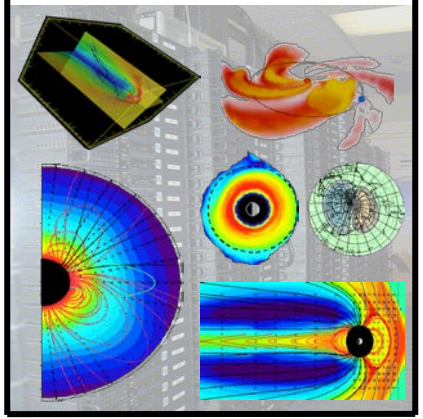


Quantifying the Effects of of Geomagnetic Storms on foF2 and TEC

Ja Soon Shim[1*], Ioanna Tsagouri[2], Larisa Goncharenko[3]
Lutz Rastaetter[4], Maria M Kuznetsova[4]
Modelers: Ionosphere/Thermosphere Models hosted at Community Coordinated Modeling Center

1. CUA/NASA GSFC, Greenbelt, MD, USA,
2. National Observatory of Athens, Greece
3. MIT Haystack Observatory, Westford, MA. USA
4. NASA/GSFC, Greenbelt, MD, USA,

NASA Goddard Space Flight Center **http://ccmc.gsfc.nasa.gov**

Outline

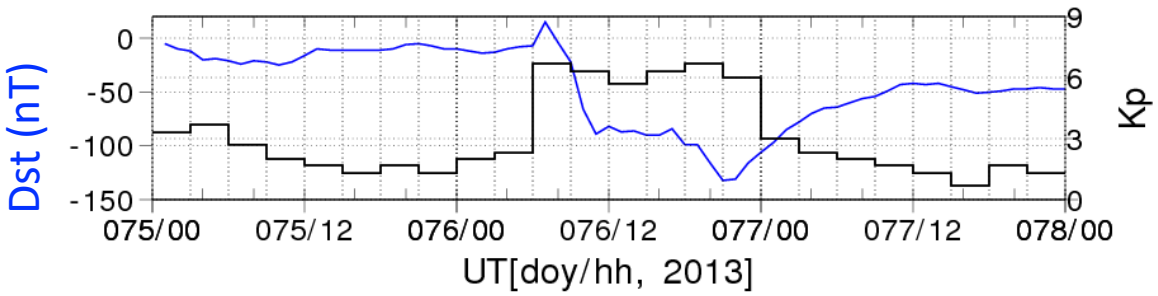
- Quiet-time background references
- Quiet-time foF2 and TEC variations
- foF2 and TEC changes
- Model/data comparison
- Summary
- International Forum for Space Weather Modeling Capabilities Assessment

TEC and foF2 at 10 Ionosonde Stations

- 4 stations from US, 4 from Europe and 2 from South America to investigate:
  - latitude and local time dependence
  - hemispheric asymmetry

- Observations:
  - foF2 data from the Global Ionosphere Radio Observatory (GIRO)
  - GPS vertical TEC data from MIT Haystack Observatory (error < 4TECU)

