Ionospheric Data Assimilation and Forecasting During Storms

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Beacons Satellite Symposium - 29 June 2016

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Summary

Aim: Predict midlatitude ionospheric electron densities 1-hour ahead during geomagnetic storms

- Data assimilation using GPS TEC and a coupled ionosphere-thermosphere model (TIEGCM) in 90-member ensemble Kalman filter

- Model drivers include randomized TIMED/SEE solar flux observations, AMIE high-latitude electric fields and precipitation (encompassing DMSP, NOAA, SuperDARN, SuperMAG data)

- One-hour ionospheric forecasts compared against CHAMP electron densities, Incoherent Scatter Radar (Millstone Hill and Arecibo) and GPS TEC.

Motivation

- During geomagnetic storms there is a tremendous deposition of energy and momentum into the high-latitude ionosphere-thermosphere system
- The atmosphere responds through penetration electric fields, rapid equatorward neutral winds (TADs/TIDs) and a global reconfiguration of thermospheric composition
- To predict the midlatitude ionospheric response to extreme space weather events, we need an accurate specification of the Solar and geomagnetic inputs, a self-consistent description of the thermospheric response and large-scale data assimilation to correct model biases

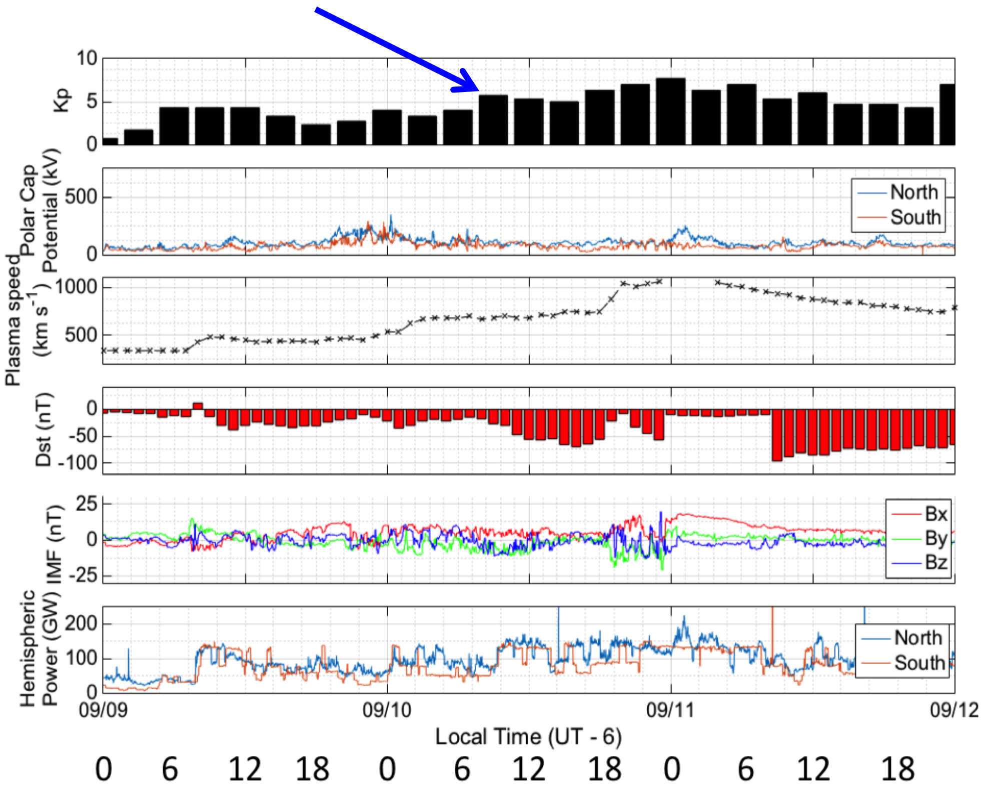
Data Assimilation Research Testbed (DART) provides a state-of-the-art open-source platform to build such a system within a multivariate ensemble Kalman filter framework: image.ucar.edu/DAReS/DART/

Storm cases

Primary storm case:

10 September 2005 (**not 11 September**)

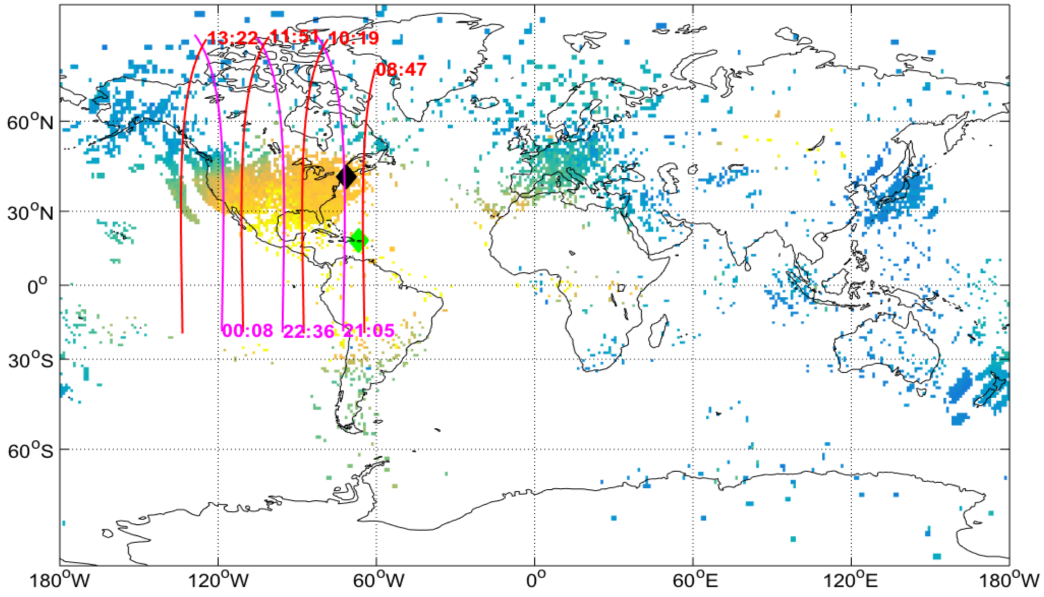
- $K_p = 6^-$ occurred in the 6-9 LT window on 10 September
- Storm-enhanced density region formed over North America between 12-13 LT
- Positive phase in North America can be defined to occur between 9-18 LT.



Secondary case: Anomalous storm of 21 January 2005 also analysed by *Chartier et al.* [2016]. The TEC results in that case are consistent with the primary case, but somewhat less accurate. ISR data are not available in that case.

Approach

- Drive a 90-member ensemble of the TIEGCM thermosphere-ionosphere model with randomized solar and geomagnetic drivers [show AMIE randomization]
- Assimilate pre-processed ground GPS data from 3000 ground receiver stations hourly. Three-dimensional, time-varying covariances are calculated from the modeled ensemble and localized in joint space.
- Compare 1-hour predictions against CHAMP (red north, pink south) in-situ electron densities from the onboard Langmuir probe, ISR electron density profiles from Millstone Hill and Arecibo, and GPS TEC from the later time.



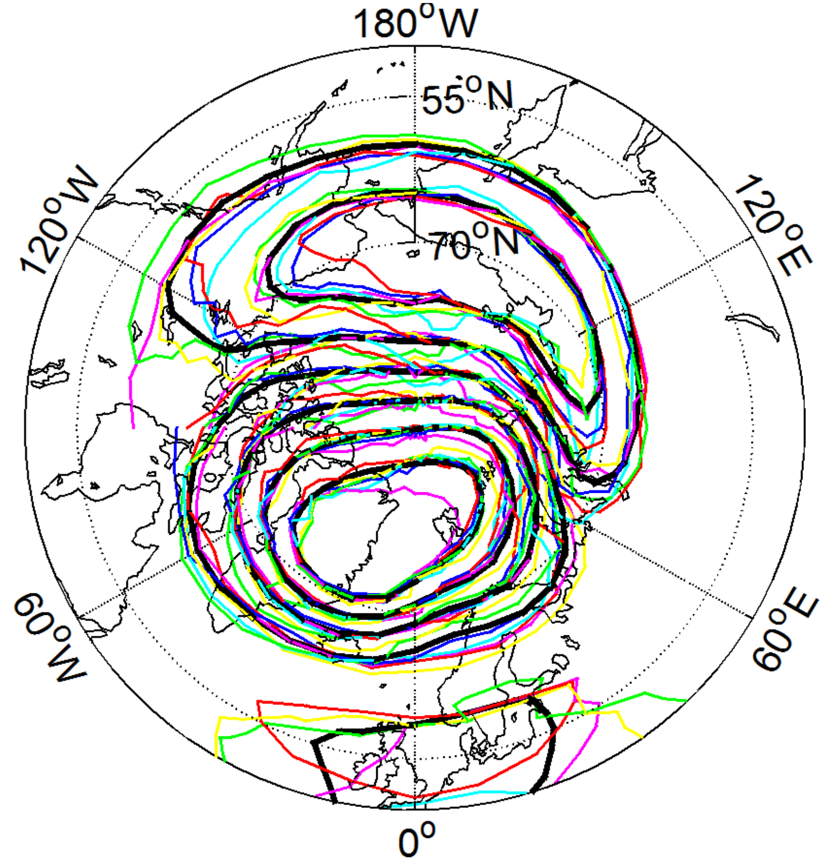
Limitations

- TIEGCM is hydrostatic, so underestimates vertical winds caused by high-lat heating.
- GPS data are ‘verticalized’ for easier assimilation, and contain a plasmaspheric contribution that has to be estimated
- EnKF must assume Gaussian error statistics

Driver perturbations

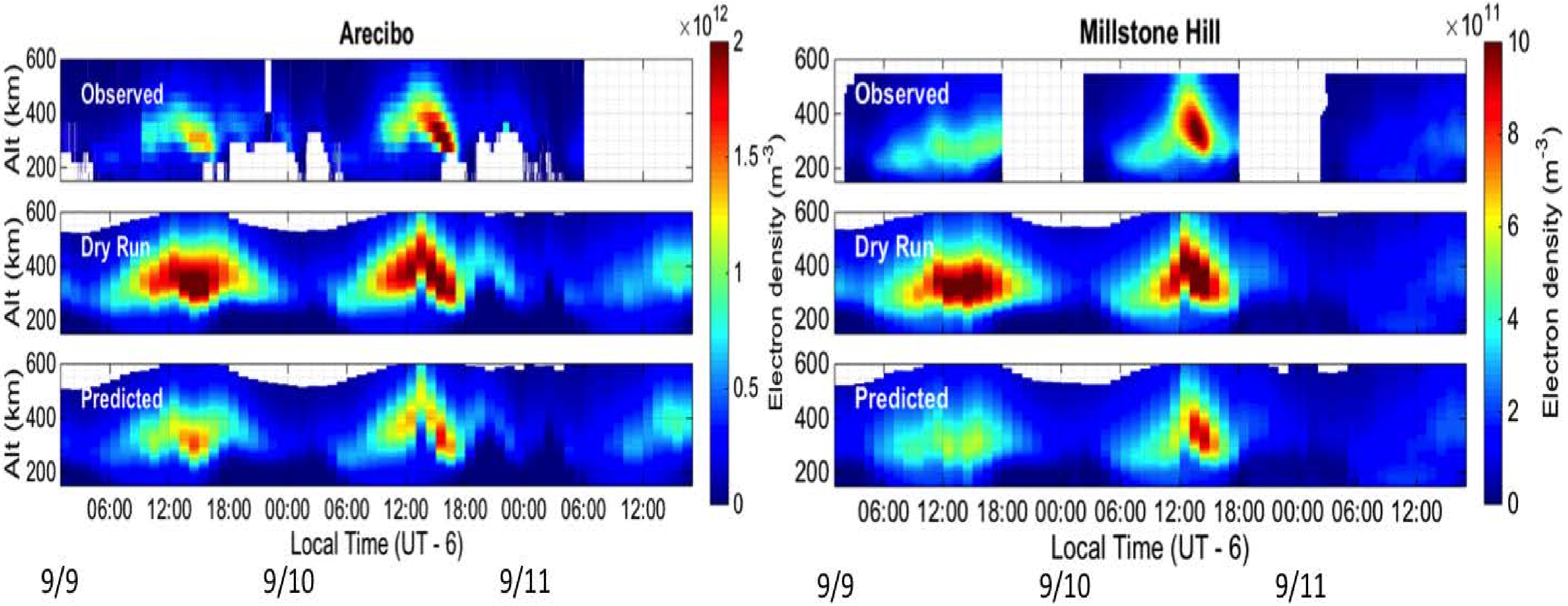
Goal: represent uncertainties in Solar and geomagnetic drivers

