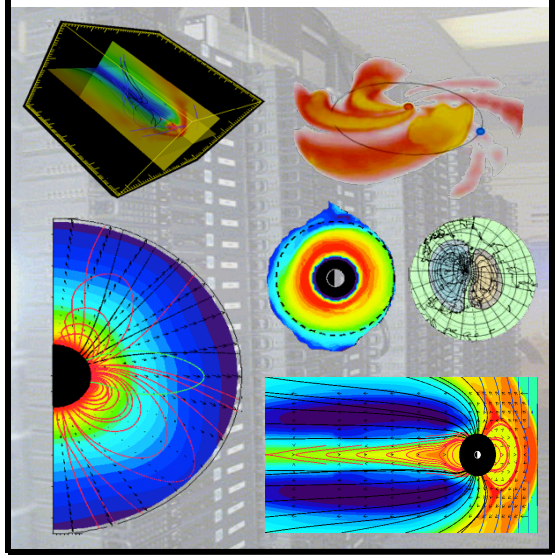
COMMUNITY COORDINATED MODELING CENTER



Assessment of modeling capability for reproducing storm impacts on TEC

Ja Soon Shim[1*], Maria M Kuznetsova[2], Lutz Rastaetter[2], Dieter Bilitza[3], Mihail Codrescu[4], Anthea J Coster[5], Barbara A Emery[6], Matthias Foerster[7], Ben T Foster[6], Timothy J Fuller-Rowell[4], Joe Huba[8], Larisa Goncharenko[5], Anthony Mannucci[9], Alexander A. Namgaladze[10], Xiaoqing Pi[9], Boris E Prokhorov[7], Aaron J Ridley[11], Ludger Scherliess[12], Robert W. Schunk[12], Jan J. Sojka[12], Lie Zhu[12]

1. CUA/NASA GSFC, Greenbelt, MD, USA, 2. NASA/GSFC, Greenbelt, MD, USA, 3. School of Physics Astronomy and Computational Science, George Mason University, Fairfax, Virginia, USA, 4. NOAA SWPC, Boulder, CO, USA, 5. Haystack Observatory, Westford, MA, USA, 6. NCAR HAO, Boulder, CO, USA, 7. Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Potsdam, Germany, 8. Plasma Physics Division, Naval Research Laboratory, Washington, D. C., USA, 9. JPL, Caltech, Pasadena, CA, USA, 10. Murmansk State Technical University, Murmansk, Russia, 11. Space Physics Research Laboratory, Univ. of Michigan, Ann Arbor, MI, USA, 12. Utah State Univ. Logan, UT, USA

http://ccmc.gsfc.nasa.gov

NASA Goddard Space Flight Center

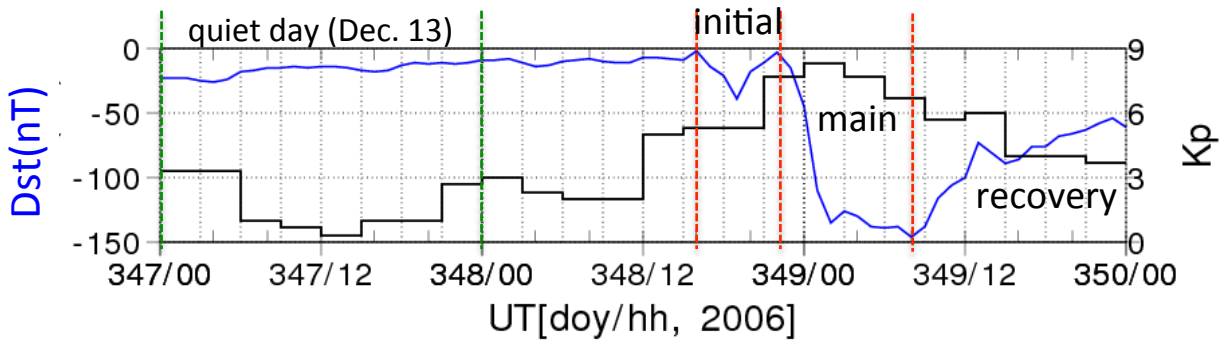
Abstract

During geomagnetic storm, the energy transfer from solar wind to magnetosphere-ionosphere system adversely affects the communication and navigation systems. Quantifying storm impacts on TEC (Total Electron Content) and assessment of modeling capability of reproducing storm impacts on TEC are of importance to specifying and forecasting space weather. In order to quantify storm impacts on TEC, we considered several parameters: TEC changes compared to quiet time (the day before storm), TEC difference between 24-hour intervals, and maximum increase/ decrease during the storm. We investigated the spatial and temporal variations of the parameters during the 2006 AGU storm event (14-15 Dec. 2006) using ground-based GPS TEC measurements in the selected 5 degree two longitude sectors (140°E and 285°E) where data coverage is relatively better. The latitudinal variations were also studied. We obtained modeled TEC from various ionosphere/thermosphere (IT) models. The parameters from the models were compared with each other and with the observed values. We quantified performance of the models in reproducing the TEC variations during the storm using skill scores. This study has been supported by the Community Coordinated Modeling Center (CCMC) at the Goddard Space Flight Center. Model outputs and observational data used for the study will be permanently posted at the CCMC website (http://ccmc.gsfc.nasa.gov) for the space science communities to use.

- Time interval

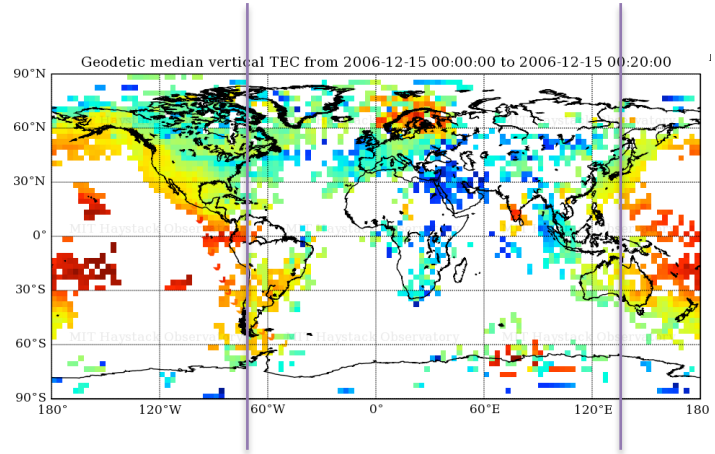
  : 2006/12/13 (doy 347) 00:00 UT - 12/15 (doy 350) 00:00 UT

- Dst and Kp index during the time interval



- GPS TEC

  - in 5 degree two longitude sectors (140°E-145°E and 285°E-290°E)
  - Three TEC measurement sets were compared (MIT, JPL and IGS (International GNSS Service) TEC):
    - MIT and JPL TEC every 15 min (5° lat x 5° lon)
    - IGS TEC every 2 hrs (2.5° lat x 5° lon)



