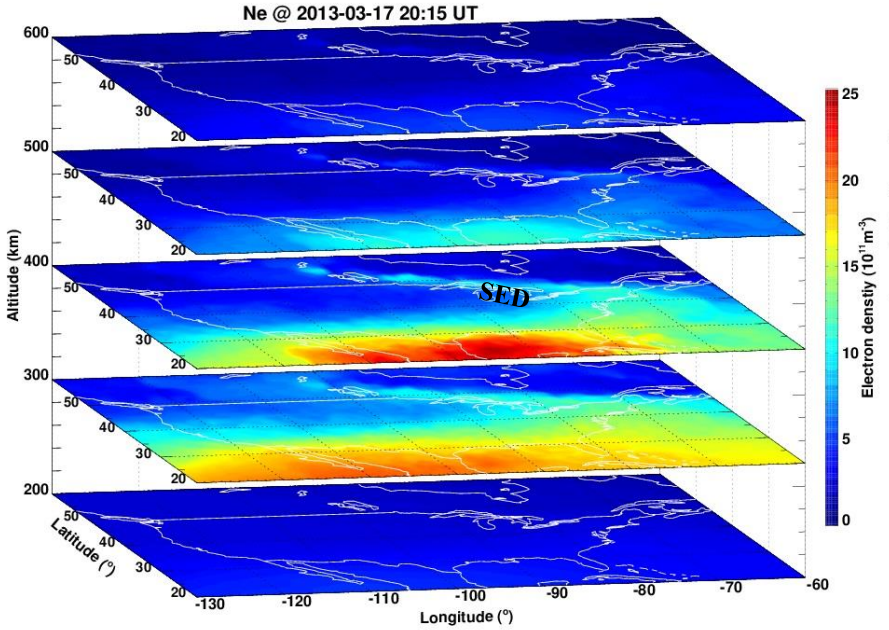
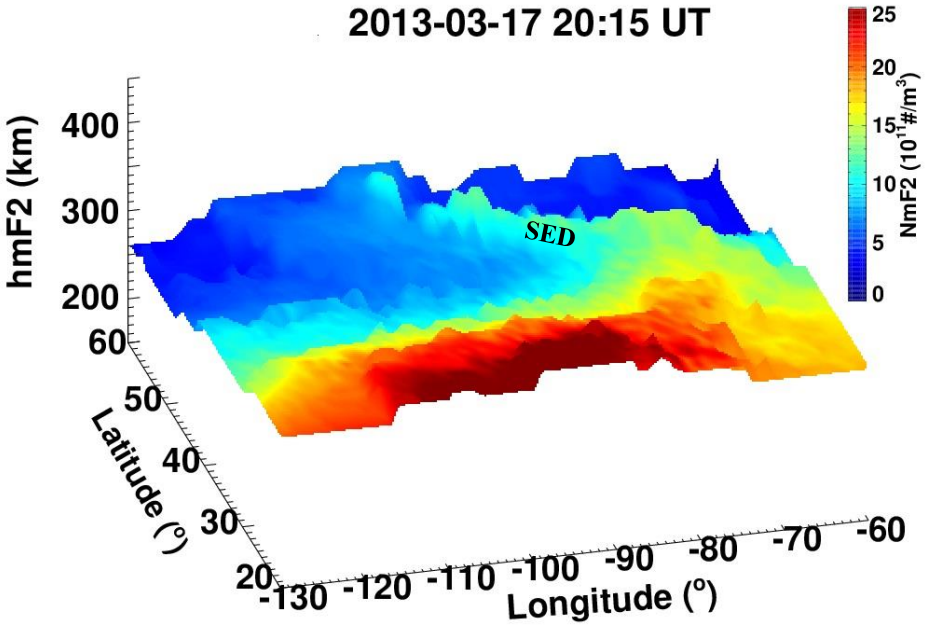
3-D Ionosphere Imaging and Storm-enhanced density (SED) Reconstruction With a New TEC-Based Ionospheric Data Assimilation System (TIDAS)

Ercha Aa[1], Shun-Rong Zhang[1], Philip J. Erickson[1], Wenbin Wang[2], Anthea J. Coster[1], and William Rideout[1]
[1]MIT Haystack Observatory; [2]NCAR HAO



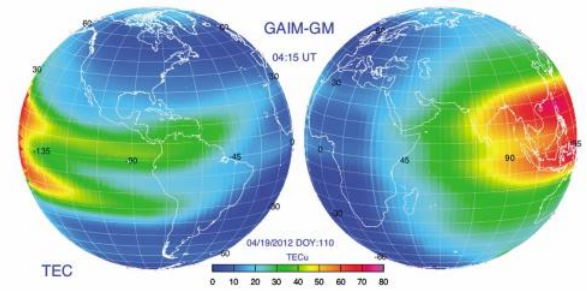


Ionospheric Data Assimilation

The data assimilation technique has been proved as an effective and efficient way of specifying ionosphere, which is implemented by using certain optimization schemes to incorporate measurements into background models.

