



Space Weather Nowcast and Forecast

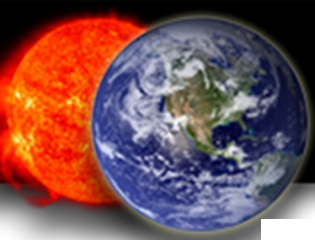


Tzu-Wei Fang

NOAA Space Weather Prediction Center, USA

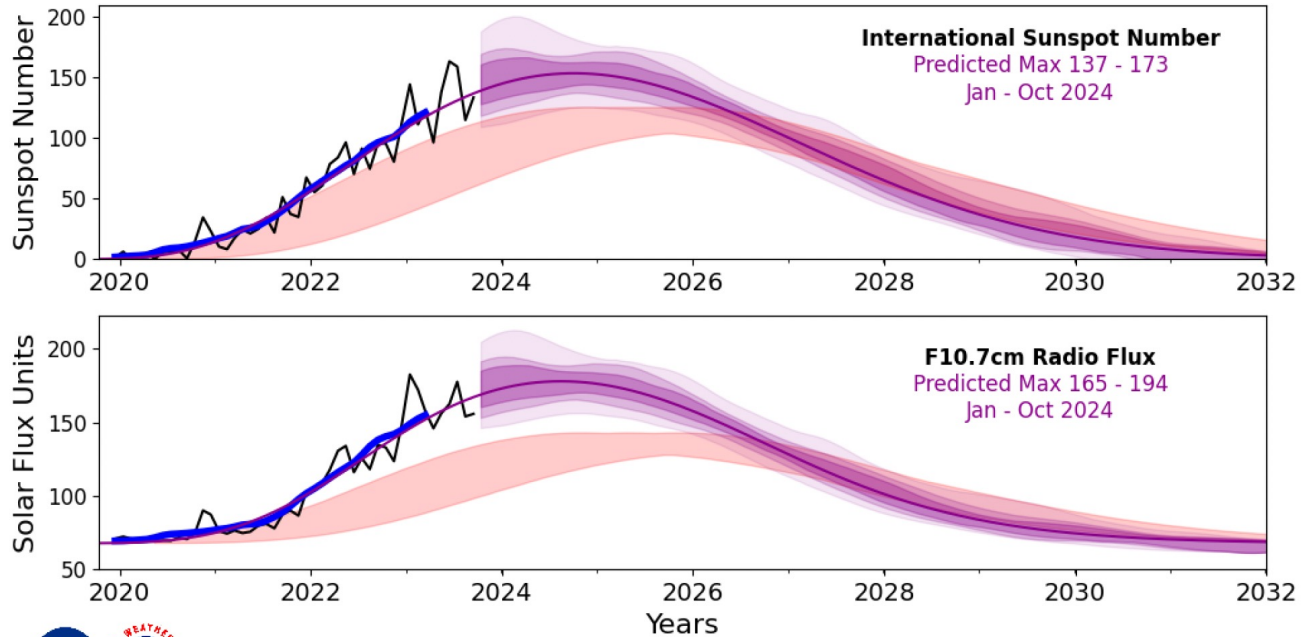
*Safeguarding Society with
Actionable Space Weather Information*





Solar Cycle and Solar Activities

Experimental Solar Cycle 25 Prediction



 
Space Weather Prediction Testbed
issued 10 Oct 2023

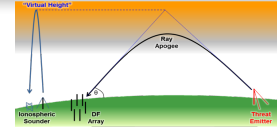
- Monthly observations
- Smoothed monthly observations
- 2019 NOAA/NASA/ISES Panel Prediction (range)
- Experimental Prediction
- 25% quartile
- 50% quartile
- 75% quartile



Impact of Space Weather

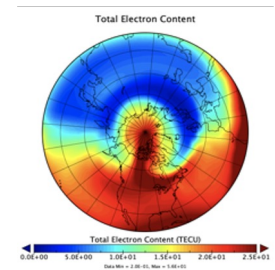
- **For HF communication:**

- Changes in the Minimum Usable Frequency (LUF) due to D-region absorption (DRAP)
- Changes in the Maximum Usable Frequency (MUF) associated with negative storm
- Undulations in bottom-side F-region



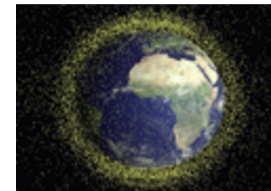
- **For satellite positioning, navigation, timing, and communication:**

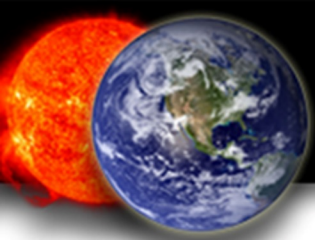
- Mesoscale structure and gradients in plasma density
- Delay in navigation signal due to line of sight electron content
- Small-scale ionospheric irregularities causing scintillations/fluctuation or complete loss of signal



- **For satellite drag**

- Neutral density and its uncertainty (for decision making, maneuver planning, orbit prediction, collision avoidance)

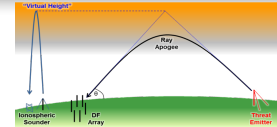




Impact of Space Weather

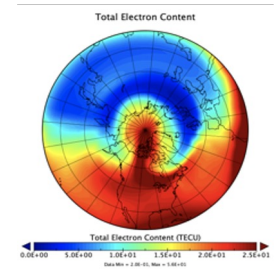
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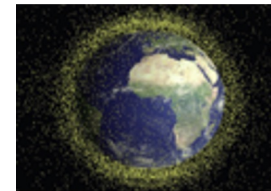
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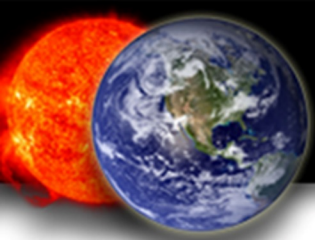
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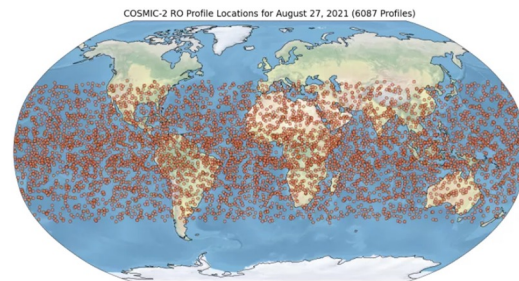
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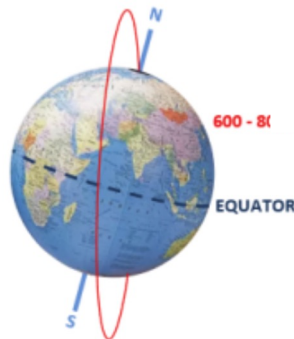


