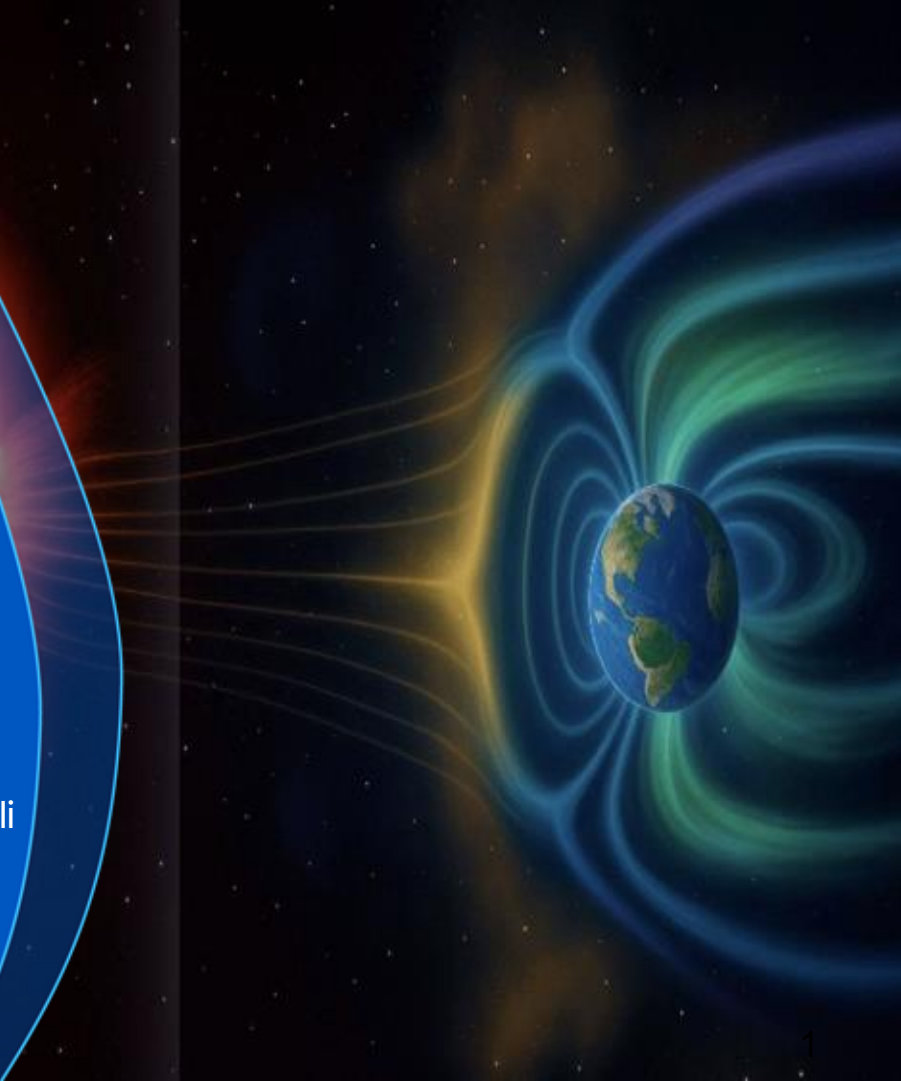
June 22nd, 2026

Introduction to CEDAR 2026 Grand Challenge: Cross-Scale Coupling and Variability in the Upper Atmosphere and Ionosphere

Pathways to Improved Space Weather Predictability

Presenters: Liying Qian, Yaga Richter, Soudeh Kamali
Grand Challenge Co-Conveners: Hanli Liu, Federico Gasperini, Tomoko Matsuo, Anastasia Newheart, Hui Shao, Xian Lu, and Koki Chau.



