IDA2017 – A Next-Generation Coupled Modular Assimilation Package

IES 2017

Alexandria, VA

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Outline

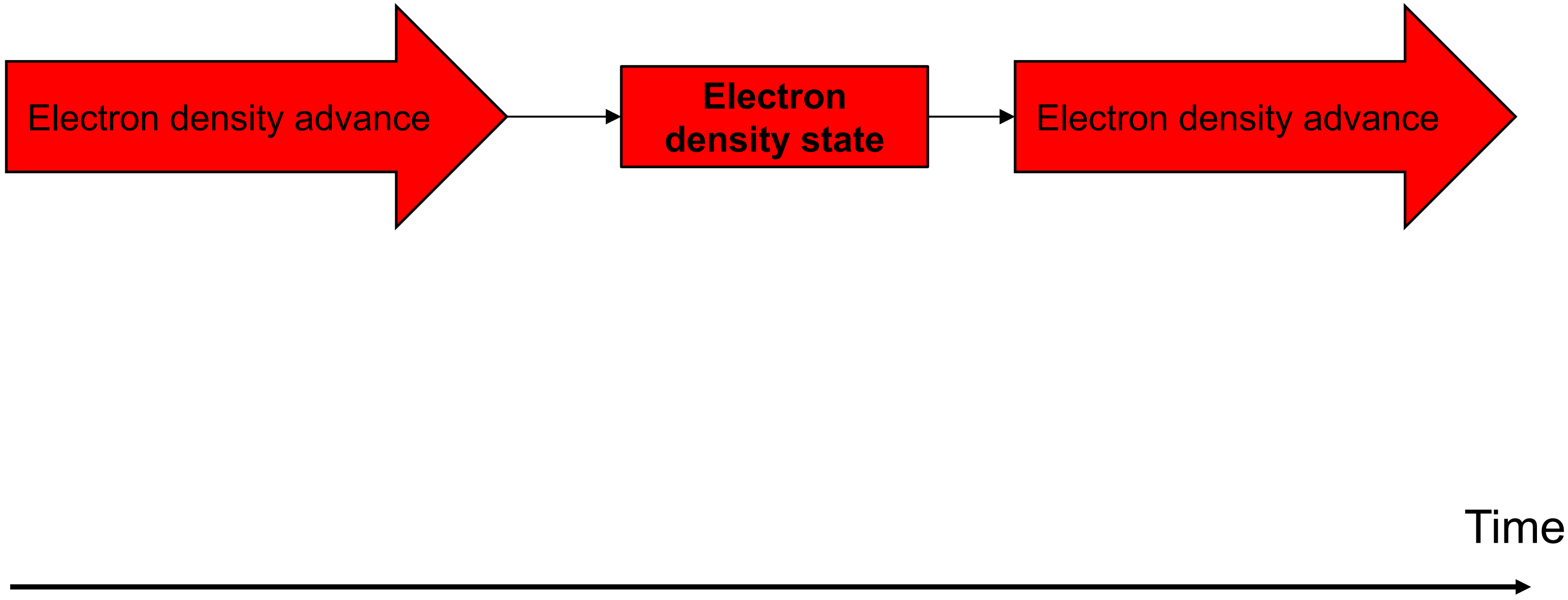
IDA2017 overview and motivation:

- Provide a unified interface for a range of coupled and interlinked geospace models – **one makefile and one configuration file**
- Automated data download and pre-processing for many data-types
- Develop new tools to integrate diverse observational datasets, ranging from the plasmasphere to the thermosphere

Principal modules:

- Ionospheric physics temporal advance
- Ionospheric data assimilation
- Thermospheric composition assimilation
- Thermospheric wind estimation
- Plasmaspheric data assimilation

IDA2017 schematic overview



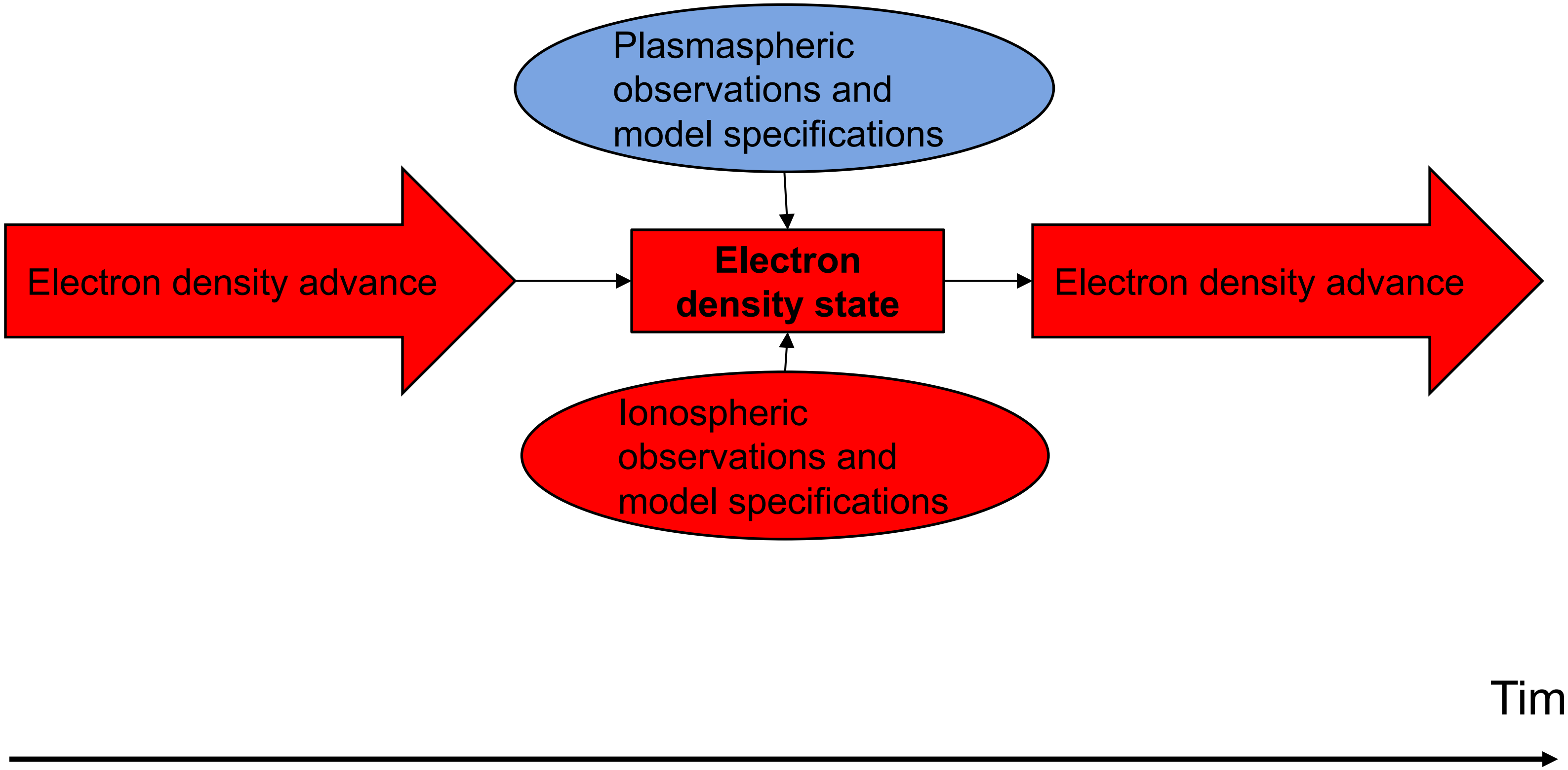
Electron density advance

Electron density state

Electron density advance

Time

IDA2017 schematic overview



Plasmaspheric observations and model specifications

Electron density advance

Electron density state

Electron density advance

Ionospheric observations and model specifications

Time

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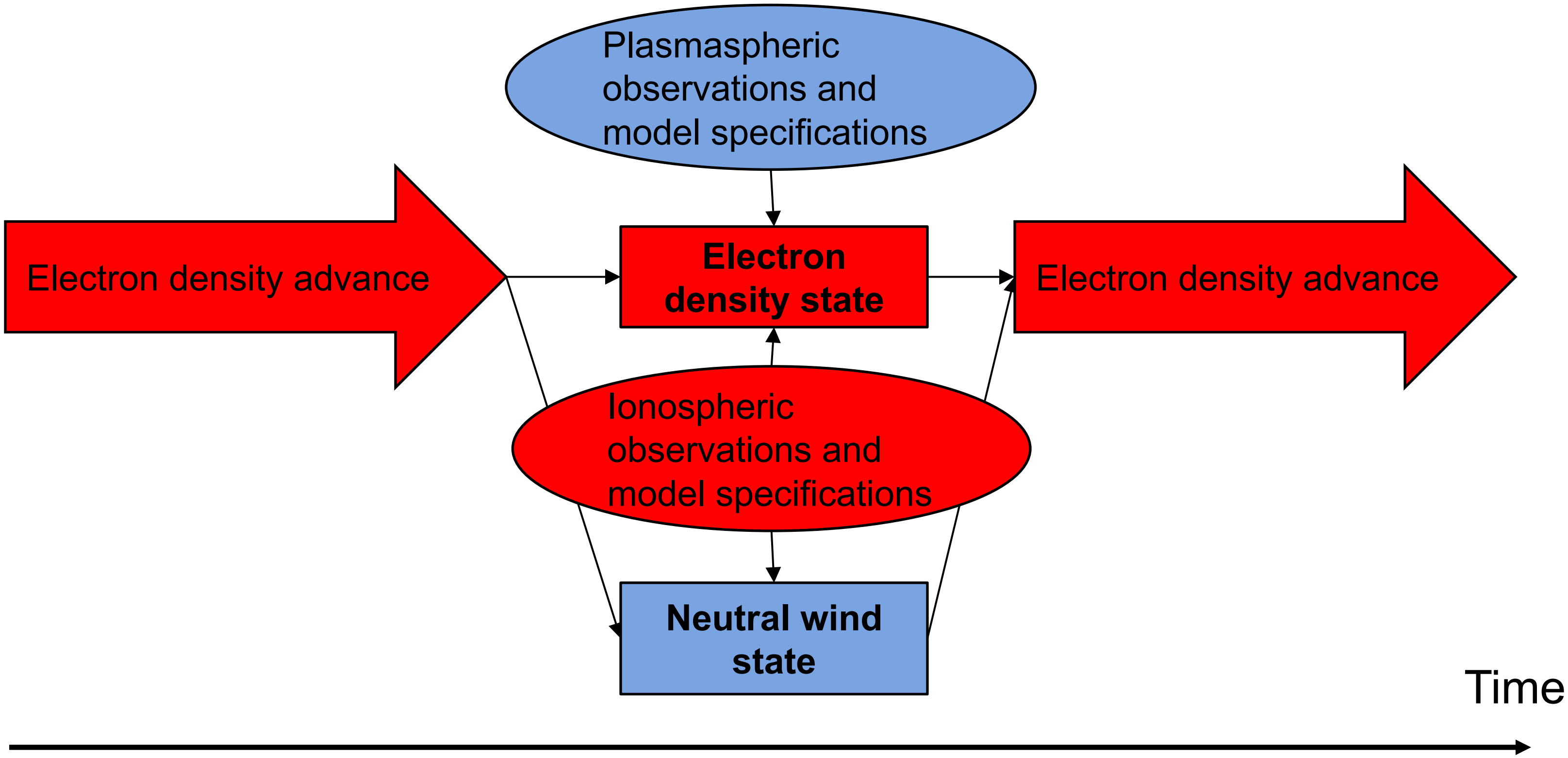

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Ionospheric observations and model specifications

Neutral wind state

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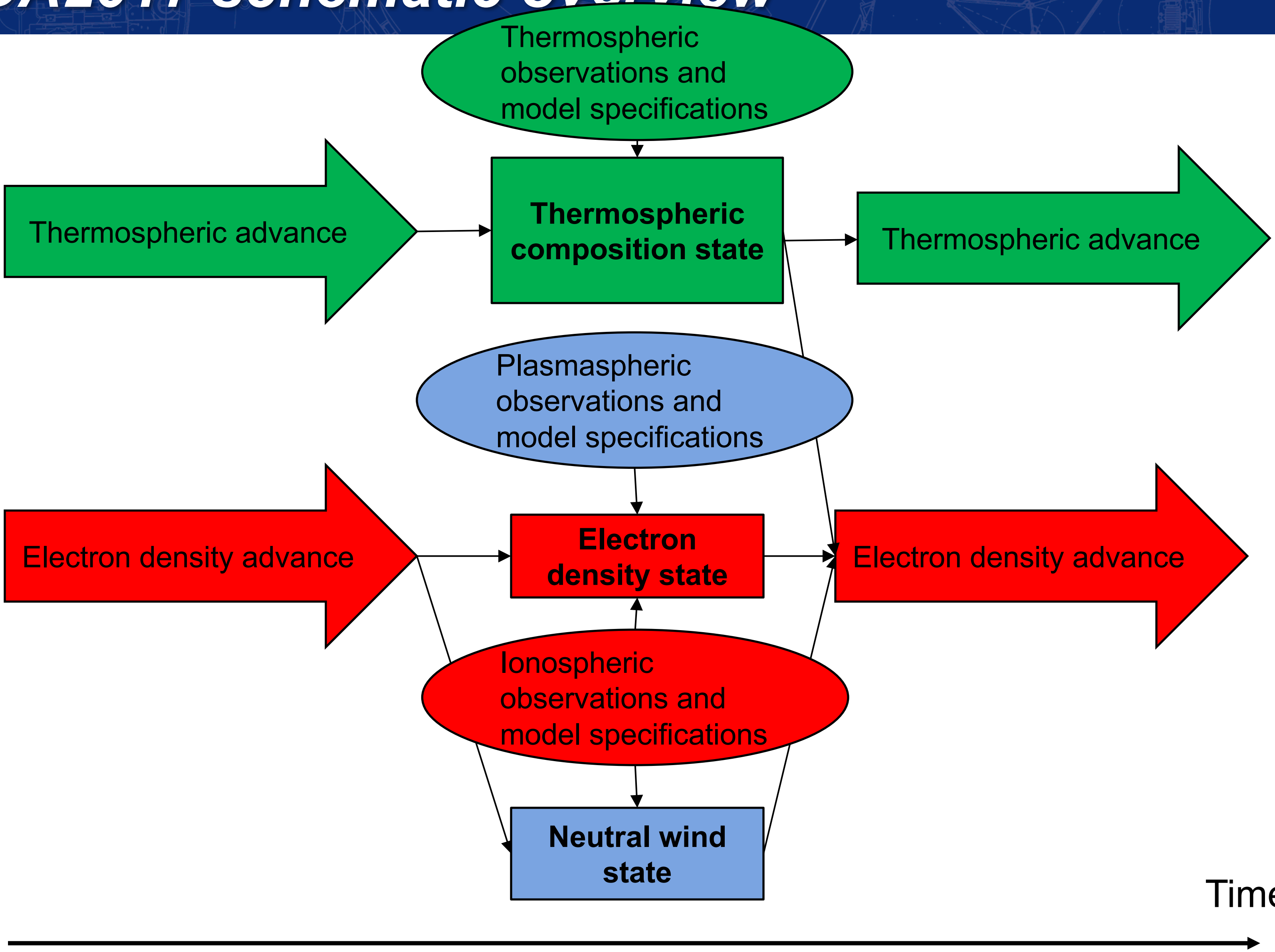