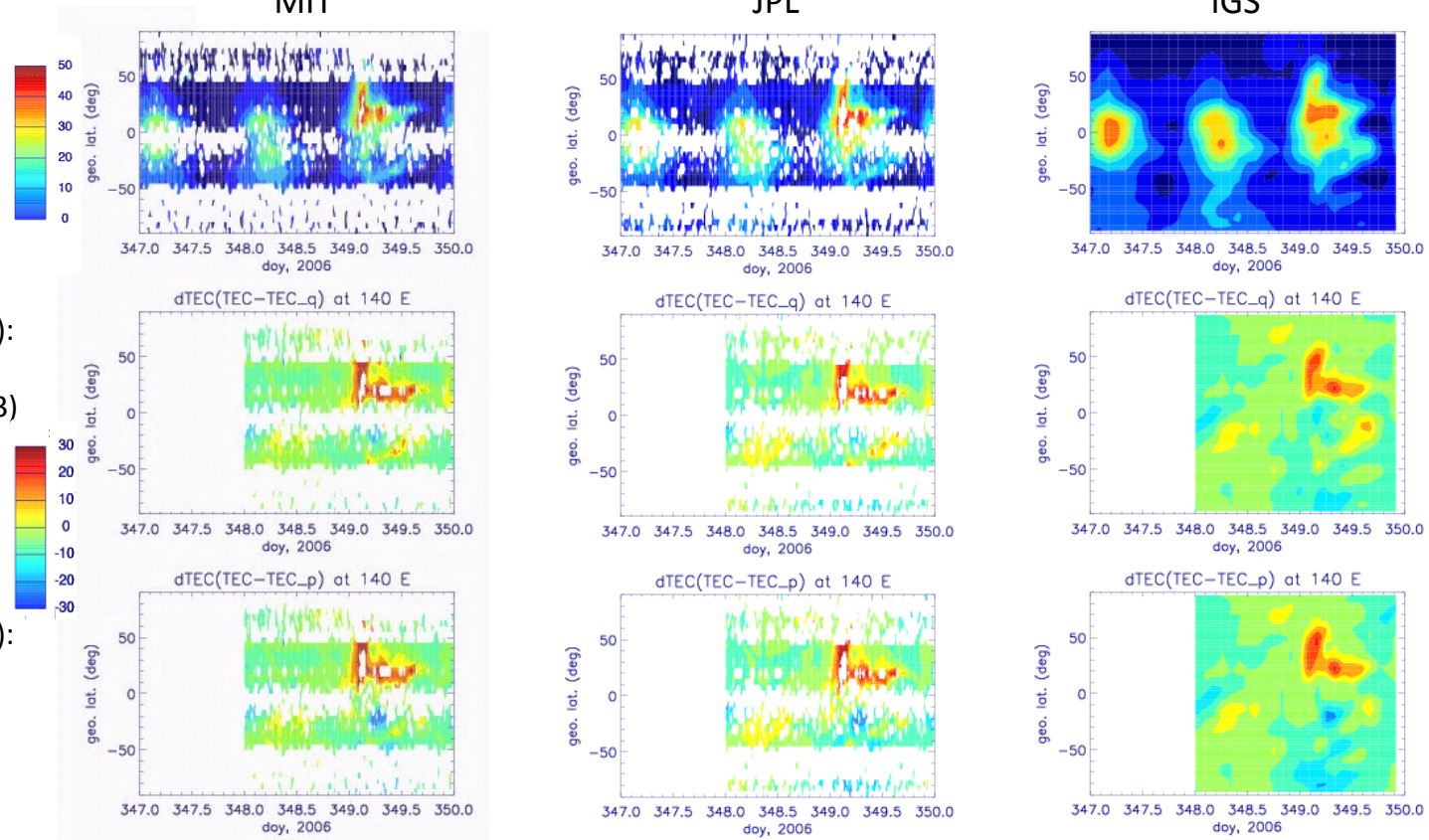
Observed TEC and TEC Changes (dTEC_q & dTEC_p) in 140°E (GPS TEC from MIT, JPL and IGS)

MIT JPL IGS

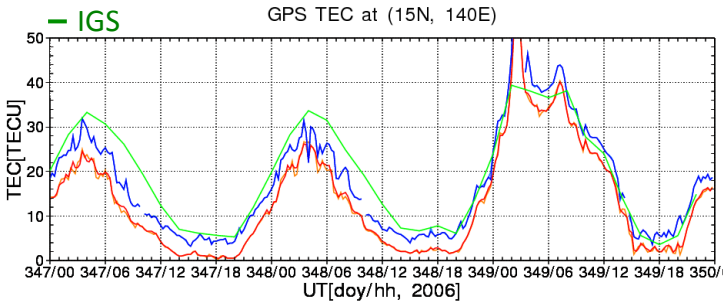
TEC [TECU]

TEC Change (dTEC_q):
TEC_today –
TEC (quiet day:12/13)

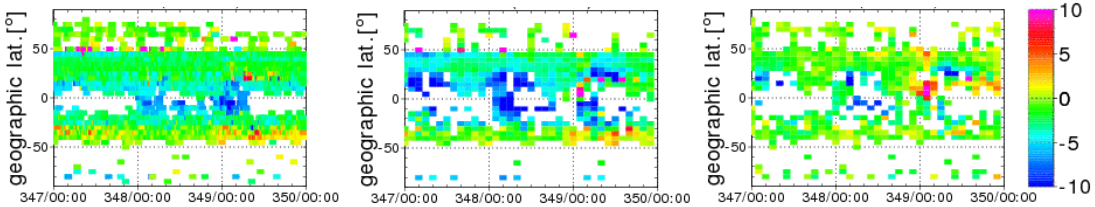
TEC Change (dTEC_p):
TEC_today –
TEC (previous day)



– MIT TEC
– JPL TEC
– IGS



MIT TEC - JPL TEC MIT TEC - IGS TEC JPL TEC - IGS TEC

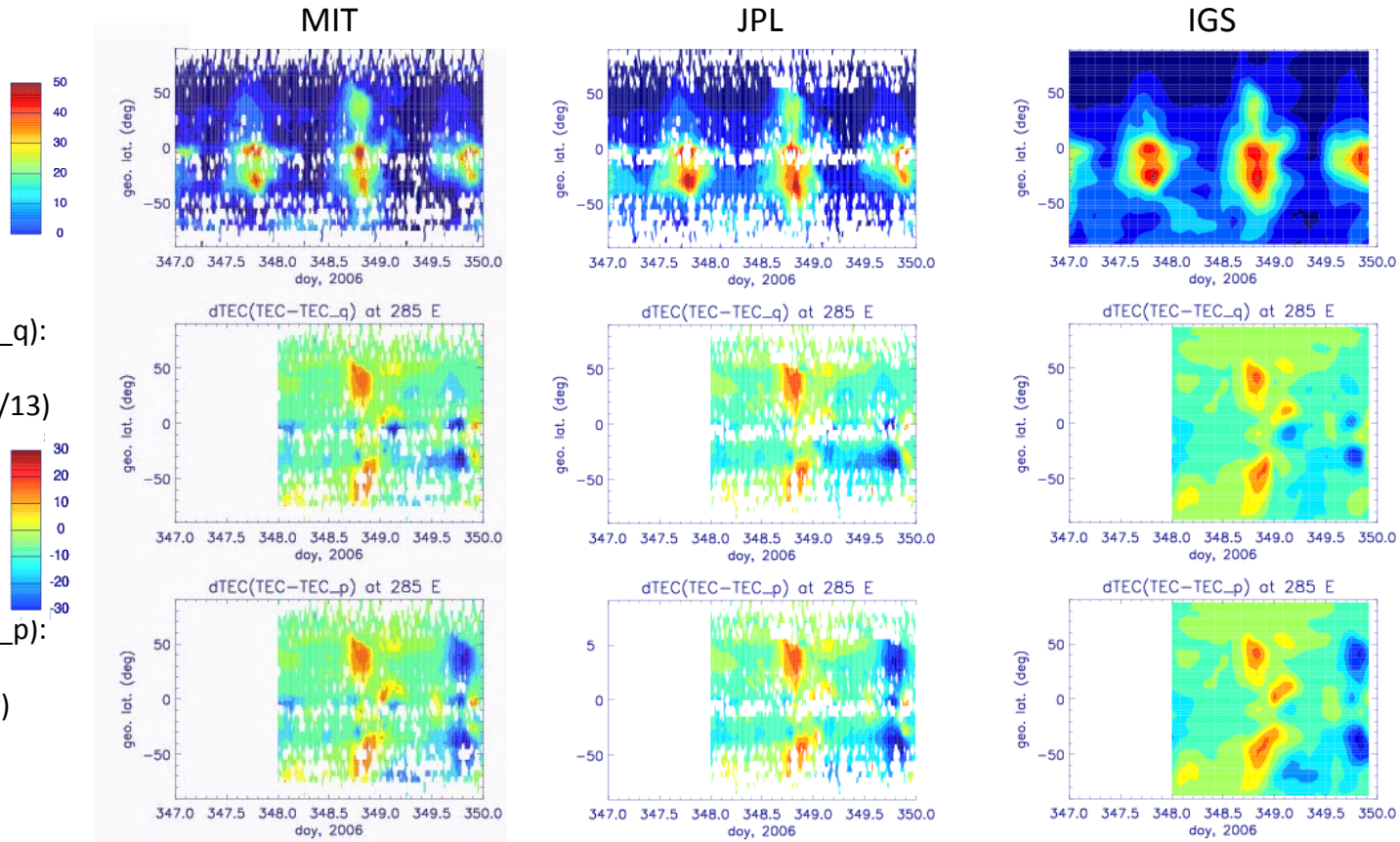


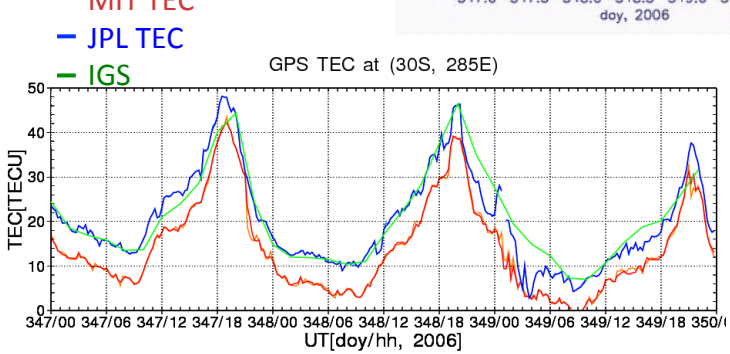
Observed TEC and TEC Changes (dTEC_q & dTEC_p) in 285°E (GPS TEC from MIT, JPL and IGS)