Overview

- Scientific motivation
- NSF NCAR ESPAT Initiative: an introduction for the CEDAR community
- Systems and team-based approaches

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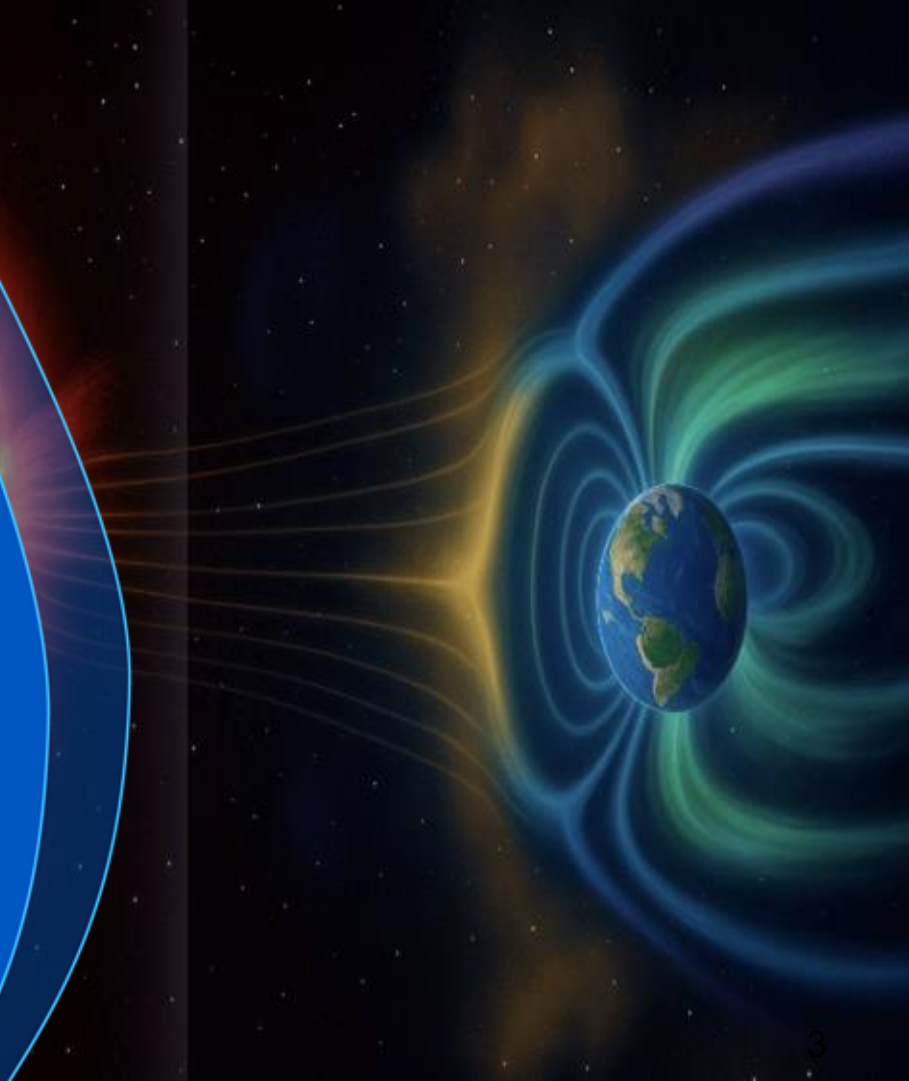
CEDAR Grand Challenge 2026

Scientific Motivation

Presenter: Liying Qian
Contributor: Hanli Liu



Building on advances in understanding "what are the effects?" to address the next question: "what controls their predictability?"

