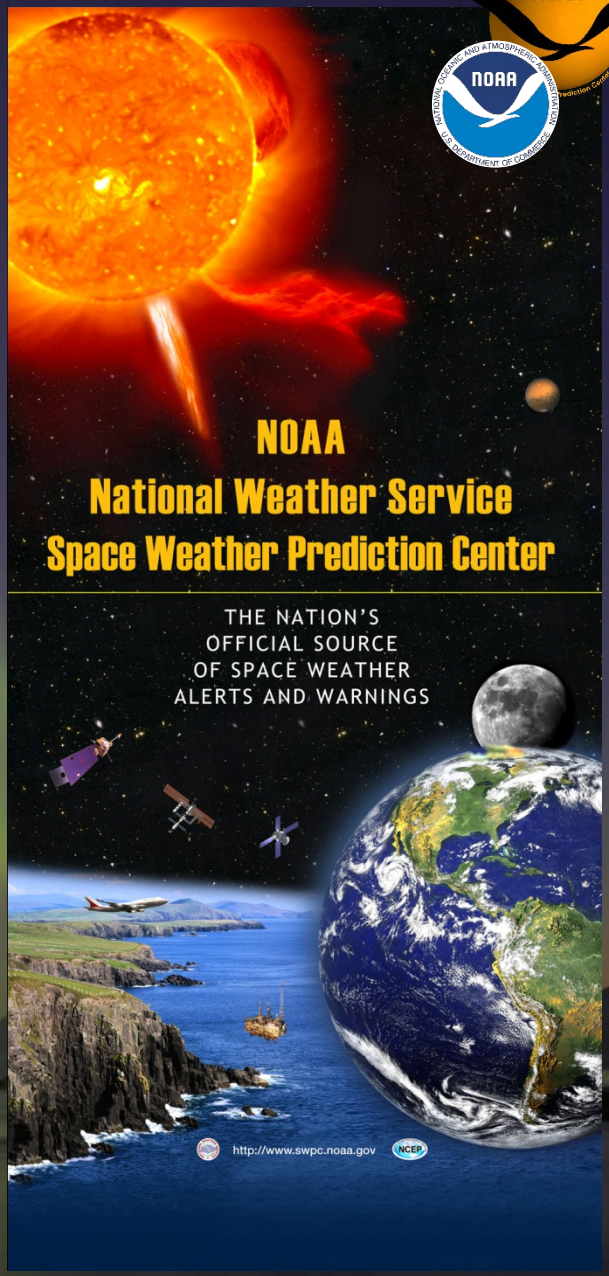
Observations and Data to Support Space Weather Operations

Rodney Viereck

NOAA Space Weather Prediction Center
Research Director



Mission: To provide space weather products and services that meet the evolving needs of the Nation.

Putting Science to Work to Protect the Nation's Technologies from Adverse Space Weather

Outline

- Space Weather Prediction Center: Organization and Customers
- Sources of Data: Space-based and Ground-based
- Data for Models
- Data Assimilation Challenges
- Challenges and Data Gaps

NOAA/NWS/NCEP

Space Weather Prediction Center

established 1949

Operations – Space Weather Forecast Office

Putting out daily forecast since 1965.

Specifications; Current conditions
Forecast; Conditions tomorrow
Watches; Conditions are favorable for storm
Warnings; Storm is imminent with high probability
Alerts; observed conditions meeting or exceeding storm thresholds

R & D – Space Weather Prediction Testbed

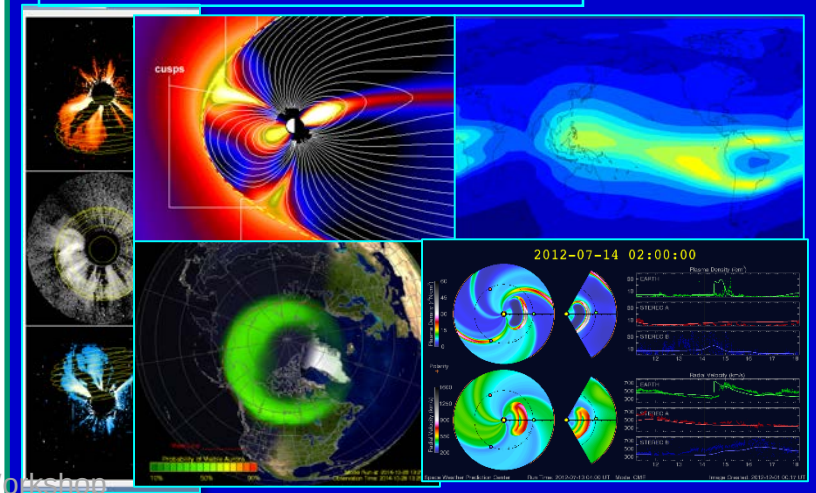
Transitioning data and models into operations

R2O

Research-to-Operations
- Applied Research
- Model Development
- Model Test/Evaluation
- Model Transition
- Operations Support

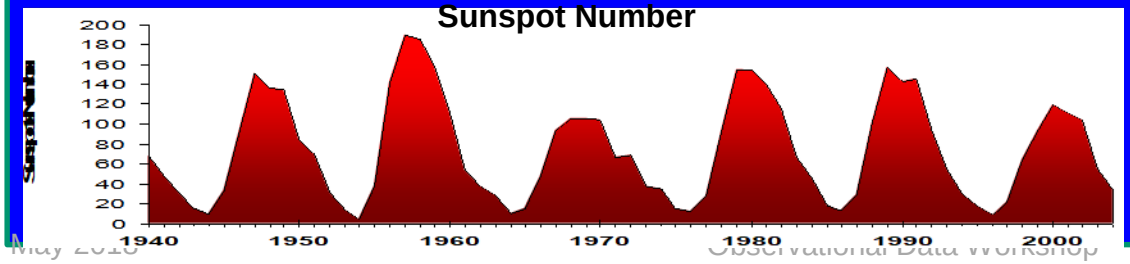
Operations-to-Research
- Customer Requirements
- Observation Requirements
- Research Requirements