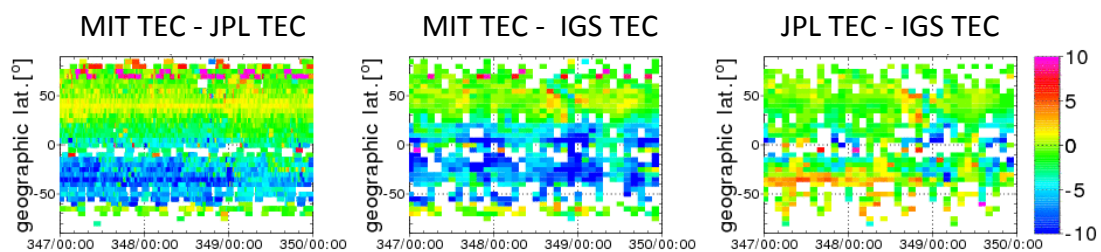
TEC [TECU]

TEC Change (dTEC_q):
TEC_today –
TEC (quiet day:12/13)

TEC Change (dTEC_p):
TEC_today –
TEC (previous day)







GPS TEC from MIT, JPL and IGS in 140°E and 285 °E

- Three TEC measurement sets:
  - number of data points: MIT > JPL ,
  - average error: MIT > JPL,
  - MIT TEC < JPL TEC (not all cases, but most cases)
  - JPL TEC and IGS TEC are similar to each other.
- IGS TEC values are similar to JPL TEC, but peak values tend to be smaller than JPL and MIT peak values (e.g., difference between JPL and IGS TEC values is larger in equatorial anomaly region).
- In 140°E sector, difference between the three data sets are larger in low latitudes than middle latitudes in northern and southern hemispheres.
- In 285°E sector, MIT maximum TEC and TEC changes (dTEC_q and dTEC_p) are smaller than JPL and IGS values in most cases, but MIT TEC values are larger than JPL and IGS values in northern middle and high latitudes.

- For this study, MIT GPS TEC median values with error less than 4 TECU were used as a ground truth: for 140°E and 285°E sector:
  - average error = about 2 TECU,
  - average number of data point per 5x5 bin = about 20

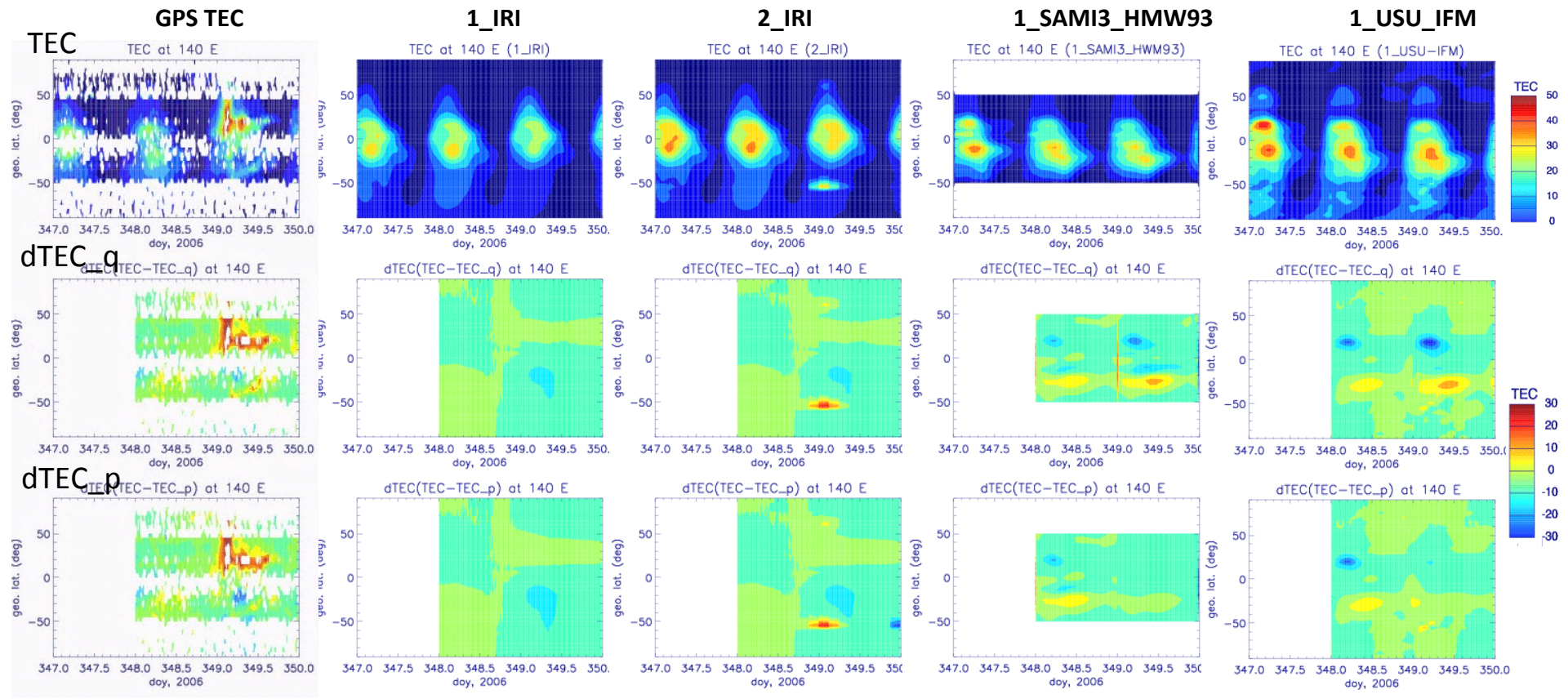
- Storm effects on TEC depend on latitude and longitude:
  - 285 lon : increase in both higher and lower latitude
  - 140 lon : large increase in northern mid-latitude

Model Simulations used for the study

Model Setting ID	
empirical model	
1_IRI*	IRI-2007, empirical ionospheric model
2_IRI*	IRI-2012 using IRI-corr for topside Ne and CCIR F-peak
physics-based ionosphere model	
1_SAMI3_HWM93*	SAMI3 with the neutral wind model HWM93
1_USU-IFM*	IFM driven by F10.7, Kp and empirical inputs for the thermosphere parameters
physics-based coupled ionosphere-thermosphere model	
1_CTIPE*	CTIPe driven by Weimer electric potential model, 2°×18°, 15 levels in logarithm of pressure
2_CTIPE	CTIPe runs at NOAA/SWPC with Weimer 2005 using 1-minute solar wind and IMF from ACE; (f10.7+f81)/2; and the (2,2), (2,3), (2,4), (2,5), and (1,1) propagating tidal modes are imposed at 80 km altitude with a prescribed amplitude and phase
1_TIE-GCM*	TIE-GCM1.93 driven by Heelis electric potential model with constant critical co-latitudes
2_TIE-GCM	TIE-GCM1.94 driven by Weimer electric potential model with dynamic critical co-latitudes
1_UAM	Upper Atmosphere Model (UAM), A.A. Namgaladze et al., FAC as external driver
physics-based data assimilation ionosphere model	
1_USU-GAIM*	USU-GAIM23 with GPS TEC observations from up to 400 ground stations

