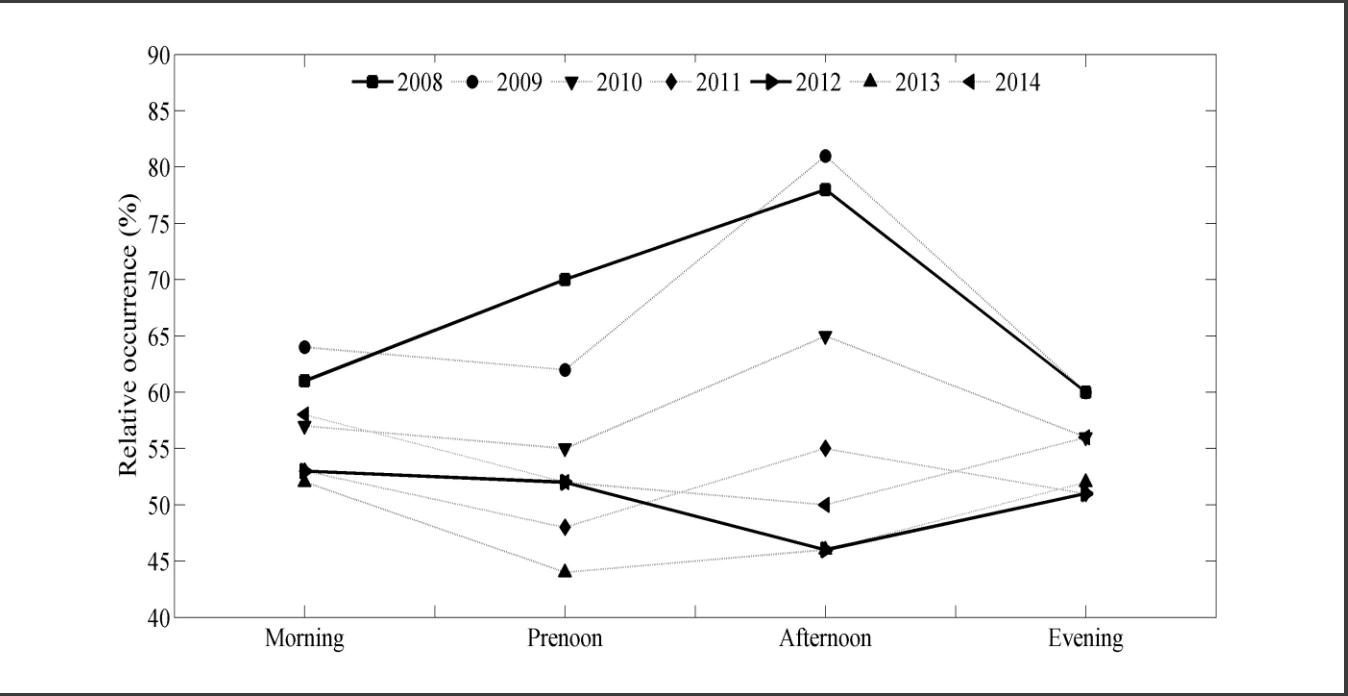
The different cases were distinguished through the examination of the list of ICMEs that is available at http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm (Richardson and Cane, 2010).

Long term predictions of space weather effects in the ionosphere during solar cycle 24 over Europe *(Tsagouri et al., 2016)*