Thermospheric observations and model specifications

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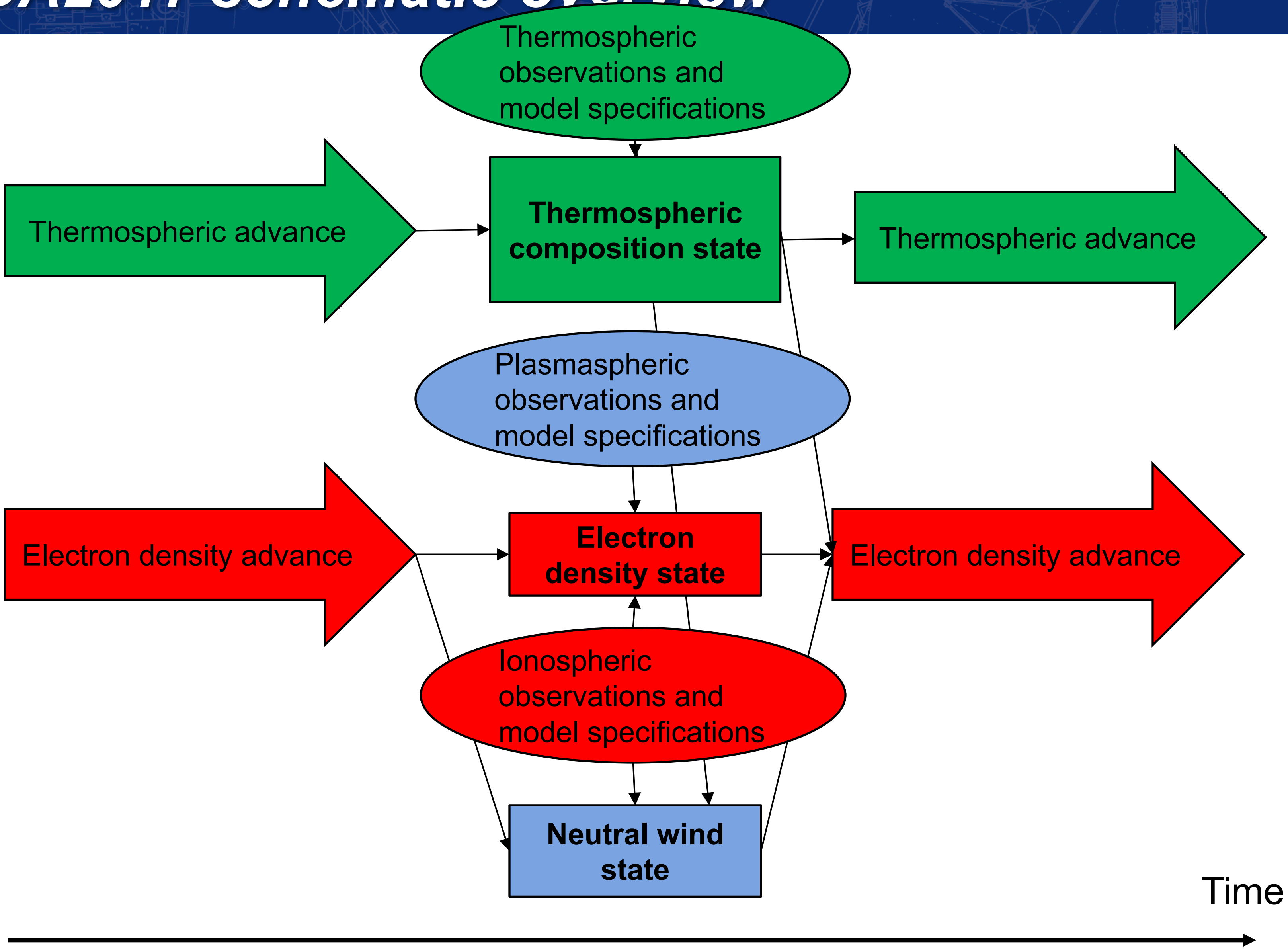

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Ionospheric physics module

The ionospheric physics module provides short predictions of ionospheric electron density based on established physics, external drivers and initial conditions

Drivers:

Parameter	Options
Solar EUV flux	• EUVAC (empirical model based on observed $F_{10.7}$) • TIMED/SEE 37-band observational product • SDO/EVE 37-band observational product
Thermospheric composition	• MSIS empirical model (all versions) • TIEGCM physics-based model output files • COMPASS composition assimilation module
Neutral winds	• HWM empirical model (all versions) • TIEGCM physics-based model output files • EMPIRE wind estimation module
Initial electron density	• IRI empirical model (all versions) • TIEGCM physics-based model output files • Ionospheric assimilation module • Previous output
Ionospheric temperatures	• IRI empirical model (all versions) • TIEGCM physics-based model output files
Ion drifts	• Scherliess-Fejer equatorial ionospheric drift model

Ionospheric physics module

Continuity equation (solved at 1 Hz):

production + loss + **∇**. (parallel flux + perpendicular flux)

Production rate (recalculated every five minutes):

$$q = \sum_{s} N_s \sum_{w} \sigma^{sw} \phi^{w} exp(-\tau^{w})$$

where s: neutral species (normally O, O_2, N_2)

N: number density

w: EUV wavelength band (37 EUVAC-style bands)

σ: ionization cross section

ϕ: Solar flux

τ: Optical depth (using Chapman grazing angle approximation)

Ionospheric physics module

Continuity equation (solved at 1 Hz):

production + **loss** + **∇**. (parallel flux + perpendicular flux)

Kirchengast [1996] loss rate (recalculated every second):

$$\frac{\beta_1+\beta_2}{1+\frac{\beta_1}{\alpha_1 N_e}+\frac{\beta_2}{\alpha_3 N_e}} N_e - \frac{q_{N_2}}{\beta_3+\alpha_2 N_e}\,\frac{1+\beta_3}{\alpha_1 N_e} - \frac{q_{O_2}}{\alpha_3 N_e}$$

where

α_1 = 4.2E-13 x (300 / $T_e)^{0.85}$

α_2 = 1.8E-13 x (300 / $T_e)^{0.39}$

α_3 = 4.2E-13 x (300 / $T_e)^{0.55}$

$\beta_1 = N_{N_2}\gamma_1$

$\beta_2 = N_{O_2}\gamma_2$

$\beta_3 = N_O\gamma_3$

γ_1 = 1.533E-12 - 5.920E-13 x T_i / 300 + 8.600E-14 x (T_i / 300$)^2$ **below 1700 K**

= 2.730e-12 - 1.155e-12 x T_i / 300 + 1.483E-13 x (T_i / 300$)^2$ **above 1700 K**

γ_2 = 2.82e-11 - 7.74e-12 x T_i / 300 + 1.073e-12 x (T_i / 300$)^2$ - 5.17e-14 x (T_i / 300$)^3$ + 9.65e-16 x (T_i / 300$)^4$

γ_3 = 1.1410e-10 x (300 / T_i) $^{0.44}$

Ionospheric physics module

Continuity equation (solved at 1 Hz):

production + loss + ∇. (**parallel flux** + perpendicular flux)

Parallel flux is composed of the field-aligned wind, gravity and diffusion:

$$N_e . \left\{ u_{||} + \frac{g_{||}}{v_{in}} + \frac{k_B (T_i + T_e)}{m_i v_{in}} \frac{\nabla_{||} N_e}{N_e} \right\}$$

where v_{in}: ion-neutral collision frequency

$u_{||}$: magnetic meridional wind

$g_{||}$: Field-aligned component of gravity

k_B: Boltzmann's constant

T: Temperature

m: mass

∇: Gradient calculated using a spline derivative approach

The diffusion term is simplified by neglecting thermal diffusion coefficients and the field-aligned component of the ion stress tensor.

Ionospheric physics module

Continuity equation (solved at 1 Hz):

production + loss **-** $\boldsymbol{\nabla}\cdot$ (parallel flux + **perpendicular flux**)

Perpendicular flux is calculated from specified equatorial ion drifts:

$$N_e. -\mathbf{v}_{ExB}(cos I\hat{r} + \sin \mathrm{I}\hat{\theta})$$

where $\mathbf{v}_{ExB}$: ion-neutral collision frequency

I: inclination

$\hat{r}$: Radial unit vector

$\hat{\theta}$: Meridional unit vector

The perpendicular flux term is simplified by neglecting the zonal component. Velocities are set to zero poleward of 45^o

Ionospheric assimilation module

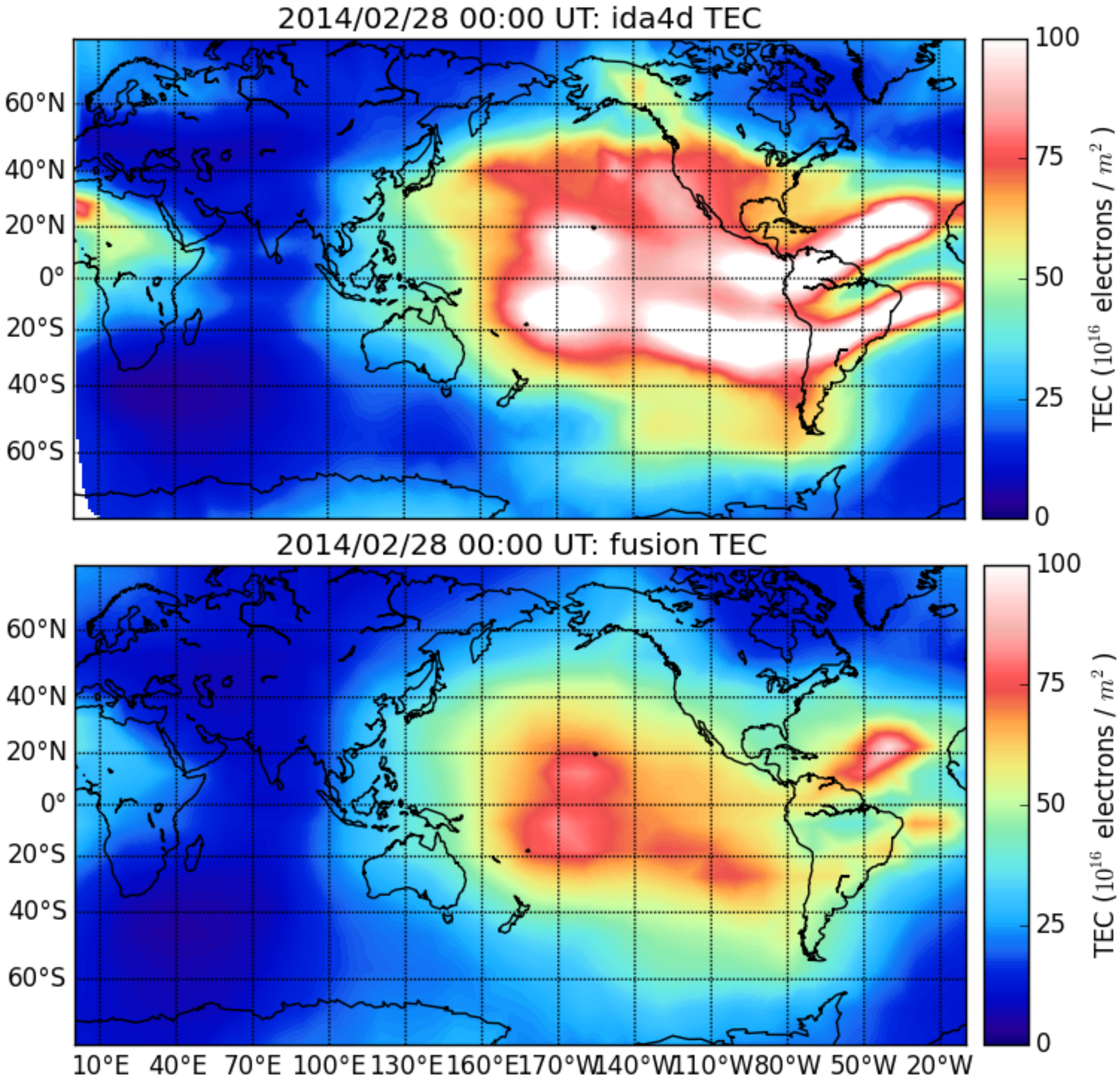
Ionospheric Data Assimilation Four-Dimensional (IDA4D) (*Bust and Datta-Barua,* [2014])

Assimilates ionospheric observations from ground- and space-borne GNSS receivers, HF instruments, Beacon transmitters, *in situ* densities, satellite radiances and other data sources.

Standalone mode, temporal advance is achieved using a Gauss-Markov Kalman Filter approach with IRI as an empirical background model

Coupled physics mode: temporal advance achieved using the physics module. Data are assimilated to the model background at each timestep

Bust, G. S., & Datta-Barua, S. (2014). Scientific investigations using IDA4D and EMPIRE. *Modeling the Ionosphere-Thermosphere System*, 283-297.