- 90 randomized versions of AMIE are sampled from zero-mean normal distributions of parameters: electric potential (Δ30%), cusp latitude, mean energy and energy flux (all Δ10%)
- TIMED/SEE observations of solar flux spectrum (taken ~15x daily) are sampled from zero-mean normal distribution of Δ10%



Results: Profiles at Arecibo and Millstone Hill

- At Arecibo (lat/lon) and Millstone Hill (lat/lon), the model captures the storm-time height variation of the ionosphere accurately, but has a large positive bias in electron density. Ensemble means are shown.
- Using GPS TEC data assimilation, 1-hour predictions matches the observed electron density distribution much better.



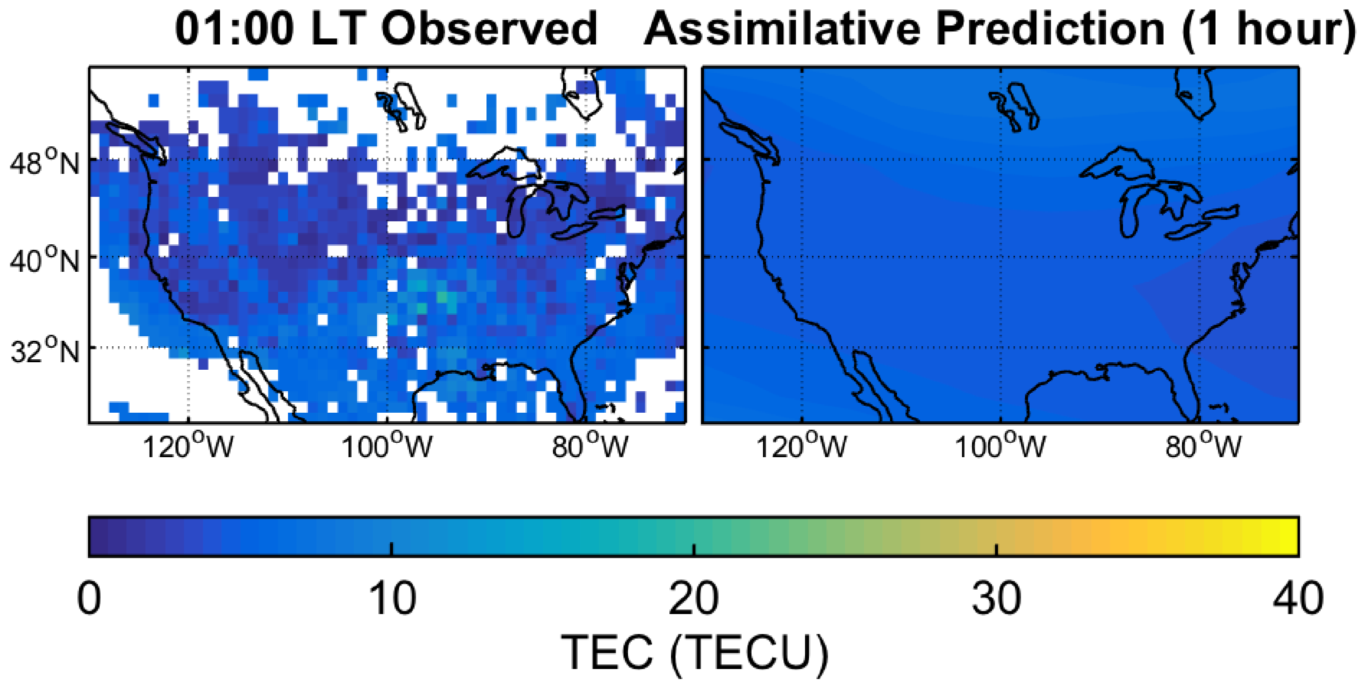
Results: VTEC comparison

- One-hour assimilative predictions of TEC match the large-scale trends and magnitudes over the continental USA observed using GPS data.

- Primary discrepancy is the lack of a ridge-like enhancement extending northwards from low latitudes. This is likely to be the storm-enhanced density plume described by *Foster et al.* [2002], which is above the model top (>2 Re according to *Foster et al.* [2002])

- Assimilative predictions do not show the small-scale variability of the GPS TEC observations

TEC results



01:00 LT Observed
Assimilative Prediction (1 hour)
48°N
40°N
32°N
120°W
100°W
80°W
120°W
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80°W
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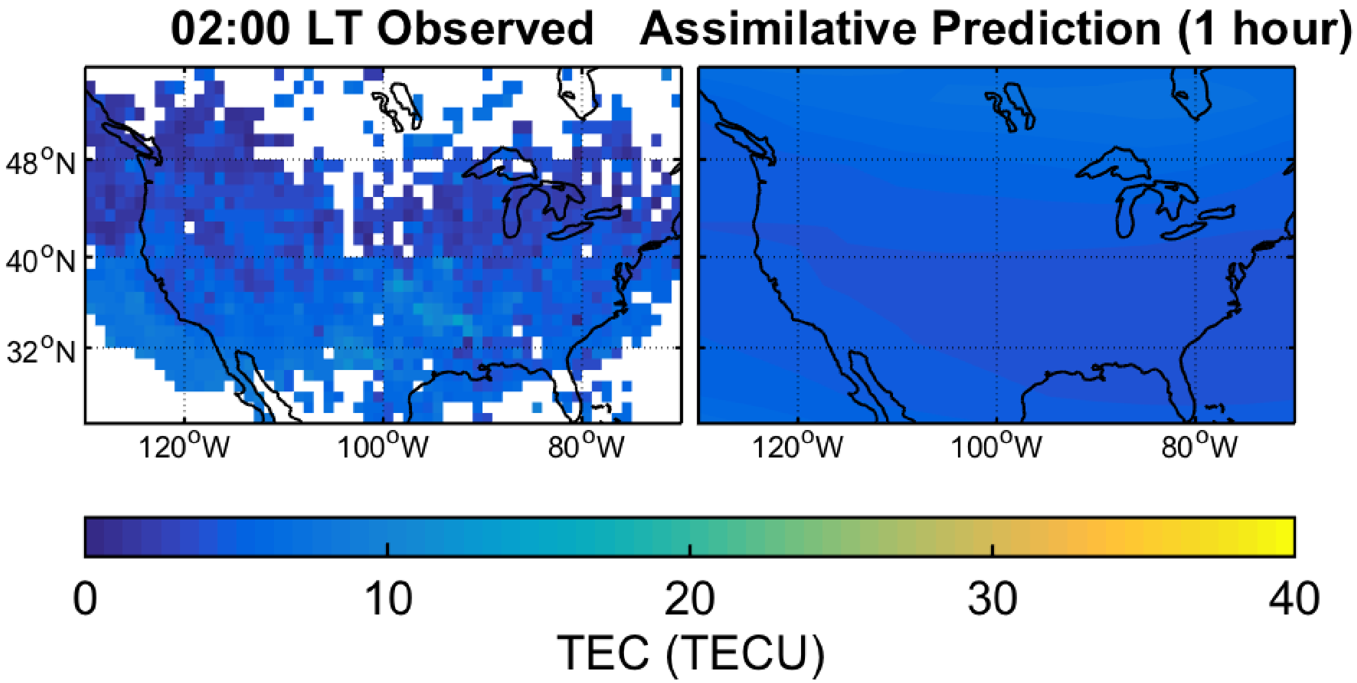
TEC (TECU)

TEC results



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40°N
32°N
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80°W
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80°W
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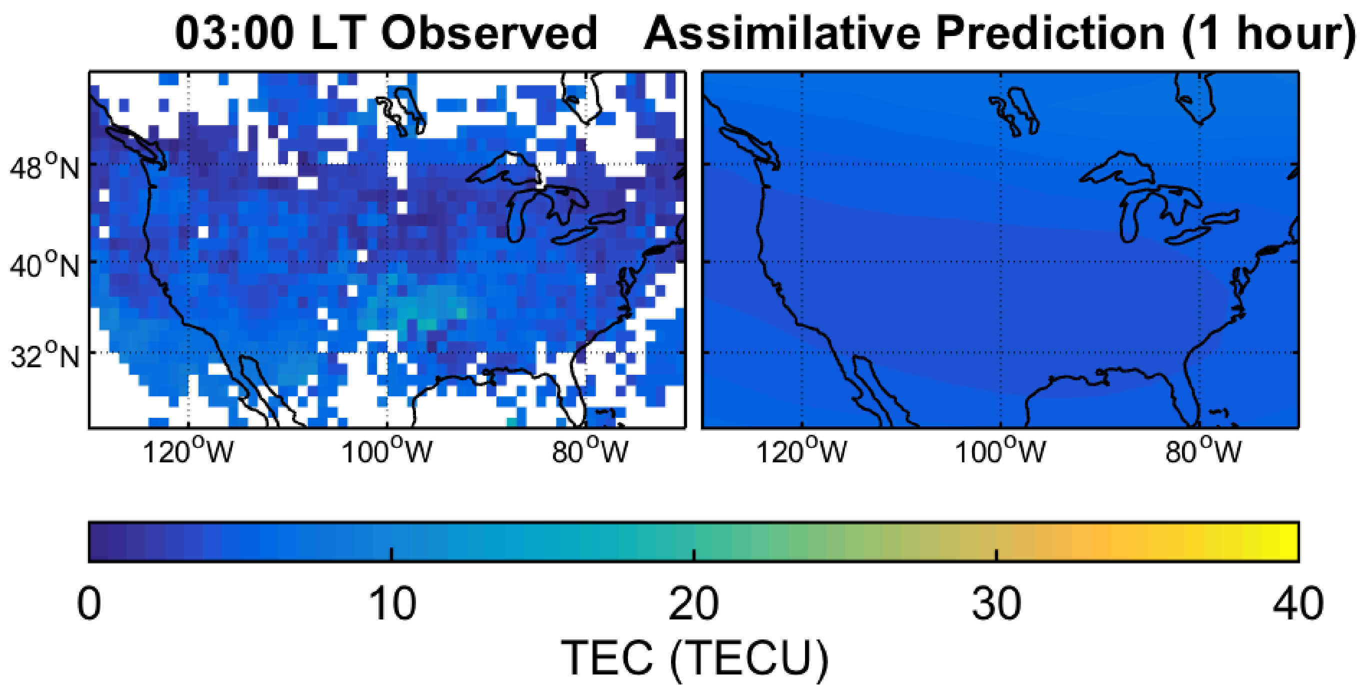
TEC (TECU)

