2021 Virtual CEDAR Workshop

Space Weather Forecast with the Operational WAM-IPE

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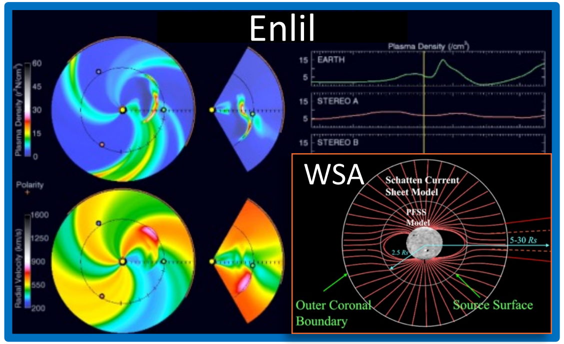
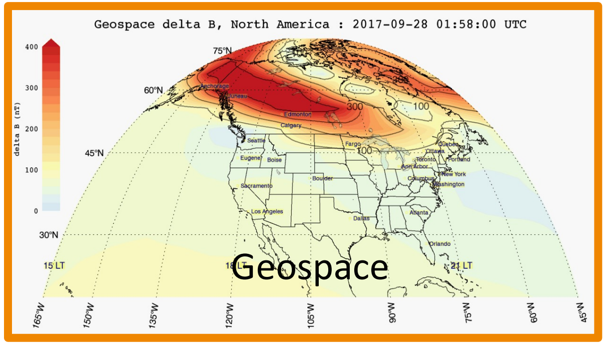
CIRES

Operational Space Weather Models at NOAA NWS

- WSA-ENLIL and the SWMF Geospace models have been transitioned to NOAA operations and are now providing real-time space weather products
  - WSA-ENLIL follows the propagation of plasma from Sun to Earth through interplanetary space for arrival time of coronal mass ejection (CME)
  - The SWMF Geospace model simulates the response of near-Earth magnetic fields (Earth’s magnetosphere) for impacts of induced currents on power grids and impacts of energetic particle on satellite systems
- Transitioning WAM-IPE to operations adds an important link in the Sun to Earth modeling framework.

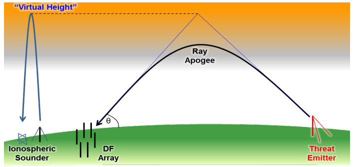




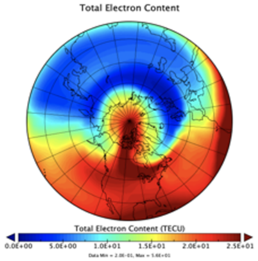
What operators care about

what WAM-IPE contributes marked in red

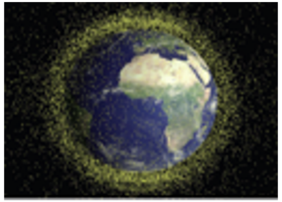
- **For HF communication:**
  - Changes in the Minimum Usable Frequency (LUF) due to D-region absorption (DRAP)
  - Changes in the Maximum Usable Frequency (MUF) due to the peak plasma density (NmF2) and height of peak (hmF2)
  - Undulations in bottom-side F-region



- **For satellite positioning, navigation, timing, and communication:**
  - Mesoscale structure and gradients in plasma density (diffract radio signals and cause amplitude or phase fluctuation in GNSS signals)
  - Delay in navigation signal due to line of sight electron content (position error)
  - Small-scale ionospheric irregularities causing scintillations/fluctuation or complete loss of signal

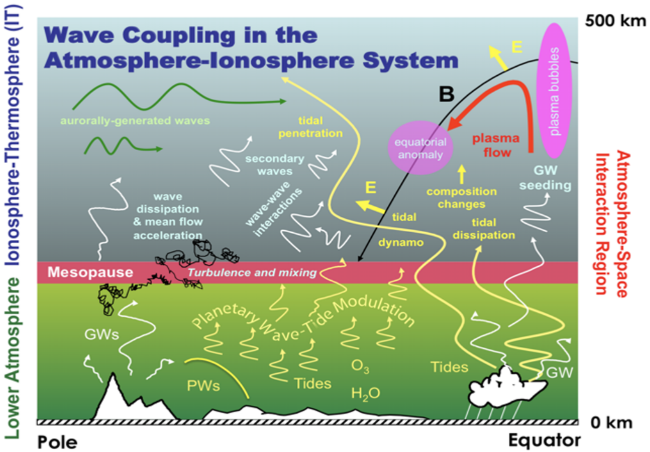


- **For satellite drag**
  - Neutral density and its uncertainty (for decision making, maneuver planning)

