Unpredictable variability in the I-T system and GDC's role in closing critical knowledge gaps

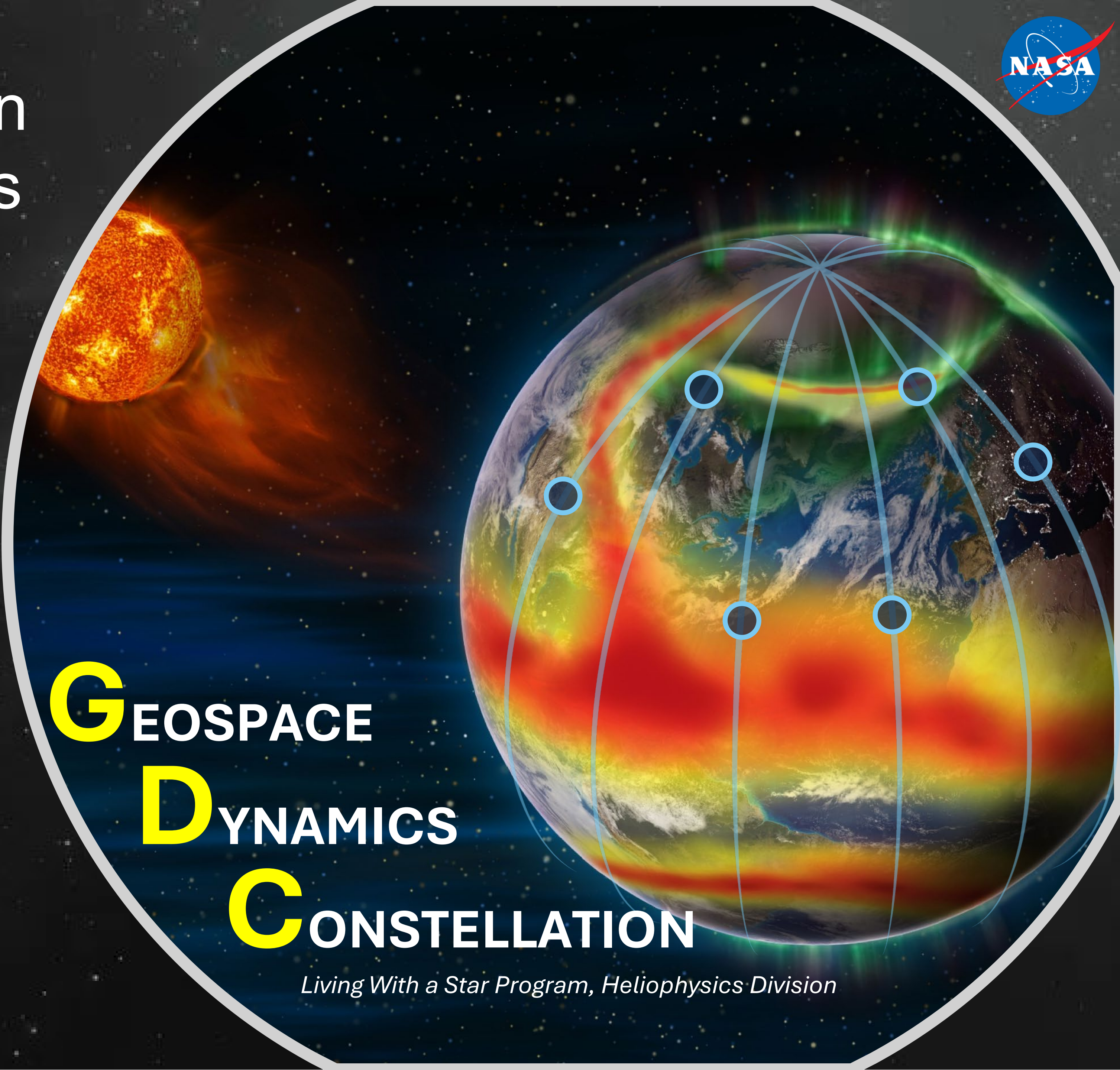
GDC Project Scientist

Doug Rowland

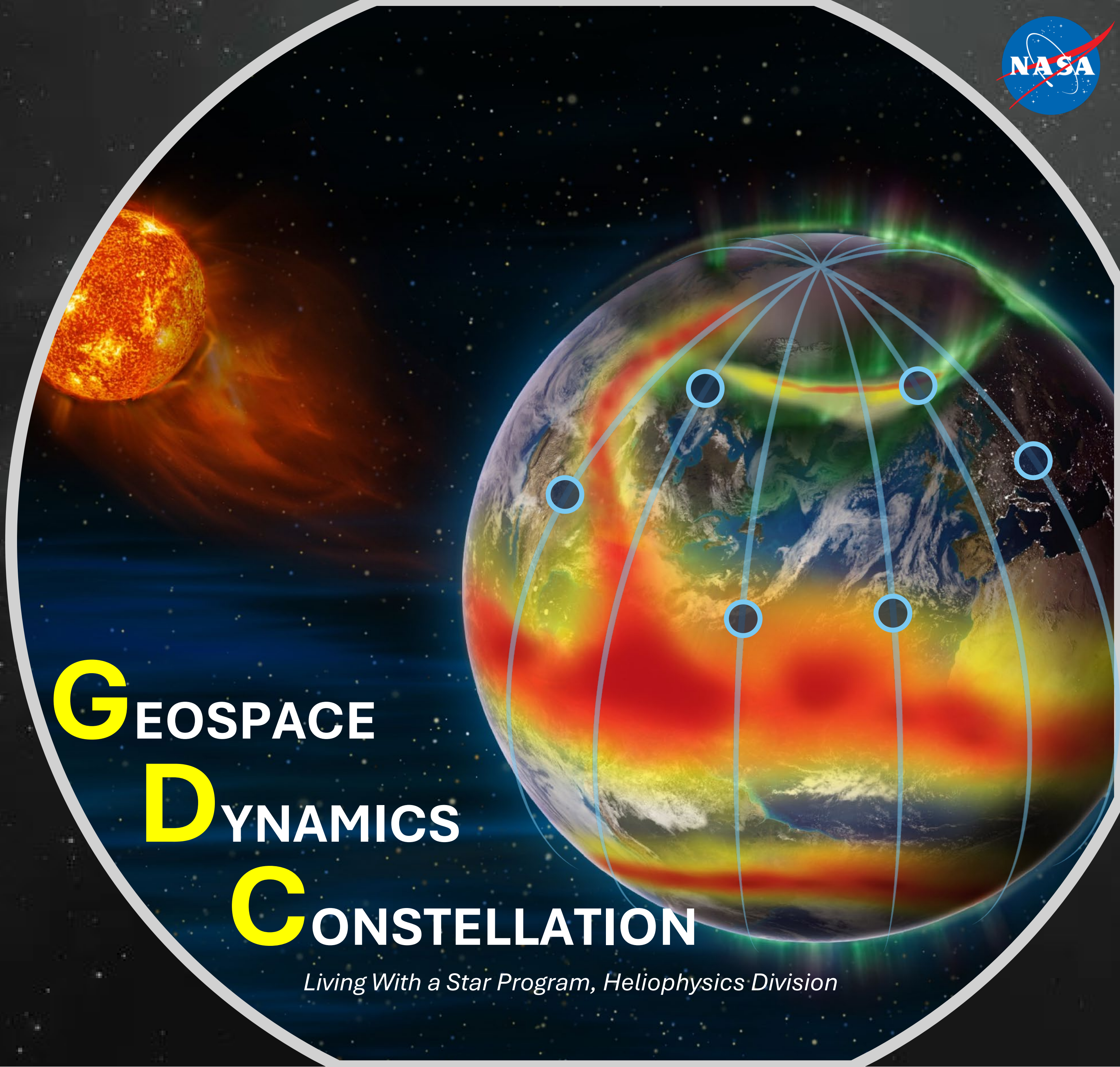
GDC Deputy Project Scientists

Katherine Garcia-Sage

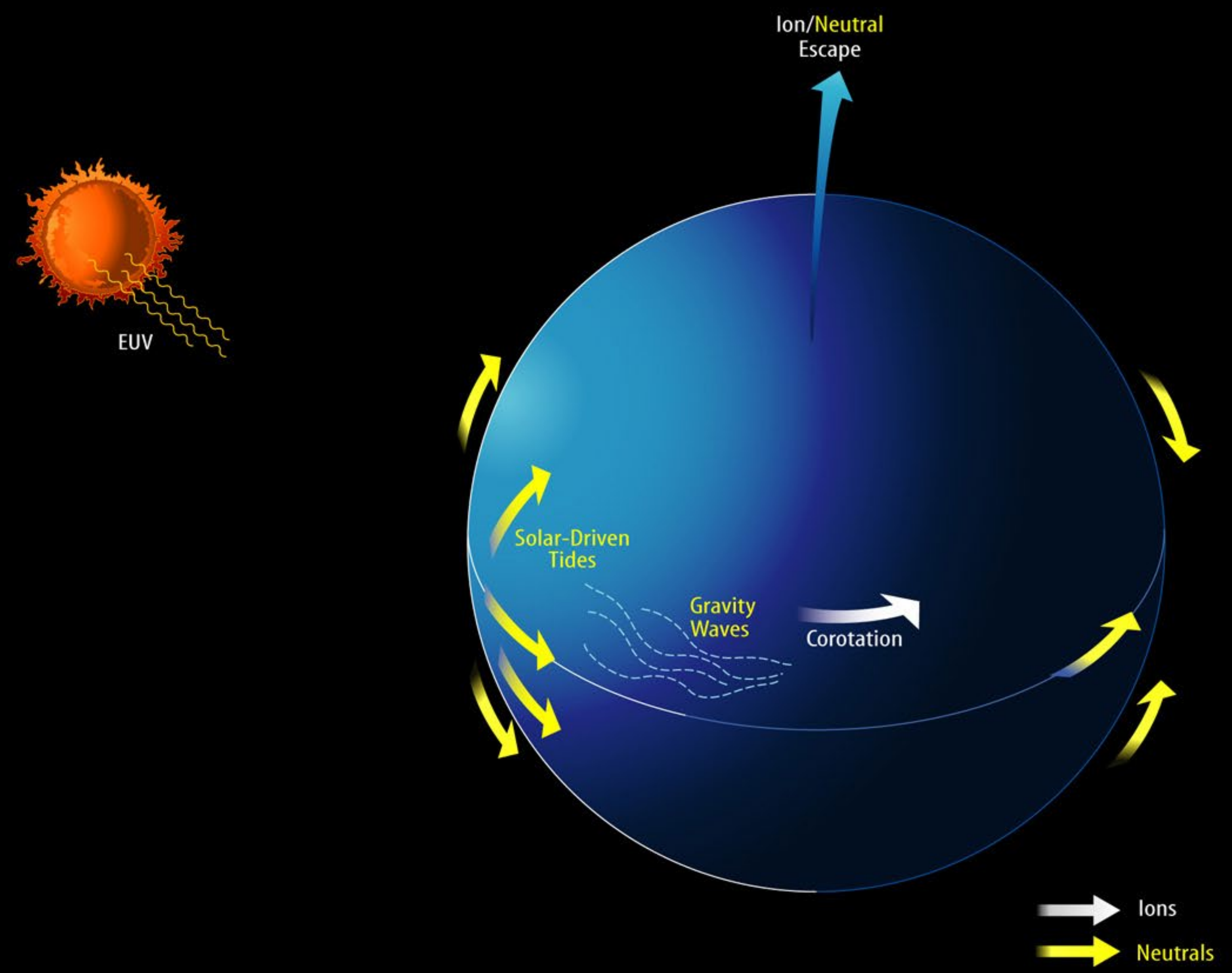
Larry Kepko



- GDC is designed to answer critical science gaps in ITM system
- Strong societal relevance/impact
- 6 identical spacecraft, ~<400 km.
- Exquisitely instrumented
- state-of-the-art modeling and theory team.



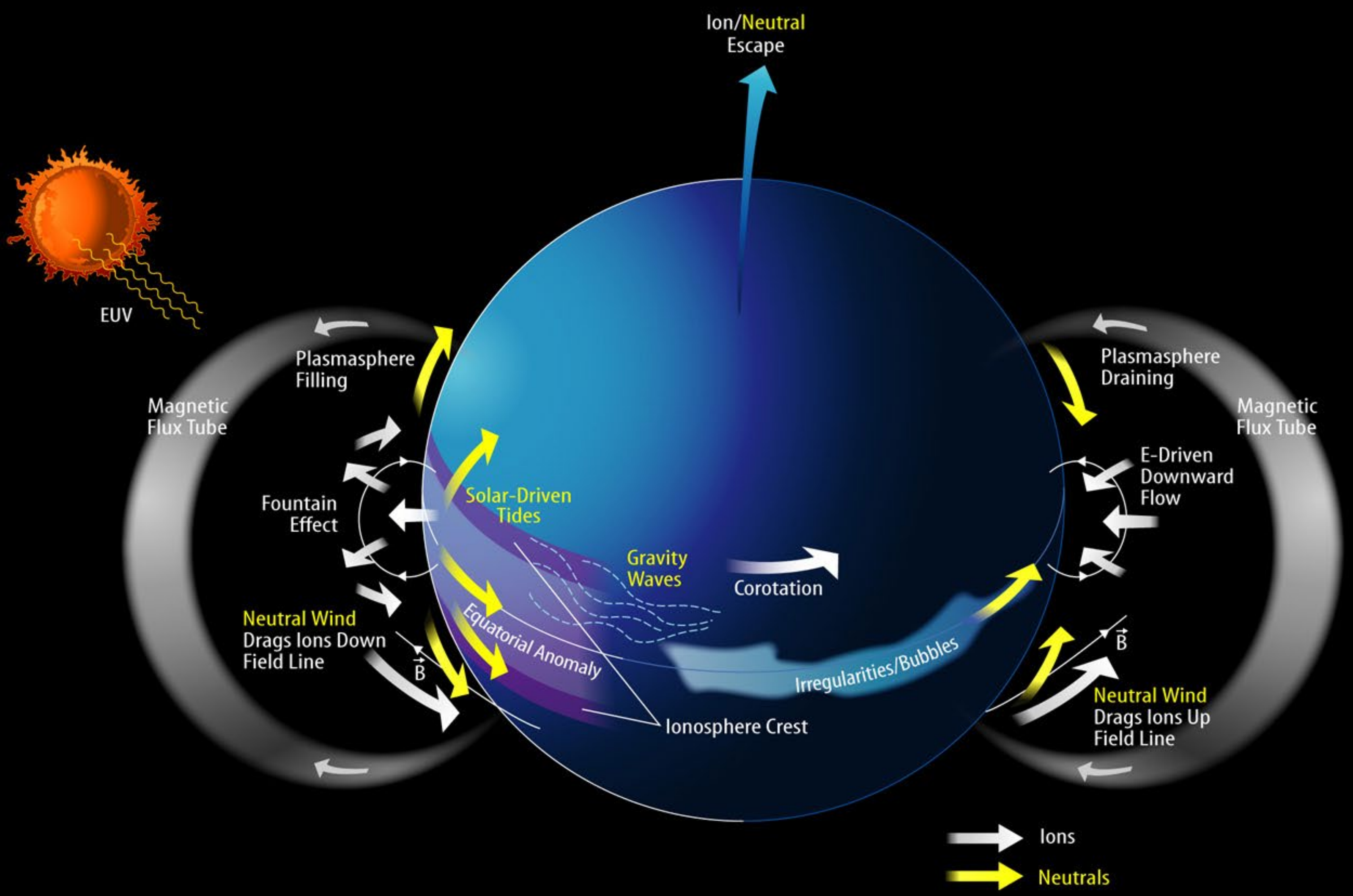
Solar EUV Effects
No Magnetic Fields



The Sun establishes the base state of the ionosphere by ionizing the dayside. Even this simple process produces dynamics, due to separate motions of the ions & neutrals.

J. Grebowsky / NASA GSFC

Addition of Earth's magnetic Field



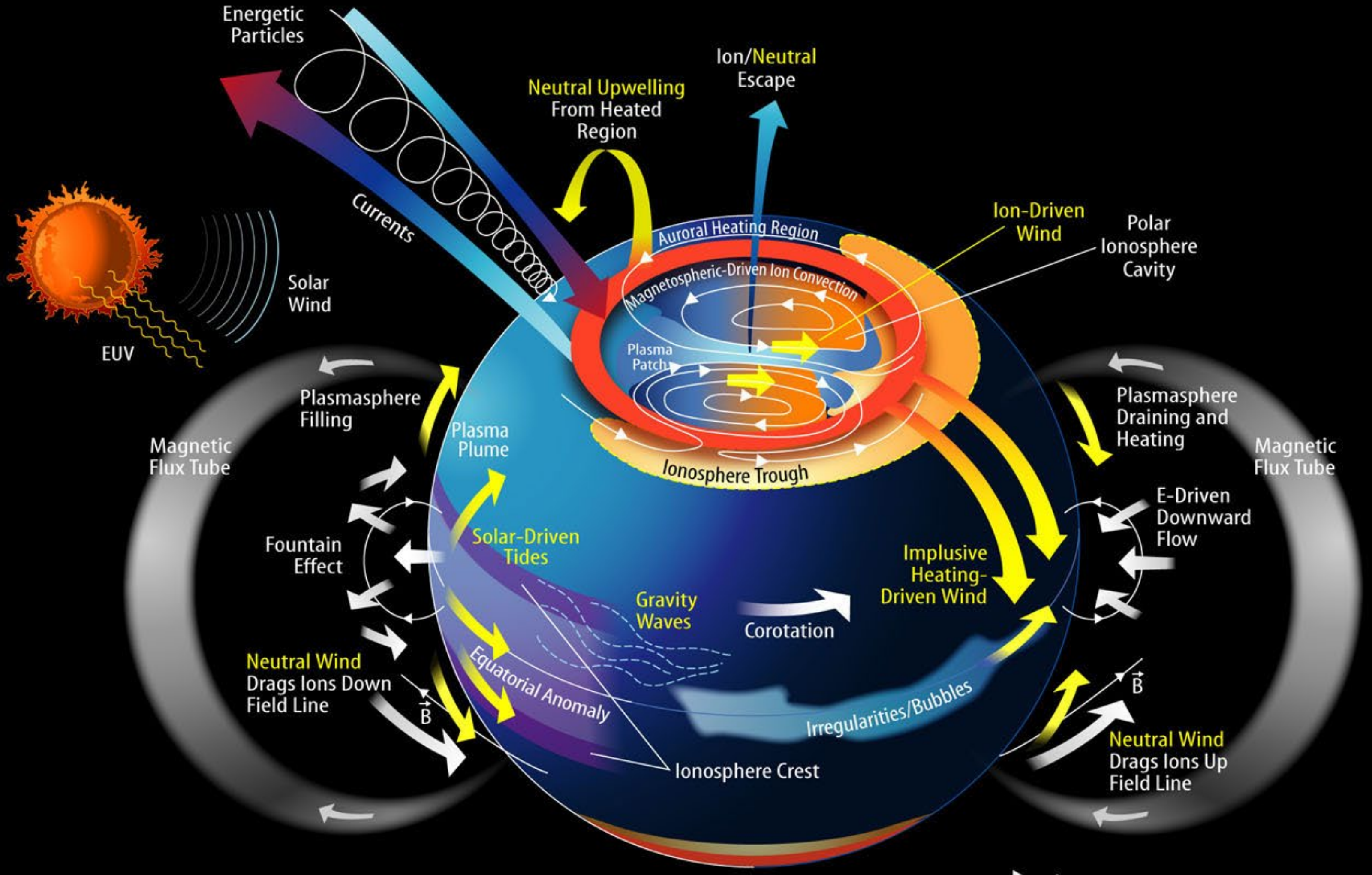
J. Grebowsky / NASA GSFC

Adding Earth's dipole field separates ion and neutral motions.