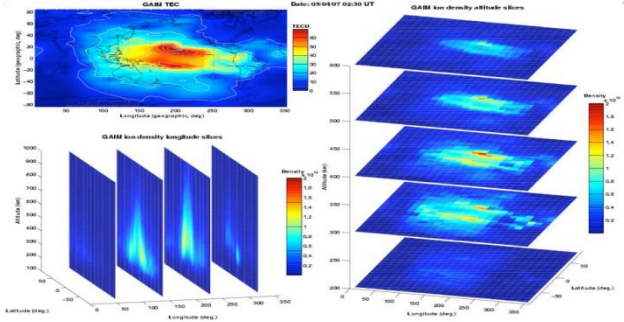
USU-GAIM

Schunk+, (2004); Scherliess+, (2004), etc



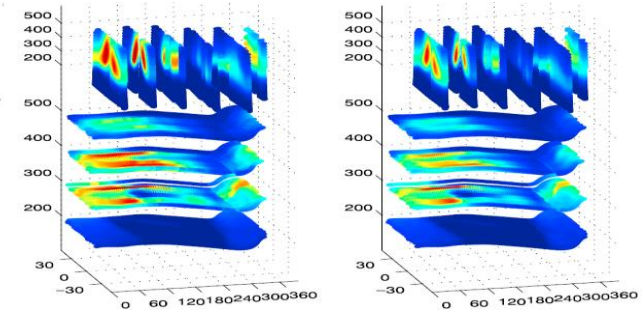
JPL/USC-GAIM:

Wang+, (2004); Pi+(2009); Komjathy+, (2010), etc



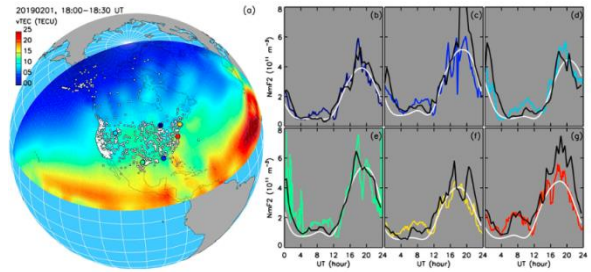
TIEGCM-DART; GSI Ionosphere

Matsuo+ (2013); Chartier+ (2016); Hsu+(2018), etc



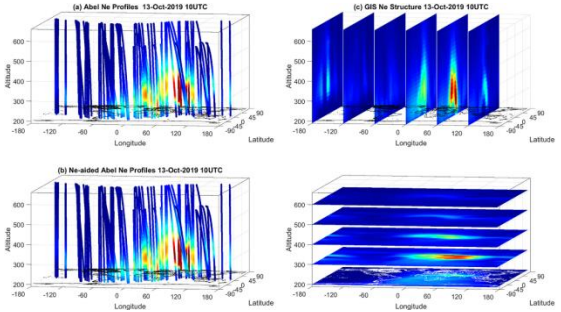
IDA3D/IDA4D:

Bust+, (2004, 2007, 2014), Datta-Barua, (2011), Azeem+, (2015); Forsythe+, (2020), etc.



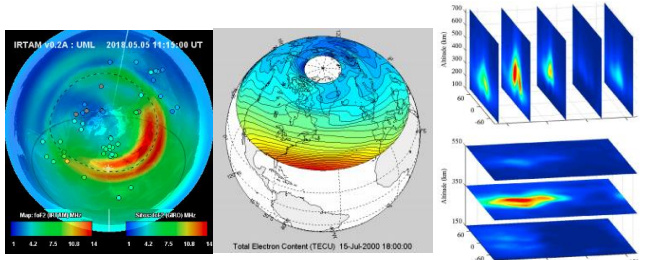
GIS:

Lin+, (2015, 2017); etc



IRTAM, MIDAS, IRI-based global DA, etc.