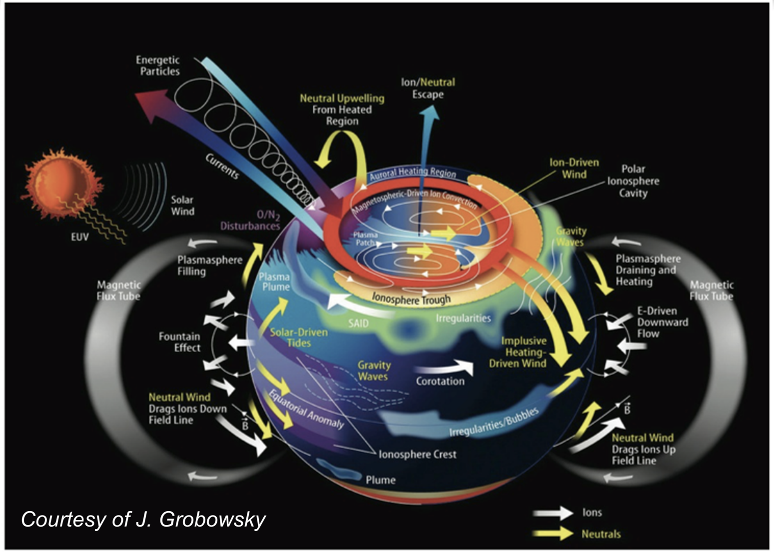


The Ionosphere and Thermosphere

- The upper atmosphere exhibits significant variability just like the troposphere weather system.
- The system is driven by conditions in the incoming solar wind (velocity, density, and magnetic field), solar UV and EUV radiation, as well as the waves/tides from the lower part of the atmosphere.



Courtesy of J. Forbes



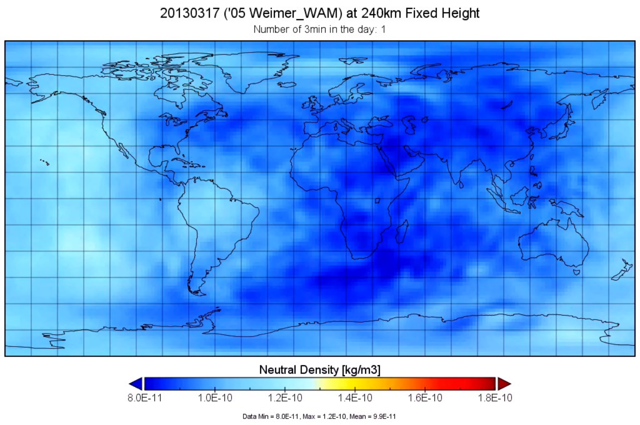
Courtesy of J. Grobowsky

Lower Atmosphere Forcing

- Longitude structure in tropical convection drives non-migrating tides
- Sudden stratospheric warmings modulate the migrating tides
- TW3 migrating tide drives nightside density, temperature and winds
- Background variability

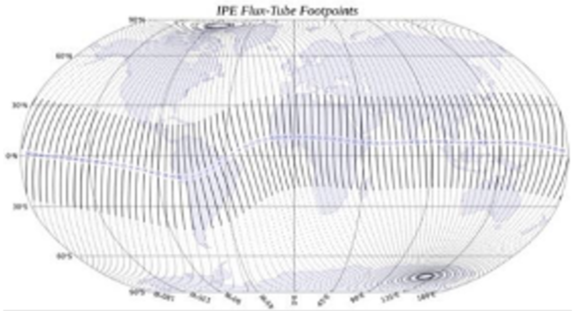
Whole Atmosphere Model (WAM)