Radio Occultation Constellations and Data

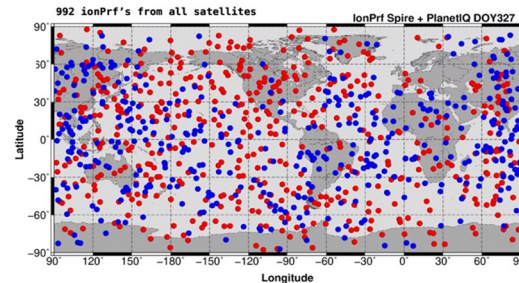
- **FORMOSAT-7/COSMIC-2**
 - Achieved full operational capability on October 12, 2021 (Set 1)
 - Six remote-sensing smallsats
 - Multi-GNSS

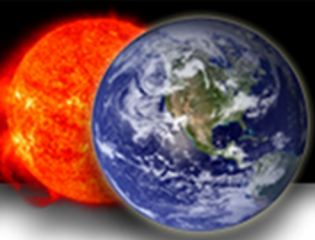


- **Spire LEMUR cubesats**
- **PlanetIQ GNOMES microsats**
 - Regularly expanding, 150+ satellites
 - SSO
 - Multi-GNSS



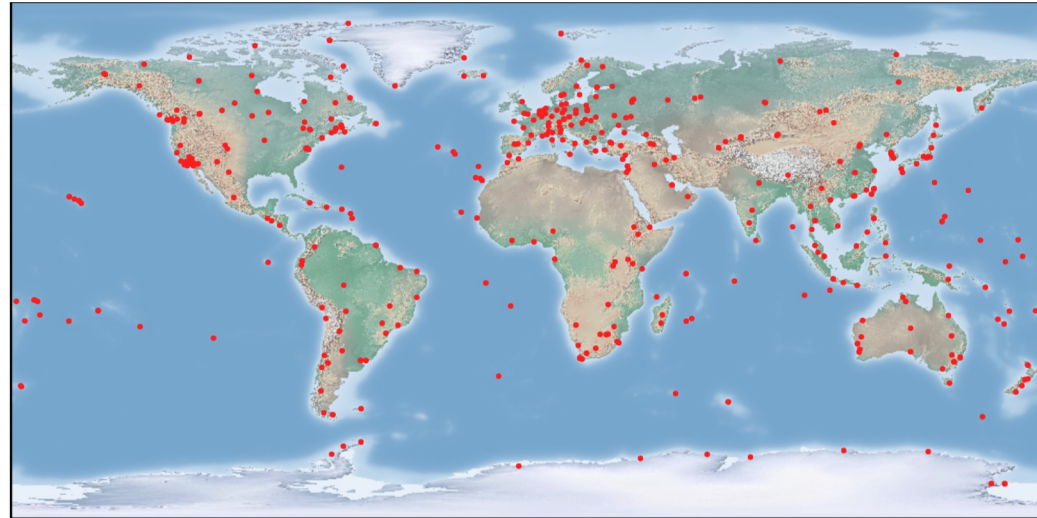
SUN-SYNCHRONOUS ORBIT (SSO)



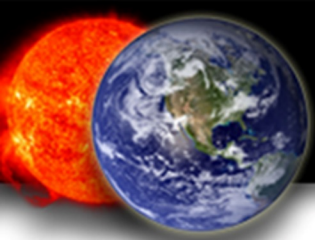


Ground Receiver Data

- **Ground GNSS networks - Geodetic:**
 - 30 sec (or 1 sec) sampling rate
 - Good quality antenna (reduced multipath)
 - Good phase data
 - Low SNR resolution
 - SNR is strongly HW and FW dependent
 - Good TEC, ROTI, and σ_ϕ
- **Ground GNSS networks - Scintillation:**
 - 50-100 Hz sampling rate
 - Typically newer installations
 - Variable antenna quality
 - Receiver calculated TEC, σ_ϕ , S4 etc.
 - Improved oscillator quality

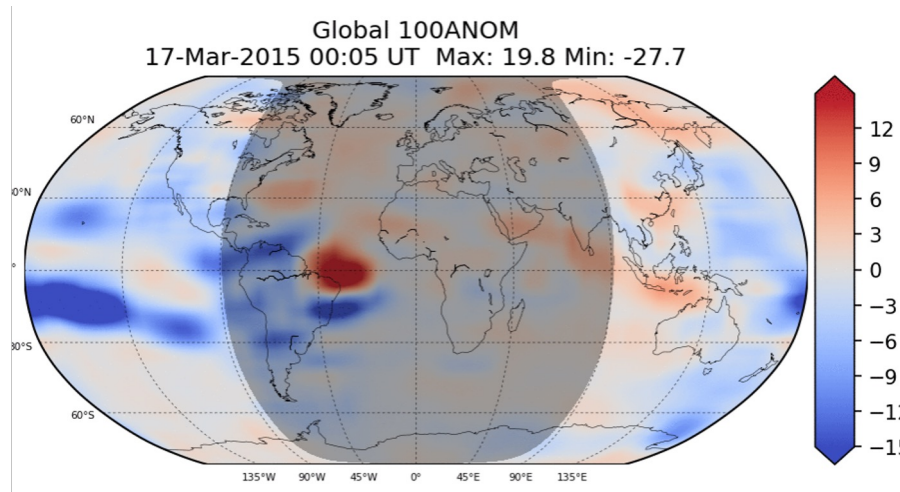


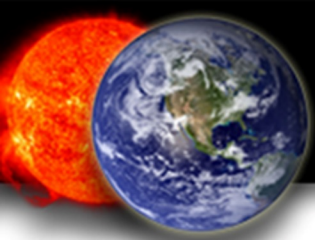
IGS Stations, 2019



GloTEC

- GloTEC is a data assimilative model that ingests various TEC observations from ground-based and space-based platforms to optimally estimate global 3D electron density.
- The background model is IRI 2016 driven with real-time F10.7.
- Products include specifications for: **VTEC**, **NmF2**, **hmF2**, **MUF3000**, and **ionosphere profiles** that can be used for situational awareness, model validation, and evaluation of new data streams.