Galkin+, (2012), Mitchell+(2003), Yue+, (2012); etc.

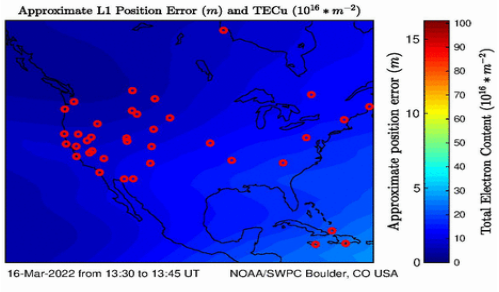


Merits: Valid specification of global-scale ionosphere variation with good forecast (theoretical) and/or nowcast (empirical) ability

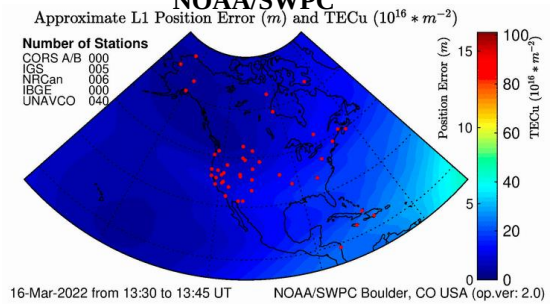
Needs: Incorporating newly available datasets from above/below; Better specification of error/uncertainty covariance; Improving forecast/nowcast time lead and accuracy; R2O transition; Resolving regional meso-scale structures with high-resolution

Current regional/operational Ionospheric data assimilation products

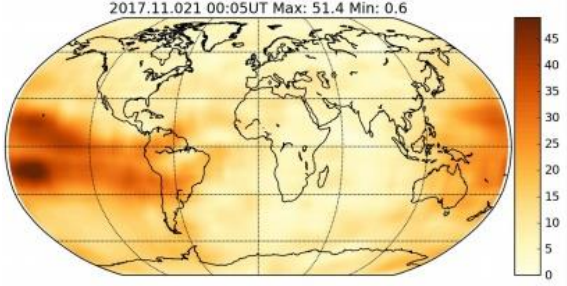
US TEC (Fuller-Rowell et al., 2006)
NOAA/SWPC



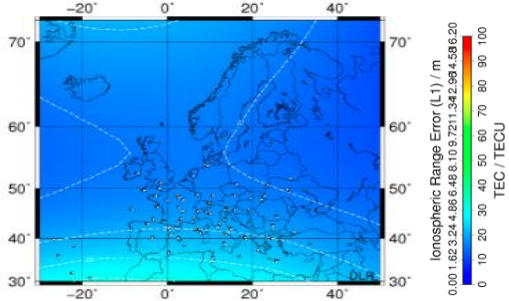
North American TEC (Fuller-Rowell et al.)
NOAA/SWPC



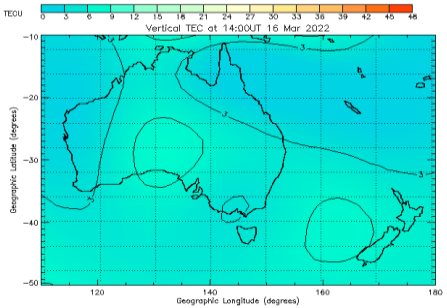
GLO TEC (Fuller-Rowell et al.)
NOAA/SWPC



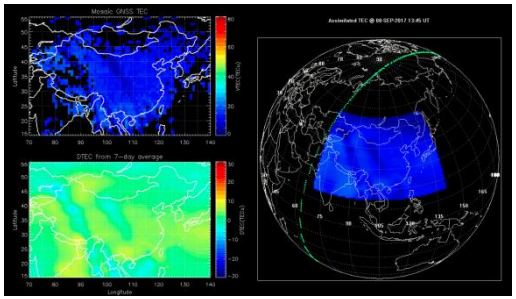
European TEC (Jakowski et al., 2011)
IMPC DLR



AU/NZ TEC (Bouya et al.)
SWS, AU Bureau of Meteorology



CN TEC (Aa et al., 2015; 2016)
NSSC/SEPC CAS



Merits: Quasi-Real-Time 2-D ionospheric TEC products for fast space weather nowcasting services