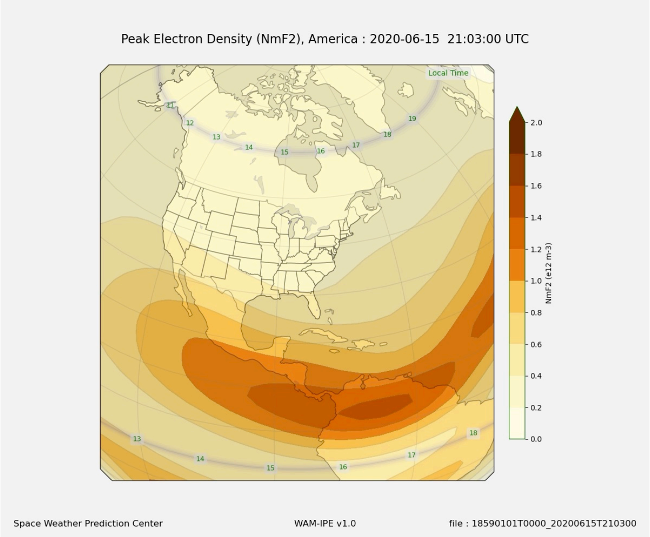
- An extension of the US weather model (Global Forecast System spectral hydrostatic dynamical core) to 600 km altitude, 150 layers, variable g
- *5 species* dynamical core of O, O_2, O_3, N_2, H_2O enthalpy thermodynamics
- WAM runs at ~180 km horizontal resolution, T62, compared to operational weather model of ~12 km, T1534
- Includes all the lower atmosphere weather and dynamics processes, as well as all the additional T-I physics (including electrodynamics and plasma processes)
- Provides the 3D fields for neutral winds, temperature, density, major species composition O, O_2, N_2
- WAM coupling to IPE based on time-dependent 3D re-gridding in SW mediator (ESMF/NUOPC)



Ionosphere Plasmasphere Electrodynamics (IPE)

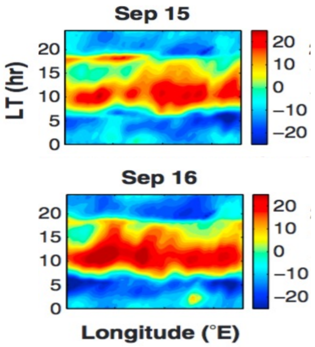
- Space weather *plasma* component of the atmosphere
- Time-dependent, global 3D model of the ionosphere and plasmasphere 90 km to ~10,000 km
- Flux-tube solver based on the Field Line Interhemispheric Plasma (FLIP) model
- IGRF coordinate system, accurately represents Earth's magnetic field
- Seamless perpendicular plasma transport pole-to-pole
- Weimer/Heelis empirical ion convection model driven by solar wind data, TIROS auroral empirical model
- Provides: plasma densities and velocities (9 ion species), ion and electron temperatures in the ionosphere and plasmasphere



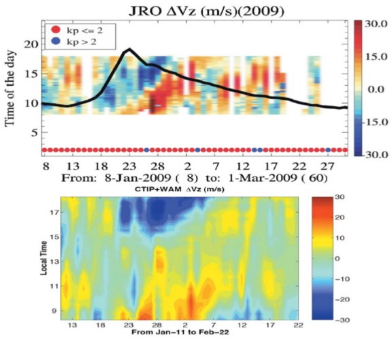


Previous and Ongoing WAM-IPE Research

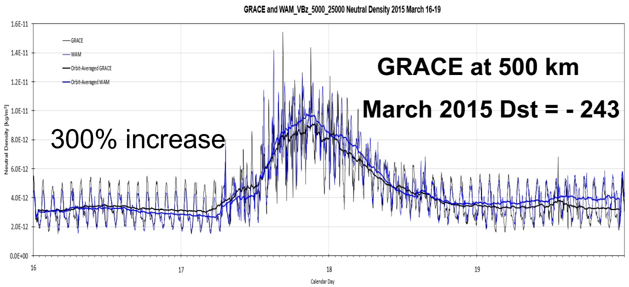
- ✓ Sudden stratosphere warming events (SSWs)
- ✓ Day-to-day and longitudinal ionosphere variability
- ✓ Quantifying the sources of the ionosphere variability
- ✓ Impact of midnight thermosphere dynamics on the nighttime equatorial ionosphere
- ✓ Improving lower boundary of CTIPe
- ✓ Forecast the nighttime equatorial ionospheric irregularity
- ✓ Small-scale waves in the ionosphere
- ✓ High resolution WAM-IPE
- ✓ Thermosphere data assimilation
- ✓ Plasmasphere Erosion