TEC results



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40°N
32°N
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80°W
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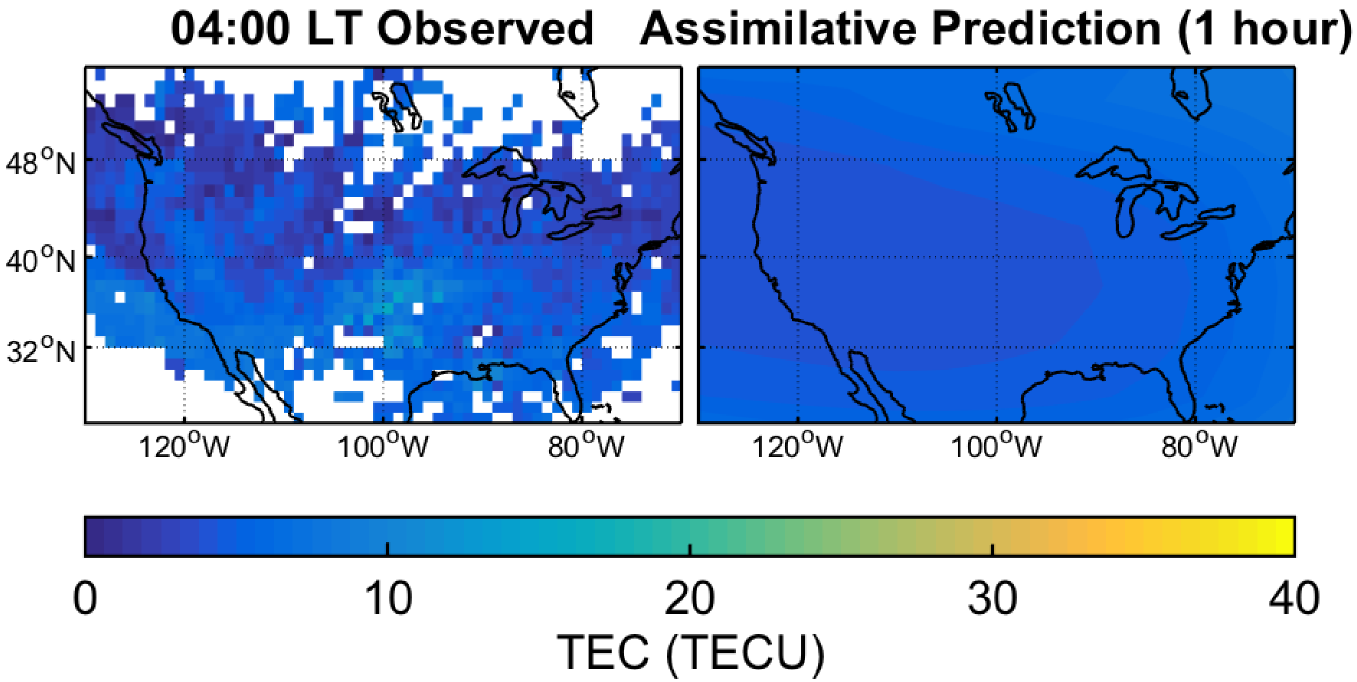
TEC (TECU)

TEC results



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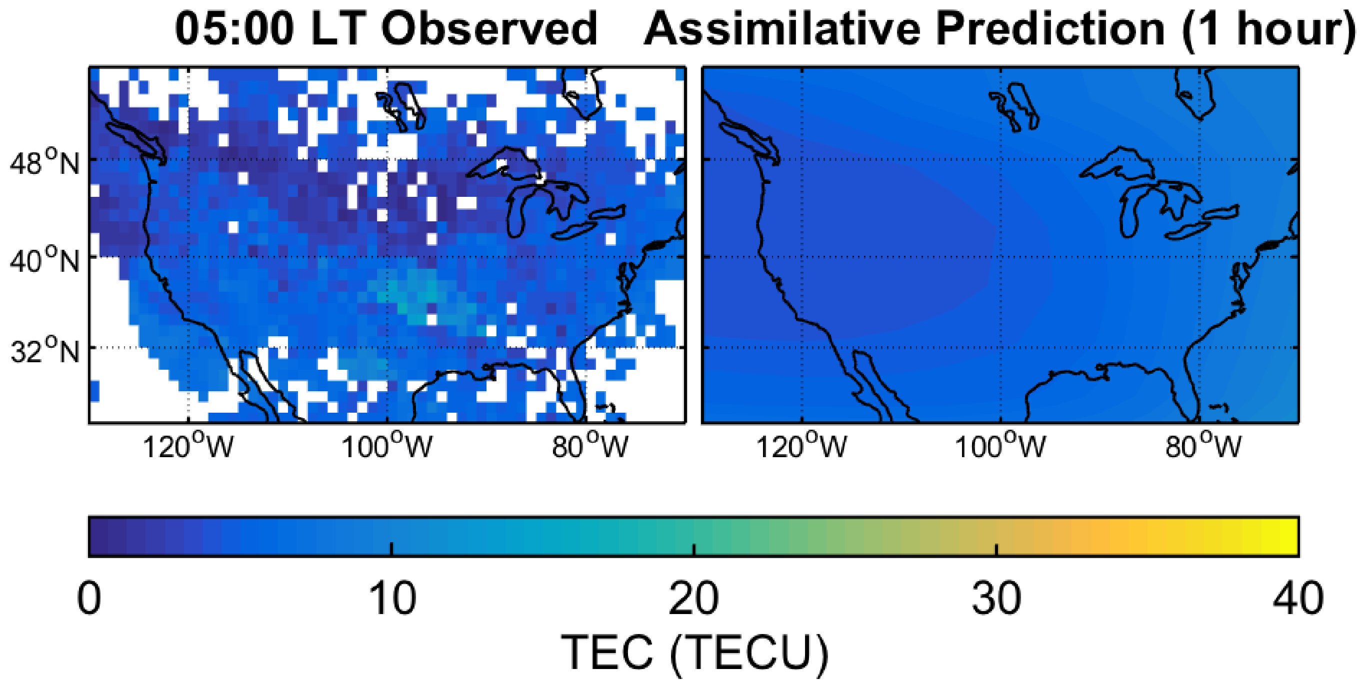
TEC (TECU)

TEC results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40°N
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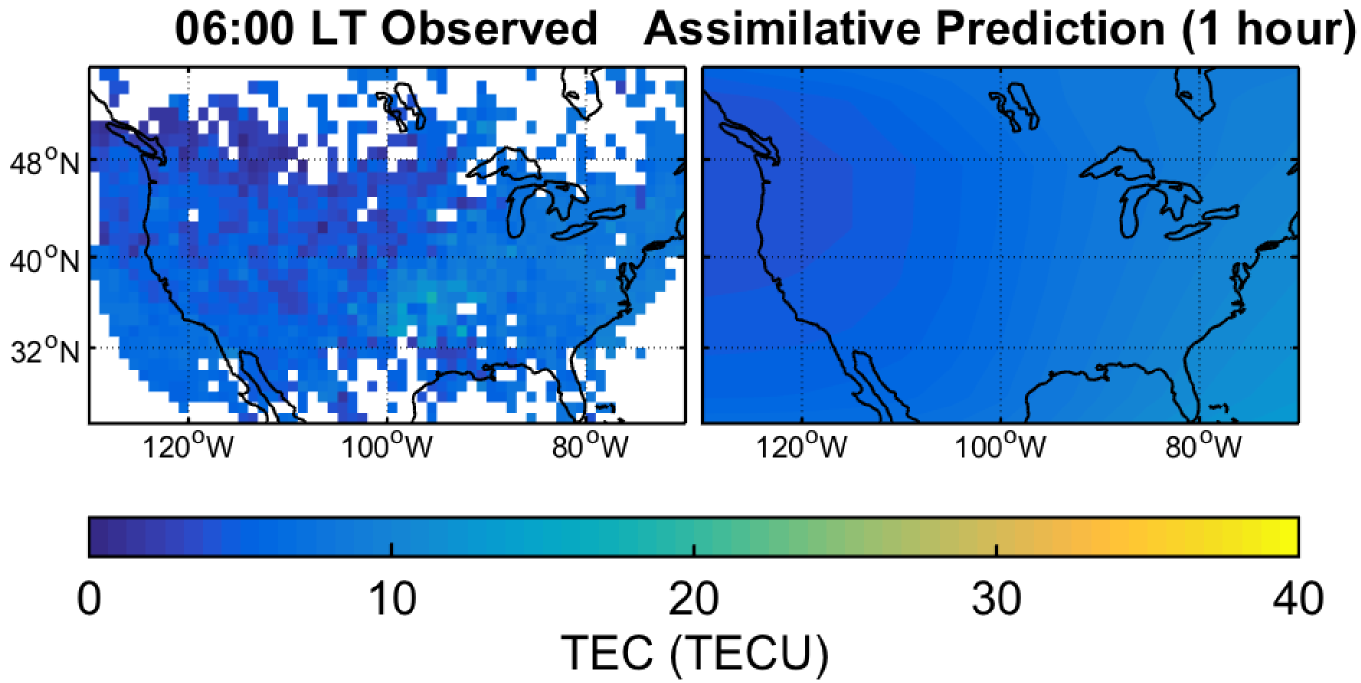
TEC (TECU)

TEC results



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Assimilative Prediction (1 hour)
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40°N
32°N
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80°W
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80°W
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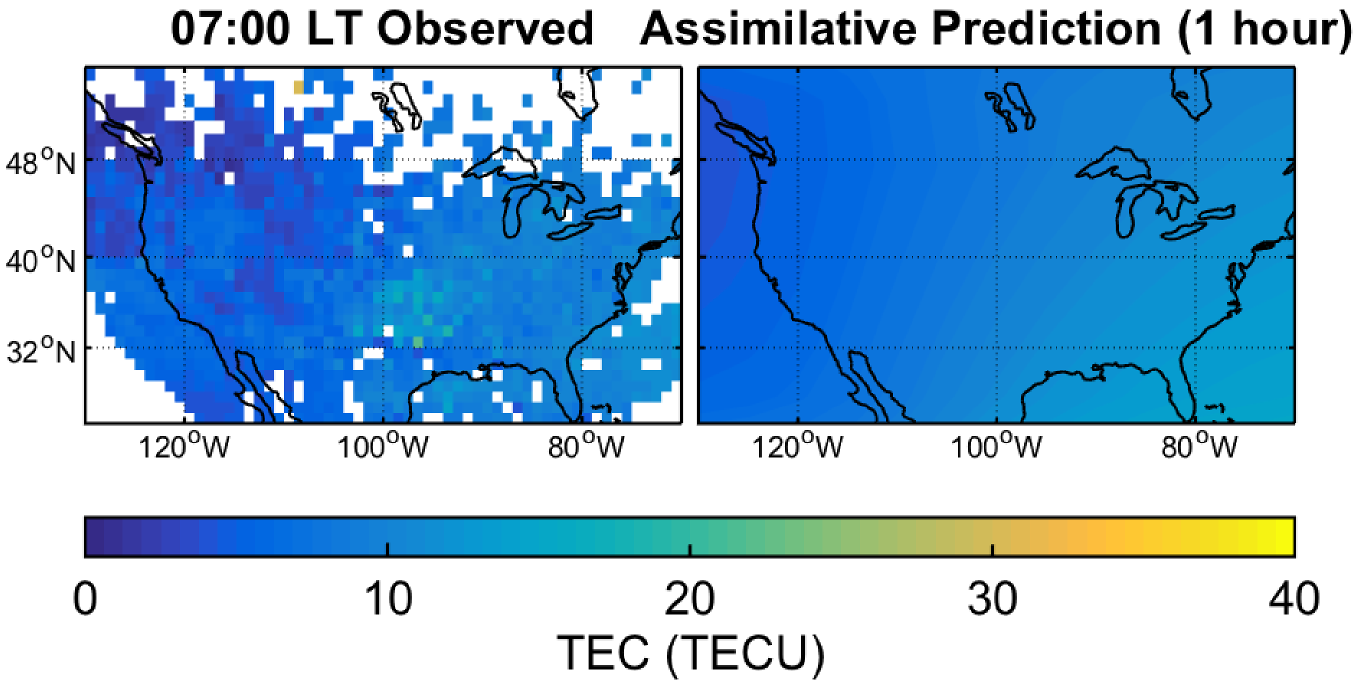
TEC (TECU)