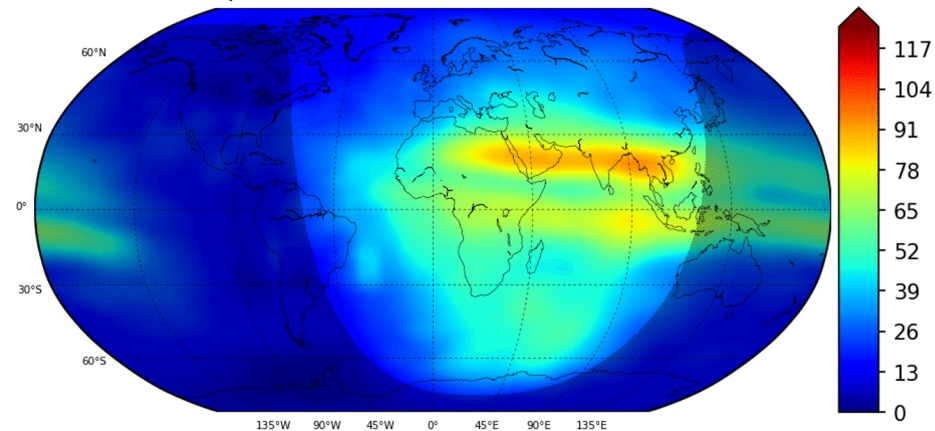


GloTEC VTEC

- GloTEC can ingest STEC from GNSS-RO or even from GNSS-R observations
- Working with UCAR to evaluate usage of commercial RO data
- Customer engagement to ensure these development are meeting customers' needs

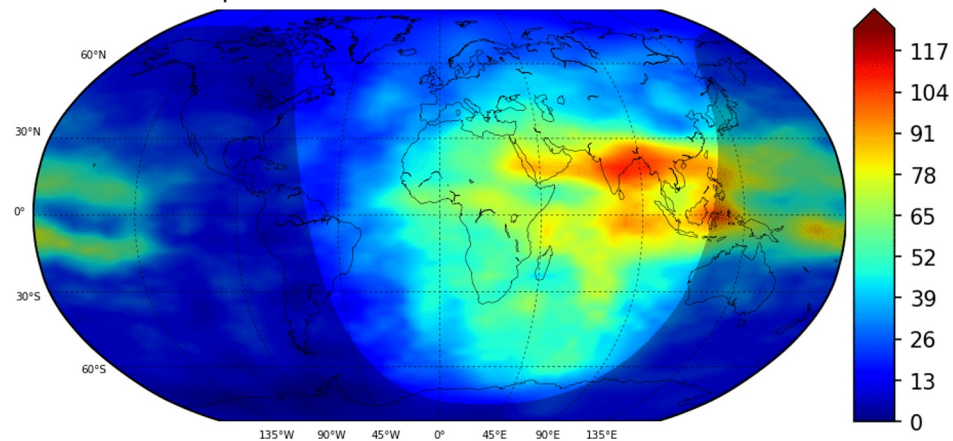
A) Ground-stations only

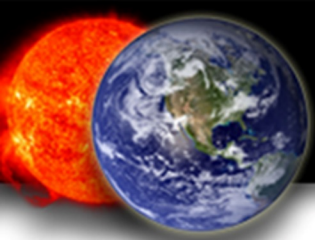
Global TEC (10^{16}m^{-2})
23-Apr-2023 09:55 UT Max: 94.4 Min: 4.9



B) Combined ground-stations and RO

Global TEC (10^{16}m^{-2})
23-Apr-2023 09:55 UT Max: 108.8 Min: 3.3





GNSS Positioning, Navigation, and Timing (PNT) and Satellite Communications

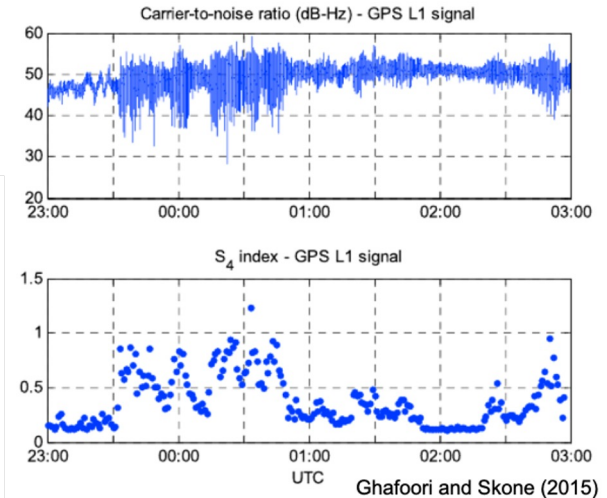
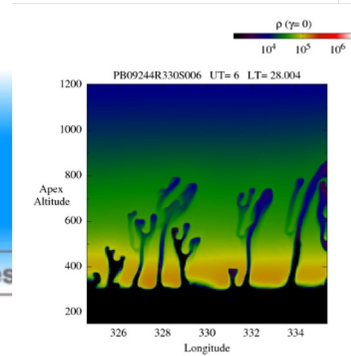
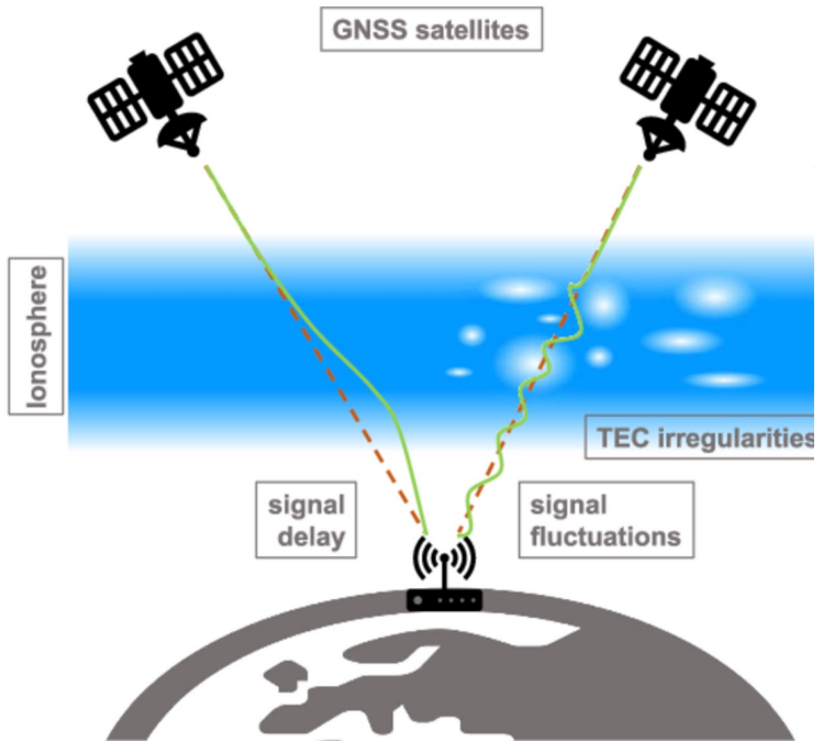