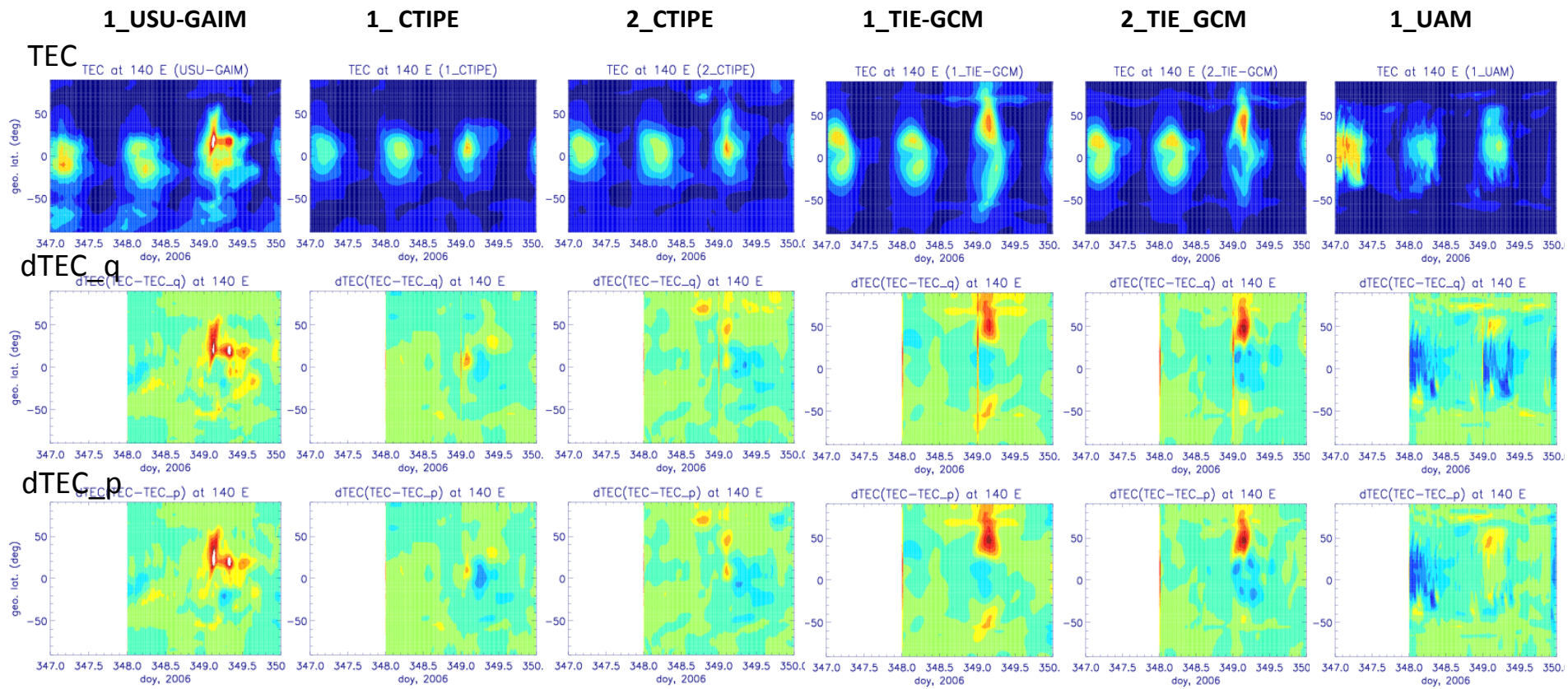
*Runs performed at the CCMC

Observed/Modeled TEC and dTEC at 140°E



- None of empirical and ionospheric physics based models predict well TEC increase in northern low latitudes in 140 °E longitude sector.
- Two physics based ionosphere models, 1_SAMI3 and 1_USU-IFM, do not catch the high TEC increase in northern low latitudes, but relatively well predict TEC increase in southern middle latitudes in doy 349 compared to IRIs.

Observed/Modeled TEC and dTEC at 140°E



- Data assimilation model run 1_USU-GAIM shows the best performance of predicting all three quantities, TEC, dTEC_p and dTEC_q.
- Data assimilation and coupled models show TEC increase in northern hemisphere better than empirical and ionosphere models during the storm in 140 °E longitude sector.
- TIE-GCMs show high TEC increase in higher latitudes compared to other simulations.
- Among physics-based coupled models, CTIPEs show better TEC increase in low latitudes during storm.
- CTIPEs and 1_UAM do not produce equatorial anomaly.

RMS error in predicting TEC at 140°E (in TECU)

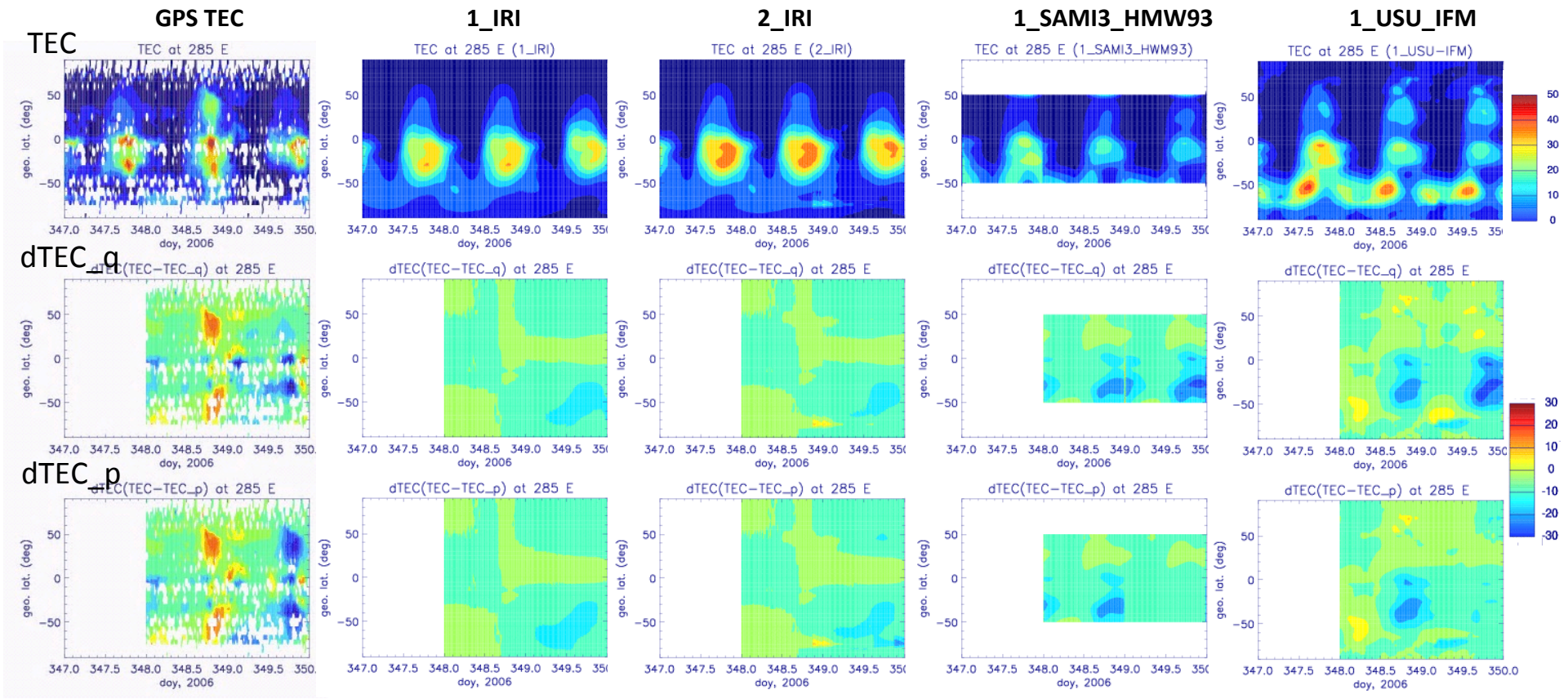
low lat (0°<|lat|<25°), mid-lat (25°<|lat|<50°), high lat (|lat|>50 °)

1st among the same type
1st among all models

	low lat			mid-lat (south)			mid-lat (north)		
	TEC	dTEC_q	dTEC_p	TEC	dTEC_q	dTEC_p	TEC	dTEC_q	dTEC_p
empirical model									
1_IRI	6.3	8.5	8.0	3.7	4.7	3.6	5.2	6.7	7.1
2_IRI	7.4	8.5	7.8	3.8	4.5	3.6	5.2	6.8	7.1
physics-based ionosphere model									
1_SAMI3_HWM93	7.9	10.5	8.7	3.3	3.2	3.1	6.8	8.2	7.8
1_USU-IFM	8.8	11.0	8.8	5.6	3.2	3.3	6.5	8.5	7.9
physics-based coupled ionosphere-thermosphere model									
1_CTIPE	6.4	8.4	8.7	6.0	3.5	2.9	5.5	7.1	6.9
2_CTIPE	6.5	9.8	9.0	5.1	3.8	3.2	4.7	6.0	6.5
1_TIE-GCM	6.9	9.7	9.4	4.2	4.0	4.2	6.2	6.4	6.9
2_TIE-GCM	7.5	11.2	10.5	4.7	3.8	3.4	5.4	6.3	6.1
1_UAM	7.6	13.5	9.6	6.9	6.2	5.6	6.2	9.9	7.6
physics-based data assimilation ionosphere model									
1_USU-GAIM	3.8	2.4	2.7	2.0	2.0	2.0	1.9	2.3	2.0
GPS_TEC error	2.2 (n = ave_num_data/bin = 9)			2.2 (n = 12)			1.5 (n = 35)		