2013 March Storm Event: GEM-CEDAR Event

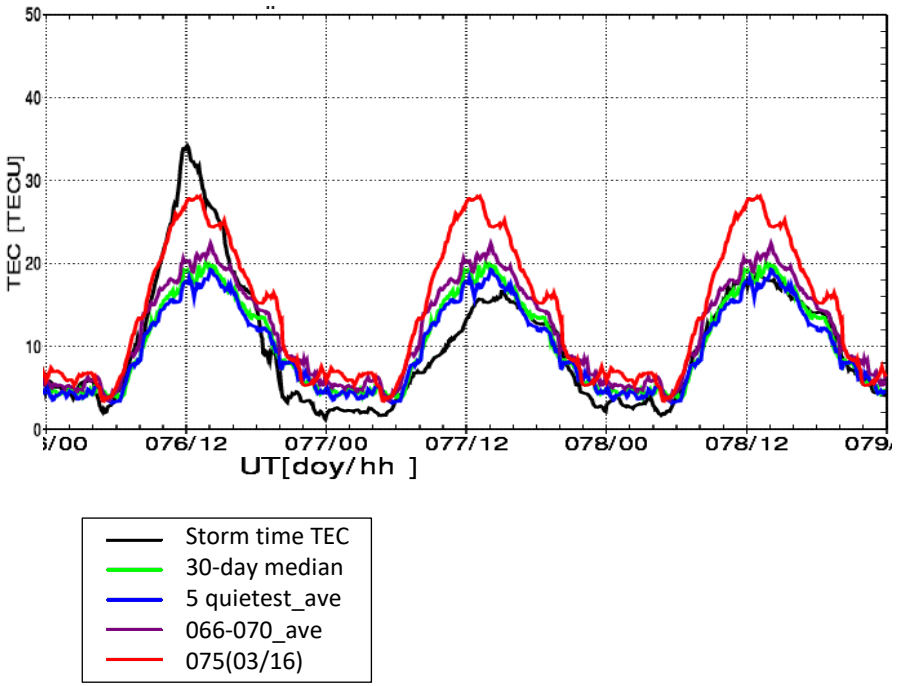


Quiet-time References:

- one day before the storm onset (doy 075)
- mean of five consecutive days before the storm onset (doy 060-070)
- mean of five quietest days within 30 days prior to the storm (based on daily Kp, Dst, and AE)
- median of 30 days prior to the storm

TEC: Comparison of Four Backgrounds

Chilton (359.4E, 51.5N)



- The backgrounds are repeated across 3 days of the storm event.
- TEC of one day prior to the storm (red line) is larger than other references.
- 30-day median (green) and the mean of the 5 quietest days (blue) are more suitable.

- Ionosphere-thermosphere model simulations also show similar features (not shown here).

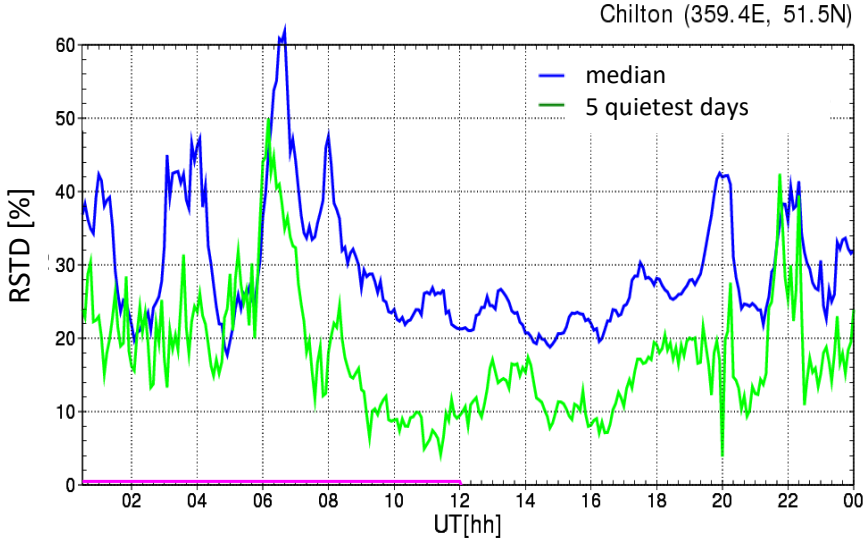
Quiet-time TEC variations

- Relative STandard Deviation:

  RSTD = (STD_TEC_x /TEC_x)*100

  x: median; average over the 5 quietest days

- RSTD is estimated over each time of the day



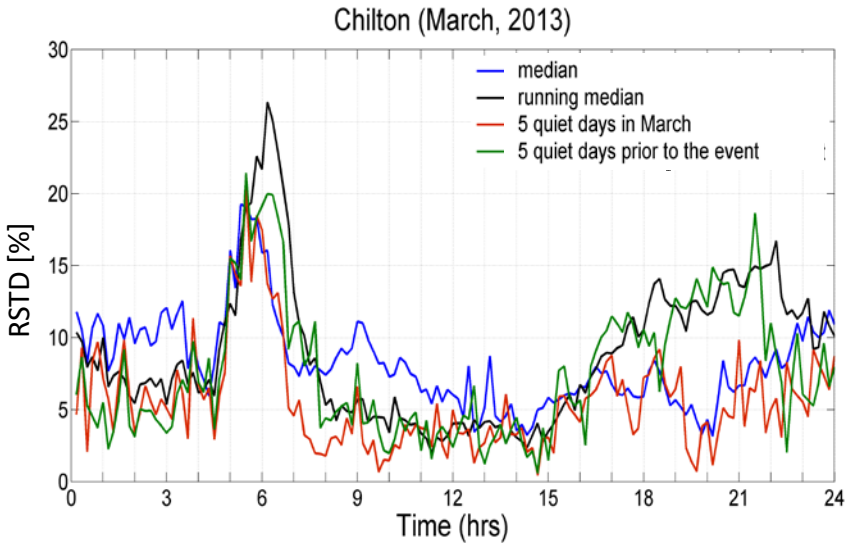
- At Chilton (UT=LT), mean of RSTD of
  - 30 day median: **30%**
  - 5 quietest days: **18%**