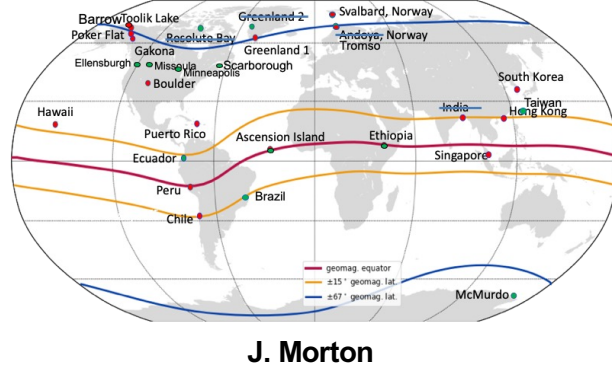
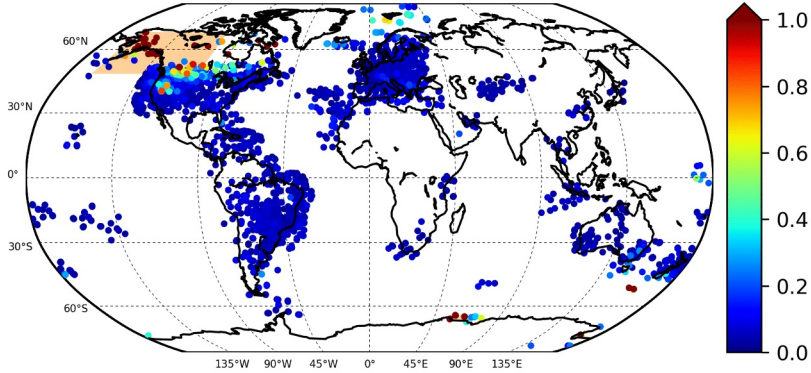
Figure 3. (top) Carrier-to-noise ratio for GPS L1 signal, PRN12 and (bottom) corresponding intensity scintillation index.

Amplitude scintillation (S_4)
Phase scintillation (σ_ϕ)

Rate of TEC Index (ROTI)

Ground based ROTI
23-Mar-2023 from 12:00 to 12:10 UT

ROTI to S4



J. Morton



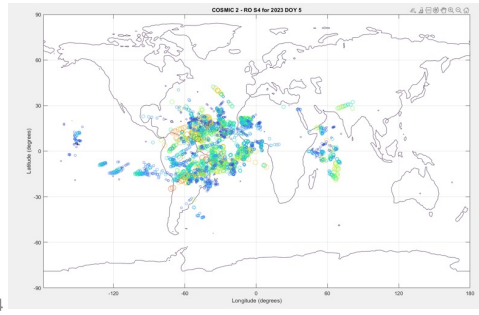
COSMIC-2 and Commercial Scintillation Products

All-Clear

COSMIC-2 All Clear Product Map - 2021/03/11 (070) 12:00 UT

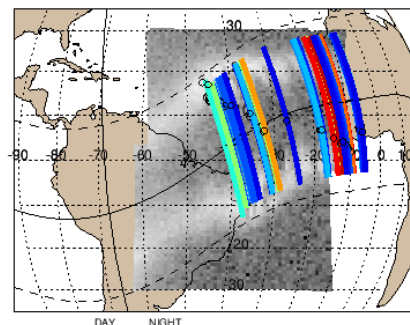


Geolocation



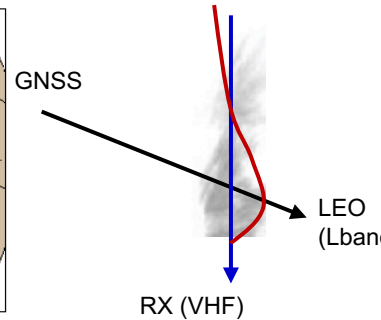
Bubble Map

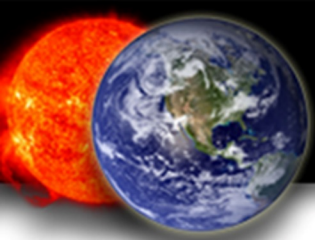
TGRS Bubble Map 2021 Day 068, 22:30 - 23:00 UT



Limb to Disk

Zenith

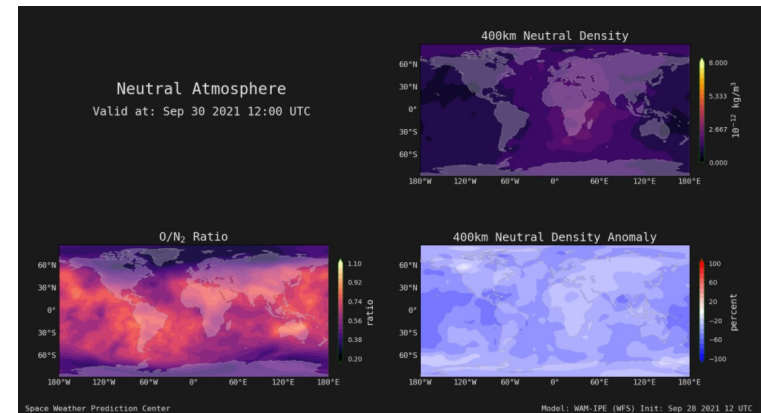
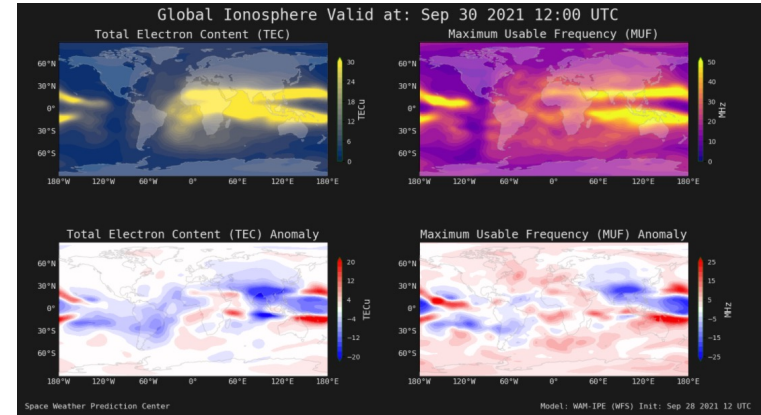




