Space Weather Prediction at NOAA SWPC

Tzu-Wei Fang

NOAA Space Weather Prediction Center, USA

Safeguarding Society with Actionable Space Weather Information

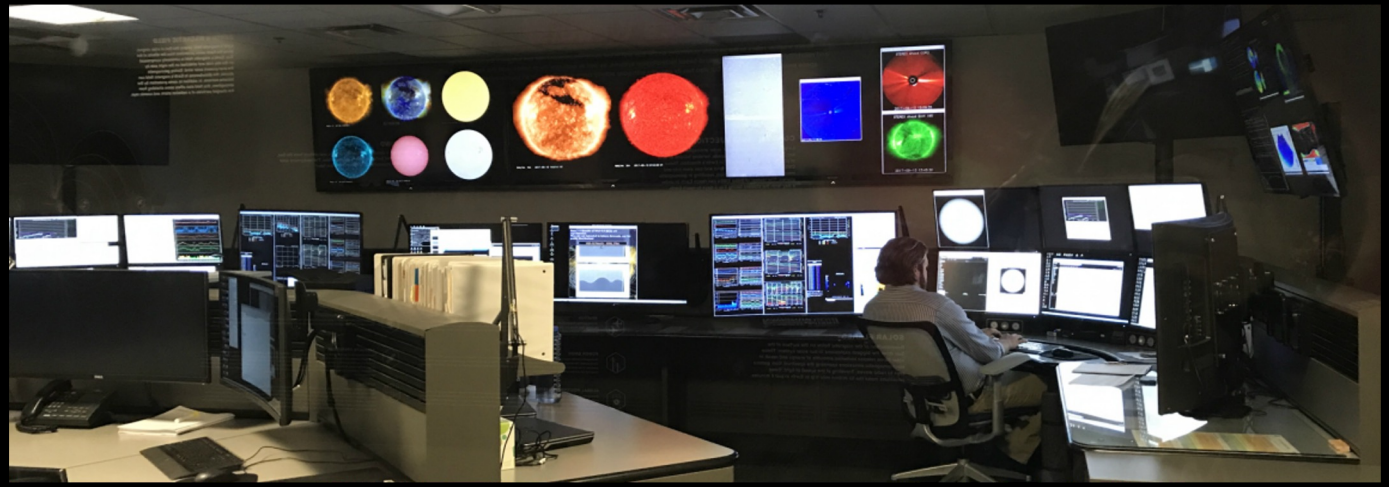
Space Weather Prediction Center (SWPC)

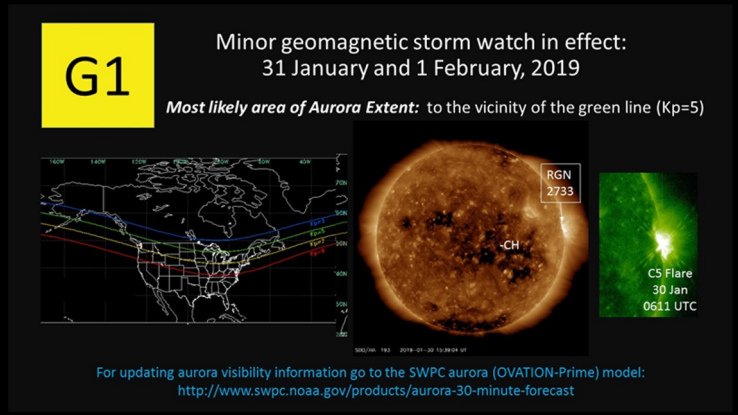
Boulder, CO

"Safeguarding Society with Actionable Space Weather Information"

We are under the NWS and part of our mission
is protection of life & property

SWPC Forecast Operations (SWFO)





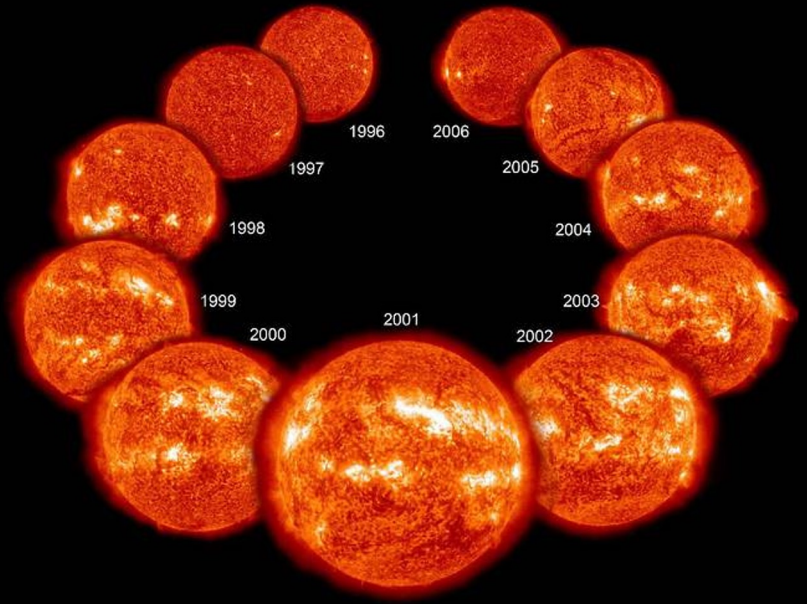
Always staffed 24 hours all year round:

Observations,
Analysis,
Forecasts,
Watches & Warnings
Alerts

Important Core Partner with USAF and USSF

Work closely and collaboratively with the 557th Space Weather Operations Center

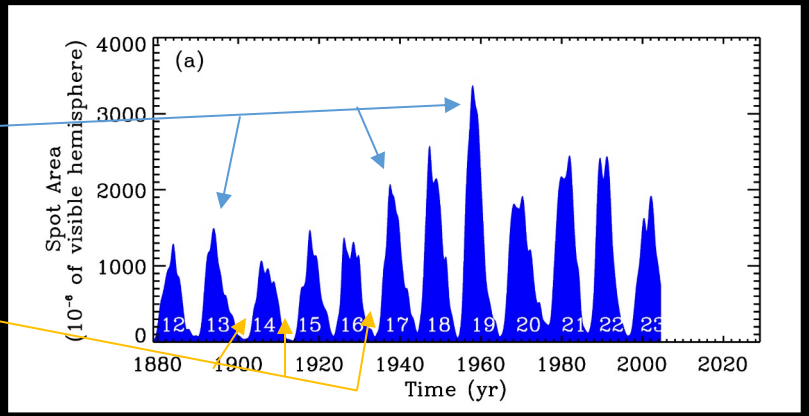
SWPC even has an assigned USAF liaison officer: Maj Austin Gibbons



On average, every 11 years the Sun goes from quiet to active and back to more quiet. This is called the "Solar Cycle".

Solar Maximums

Solar Minimums



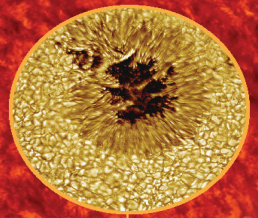
Images Credit: nasa.gov

Space Weather

Space weather refers to the variable conditions on the Sun and in the space environment that can influence the performance and reliability of space-based and ground-based technological systems, as well as endanger life or health. Just like weather on Earth, space weather has its seasons, with solar activity rising and falling over an approximate 11 year cycle.

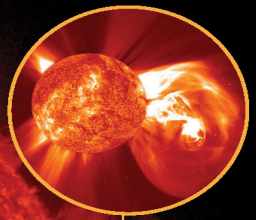
Sunspots

Sunspots are comparatively cool areas at up to 7,700° F and show the location of strong magnetic fields protruding through what we would see as the Sun's surface. Large, complex sunspot groups are generally the source of significant space weather.



Coronal Mass Ejections (CMEs)

Large portions of the corona, or outer atmosphere of the Sun, can be explosively blown into space, sending billions of tons of plasma, or superheated gas, Earth's direction. These CMEs have their own magnetic field and can slam into and interact with Earth's magnetic field, resulting in geomagnetic storms. The fastest of these CMEs can reach Earth in under a day, with the slowest taking 4 or 5 days to reach Earth.



Solar Wind

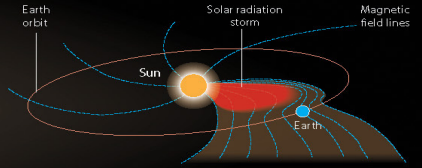
The solar wind is a constant outflow of electrons and protons from the Sun, always present and buffeting Earth's magnetic field. The background solar wind flows at approximately one million miles per hour!

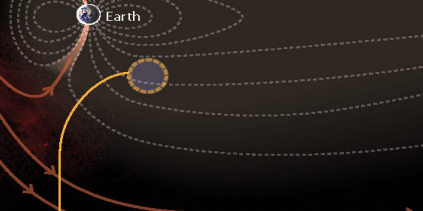
Sun's Magnetic Field

Strong and ever-changing magnetic fields drive the life of the Sun and underlie sunspots. These strong magnetic fields are the energy source for space weather and their twisting, shearing, and reconnection lead to solar flares.