O2R



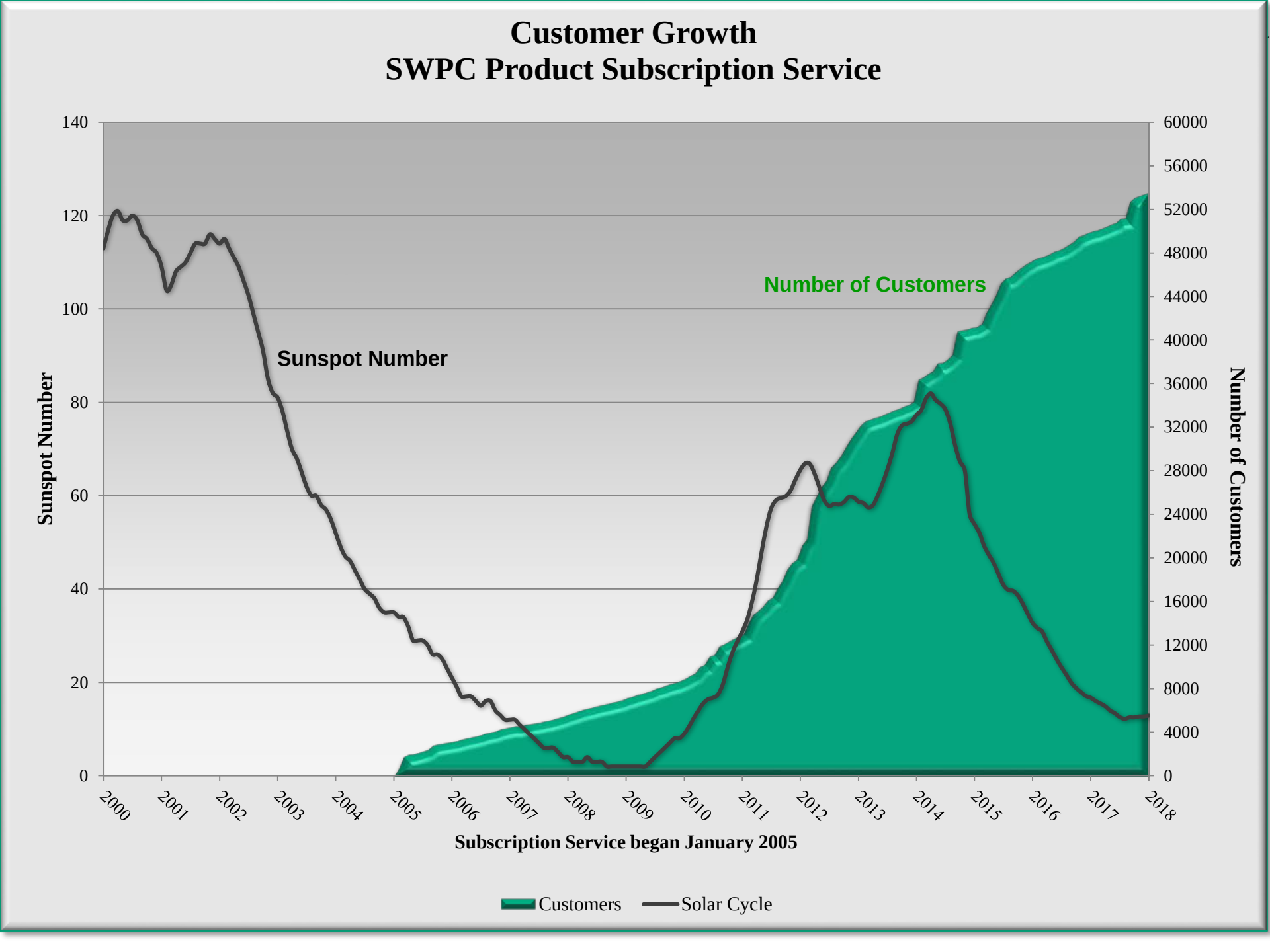
70 Years of Customer Growth

Aurora Tourism
Commercial Space Trans
Airline Polar Flights
Microchip technology
Precision Guided Munitions
Cell phones
Atomic Clock
Satellite Operations
Carbon Dating experiments
GPS Navigation
Ozone Measurements
Aircraft Radiation Hazard
Commercial TV Relays
Communications Satellite Orientation
Spacecraft Charging
Satellite Reconnaissance & Remote Sensing Instrument Damage
Geophysical Exploration.
Pipeline Operations
Anti-Submarine Detection
Satellite Power Arrays
Power Distribution
Long-Range Telephone Systems
Radiation Hazards to Astronauts
Interplanetary Satellite experiments
VLF Navigation Systems (OMEGA, LORAN)
Over the Horizon Radar
Solar-Terres. Research & Applic. Satellites
Research & Operations Requirements
Satellite Orbit Prediction
Solar Balloon & Rocket experiments
Ionospheric Rocket experiments
Radar
Short-wave Radio Propagation

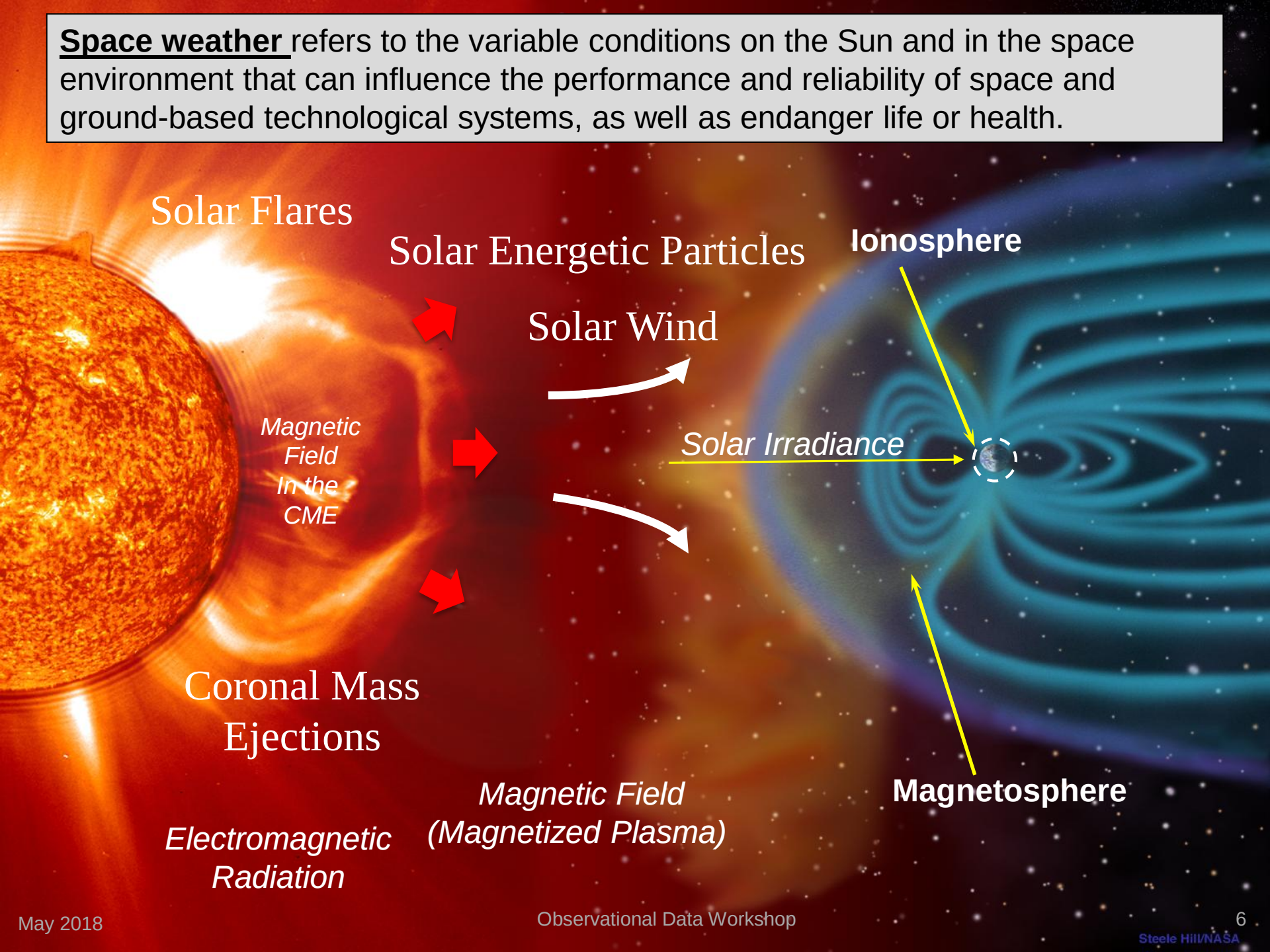


Critical Customers

- **Electric Utilities**
  - Potential for significant disruption of service due to geomagnetic storm with major financial consequences
- **Aviation**
  - HF Communication
  - GPS Navigation
  - Radiation Exposure
- **Communication**
  - HF radio
  - Satellite Communication
- **GPS Navigation**
  - Space Weather Introduces Errors
  - Space Weather Blocks Signal
- **Space Systems**
  - Satellite Anomaly Assessment
  - Space Weather Database for Satellite Design
  - Humans in Space


Customer Growth
SWPC Product Subscription Service
Number of Customers
Sunspot Number
Sunspot Number
Number of Customers
140
120
100
80
60
40
20
0
60000
56000
52000
48000
44000
40000
36000
32000
28000
24000
20000
16000
12000
8000
4000
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Subscription Service began January 2005
Customers
Solar Cycle

Space weather refers to the variable conditions on the Sun and in the space environment that can influence the performance and reliability of space and ground-based technological systems, as well as endanger life or health.



Primary Space Weather Satellites

White: Currently Operating

Red: Future Missions

STEREO (Ahead)

- **SOHO (NASA/ESA)**
  - Solar EUV Images
  - Solar Corona (CMEs)
- **ACE (NASA)**
  - Solar wind composition, speed, and direction
  - Magnetic field strength and direction
- **GOES (NOAA)**
  - Energetic Particles
  - Magnetic Field
  - Solar X-ray Flux
  - Solar X-Ray Images
- **COSMIC II (Taiwan/NOAA)**
  - Ionospheric Electron Density Profiles
  - Ionospheric Scintillation
- **DSCOVR (NOAA)**
  - Solar wind composition, speed, and direction
  - Magnetic field strength and direction
- **SDO (NASA)**
  - Solar EUV Images
  - Solar Magnetograms
  - Solar EUV spectra
- **STEREO (NASA)**
  - CME Direction and Shape
  - Solar wind composition, speed, and direction
  - Magnetic field strength and direction
- **POES (NOAA)**
- **METOP (EUMETSAT)**
  - High Energy Particles
  - Total Energy Deposition
  - Solar UV Flux