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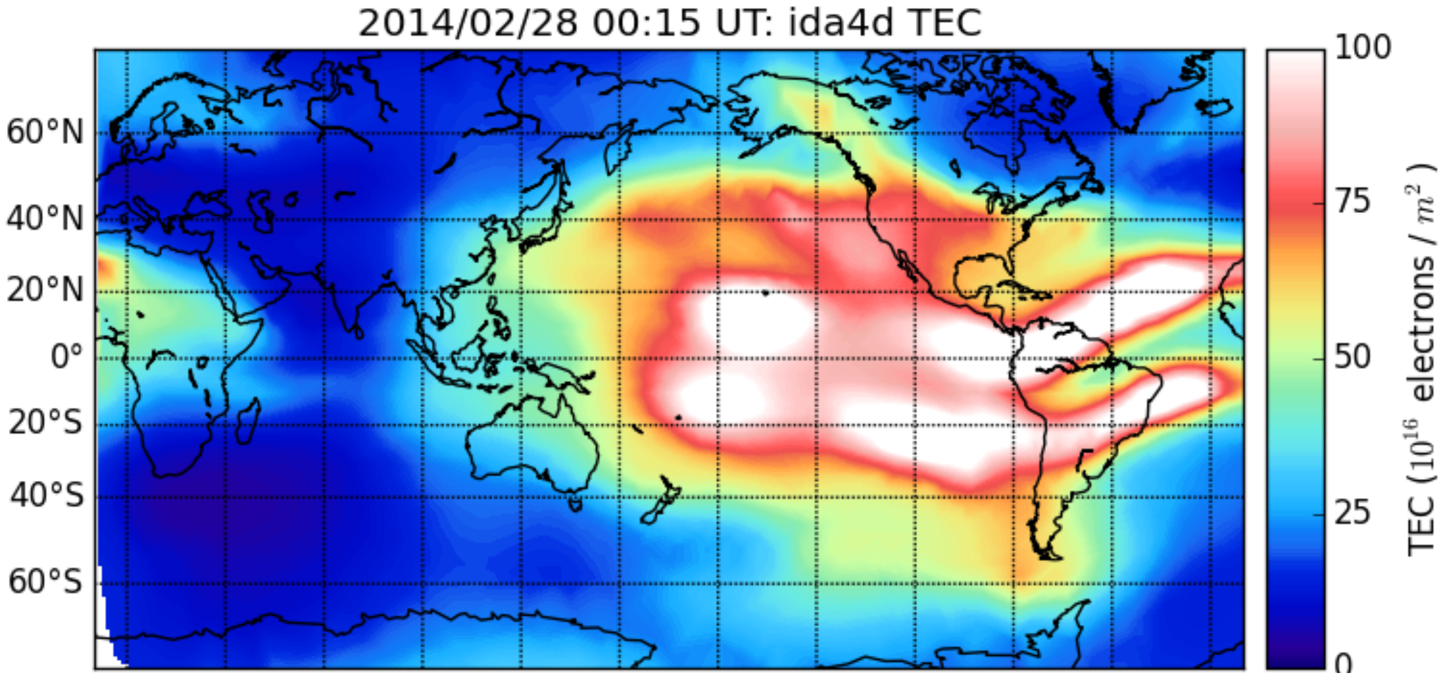
2014/02/28 00:00 UT: fusion TEC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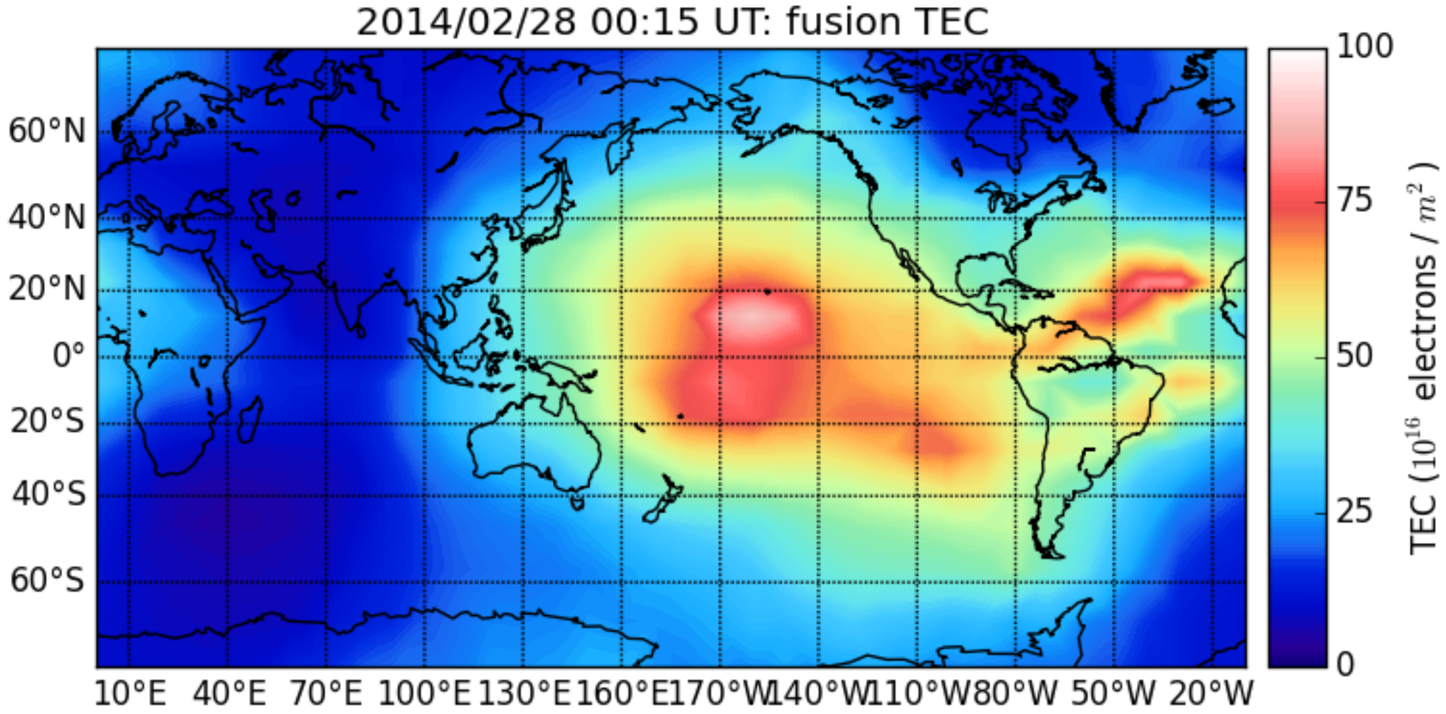
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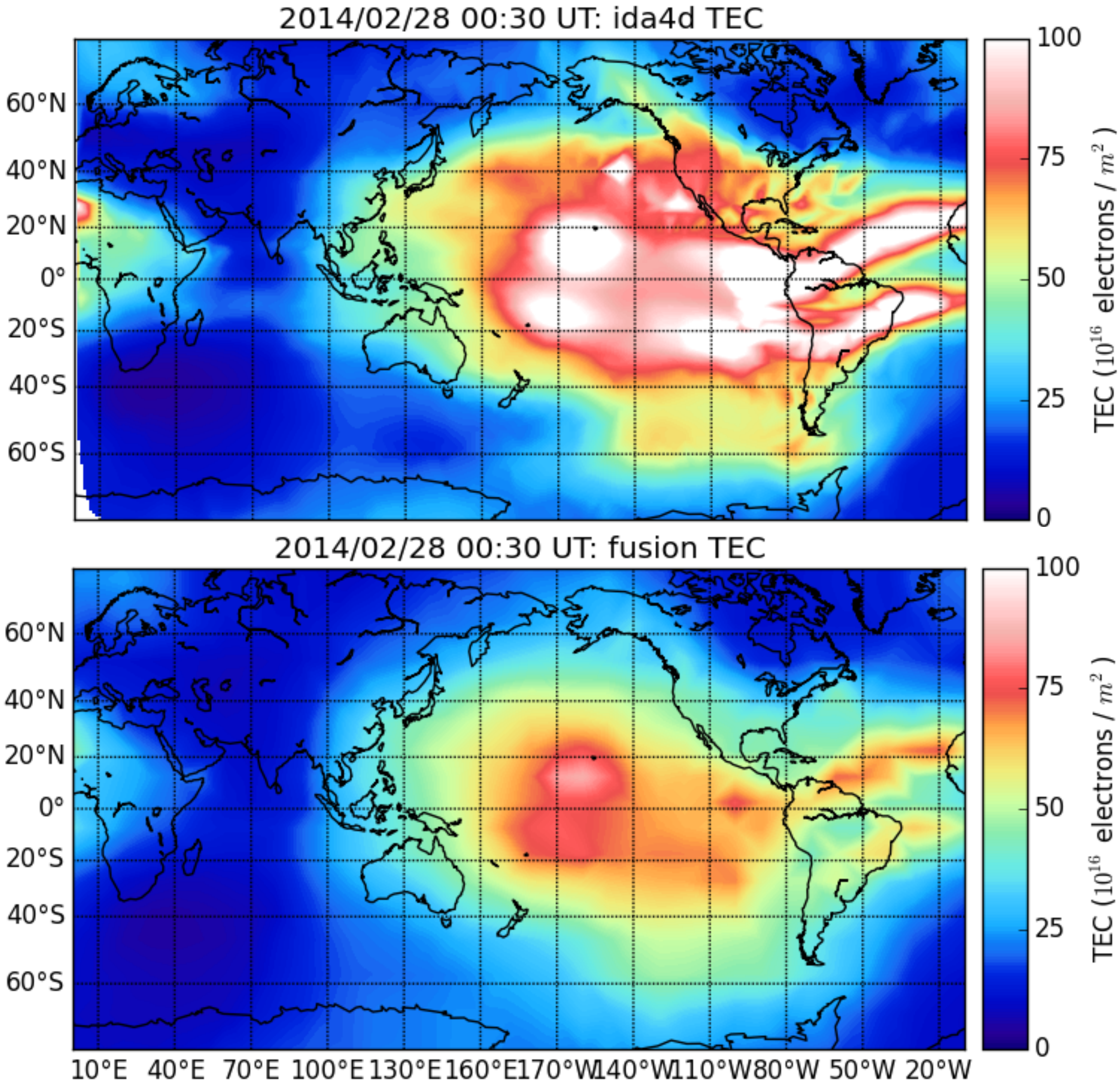
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60°N
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70°E
100°E
130°E
160°E
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140°W
110°W
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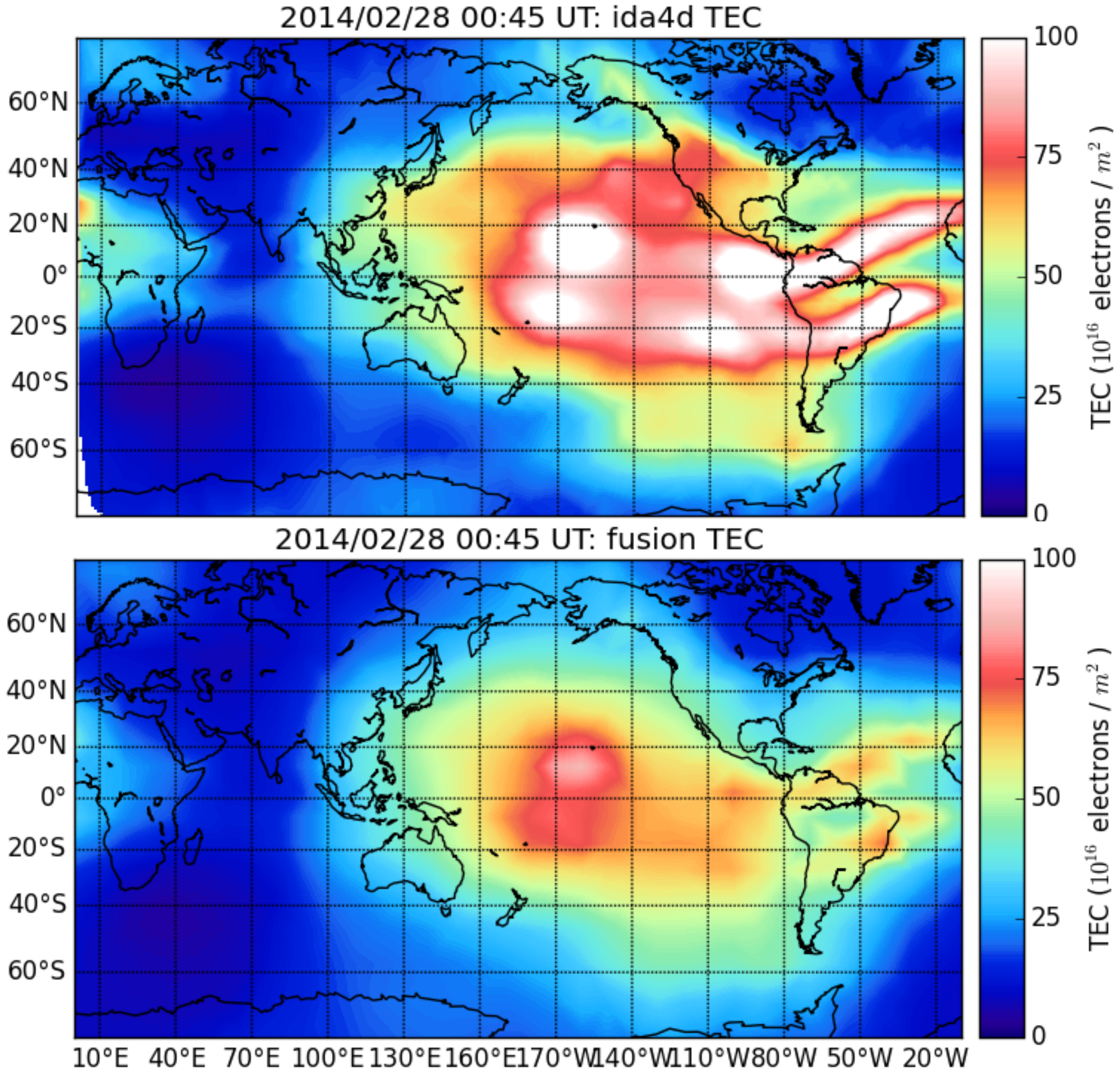
100
75
50
25
0
TEC (10^{16} electrons / m^2)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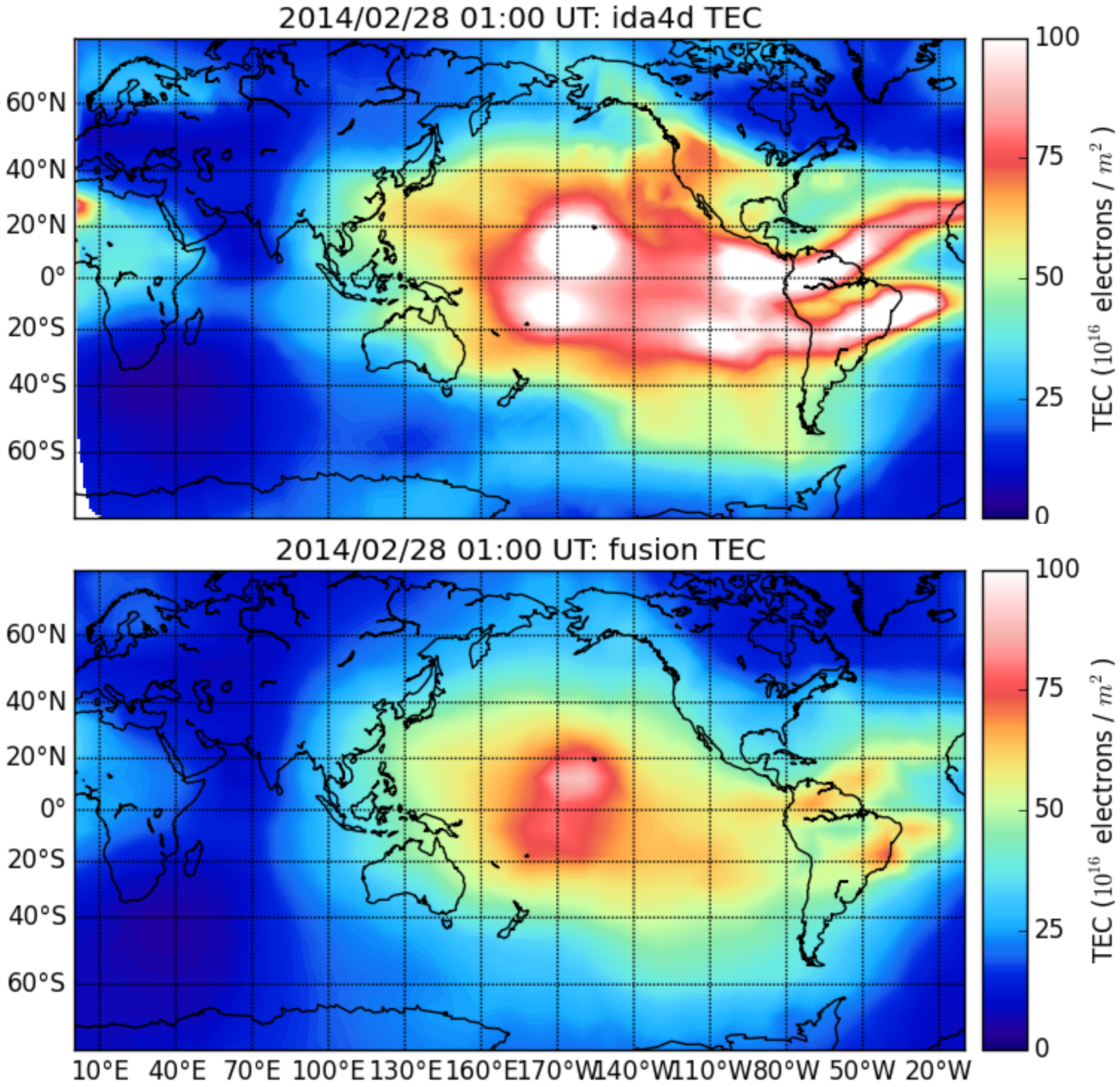2014/02/28 01:00 UT: ida4d TEC
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10°E
40°E
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100°E
130°E
160°E
170°W
140°W
110°W
80°W
50°W
20°W
100
75
50
25
0
TEC (10^{16} electrons / m^2)

Thermospheric composition assimilation module

Assimilates thermospheric O/N_2 observations from SSUSI and (soon) GUVI
MSIS empirical background used in 3DVar approach
O/N_2 is calculated in a column down to a depth that contains 10^{21} N_2 / m^2

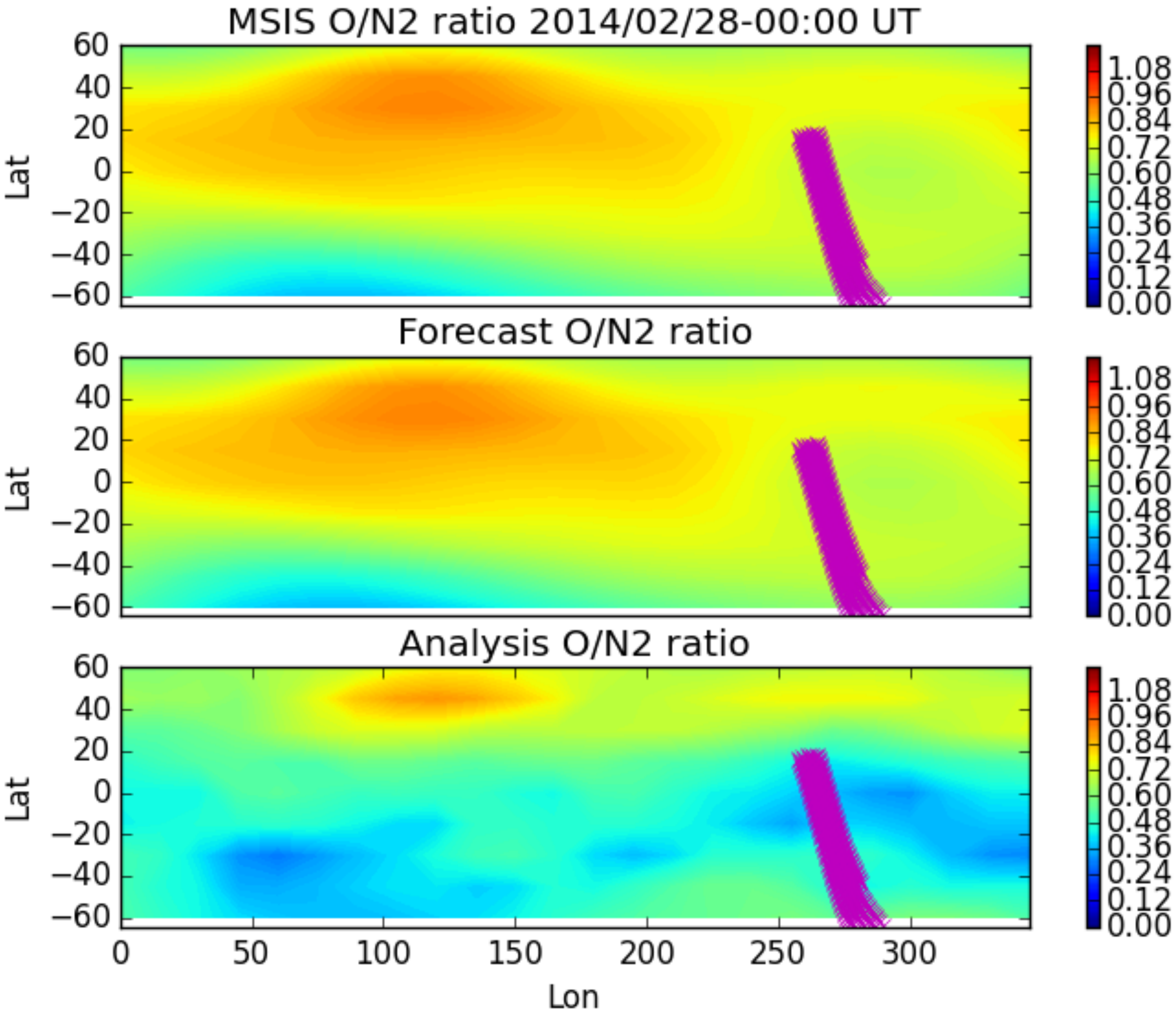
$$J = (\mathbf{x} - \mathbf{x}_b)^T \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x}_b) + (\mathbf{y} - \mathbf{H}\,\mathbf{x})^T \mathbf{R}^{-1} (\mathbf{y} - \mathbf{H}\,\mathbf{x})$$