Solar Radiation Storms

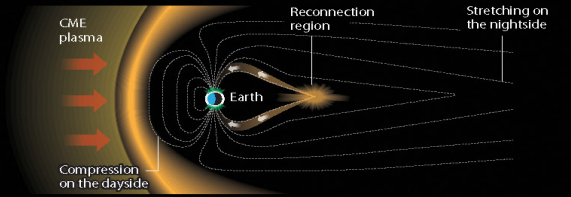
Charged particles, including electrons and protons, can be accelerated by coronal mass ejections and solar flares. These particles bounce and gyrate their way through space, roughly following the magnetic field lines and ultimately bombarding Earth from every direction. The fastest of these particles can affect Earth tens of minutes after a solar flare.





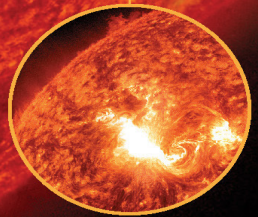
Geomagnetic Storms

A geomagnetic storm is a temporary disturbance of Earth's magnetic field typically associated with enhancements in the solar wind. These storms are created when the solar wind and its magnetic field interacts with Earth's magnetic field. The primary source of geomagnetic storms is CMEs which stretch the magnetosphere on the nightside causing it to release energy through magnetic reconnection. Disturbances in the ionosphere (a region of Earth's upper atmosphere) are usually associated with geomagnetic storms.



Source images: NASA, NOAA.

Corona



Solar Flares

Reconnection of the magnetic fields on the surface of the Sun drive the biggest explosions in our solar system. These solar flares release immense amounts of energy and result in electromagnetic emissions spanning the spectrum from gamma rays to radio waves. Traveling at the speed of light, these emissions make the 93 million mile trip to Earth in just 8 minutes.

Earth's Magnetic Field

Earth's magnetic field, largely like that of a bar magnet, gives the Earth some protection from the effects of the Sun. Earth's magnetic field is constantly compressed on the day side and stretched on the night side by the ever-present solar wind. During geomagnetic storms, the disturbances to Earth's magnetic field can become extreme. In addition to some buffering by the atmosphere, this field also offers some shielding from the charged particles of a radiation storm.

NOAA

Space Weather refers to the environmental conditions in Earth's magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind that can influence the functioning and reliability of spaceborne and ground-based systems and services or endanger property or human health.

The Only Way to See Space Weather

Colors of the Aurora

Focus areas

(3 main activity types SWPC forecasts)

Impacts & Phenomena Based Forecasts

Radio Blackouts **(R-scale):** as related to *Solar Flares*

Solar Flare Alerts

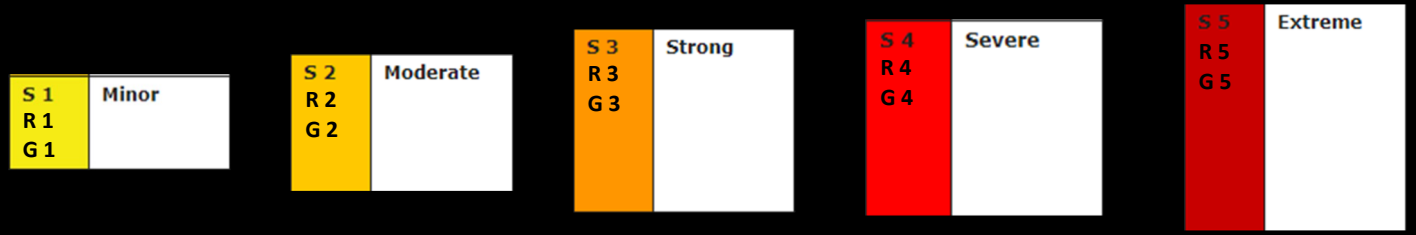
Solar Radiation Storms **(S-scale) :** related to *Solar Proton Events*

Solar Radiation Storm Warnings and Alerts

Geomagnetic Storms **(G-scale):** as related to origin source

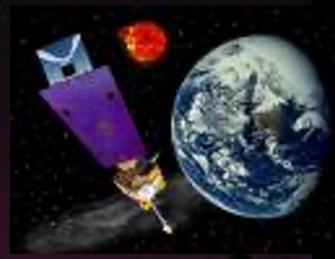
Coronal Mass Ejection (CME), *Coronal Hole* (CH)

Geomagnetic Storm Watches, Warnings, and Alerts



IMPACTS are Wide Ranging

Satellite Malfunctions; Surface Charging
SATCOM Interference/Disruption; Satellite Drag



Satellite Operations

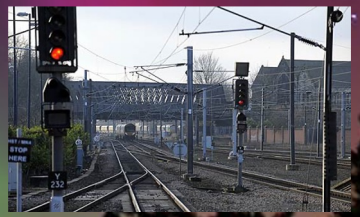
Extreme events can have potentially significant consequences.