SOHO
ACE
DSCOVR
L1
Space Weather Follow-on

GOES
SDO
GOLD
POES
METOP
COSMIC II

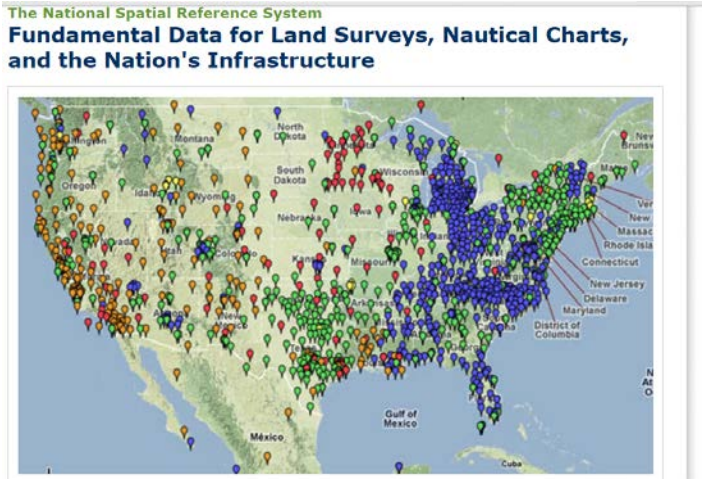
~~STEREO (Behind)~~

Ground-based Observations

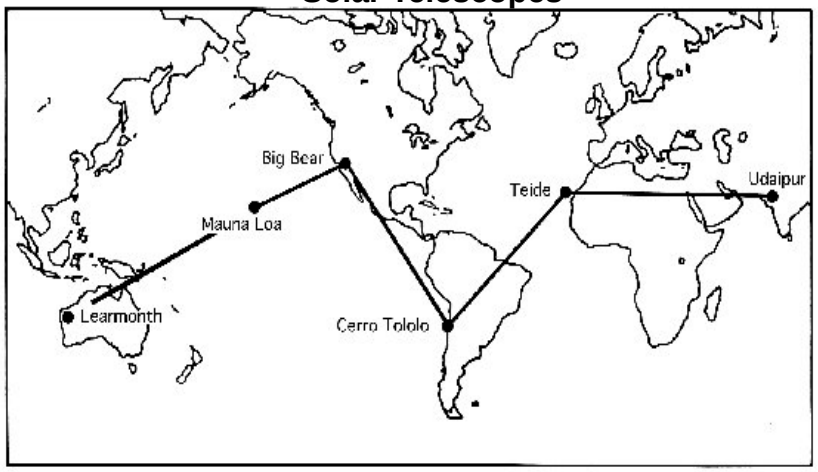
Partnering with State and Federal Agencies

US Geological Survey
Ground Magnetometer Network

USCG, FAA, State/local Govt., Ground
GPS/GNSS Sensors

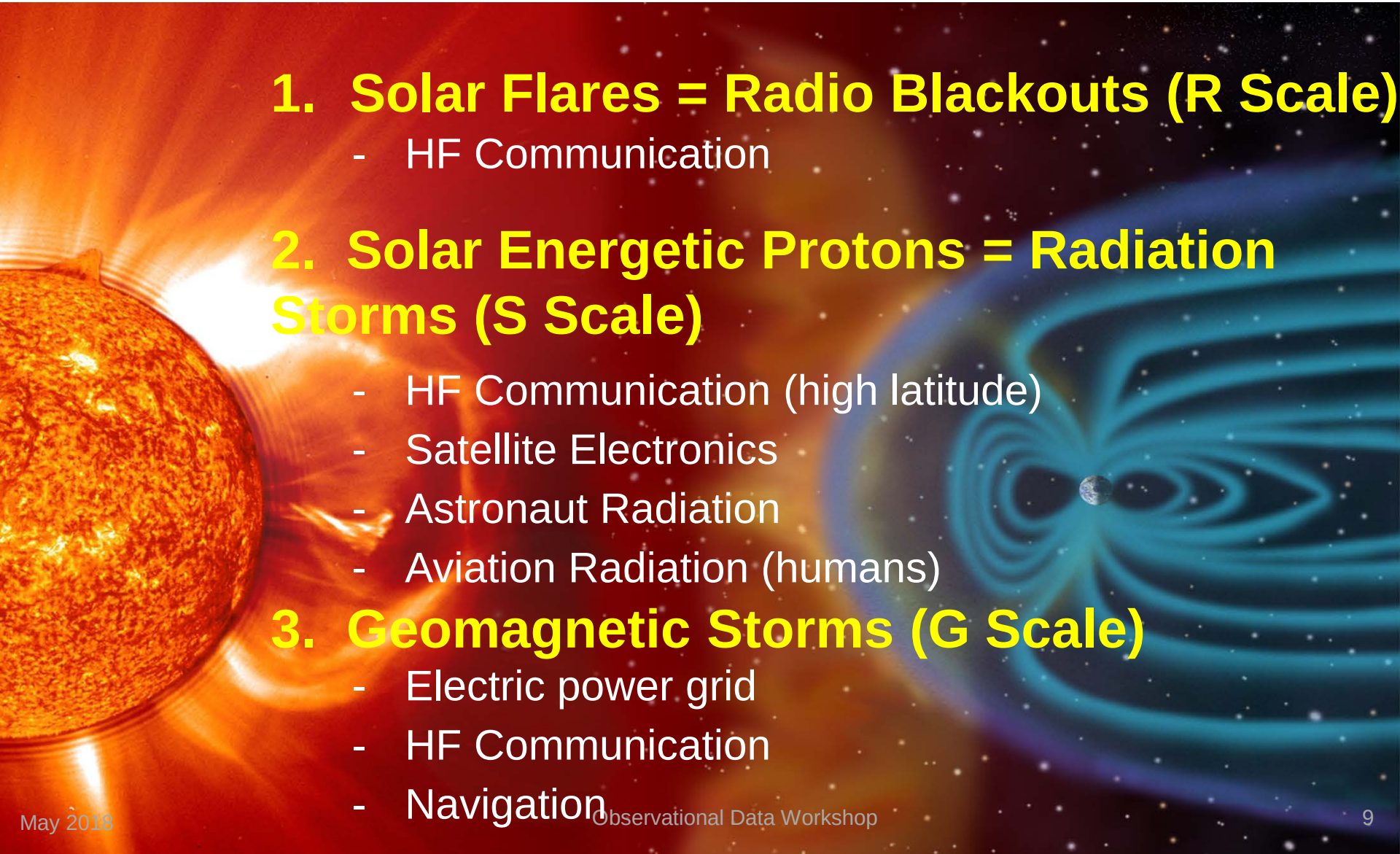


National Science Foundation
Global Oscillation Network Group (GONG)
Solar Telescopes



US Air Force
Radio Solar Telescope Network

Three Primary Types of Space Weather



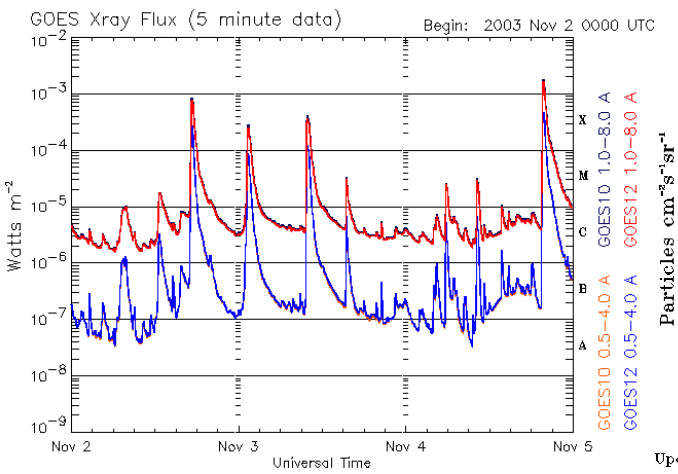
1. **Solar Flares = Radio Blackouts (R Scale)**
   - HF Communication
2. **Solar Energetic Protons = Radiation Storms (S Scale)**
   - HF Communication (high latitude)
   - Satellite Electronics
   - Astronaut Radiation
   - Aviation Radiation (humans)
3. **Geomagnetic Storms (G Scale)**
   - Electric power grid
   - HF Communication
   - Navigation

Primary Space Weather Observations

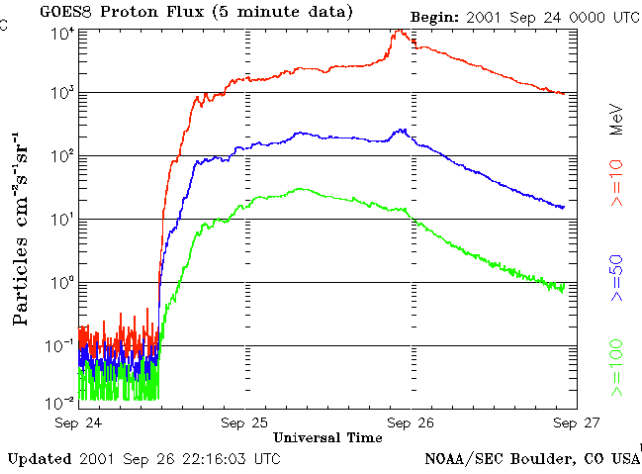
NOAA Space Weather Scales

Observation	Platform	Agency	Issues
Solar X-ray Flux	GOES	NOAA	None
Solar Energetic Protons	GOES	NOAA	None
Ground Magnetic Field	Ground Magnetometers	USGS	Insecure Funding SWx is not a primary USGS mission.