Region	Mean RSTD (%) Median	Mean RSTD (%) 5 quietest days
Europe	28	18
N/S America	22	18
Jicamarca	27	26
Average	25	18

- Local time dependency of the variations:
  - relatively larger in dawn and dusk sectors in most cases

- TEC variations of about **20-30%** w.r.t. quiet conditions may be ignored on average.

Quiet-time foF2 variations at Chilton



- Mean of RSTD of
  - monthly medians: **8%**
  - 5 quiet days in the month: **6%**
  - running medians: **9%**
  - 5 quiet days before the event: **8%**

- Local time dependency of the variations: e.g., for the case under study here the uncertainties are significantly larger in dawn sector in all terms (for Chilton UT=LT)

- Monthly medians are comparable to the average of 5 quiet days within the month, while running medians are comparable to the average of 5 quiet days prior to the storm event.

- On average, all approaches may be considered comparable

- On average, ionospheric variations of about **10%** w.r.t. quiet conditions may be ignored.

courtesy of Ioanna Tsagouri

Storm Impacts on foF2 and TEC

- dfoF2 = (foF2 –foF2_med)/foF2_med *100
- dTEC = (TEC –TEC_med)/TEC_med *100
- |dfoF2| > 20%
- |dTEC| > 50%
- Start time at which foF2 (TEC) change starts to exceed 20% (50%)
- Duration when foF2 (TEC) change are larger than 20% (50%)
- Time_max at which the maximum change occurs

foF2 changes during the main phase

Station	dfoF2 > 20%						dfoF2 < -20%					
	Start Time		Max (%)	t_max		Duration (hrs)	Start time		Min (%)	t_min		Duration (hrs)
	UT	LT		UT	LT		UT	LT		UT	LT	
Europe												
Chilton	18.2	18.2	**24%**	**18.2**	**18.2**	0.3						
Pruhonice	11.0	12.0	**46%**	**11.8**	**12.8**	3.3						
Ebre	11.75	12.75	**97%**	**23.0**	**0.0**	8.3	6.75	7.75	-31%	7.7	8.7	2.7
Athens	11.5	13.5	**83%**	**22.8**	**0.8**	7.3						
North America												
Idaho Nat. Lab							7.5	0.5	**-45%**	**9.5**	**2.5**	11
Boulder							9.5	2.5	**-45%**	**16.0**	**9.0**	16
Millstone Hill							7.8	2.8	**-48%**	**9.3**	**4.3**	6.7
Eglin AFB							15.4	9.4	**-31%**	**15.8**	**9.75**	1
South America												
Jicamarca												
Port Stanley	19.5	15.5	**58%**	**19.5**	**15.5**	4.5						