Human Spaceflight

Radiation Exposure; Power Outages,
Communication Dropouts; GPS Degradations

GNSS (GPS)

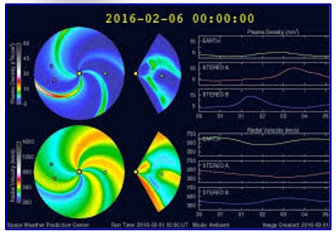
Power Grid Operations



Rail

Aircraft Operations

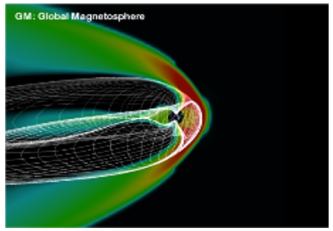
Operational Sun-to-Earth Modeling



GMU/AFRL
WSA/Enlil

Predict solar wind as it propagates from the Sun to Earth

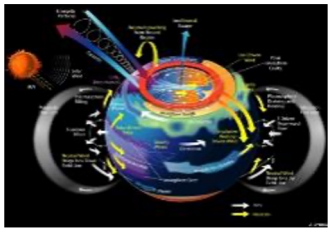
Operational 2011
Upgraded 2019



U. Michigan
Geospace

Predict and understand regional geomagnetic response to solar wind

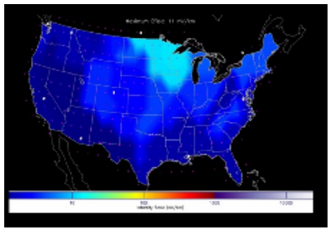
Operational 2016
Upgraded 2021



NOAA/CIRES
WAM-IPE

Predict and understand links between the upper and lower atmosphere during space weather events

Operational
July 2021



NOAA/USGS
Geoelectric field

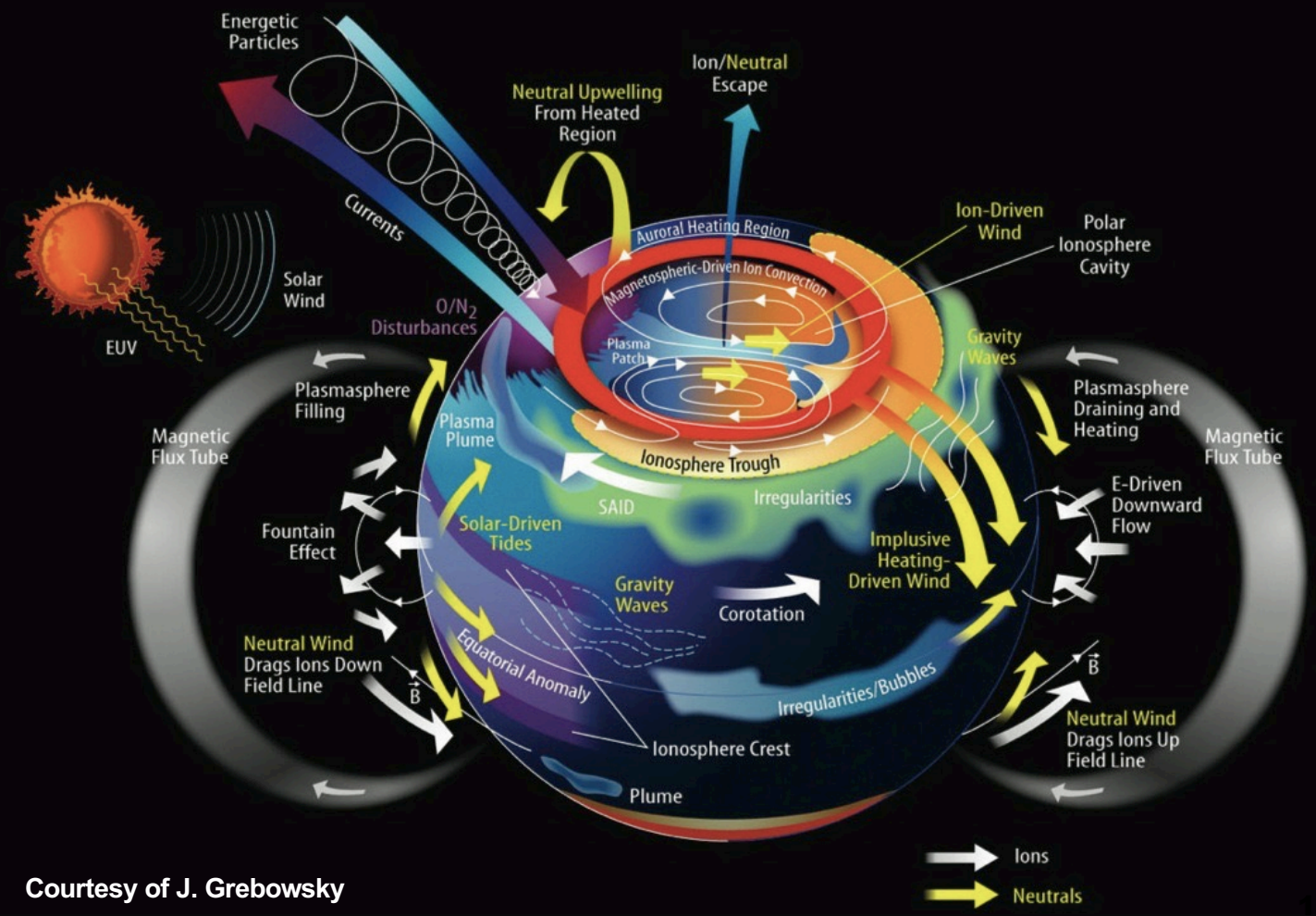
Characterize and predict the regional electric field and associated currents that impact electric power grids