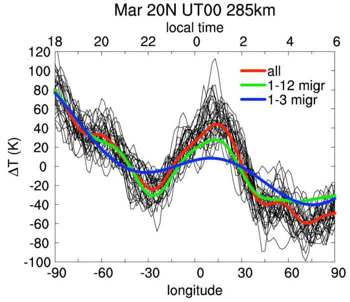


(*Fang et al.*, 2013)



(*Fuller-Rowell et al.*, 2011; *Fang et al.*, 2012)



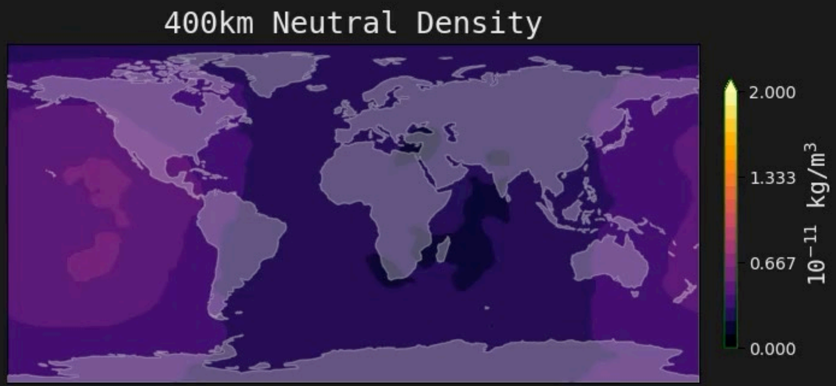


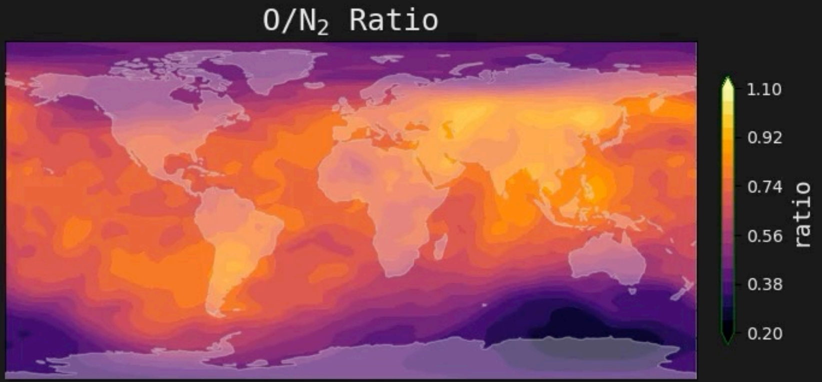
(*Akmaev et al.*, 2009)