TEC results



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Assimilative Prediction (1 hour)
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40°N
32°N
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80°W
120°W
100°W
80°W
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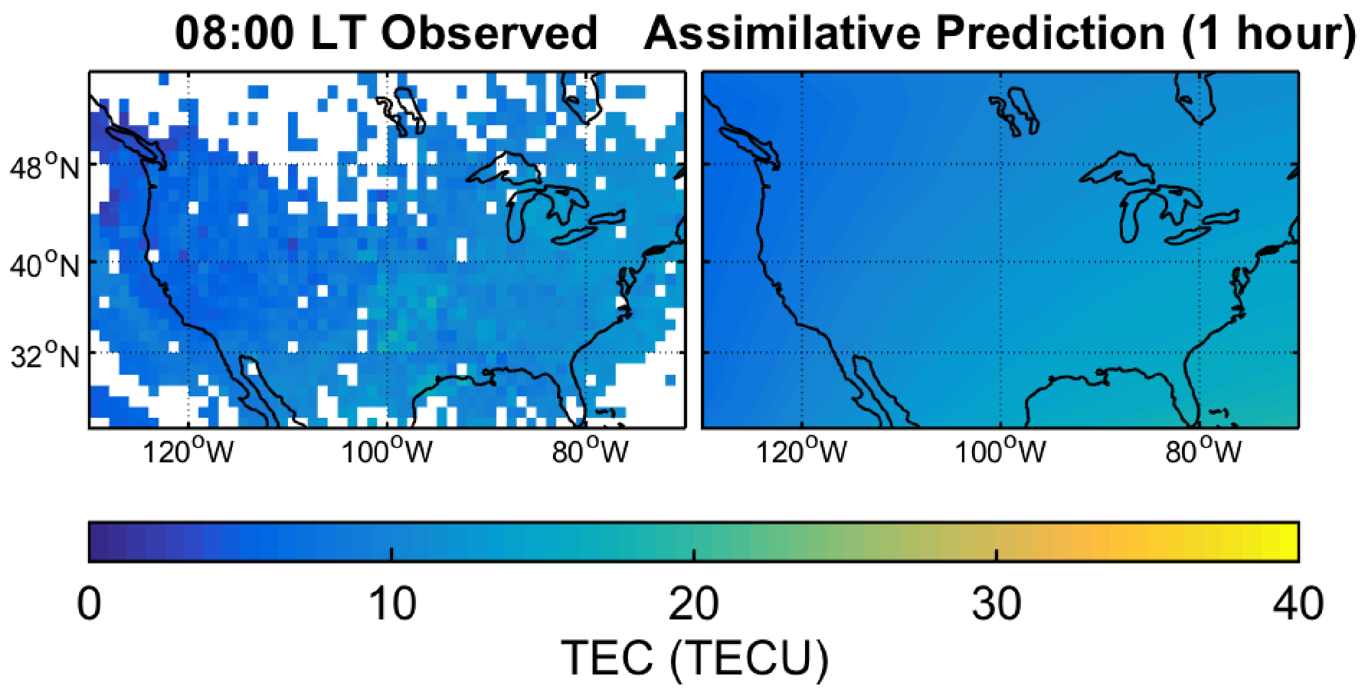
TEC (TECU)

TEC results



08:00 LT Observed
Assimilative Prediction (1 hour)
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40°N
32°N
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80°W
120°W
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80°W
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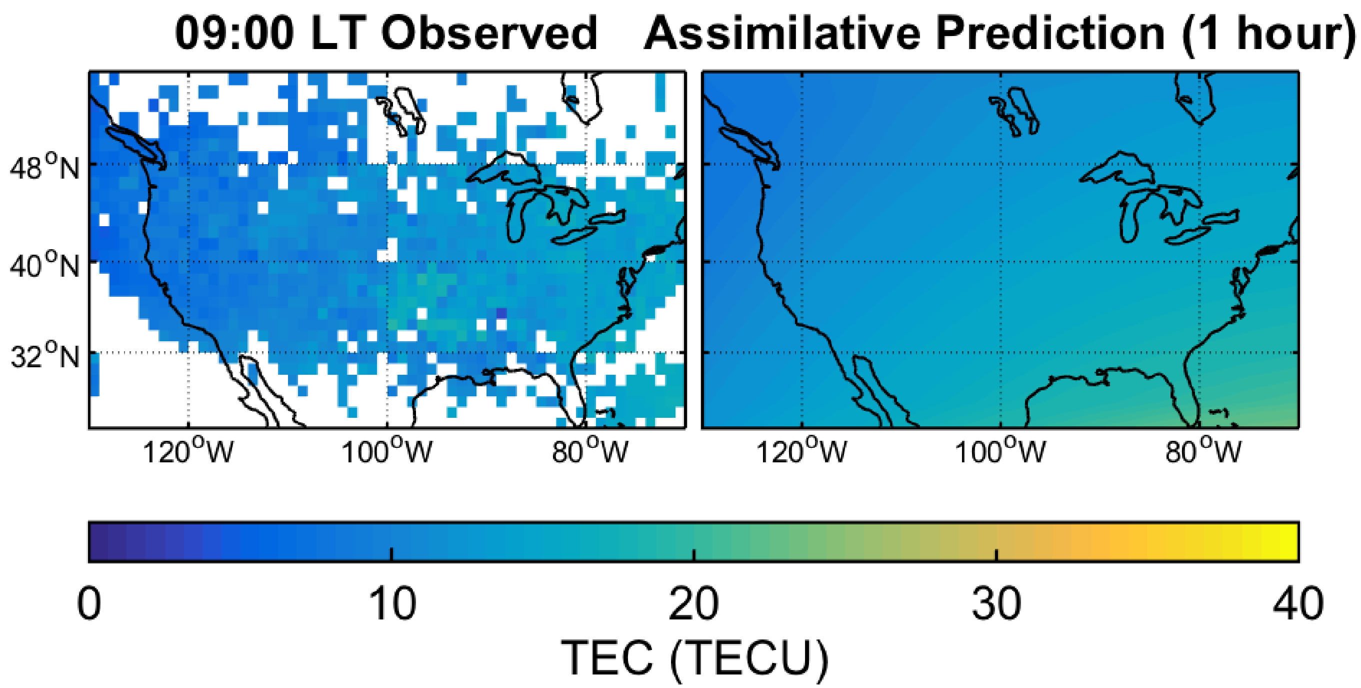
TEC (TECU)

TEC results



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Assimilative Prediction (1 hour)
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40°N
32°N
120°W
100°W
80°W
120°W
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80°W
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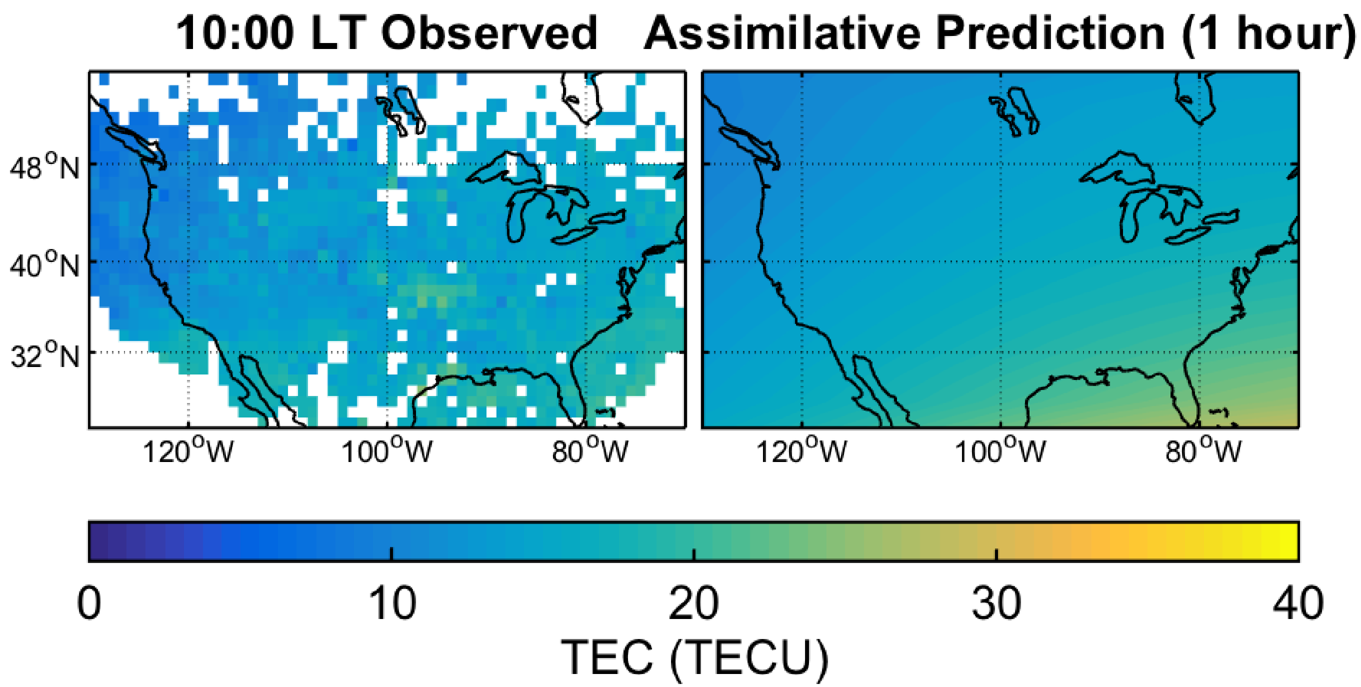
TEC (TECU)