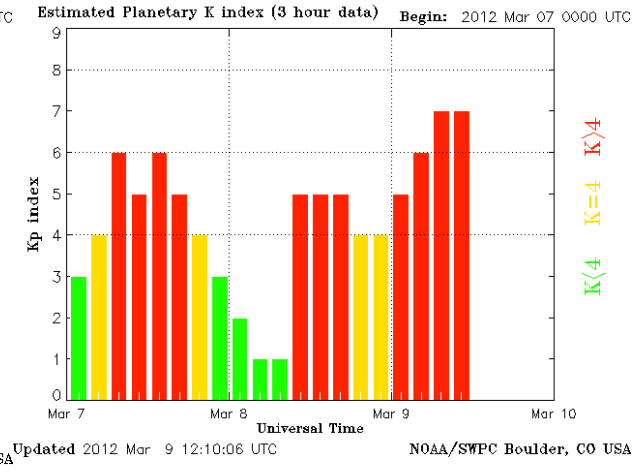
GOES Solar X-Ray Flux



GOES Solar Proton Flux



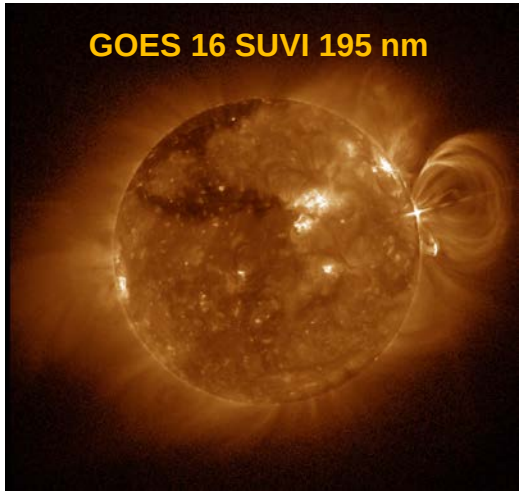
Planetary K Index
Derived from USGS Magnetometer Data

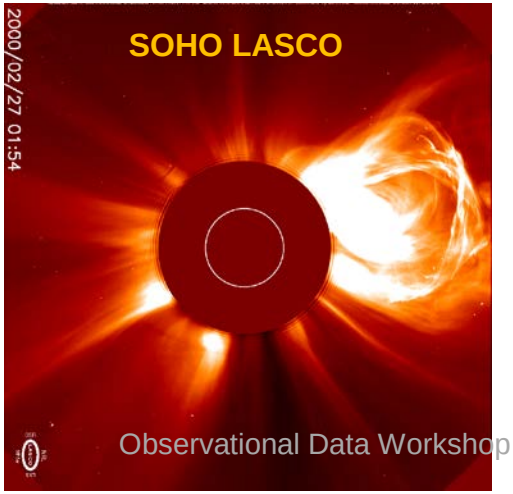


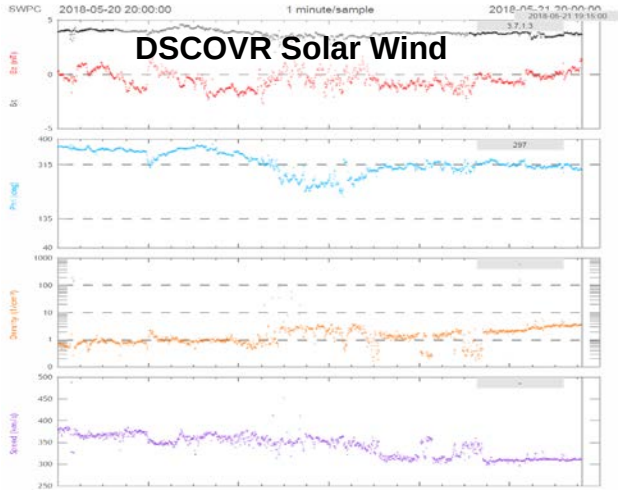
Primary Space Weather Observations

Solar, Solar Wind, Magnetosphere

Observation	Platform	Agency	Issues
Solar Imagery	GOES, SDO, GONG,	NOAA, NASA, NSF	None
Corona Imagery	SOHO	NASA/ESA	SOHO is on year 22 of a 5 year mission.
Solar Wind, Particles, and Fields	DSCOVR	NOAA	Uncertain Future: Very little flexibility in schedule for DSCOVR follow-on
Magnetosphere Particles and Fields	GOES	NOAA	None
Solar Radio Emission	RSTN	USAF	None





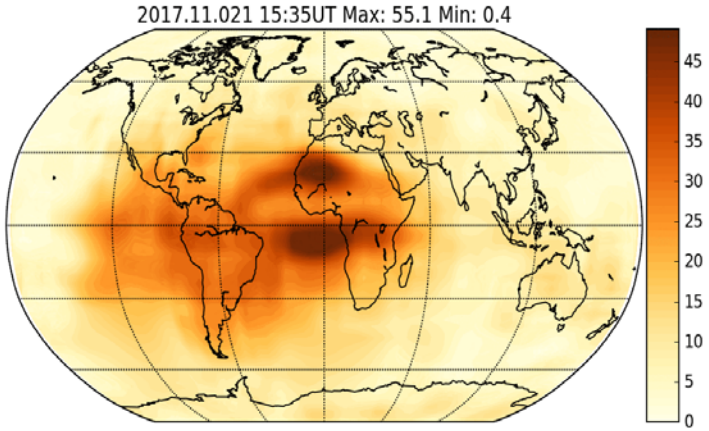


Primary Space Weather Observations

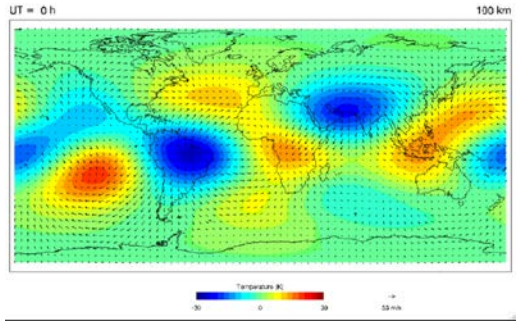
Ionosphere, Middle Atmosphere

Observation	Platform/Sensor	Agency	Issues
Ionosphere Electron Density	Ground-base GPS	US Coast Guard, FAA	Inadequate Coverage
	COSMIC II Space-base Radio Occultation	NOAA/USAF, Commercial data-buy	30 min Latency. Delays in obtaining full coverage.
Middle Atmosphere	Microwave Limb Sounder, TIMED	NASA	Not currently part of the GFS/GDAS system

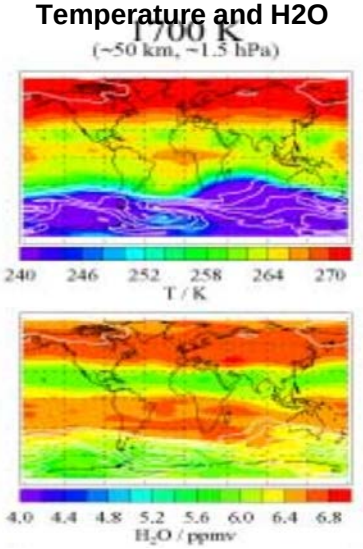
Global Total Electron Content
Derived from Ground and Space based GPS Data