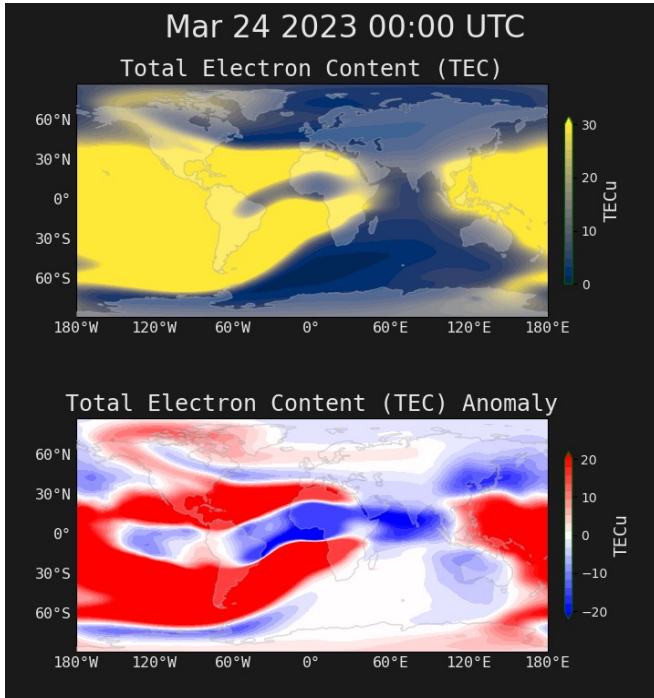
WAM-IPE Operational Model

Whole Atmosphere and Ionosphere Plasmasphere Electrodynamics Model

- An extension of the US weather model to 600 km altitude and coupled with a plasma component of the atmosphere.
- Includes all the lower atmosphere weather and dynamics processes, as well as all the additional T-I physics (including electrodynamics and plasma processes)
- WAM provides the 3D fields for neutral winds, temperature, density, major species composition O, O₂, N₂. IPE provides plasma densities and velocities, thermal electron and ion temperatures in the ionosphere and plasmasphere 90 km to ~10,000 km
- WAM-IPE is in operation since July 2021. Two operational CONOPS provide T-I forecast two days in advance as well as nowcast.
<https://www.swpc.noaa.gov/products/wam-ipe>

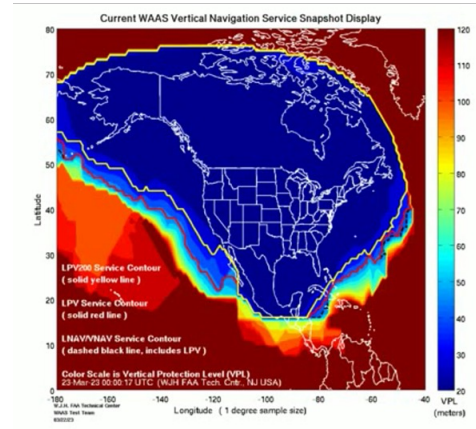


WAM-IPE captures the storm enhanced densities (SED) as it develops over the CONUS. At 00UT on March 24th the SED feature was well developed stretching from north west to south east across CONUS, which coincided with the outage of the WAAS commercial aviation navigation system, and reports of interference in airline satellite communication.



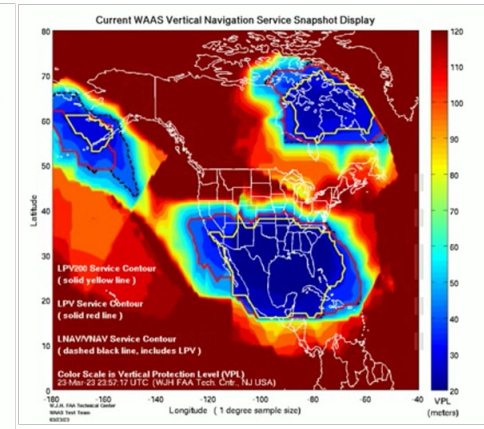
FAA Wide Area Augmentation System

WAAS 23 MAR/0017 UTC

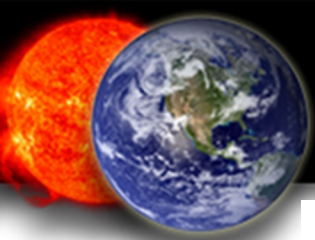


Quiet day before the storm:
full WAAS coverage

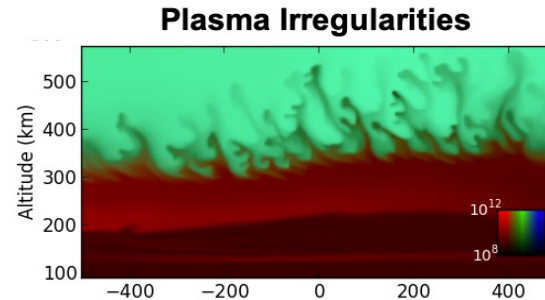
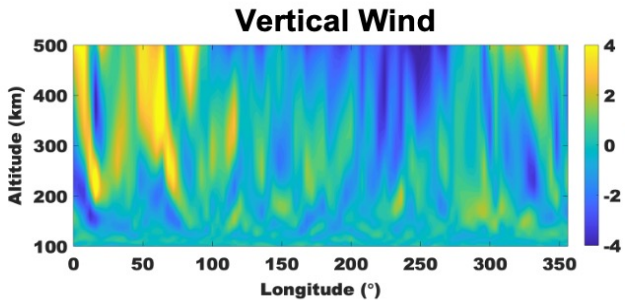
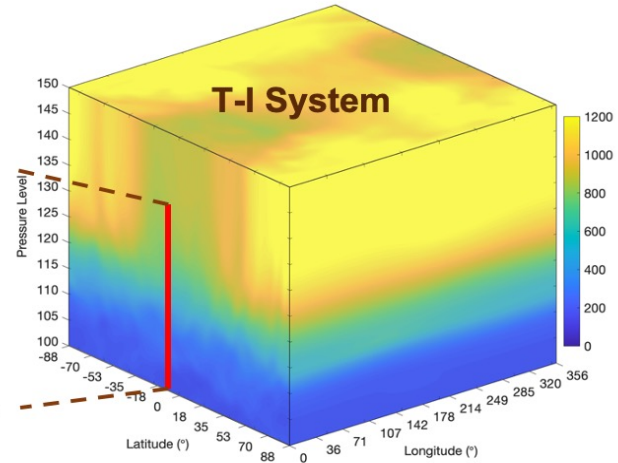
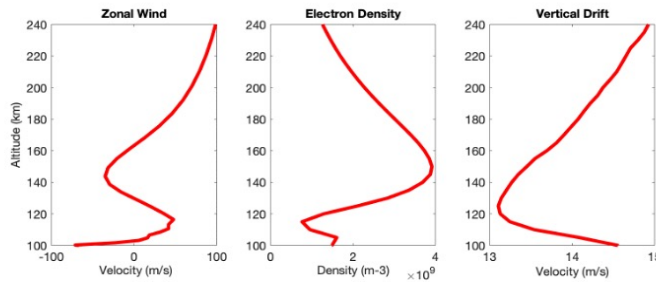
WAAS 23 Mar/2357UTC

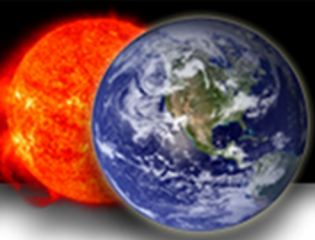


Vertical error limits exceeded
over large part of continent due
to geomagnetic storm.