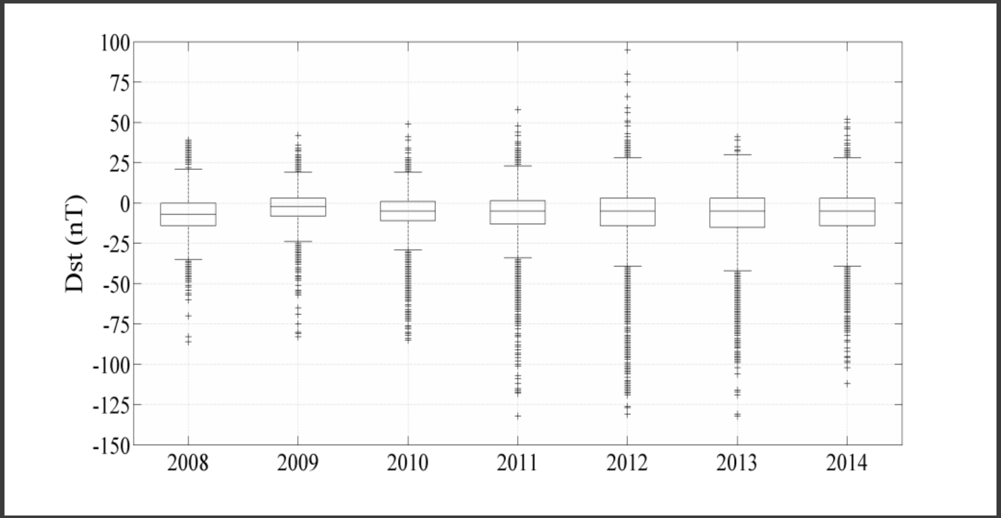
There are noticeable qualitative and quantitative differences in the ionospheric response between solar minimum and solar maximum conditions: the disturbances tend to be positive during solar minimum conditions (i.e., 2008), while both negative and positive disturbances are observed towards solar maximum in all latitudes.

Long term predictions of space weather effects in the ionosphere during solar cycle 24 over Europe *(Tsagouri et al., 2016)*

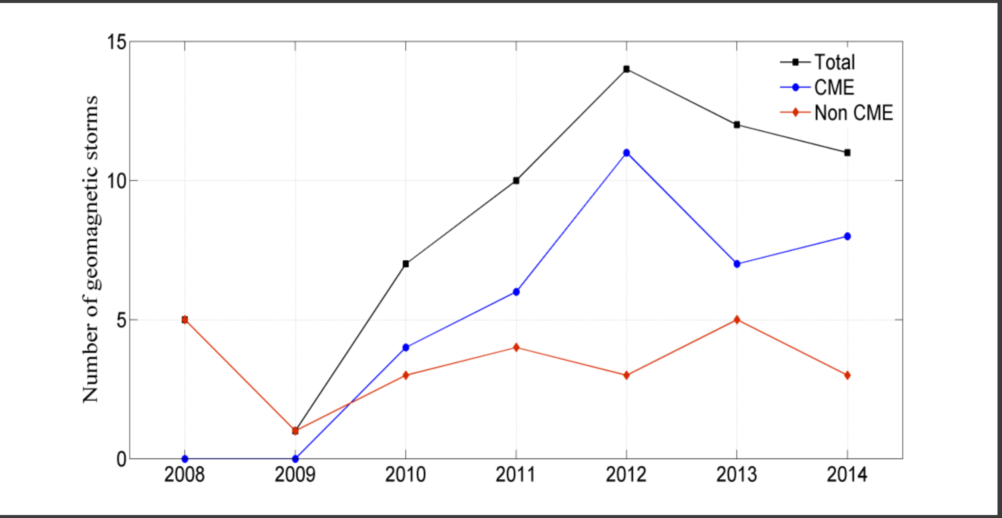


Relative occurrence of positive deviations versus local time: during solar minimum years the occurrence of positive deviations increases from the morning to the prenoon sector and peaks in the afternoon sector. In contrary, positive and negative deviations are almost equally observed in most cases in 2012, while a shallow minimum is recorded in the afternoon sector for the occurrence of positive disturbances.

Long term predictions of space weather effects in the ionosphere during solar cycle 24 over Europe *(Tsagouri et al., 2015)*