3D Operational
Sept 2020

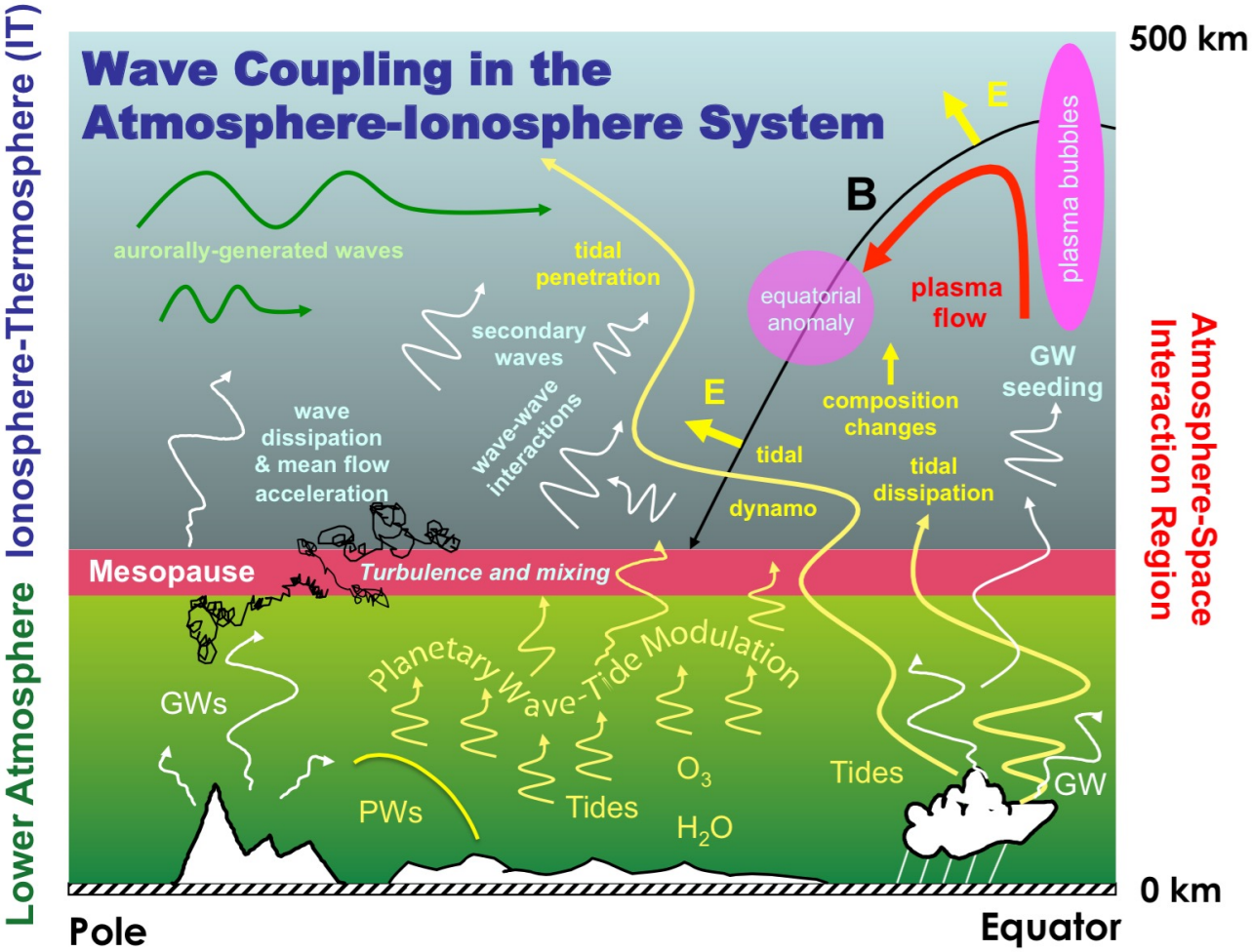
FAA
CARI-7

Characterize the radiation environment at airline altitudes

Operational
2019

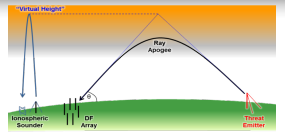


Courtesy of J. Grebowsky

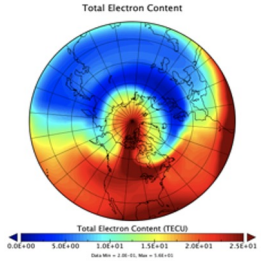


Curtsey of J. Forbes

Impact of Space Weather

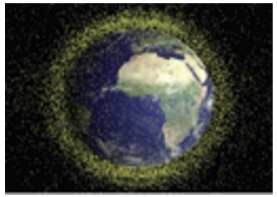


- **For HF communication:**
  - Changes in the Minimum Usable Frequency (LUF) due to D-region absorption (DRAP)
  - Changes in the Maximum Usable Frequency (MUF) associated with negative storm
  - Undulations in bottom-side F-region



- **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

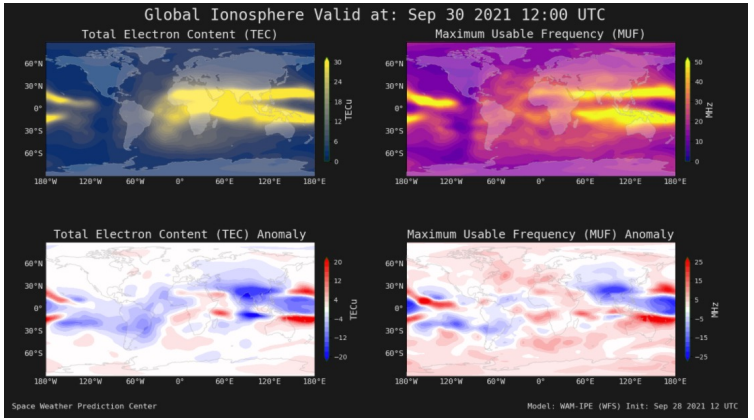
- **For satellite drag**
  - Neutral density and its uncertainty (for decision making, maneuver planning, orbit prediction, collision avoidance)