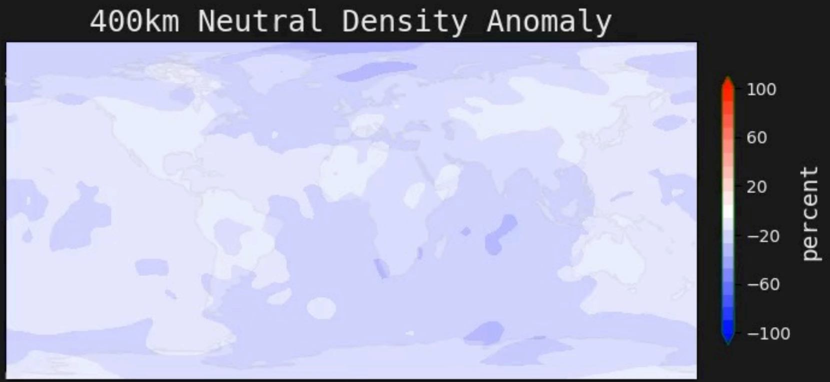
Valid at: Mar 17 2015 00:00 UTC

Neutral Atmosphere

Model: WAM-IPE Init: Mar 17 2015 00 UTC







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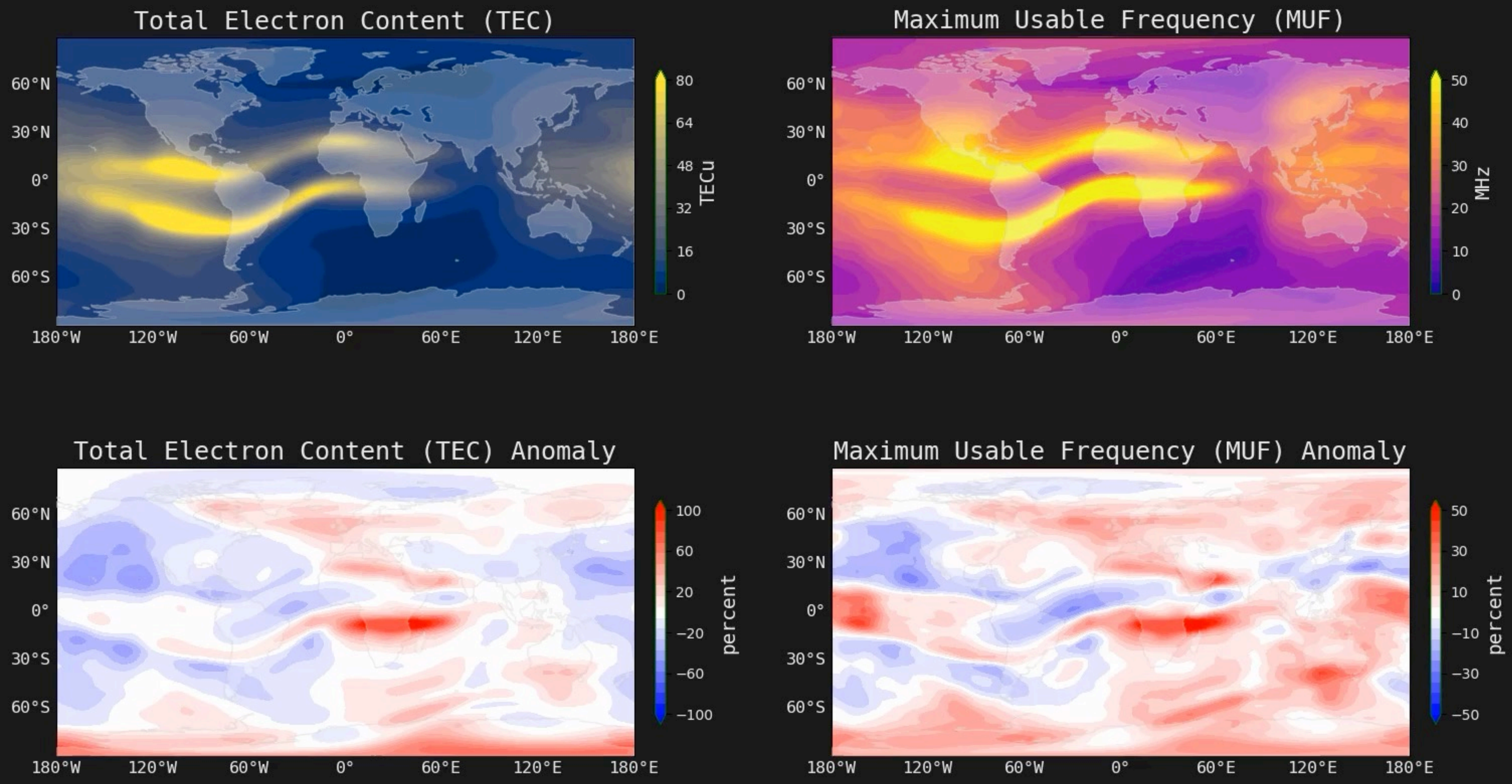
Global Ionosphere Valid at: Mar 17 2015 00:00 UTC