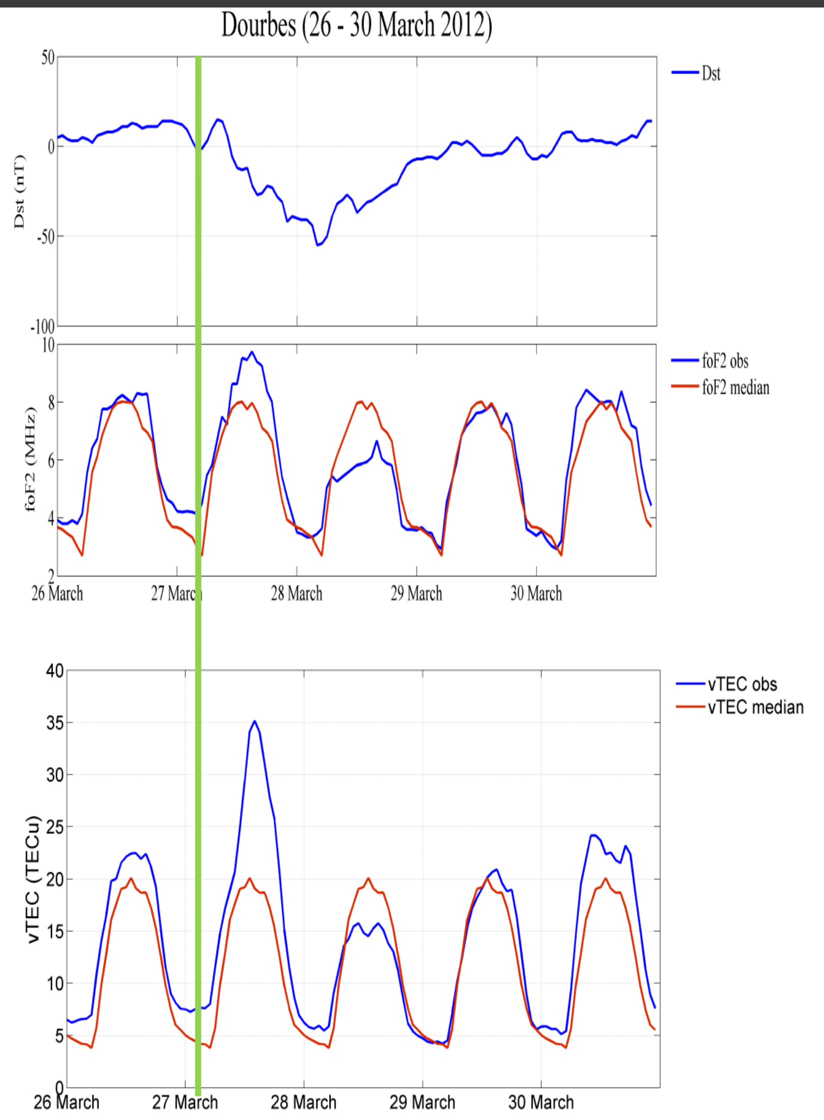
Solar minimum conditions are related to weak-to-moderate geomagnetic activity (-100 nT < minDst), while solar maximum conditions are related to intense geomagnetic disturbances (minDst < -100nT).