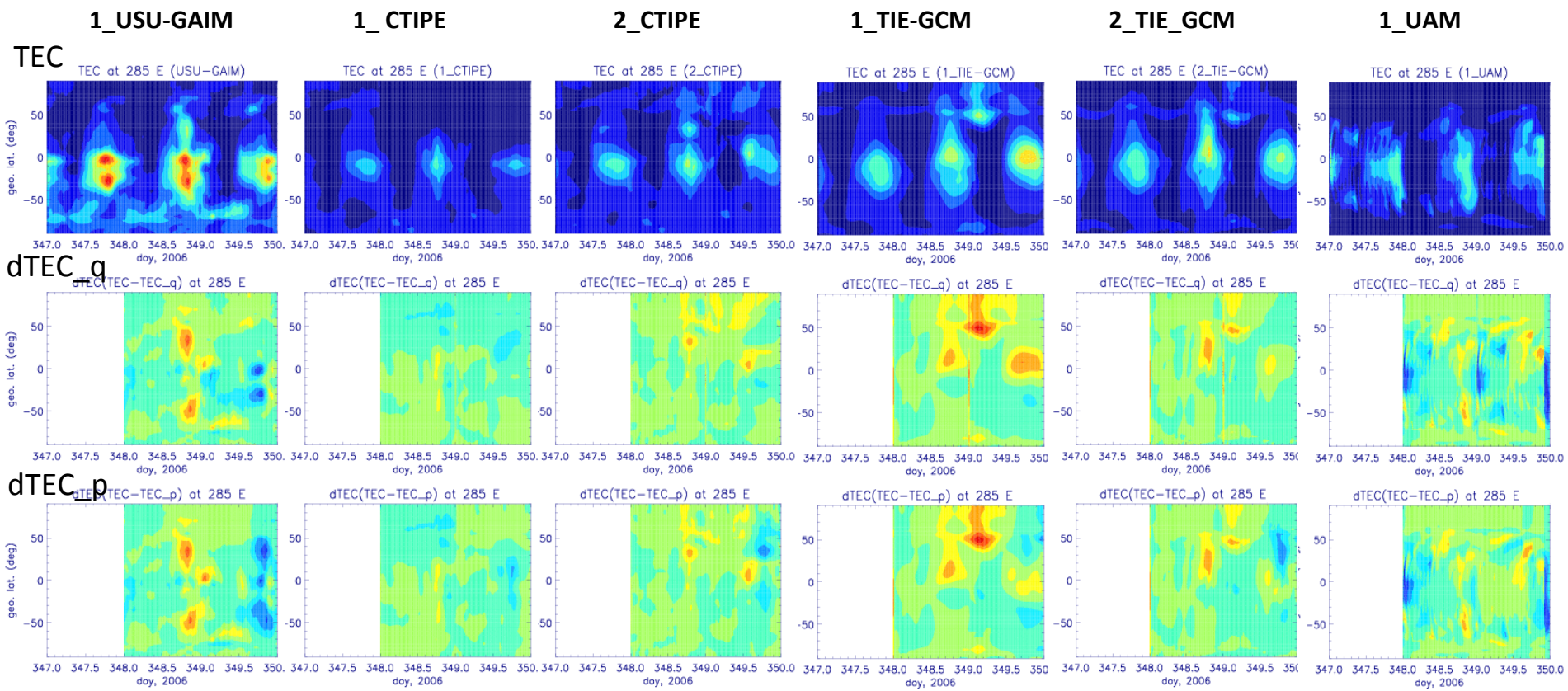
- Two IRIs have similar RMS; 1_SAMI3 produces a little bit better TEC than 1_USU-IFM for most cases; CTIPEs show better score than other physics-based coupled ionosphere-thermosphere model simulations.
- Data assimilation model, 1_USU-GAIM, shows the best performance in predicting TEC in two latitude regions.
- RMS error of 1_USU-GAIM < GPS TEC error in southern middle latitude
- Most models predict TEC better in southern mid-latitudes than northern mid-latitudes.
  - in southern mid-latitudes: RMS for TEC prediction > RMS for dTEC prediction (except for IRIs)
  - in northern mid-latitudes: RMS for TEC prediction < RMS for dTEC prediction

Observed/Modeled TEC and dTEC at 285°E



- Like in the 140°E longitude sector, none of the empirical and ionospheric physics based models predict well the increase TEC in the northern middle latitudes of the 285 °E longitude sector.
- 1_SAMI3 and 1_USU-IFM predict well the negative dTEC_q (TEC-TEC_quiet_day) in the southern middle latitudes during the recovery phase, but not dTEC_p (TEC-TEC_previous_day) due to failure of predicting TEC enhancement during the storm.

Observed/Modeled TEC and dTEC at 285°E



- 1_USU-GAIM predicts better TEC and TEC changes than other simulations.
- 2_CTIPE and 2_TIE-GCM show better performance than 1_CTIPE and 1_TIE-GCM, respectively.
- The physics-based coupled models tend to underestimate day-time TEC values in equatorial anomaly regions.
- TIE-GCMs produce larger TEC in high latitudes during main phase of the storm compared to other simulations.

RMS error in predicting TEC at 285 °E (TECU)

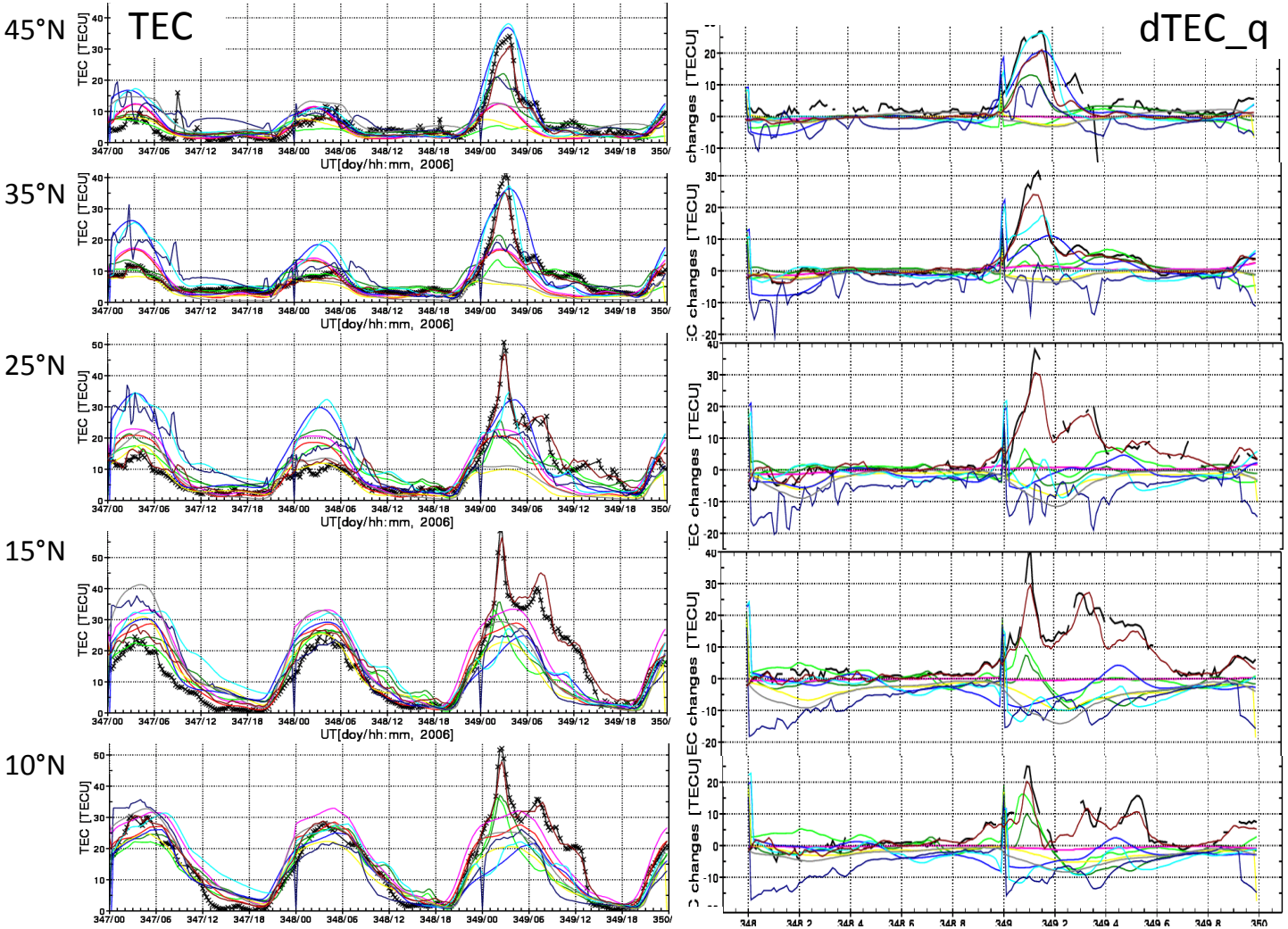
low lat (0°<|lat|<25°), mid-lat (25°<|lat|<50°), high lat (|lat|>50 °)