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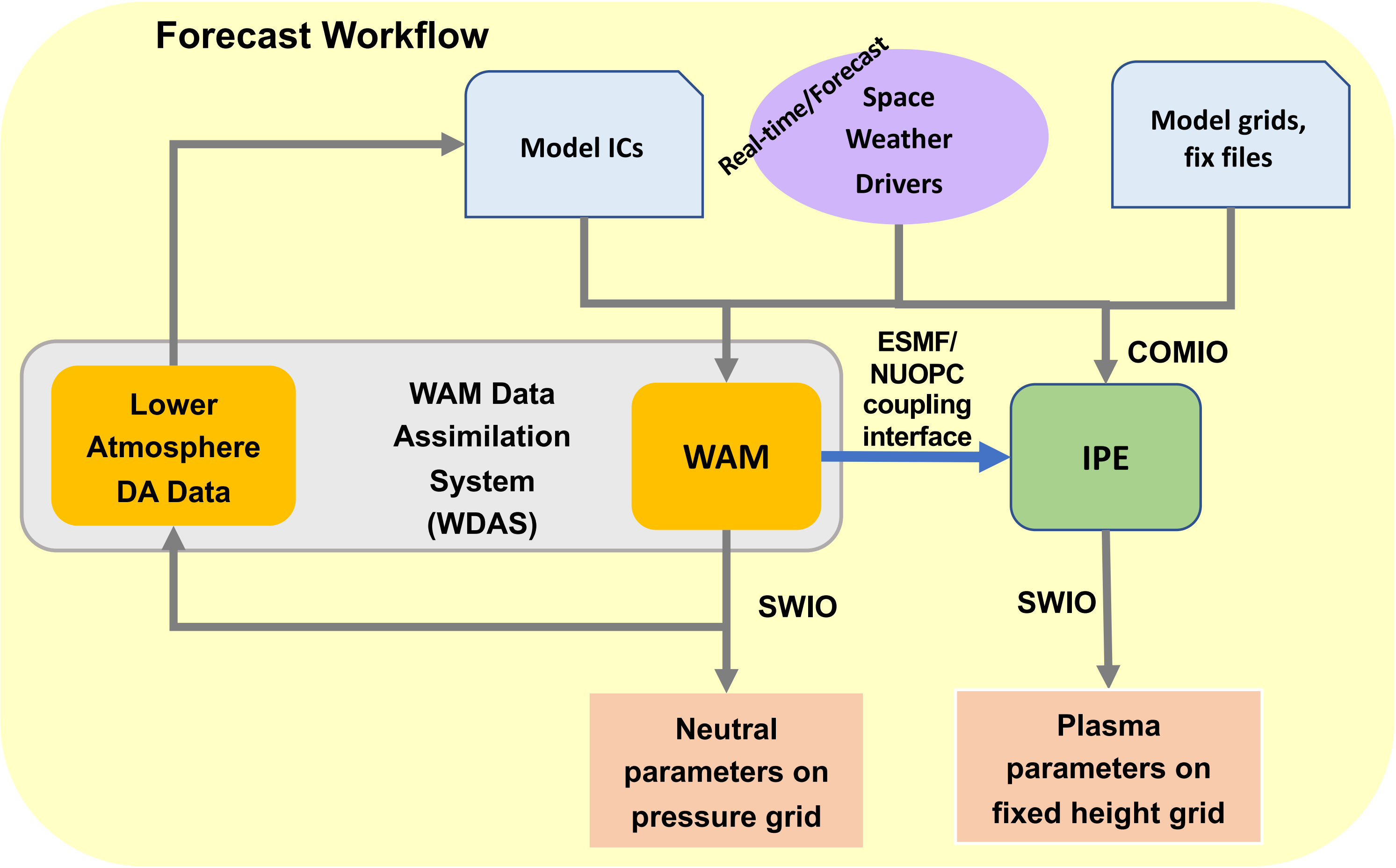
What does it take to get the model into operation?

- **Validation and verification on model physics**
- **Clean and robust code that runs faster than the real-time**
- **Well documented code with proper version control applying modern software practice**
- **Tunable parameters for model physics adjustments in operation**
- **Manageable workflow for Concept of Operations (CONOPS)**
- **Real-time solar and geomagnetic drivers, and a method to mitigate the data gaps and flagging of poor quality data**
- **Computer architecture to support 24/7 operations**
- **Usable products that Forecasters can easily work with**


Forecast Workflow
Model ICs
Real-time/Forecast
Space
Weather
Drivers
Model grids,
fix files
ESMF/
NUOPC
coupling
interface
COMIO
Lower
Atmosphere
DA Data
WAM Data
Assimilation
System
(WDAS)
WAM
IPE
SWIO
SWIO
Neutral
parameters on
pressure grid
Plasma
parameters on
fixed height grid

WAM-IPE Workflows

CONOPS I — Include tropospheric weather into upper atmosphere forecast

- Low-frequency (atmospheric data driven, hours)
- Based on NWS global workflow (6-hour cycles) with WAM data assimilation
- WAM Data Assimilation Scheme (WDAS): modified Gridpoint Statistical Interpolation (GSI) 3D-VAR with Incremental Analysis Update (IAU)
- Observed and predicted space weather drivers for external forcing