TEC results



10:00 LT Observed
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40°N
32°N
120°W
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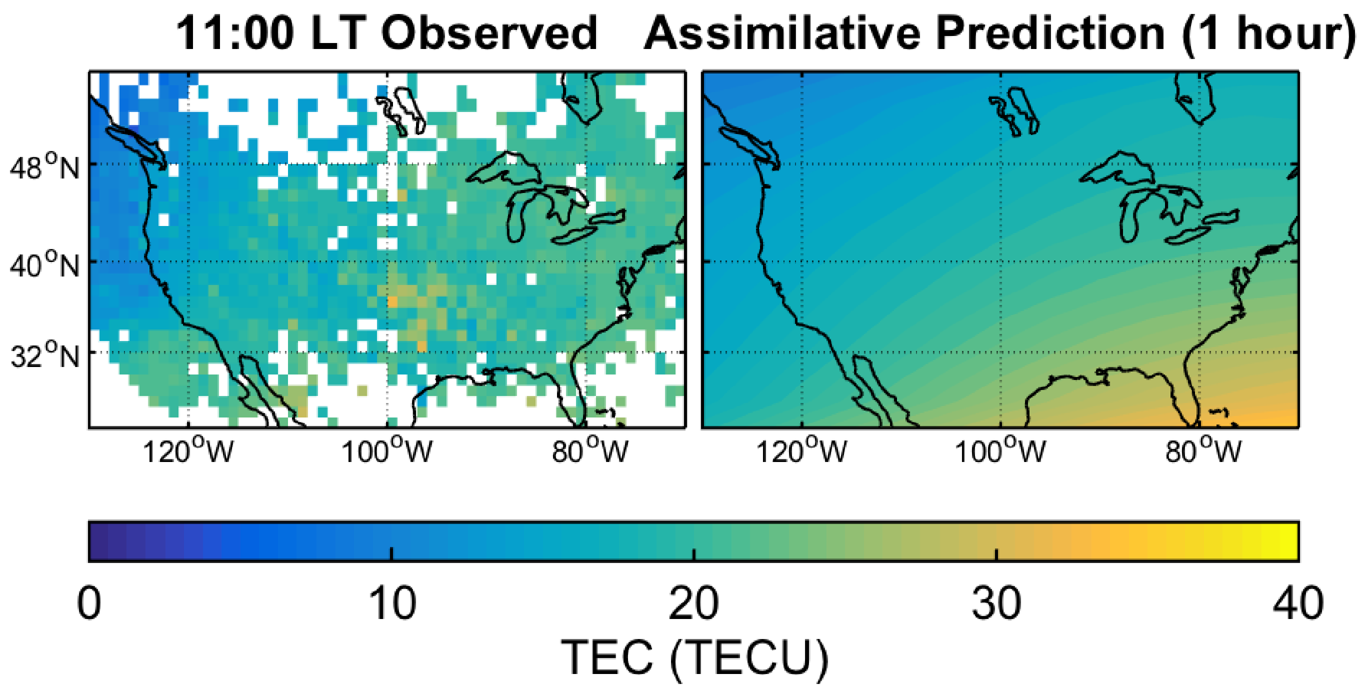
TEC (TECU)

TEC results



11:00 LT Observed
Assimilative Prediction (1 hour)
48°N
40°N
32°N
120°W
100°W
80°W
120°W
100°W
80°W
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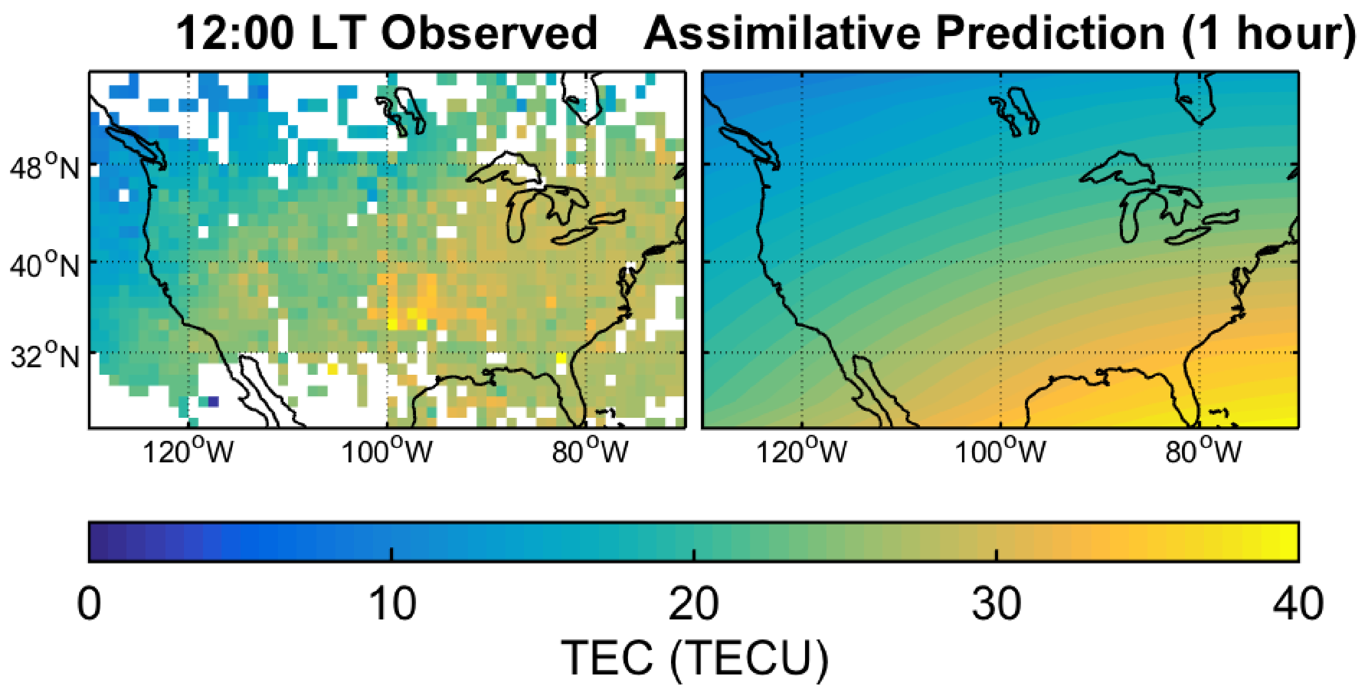
TEC (TECU)

TEC results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Assimilative Prediction (1 hour)
48°N
40°N
32°N
120°W
100°W
80°W
120°W
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80°W
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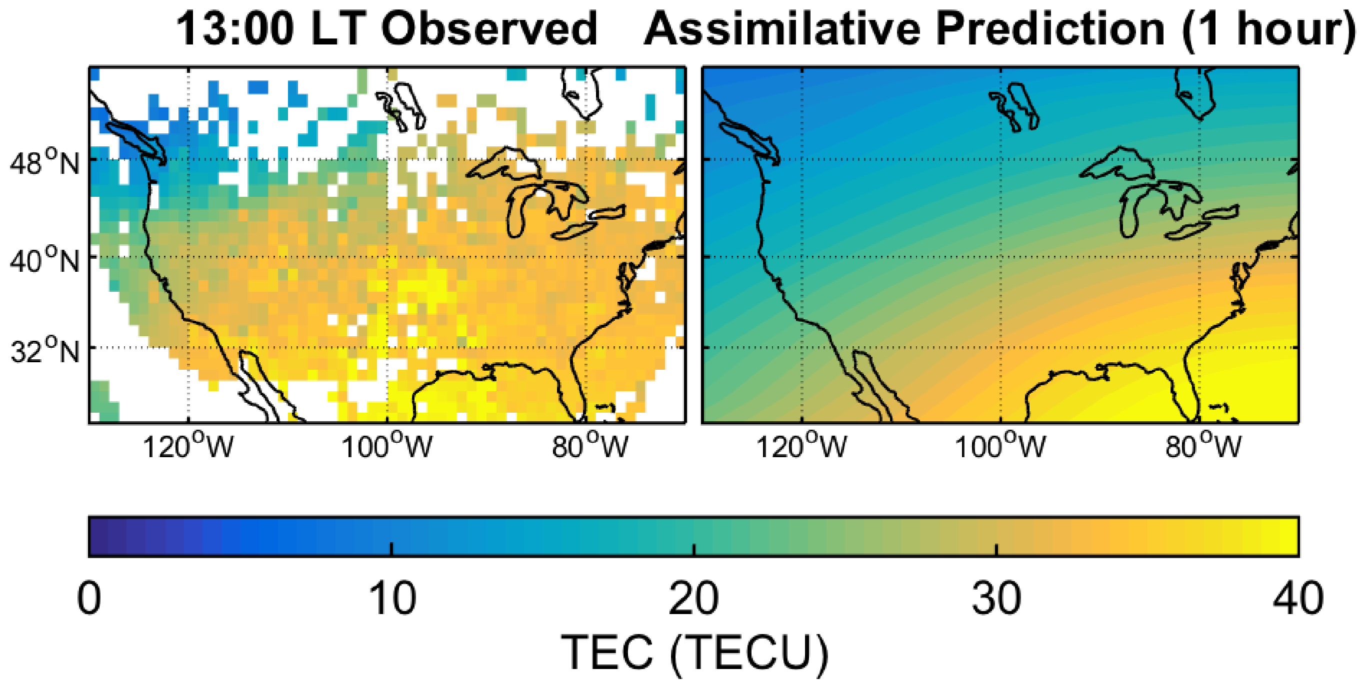
TEC (TECU)

TEC results



13:00 LT Observed
Assimilative Prediction (1 hour)
48°N
40°N
32°N
120°W
100°W
80°W
120°W
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80°W
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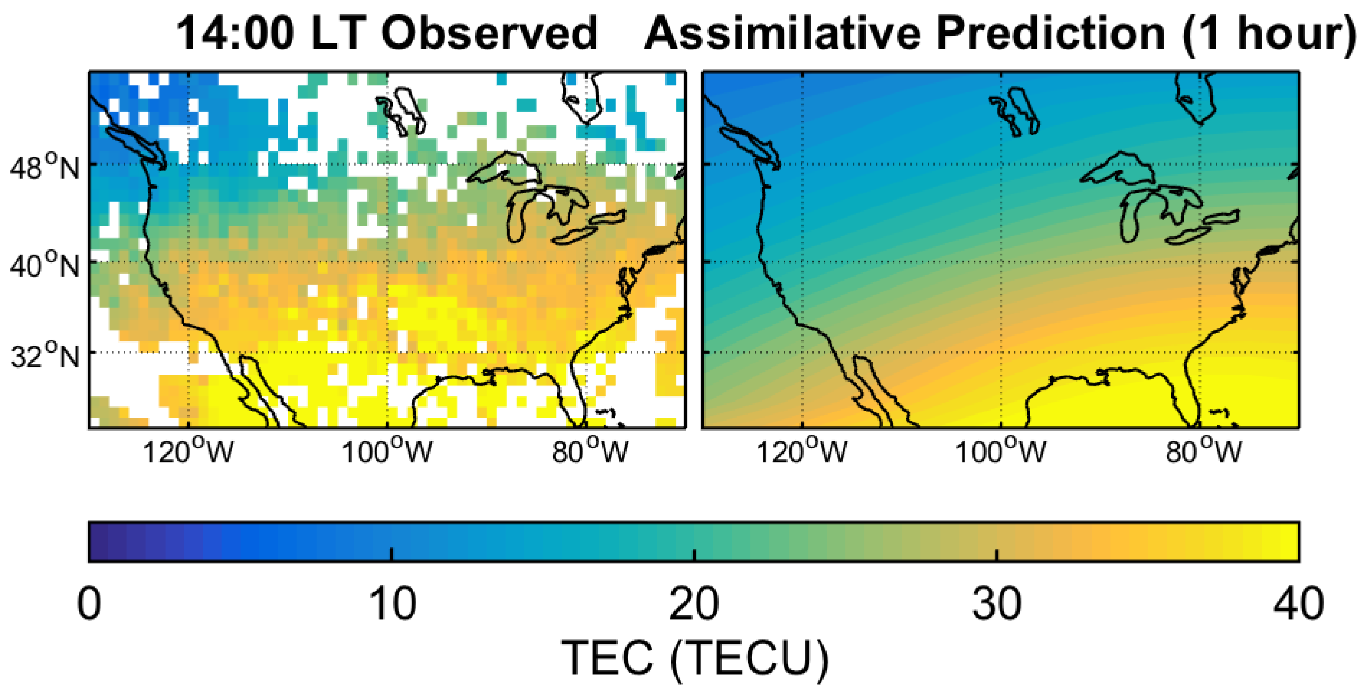
TEC (TECU)