- **Building on Momentum of Recent Grand Challenges:**
  - Terrestrial Weather Impacts (Completed)
  - Gravity Wave Coupling (3rd year)
  - Polar Patch (2nd year)
- **Leveraging advances in observations, models, theory, and data analysis from the CEDAR and broader heliophysics communities to address the next frontier: understanding the sources and limits of predictability.**
- **Adopting systems and team-science approaches through the CEDAR–ESPAT partnership to tackle nonlinear geospace variability and predictability.**

The Ionosphere and Thermosphere (IT) System Functioning as an Active Transformer

- **An externally Driven System:**
  - From Above: solar-magnetospheric forcing (solar irradiance, Joule heating, particle precipitation).
  - From Below: Multi-scale waves (Gravity waves, Tides, Planetary waves).
- **The Transformation**: The IT system transforms energy and momentum inputs into ionospheric and thermospheric variability through coupled photochemical, electrodynamic, dynamical, and radiative pathways.
- **Key Issues:**
  - still need to more accurately represent the energy and momentum input from both above and below.
  - still lack a system-level understanding of the "transformation efficiency": how much and how does energy and momentum becomes IT variability?

Science Question 1: Multi-Scale Drivers of IT Variability and Predictability

- **Forcing from Above (Sun-Magnetosphere)**
  - Highly structured and variable, with mesoscale electrodynamic forcing embedded within larger-scale convection.
  - Incomplete characterization and representation of high-latitude forcing in observations and models.
- **Forcing from Below (Lower Atmosphere)**
  - Gravity waves, tides, planetary waves, and secondary waves interact across a broad range of scales.
  - Many important processes remain unresolved or inadequately represented in global models.

Goal: Identify which drivers, processes, and scales contribute most to IT variability and determine the limits of predictability.

Science Question 2: Background State and Cross-Scale Coupling Pathways

- **Background State**
  - Temperature, composition, neutral winds, plasma density, and conductivity establish the state upon which external forcing acts.
  - Variations associated with local time, season, solar cycle phase, and lower-atmosphere forcing can strongly influence IT responses.
- **Cross-Scale Coupling Pathways**
  - Energy and momentum are transmitted through cross-scale dynamical and electrodynamical processes, driving responses across regions, scales, and times.

Goal: Determine how background conditions and coupling pathways control the magnitude, timing, structure, and predictability of IT responses to external forcing.

Science Question 3: Predictability and Uncertainty

- **Integrated Observations and Models**
  - Combine observations, physics-based models, and data assimilation to characterize the evolving state of the IT system.
  - Quantify sources of uncertainty in drivers, background conditions, and system response.
- **New Approaches**
  - Use AI/ML and other advanced analysis techniques to identify relationships, hidden patterns, and missing physics.
  - Develop hybrid approaches that leverage the strengths of both physical understanding and data-driven methods.

Goal: Determine the sources and limits of predictability and improve prediction of IT variability and space weather impacts.

Why CEDAR? Why Now?

- **Scientific Opportunity**
  - Predictability has emerged as a central challenge in heliophysics and geospace science.
- **Community Strength**
  - The CEDAR community brings together observations, models, theory, data assimilation, and AI/ML capabilities spanning the coupled IT system.
- **Strategic Opportunity**
  - Through partnerships such as ESPAT, the CEDAR community has an opportunity to lead efforts to understand and improve geospace predictability.