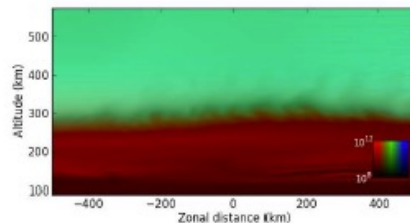
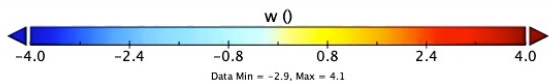
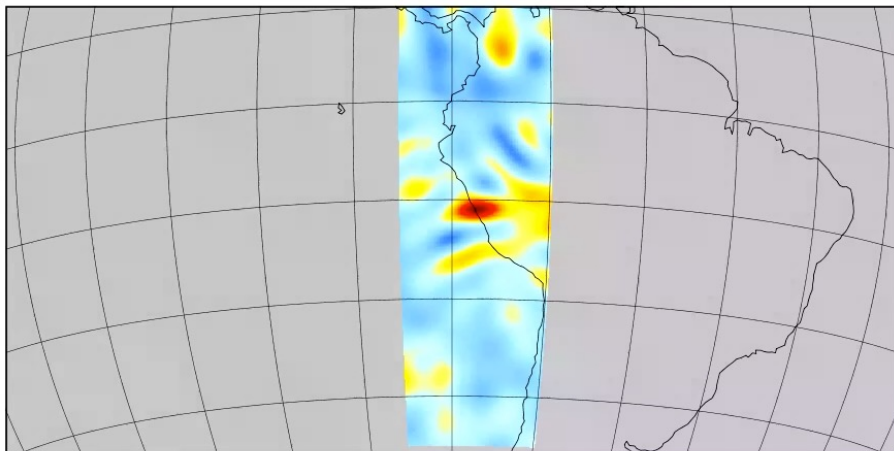
Forecasting the Small-scale Plasma Irregularities



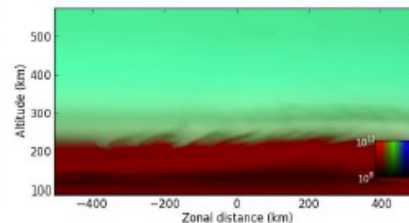


Forecasting the Small-scale Plasma Irregularities

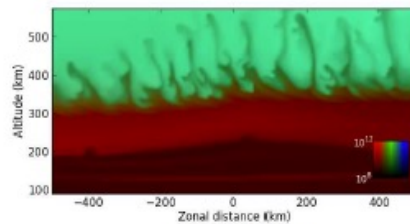
Jicamarca Vertical Wind 170km altitude
Null: 1