dfoF2 = (foF2 –foF2_med)/foF2_med *100

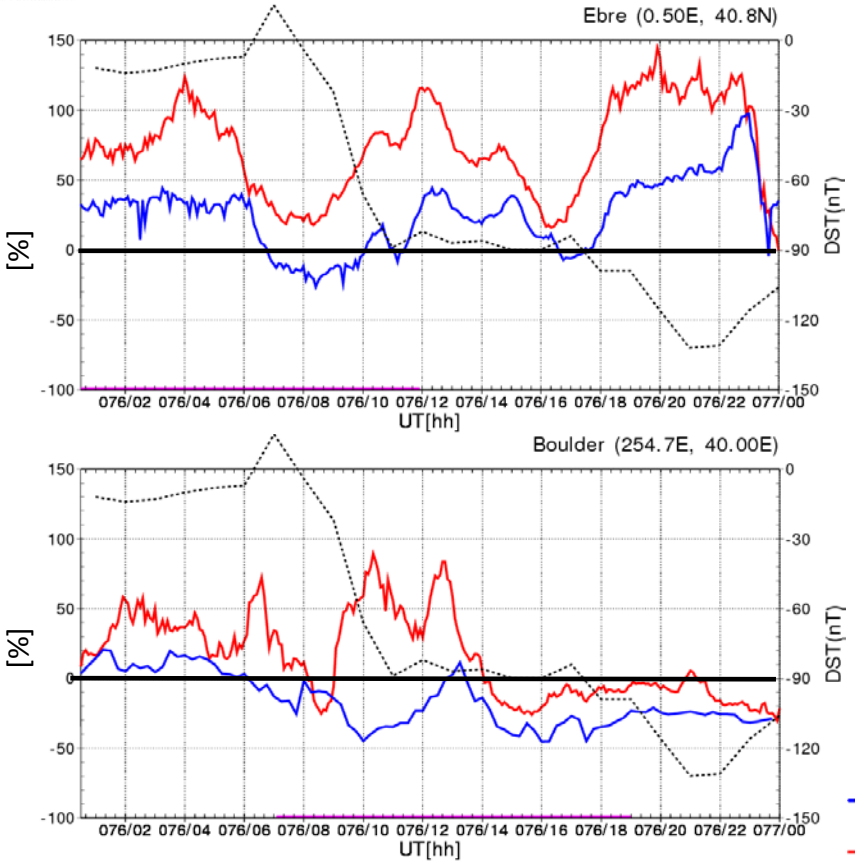
- A few hours after storm onset:
  - European sector in the daytime: positive effects due to increases in ionization (e.g., caused by TAD)
  - North America in the post-midnight sector: negative storm effects caused by the neutral composition disturbance (*Prölss,* 1993)

TEC changes during the main phase

Station	dTEC > 50%						dTEC < -50 %					
	start time		Max[%]	t_max		duration (hrs)	Start time		Min[%]	t_min		duration (hrs)
	UT	LT		UT	LT		UT	LT		UT	LT	
Europe												
Chilton	10.6	10.5	**91.6%**	**11.5**	**11.5**	**2.8**	20.2	20.1	-59.1%	11.5	11.5	1.6
Pruhonice	8.8	9.7	**123.4%**	**11.4**	**12.4**	**5.8**						
Ebre	9.6	9.6	**144.5%**	**19.9**	**20.0**	**10.7**						
Athens	8.3	9.8	**148.9%**	**17.3**	**18.8**	**13.7**						
North America												
Idaho Nat. Lab.	9.1	1.6	**209.3%**	**11.8**	**4.3**	**5.2**						
Boulder	9.5	2.5	**89.4%**	**10.3**	**3.3**	**3.0**						
Millstone Hill	10.5	5.7	**75.1%**	**19.5**	**14.7**	**3.2**						
Eglin AFB	11.0	5.2	***89.6%***	***19.0***	***13.2***	***2.6***						
South America												
Jicamarca	8.7	3.5	**232.2%**	**8.9**	**3.8**	**5.1**						
Port Stanley	17.0	13.1	***270.7%***	***20.3***	***16.4***	***2.8***						

- Same color depicts similar latitudes and it shows similar responses to the storm.
- Both foF2 and TEC responses to the storm are positive phase in European sector.
- Noticeable difference between the foF2 and TEC response in North America sector:
  - TEC shows mainly positive effects, while foF2 shows negative effects.
- TEC enhancement at Port Stanley (41S MLAT) is about three times larger than that at Eglin (40N MLAT).
- At Jicamarca, foF2 change < |20%|, while TEC change goes up to 230%.

foF2 and TEC Changes at Ebre and Boulder



- Ebre:
  - Both foF2 and TEC increase
- Boulder:
  - TEC increases, while foF2 decreases
  - Possible cause:
    - TEC increase due to the transport by the ExB drift caused by penetration eastward electric fields in low latitudes
    - foF2 decrease due to molecular-rich air (small O/N2) from high latitudes