NASA TIMED SABER and TIDI
100 Km Temperature

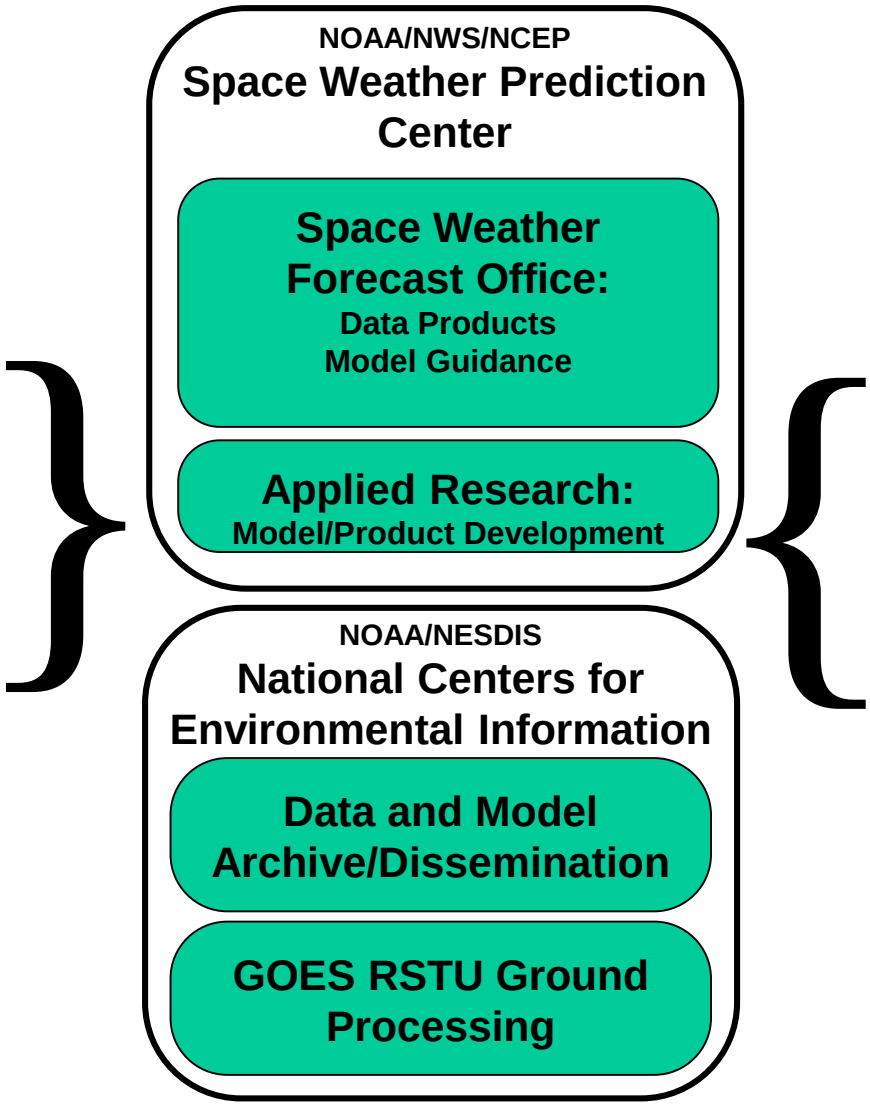


NASA MLS
Temperature and H2O



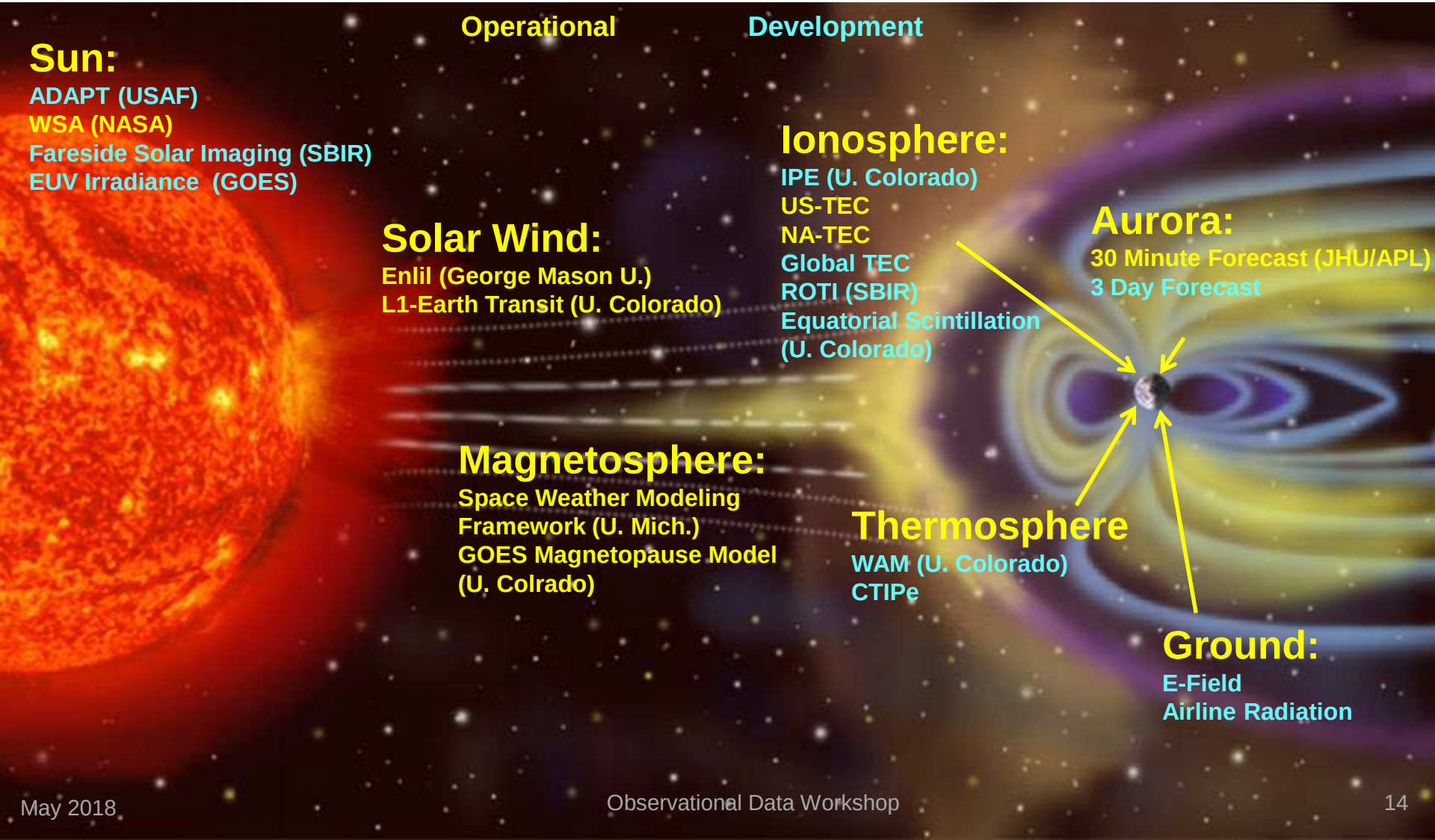
Data Flow

Data Sources
- NOAA
- NASA
- USGS
- US Air Force
- FAA
- International Partners
- Commercial Data Providers



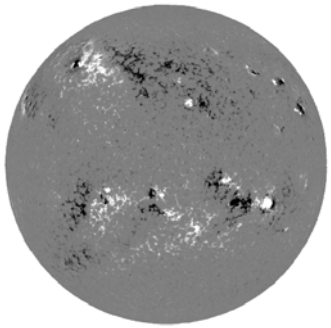
Data/Product Users
- Space Weather Forecast Office
- US Air Force
- DHS/FEMA
- NASA
- FAA
- Commercial Partners
- International Space Environment Services
- ICAO
- Customers

Space Weather Models

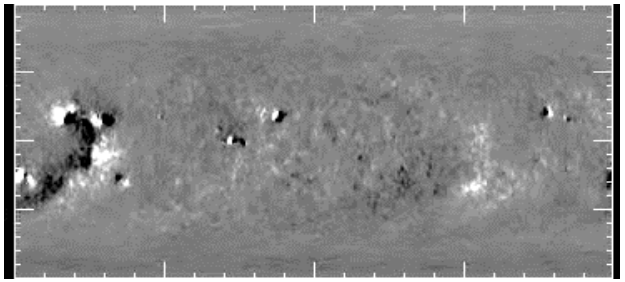


Data for Models
WSA-Enlil

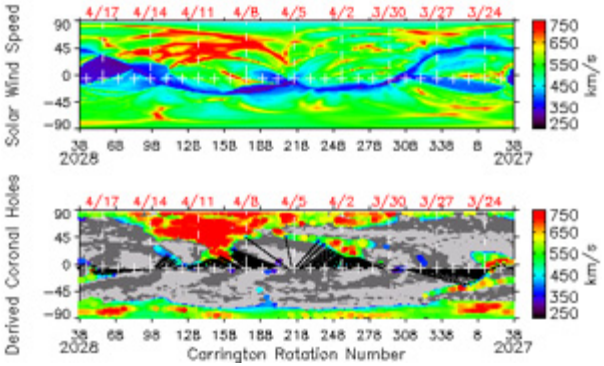
Solar Magnetogram (NSF)



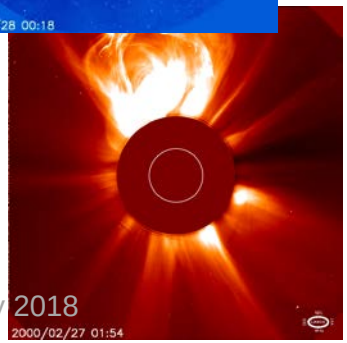
Synoptic Map



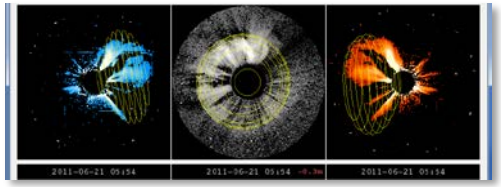
WSA
Background Solar Wind



SOHO Coronagraph (NASA/ESA)