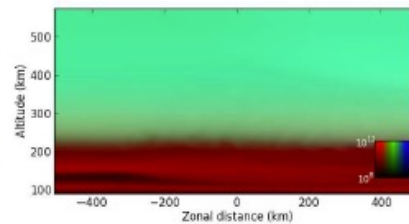
Sep. 21/22, 2021, 0100 UT



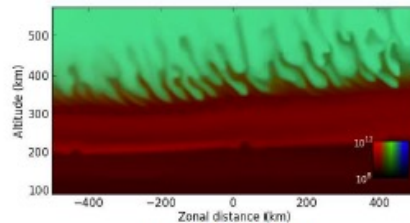
Sep. 24/25, 2021, 0100 UT



Sep. 22/23, 2021, 0100 UT

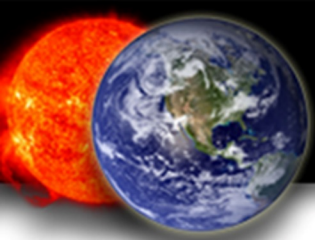


Sep. 25/26, 2021, 0100 UT



Sep. 23/24, 2021, 0030 UT

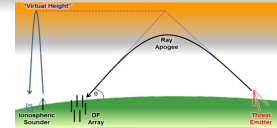
Hysell, et al, 2022



Impact of Space Weather

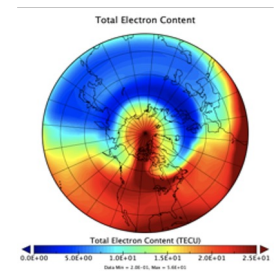
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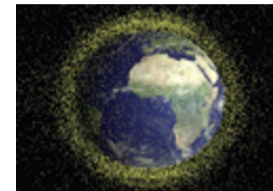
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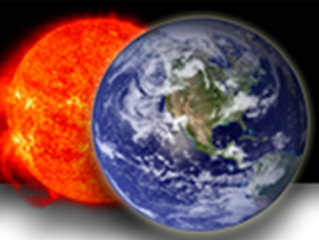
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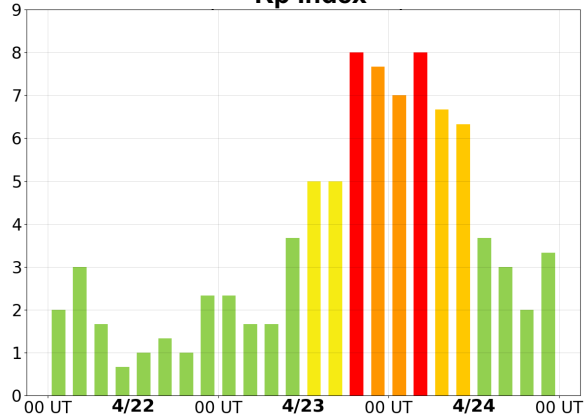
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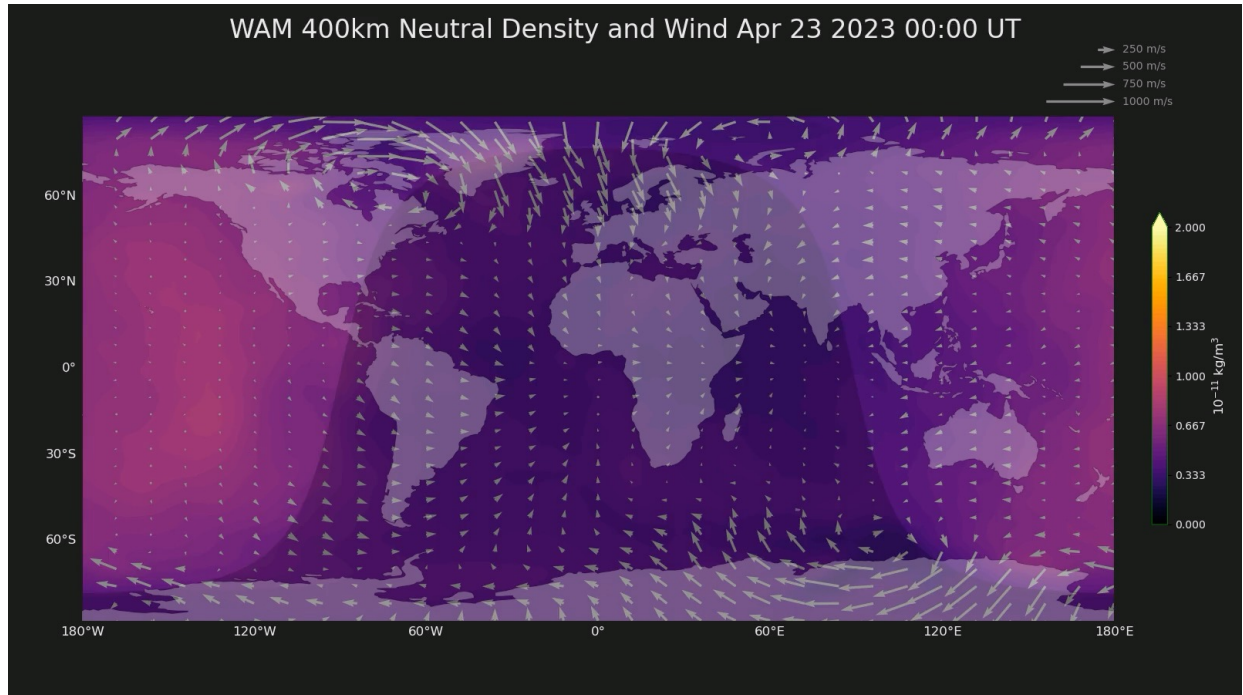


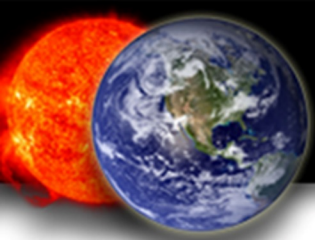
Geomagnetic Storm 23-24 April 2023

Kp Index



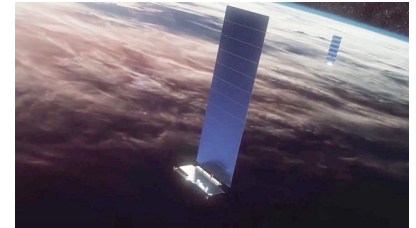
WAM 400km Neutral Density and Wind Apr 23 2023 00:00 UT





Outcomes from SpaceX Starlink Engagement

- Better understanding of the current and future needs of a satellite company that operates a large number of constellations.
- Make space weather forecasts accessible and useful to satellite industries and their operations.
- With Starlink providing one-year satellite ephemeris free of charge and possible continuously low-latency data for real-time operation, an NOAA-funded project to estimate neutral density environment and improve DA system is making great progress.






Space Weather[®]

RESEARCH ARTICLE
10.1029/2022SW003193

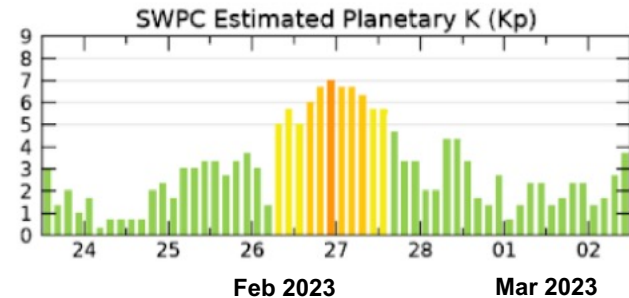
Key Points:

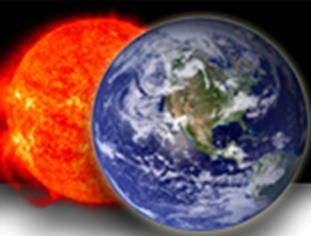
- Geomagnetic storms lead to thermosphere expansion and increase satellite drag
- National Oceanic and Atmospheric Administration's coupled Whole Atmosphere Model and Ionosphere

Space Weather Environment During the SpaceX Starlink Satellite Loss in February 2022

Tzu-Wei Fang¹ , Adam Kubaryk^{1,2}, David Goldstein³, Zhuxiao Li^{1,2}, Tim Fuller-Rowell^{1,2}, George Millward^{1,2}, Howard J. Singer¹ , Robert Steenburgh¹ , Solomon Westerman³, and Erik Babcock³

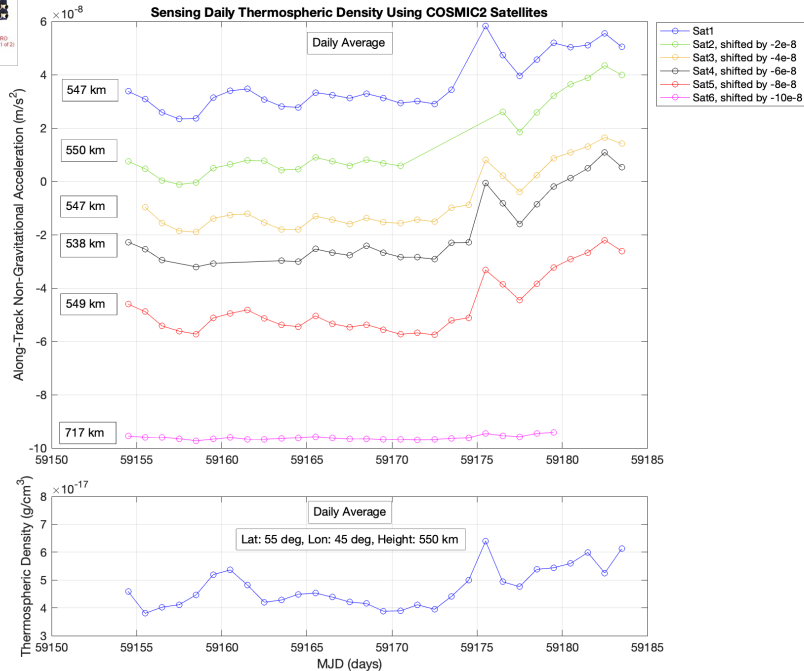
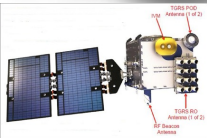
¹NOAA Space Weather Prediction Center, Boulder, CO, USA, ²CIRES, University of Colorado Boulder, Boulder, CO, USA, ³SpaceX Starlink, Hawthorne, CA, USA