dfoF2 = (foF2 – foF2_med)/foF2_med *100

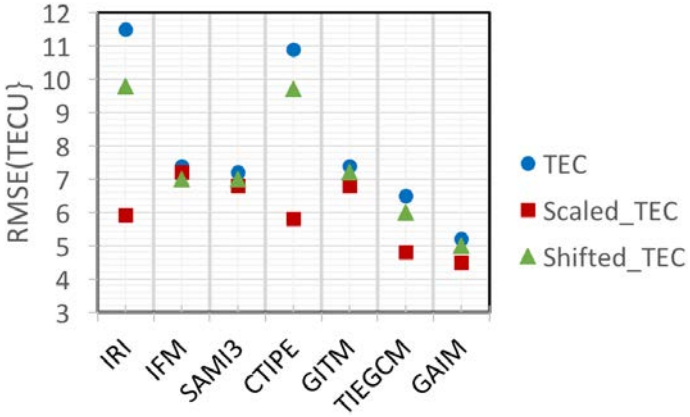
dTEC = (TEC – TEC_med)/TEC_med *100

Assessment of Model Prediction

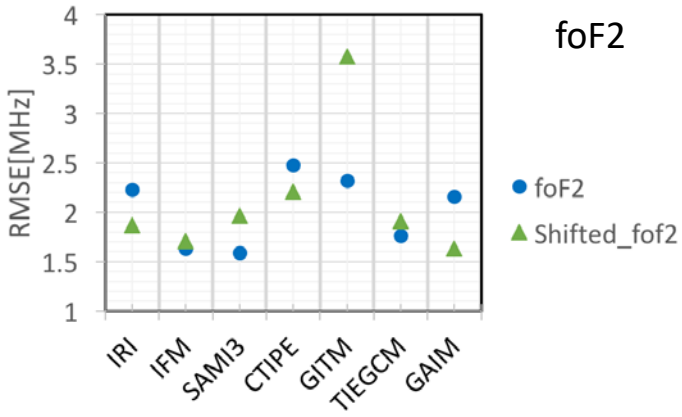
Model	Model Setting Description/Modelers	Lower and Upper boundary for TEC calculation (km)	
Empirical Model			
IRI 2012	IRI-2012 using IRI-corr model for topside Ne and using CCIR (International Radio Consultative Committee) for F-peak plasma frequency foF2, Dieter Bilitza (GMU, NASA/GSFC)	~60	~2,000
Physics Based Ionosphere Model			
IFM	IFM driven by F10.7 and Kp, Robert W. Schunk et al. (USU)	~90	~1,400
SAMI3	SAMI3 with the neutral wind model HWM93, Joseph Huba et al. (NRL)	~90	~2,000
Physics-based Coupled Ionosphere-Thermosphere Model			
CTIPE	CTIPe3.2 driven by Weimer [2005], Timothy Fuller-Rowell et al. (NOAA SWPC)	~140	~2000
GITM	GITM 2.3 driven by Weimer 2005, Aaron Ridley et al. (UM)	~90	~600
TIE-GCM	TIE-GCM2.0 driven by Weimer [2005], R. G. Roble et al. (HAO, NCAR)	~90	~600
Physics-based Data Assimilation Model			
USU-GAIM	USU-GAIM2.4.3 with GPS TEC observations from up to 400 ground stations (-60° < lat < 60°), Robert W. Schunk et al. (USU)	~90	~1,400

RMSE

TEC



foF2



- Average RMSE for 10 and 6 stations for TEC and foF2, respectively
- Scaled TEC = TEC*(Obs_med/TEC_med)
- Shifted TEC = TEC –min(TEC_med)
- Degree of Improvement of predicting performance by scaling depends on models.
- Averaged GPS TEC error < 2 TECU
- 3 TECU <TEC RMSE < 12 TECU
- 1.6 MHz < foF2 RMSE < 3.6 MHz

Ratio of Changes

Model	dfoF2>20%		dfoF2<-20%		dTEC > 50 %			dTEC < -50 %		
	ratio_max	dt_max	ratio_min	dt_min	ratio_max	dt_max	# of event/10	ratio_min	dt_min	# of event/1
IFM	0.99	8.25	0.71	2.95	1.5	4.6	8			
SAMI3	0.92	4.50	1.84	2.38	2.0	6.3	4			
CTIPE	2.54	0.00	0.78	2.67	0.5	3.6	4	1.3	1.2	1
GITM	2.42	1.00	0.60	2.12	3.7	3.9	10			
TIE-GCM	0.97	3.5	1.24	2.92	0.8	4.6	9			
USU-GAIM	0.84	0.88			0.9	3.1	7			

where,

- ratio_max =max_model/max_obs
- dt_max=|t_max_obs - t_max_mod|

- Average ratio for 10 and 6 stations for TEC and foF2, respectively
- red: better ratio
- blue: better time prediction
- green: better probability of change prediction
- No one model outperforms the others in all cases.