1st among the same type
1st among all models

	low lat			mid-lat (south)			mid-lat (north)			high lat (south)			high lat (north)		
	TEC	dTEC_q	dTEC_p	TEC	dTEC_q	dTEC_p	TEC	dTEC_q	dTEC_p	TEC	dTEC_q	dTEC_p	TEC	dTEC_q	dTEC_p
empirical model															
1_IRI	5.2	5.5	5.1	7.1	7.3	6.9	4.4	5.0	7.3	6.1	6.2	6.8	3.8	2.7	2.7
2_IRI	6.4	5.4	5.0	7.9	7.2	7.0	4.2	4.8	7.0	6.1	6.1	7.2	3.7	2.8	2.7
physics-based ionosphere model															
1_SAMI3_HWM93	6.1	5.6	5.0	8.2	10.0	10.1	5.4	5.4	7.8						
1_USU-IFM	5.9	6.3	5.6	9.9	10.5	10.5	4.8	5.3	7.6	16.0	7.7	8.7	3.6	3.3	3.2
physics-based coupled ionosphere-thermosphere model															
1_CTIPE	8.3	5.5	4.7	8.8	8.8	8.1	6.4	6.1	8.2	5.3	5.4	7.6	3.9	4.6	4.2
2_CTIPE	6.6	6.0	5.4	7.6	8.3	7.8	3.4	4.0	4.9	5.1	5.5	7.8	4.8	3.9	3.6
1_TIE-GCM	6.7	8.1	6.4	5.7	7.4	6.6	4.5	5.5	6.5	5.7	5.8	7.4	5.5	5.1	4.8
2_TIE-GCM	6.1	6.5	5.7	6.7	8.4	7.8	3.4	3.4	4.2	5.9	5.6	7.7	3.9	2.6	2.6
1_UAM	6.9	7.9	6.5	7.2	9.2	8.2	5.9	7.3	9.2	7.2	7.0	8.8	4.3	3.5	2.9
physics-based data assimilation ionosphere model															
1_USU-GAIM	3.4	2.4	2.2	4.2	3.1	2.9	2.2	2.3	2.5	7.2	5.3	6.7	3.6	3.4	3.2
GPS-TEC error	2.2 (n=ave_num_data/bin = 11)			2.3 (n = 15)			1.3 (n = 47)			2.3 (n = 8)			2.4 (n = 9)		

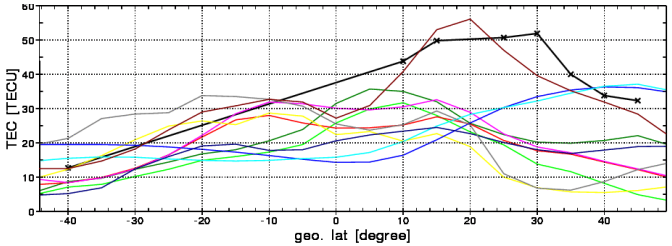
- Two IRIs have similar RMS; 1_SAMI3 and 1_USU-IFM show similar performance for most cases; TIE-GCMs show better score than CTIEs and 1_UAM for more cases; 2_TIE-GCM has the best score for predicting TEC changes in northern high latitudes.
- Data assimilation model, 1_USU-GAIM, shows the best performance in predicting TEC in low and middle latitude regions.
- All models show better scores for dTEC than TEC in northern high latitudes except for 1_CTIPE.
- CTIPEs show better scores for dTEC than TEC in low latitudes.
- Most models predict TEC worse in southern than northern middle and high latitude regions.
- For all cases, RMS error of models > GPS TEC error, except for 1_USU_GAIM's RMS for dTEC_p in low latitude

Latitudinal Variations in Observed/Modeled TEC and dTEC at 140°E

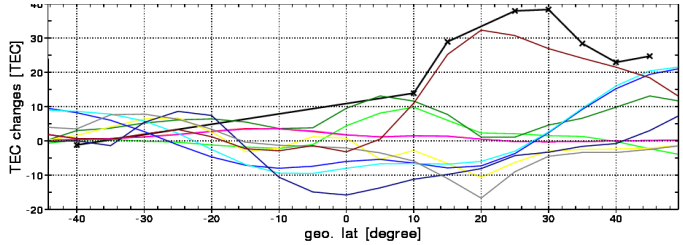


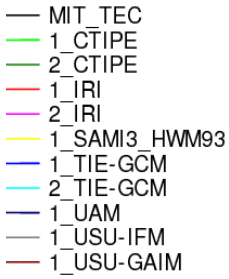
- Models tend to overestimate daytime TEC during quiet time and underestimate during the storm time.
- Modeled dTEC_q values are smaller than observed values during the storm.
- Data assimilation and coupled models predict TEC increase during the storm better than others.
- TEC increase due to the storm is larger in northern hemisphere.

TEC at 0300 UT on DOY 349 (as a function of latitude)