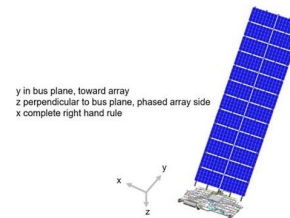
Neutral Density Estimation

COSMIC-2 Mission

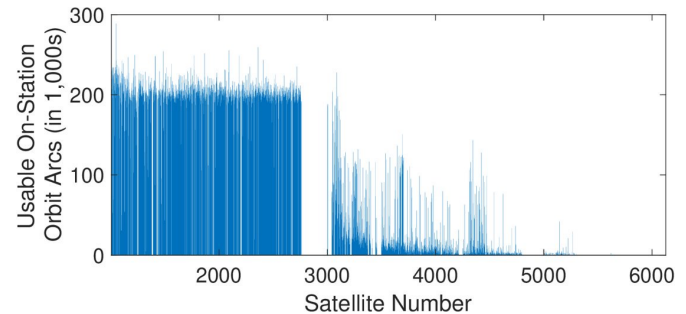


Courtesy of Jian Yao and COSMIC Team

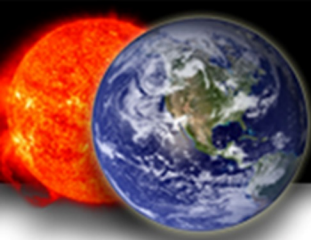
SpaceX Starlink



- Position & velocity ephemeris
- Attitude & panel articulation
- Estimated non-conservative accelerations
- Initial satellite geometry
- Time period: April 2022—April 2023
- ~3,900 satellites (v1.0, v1.5, v2-mini)
- ~1 minute cadence
- ~250 GB



Courtesy of Eric Sutton and the Starlink Team



SWPC's Customer Engagement

<https://registry.opendata.aws/noaa-nws-wam-ipe/>



NOAA Whole Atmosphere Model-Ionosphere Plasmasphere Electroynamics (WAM-IPE) Forecast System (WFS)

Description

The coupled Whole Atmosphere Model-Ionosphere Plasmasphere Electroynamics (WAM-IPE) Forecast System (WFS) is developed and maintained by the NOAA Space Weather Prediction Center (SWPC). The WAM-IPE model provides a specification of ionosphere and thermosphere conditions with real-time nowcasts and forecasts up to two days in advance in response to solar, geomagnetic, and lower atmospheric forcing. The WAM is an extension of the Global Forecast System (GFS) with a spectral hydrostatic dynamical core utilizing an entropy-thermodynamic variable to 150 vertical levels on a hybrid pressure-sigma grid, with a model top of approximately 3 x 10⁷ Pa (typically 400-600km depending on levels of solar activity). Additional upper atmospheric physics and chemistry, including electrodynamics and plasma processes, are included. The IPE model provides the plasma component of the atmosphere. It is a time-dependent, global 3D model of the ionosphere and plasmasphere from 90 km to approximately 10,000 km. WAM fields of winds, temperature, and molecular and atomic atmospheric composition are coupled to IPE to enable the plasma to respond to changes driven by the neutral atmosphere.

Resources on AWS

Description
NOAA WAM-IPE Products

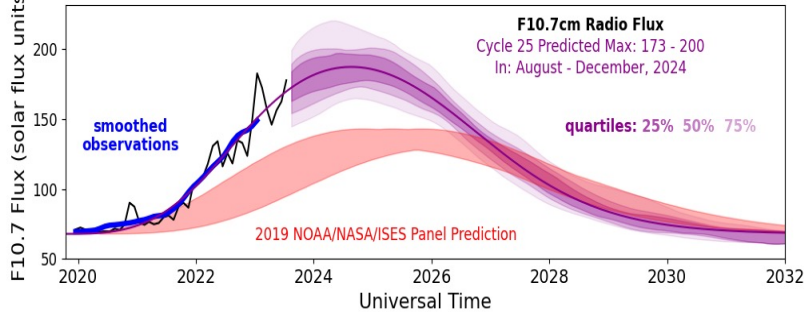
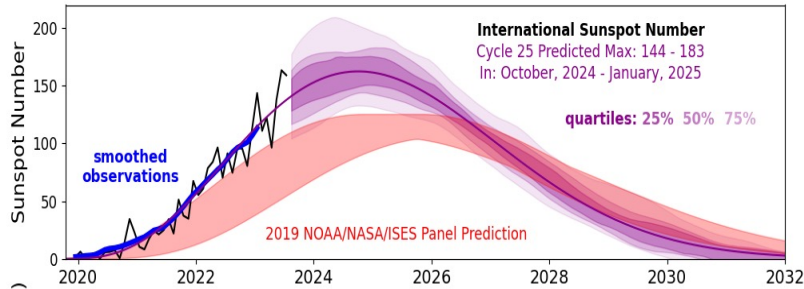
Resource type
S3 Bucket

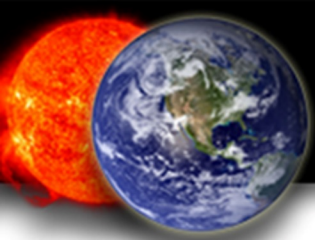
Amazon Resource Name (ARN)
`arn:aws:s3:::noaa-nws-wam-ipe-pds`

AWS Region
us-east-1

AWS CLI (No AWS account required)
`aws s3 ls --no-sign-request s3://noaa-nws-wam-ipe-pds/`

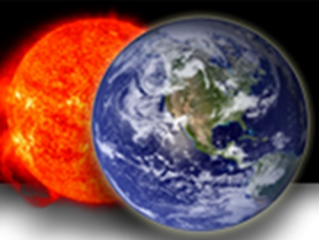
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Space Weather Testbed Exercise with Satellite Industry





Questions and Feedback?

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