Ions are tied to the field, neutrals are not.

Sets the stage for Rayleigh-Taylor instabilities (plasma bubbles).

Addition of Solar Wind and IMF

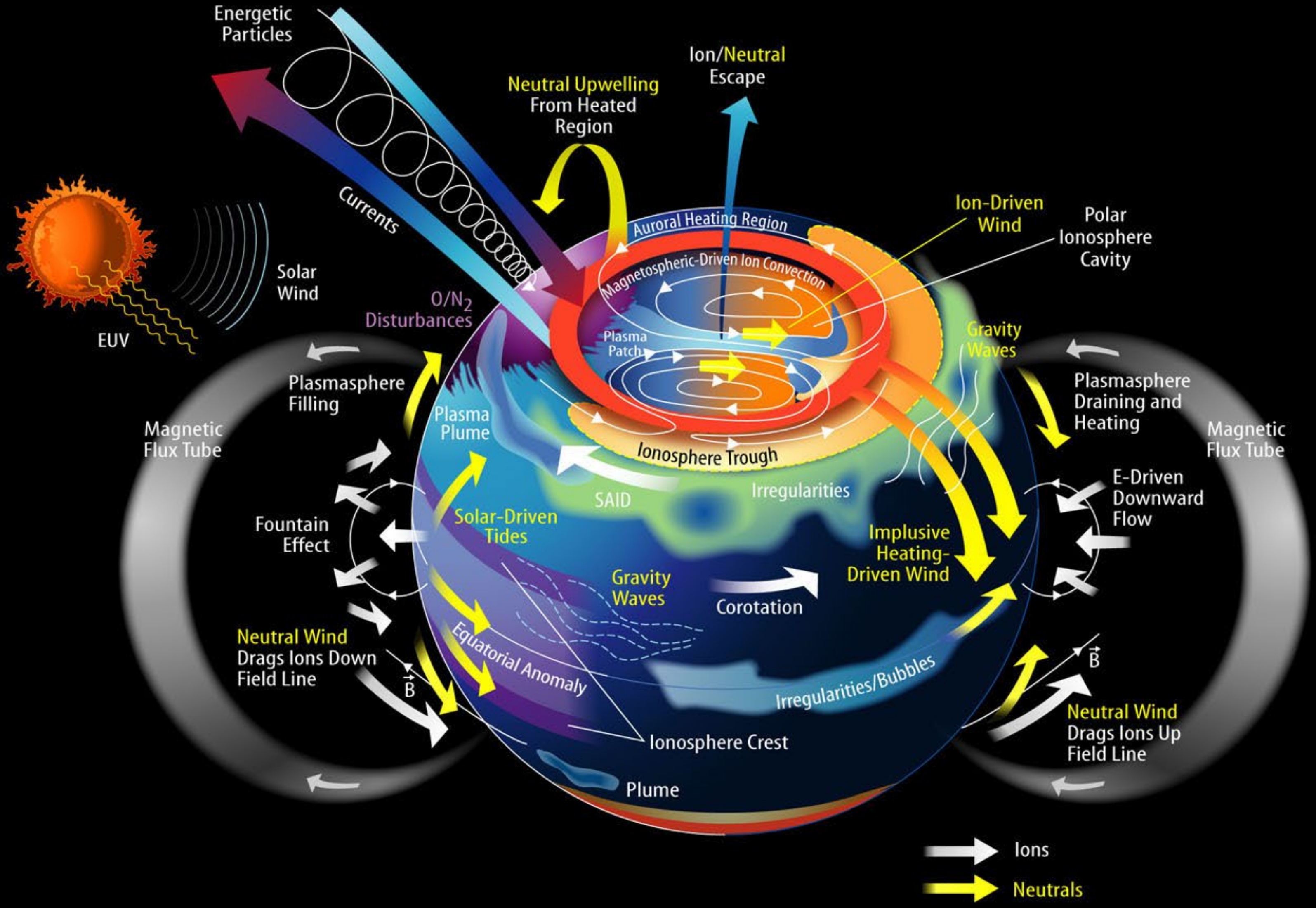


J. Grebowsky / NASA GSFC

Energy from the solar wind enters primarily into the auroral zones - but the impacts don't stay there.

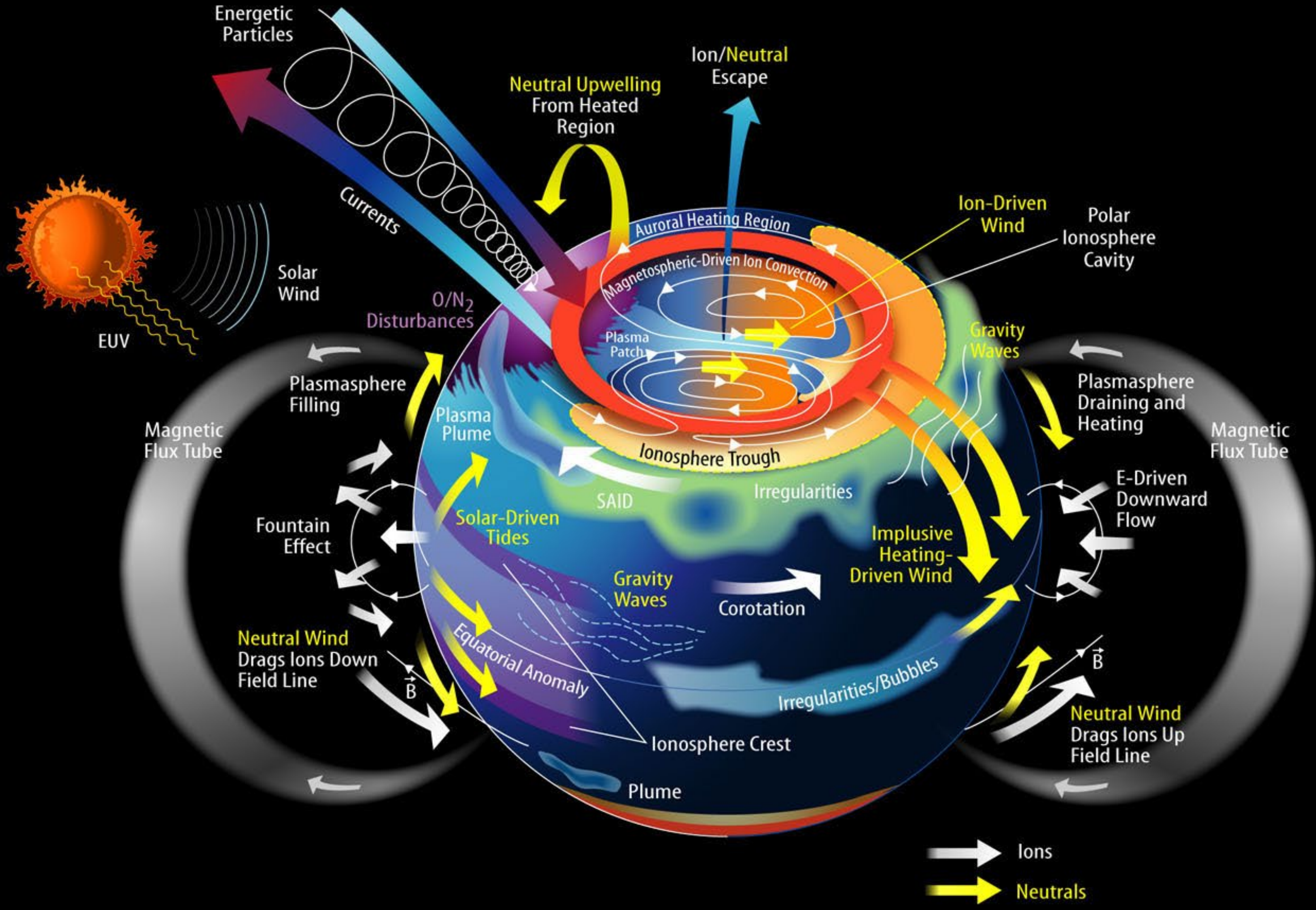
Density & composition changes don't stay here - they propagate through the entire, global ITM system.

Addition of Geomagnetic storms



J. Grebowsky / NASA GSFC

Geomagnetic storms push activity to mid and low latitudes, create large space weather impacts, such as plasma plumes and large-scale ionospheric irregularities.

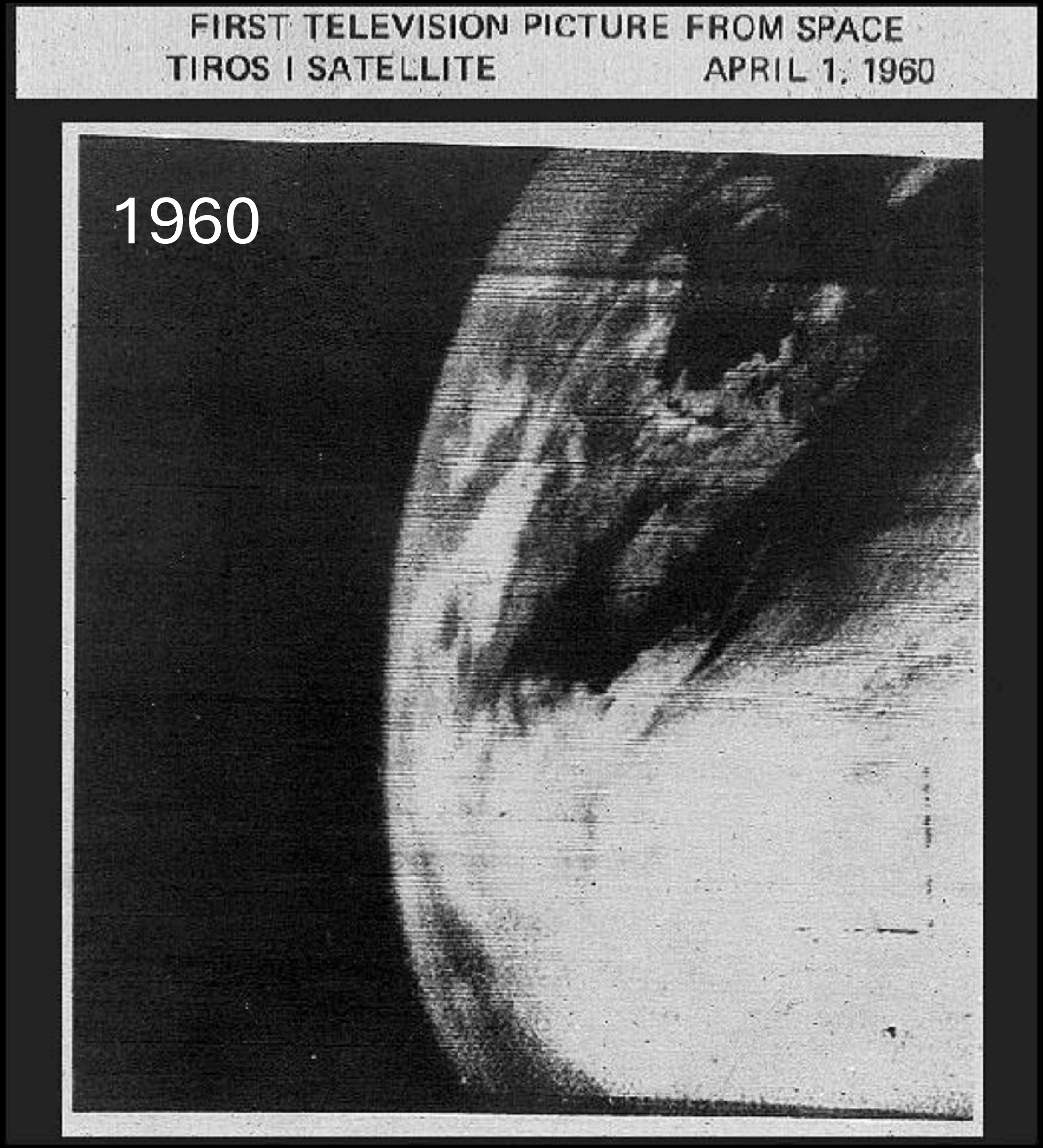


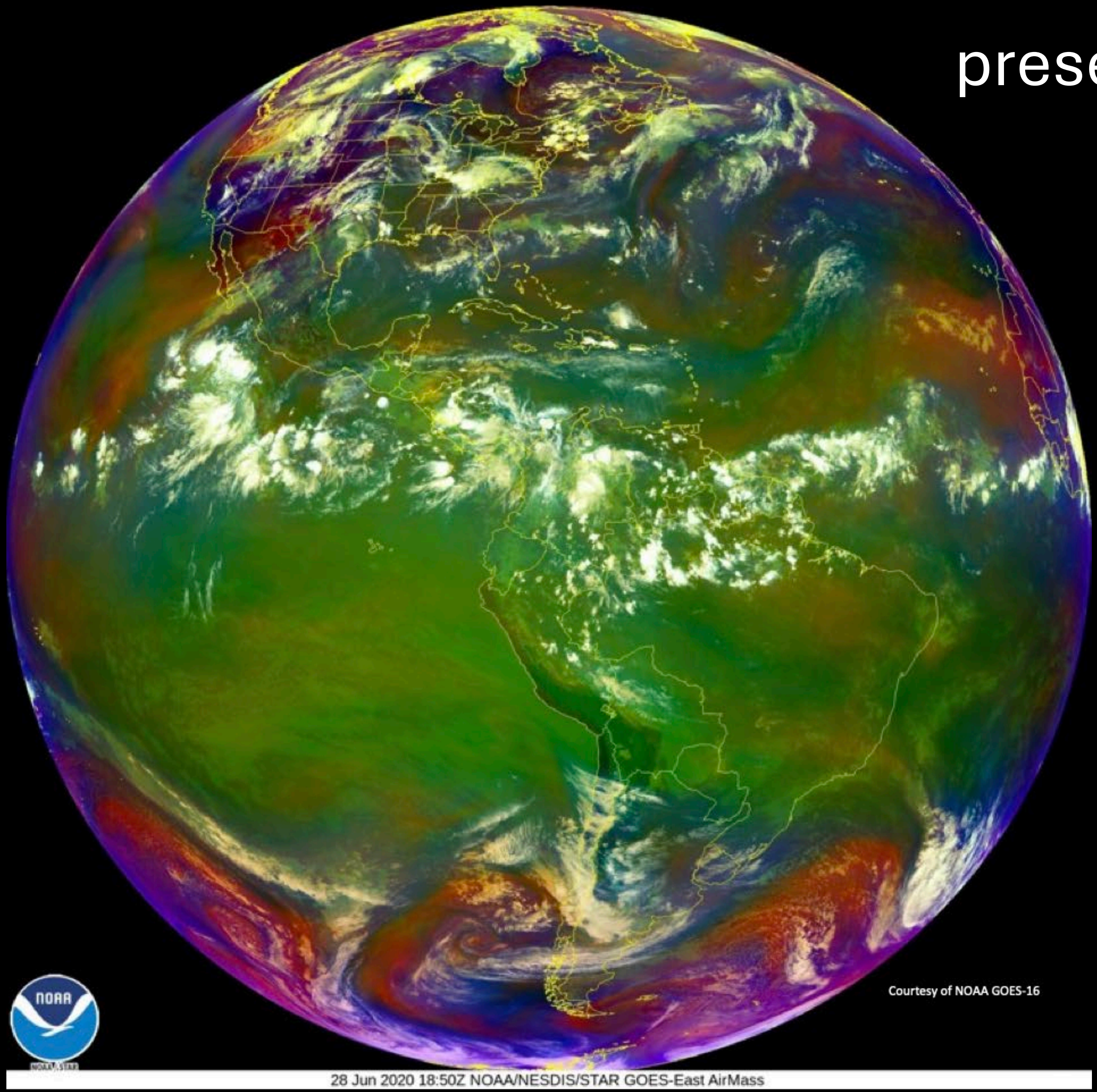
J. Grebowsky / NASA GSFC

The overall picture is that the ITM system-of-systems is complex, driven by the sun, the solar wind/magnetosphere interaction, and troposphere, with ionized plasma and the neutral atmosphere entangled on multiple spatial (small to global) and temporal (second to minutes to hours/days) scales.