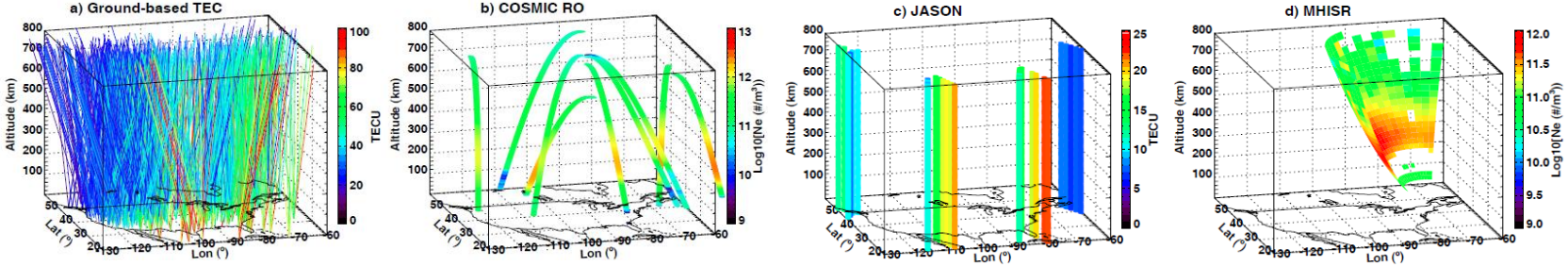
Needs: Developing **high-fidelity high-resolution storm-time 3-D Ne reconstruction for retrospective studies** on complicated midlatitude density gradient structures (e.g., storm-enhanced density, mid-latitude trough), using extensive ground-based datasets (e.g., slant TEC from 2000+ GNSS receivers over North America, Millstone Hill ISR data) and space-borne (e.g., COSMIC, JASON) measurements

Science objective: Better understand the 3-D spatial distribution and temporal variation of midlatitude ionospheric density gradients

Regional 3-D electron density specification with a new TEC-based Ionospheric Data Assimilation System (TIDAS)

Region: the continental U.S.; Data assimilation Method: En3DVAR; Background: NeQuick

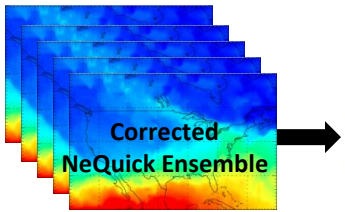
1. Ground-based and Space-borne Datasets: GNSS TEC + COSMIC RO + JASON TEC + Millstone Hill ISR

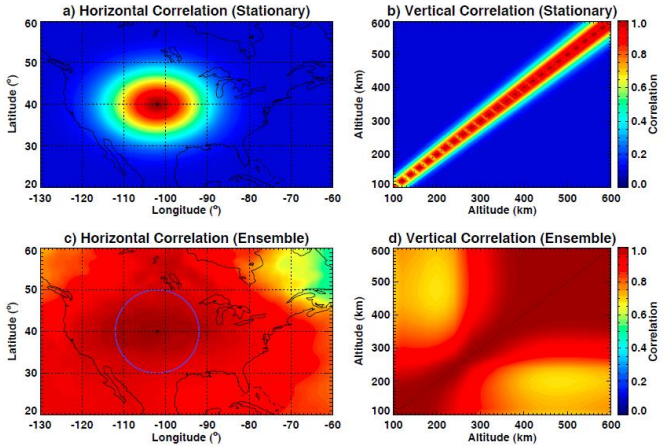


2. Ensemble-based background error covariance

$$P_b = \frac{(X_b - \overline{X_b}) \cdot (X_b - \overline{X_b})^T}{N_{\text{ensem}} - 1}$$

$$X_b = [x_b^1, x_b^2, ..., x_b^{N_{\text{ensem}}}]$$





(a and b) Stationary ionospheric correlation using an elliptical Gaussian expression
(c and d) Ensemble-based ionospheric correlation using corrected NeQuick outputs

3. Three-Dimensional Variation (3DVAR) Approach

3DVAR is a statistical optimization method that seeks to minimize a cost function J(x) which represents the measure of the closeness between background model predictions and the measurements.