The CEDAR–ESPAT Partnership

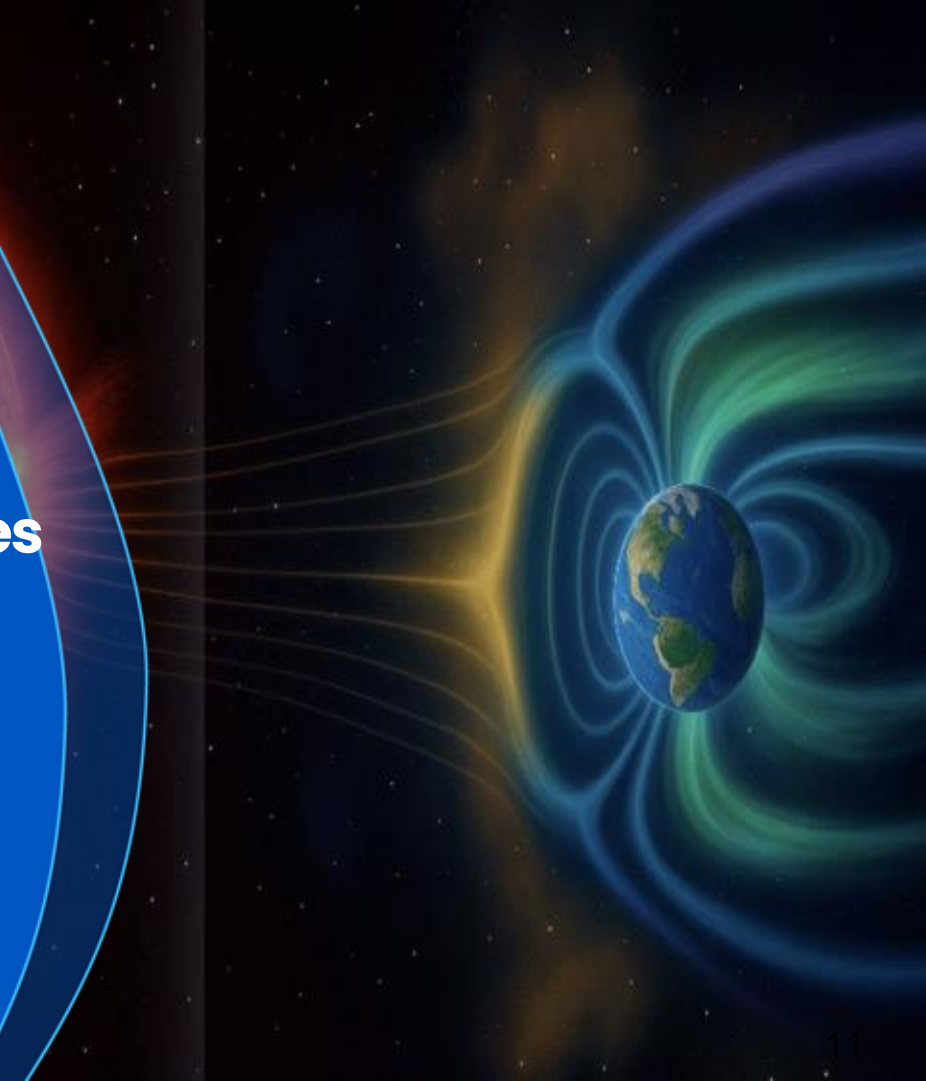
Connecting
Geospace Predictability
with
Earth System Predictability

June 22nd, 2026

NSF NCAR Earth System Predictability Across Timescales (ESPAT) Initiative

An introduction for the CEDAR Community

Presenter: Yaga Richter

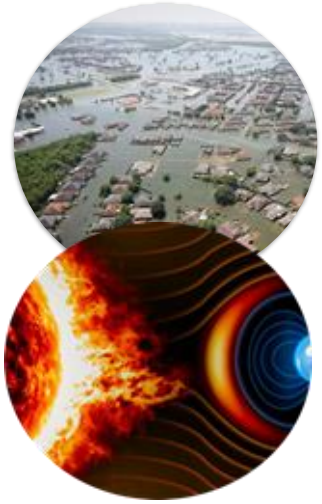


ESPAT: Overview

Every country, region, and community is progressively more impacted by effects of **extreme weather including space weather**

Growing societal dependence on satellite communication makes space weather forecasting essential for mitigating disruptions to navigation, communication, and power systems that underpin critical infrastructure

There is an **urgent need for more research** to advance Earth system predictability to empower communities to become more resilient



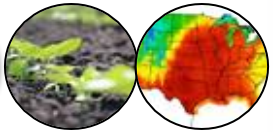
NSF NCAR initiative focused on **deeper understanding of the Earth system through coordinated and collaborative research** integrated across disciplines and timescales to enhance societal **resilience**