Summary

- Quantified storm impacts on foF2 and TEC at 10 selected ionosonde locations.
- Compared four different quiet-time references:
  - 30-day median and mean of five quietest days are comparable.
  - one day before the storm may not be suitable.
- Quiet-time foF2 and TEC variations
  - Local time dependency of the uncertainties: e.g., relatively larger in dawn and dusk sectors
  - About 10% of foF2 and 20-30% of TEC variations were found.
- During main phase,
  - European sector: both foF2 and TEC response to the storm are positive phase
  - North America sector: foF2 shows negative effects, while TEC shows positive response.
  - TEC enhancement at Port Stanley (41S MLAT) is about three times larger than that at Eglin (40N MLAT).

Summary

- Evaluated how well Ionosphere-thermosphere models reproduce the TEC and foF2 changes during the main phase.
  - RMS errors for TEC prediction are larger at Jicamarca and Port Stanley than other locations for most models.
  - Performance depends on the metrics selected and the quantities considered.
  - No one model outperforms the others in all cases.

International Forum for Space Weather Modeling Capabilities Assessment

- **Goals:**
  - Define metrics to assess the current state of space weather modeling capabilities from the perspective of end-users and science for space weather
  - Develop a process to capture science progress in first principles models that feed into operations
- To address the goals of the forum, six physical domains were identified, with multiple working teams within each domain.

SUPERTOPIC: QUANTIFYING SCIENTIFIC PROGRESS

CCMC facilitator(s): B.Thompson

- Assessment of Understanding and Quantifying Progress Toward Science Understanding and Operational Readiness
  (Leads: A. Halford, S. Morley, A. Kellerman, B. Thompson) TEAM AGENDA

SOLAR DOMAIN AGENDA

CCMC facilitator(s): P. Macneice

- Solar Flare Prediction (Leads: S. Murray, M. Georgoulis, S. Bloomfield, K.D. Leka
  Scoreboard Leads: S. Murray, M.L Mays) SSA-0,SSA-6 TEAM AGENDA
- Coronal & Solar Wind Structure
  Coronal & SW Structure; Ambient SW; Coronal Hole Boundaries
  (Leads: P. Macneice, L. Jian) SSA-? TEAM AGENDA
- 3D CME kinematics and topology (Leads: B.Thompson, C.Moestl, D.Barnes) TEAM AGENDA
- Solar Indices and Irradiance (Leads: J. Klenzing, C. Henney, K. Muglach) SSA-0 TEAM AGENDA

GEOSPACE: Geomagnetic Environment DOMAIN AGENDA

CCMC facilitator(s): L.Rastaetter

- Ground Magnetic Perturbations: dBdt, delta-B, GICs, FACs
  (Leads: D. Welling, H. Opgenoorth, C. Ngwira) SSA-1 TEAM AGENDA
- Geomagnetic Indices (Leads: M. Liemohn) SSA-1 TEAM AGENDA
- Magnetopause location and geosync. orbit crossing
  (Leads: Y. Collado-Vega, S. Merkin) SSA-1 TEAM AGENDA

HELIOSPHERE DOMAIN AGENDA

CCMC facilitator(s): M.L. Mays, A. Taktakishvili, P. Macneice

- CME Arrival Time (Leads: C. Verbeke, M.L. Mays, A. Taktakishvili) SSA-1 TEAM AGENDA
- IMF Bz at L1 (Leads: N. Savani, P. Riley) SSA-1 TEAM AGENDA
- SEPs (Leads: I.G. Richardson. P. Quinn, M. Marsh, M.L. Mays
  Scoreboard Leads: M. Dierckxsens, M. Marsh) SSA-3,SSA-6 TEAM AGENDA

GEOSPACE: Auroral Region DOMAIN AGENDA

CCMC facilitator(s): M.Kuznetsova

- Auroral precipitation and high latitude ionosphere electrodynamics
  (Leads: R. Robinson, Y. Zhang, B. Kosar) TEAM AGENDA