4. Sparse-Matrix Storage

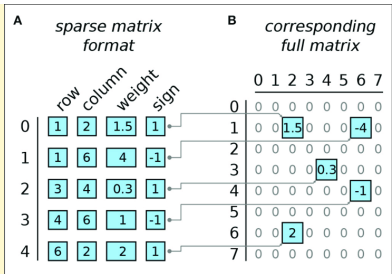
A sparse matrix storage scheme is used to address the issue of enormous storage space and computation inefficiency associated with large matrices of background and observation error covariance

- Format of cost function $J(x)$

$$J(x) = \frac{1}{2}(x - x_b)^T P^{-1}(x - x_b) + \frac{1}{2}(y - Hx)^T R^{-1}(y - Hx),$$

  - x: the state variable (the analyzed N_e)
  - x_b: the background field (NeQuick estimation)
  - P: the background error covariance matrix
  - R: the observation error covariance matrix
  - y: the observation vector (TEC and/or Ne)
  - H: the observation forward operator (length that each satellite-receiver ray passes through every grid point)
- The optimal solution of x is given by

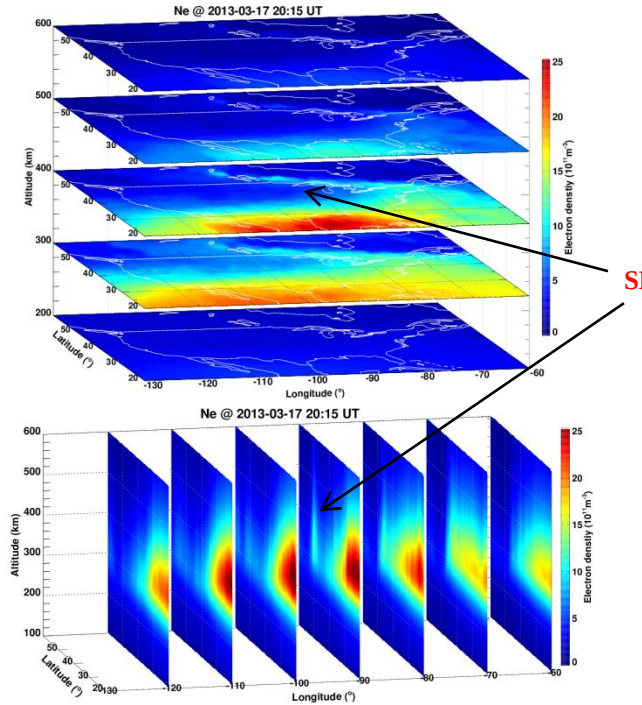
$$x = x_b + PH^T[HPH^T + R]^{-1}(y - Hx_b).$$



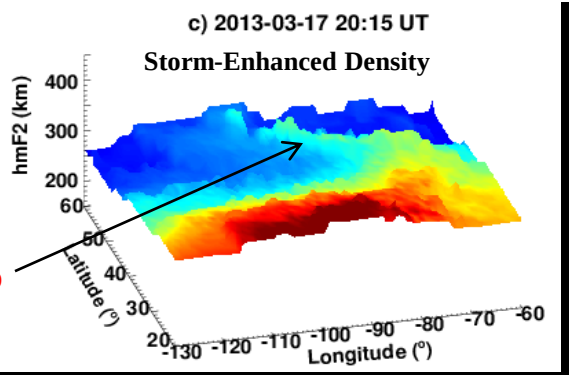
Regional 3-D electron density specification with a new TEC-based Ionospheric Data Assimilation System (TIDAS)

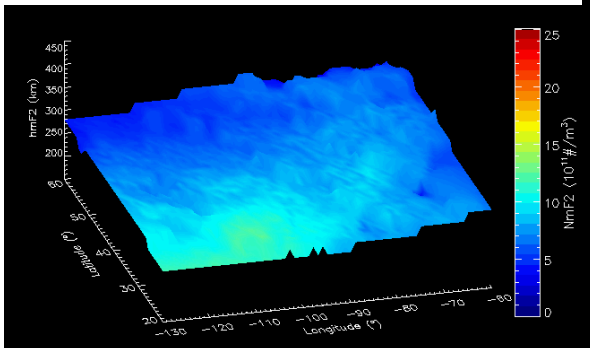
Resolution: 1° (Latitude) x 1° (Longitude) x 20 km (Altitude) x 5 min