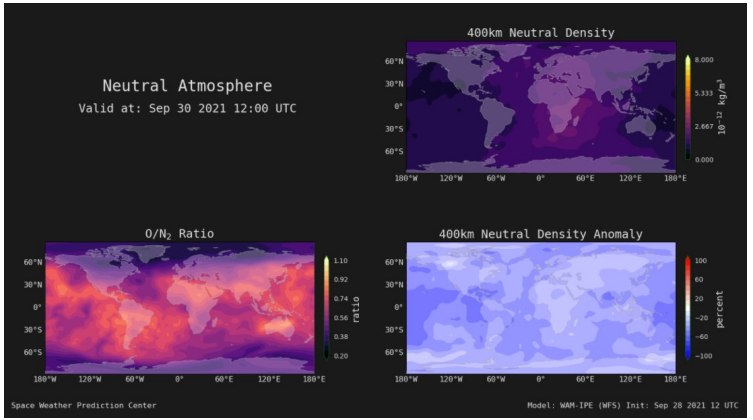


WAM-IPE Operational Model

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, O_2, N_2. 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. The current CONOPS provides T-I forecast two days in advance.
- https://www.swpc.noaa.gov/products/wam-ipe





WAM-IPE Workflows

CONOPS I — Include tropospheric weather into upper atmosphere forecast (in operation)

- 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, 5 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

WAM Neutral Density Data Sources

1. **Historical outputs are provided through NASA CCMC website**
   WAM was driven by solar wind parameters and lower atmosphere data-assimilation. **July 2021 – July 2022**
   https://ccmc.gsfc.nasa.gov/news/wamipe-update/