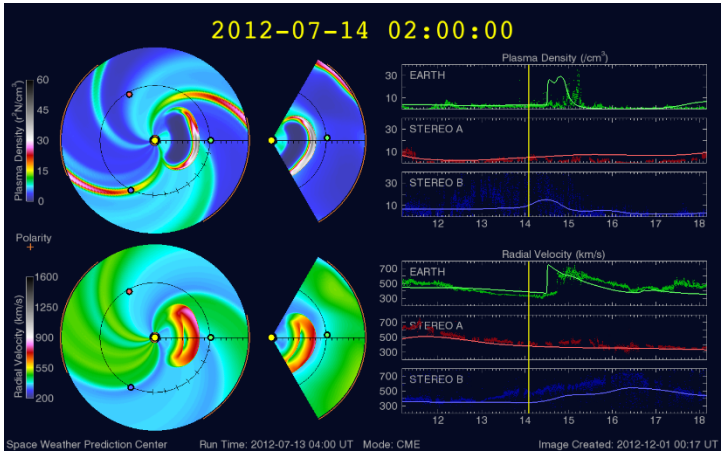
CME Analysis Tool



Stereo Behind Earth Stereo Ahead

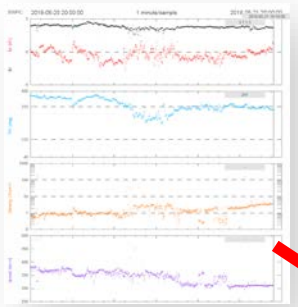
CME Direction, Speed, Size

Enlil Solar Wind Model
Multi-day forecast of conditions near Earth

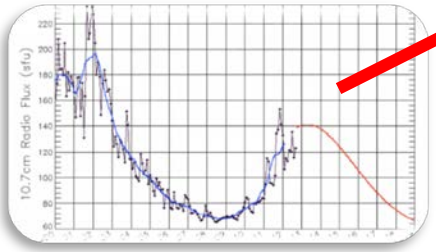


Data for Models
Geospace Model

Inputs

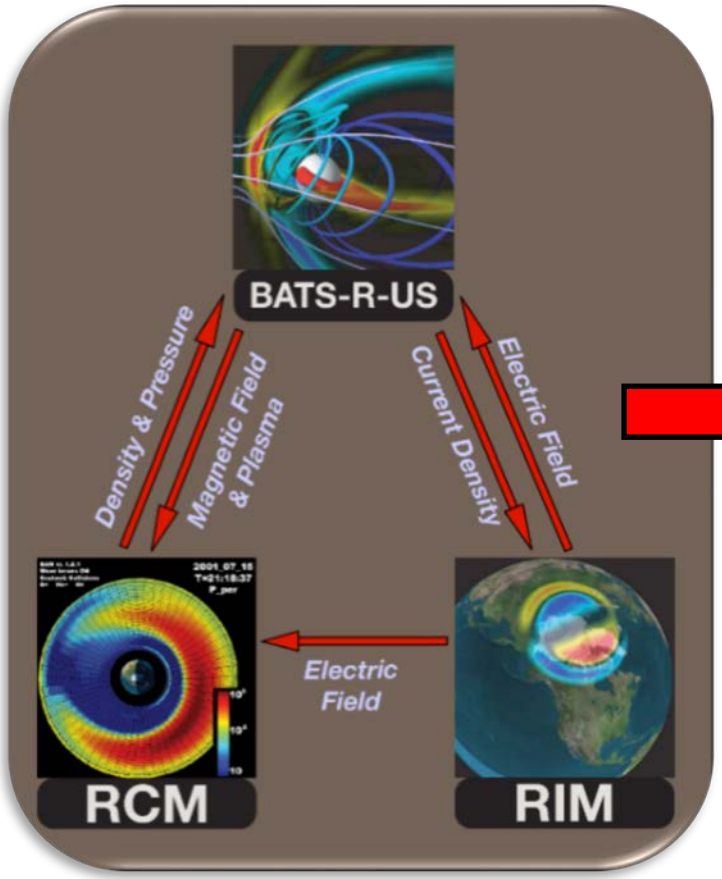


DSCOVR
Solar Wind Data:
V, n, T, B



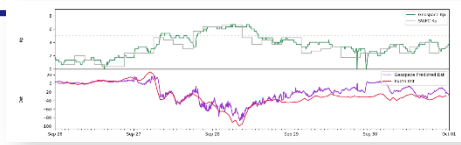
Solar F10.7 Radio Flux

Operational Geospace Model
U. Mich. Space Weather Modeling Framework

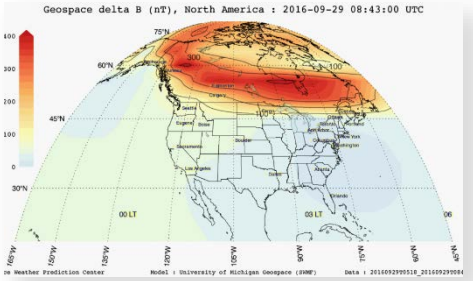


SWMF Components

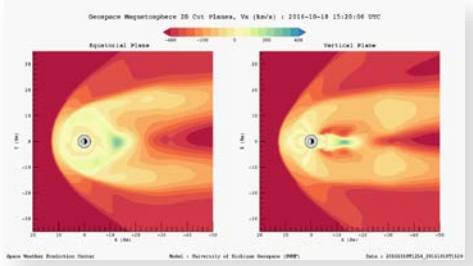
Global and Local Plots



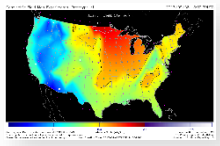
Regional and Global Maps

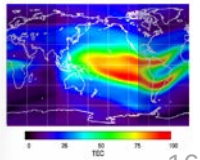


Magnetosphere Plots



Outputs to Drive Other Models (Coming Soon)

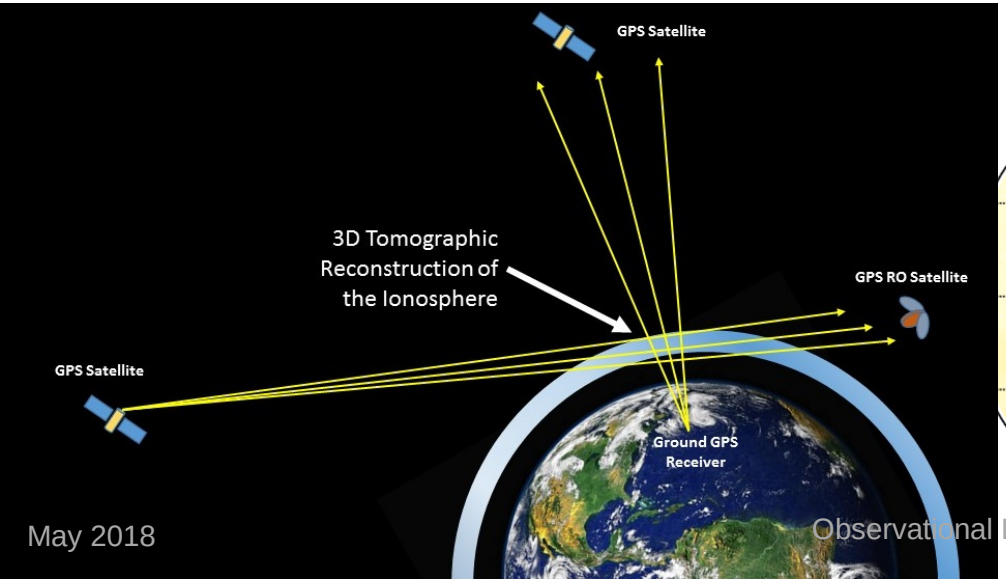


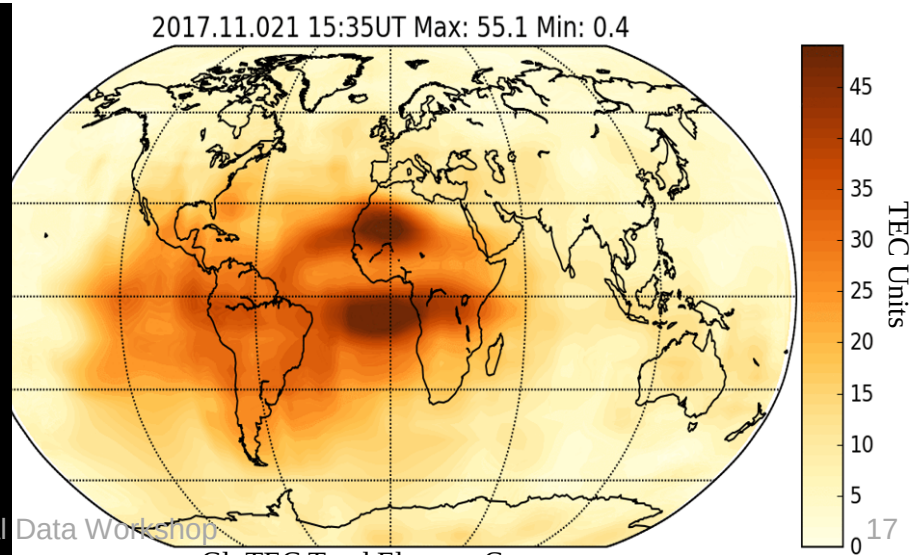


Ground-Based and COSMIC 2 Data into GloTEC

Assimilative model of the ionosphere

- **Global Total Electron Content (GloTEC):**
  - **Combines ground-based and space-base (COSMIC) GPS/GNSS observations to create a 3D assimilative map of the ionosphere**
  - **Proves specification of parameters relevant to a number of users**
    - **GPS/GNSS, HF Communication, Satellite Communication**