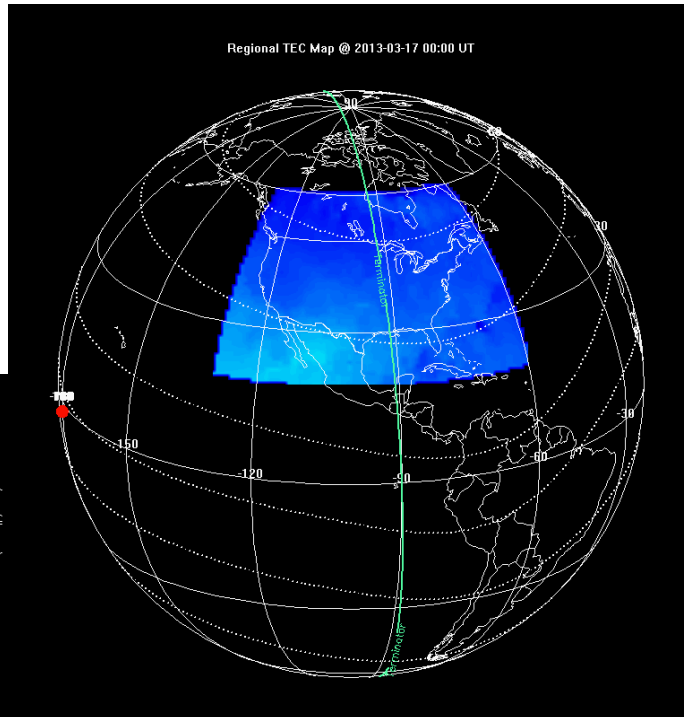
- TIDAS data assimilation results provide a reasonable representation of the morphology and evolution of well known large-scale ionospheric characteristics, such as the equatorial ionization anomaly (EIA) at low latitudes, mid-latitude storm-enhanced density (SED) containing a remarkable density gradient, and the main ionospheric trough with TEC depletions at subauroral
- **In particular, TIDAS data assimilation product captures well the 3-D fine structures and dynamic evolution of SED**