J – cost function minimized using Powell's method
$\mathbf{x}_a$ – O/N_2 ratio analysis for which J is minimum
$\mathbf{x}_b$ – O/N_2 ratio background
B – Background error covariance matrix calculated from a 10-year MSIS run (8x daily, 50 days between 2000 and 2010)
R – The (diagonal) observation error covariance as reported by SSUSI/GUVI
H – A linear observation operator that interpolates $\mathbf{x}_b$ to the observation locations using inverse-distance weighting of its four nearest neighbours

$\mathbf{x}_b$ is propagated forwards in time as follows:

$$\mathbf{x}_{b\ t2} = 0.9\ (\mathbf{x}_{b\ t1} + \mathrm{MSIS}_{t2} - \mathrm{MSIS}_{t1}) + 0.1\ \mathrm{MSIS}_{t2}$$

Thermospheric composition assimilation module



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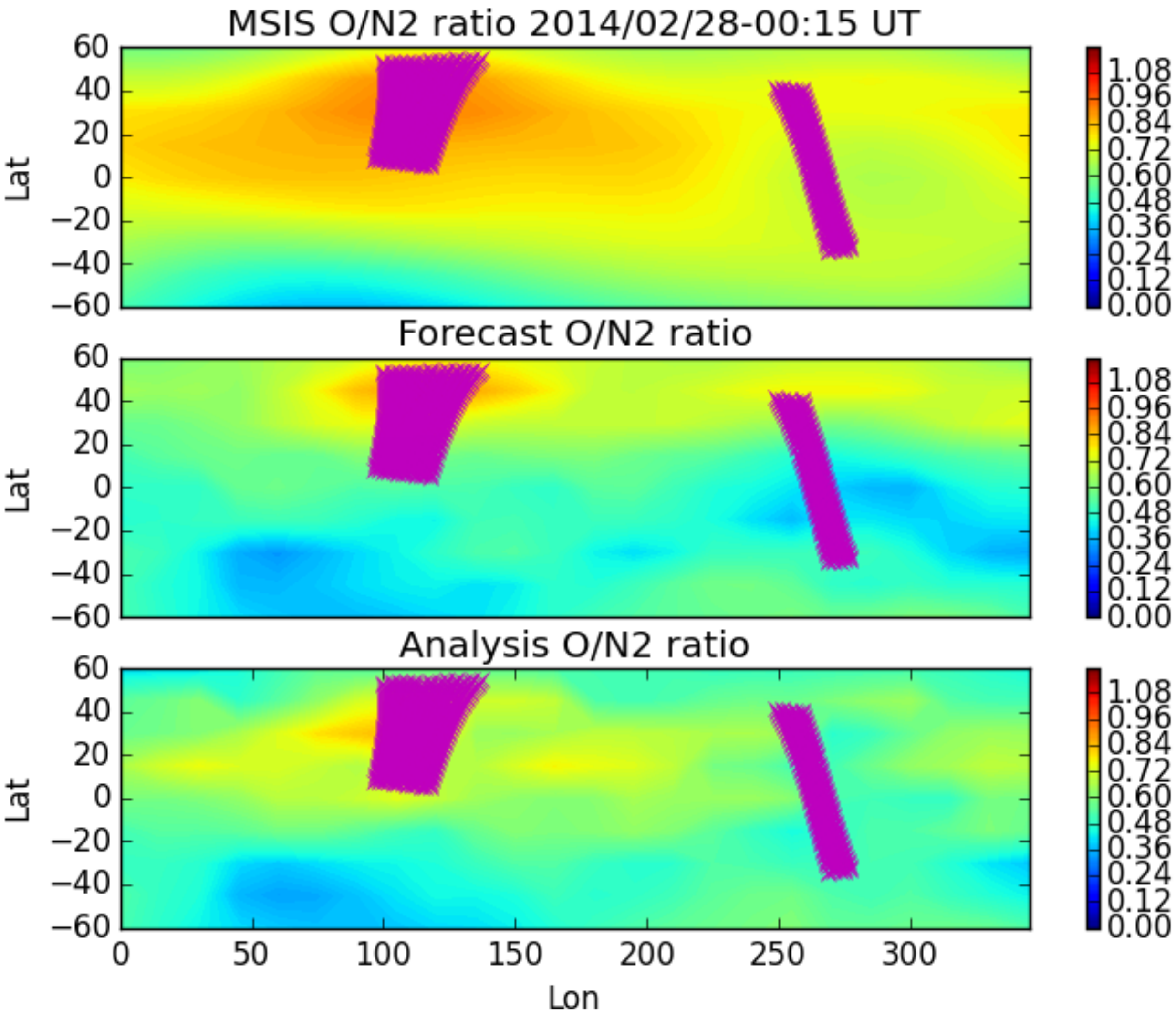

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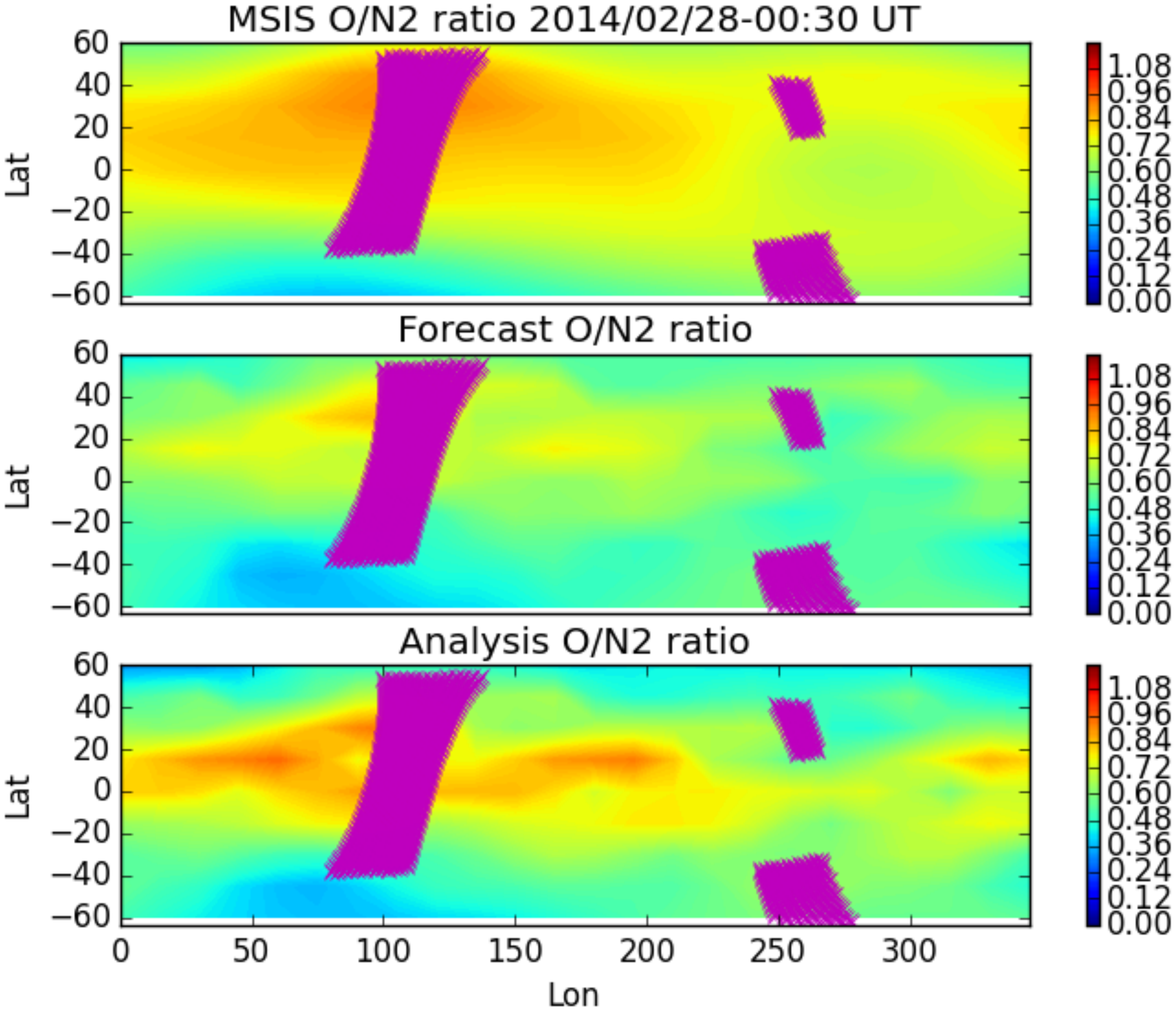

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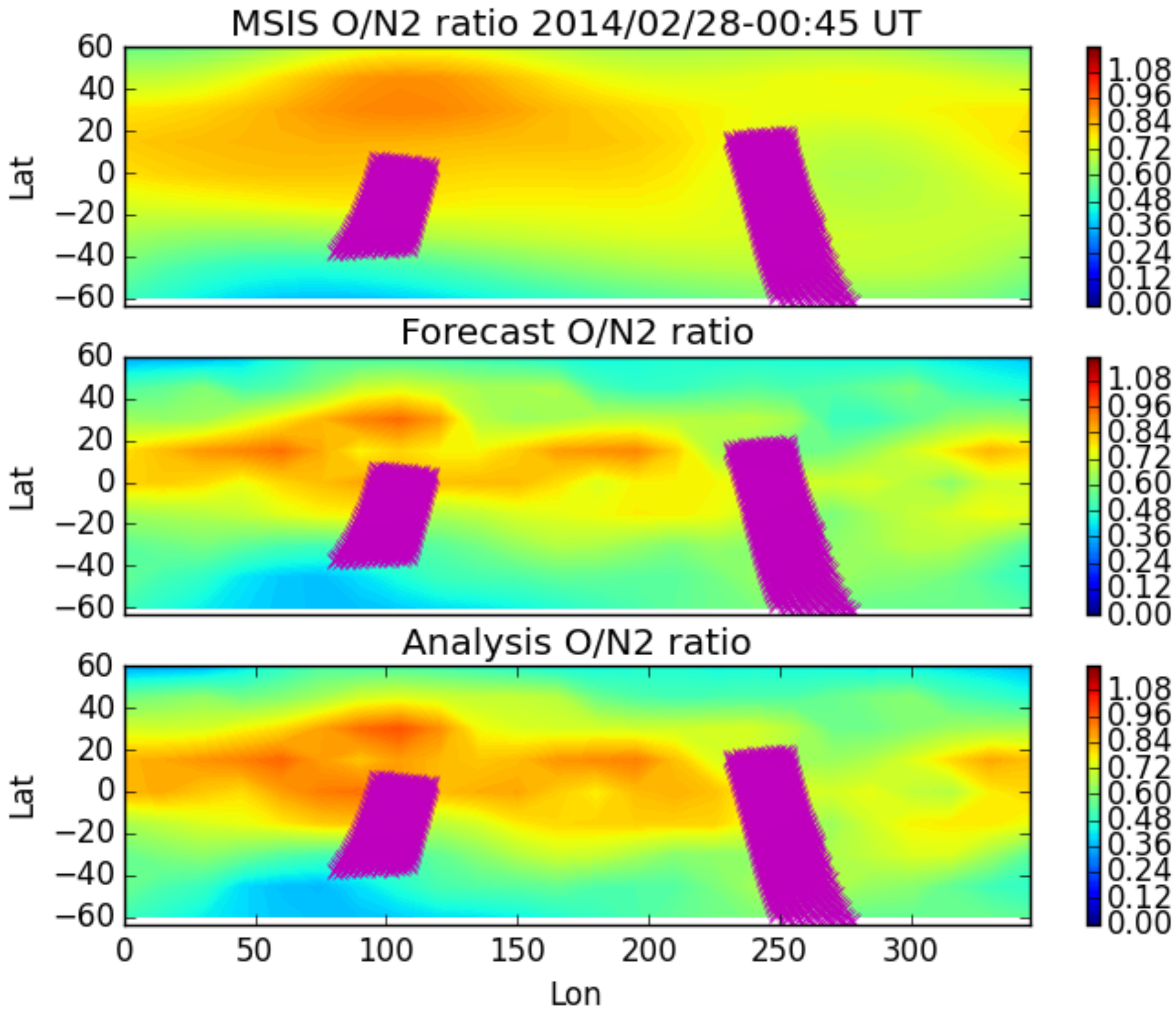

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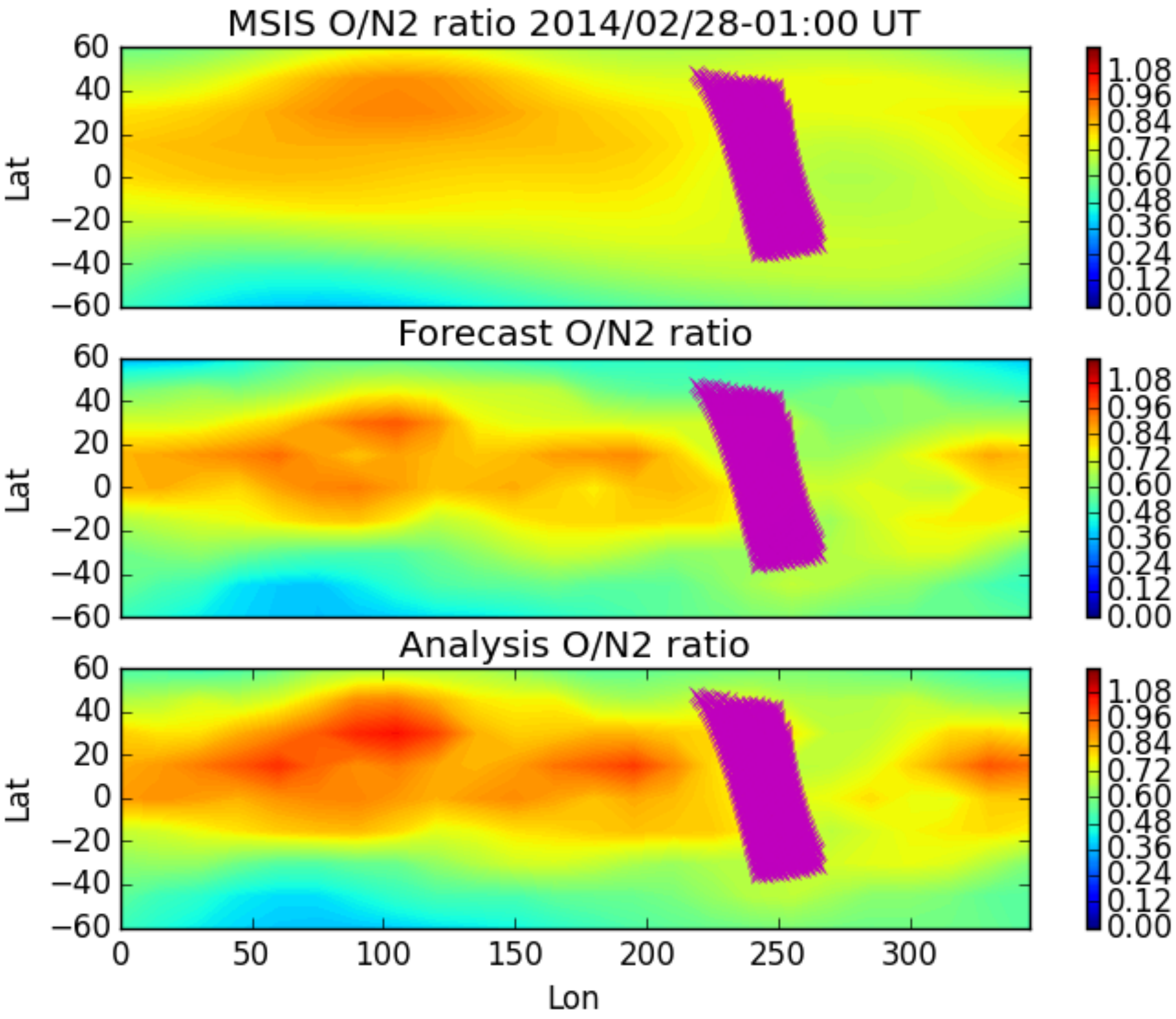