CONOPS II — Capture the impact of near real-time solar wind conditions

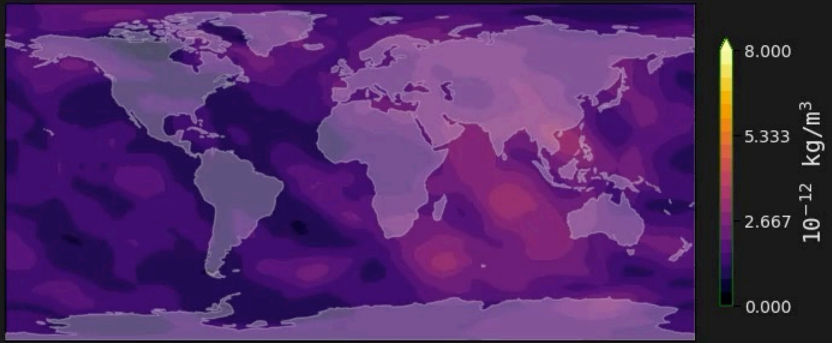
- High-frequency (solar data driven, minutes)
- Extension of global workflow (CONOPS I) with online solar data polling
- Initialize at end of IAU “corrector” segment from CONOPS I with available solar wind drivers
- Advance as soon as observed solar wind data are available

Valid at: May 12 2021 09:05 UTC

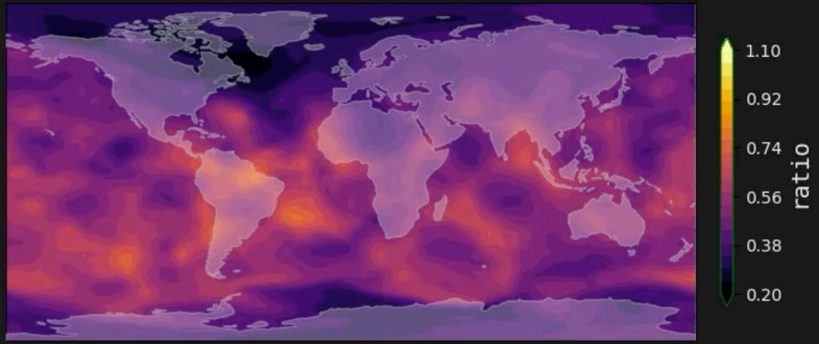
Neutral Atmosphere

Model: WAM-IPE Init: May 12 2021 12 UTC

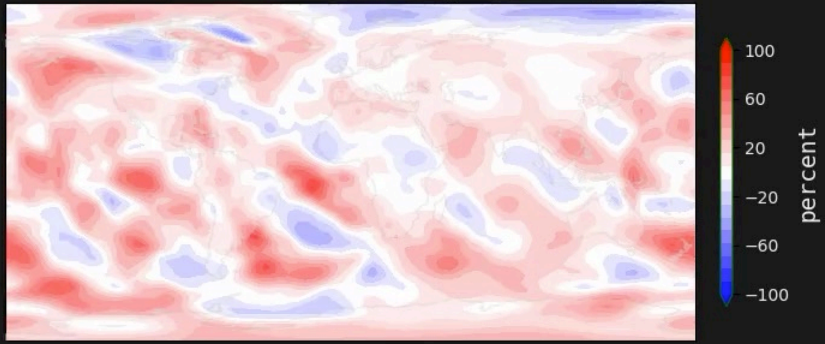
400km Neutral Density



O/N_2 Ratio



400km Neutral Density Anomaly



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Summary and Conclusion

- The WAM-IPE is being transitioned into operation and will start to provide products in early July (https://www.swpc.noaa.gov/products/wam-ipe).
- New products include ionosphere TEC, MUF, and thermosphere neutral density that will be used at the NOAA Space Weather Forecast Office for issuing alerts and warnings.
- Future development of the WAM-IPE
  - Engaging user community to improve product designs.
  - Extend the neutral density output above the WAM model top.
  - High-resolution model for capturing small-scale plasma irregularities (funded by NSF SWQU).
  - New WAM based on the Finite-Volume Cubed-Sphere Dynamical Core FV3 model for the US global forecast system.