SED

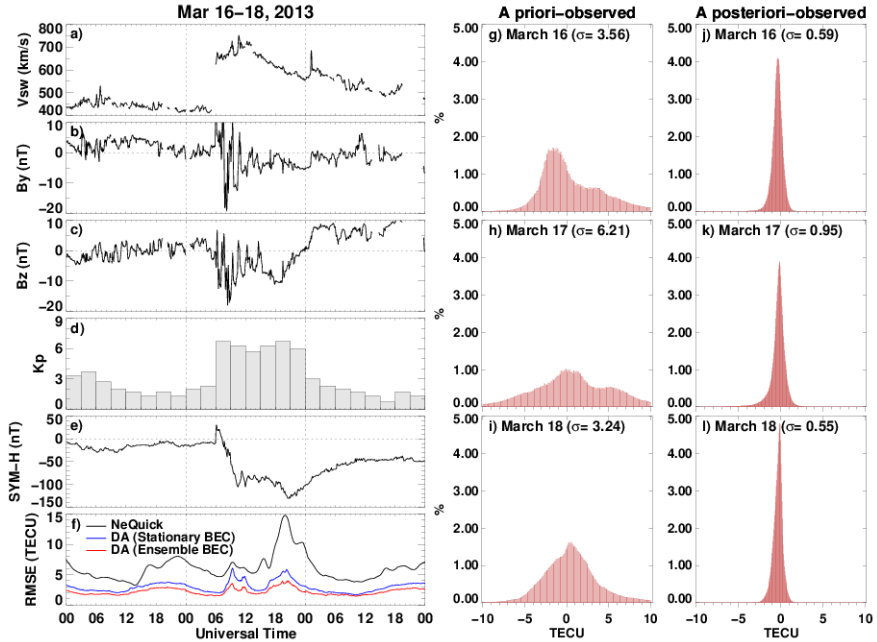






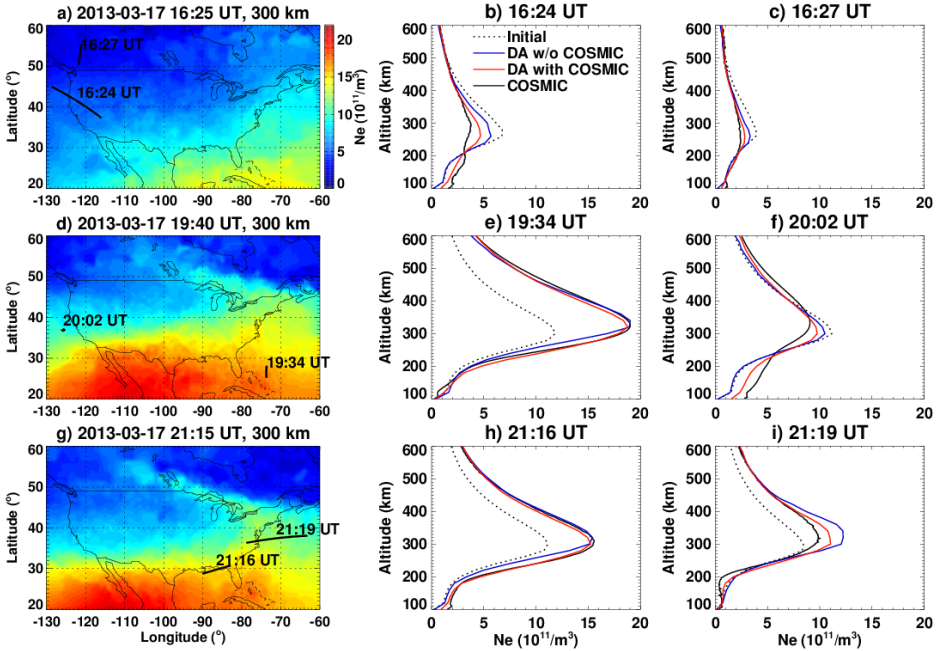
3-D ionosphere imaging and SED reconstruction with a new TEC-based Ionospheric Data Assimilation System (TIDAS)

Validation: pre-excluded TEC observations



(a–e) Temporal variations of solar wind velocity, IMF By, IMF Bz, Kp index, and SYM-H during 16–18 March 2013. (f) TEC root mean square error comparing to Madrigal results. (g–i) The corresponding daily histogram statistics of the differential TEC between NeQuick (a priori) and Madrigal observations during 16–18 March 2013, respectively. (j–l) are the same as (g–i), but for differential TEC between TIDAS data assimilation (a posteriori) and Madrigal results.

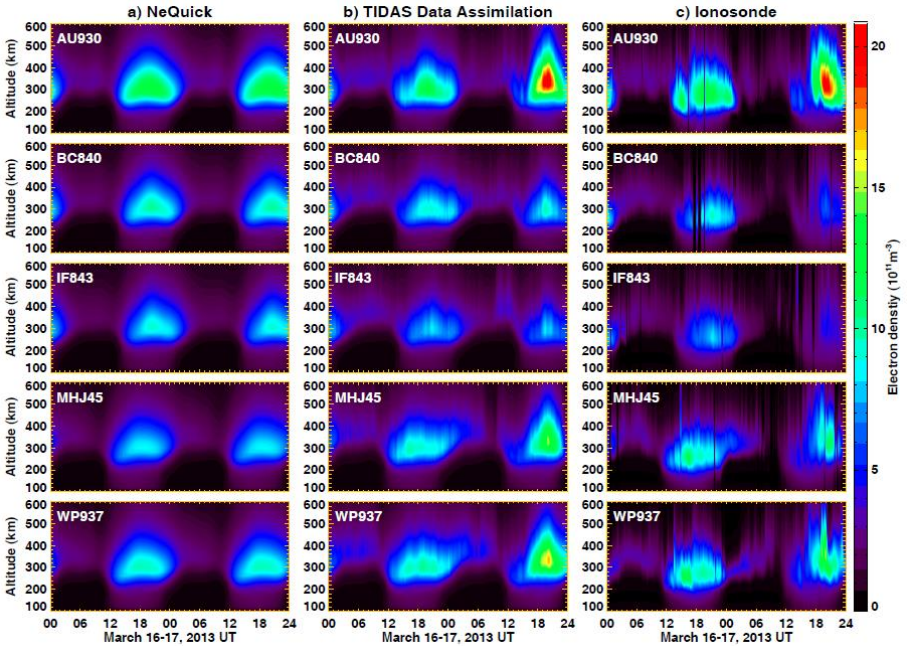
Internal Validation: COSMIC profiles



(Left column) Reanalyzed Ne map at 300 km given by data assimilation at three UT intervals, respectively. Overlapping lines show the tangent points trajectory of Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC) radio occultation events. (Middle and right columns) Comparison of Ne profiles between initial NeQuick values (black dotted lines), TIDAS data assimilation without(blue)/with(red) COSMIC radio occultation data, and COSMIC measurements (black lines).