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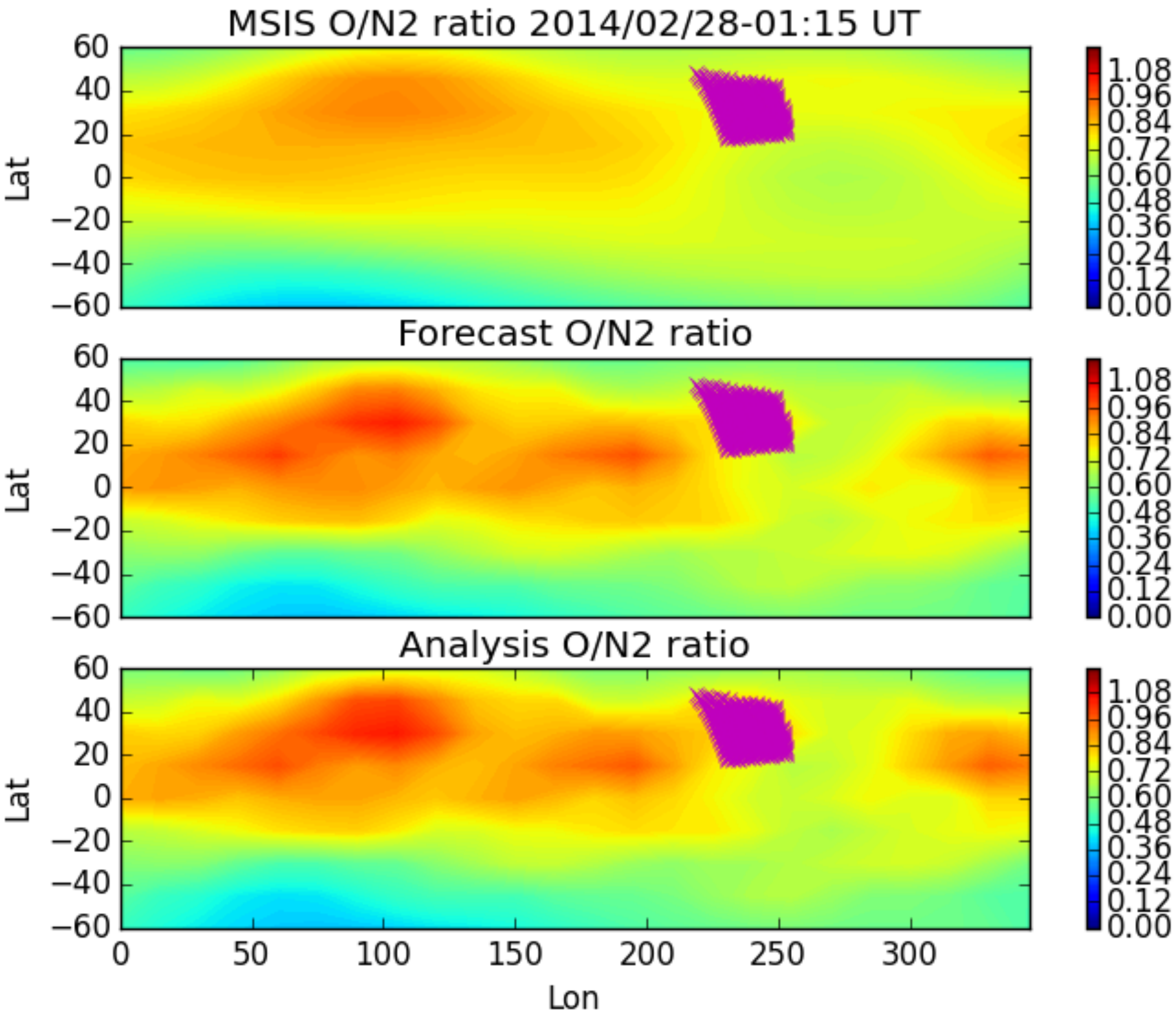

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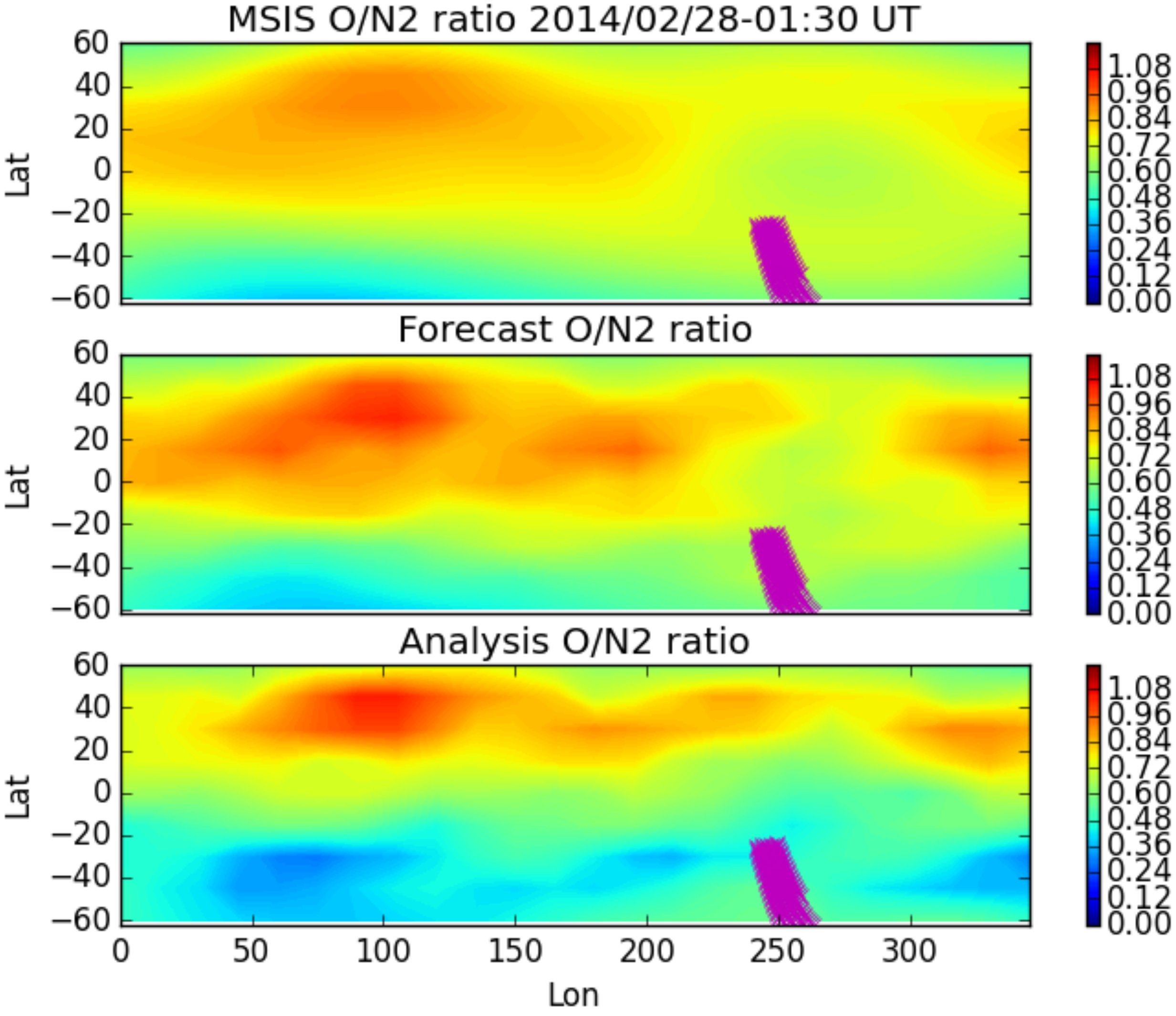

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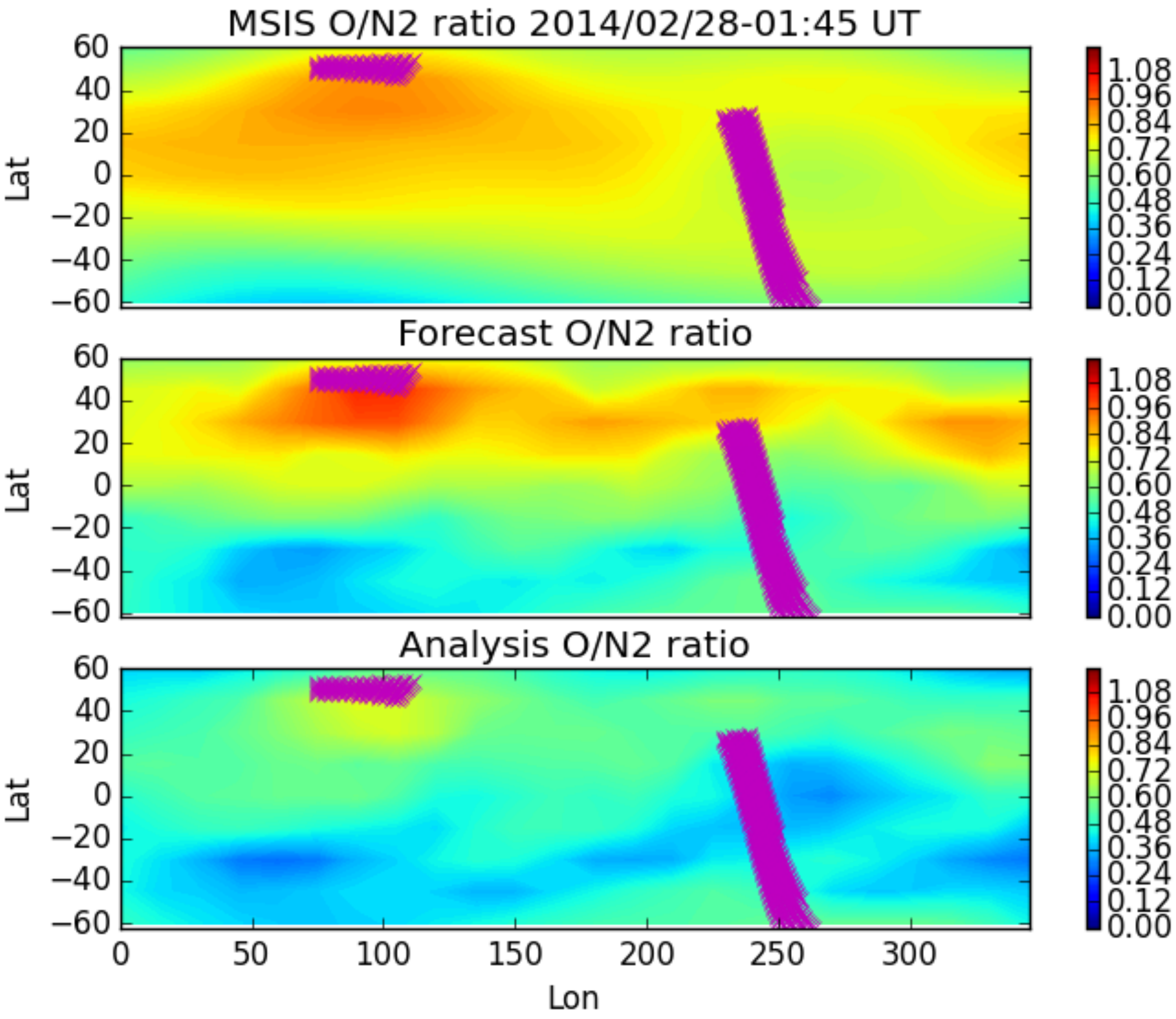

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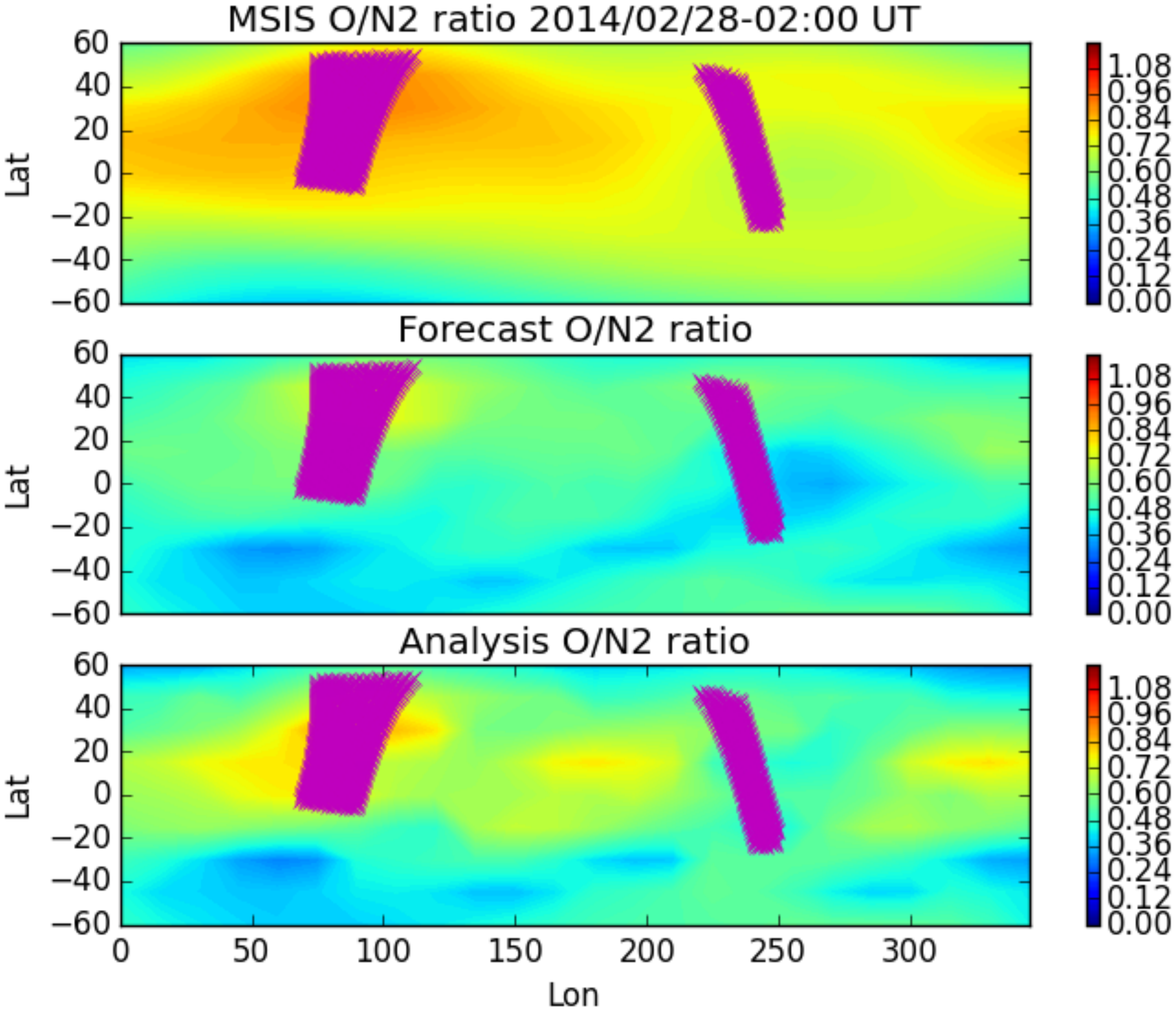

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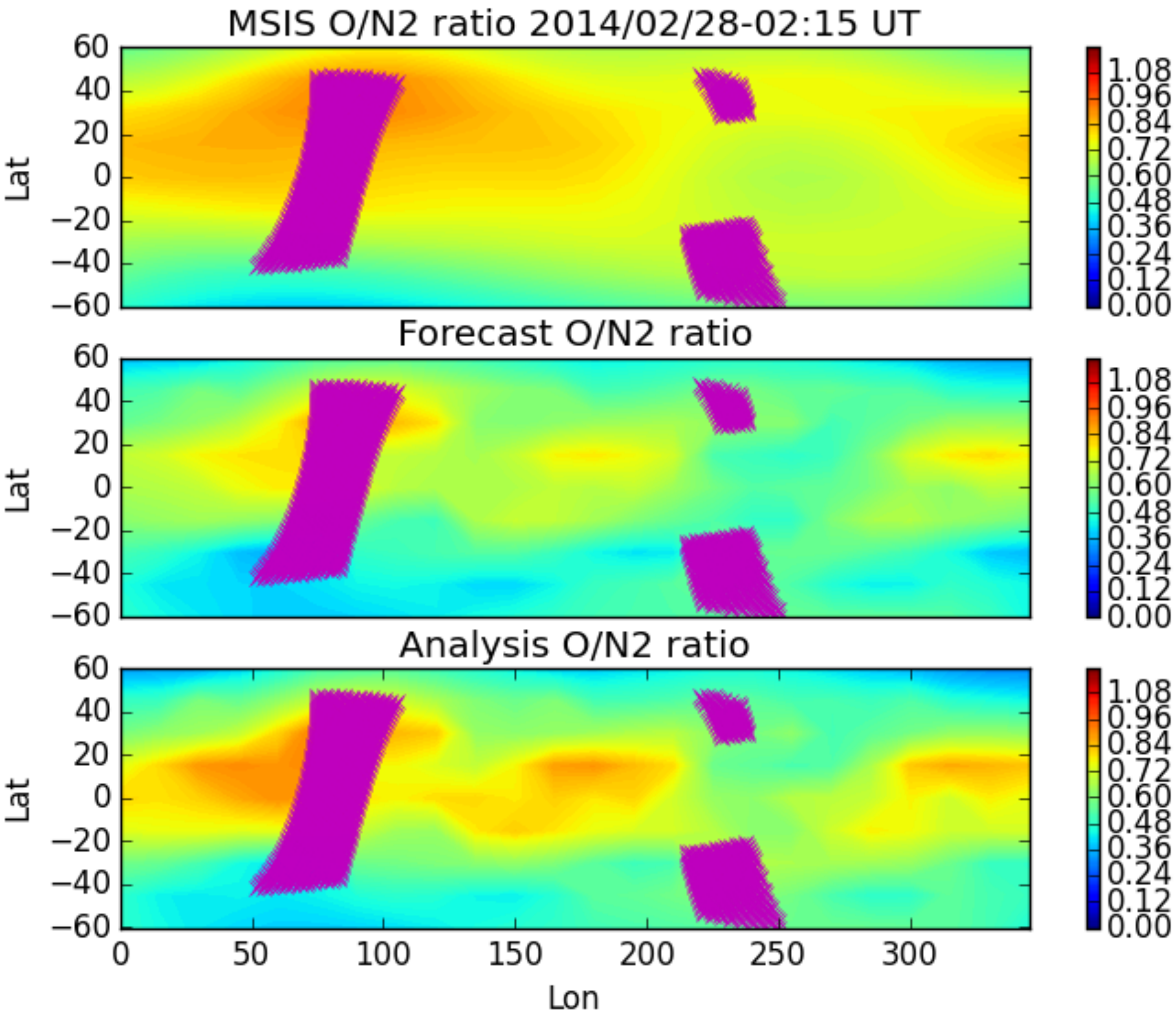