TEC results



14:00 LT Observed
Assimilative Prediction (1 hour)
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40°N
32°N
120°W
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80°W
120°W
100°W
80°W
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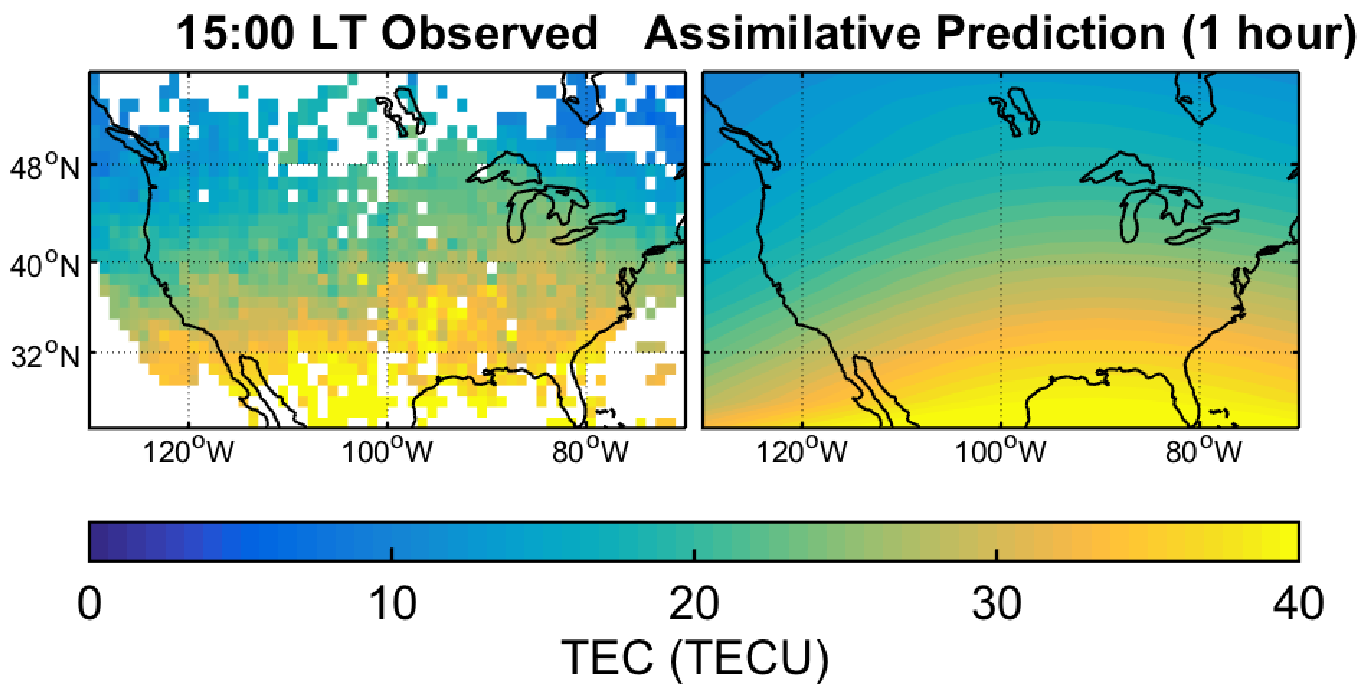
TEC (TECU)

TEC results



15:00 LT Observed
Assimilative Prediction (1 hour)
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40°N
32°N
120°W
100°W
80°W
120°W
100°W
80°W
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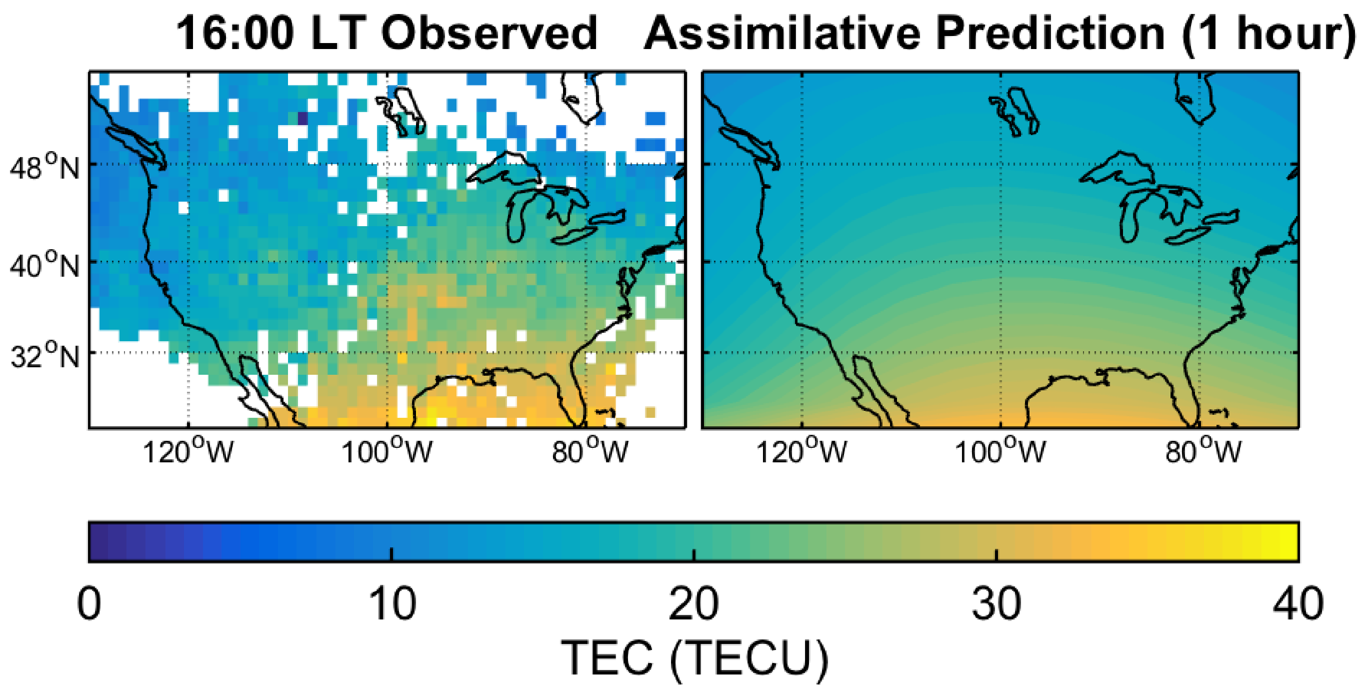
TEC (TECU)

TEC results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Assimilative Prediction (1 hour)
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40°N
32°N
120°W
100°W
80°W
120°W
100°W
80°W
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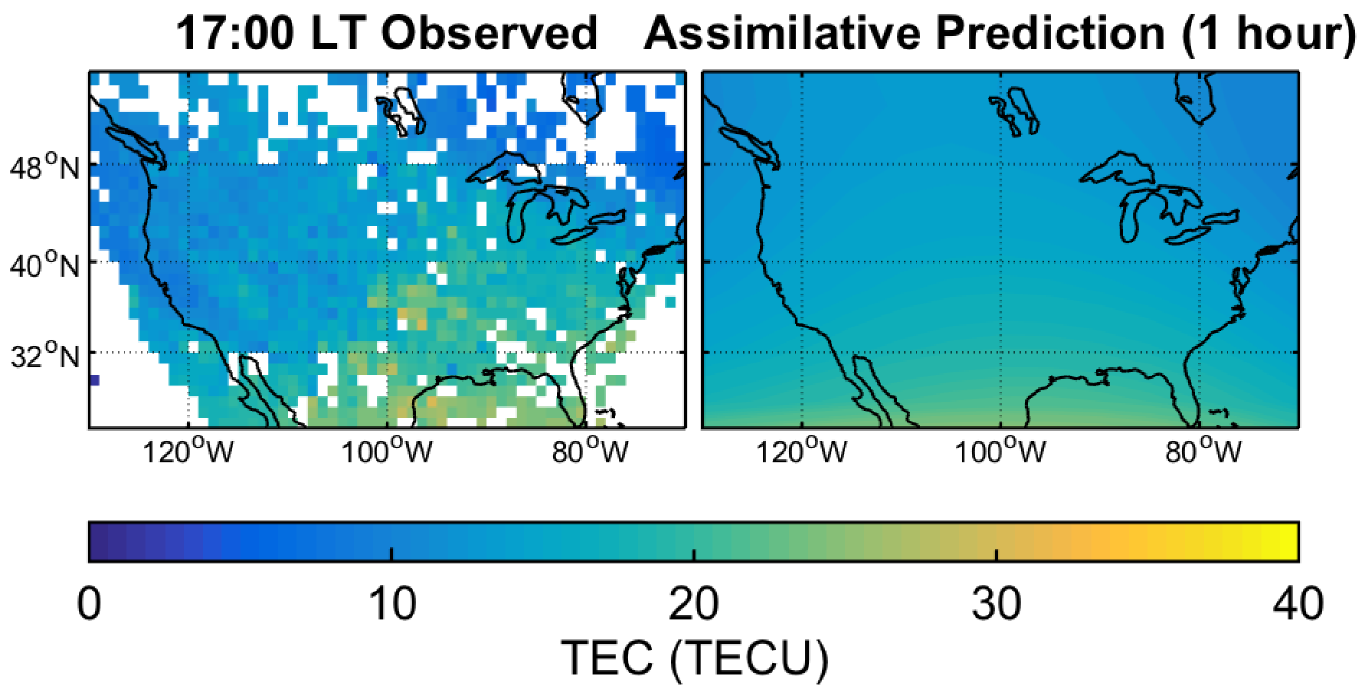
TEC (TECU)