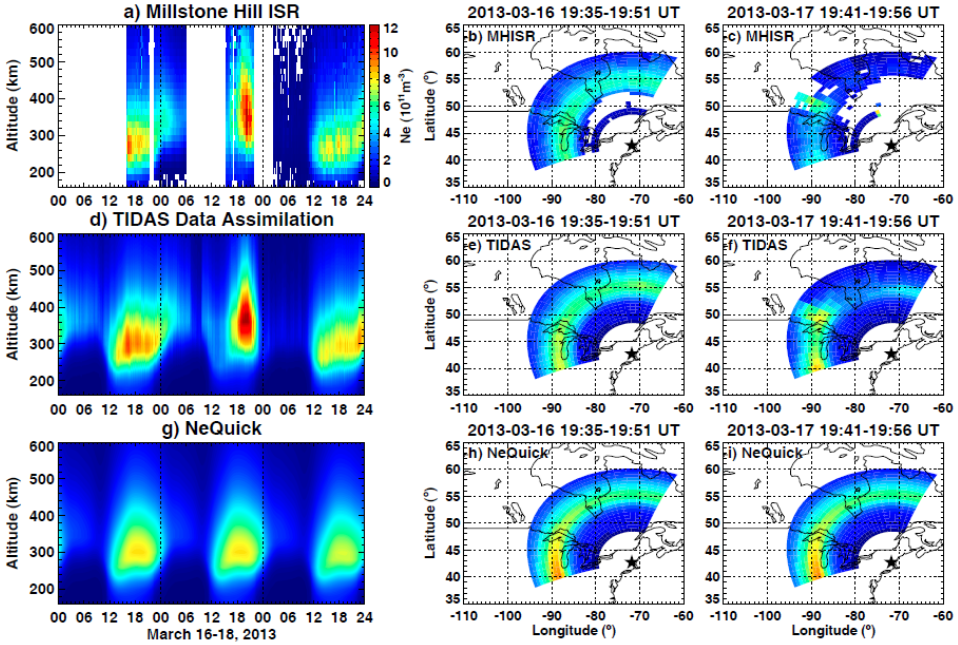
3-D ionosphere imaging and SED reconstruction with a new TEC-based Ionospheric Data Assimilation System (TIDAS)

Independent Validation: Ionosonde profiles



Comparisons of electron density profiles between (a) NeQuick values, (b) TIDAS data assimilation results, and (c) ionosonde measurements at five stations during 16-17 March 2013.

Internal Validation: MHISR profiles



(a) Temporal variation of electron density profiles measured by the zenith antenna of Millstone Hill incoherent scatter radar during March 16-18, 2013. (b and c) Wide-coverage azimuth scan of electron density measured by the steerable antenna of the Millstone Hill incoherent scatter radar at two UTs on March 16 and March 17, respectively. (d--f) and (g--i) are the same as (a--c), but for the corresponding TIDAS data assimilation and initial NeQuick results, respectively. The location of Millstone Hill ISR is marked by a star.

Summary

- A new regional 3-D ionospheric data assimilation system TIDAS was developed over the continental U.S. and adjacent areas using a background empirical model NeQuick and vast ionospheric observations. These include dense ground-based GNSS TEC observations from 2000+ receivers, COSMIC radio occultation data, JASON altimeter TEC data, and Millstone Hill ISR measurements.
- In TIDAS, a hybrid Ensemble-3DVAR assimilation scheme is developed to obtain an optimal state estimation through utilizing a more realistic background error covariance description based on the ensemble of the corrected NeQuick outputs, and a sparse matrix method is used to alleviate the storage and computation demand.
- TIDAS provides a high-fidelity three-dimensional Ne distribution with the spatial-temporal resolution being as high as **1^o x 1^o x 20 km x 5 min**. This high-resolution regional data assimilation system represents a powerful tool that provides much-needed altitudinal information for storm-time ionospheric structures on regional and local scales. Such information is of considerable value in accelerating continued improvements in understanding of fine-scale structuring and underlying mechanisms of SED and related midlatitude ionospheric density gradients.

Reference

Aa, E., Zhang, S.-R., Erickson, P. J., Wang, W., Coster, A. J., and Rideout, W., (2022), 3-D regional ionosphere imaging and SED reconstruction with a new TEC-based ionospheric data assimilation system (TIDAS), Space Weather, doi: 10.1029/2022SW003055.

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