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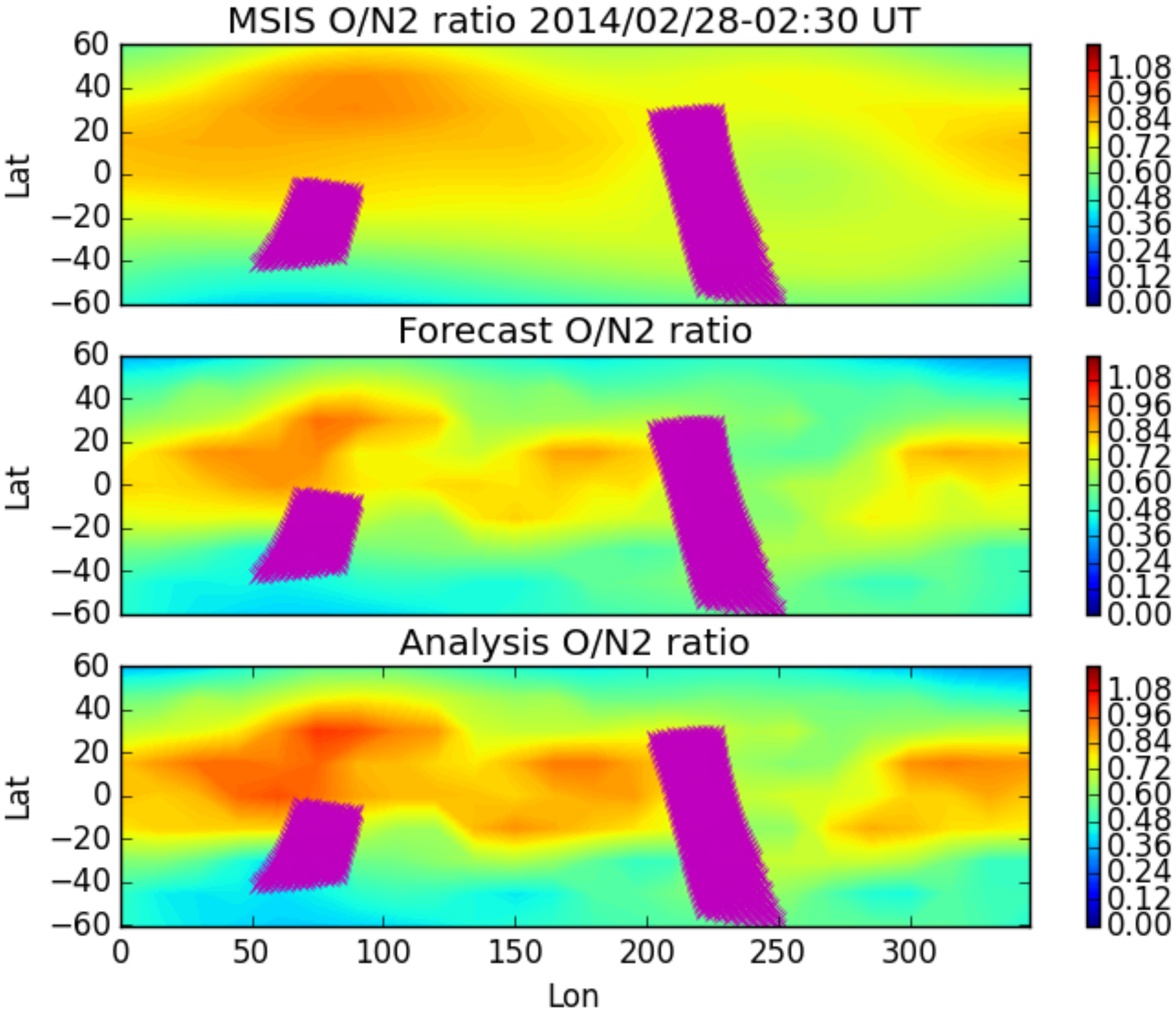

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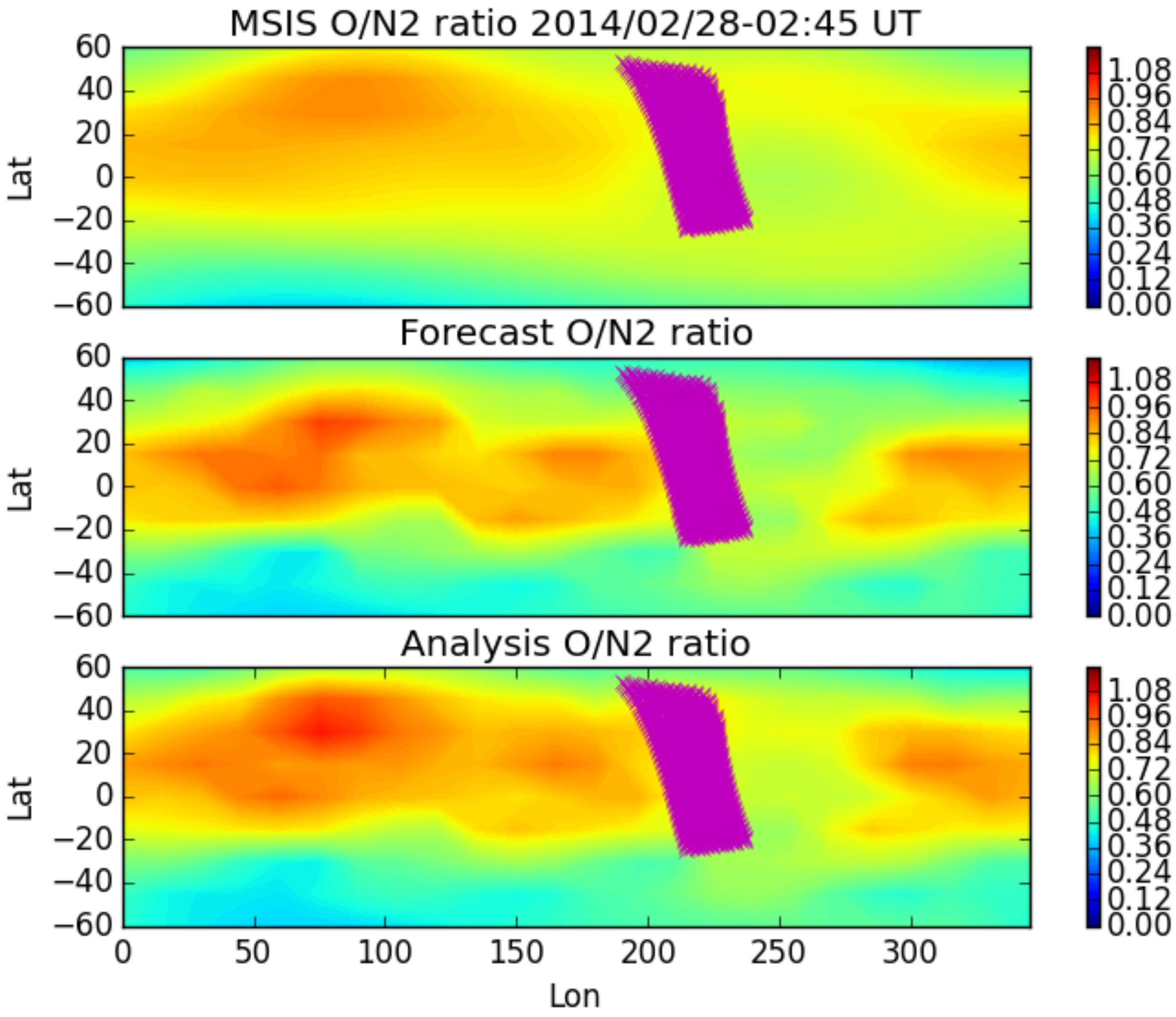

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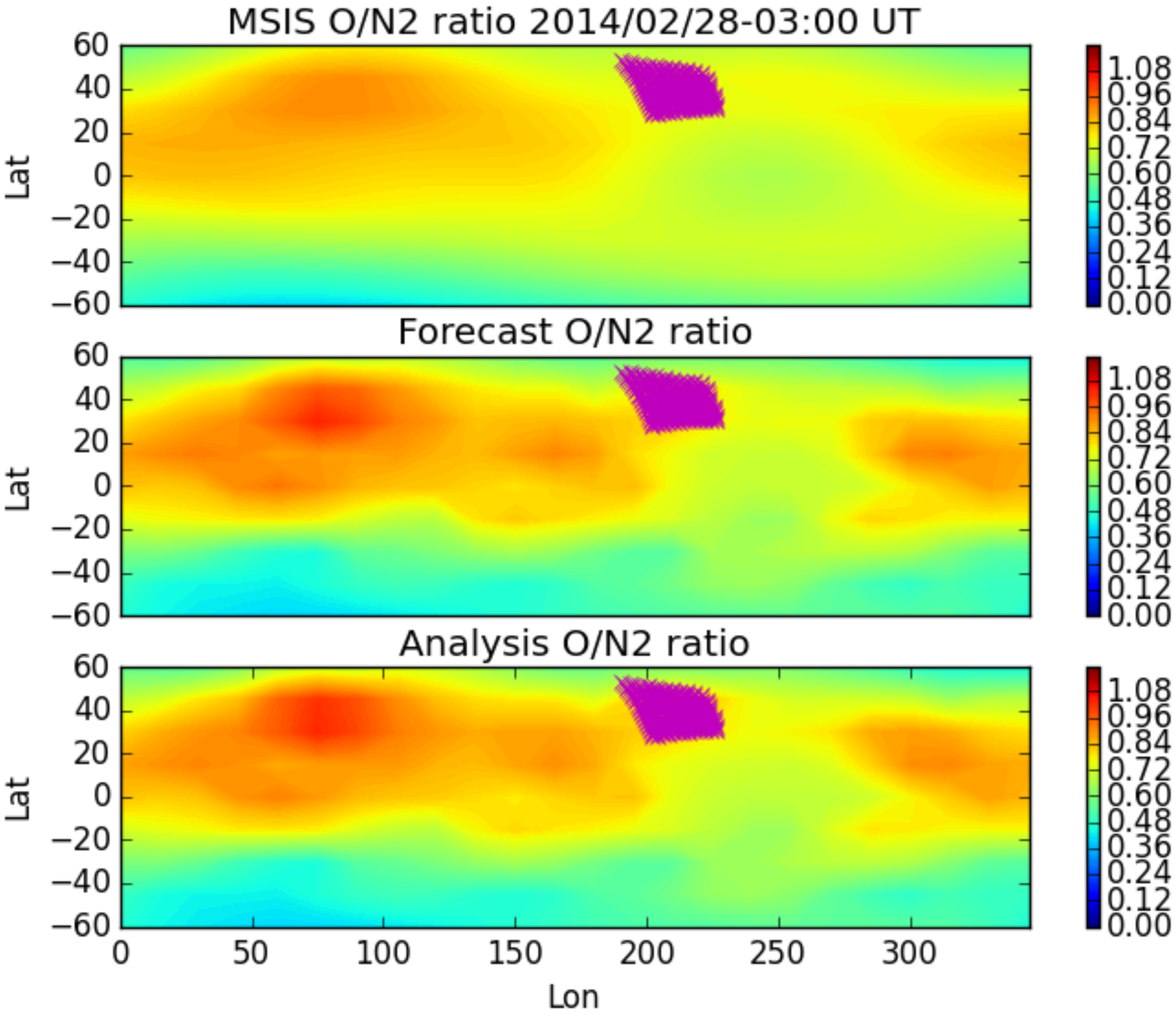

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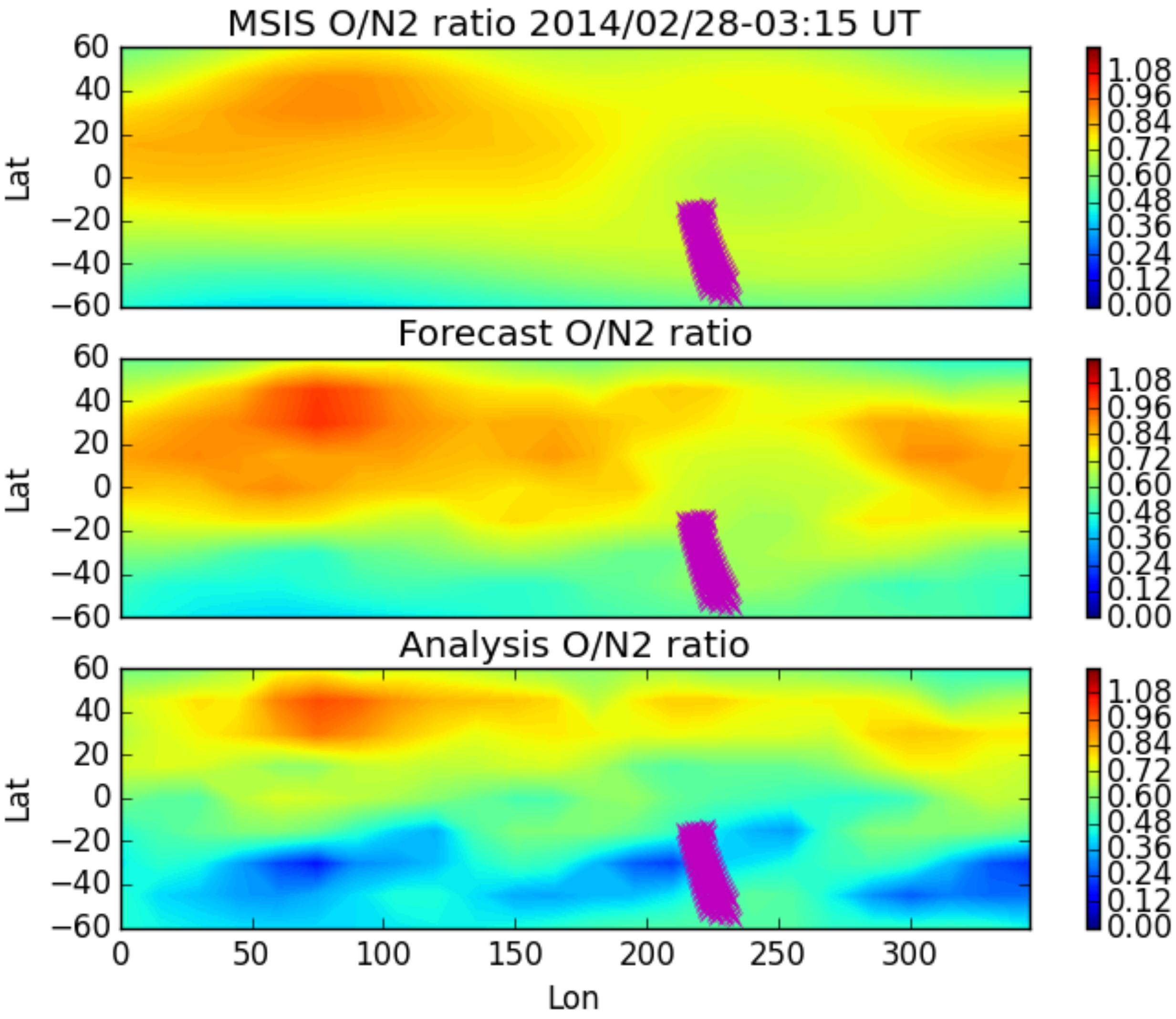