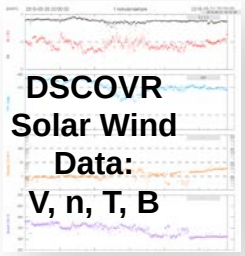


GloTEC Total Electron Content

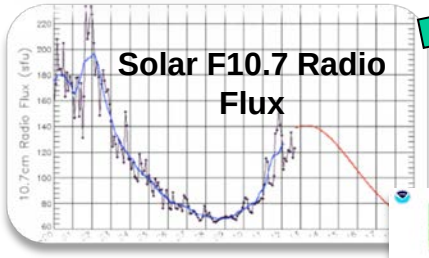
Data for Models

Whole Atmosphere Model – Ionosphere Plasmasphere Electrodynamics Model
WAM-IPE

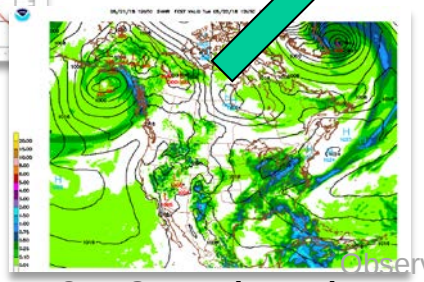
Specification and Forecasts of space weather (Kp and F10)



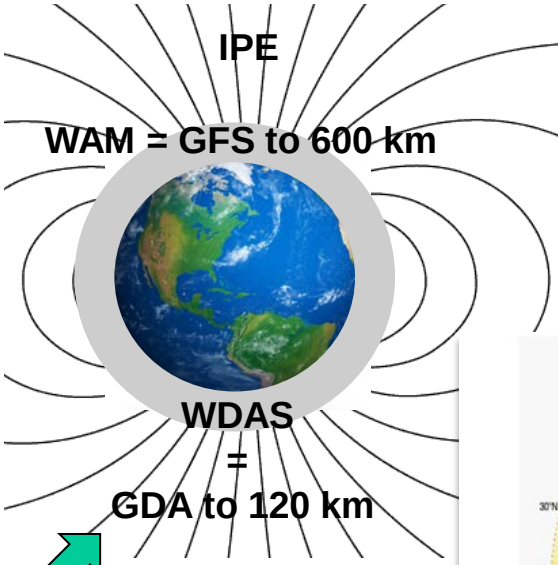
DSCOVR Solar Wind Data: V, n, T, B



Solar F10.7 Radio Flux



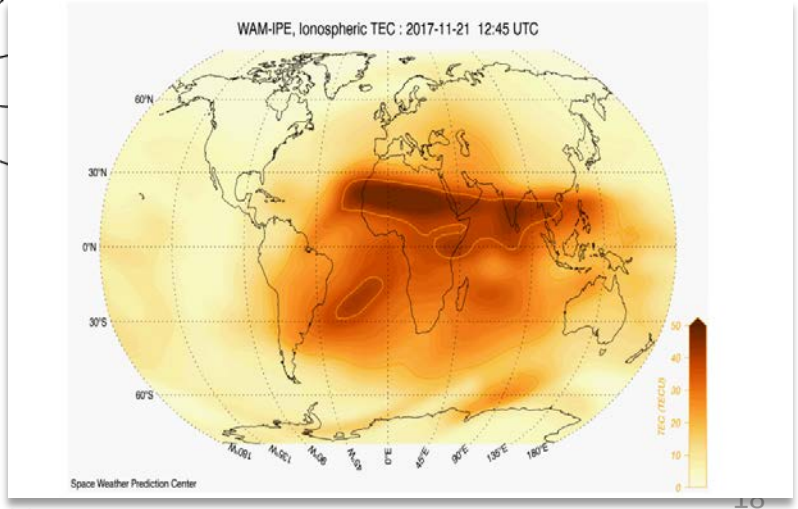
GDAS Weather Drivers



Whole Atmosphere Model:

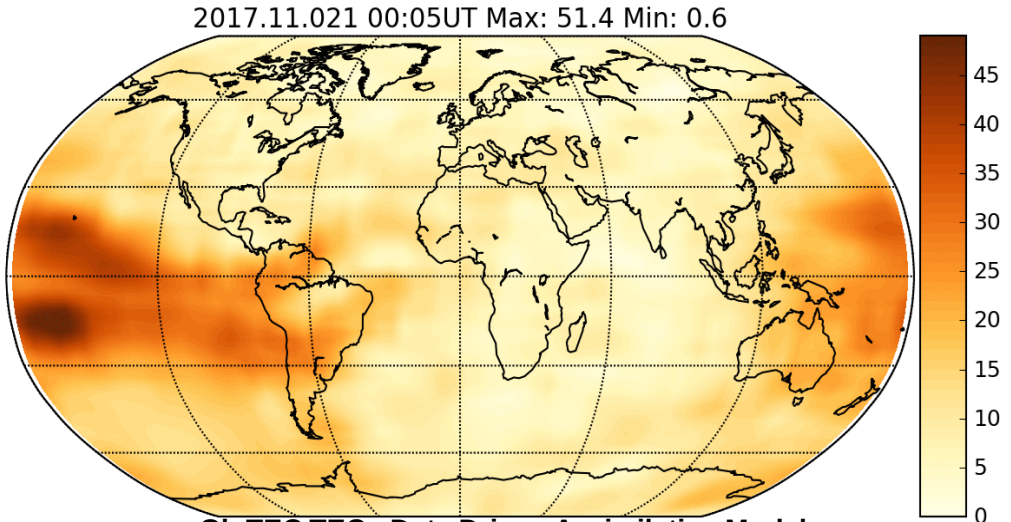
- Extended GFS (up to 600 km)
- Coupled with ionosphere model
- Imparts terrestrial weather structures onto the ionosphere.
  - planetary, tidal, gravity wave impacts

Forecasts of Ionospheric/Thermosphere conditions support users of GPS/GNSS, HF Radio, Satellite Com. Satellite Drag,…



WAM-IPE Validation with COSMIC-2

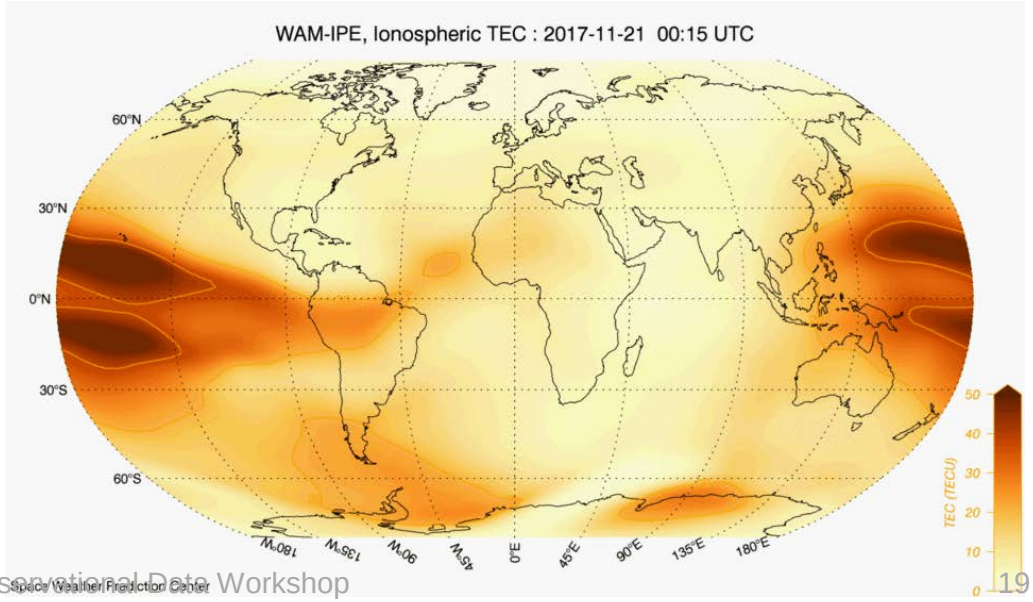
GloTEC: Will use COSMIC-2 data to create a real-time 3D specification maps of the ionosphere and TEC