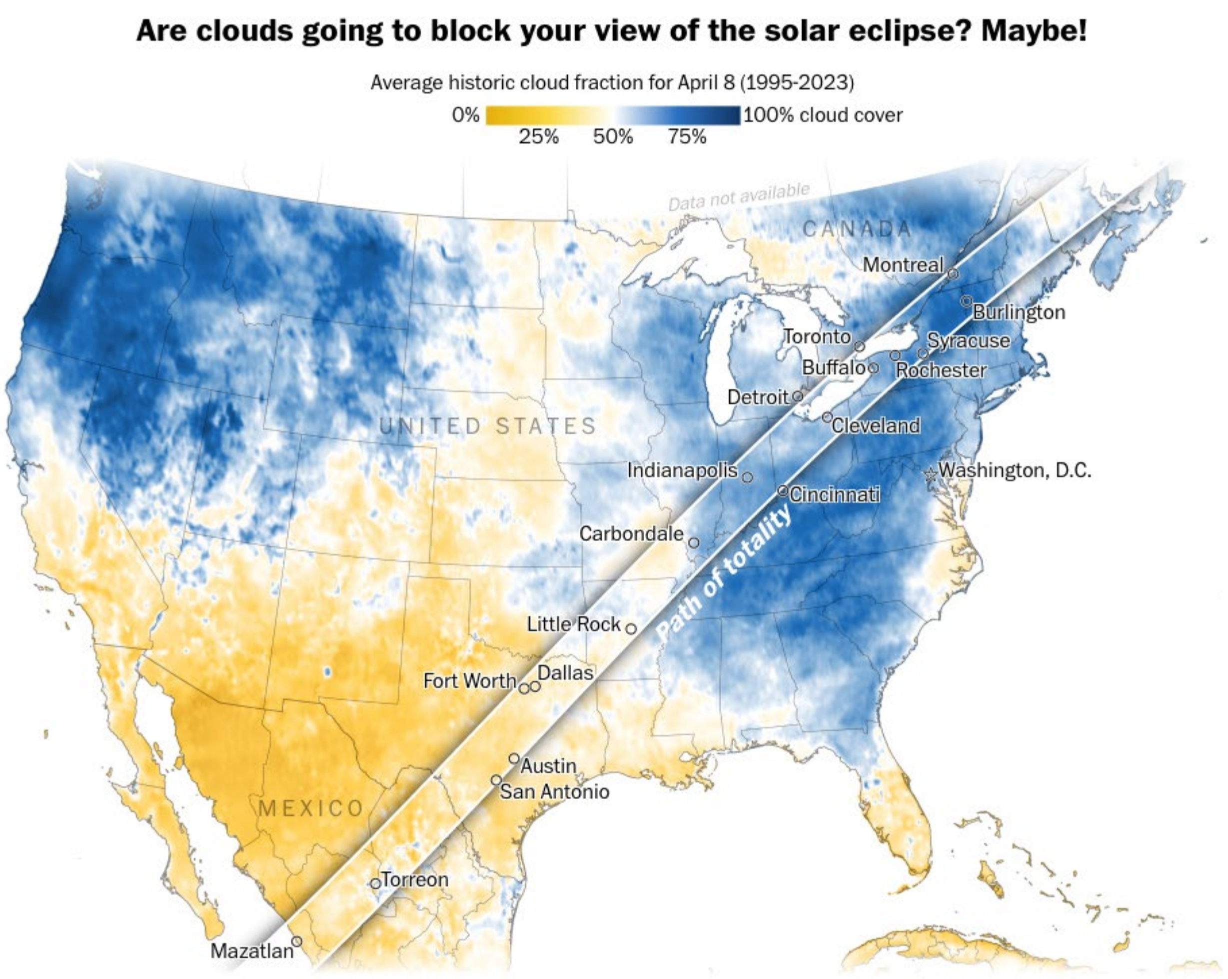
We are still missing scientific understating of key processes - this severely limits our predictive capabilities.

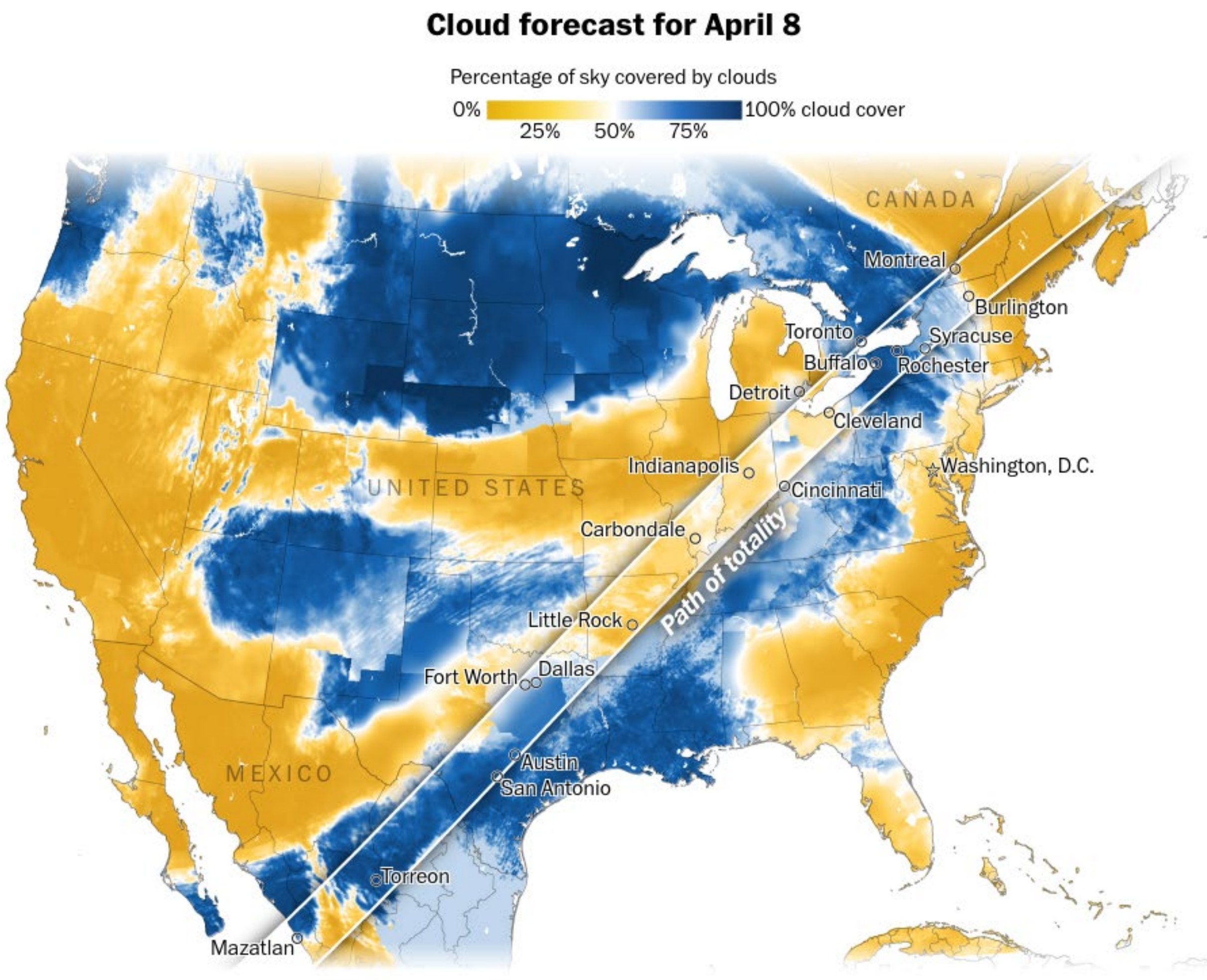
The space age has transformed our ability to understand and predict terrestrial weather, but space weather capabilities remain nascent



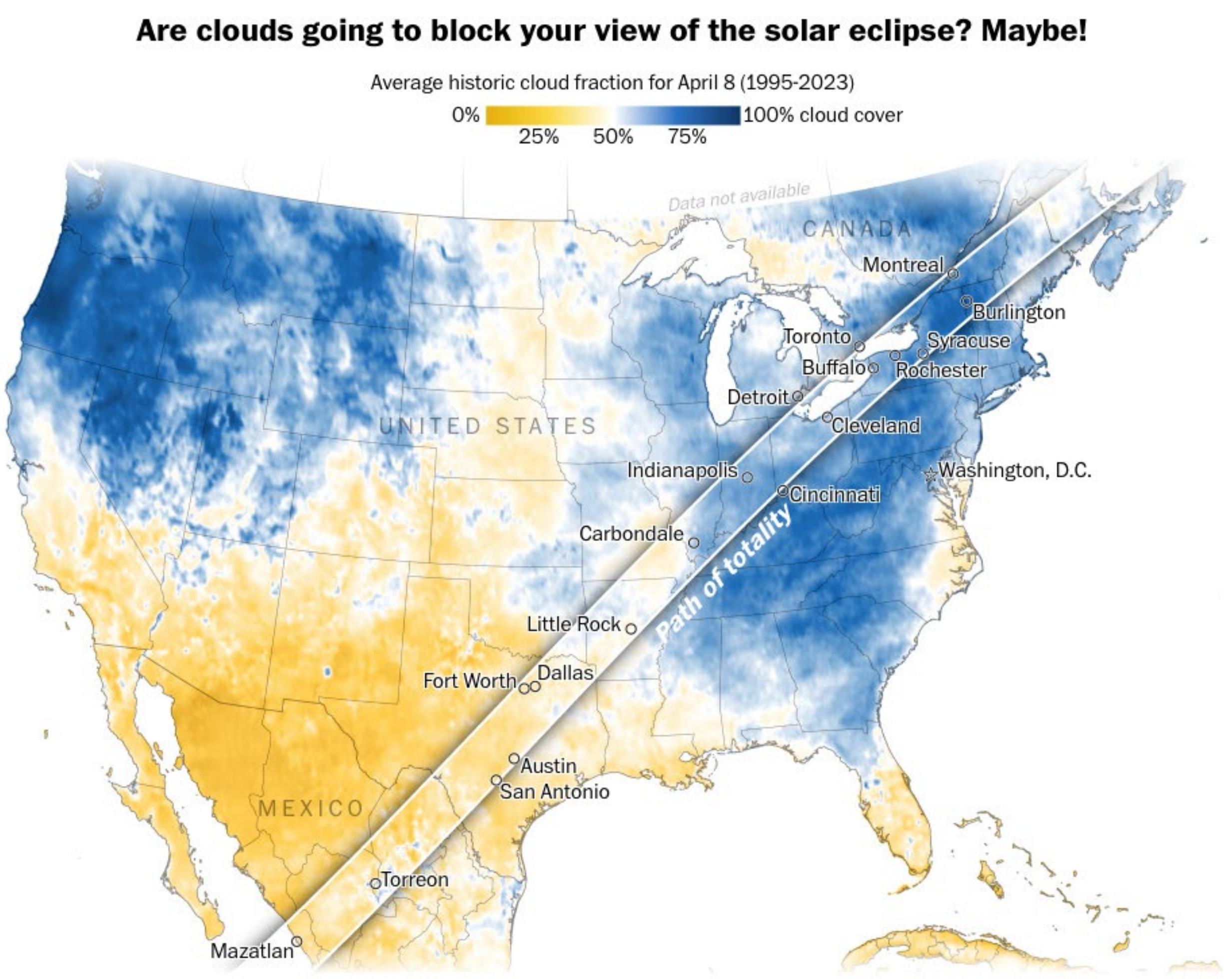


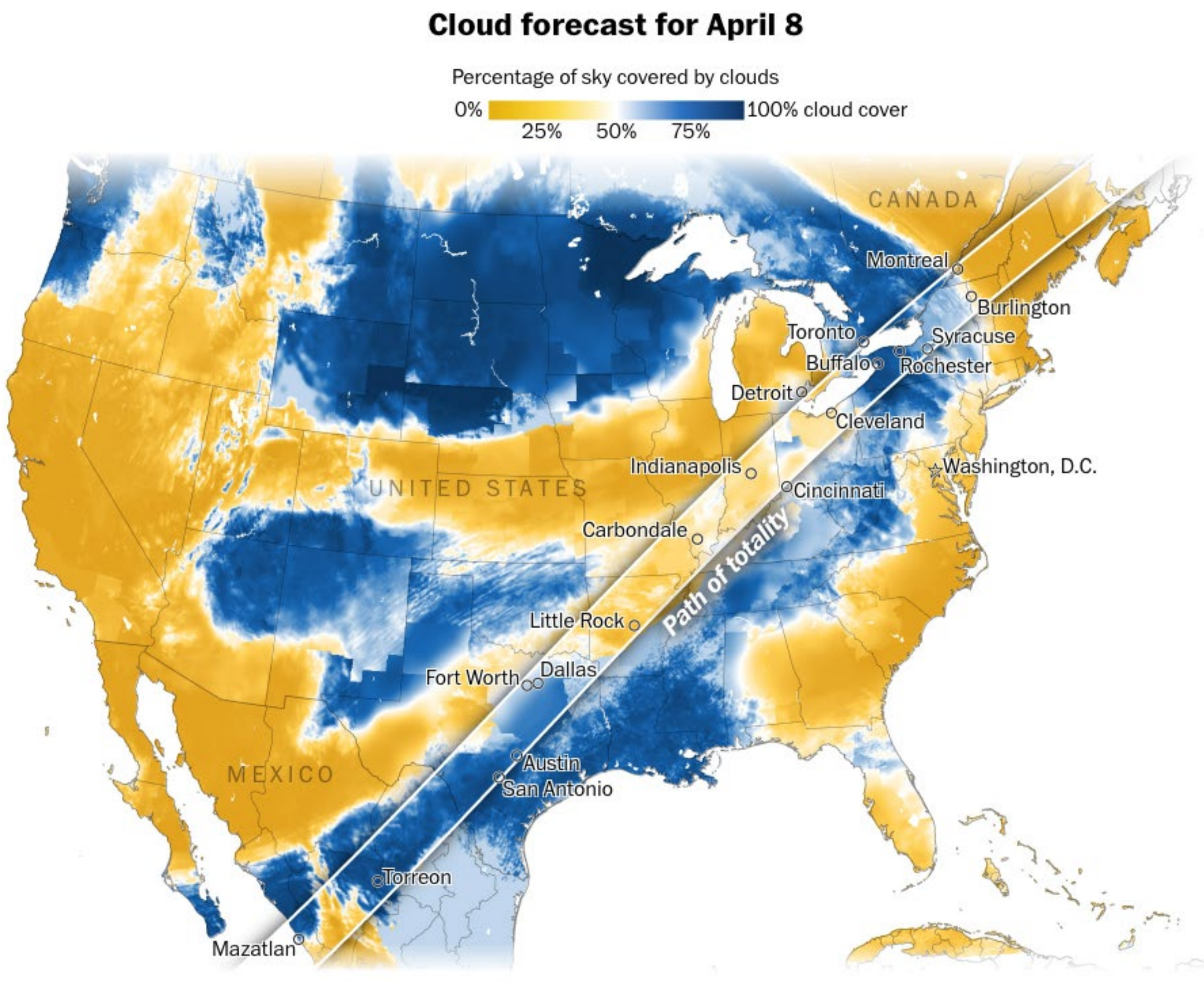
Climatological models (e.g., generally hot in summer and cold in winter) can only take you so far…





The details matter for operational decisions

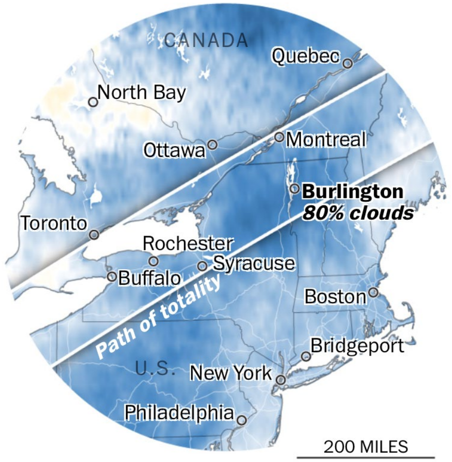




Accurate prediction flows from climatology & physical understanding, layering the detailed physics, and assimilation & validation

Step 1: Climatological

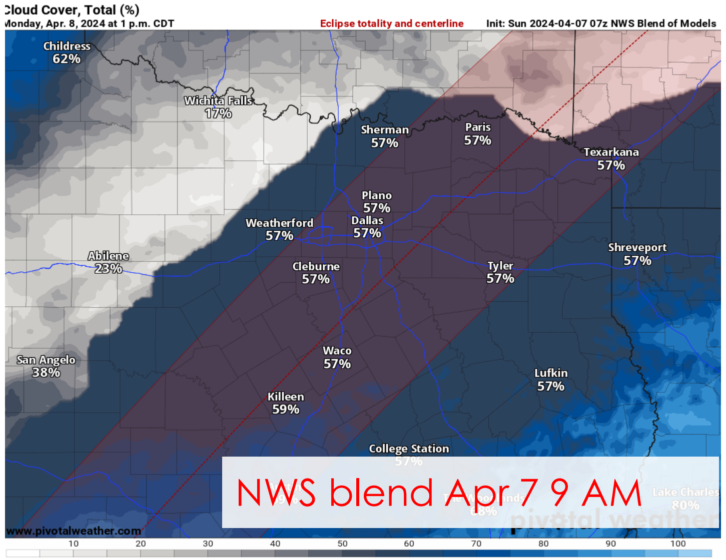
Most cloud cover over Burlington



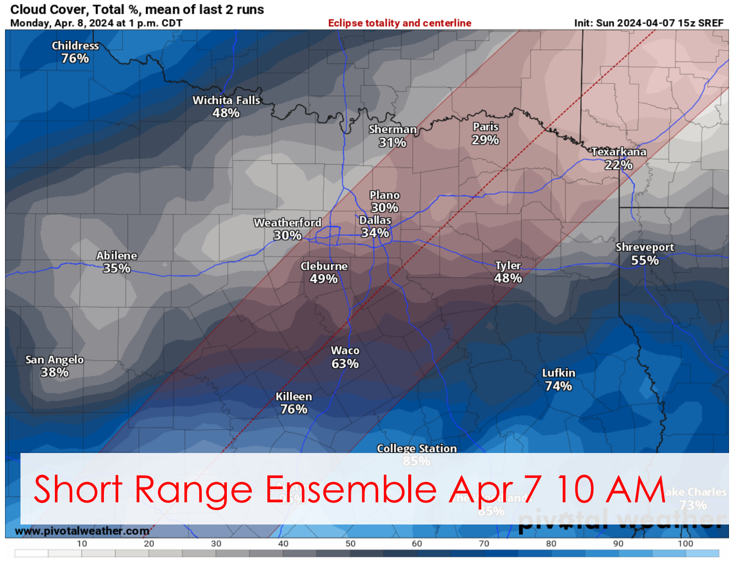
Least cloud cover around San Antonio

Source: GOES imagery analysis by University of Wisconsin-Madison C... Satellite Studies (CIMSS)

Step 2: NWP with assimilation



NWS blend Apr 7 9 AM

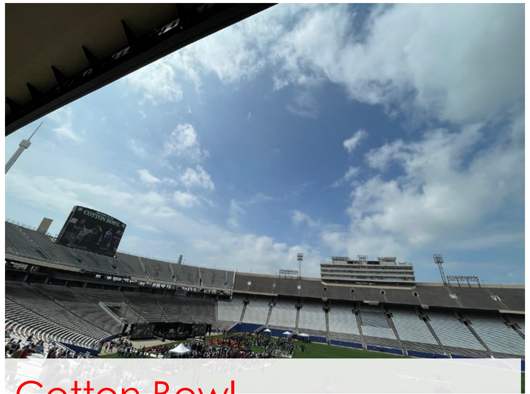


Short Range Ensemble Apr 7 10 AM

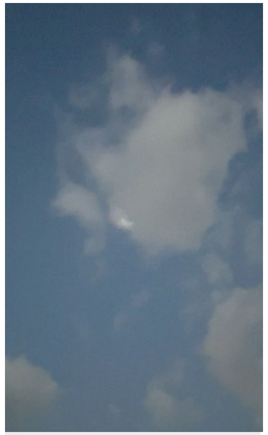
Step 3: Validate with observations

Pearl/Arts (Dallas), 1033 AM

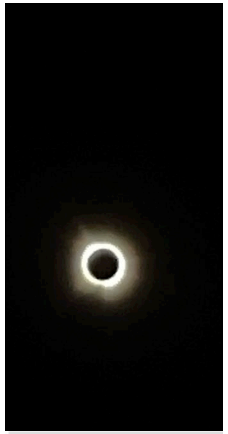
Cotton Bowl (Dallas), 1118 AM



Cotton Bowl (Dallas), 1153 AM



Cotton Bowl (Dallas) – 30 s into totality



Cotton Bowl (Dallas) -- 143 PM

In ITM science we are in Step 1 (Climatology)!