TEC results



17:00 LT Observed
Assimilative Prediction (1 hour)
48°N
40°N
32°N
120°W
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120°W
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80°W
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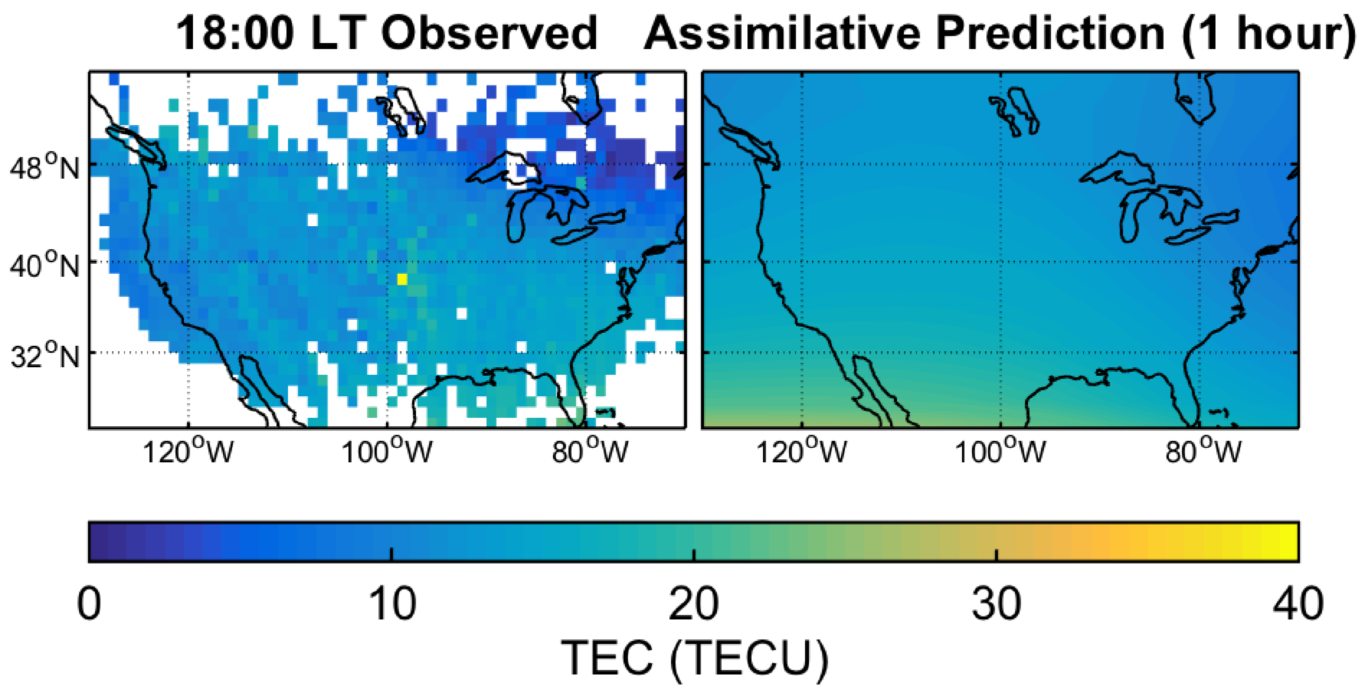
TEC (TECU)

TEC results



18:00 LT Observed
Assimilative Prediction (1 hour)
48°N
40°N
32°N
120°W
100°W
80°W
120°W
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80°W
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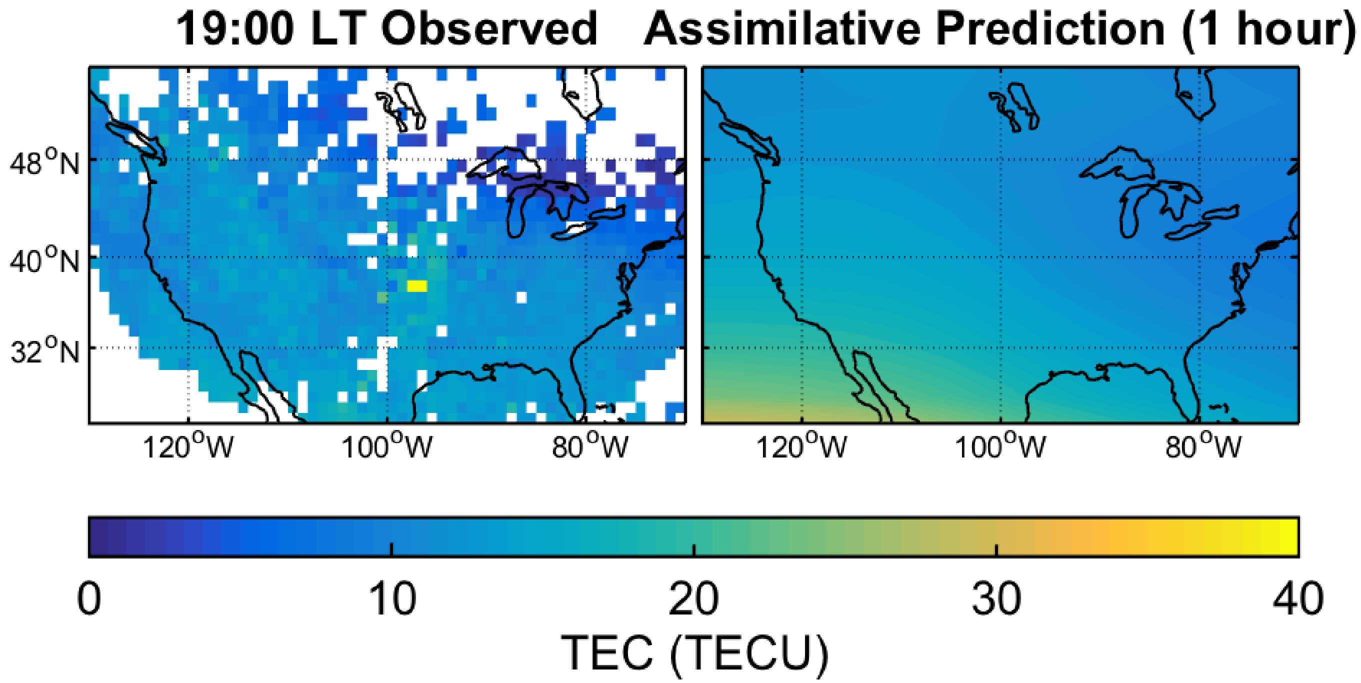
TEC (TECU)

TEC results



19:00 LT Observed
Assimilative Prediction (1 hour)
48°N
40°N
32°N
120°W
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80°W
120°W
100°W
80°W
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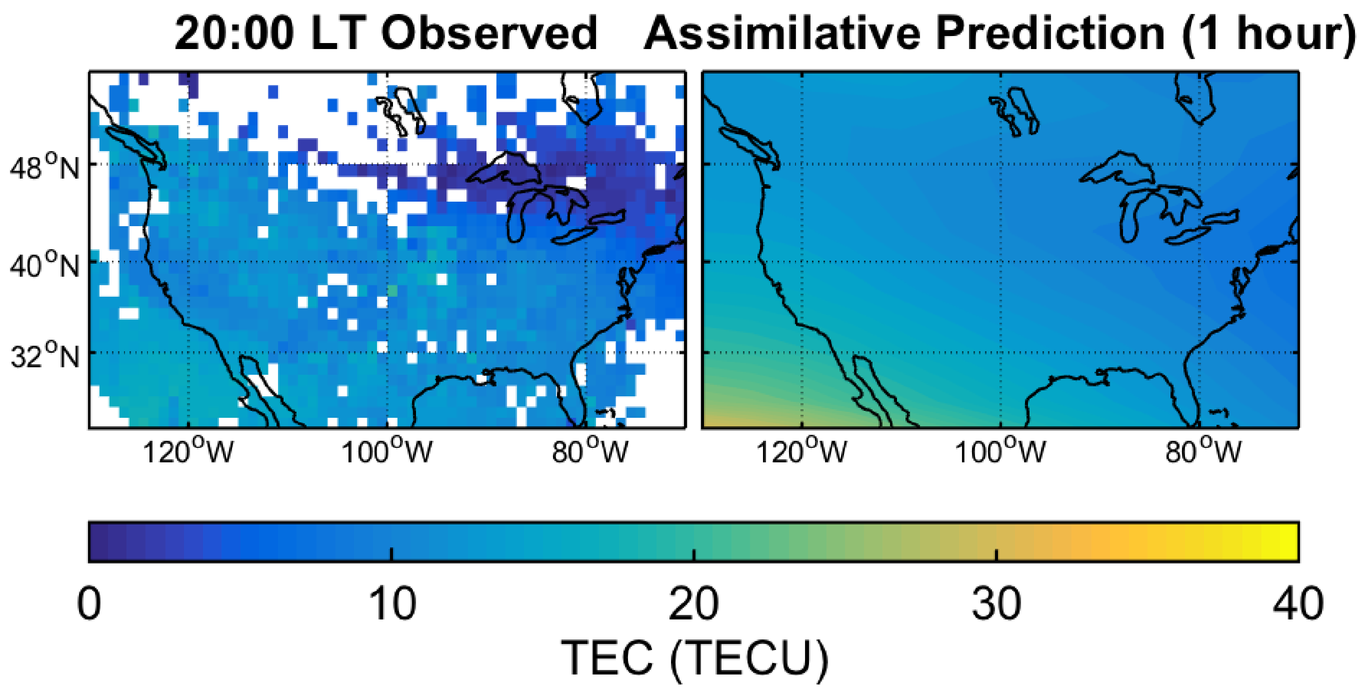
TEC (TECU)

TEC results



20:00 LT Observed
Assimilative Prediction (1 hour)
48°N
40°N
32°N
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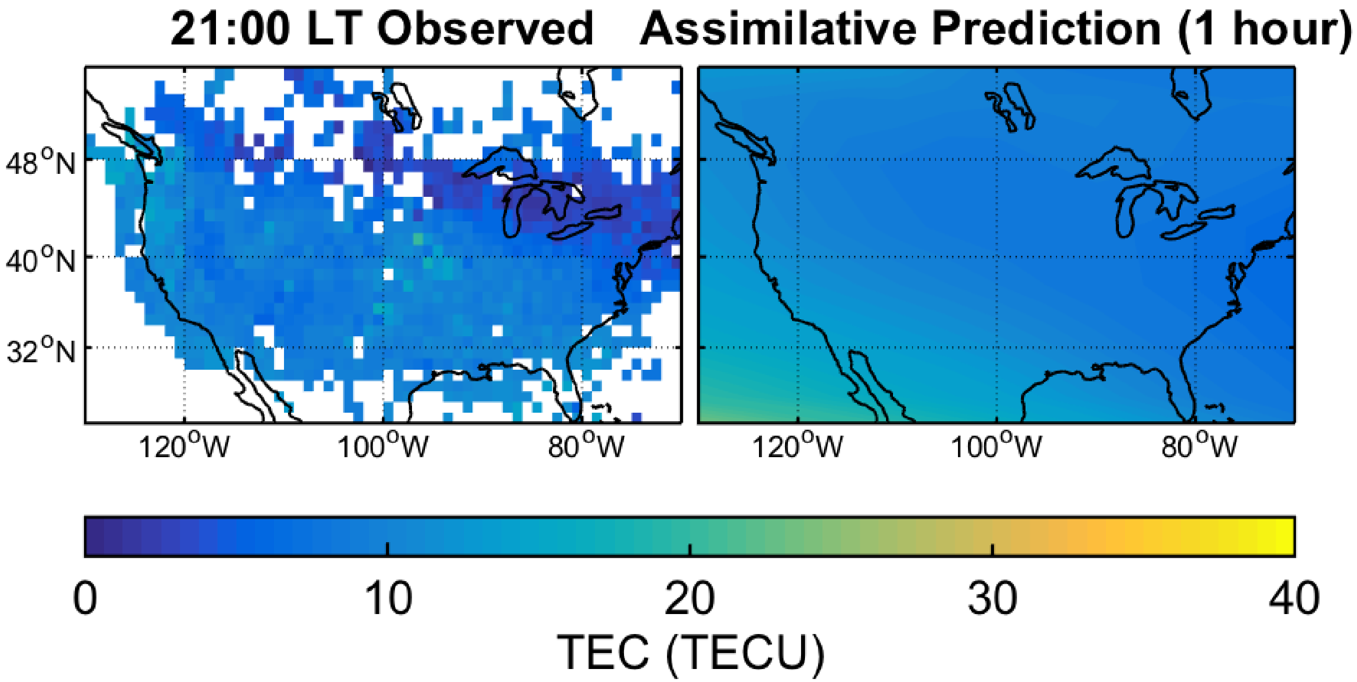
TEC (TECU)