Initial ESPAT Focus Areas

Selected based on current NCAR's strengths as well as societal need

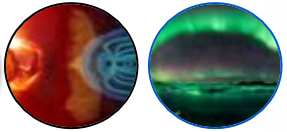
FOCUS AREAS

- Subseasonal to seasonal predictability

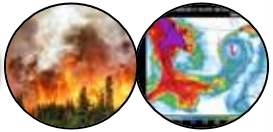


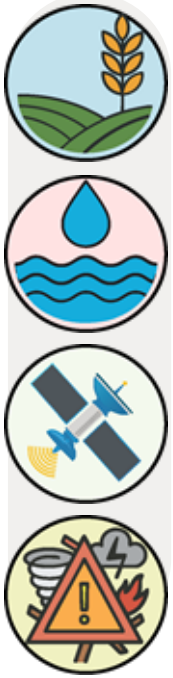
- Hydrological Predictability

- Space Weather



- Wildfires & Cloud-Aerosol Interactions, Urban





Resilience Drivers

Concrete plans have been made for moving these forward by bringing teams of staff across center together

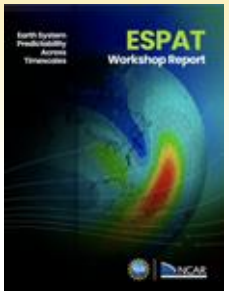
ESPAT To-date

The science needed to transform Earth system predictability is that of intersections and connectability: in science & to societal needs

Workshops

- **Feb 2024:** Internal NCAR strengths interests
- **Apr 2024:** Community Workshop: Grand challenges & Key Science Questions
- **Sep 2024:** Mini Wkshp Space Weather
- Oct 2024: Launched S2S Focus Area
- Apr 2025: Kicked-off S2S Working Groups
- **June 2025:** 1st S2S Workshop
- **June 2026:** CEDAR-ESPAT SWx GC
- August 2026: 2nd S2S Workshop

Publications:



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AMS American Meteorological Society