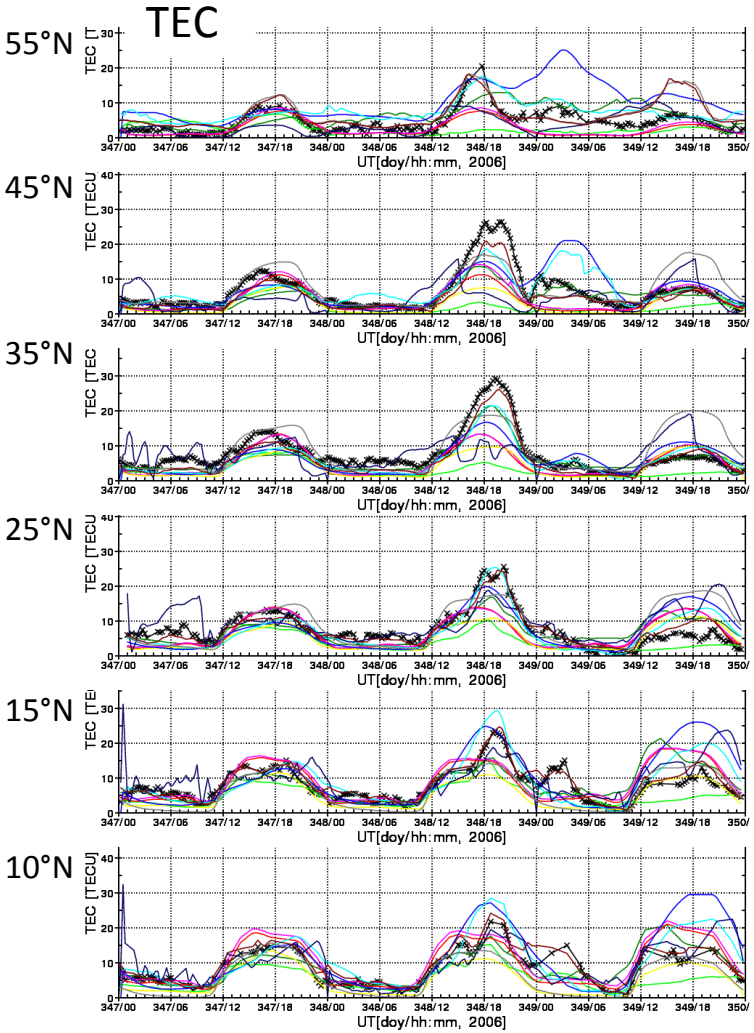


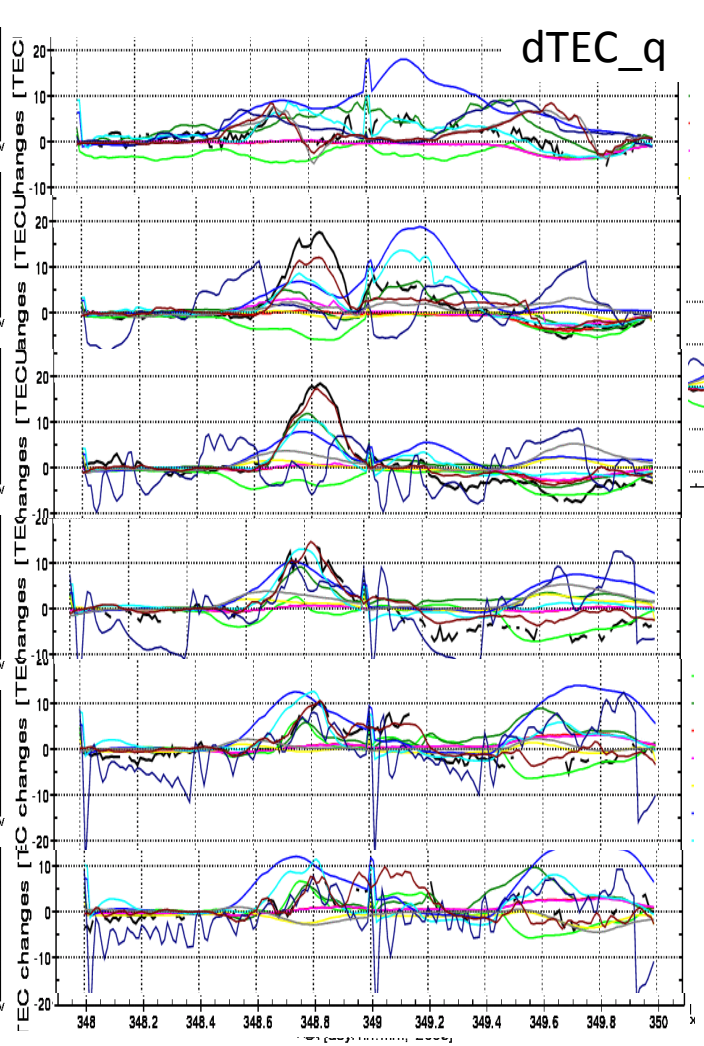
dTEC_q at 0300 UT on DOY 349 (as a function of latitude)

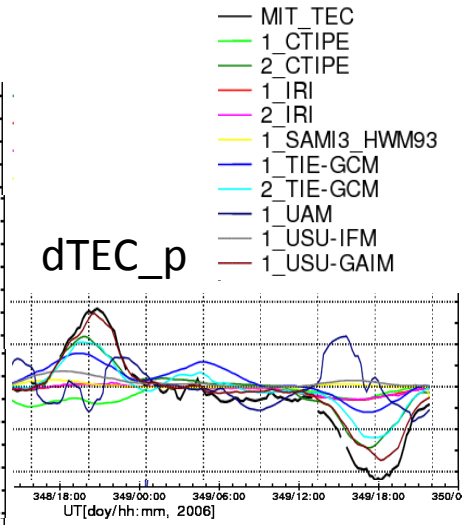




Latitudinal Variations in Observed/Modeled TEC and dTEC at 285°E

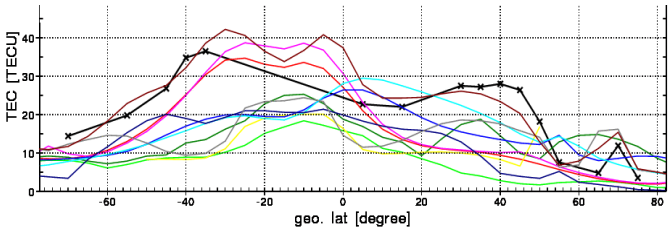




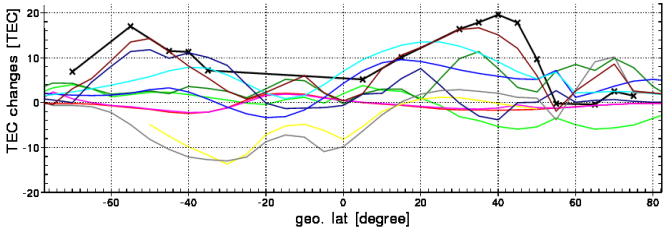


- During the storm recovery phase, modeled TEC values are larger than observed values. Therefore, observed dTEC_p is more negative value than modeled one.
- Data assimilation and coupled models predict TEC increase during the storm better than others.
- TEC increase due to the storm is seen in both hemispheres.

TEC at 2000 UT on DOY 348 (as a function of latitude)



dTEC_q at 2000 UT on DOY 348 (as a function of latitude)



Ratio of maximum TEC & dTEC at 140°E

(Model/Observation)

low lat (0°<|lat|<25°), mid-lat (25°<|lat|<50°), high lat (|lat|>50 °)

1st among the same type
1st among all models

	low lat			mid-lat (south)			mid-lat (north)		
	TEC	dTEC_q	dTEC_p	TEC	dTEC_q	dTEC_p	TEC	dTEC_q	dTEC_p
empirical model									
1_IRI	0.58	0.04	0.04	0.68	0.08	0.10	0.40	0.07	0.08
2_IRI	0.63	0.03	0.04	0.88	0.82	0.96	0.43	0.06	0.07
physics-based ionosphere model									
1_SAMI3_HWM93	0.60	0.53	0.22	1.03	0.94	0.56	0.23	0.22	0.01
1_USU-IFM	0.63	0.28	0.18	1.19	0.69	0.60	0.28	0.08	0.05
physics-based coupled ionosphere-thermosphere model									
1_CTIPE	0.60	0.47	0.31	0.49	0.51	0.36	0.45	0.29	0.17
2_CTIPE	0.62	0.47	0.31	0.49	0.47	0.25	0.49	0.38	0.32
1_TIE-GCM	0.53	0.42	0.15	0.85	0.78	0.82	0.71	0.59	0.62
2_TIE-GCM	0.58	0.48	0.18	0.68	0.70	0.43	0.73	0.69	0.62
1_UAM	0.45	0.42	0.21	0.57	0.43	0.55	0.43	0.38	0.29
physics-based data assimilation ionosphere model									
1_USU-GAIM	0.94	0.81	0.88	0.81	0.70	0.75	0.90	0.79	0.81

- Ratios of two IRIs are similar to each other, but 2_IRI is better than 1_IRI in southern middle latitude; 1_SAMI3 shows better ratios of dTEC than 1_USU-IFM for most cases; TIE-GCMs show better ratios than other physics-based coupled ionosphere-thermosphere model simulations.
- TEC ratios of IRIs similar ratios to those from physics based models but ratios of dTEC_q and dTEC_p are much less than those of other simulations
- Data assimilation model, 1_USU-GAIM, shows the best performance in predicting TEC in low and northern middle latitude regions.