TEC results



21:00 LT Observed
Assimilative Prediction (1 hour)
48°N
40°N
32°N
120°W
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80°W
120°W
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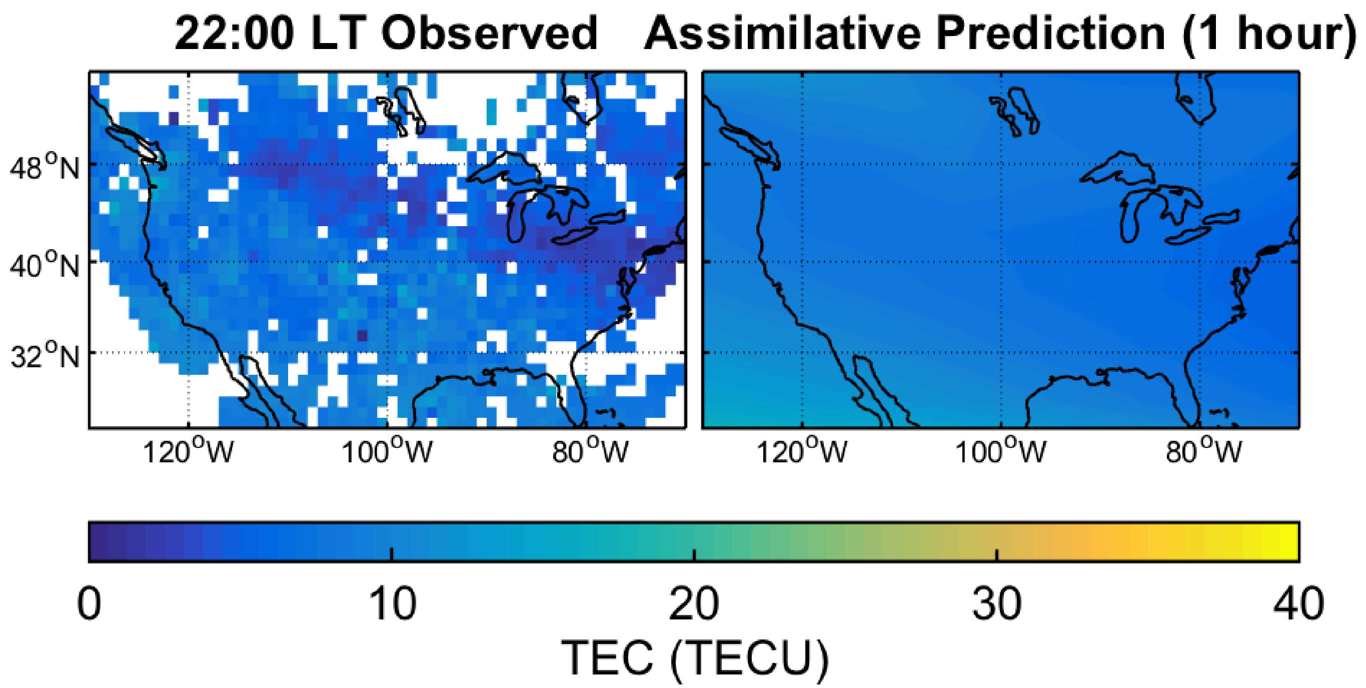
TEC (TECU)

TEC results



22:00 LT Observed
Assimilative Prediction (1 hour)
48°N
40°N
32°N
120°W
100°W
80°W
120°W
100°W
80°W
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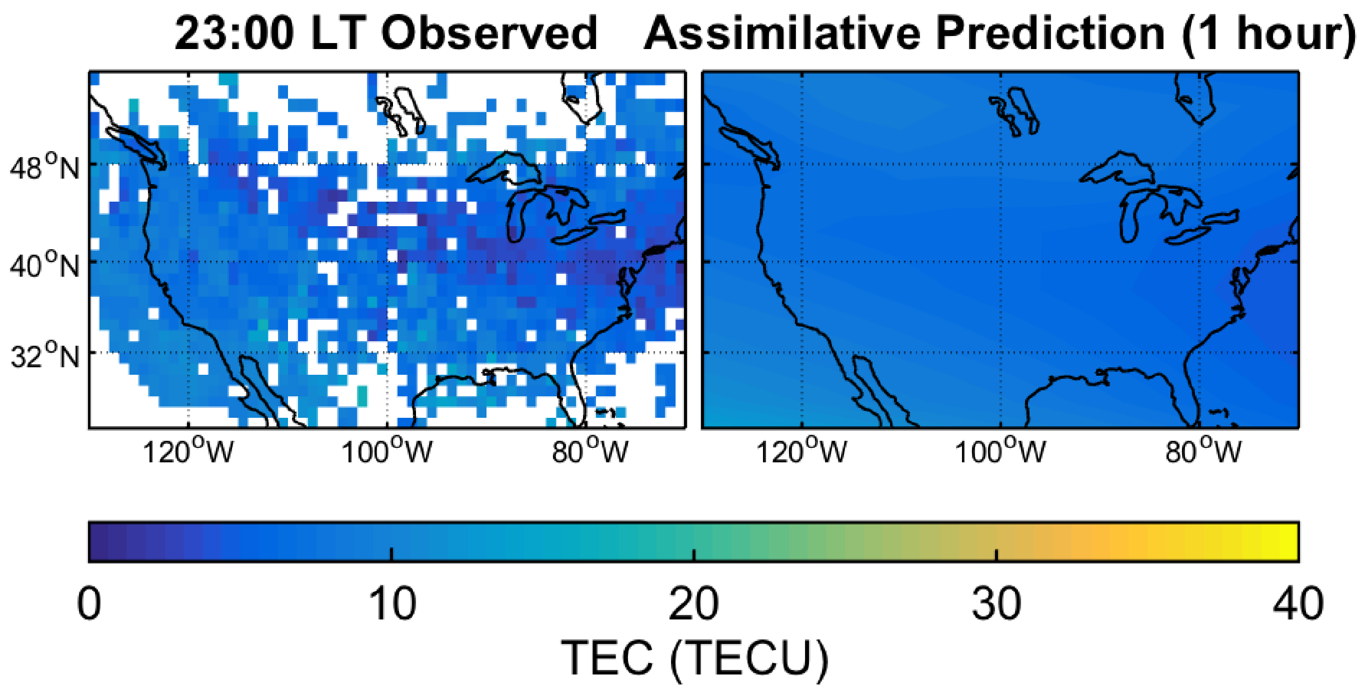
TEC (TECU)

TEC results



23:00 LT Observed
Assimilative Prediction (1 hour)
48°N
40°N
32°N
120°W
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120°W
100°W
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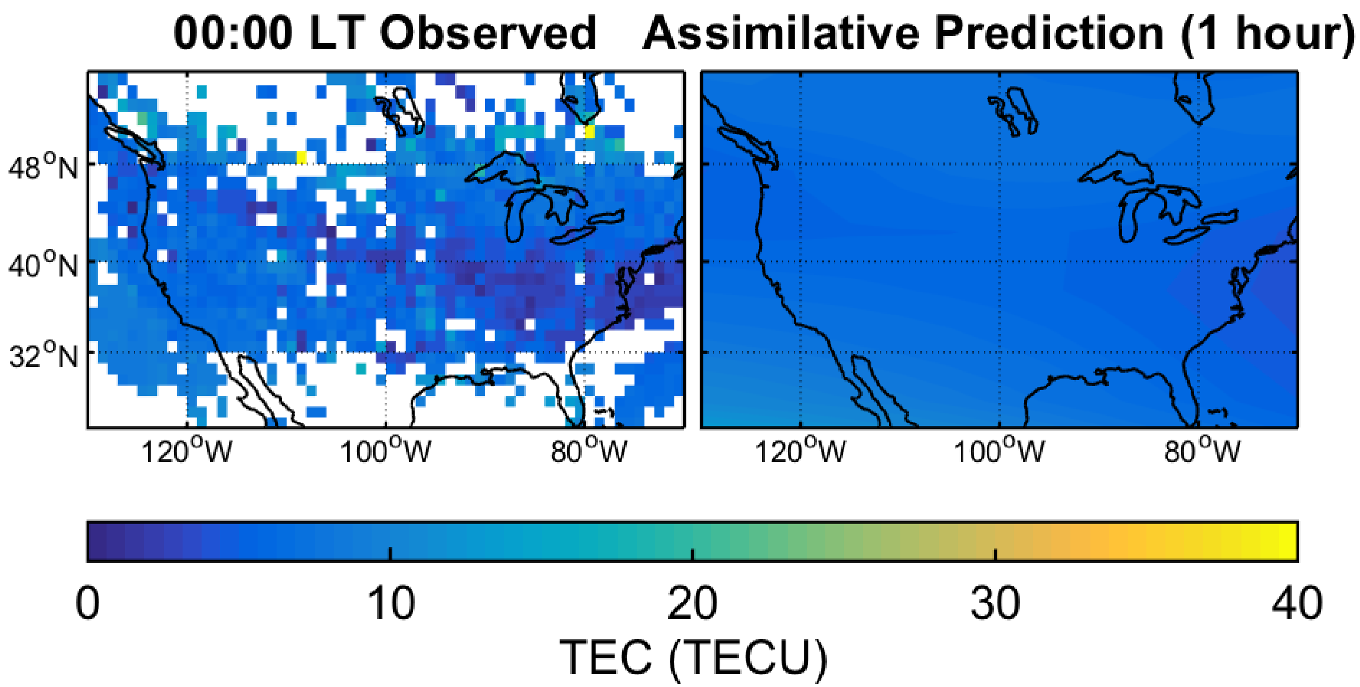
TEC (TECU)

TEC results



00:00 LT Observed
Assimilative Prediction (1 hour)
48°N
40°N
32°N
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TEC (TECU)

Results: CHAMP comparison

	21 January (local time)		10 September (local time)	
	Dry Run	One-hour prediction	Dry Run	One-hour prediction
Bias (%)	55.4	18.7	26.7	6.7
RMS (%)	73.7	71.9	64.3	64.4

- Assimilation reduces N_e prediction biases to <20% (January event) and <10% (main September event)
- RMSE is not improved by this approach (model resolution is 5^o x 5^o)

Conclusions

- Experiment shows potential for predicting storm-time ionospheric behavior using a coupled, physics-based approach
- Substantial improvements in one-hour prediction accuracy are achievable using ionospheric data assimilation
- The new approach provides self-consistent predictions (including uncertainties) of the main thermospheric and ionospheric parameters
- DART allows for hidden parameter estimation and straightforward incorporation of other observation types. *Chen et al.* [2016] have since used the same approach to estimate GUVI O/N_2 data

References

Chartier, A. T., T. Matsuo, J. L. Anderson, N. Collins, T. J. Hoar, G. Lu, C. N. Mitchell, A. J. Coster, L. J. Paxton, and G. S. Bust (2016), Ionospheric data assimilation and forecasting during storms, J. Geophys. Res. Space Physics, 121, 764–778, doi:10.1002/2014JA020799.

Chen, C. H., C. H. Lin, T. Matsuo, W. H. Chen, I. T. Lee, J. Y. Liu, J. T. Lin, and C. T. Hsu. "Ionospheric data assimilation with TIE-GCM and GPS-TEC during geomagnetic storm conditions." *Journal of Geophysical Research: Space Physics* (2016).

Foster, J. C., P. J. Erickson, A. J. Coster, J. Goldstein, and F. J. Rich, Ionospheric signatures of plasmaspheric tails, Geophys. Res. Lett., 29(13), doi:10.1029/2002GL015067, 2002.

Extrapolation for TEC calculation