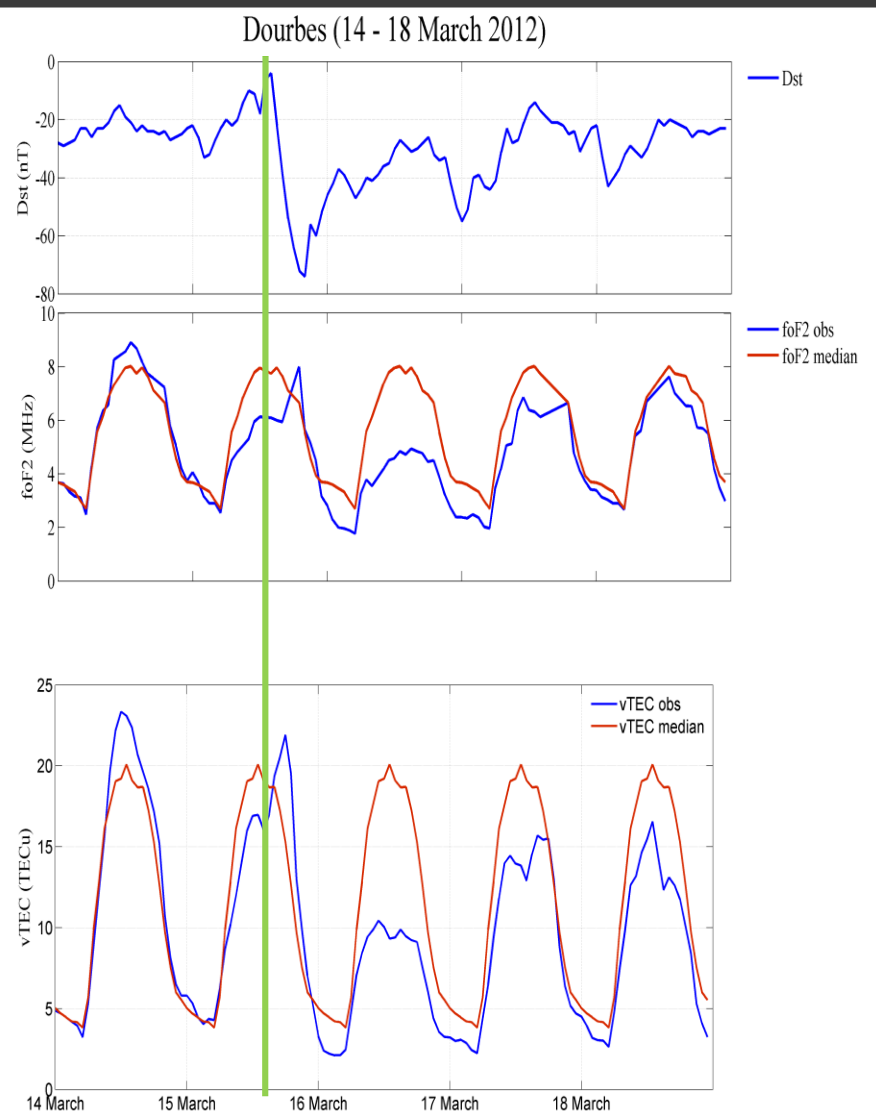


The storm activity during solar minimum (i.e., 2008) is related entirely with non CME events (mainly HSSs), while the storm activity towards the solar