RADIATION and PLASMA EFFECTS DOMAIN AGENDA

CCMC facilitator(s): Y. Zheng, M. Kuznetsova

- Surface Charging *few eV - keV electrons, plasma density*
  (Leads: J. Minow, D. Pitchford, N. Ganushkina) SSA-6 TEAM AGENDA
- Internal Charging *keV–MeV electrons*
  (Leads: P. O'Brien, Y. Shprits) SSA-6 TEAM AGENDA
- Single Event Effects *MeV–GeV-TeV protons, ions*
  (Leads: M. Xapsos, J. Mazur, P. Jiggens) SSA-3,SSA-6 TEAM AGENDA
- Total Ionizing Dose *keV–MeV electrons, keV–GeV protons,ions*
  (Leads: I. Jun, T. Guild, M. Xapsos) SSA-6 TEAM AGENDA
- Radiation effects for aviation (Leads: K. Tobiska, M. Meier) SSA-6 TEAM AGENDA

IONOSPHERE DOMAIN AGENDA

CCMC facilitator(s): J. Shim, M. Kuznetsova

- Neutral Density and Orbit Determination at LEO
  (Leads: S. Solomon, T. Fuller-Rowell, S. Bruinsma, E. Sutton) SSA-2 TEAM AGENDA
- Global & Regional TEC (Leads: L. Scherliess, R. Calfas) SSA-4 TEAM AGENDA
- Ionosphere Plasma Density: NmF2/foF2, hmF2, TEC
  (Leads: I. Tsagouri, M. Angling, J. Shim) SSA-5 TEAM AGENDA
- Ionosphere Scintillation (Leads: E. Yizengaw) SSA-5 TEAM AGENDA

INFORMATION ARCHITECTURE

CCMC facilitator(s): C. Wiegand

- Information Architecture for Interactive Archives (IAIA)
  (Leads: C. Wiegand, D. Heynderickx, D. De Zeeuw, T. King) TEAM AGENDA

International Forum for Space Weather Modeling Capabilities Assessment

IONOSPHERE

CCMC facilitator(s): J. Shim, M. Kuznetsova

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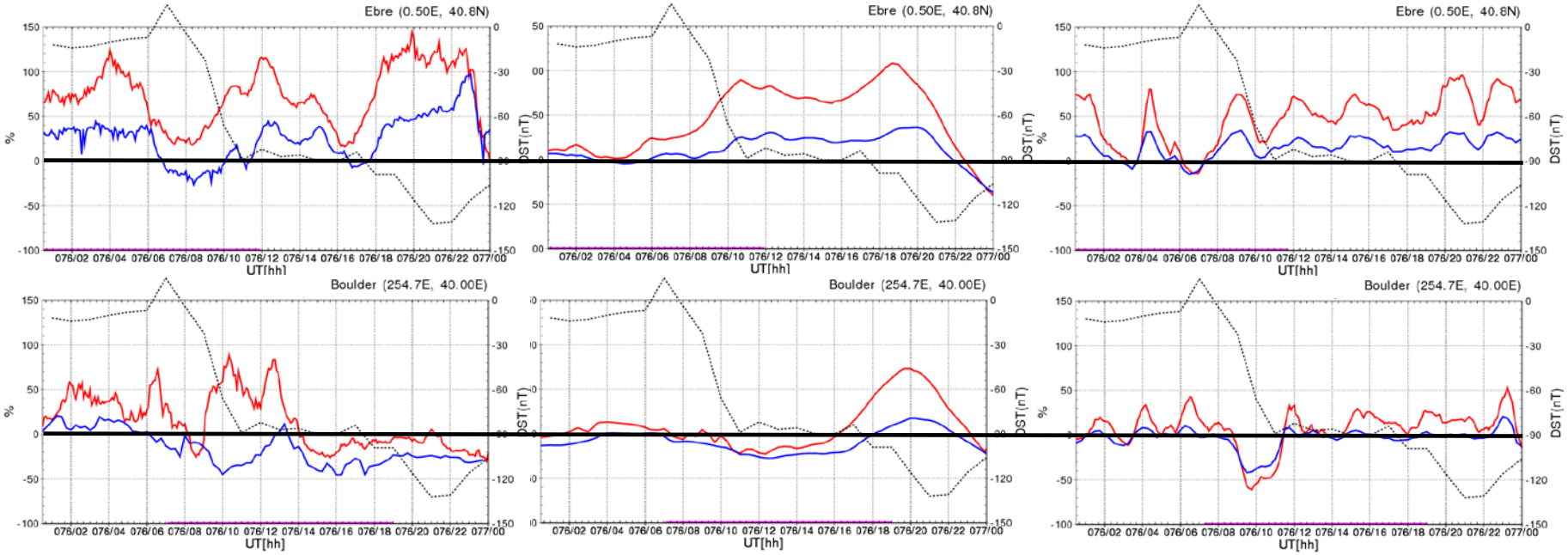
  - Develop a process to capture science progress in first principles models that feed into operations
- To address the goals of the forum, six physical domains were identified, with multiple working teams within each domain.
- The CCMC organized the "International CCMC-LWS working meeting: Assessing Space Weather Understanding and Applications", held on April 3-7, 2017 in Cape Canaveral (120 participants).
- Long-term activity: regular telecons and mini-meetings at community conferences (e.g., 2017 CEDAR Workshop: Jun. 19, from 4-6pm)
- **JOIN this community-wide International Forum**
- https://ccmc.gsfc.nasa.gov/assessment/index.php