2. **Real-time operational outputs are released through NOAA website**
   https://registry.opendata.aws/noaa-nws-wam-ipe/ **March 21, 2023 – now**

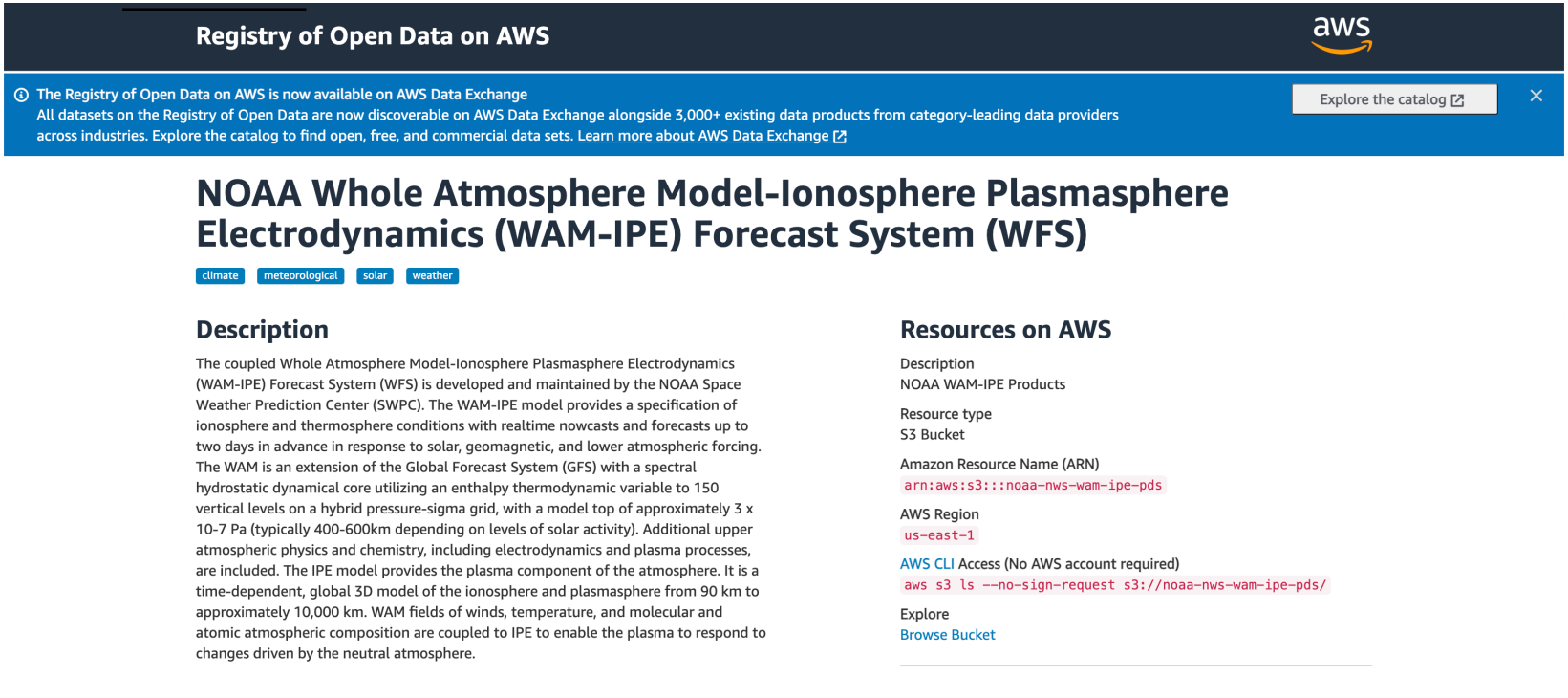
   - WAM-IPE Forecast System (WFS, wfs.yyyyddd): the first 6 hours is driven by F10.7, real-time solar wind parameters, and lower atmosphere data-assimilation. Forecast F10.7 and Kp are used to achieve 2-day forecast. Outputs are provided every 6 hours with higher latency.

   - WAM-IPE Realtime System (WRS): model is driven continuously by real-time solar wind parameters with the best lower atmosphere specification. Outputs are provided continuously to capture on going storm conditions with low latency. Coming this July!