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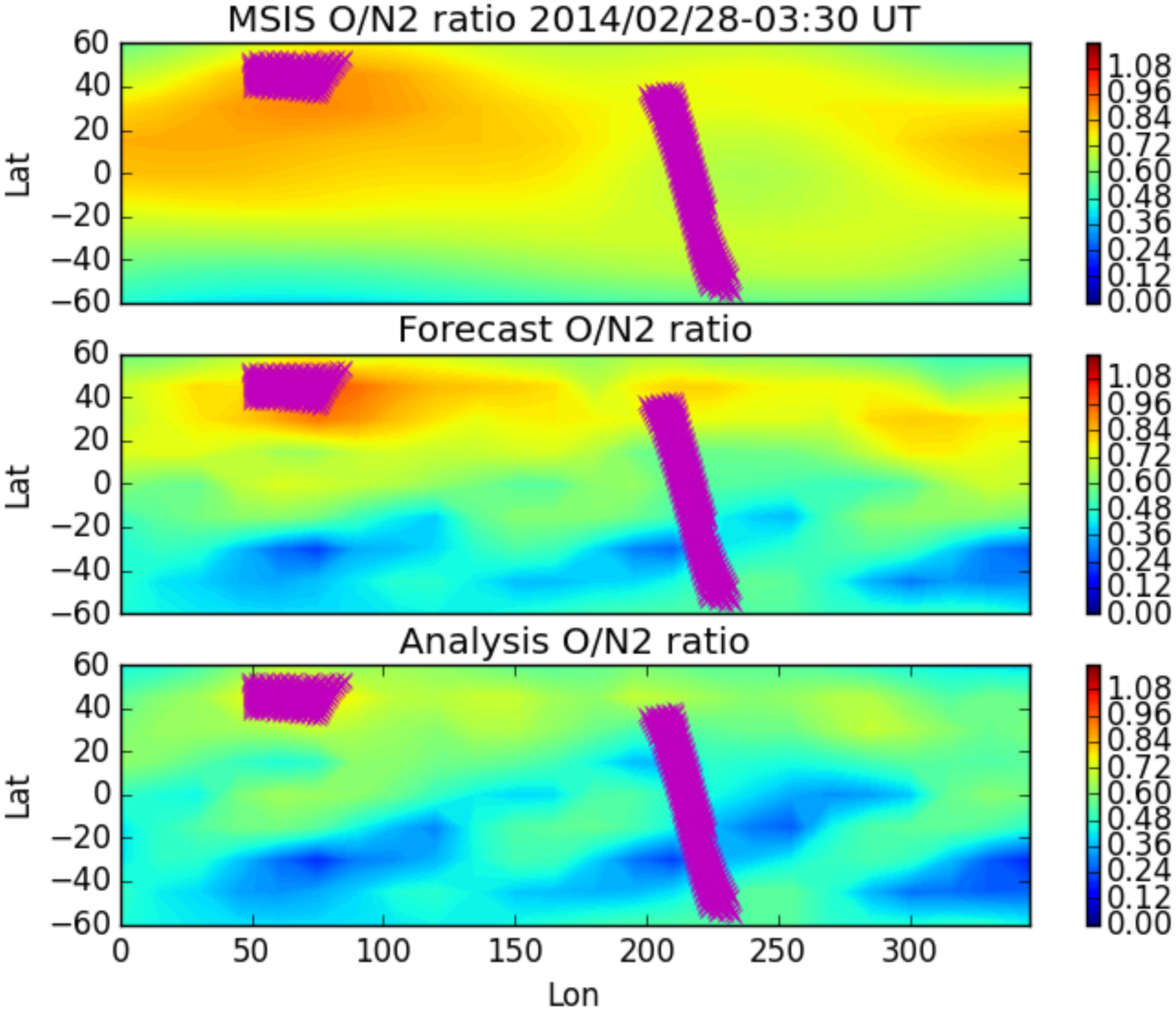

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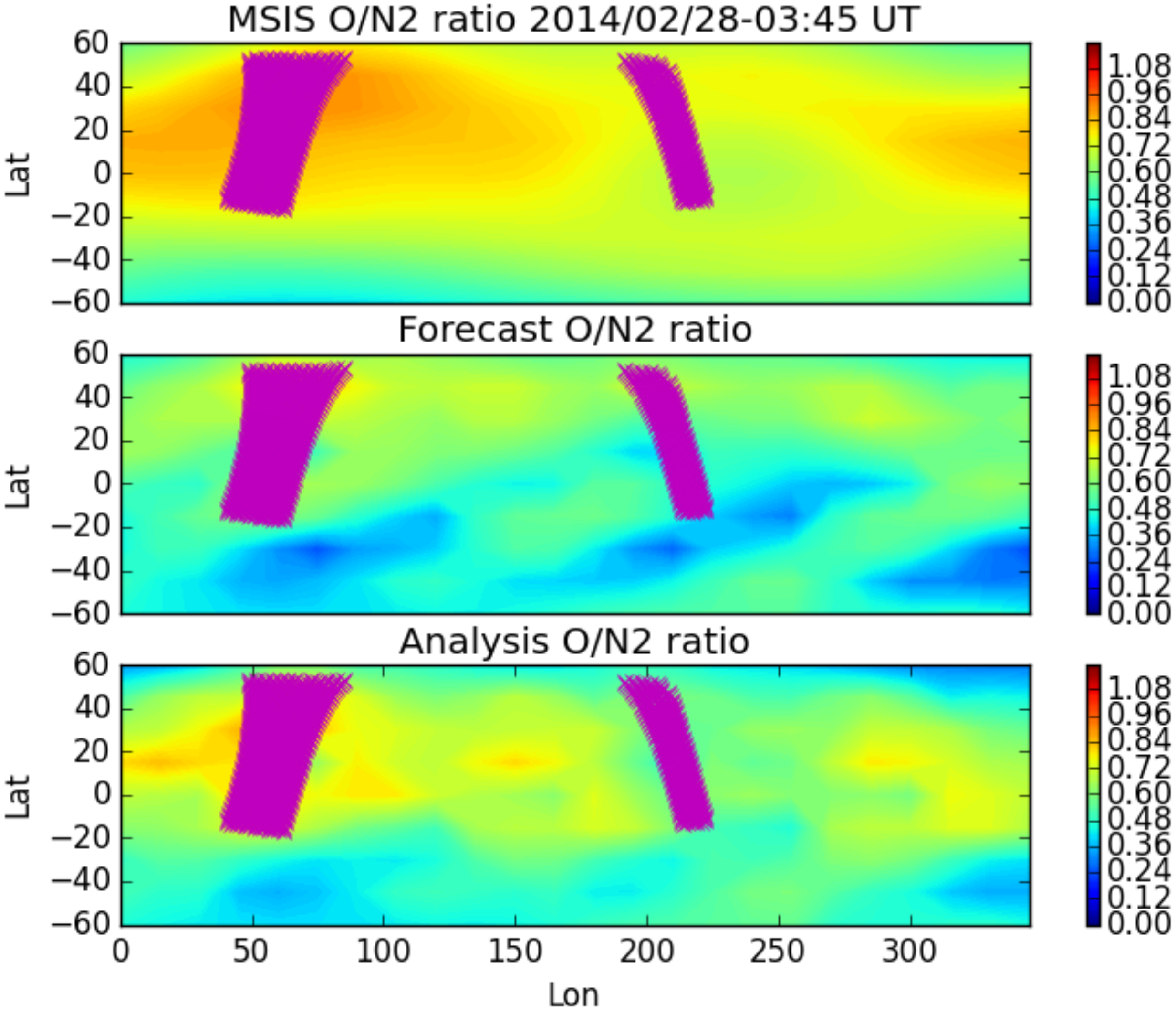

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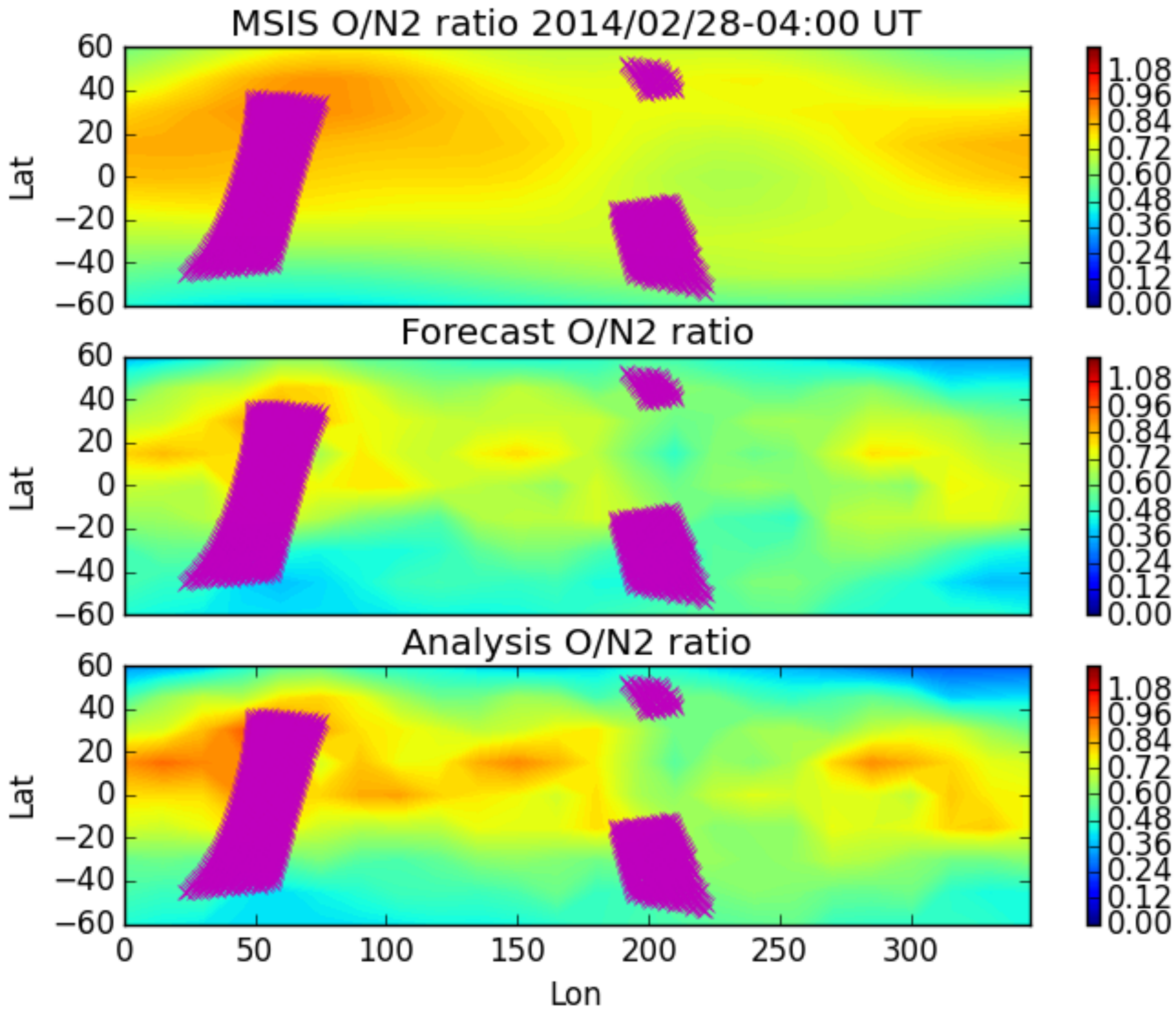

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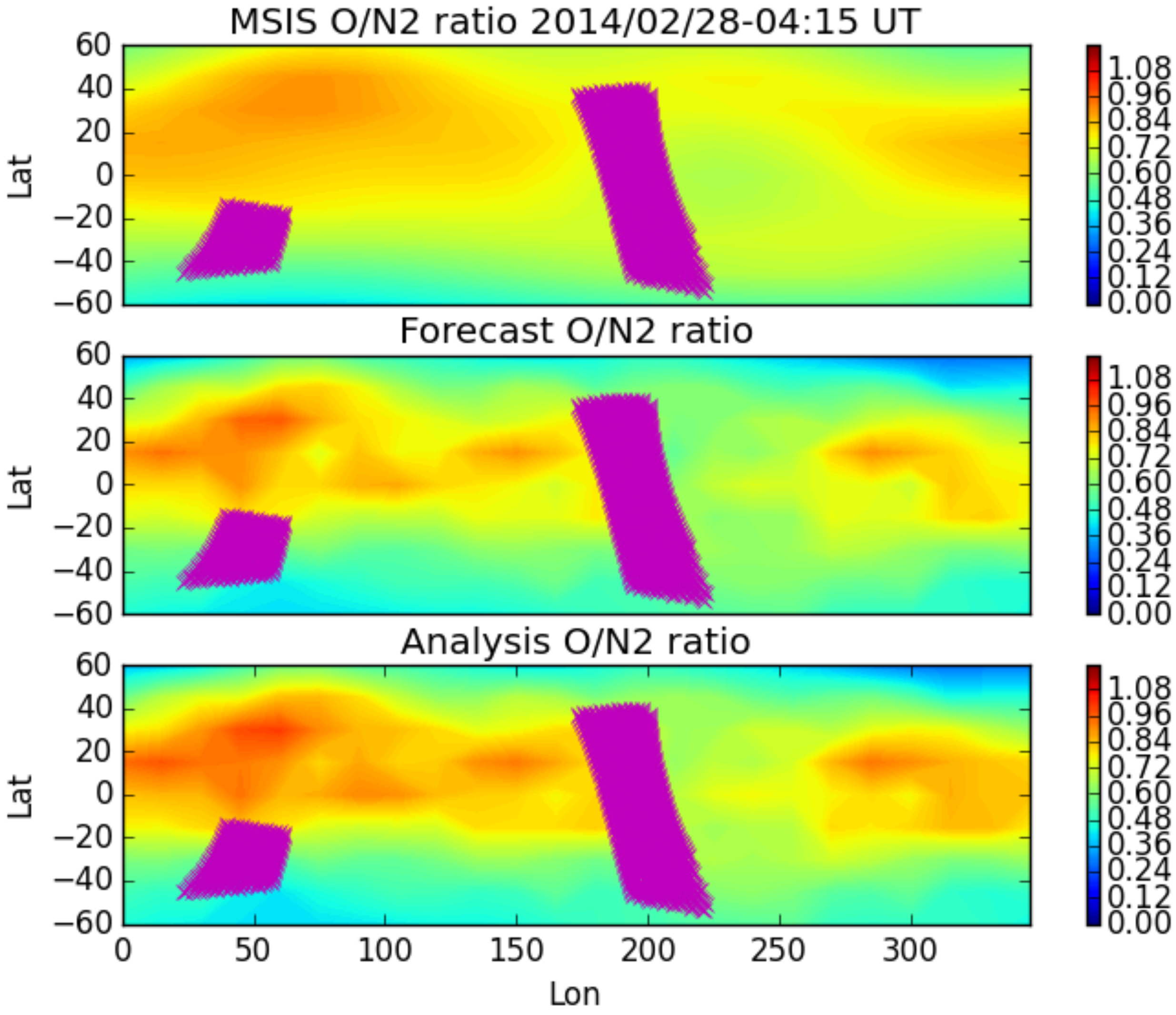