Satellite/spacecraft engineers use climatological models for design.

Our existing climatological / empirical models are based on very limited satellite data

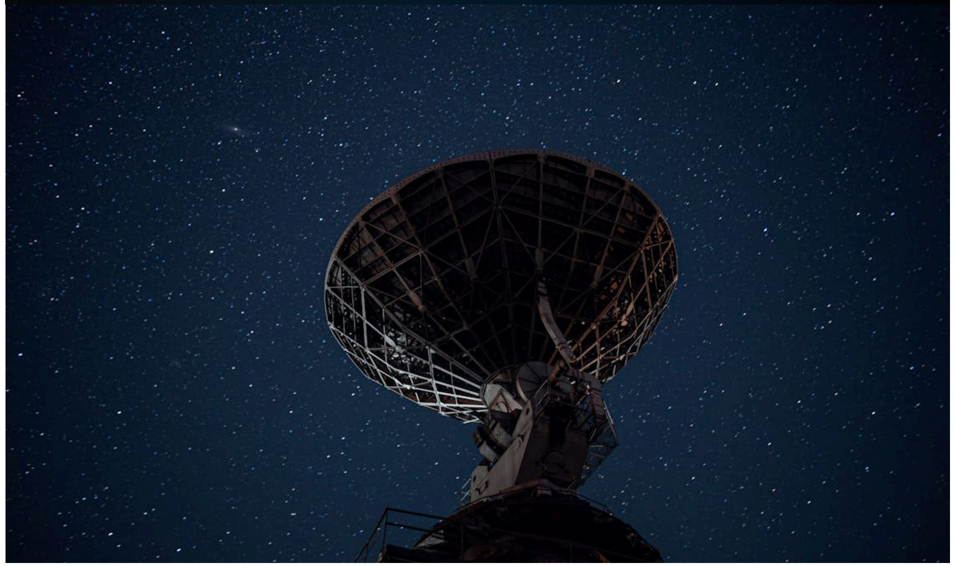
"It's generally hot in July."

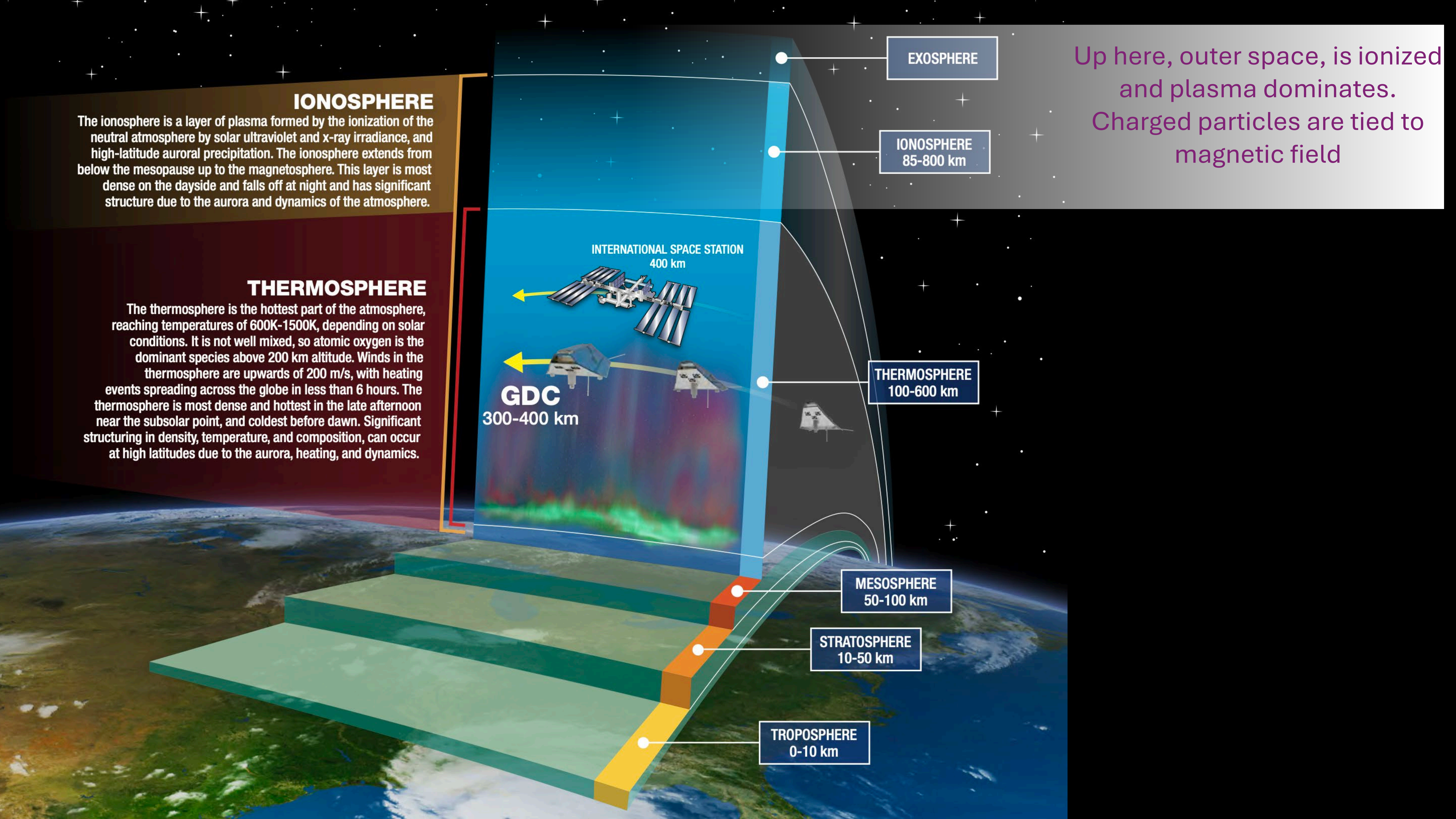
Satellite/spacecraft operators use numerical operational models for situational awareness.

Our existing operational models are not heavily validated against observations or constrained by data assimilation. Often they are driven by the poorly-constrained empirical models.

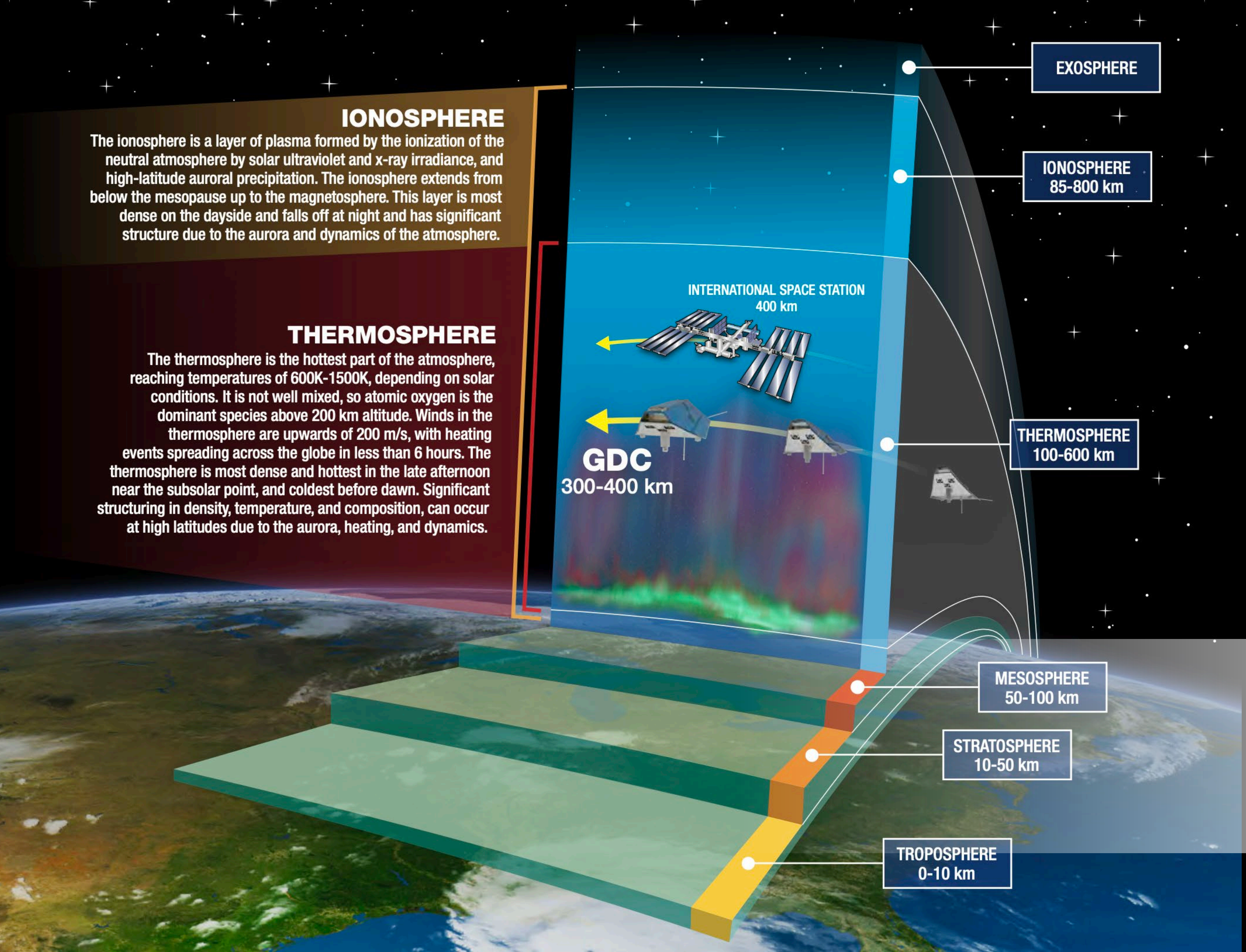
"There might be a heat wave next week. Or maybe not."

It's even worse – we don't even have the observations to know if our models are working!

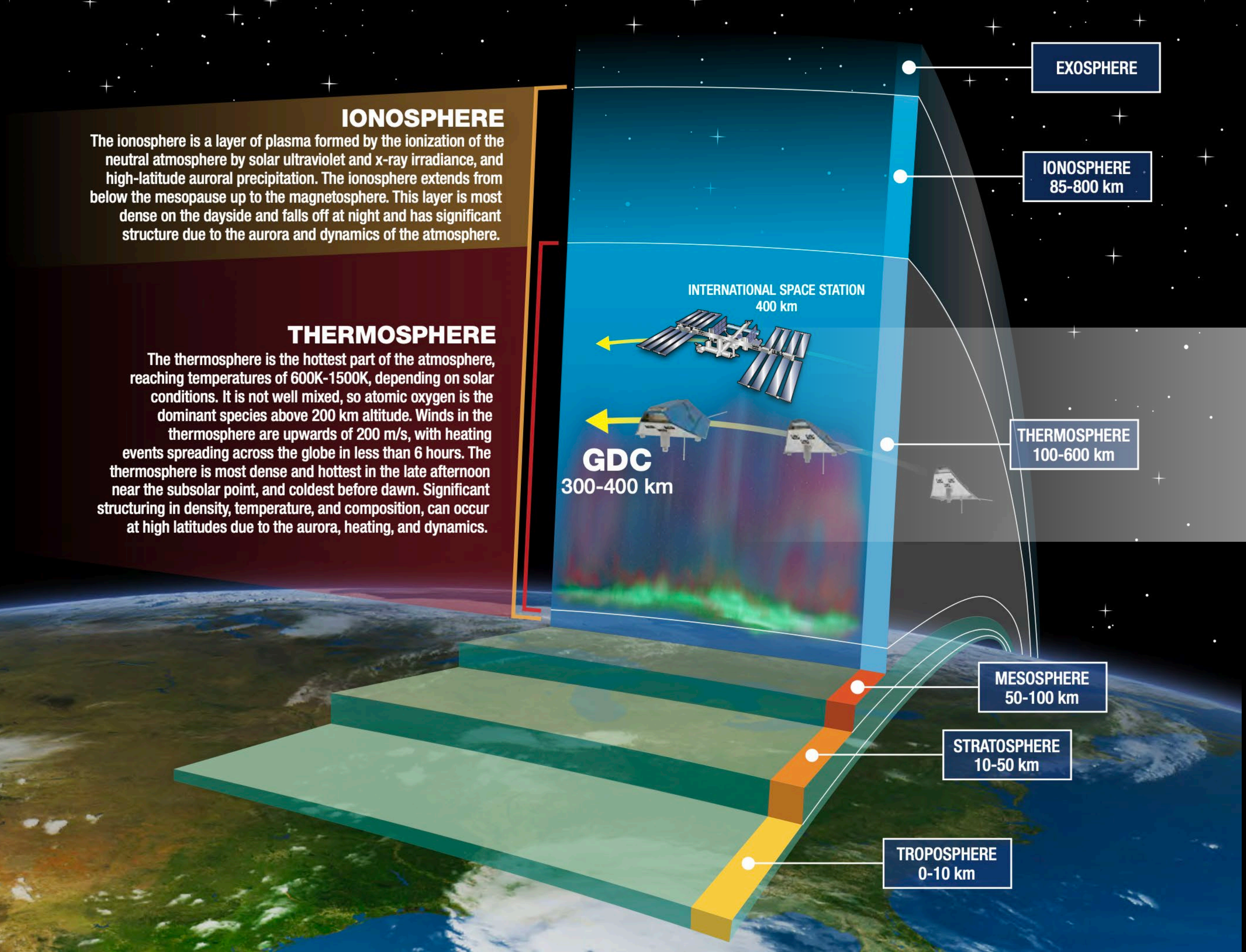




EXOSPHERE
Up here, outer space, is ionized and plasma dominates. Charged particles are tied to magnetic field
IONOSPHERE
The ionosphere is a layer of plasma formed by the ionization of the neutral atmosphere by solar ultraviolet and x-ray irradiance, and high-latitude auroral precipitation. The ionosphere extends from below the mesopause up to the magnetosphere. This layer is most dense on the dayside and falls off at night and has significant structure due to the aurora and dynamics of the atmosphere.
IONOSPHERE 85-800 km
INTERNATIONAL SPACE STATION 400 km
THERMOSPHERE
The thermosphere is the hottest part of the atmosphere, reaching temperatures of 600K-1500K, depending on solar conditions. It is not well mixed, so atomic oxygen is the dominant species above 200 km altitude. Winds in the thermosphere are upwards of 200 m/s, with heating events spreading across the globe in less than 6 hours. The thermosphere is most dense and hottest in the late afternoon near the subsolar point, and coldest before dawn. Significant structuring in density, temperature, and composition, can occur at high latitudes due to the aurora, heating, and dynamics.
GDC
300-400 km
THERMOSPHERE 100-600 km
MESOSPHERE 50-100 km
STRATOSPHERE 10-50 km
TROPOSPHERE 0-10 km



Down here, neutrals dominate.
Neutrals move differently than ions & electrons



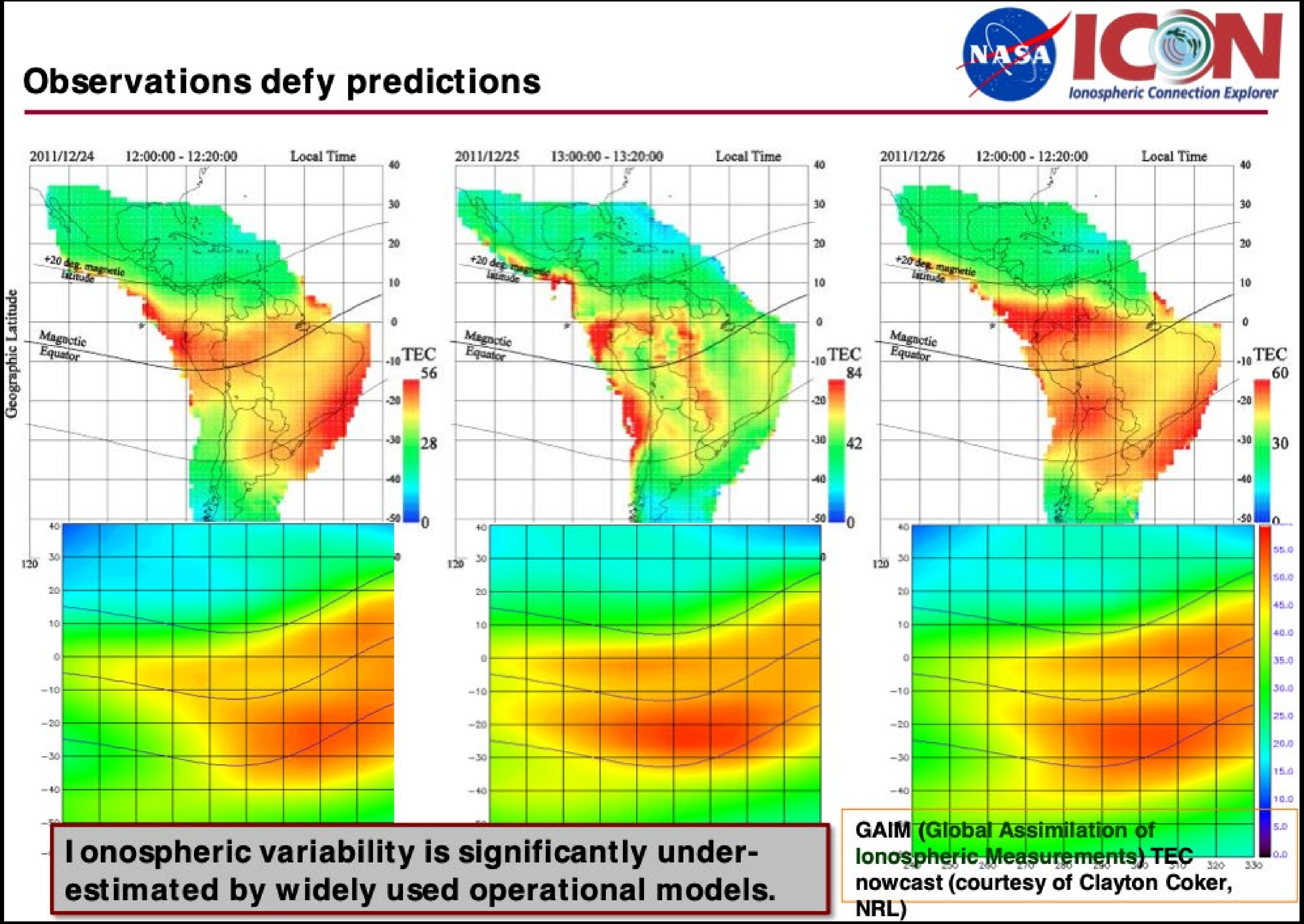
Up here, outer space, is ionized and plasma dominates. Charged particles are tied to magnetic field

In the middle, outer space and air mix, yielding complex dynamics. We have a severe knowledge gap in this area.