ESPAT for a Resilient Society: A Research Community Perspective

BAMS Article In Early Release

AMS American Meteorological Society

S2S Land-atmosphere Interactions

BAMS MEETING SUMMARY

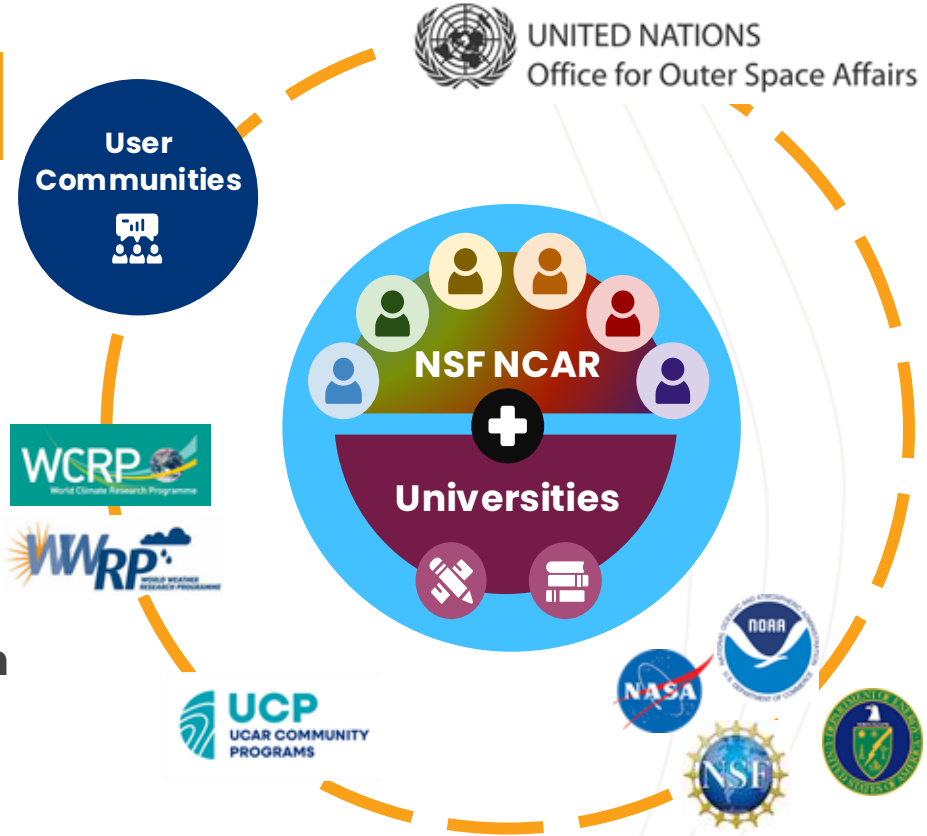
GRAND CHALLENGES

- Interaction between various components of the Earth system
- Interactions between spatial and time scales
- Interaction with external forcing

ESPAT Approach

Interdisciplinary Team Based Approach

- Integrates expertise across NSF NCAR, University Community **into focused Working Groups**
- Fosters cross-agency & cross UCAR coordination (where applicable)
- Integrates **modeling, observations, data assimilation, ML/AI**
- Aims to employ **convergence research** to connect across geoscience disciplines and societal needs



Convergence research

Convergence research is a means of solving vexing research problems, especially those focusing on societal needs. It has two primary characteristics:

- **It is driven by a specific and compelling problem,** whether that problem arises from deep scientific questions or pressing societal needs.
- **It shows deep integration across disciplines.** Convergence research intentionally brings together intellectually diverse researchers to develop effective ways of communicating across disciplines.

Collaboration between ESPAT and Convergence Science Research program

- Develop and initiate a pilot research effort with select users to understand their decision contexts and corresponding predictive information uses, interpretations, and needs over time; and
- Facilitate convergence among space weather scientists, social scientists, engineers, and users.
- The first user group that we are focusing on is the **LEO sector in space traffic management**

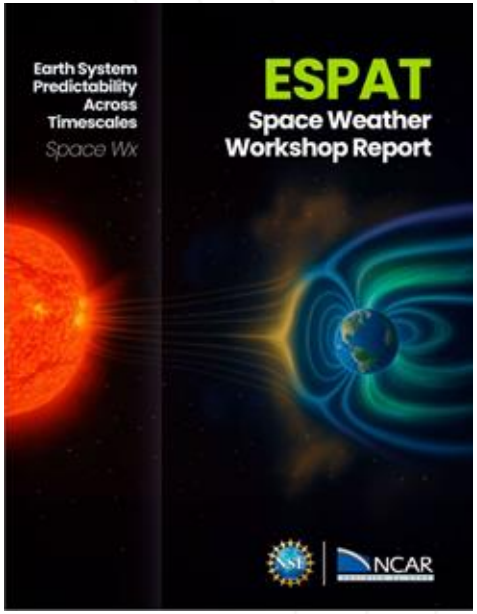
Key outcomes from workshop report

Grand Challenges:

- Understanding interactions across Earth-Sun system components — including solar magnetic eruptions, solar wind evolution, and magnetosphere–ionosphere–thermosphere coupling;
- Determining how Earth system variability affects geospace predictability; and,
- Exploring how cross-scale processes affect geospace-atmosphere interactions and predictability.

Addressing these challenges requires advances in observations, DA, modeling, and integration of AI and ML.

Alignment with the Decadal Survey: Workshop outcomes strongly align with key priorities identified in the Decadal Survey, including improving system-level understanding of solar–terrestrial interactions, developing community-accessible modeling frameworks, and expanding DA capabilities