COMMUNITY COORDINATED MODELING CENTER

foF2 and TEC Changes at Ebre and Boulder

observations | TIE-GCM | USU-GAIM

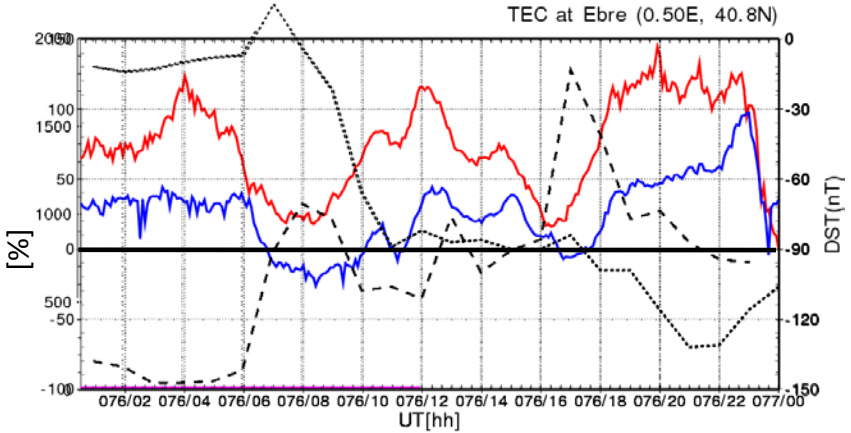


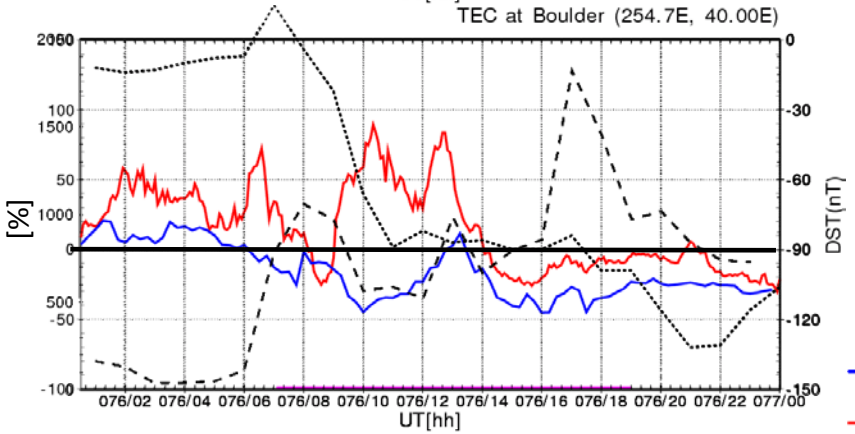
dfoF2 = (foF2 – foF2_med)/foF2_med *100

dTEC = (TEC – TEC_med)/TEC_med *100

- Models show the same trend in dfoF2 and dTEC.
- None of the models catch the opposite changes in foF2 and TEC at Boulder.

foF2 and TEC Changes at Ebre and Boulder





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  - Both foF2 and TEC increase
- Boulder:
  - TEC increases while foF2 decreases
  - Possible cause:
    - TEC increase due to ExB drift caused by penetration eastward electric fields during the storm main phase
    - foF2 decrease due to molecular-rich air (small O/N2)

dfoF2 = (foF2 – foF2_med)/foF2_med *100

dTEC = (TEC – TEC_med)/TEC_med *100

Quiet-time TEC variations (RSTD)