Down here, neutrals dominate. Neutrals move differently than ions & electrons

- Everything I just showed you was model output.
- Models rely on physics we put into the model (and assumptions about how the system works), boundary conditions, and inputs (solar wind, indices, etc.).
- So, how are the models doing?

Even on 'quiet' days, the IT system is dynamic in ways we cannot predict or model



This example, from Tom Immel (ICON PI), shows the ionospheric state over South America Dec 24-26, 2011

Measured by C. Valledares' LISN network of GPS-TEC receivers.

The solar wind and geomagnetic activity are very quiet during this time, but the ionosphere varies wildly day to day (top row), and this is not captured by our models (bottom row)

We need GDC to fill our science knowledge gaps

- Our limited observations are telling us that the models do not accurately capture the IT system, even during so-called "quiet" days:
  - We are missing physics
  - We are missing accurate inputs
  - We are we not capturing preconditioning and cross-scale coupling correctly
- Scientific understanding is the key to prediction/forecasting. Theory establishes cause and effect, but data establishes correlation.
  - GDC provides the missing observations, and links them with state-of-the-art modeling & theory, to address the known science gaps
- GDC will focus on the critical 300-400 km region where ions and neutral gas couple most strongly

GDC is designed to address our major knowledge gaps, answering scientific questions with real-world applications

Science Mysteries	Practical applications
What drives ionospheric turbulence?	How do we predict HF interference?
What drives localized ionospheric currents?	How do we prepare for terrestrial effects of GICs?
What causes thermospheric variability and expansion?	How do we predict orbital drag and satellite lifetimes?
What is the origin of ionospheric ionized patches?	How do we forecast polar auroral clutter?

GDC is designed to address our major knowledge gaps, answering scientific questions with real-world applications

Science Mysteries	**Practical applications**
What drives ionospheric turbulence?	How do we predict HF interference?
What drives localized ionospheric currents?	How do we prepare for terrestrial effects of GICs?
What causes thermospheric variability and expansion?	How do we predict orbital drag and satellite lifetimes?
What is the origin of ionospheric ionized patches?	How do we forecast polar auroral clutter?

Equatorial plasma bubbles (EPBs) are an unpredictable space weather phenomenon that occurs near the magnetic equator.

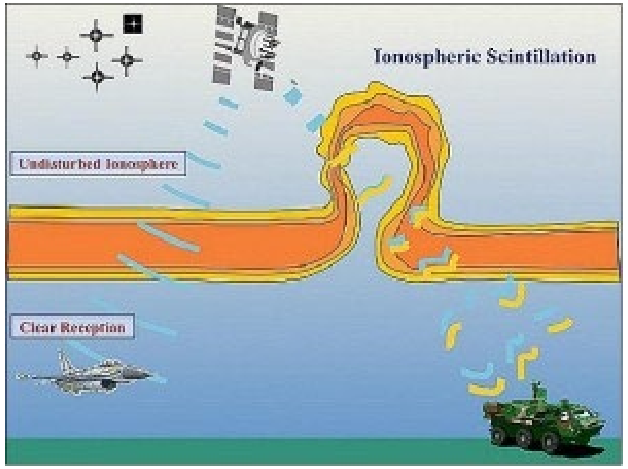
EPBs are huge “tubes” of plasma that are 10-1000x lower density than the surrounding ionosphere

EPBs are buoyant and move upwards, developing corrugations and structure at scales that greatly interfere with radiowave propagation. (radio-frequency “scintillation”)

If you want to know where scintillation is now, that’s one measurement (**AETHER**, **PROFILE**), but if you want to predict where it will occur you need the neutrals (**MOSAIC**).

NASA GOLD L1C DAY/NI1 135.6 nm
https://gold.cs.ucf.edu

High Frequency (HF) radio interference has real world consequences



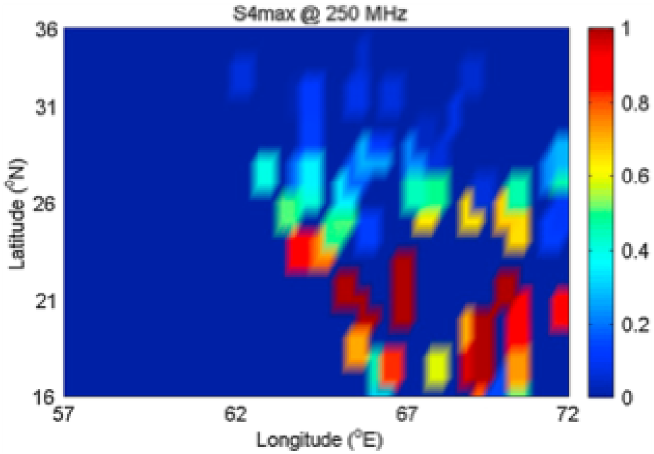


Figure 7. Example of a MIST scintillation map from 16 October 2011 over the Afghanistan theater at 2000 LT. This map shows which areas on the ground will experience scintillation when communicating at 250 MHz with a hypothetical UHF SATCOM satellite in a GEO at 80°E longitude. This map is derived from assimilating SSUSI F18 UV data.

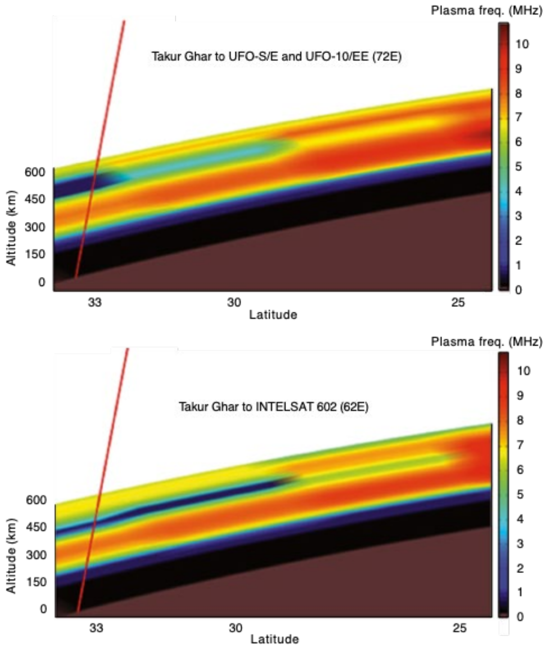
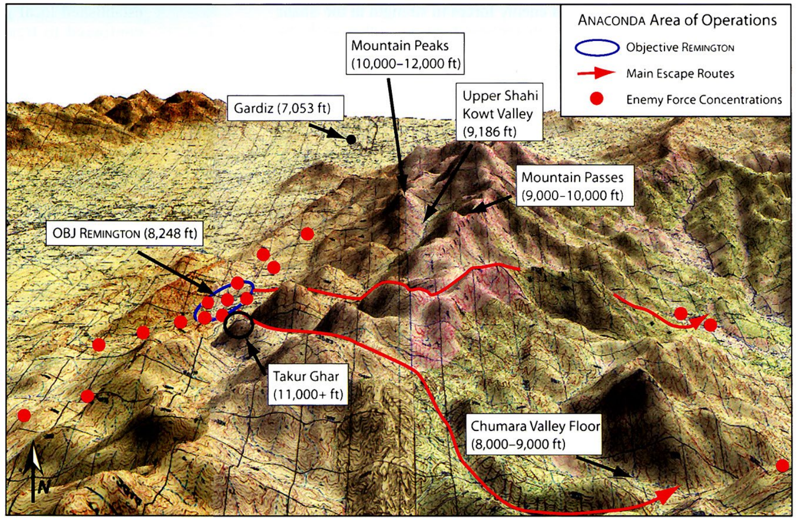


Figure 3. Lines of sight from Takur Ghar to available SATCOM satellites. Both lines of sight (red lines) pass through regions of depleted electron density (blue). The ionosphere is shown above the curved Earth (brown). (Reproduced from Ref. 3.)



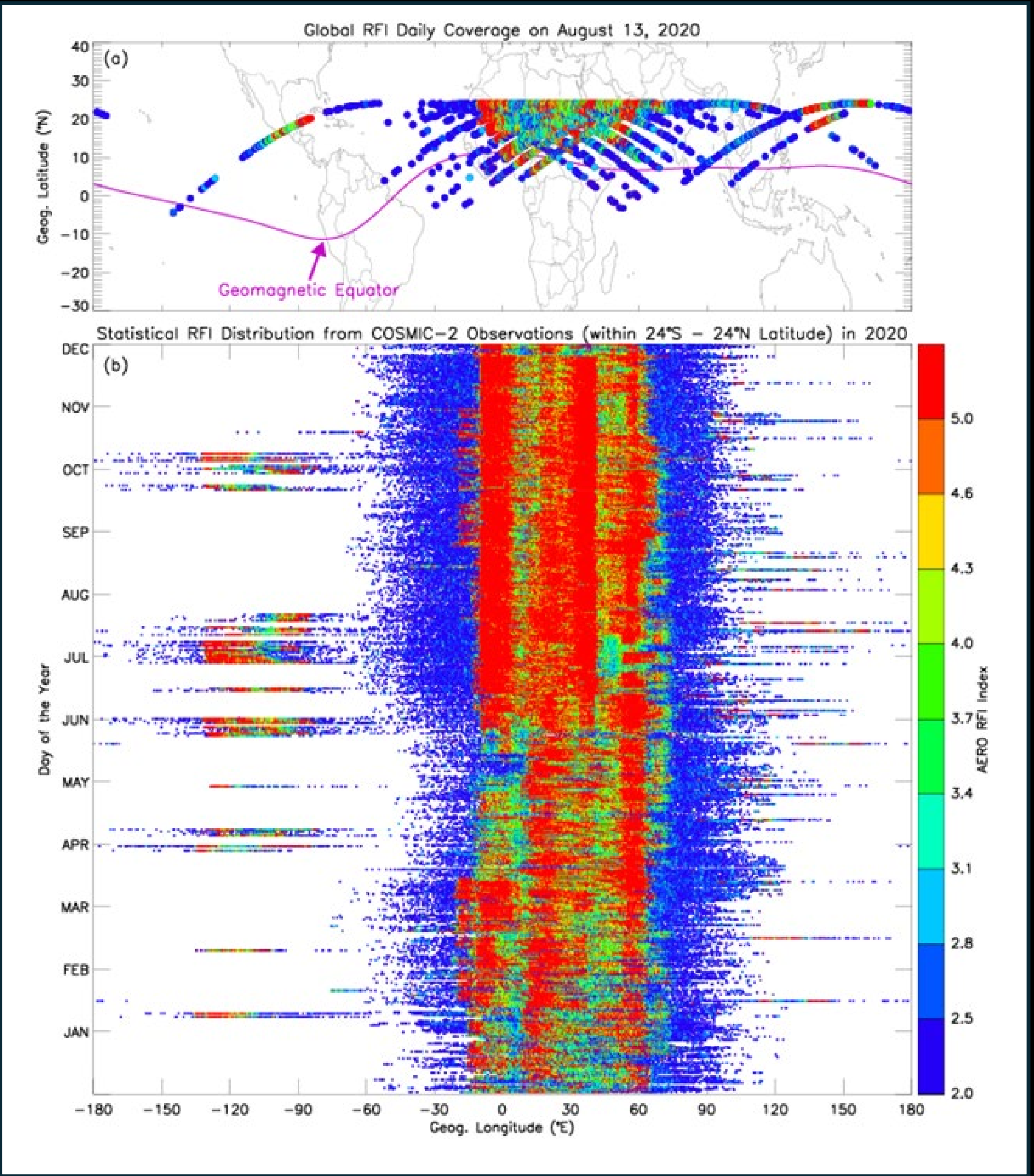
This example, from a study by *Kelly et al.*

(Kelly, M. A., J. M. Comberiate, E. S. Miller, and L. J. Paxton (2014), Progress toward forecasting of space weather effects on UHF SATCOM after Operation Anaconda, Space Weather, 12, 601–611, doi:10.1002/2014SW001081.)

Shows a tragic event during Operation Anaconda where space weather in the form of ionospheric instabilities may have impacted satellite radio communications at UHF frequencies (https://news.agu.org/press-release/space-bubbles-may-have-aided-enemy-in-fatal-afghan-battle/) preventing a rescue team from receiving critical information about enemy force concentrations near their objective, near Takur Ghar in Afghanistan in 2011. The 21-man rescue team was ambushed and three men were killed.

We do not fully understand what creates these ionospheric structures that drive HF interference

Anthropogenic RFI (radiofrequency interference)



This example, from analysis by Endawoke Yizengaw (The Aerospace Corporation, https://www.linkedin.com/pulse/impact-sources-radio-frequency-interference-gnss-signals-ajxyc/) shows a survey of anthropogenic RFI in the GPS bands measured by COSMIC-2 satellites at low latitudes. This represents a combination of accidental RFI that can degrade GPS performance and intentional jamming / spoofing for military purposes or by criminal organizations

GDC has the capability to provide full global maps at high sensitivity to detect GPS spoofing and GPS-band RFI (including the potential for real-time monitoring via the space weather beacon) from the PROFILE instrument.

as well as similar surveys in lower frequency bands from 4 Hz to 20 MHz from the AETHER instrument.

GDC is designed to address our major knowledge gaps, answering scientific questions with real-world applications

Science Mysteries	**Practical applications**
What drives ionospheric turbulence?	How do we predict HF interference?
What drives localized ionospheric currents?	How do we prepare for terrestrial effects of GICs?
What causes thermospheric variability and expansion?	How do we predict orbital drag and satellite lifetimes?
What is the origin of ionospheric ionized patches?	How do we forecast polar auroral clutter?

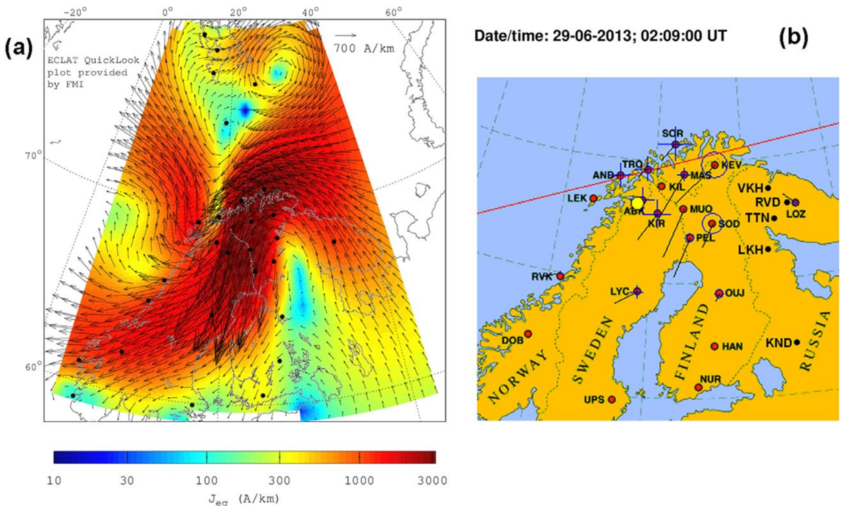
Simulation of the May Superstorm. Does not capture small- and medium-scales we know are important.

US has invested considerable resources making our power grid robust. Other countries may be more vulnerable.

A key variable is localized conductance patches. Conductance is a major unknown; we will be able to accurately calculate it (CAPE)

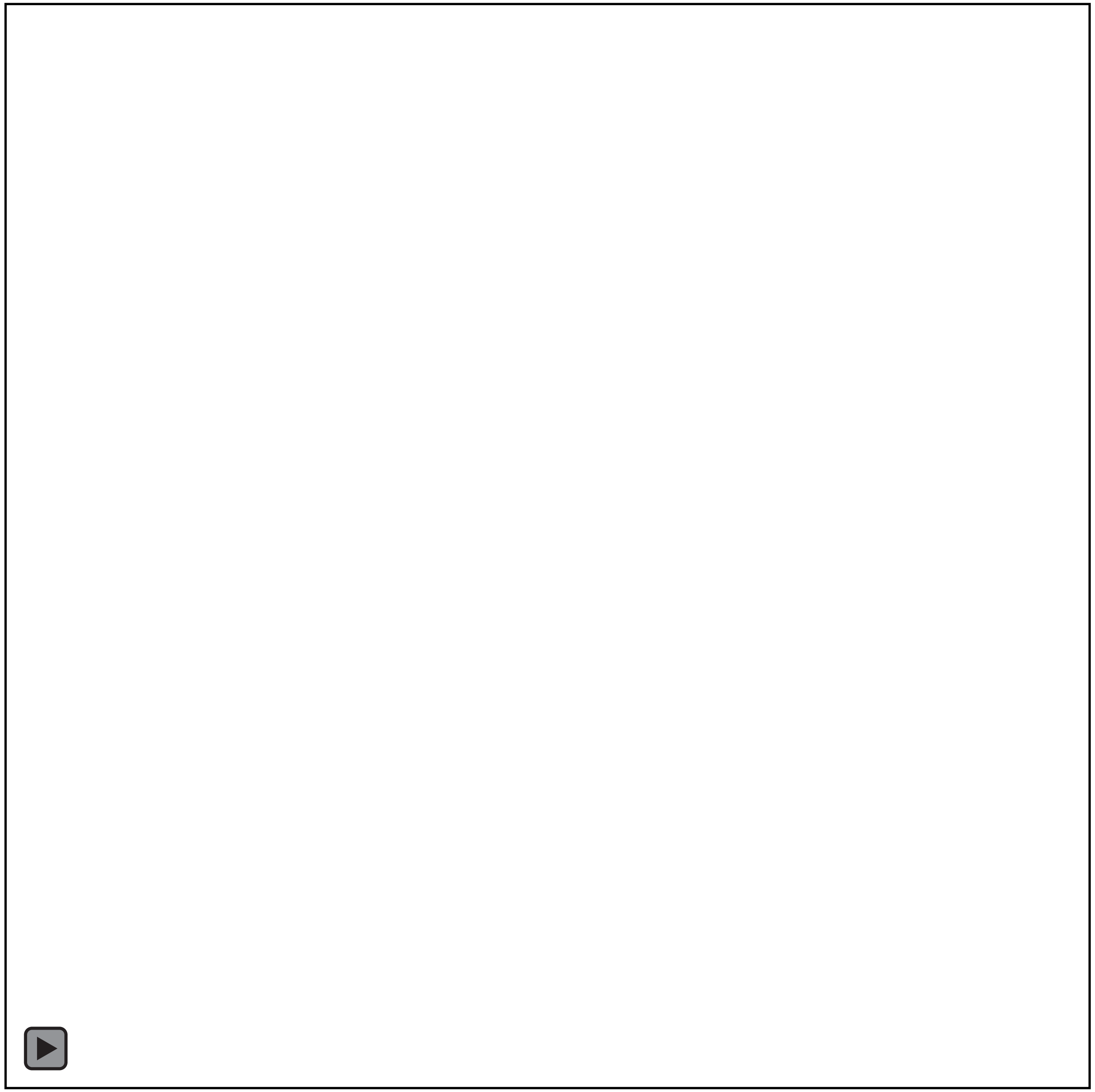
$$\mathbf{J}_\perp = \Sigma_P \mathbf{E} + \Sigma_H \frac{\mathbf{B}}{B} \times \mathbf{E}$$

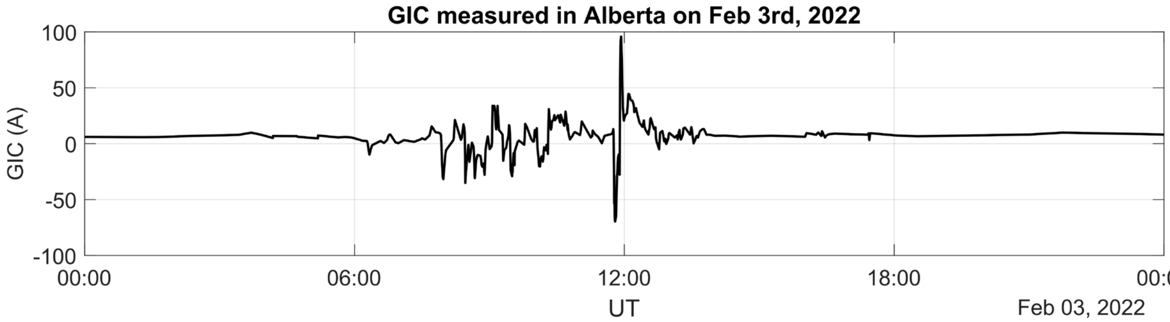
$$\nabla \cdot \mathbf{J}_\perp = \nabla \Sigma_P \cdot \mathbf{E} + \Sigma_P \nabla \cdot \mathbf{E} + (\mathbf{E} \times \nabla \Sigma_H) \cdot \hat{u}$$



Mesoscale phenomena (here omega band) are a newly recognized significant source of GIC.