maximum is mainly driven by CMEs.

Non – CME*

CME*





http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm

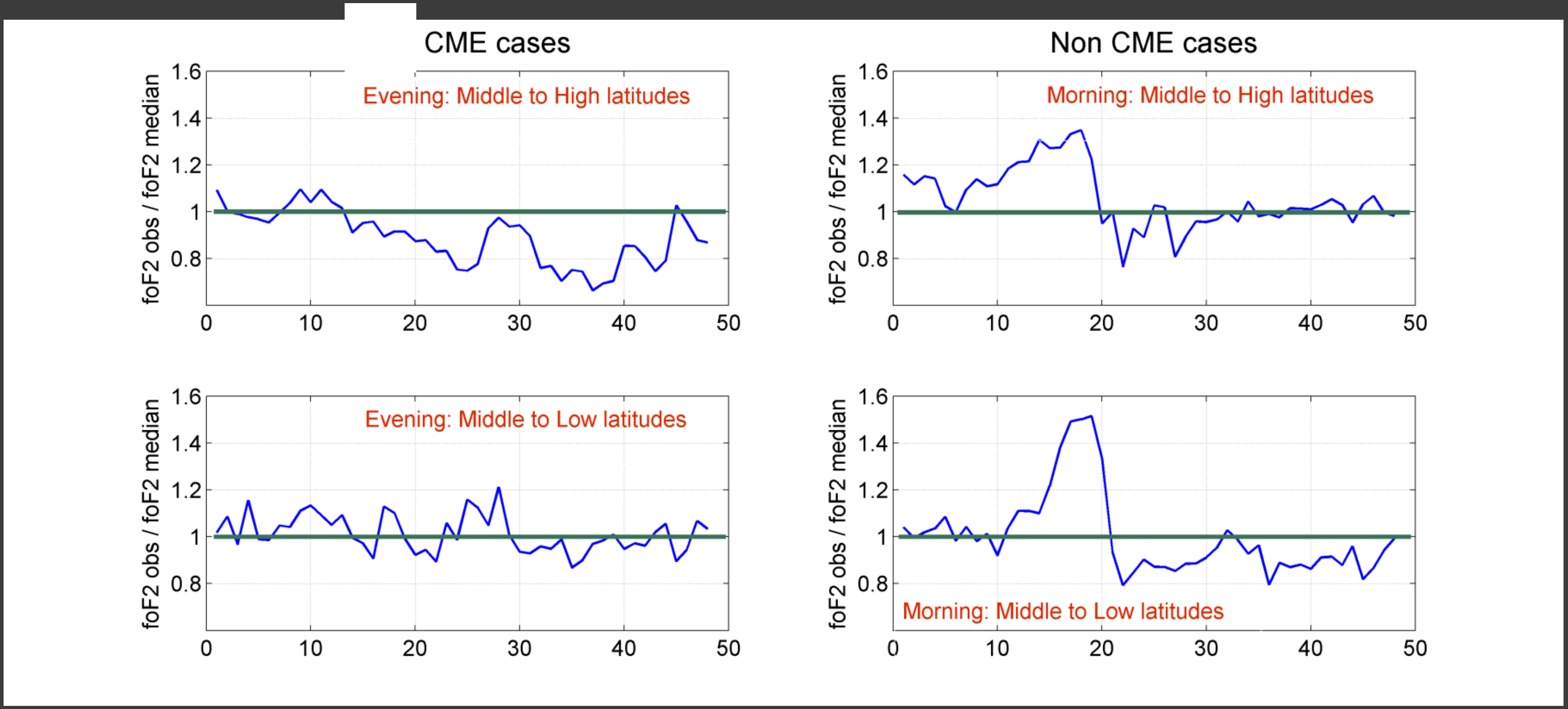
Ionospheric forecast: further developments