GloTEC TEC: Data Driven Assimilative Model

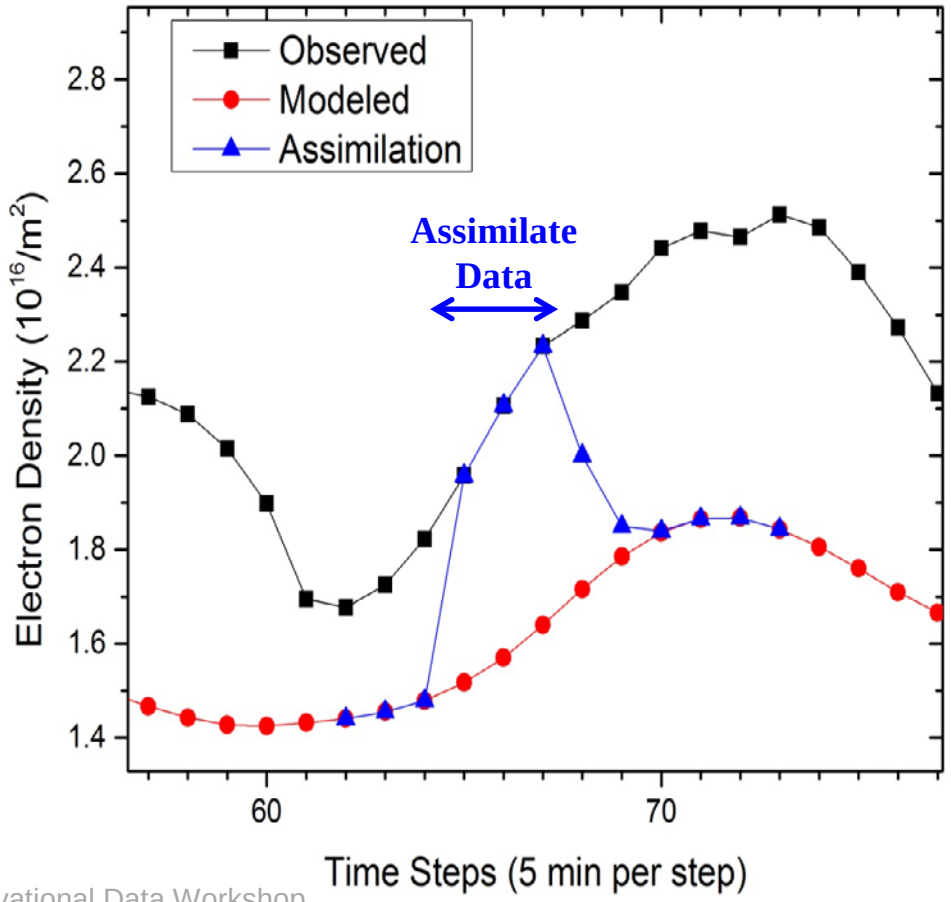
WAM-IPE: Will provide multi-day forecasts of ionosphere and TEC.

- **Phase 1: COSMIC-2 and GloTEC will be used to validate WAM-IPE forecasts (FY19)**
- **Phase 2: COSMIC-2 data will be assimilated into WAM-IPE to improve forecasts (FY20)**



Space Weather Data Assimilation Challenge

- **The Ionosphere-Thermosphere system is a strongly driven system**
  - **Order of magnitude electron density changes…**
    - **Driven by order of magnitude changes in solar EUV and Geomagnetic activity.**
    - **Occur on timescales of minute**
- **Data assimilation is challenging**
  - **Adjusting ionospheric conditions to match observations does not work very well**
  - **The ionosphere returns to its original state in the next few time steps.**



Ionosphere-Thermosphere Data Assimilation

Assimilating electron density data alone to correct the model is not effective.

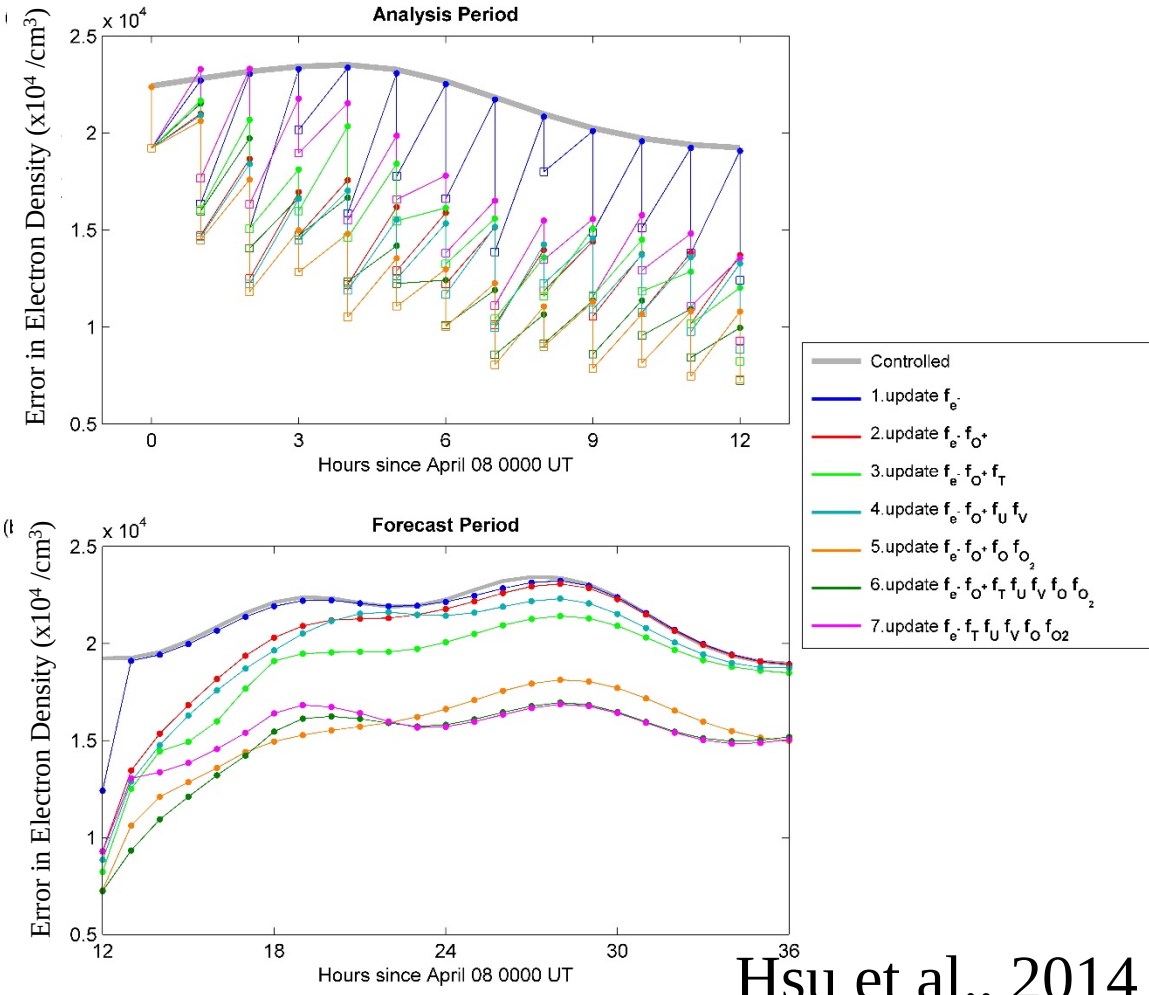
- **The electron density one hour from now has little dependence on the density now.**

Assimilating neutral composition and temperature is much more effective.

- **The neutral atmosphere has a longer memory**

Not sure which DA scheme is best

a. **Extended GSI/hybrid (3D EnVar)**
b. **Extended 4D hybrid (4D EnVar)**
c. **Separate Iono-Thermo ensemble Kalman Filter**



Hsu et al., 2014

Data Assimilation: Status

- **Lower Atmosphere**
  - **GDAS/WDAS systems well established and supported**
- **Middle Atmosphere (>60 km)**
  - **Research data (MLS, SABER) not operational**
- **Upper Atmosphere (>120 km)**
  - **Very little data (all research)**
  - **Assimilation techniques require further research**
- **Ionosphere (100 – 800 km)**
  - **Assimilation techniques require further research**

Challenges and Gaps: Schedules/Latency

Three Primary Challenges in Red

- **Coronagraph**
  - **Currently using SOHO LASCO, Launched in 1996 (for a 5 year mission)**
  - **Plans to add coronagraph to GOES U**
  - **Plans to include coronagraph on the next L1 solar wind satellite**
- **Solar Wind**
  - **Need a follow-on to DSCOVR by 2024**
  - **Current schedule (funding) has significant risk**
- **GOES 16-17 Data in Operations:**
  - **Current schedule is for FY19Q2 (2.5 years after launch)**
- **LEO Data Latency (Requirement 5 minutes)**
  - **Typical downlink schedule provides 30-90 min latency**
  - **COSMIC 2 will provide 30 min latency**

Challenges and Gaps: Coverage/Observations

Three Primary Challenges in Red

- **Solar Wind and Interplanetary Magnetic Field**
  - Would like to go closer to the sun (longer forecast lead time)
  - Solar wind and coronagraph at L5 (65 degrees behind Earth)
- **Unmet Polar Observation Requirements**
  - Energetic particles
  - Ionosphere (COSMIC 2 b)
  - Aurora
- **Unmet Upper Atmosphere**
  - Neutral density
  - Composition (NASA GOLD)
  - Winds
- **Ground Based Observations**
  - More real-time GPS receivers with scintillation capabilities especially at high latitudes
  - More complete coverage (GPS Receivers on buoys)
  - **Better Support for USGS**
    - More real-time ground magnetometers
    - Better global coverage for the magnetometer network.
    - Complete the Ground Conductivity Survey
    - Electric Field Observations

Questions?