Ratio of maximum TEC & dTEC at 285°E

(Model/Observation)

low lat (0°<|lat|<25°), mid-lat (25°<|lat|<50°), high lat (|lat|>50 °)

1st among the same type
1st among all models

	low lat			mid-lat (south)			mid-lat (north)			high lat (south)			high lat (north)		
	TEC	dTEC_q	dTEC_p	TEC	dTEC_q	dTEC_p	TEC	dTEC_q	dTEC_p	TEC	dTEC_q	dTEC_p	TEC	dTEC_q	dTEC_p
empirical model															
1_IRI	0.73	0.23	0.19	0.92	0.06	0.06	0.48	0.04	0.04	0.63	0.07	0.07	0.37	0.03	0.03
2_IRI	0.81	0.21	0.17	0.98	0.06	0.06	0.49	0.15	0.15	0.89	0.68	0.68	0.41	0.04	0.04
physics-based ionosphere model															
1_SAMI3_HWM93	0.47	0.76	0.09	0.52	0.89	0.14	0.65	0.16	0.10						
1_USU-IFM	0.61	0.27	0.16	0.93	0.32	0.32	0.70	0.30	0.21	1.65	0.61	0.37	0.91	1.02	1.02
physics-based coupled ionosphere-thermosphere model															
1_CTIPE	0.50	0.61	0.40	0.39	0.46	0.34	0.36	0.15	0.13	0.48	0.43	0.31	0.22	0.22	0.26
2_CTIPE	0.58	0.82	0.71	0.45	0.51	0.31	0.75	0.60	0.60	0.50	0.52	0.30	0.71	0.99	0.82
1_TIE-GCM	0.70	1.06	0.64	0.51	0.83	0.21	0.96	1.19	1.21	0.57	0.72	0.50	1.20	1.72	1.78
2_TIE-GCM	0.67	0.88	0.69	0.49	0.59	0.26	0.88	0.69	0.68	0.46	0.56	0.30	0.86	0.96	0.82
1_UAM	0.51	0.92	0.48	0.58	0.90	0.71	0.72	0.64	0.65	0.76	0.69	0.69	0.56	0.85	0.81
physics-based data assimilation ionosphere model															
1_USU-GAIM	0.93	0.96	0.87	1.09	0.97	0.97	0.93	0.88	0.88	1.23	0.81	0.81	0.87	0.87	0.87

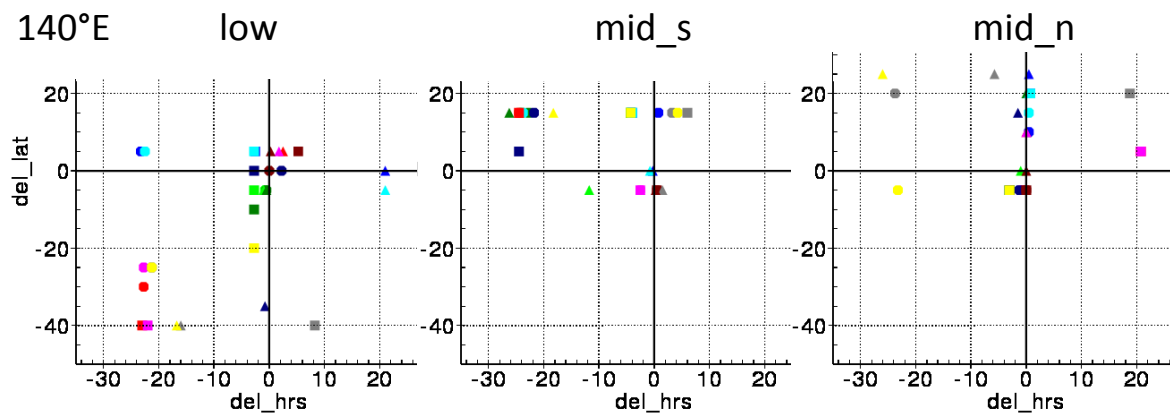
- 2_IRI produce better ratios than 1_IRI for most cases; 1_SAMI3 shows better ratios of dTEC than 1_USU-IFM for low and southern middle latitude cases; 1_UAM and 1_TIE-GCM show better ratios than other coupled model simulations.
- TEC ratios of IRIs similar ratios to those from physics based models but ratios of dTEC_q and dTEC_p are much less than those of other simulations for most cases.
- 1_USU-GAIM shows better ratios than others for many cases; the locations where the peak values occur should be considered.

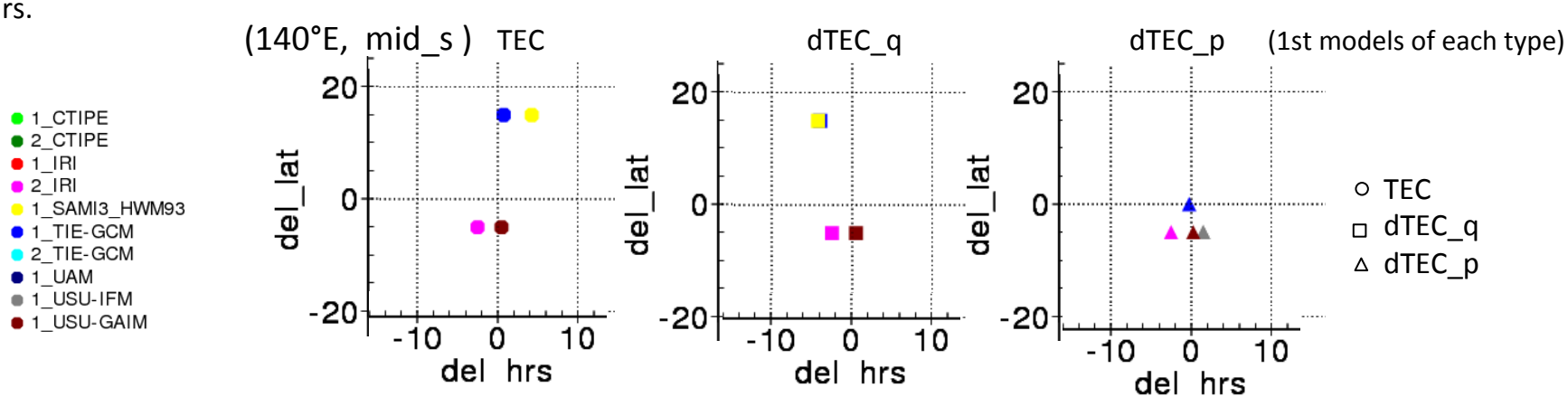
Example of locations of maximum TEC & dTEC at 140°E

low lat (0°<|lat|<25°), mid-lat (25°<|lat|<50°), high lat (|lat|>50 °)

del_hrs = time when maximum of modeled TEC or dTEC occurs – time when GPS TEC or dTEC max. occurs.

del_lat = latitude where maximum of modeled TEC or dTEC occurs – latitude when GPS TEC or dTEC max. occurs.





- For most cases, 1_USU-GAIM performs better in predicting time and location at which maximum values of TEC and dTEC occur.
- In southern mid-latitude at 140°E:
  - 1_SAMI3 has the best ratios of TEC and dTEC_q, but 1_USU-GAIM and 2_IRI have better del_hrs and del_lat.
  - 2_IRI has the best ratios of dTEC_p, but 1_TIE-GCM and 1_USU-GAIM and 1_USU-IFM show better prediction of timing and location.

Summary

- For 2006 Dec. event, we evaluated IT model performance of predicting TEC in two 5 degree longitude sectors 140°E (140-145) and 285°E (285-290)
  - The IT models used for the study range from empirical model (IRI), physics-based ionosphere model (SAMI3 and USU-IFM), coupled ionosphere-thermosphere physics-based model (CTIPe, TIE-GCM, and UAM) to data assimilation model (USU-GAIM).
  - RMS error of three quantities, TEC and TEC changes (dTEC_q = TEC-TEC_quiet_day and dTEC_p = TEC-TEC_yesterday), of the models were calculated.
  - Ratio of maximum of the three quantities of the models were also compared.

- Three TEC measurement sets were compared:
  - number of data points: MIT > JPL ,
  - average error: MIT > JPL,
  - MIT TEC < JPL TEC (not all cases, but most cases)
  - JPL TEC and IGS TEC are similar to each other.

- GPS-TEC (provided by MIT) was used as a ground truth.
  - TEC values with error less than 4 TECU were only used
  - For 140 °E and 285 °E sector: average error = about 2 TECU,
    average number of data point per 5x5 bin = about 20

- Performance of models depends on

longitudes:

- e.g., in terms of RMS error, CTIPEs show better performance than TIE-GCMS in 140 °E longitude sector, however, TIE-GCMs are better than CTIPEs for more cases in 285 °E longitude sector.
- In low latitude regions, all models have smaller RMS error in 285 °E than 140 °E sector.
- 1_UAM shows better performance in predicting peak values of TEC and dTEC in 285 °E than 140 °E sector.

latitudes:

- Data assimilation model, 1_USU-GAIM, shows the best performance in predicting TEC and dTEC in low and middle latitude regions in the both longitude sectors, but in high latitudes in 285 °E region, 2_CTIPE (for TEC in southern high latitude) and 2_TIE-GCM(for dTECs in northern high latitude) have better score than 1_USU-GAIM.
- 1_USU-GAIM.

metrics:

- Among physics-based coupled models, in terms of RMS error, CTIPEs and TIE-GCMs have better scores than 1_UAM, while 1_UAM shows better performance than others in predicting peak values of TEC and dTEC in 285 °E.

parameters:

- in 285 °E (in southern middle and high latitudes), 2_IRI and 1_USU-GAIM show the best performance in predicting peak values of TEC, and dTEC, respectively.