One of the largest GIC we've measured occurred during the Starlink event





The storm was not particularly large. The GIC was related to an omega band moving overhead.

We often think of GIC as the temporal change in magnetic field ($\partial b/\partial t$) but spatial motion of structures is important too!

GDC will fly over such medium-scale structures with 6 spacecraft, and key instrumentation (CAPE, NEMISIS, TPS, PROFILE)

GDC is designed to address our major knowledge gaps, answering scientific questions with real-world applications

Science Mysteries	**Practical applications**
What drives ionospheric turbulence?	How do we predict HF interference?
What drives localized ionospheric currents?	How do we prepare for terrestrial effects of GICs?
What causes thermospheric variability and expansion?	How do we predict orbital drag and satellite lifetimes?
What is the origin of ionospheric ionized patches?	How do we forecast polar auroral clutter?

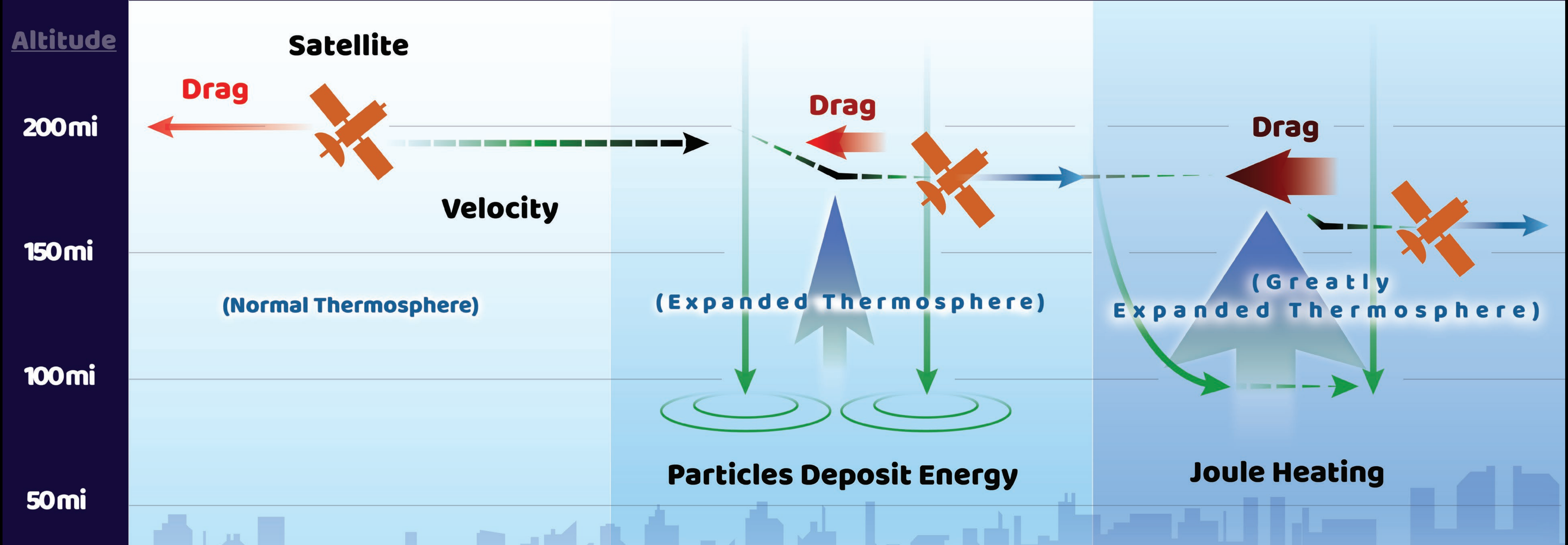
Feb 2022: Loss of 40 Starlink satellites due to a geomagnetic storm, resulting in a projected **$12-24M in financial losses plus launch costs**

GDC provides key observables identified for fore/nowcasting

Thermospheric Expansion

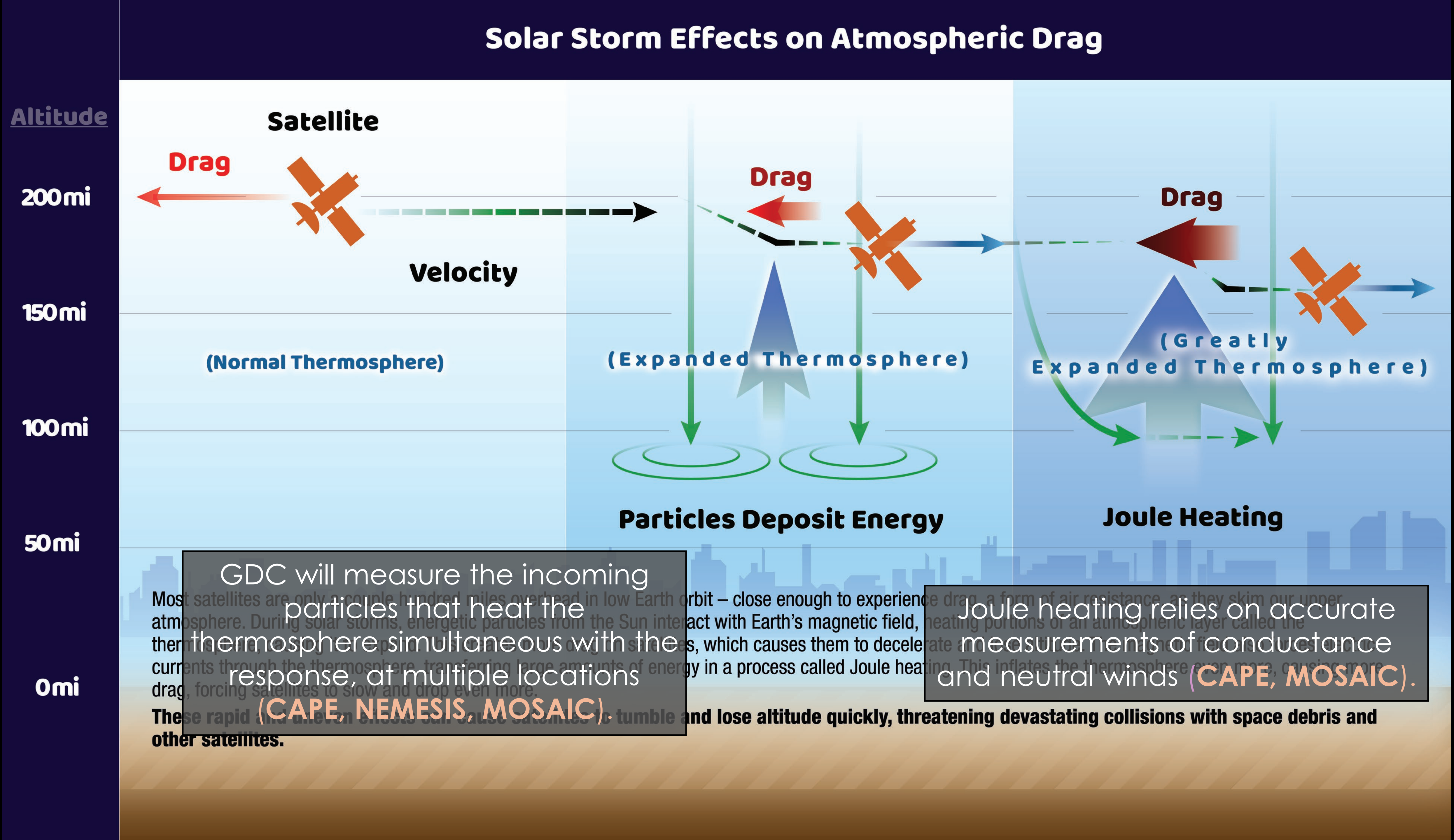
Real-time data from GDC would have clearly shown increase in orbital drag environment, with ~12 hour notice ahead of the launch. Operators could have used this information to delay the launch.

Solar Storm Effects on Atmospheric Drag



Most satellites are only a couple hundred miles overhead in low Earth orbit – close enough to experience drag, a form of air resistance, as they skim our upper atmosphere. During solar storms, energetic particles from the Sun interact with Earth's magnetic field, heating portions of an atmospheric layer called the thermosphere, causing it to expand. This creates more drag on satellites, which causes them to decelerate and lose altitude. The magnetic field also forces electric currents through the thermosphere, transferring large amounts of energy in a process called Joule heating. This inflates the thermosphere even more, causing more drag, forcing satellites to slow and drop even more.

These rapid and uneven effects can cause satellites to tumble and lose altitude quickly, threatening devastating collisions with space debris and other satellites.



Solar Storm Effects on Atmospheric Drag
Altitude
200mi
150mi
100mi
50mi
0mi
Satellite
Drag
Velocity
(Normal Thermosphere)
Drag
(Expanded Thermosphere)
Particles Deposit Energy
Drag
(Greatly Expanded Thermosphere)
Joule Heating
GDC will measure the incoming particles that heat the thermosphere simultaneous with the response, at multiple locations (CAPE, NEMESIS, MOSAIC).
Joule heating relies on accurate measurements of conductance and neutral winds (CAPE, MOSAIC).

Our ability to model the physical parameters that affect orbital drag is woefully inadequate

$$\bar{a}_D = -\frac{1}{2} C_D \frac{A_S}{m_S} \rho v_r \bar{v}_r$$

drag acceleration

drag coefficient

mass density

The drag formula is deceptively simple, but hides a lot of physics

GDC will provide the needed scientific understanding

$$\bar{a}_D = -\frac{1}{2} C_D \frac{A_S}{m_S} \rho v_r \bar{v}_r$$

drag acceleration

Function of composition, density, and temperature, neutral winds

drag coefficient

May be unknown

mass density

Depends on composition

Depends on neutral winds

GDC will measure all relevant parameters (MOSAIC, AETHER, TPS, NEMESIS, CAPE), and their relationships to each other - the basis for an accurate predictive model. We will also measure the drag itself (POD, e.g.)

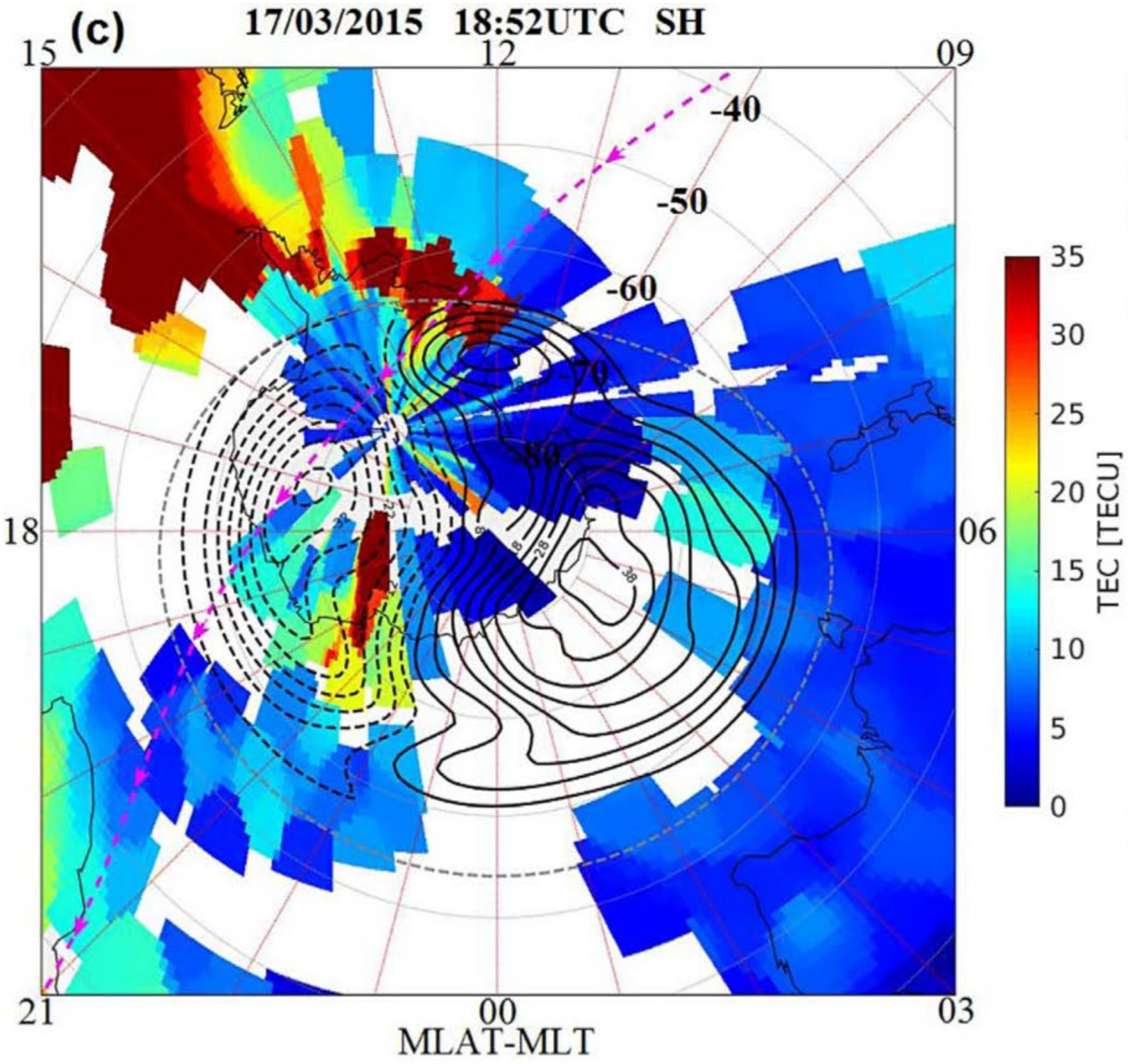
Bursty and patchy energy

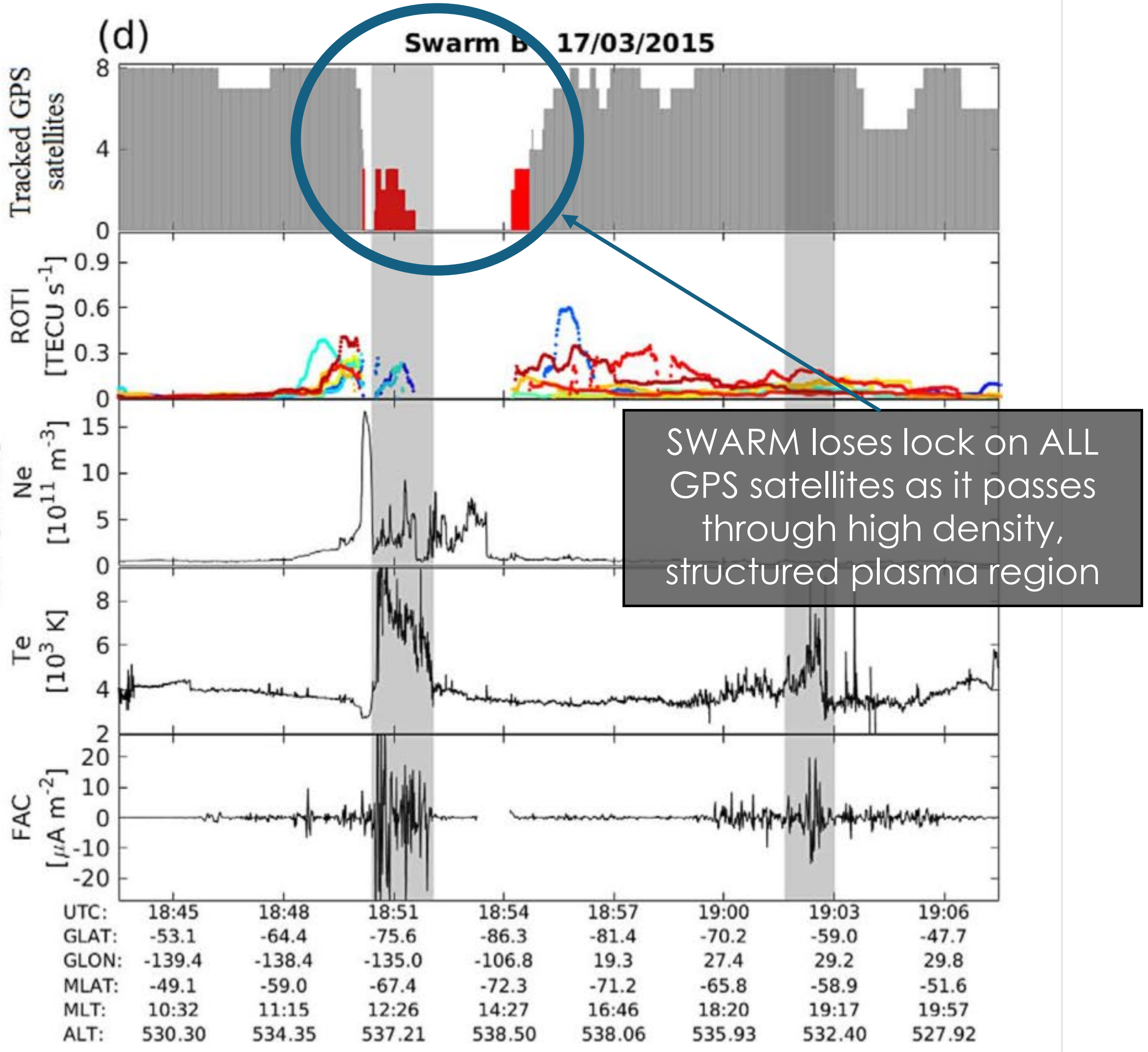
Highly variable GLOBAL neutral atmosphere density / orbital

GDC is designed to address our major knowledge gaps, answering scientific questions with real-world applications

Science Mysteries		**Practical applications**
What drives ionospheric turbulence?	→	How do we predict HF interference?
What drives localized ionospheric currents?	→	How do we prepare for terrestrial effects of GICs?
What causes thermospheric variability and expansion?	→	How do we predict orbital drag and satellite lifetimes?
What is the origin of ionospheric ionized patches?	→	How do we forecast polar auroral clutter?