Storm events analyzed

Storm time interval	SWIF alert (Date and Time in UT)	Min Dst (nT)	SWIF result	Storm Driver
6 – 8 August 1998	6 August 07:00	-138	True	CME
27-29 August 1998	27 August 06:00	-155	True	CME
24 – 29 September 1998	25 September 22:00	-207	True	CME
13 -15 January 1999	13 January 12:00	-107	True	CME
16 – 18 April 1999	16 April 22:00	-90	True	CME
22 – 25 September 1999	22 September 17:00	-173	True	CME
21 – 25 October 1999	21 October 20:00	-237	True	CME
6 – 8 April 2000	6 April 16:00	-288	True	CME
23 – 26 May 2000	23 May 23:00	-147	True	CME
15 – 18 July 2000	15 July 16:00	-301	True	CME

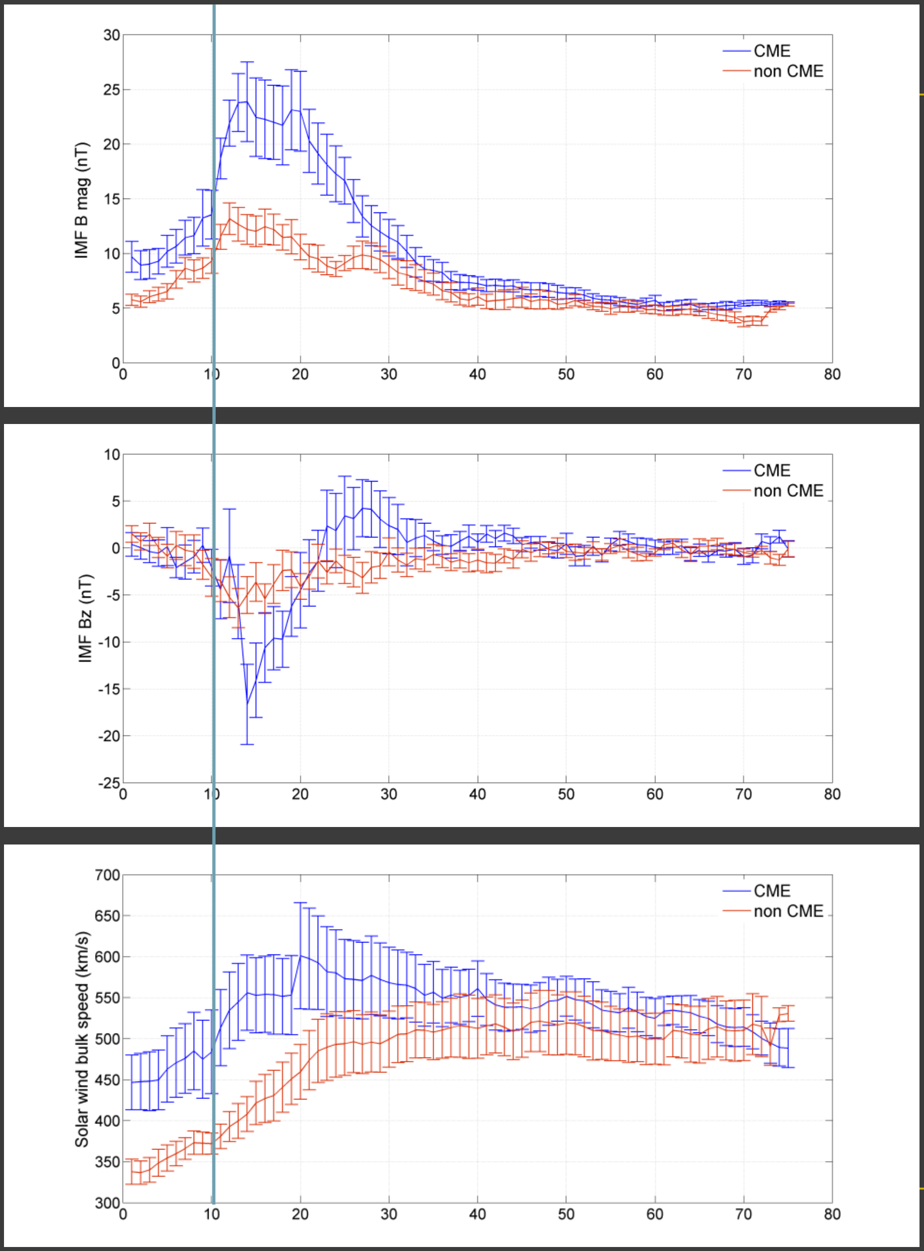
Storm time interval	SWIF alert (Date and Time in UT)	Min Dst (nT)	SWIF result	Storm Driver
2 – 4 May 2010	-	-66	Miss	Non CME
10 – 12 March 2011	-	-83	Miss	Non CME
31 Oct – 2 Nov 2011	-	-72	Miss	Non CME
30 – 31 October 2013	-	-52	Miss	Non CME
8 December 2013	-	-66	Miss	Non CME
28 – 30 August 2000	-	-60	Miss	Non CME
23 -25 April 1998	-	-69	Miss	Non CME

Ionospheric response: superposed epoch analysis



In non-CME cases the ionosphere is open to the increase in ionization especially in the Afternoon sector.

Interplanetary conditions (superposed epoch analysis)



<u>CME:</u>

B > 13 nT for both cases (compatible with SWIF's specifications)

dB/dt: 1.7 nT/h

<u>Non CME:</u> B > 13 nT for both cases (compatible with SWIF's specifications)

dB/dt: 1.7 nT/h

<u>CME:</u> IMF-Bz < -10 nT for at least 3 hours (compatible with SWIF's specifications)

<u>Non CME:</u> IMF – Bz southward directed (up to -5 nT) for several hours – highly fluctuating

<u>CME:</u> rate of bulk speed increase per hour: 10 km/h

<u>Non CME:</u> rate of bulk speed increase per hour: 8 km/h

Comparable between the two cases – Further consideration in SWIF

Summary & Conclusions

The ionospheric storm response depends on the interplanetary drivers of the geomagnetic storms:

In non CME cases (e.g., storms driven by CIRs/HSSs) the energy dissipation in the upper atmosphere tends to increase the ionospheric ionization especially in the afternoon sector.

The ionospheric effects that accompany the CME driven storms are satisfactorily captured by current ionospheric prediction models, operational and phenomenological. Substantial improvements in our prediction ability will be driven by the better description of the ionospheric response to storm events driven by CIRs/HSSs:

- More efficient proxies for warning purposes, especially within operational environments:
  efficiency of solar wind parameters (i.e., IMF and solar wind bulk speed)
- More sophisticated formulation of the storm effects:
  dependence on LT

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