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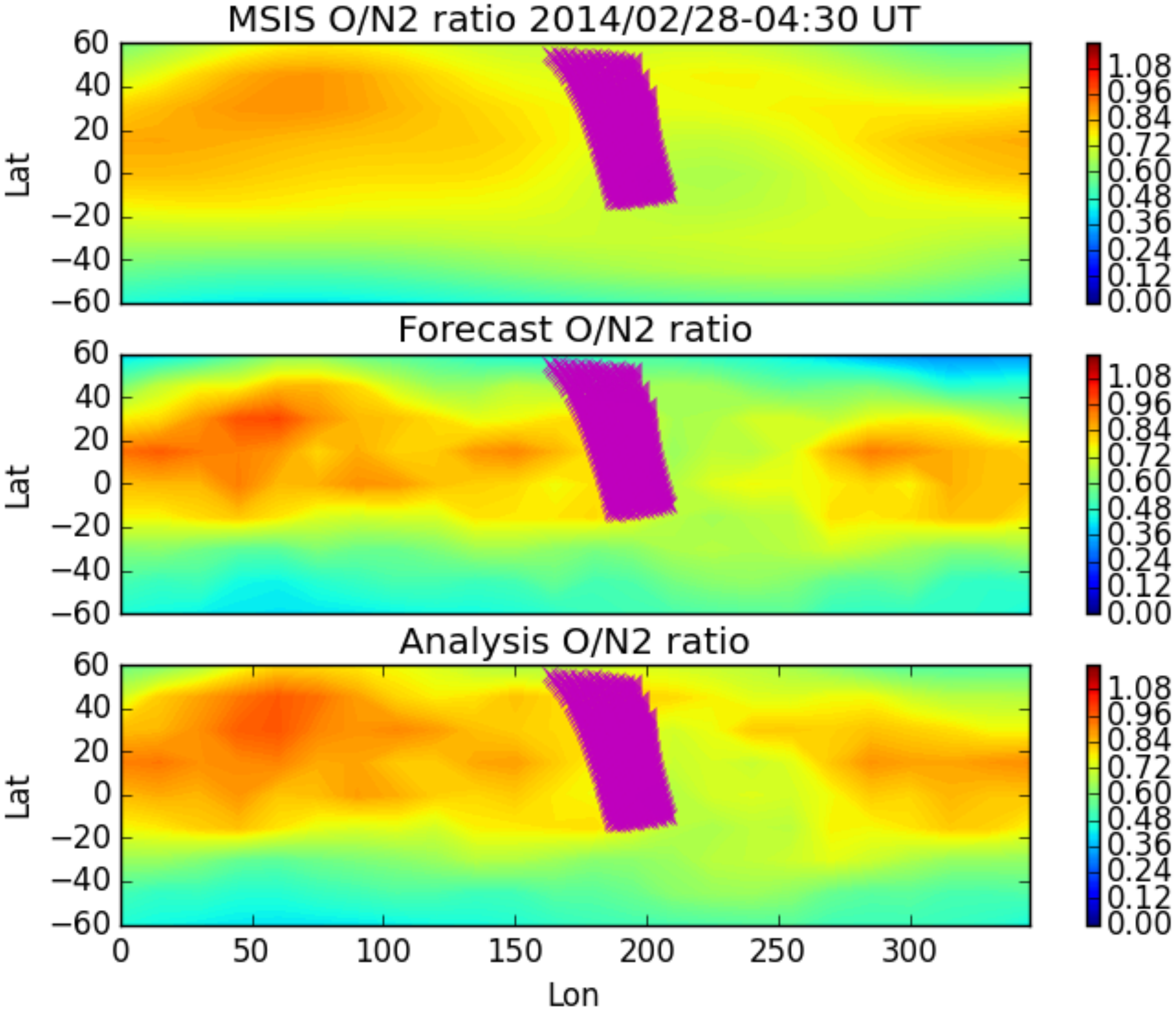

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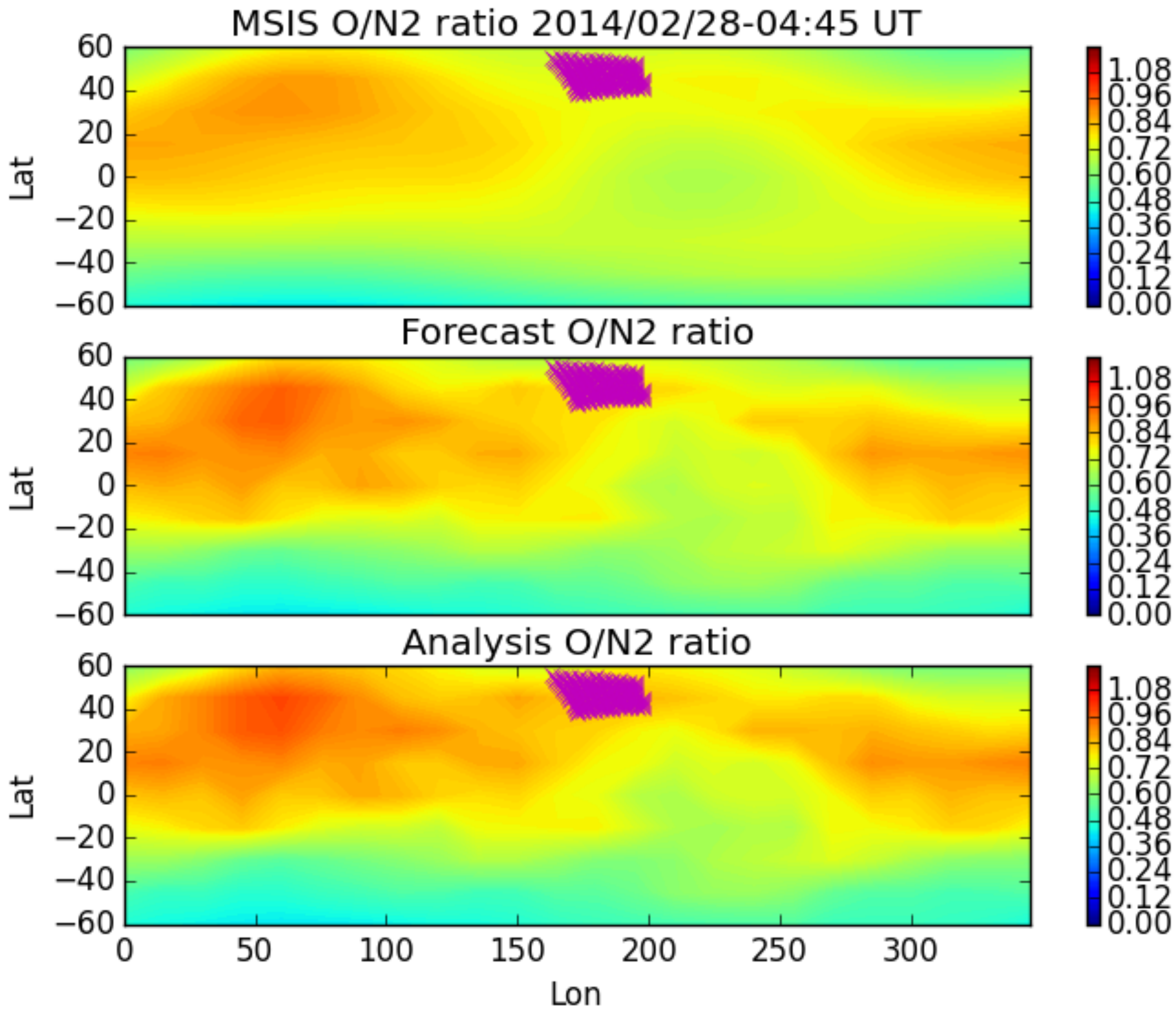
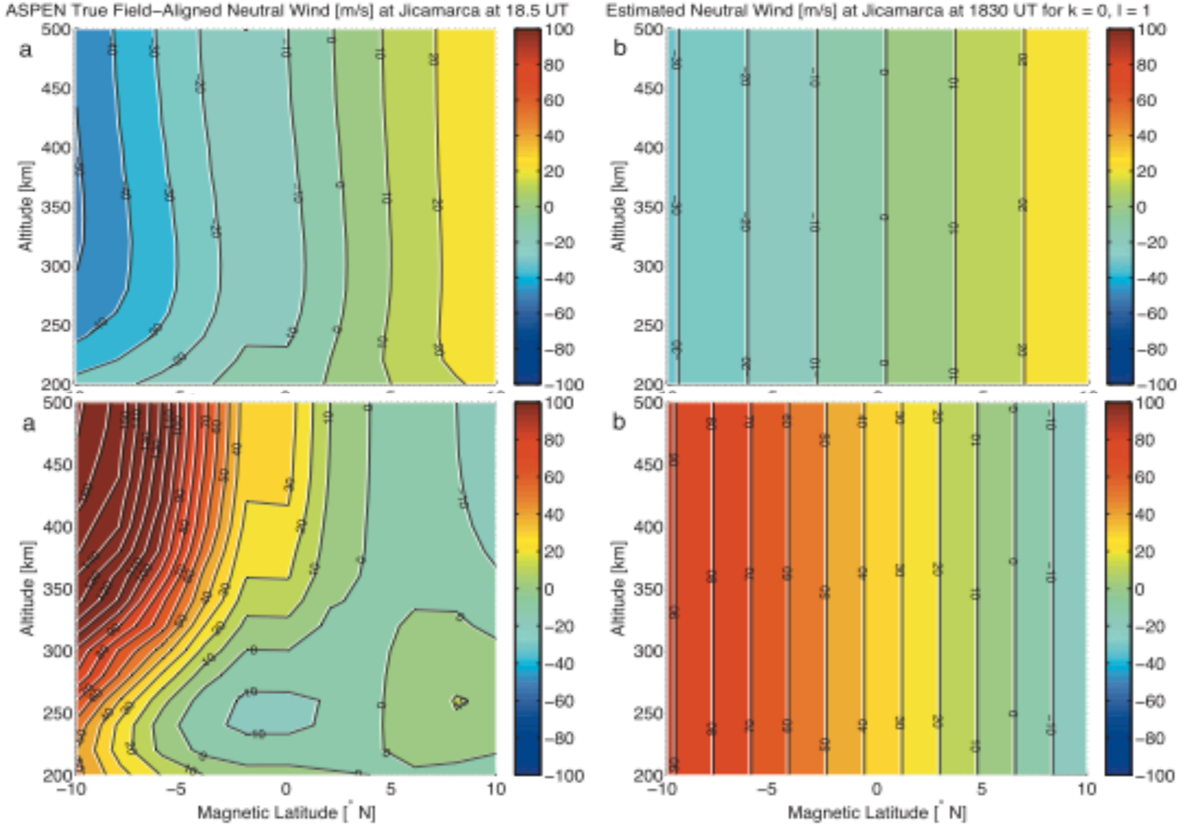


Wind estimation module

- Estimating Model Parameters through Ionospheric Reverse Engineering (EMPIRE) *Datta-Barua et al.* [2009]
- Meridional wind correction determined to explain the discrepancy between the electron density background and analysis
- All model terms are calculated using ionospheric physics described earlier

Simulated Truth

Wind estimate



ASPEN True Field–Aligned Neutral Wind [m/s] at Jicamarca at 18.5 UT

Estimated Neutral Wind [m/s] at Jicamarca at 1830 UT for k = 0, l = 1

Meridional wind in m/s

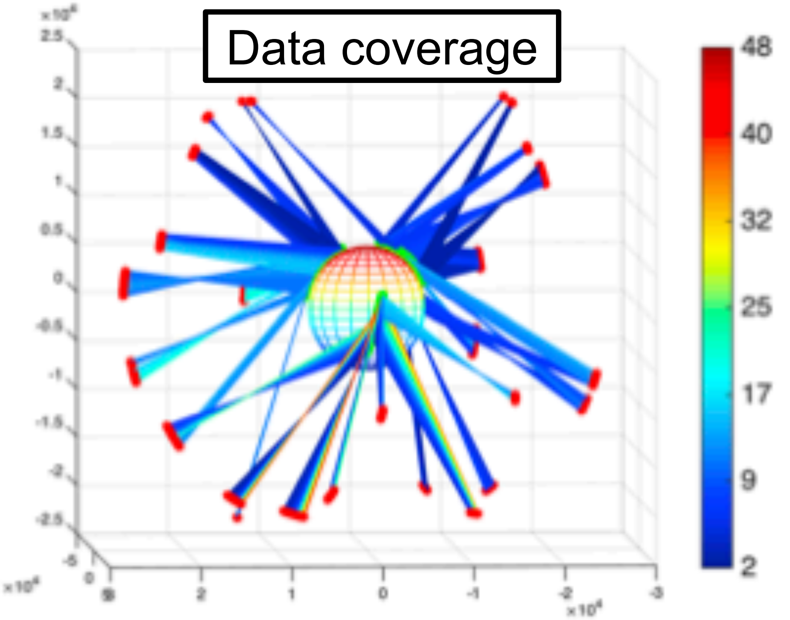
Plasmaspheric assimilation module

- Plasmaspheric Data Assimilation Four-Dimensional (*Nikoukar et al.* 2015)
- GPS data assimilated to Global Core Plasmasphere model
- Gauss-Markov Kalman Filter approach (3DVar also tested)

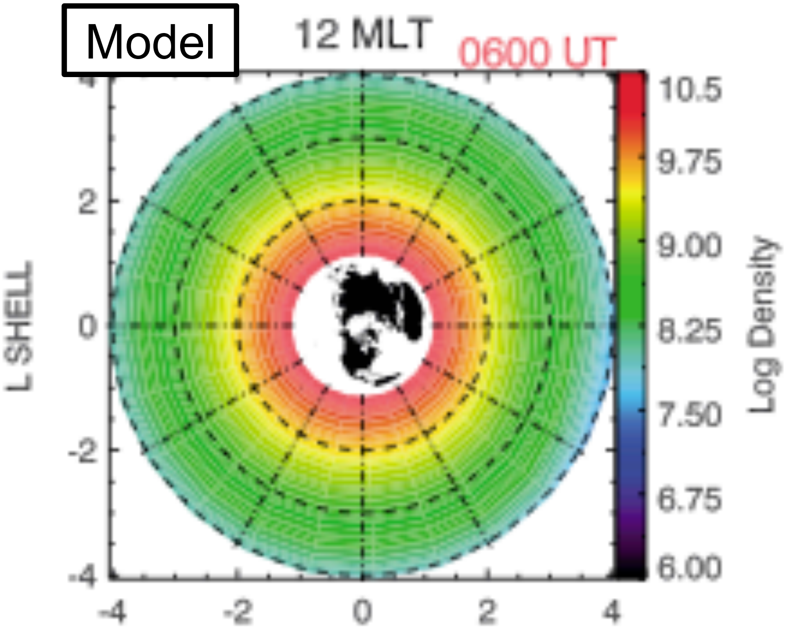
Nikoukar, R., Bust, G., & Murr, D. (2015). A novel data assimilation technique for the plasmasphere. *Journal of Geophysical Research: Space Physics*, *120*(10), 8470-8485.

Plasmaspheric assimilation module

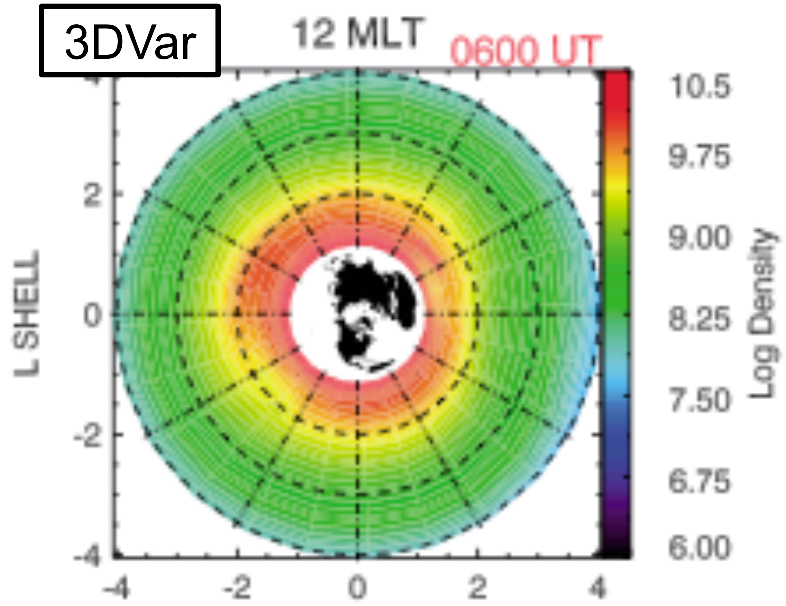
Data coverage



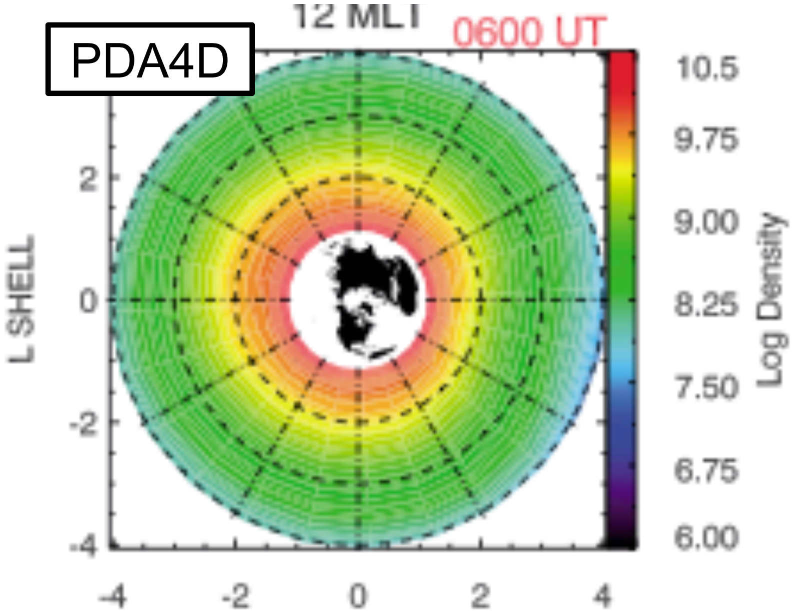
Model



3DVar



PDA4D



Summary

- **IDA2017 is a next-generation coupled, modular assimilation package**
- **Diverse modeling and data assimilation tools available and interchangeable through a common interface**
- **New developments include a physics advance module and a composition assimilation module – early results shown**