GDC will help us to learn WHY and HOW dynamically moving and evolving polar cap patch





GDC will help us to learn WHY and HOW dynamically moving and evolving polar cap patch

DEFENCE RESEARCH AND DEVELOPMENT CANADA (DRDC)
RECHERCHE ET DÉVELOPPEMENT POUR LA DÉFENSE CANADA (RDDC)

Space Weather Effects on Radio Propagation: Development of Improved Techniques for the Operation and Analysis of Data for Over-the-Horizon Radar (OTHR)

2023–2024 Mid-Year Report

T.G. Cameron
R.A.D Fiori
Kyle Reiter
Natural Resources Canada

Prepared by:
Canadian Hazards Information Service
Hazards Adaptations Operations Branch
Lands and Minerals Sector
Natural Resources Canada
2617 Anderson Road
Ottawa, Ontario
K1A 0E7

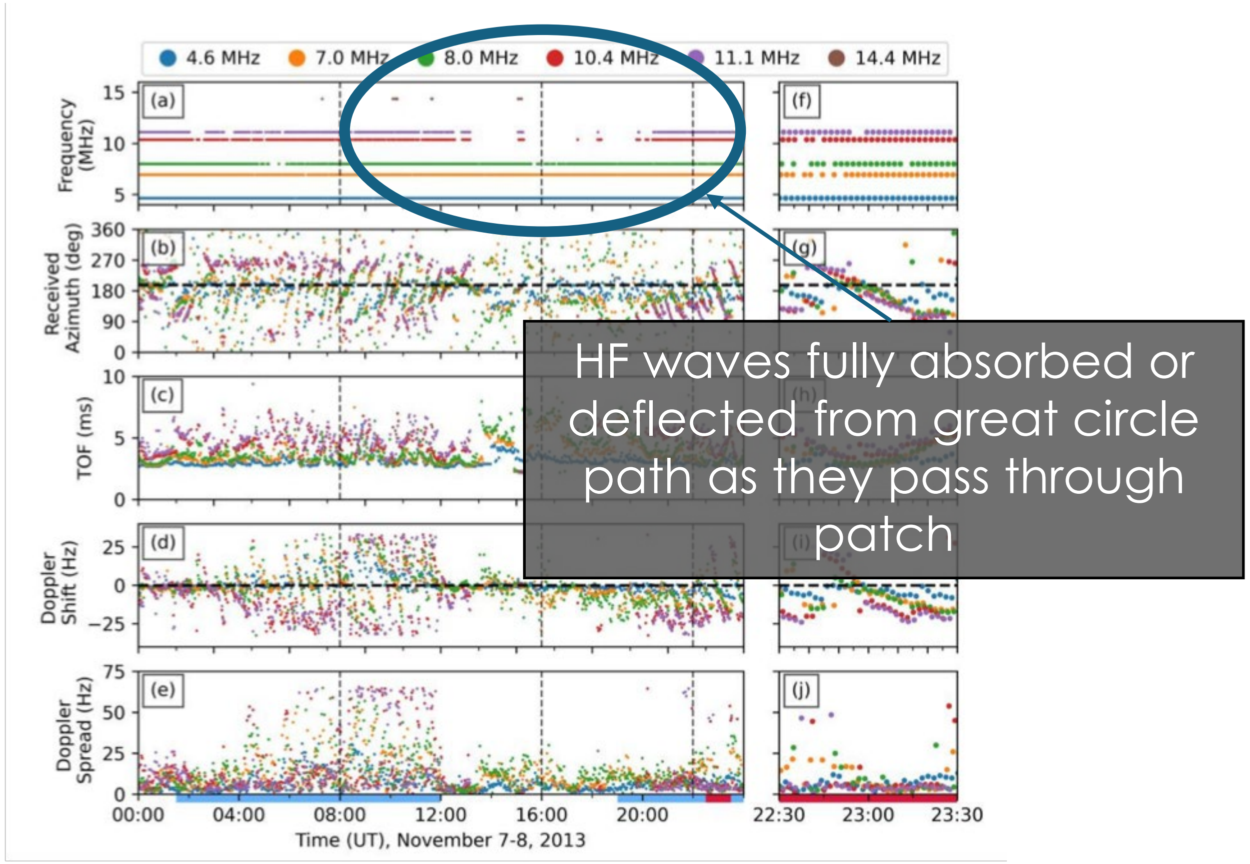
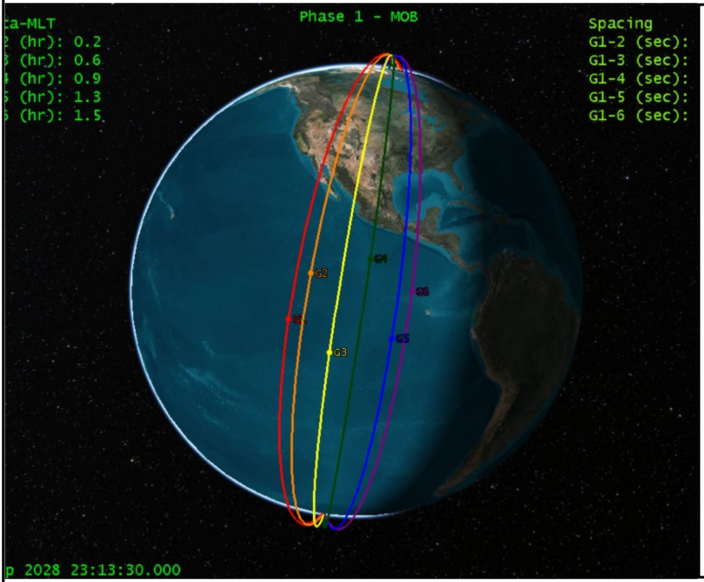
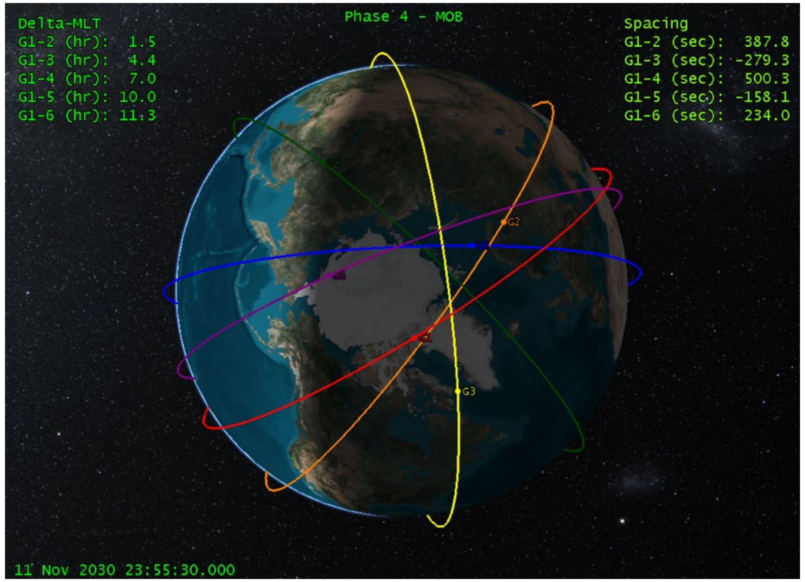


Figure 1.3. Summary plot of HF radio signals for the Qaanaaq to Alert propagation path on 07 Novem Panels (a–e) from the top-down show (a) Periods of HF reception of signals at the prescribed freq azimuthal angle of arrival, (c) time of flight (TOF), (d) Doppler shift, and (e) Doppler spread across the Panels (f–j) show a zoomed in view of the same signal parameters from 22:30–23:30 UT. Frequencies are: 4.6 MHz (blue), 7.0 MHz (orange), 8.0 MHz (green), 10.4 MHz (red), 11.1 MHz (purple), 14.4 MH: Time is indicated by day of month and HH:MM on the bottom x-axis, with the month and year indica lower right. The dashed horizontal lines in (b) and (g) indicate the great circle heading (GCH) fror Qaanaaq. Three vertical dashed lines in panels (a–e) indicate times the orientation of the HF link was the right panel of Figure 1.1. Two periods of negative IMF B_z are indicated with horizontal blue line zoomed-in period shown in panels (f–j) is indicated by a horizontal red line below the x-axis.

Mission Implementation

to systematically study the three scale size (local, regional, global), ove





ation needed to capture energy input and the resulting ITM responses, i

CAPE	Dual ESAs	Precipitating electrons and ions (energy input, ionization)
NEMESIS	Magnetometer	Field-aligned current signatures and Poynting flux
MoSAIC	Quadrupole mass spectrometer with baffles	Ion and neutral composition, density, temperature, and neutral winds
AETHER	Langmuir probe	Plasma density, AC electric field
TPS	RPA/IDM	Thermal ion velocity
PROFILE	GNSS RO	HmF2, NmF2, TEC

operate rapidly (typically <1s), allowing high temporal and spatial resolution. Also include reflec

Wrap up

- Although we are data-starved, measurements alone are not sufficient to understand the complex ITM system-of-systems. We require:
  - A carefully designed multipoint mission to address the known science gaps in the ITM system (GDC);
  - With the right instrumentation to measure inputs and the ITM response (GDC);
  - Coupled to a state-of-the-art theory and modeling program (GDC).
- GDC promises to answer longstanding science questions of great societal and strategic impact:
  - Providing SSA on the atmospheric drag environment, and understanding the science behind rapid changes.
  - Provides the context for differentiating between anthropogenic and natural signatures.
  - Understanding the triggers, growth, and evolution of ionospheric density bubbles that disrupt GPS and comms.

Instrument slides

GDC Mission Goals	GDC Baseline Science Objectives
GDC Goal 1: (high latitude forcing) *Understand how the high-latitude ionosphere-thermosphere system responds to variable solar wind/magnetosphere forcing.*	**Objective 1.1 (High-latitude neutral wind formation and evolution)** *Determine how high-latitude plasma motion, particle precipitation, and electromagnetic energy inputs drive thermospheric neutral winds*
	Objective 1.2 (High-latitude plasma density structure formation) *Determine how coherent plasma density structures arise and evolve in response to high-latitude plasma motion, particle precipitation, and electromagnetic energy inputs.*
	Objective 1.3 (High-latitude neutral density structure formation) *Determine how high-latitude magnetospheric energy inputs, plasma motion, and neutral dynamics drive the generation and evolution of high-latitude neutral density structures.*
GDC Goal 2: (global processes) *Understand how internal processes in the global ionosphere-thermosphere system redistribute mass, momentum, and energy.*	**Objective 2.1 (Pathways for magnetospheric driving of low- and mid-latitude electrodynamics)** *Determine the efficiency of electromagnetic drivers and ion-neutral coupling in driving plasma density variations at mid- and low latitudes.*
	Objective 2.2 (Formation and evolution of propagating atmospheric disturbances) *Identify the processes that create and dissipate horizontally propagating ionosphere and thermosphere structures.*
	Objective 2.3 (Drivers of low- and mid-latitude chemical composition changes) *Determine the connections between winds, temperature, and major neutral species density variations at mid and low latitudes.*
	Objective 2.4 (Hemispheric asymmetries) *Determine how seasonal variations and asymmetries in Earth's magnetic field and magnetospheric input affect the ionosphere-thermosphere system..*

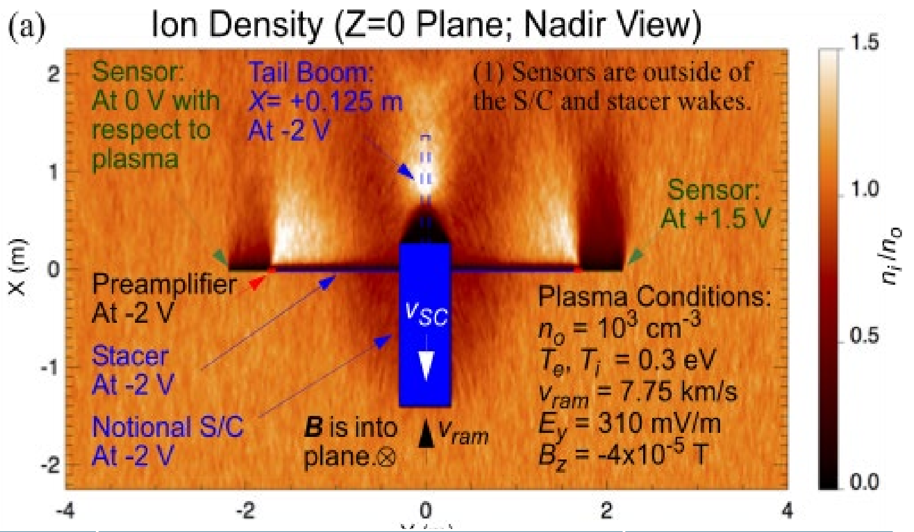
AETHER Investigation PI: L Andersson

AETHER consists of two segmented cylinder sensors mounted on two ~3 m Sabers.

To meet measurement range and accuracy the instrument combines a **Langmuir probe** with a **Thermal Noise Receiver**

Heritage built from LASP/CU and SSL/UCB

Modeling to ensure good placement of the sensors on a nominal spacecraft



Physical Quantity	Symbol	Range	Target Accuracy *	Target Precision	Cadence
Thermal plasma density	N_e	$10^2 - 10^7$ cm^{-3}	+/- 25 cm^{-3} or 2%	+/- 25 cm^{-3} or 2%	0.5 s
Thermal electron temperature	T_e	10^2 -10^5 K	+/- 100 K or 10%	>50K or 5%	0.5 s
Density fluctuations	δN_e	$10^2 - 10^7$ cm^{-3}	N/A	1%	256 Sps
E-field fluctuations	δE	+/- 2.5 V/m	N/A	+/-0.1 mV/m	256 Sps
Composition (assumes O^+/H^+ plasma)	C_{H+}	0-100 %	+-1% with <10% H+	Only when lower hybrid line in δE is available	0.5 s

CAPE – Instrument Overview - PI Dan Gershman (GSFC)

CAPE measures charged-particle energy inputs into the upper atmosphere and traces their impacts on global dynamics

CAPE is comprised of two electrostatic analyzer sensors that measure downgoing and upgoing electrons (CAPE-e) and downgoing ions (CAPE-i)

CAPE Goals

- Determine how global and regional structure in auroral precipitation drives high latitude ion and neutral structure and dynamics.
- Determine the dominant pathways through which high latitude particle energy forcing leads to (global) iono-spheric-thermospheric dynamics.