DATA FORMAT: NetCDF
https://www.unidata.ucar.edu/software/netcdf/software.html

WAM Operational Neutral Density

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



Registry of Open Data on AWS

aws

The Registry of Open Data on AWS is now available on AWS Data Exchange
All datasets on the Registry of Open Data are now discoverable on AWS Data Exchange alongside 3,000+ existing data products from category-leading data providers across industries. Explore the catalog to find open, free, and commercial data sets. Learn more about AWS Data Exchange

Explore the catalog

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

climate | meteorological | solar | weather

Description

The coupled Whole Atmosphere Model-Ionosphere Plasmasphere Electrodynamics (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 realtime 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 enthalpy thermodynamic variable to 150 vertical levels on a hybrid pressure-sigma grid, with a model top of approximately 3 x 10-7 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

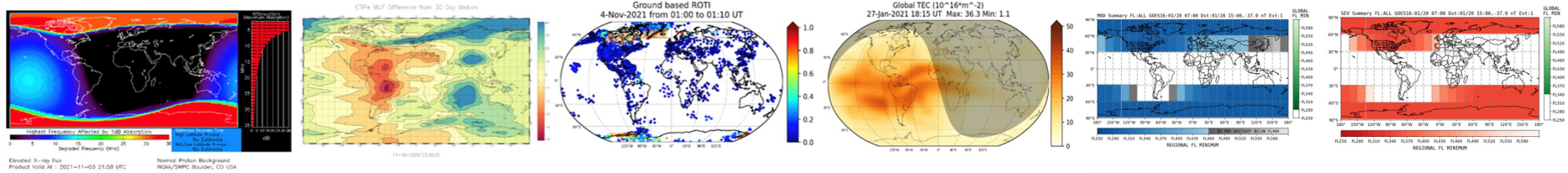
Amazon Resource Name (ARN)
`arn:aws:s3:::noaa-nws-wam-ipe-pds`

AWS Region
`us-east-1`

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

Explore
Browse Bucket

Space Weather Tabletop Exercise – Aviation Customers



EXERCISE TEAM

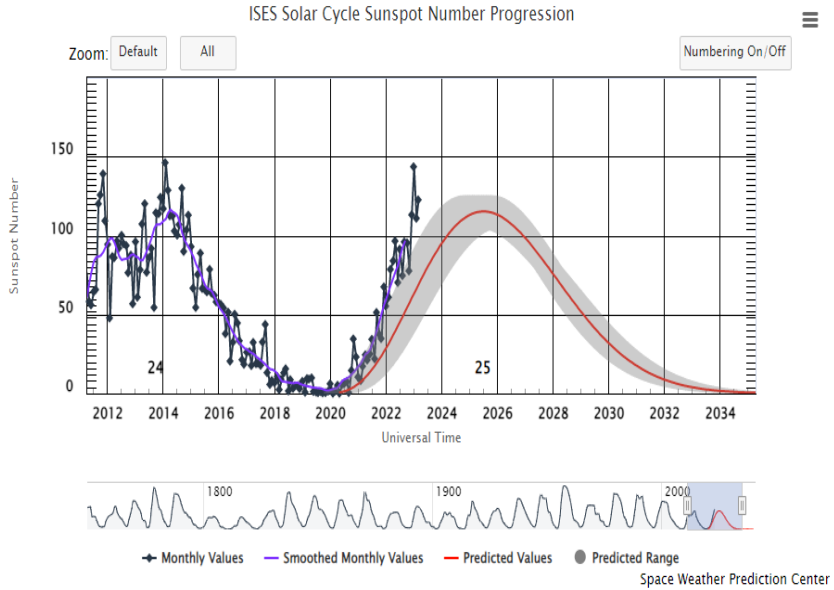
- **Operations**
  - *Forecasters*
  - *ICAO Representatives*
- **Research**
  - *Radiation Experts*
  - *Communications and Navigation Experts*

EXERCISE PLAYERS

- **Major Airline Companies**
  - *Flight Operations, Flight Safety, Dispatch, Meteorology*
  - *Pilots Union*
- Air Traffic Management and Communications Groups
- Space Weather Ops and Scientists from USA, Canada, and UK

2022 Testbed Experiment

User Engagement – Satellite Industry



SPACEX
COMSPOC
amazon | project kuiper
AGI
An Ansys Company
LEO LABS
SLINGSHOT AEROSPACE
CELESTRAK SINCE 1985
AEROSPACE
PRIVATEER
kayhan. space
SPACENAV
ensemble
planet.
MIT Aeronautics and Astronautics
XVIII
NASA
SWx TREC
Boulder
OFFICE OF SPACE COMMERCE
U.S. DEPARTMENT OF COMMERCE
MIT LINCOLN LABORATORY

Working closely with the Office of Space Commerce to fulfill the need of drag modeling for satellite industry.

SWx Research to Operations to Research Process