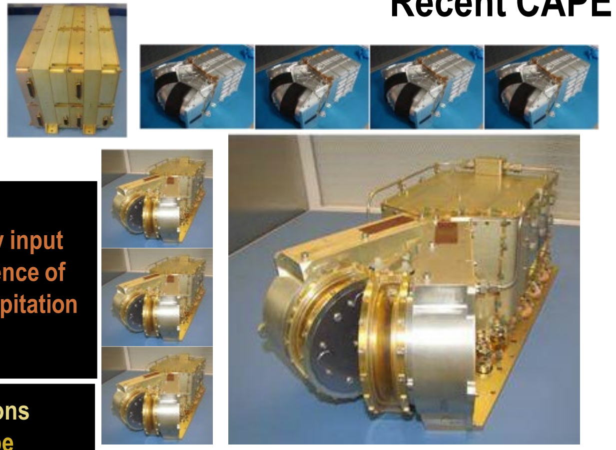
Downgoing Electrons supply energy input to the upper atmosphere

Downgoing Ions deposit significant energy input near dusk and in the absence of meaningful electron precipitation

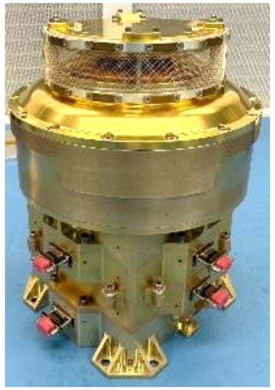
Upgoing Secondary Electrons encode the physics of electron transport in the ionosphere and thermosphere

Upgoing Reflected Electrons contain fluxes that must be measured to accurately quantify net energy input

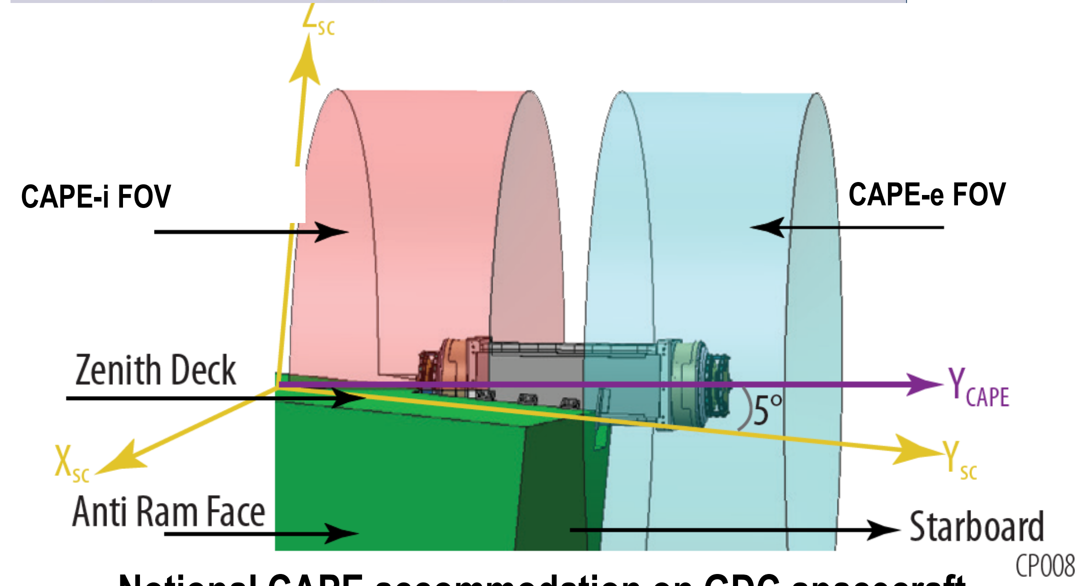
Recent CAPE heritage



MMS/Fast Plasma Investigation (FPI)



HERMES/Electron Electrostatic Analyzer (EEA)



Notional CAPE accommodation on GDC spacecraft

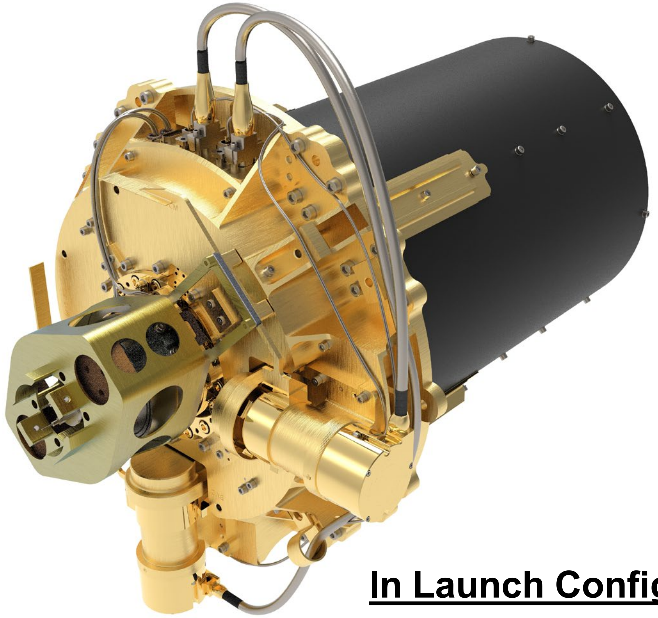
CAPE measurement capabilities

Parameter	Electrons	Ions
Energy Range (eV)	10 – 30000	10 – 50000
Energy Resolution (eV/eV)	0.18	0.18
Magnetic Pitch-Angle Sampling (°)	0-180	0-90
Magnetic Pitch-Angle Resolution (°)	8.2	8.2
Time Resolution (s)	0.05	0.05
Differential Energy Flux Range ($cm^{-2}\ sr^{-1}\ s^{-1}\ eVeV^{-1}$)	$1x10^{6}$ – $1x10^{10}$	$1x10^{5}$ – $1x10^{9}$

Modular Spectrometer for Atmosphere and Ionosphere Characterization

Investigation Goals and Capabilities

- MoSAIC provides multi-point, concurrent high cadence measurements of neutral and ionized gas density, temperature, composition, and motion.
- MoSAIC utilizes a dual-mode Quadrupole Mass Analyzer combined for neutral and ion composition analyses, combined with a Baffle Scanning System for temperature and wind/drift measurements.
- MoSAIC targets science questions and replicates techniques deployed on previous Earth and planetary aeronomy missions (Atmospheric and Dynamic Explorers, Pioneer-Venus, MAVEN).



PI: M. Benna

In Launch Configuration

instrument Specifics

- **Mass:** 7.6 kg (CBE)
- **Envelope:** 26.5 × 26.5 × 42 cm^3
- **Power:** 25.5 W average (CBE)
- **Data Rate:** 18.4 kbps (CBE)
- **Pointing:** Within 2 deg from Ram
- **Measurement Cadence:** 1- 2 seconds for all parameters (Adjustable in flight)

Institutional Roles

- **UMBC:** Science coordination
- **NASA Goddard:** PM, SE, Elec. & Mech SE, FSW, GS
- **Genesis Engineering:** Elec. Manuf., I&T
- **AMU Engineering:** Sensor and Baffle Systems Manuf.,
- **Science Partners:**

NEMISIS

NEAR EARTH MAGNETOMETER INSTRUMENT IN A SMALL INTEGRATED SYSTEM

Mark Moldwin, UM PI;
Eftyhia Zesta NASA-GSFC D-PI

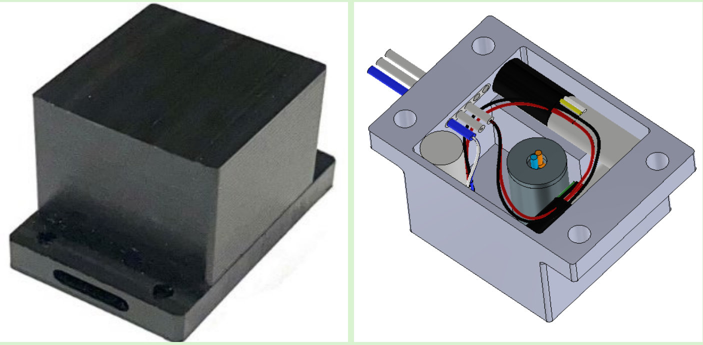
Science and Instrument Design

NEMISIS addresses GDC's Goal 1 of understanding how the ionosphere-thermosphere (I-T) responds to magnetospheric forcing. NEMISIS measures a primary magnetospheric energy input (currents and Poynting flux) through observations of magnetic field variations.

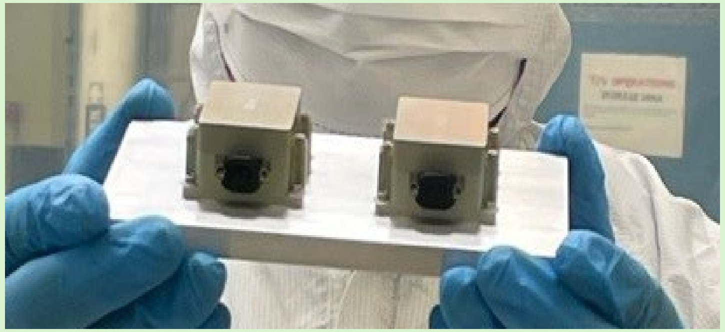
NEMISIS consists of two body mounted magneto-inductive low-resource sensors with a miniature fluxgate magnetometer on the end of a short boom to enable magnetic noise identification and cancellation using modern machine learning algorithms. These algorithms enable high-quality magnetic field observations using a short boom and magnetically noisy spacecraft.

HERMES-NEMISIS FLIGHT UNIT

Flight Fluxgate



Flight PNIs



Regoli et al. (2018, 2020); Moldwin et al., 2022; Strabel et al (2022)

Thermal Plasma Sensor for GDC

To address science questions related to ion-neutral coupling, we need the physical plasma quantities measured by TPS: 3-D ion velocity, T_i, N_i, and composition.

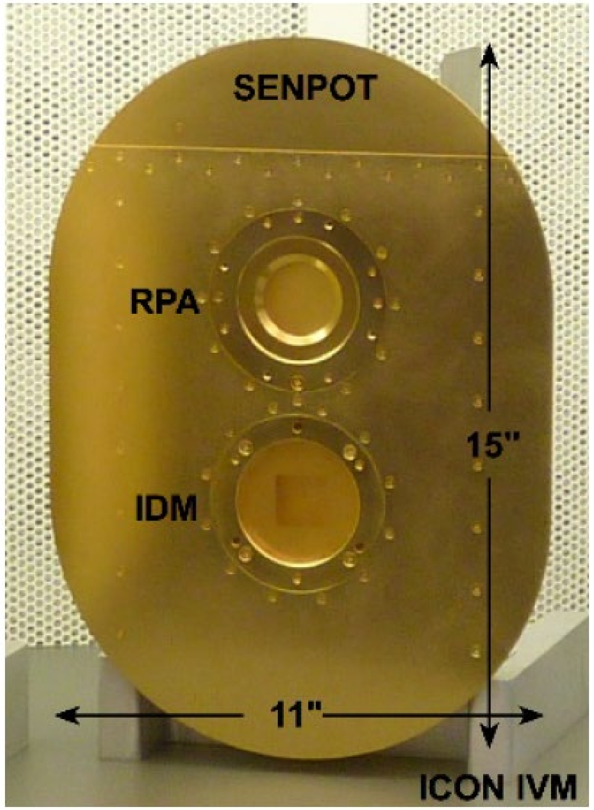
- **Retarding Potential Analyzer (RPA):**
  - Measures ram ion flux (current) as a function of retarding voltage
  - I-V curve produced 1/sec
  - Curve analyzed to infer ram ion velocity, temperature, composition and density
- **Ion Drift Meter (IDM):**
  - Measures ram ion flux on segmented (four sectors) collector
  - Ion arrival angle proportional to ratio of currents on adjacent collector halves
  - Current collected 16/sec
  - Ion drift in two directions perpendicular to ram direction produced at 1 Hz
- **SenPot (Sensor Potential)**
  - Measures offset between the local plasma potential and floating potential of SenPot plate - applied to sensor ground

Ion drifts converted to drifts parallel and perpendicular to magnetic field at 1 Hz

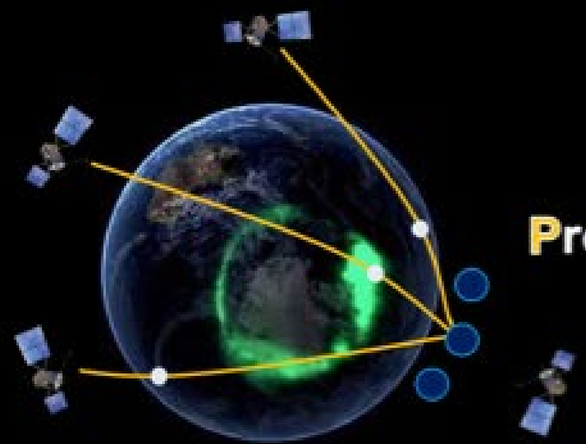
SQ 1. How does the ion-neutral velocity difference depend on the local plasma drift, neutral wind, and plasma density?

SQ 2: How are plasma structures at sub-auroral latitudes and in the polar cap related to the convective motion of the plasma with respect to the Sun?

SQ 3: How does the local plasma density at sub auroral latitudes depend the plasma drifts perpendicular and parallel to the magnetic field as a function of location and storm time epoch?



PI: P. Anderson

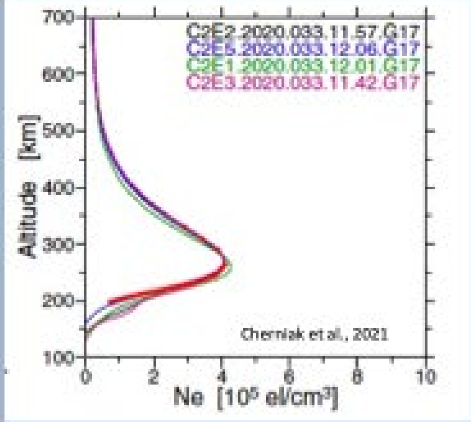


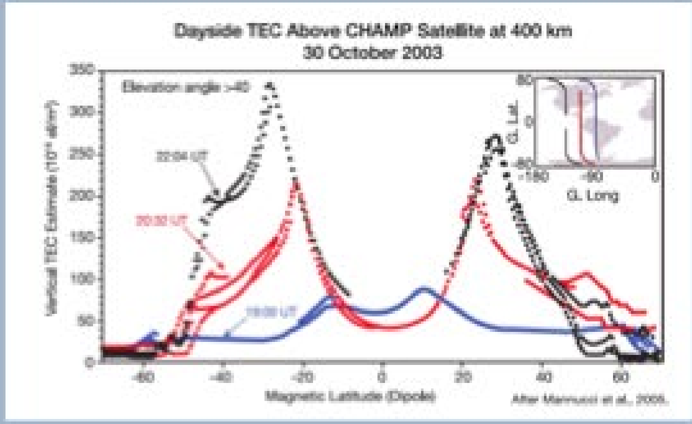
PROFILE

Probe for **R**adio **O**ccultation o**F** **I**onospheric **L**ay**E**rs

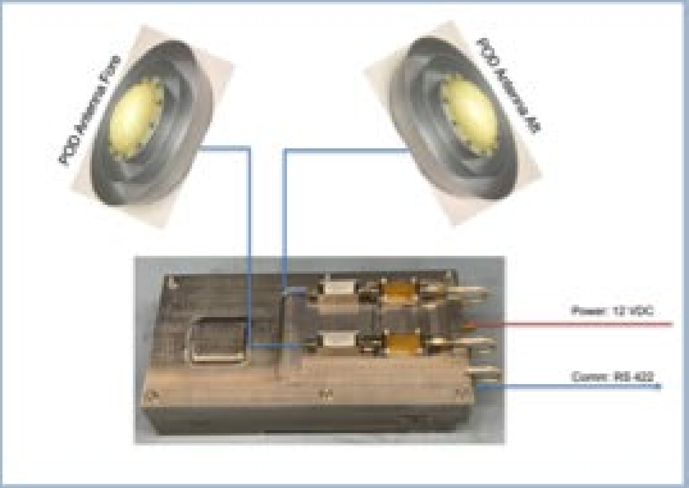
PI: O. Verkhoglyadova

Team: Olga Verkhoglyadova, Garth Franklin, Chad Galley, Anthony Mannucci, Xing Meng, Panagiotis Vergados (JPL) and Guiping Liu (GSFC)





Remote sensing measurements of ionospheric electron content



- antenna build to print from Cosmic II
- track GPS (L1CA & L2C), and Glonass or Galileo
- 1 sec radio occultation with topside TEC observations
- on board advanced navigation software
- scintillation S4 index at 50 Hz sampling rate

The Cion is a low cost, low power, high performance RO GNSS receiver for NASA and NOAA Class D missions

GDC
GEOSPACE DYNAMICS CONSTELLATION
Exploring Our Connected Atmosphere

Ionospheric RO products

- 1D vertical N_e profiles below a SC => <u>density maximum</u> within the altitude range: ~100 km-350+ km (NmF2 and HmF2 if below the SC)
- top-side TEC
- Scintillation S4 index (near-real time space weather product)

Jet Propulsion Laboratory, California Institute of Technology

Current GDC Expected Measurement Performance

GDC Expected Instrument Performance (12/05/2023)							Selected GDC Instruments (P-> prime, S -> support)					
Reference Number		**Physical Parameter**	**Dynamic Range**	**Accuracy**	**Precision**	**Sample Rate**	**MoSAIC**	**CAPE**	**AETHER**	**NEMISIS**	**TPS**	**PROFILE**
1	a	**Thermal ion velocity**, in-track (horizontal)	± 5000 m/s	18 m/s	15 m/s	1 / sec	S				P	
	b	**Thermal ion velocity**, cross-track (horizontal, verticall	± 5000 m/s	18 m/s	15 m/s		S				P	
2		**Thermal plasma density****	10^2 - 10^7 cm^{-3}	± 25 cm^{-3} or 2%	1% or 10 cm^{-3}	2 / sec	S		P		S	
3		**Thermal ion temperature**	100 - 10,000 K	2%	2%	1 / 2 sec*	P				S	
4		**Thermal ion composition**	1 - 150 amu	1%	1%	1 / sec	P				S	
5	a	**Neutral wind**, horizontal (in-track)	± 4200 m/s	4.5 m/s	4.5 m/s	1 / 2 sec*	P					
	b	**Neutral wind**, horizontal (cross-track)	± 4200 m/s	4.5 m/s	4.5 m/s		P					
	c	**Neutral wind**, vertical (cross-track)	± 3000 m/s	3.5 m/s	3.5 m/s		P					
6		**Neutral gas number density**	10^7 - 7 x 10^{12} cm^{-3}	10%	1%		P					
7		**Neutral gas temperature**	100 - 10,000 K	2%	2%		P					
8		**Neutral gas composition**	1 - 150 amu	1%	1%		P					
9	a	**Auroral electrons energy / pitch angle distribution** — Down	**Energy range**; 0.01 - 30 keV, **dE/E** <11%, **Pitch Angle resolution** 8.18°, **PA range** 0°-90° **Energy flux range** 0.1 - 500 mW/m^2 @ 15 % **precision**, 10% **accuracy**, **dE flux** 1x10^6 - 1x10^{10} cm^{-2} sr^{-1} s^{-1} eV/eV			1 / sec		P				
	b	Up	**Energy range**; 0.01 - 30 keV, **dE/E** <11%, **Pitch Angle resolution** 8.18°, **PA range** 90°-180° **Energy flux range** 0.1 - 500 mW/m^2 @ 15 % **precision**, 10% **accuracy**, **dE flux** 1x10^6 - 1x10^{10} cm^{-2} sr^{-1} s^{-1} eV/eV					P				
10	a	**Auroral ions energy / pitch angle distribution** — Down	**Energy range**; 0.025 - 40 keV, **dE/E** < 17%, **Pitch Angle resolution** 8.18°, **PA range** 0°-90° **Energy flux range** 0.1 - 100 mW/m^2 @ 7 % **precision**, 10% **accuracy**, **dE flux** 1.4x10^5 - 1.4x10^9 cm^{-2} sr^{-1} s^{-1} eV/eV					P				
	b	Up	*Not measured by AETHER, CAPE, MoSAIC*									
11	a	**Cross-track AC electric field > 4 Hz**	± 2.5 V/m† (> 4 Hz)	N/A	± 0.1 mV/m	256 / sec†			P			
	b	**Small scale thermal plasma density (0.1-25 km)**	10^2 - 10^7 cm^{-3}	N.A	1%				P			
12		**Thermal electron temperature**	100 - 10000 K	± 100 K or 10%	> 50 K or 5%	2 / sec			P			
13		**Magnetic field (DC field, vector)**	± 64,000 nT	2 nT	0.5 nT	10 / sec				P		
14	a	**HmF2**	150-350 km **(TBR)**	25 km **(TBR)**	10 km **(TBR)**	1 per occultation						P
	b	**NmF2**	10^5 - 5x10^6 cm^{-3} **(TBR)**	10% **(TBR)**	10% **(TBR)**							P

*MoSAIC measures both ions and neutrals in a 2-second cycle. If another measurement covered the ions, then MoSAIC could measure neutrals at 1 s cadence

**Thermal plasma density is measured by both AETHER and MoSAIC -- the values quoted here are combined performance

†AETHER measures electric field spatial structure along a single cross-track axis with a roll-on frequency of 4 Hz (corresponding to about 4 km spatial structure). MoSAIC measures at scales larger than 32 km.