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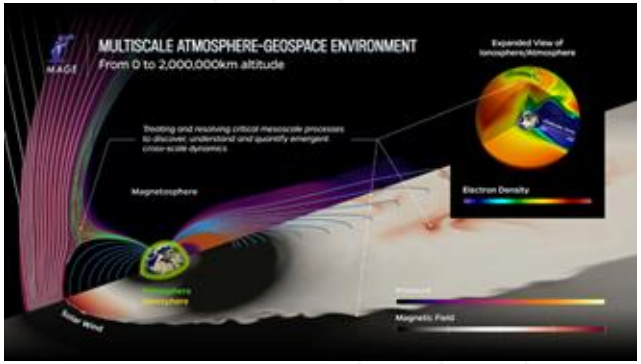
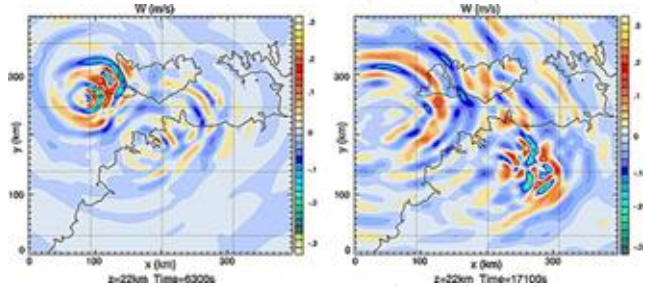
ESPAT SWx NCAR Strengths: Geospace

- **Coupling from below and above w/MAGE**
  MAGE: Multiscale Atmosphere-Geospace Environment Model - WACCM-X is the atmospheric component
- **High-resolution simulations** with WACCM-X and CESM
- **DA Advancements** and reanalysis
- **Convergence** research



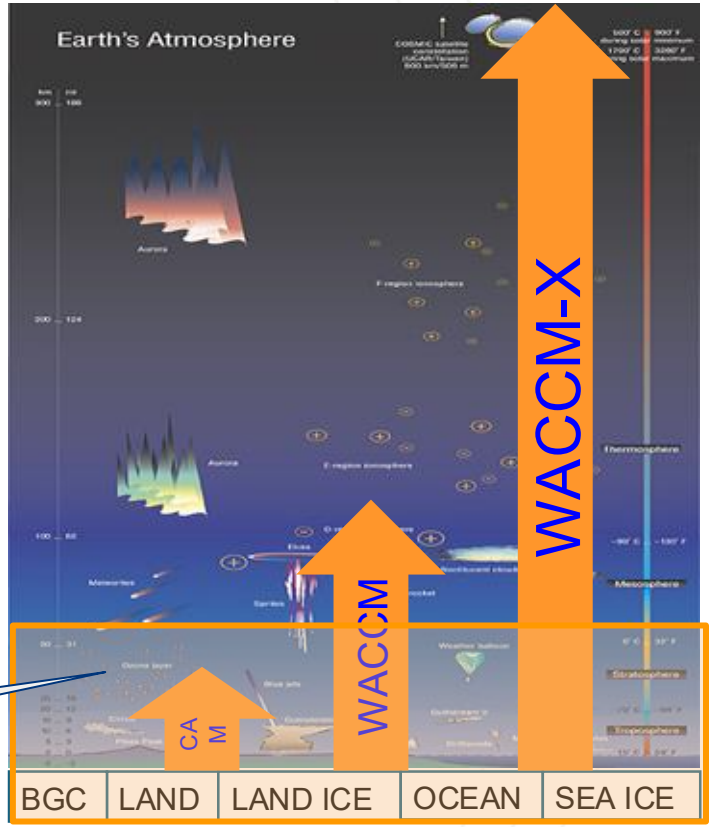


NCAR | DART

WACCM-X-RC Concept

Develop Reduced-Complexity (RC) version of WACCM-X, with lower-boundary driven by data (Reanalysis, model-daata, AI-emulator data)

Project Status:
Conceptual design and requirements capturing



Replace by data

CEDAR-ESPAT Collaboration

- Formation of working groups that meet monthly
- Envisioning 3 groups corresponding to the three key science questions
- Each group would agree on specific outcomes/deliverables and work together throughout the year
- All groups would meet annually at CEDAR and at AGU and/or AMS (if attending)

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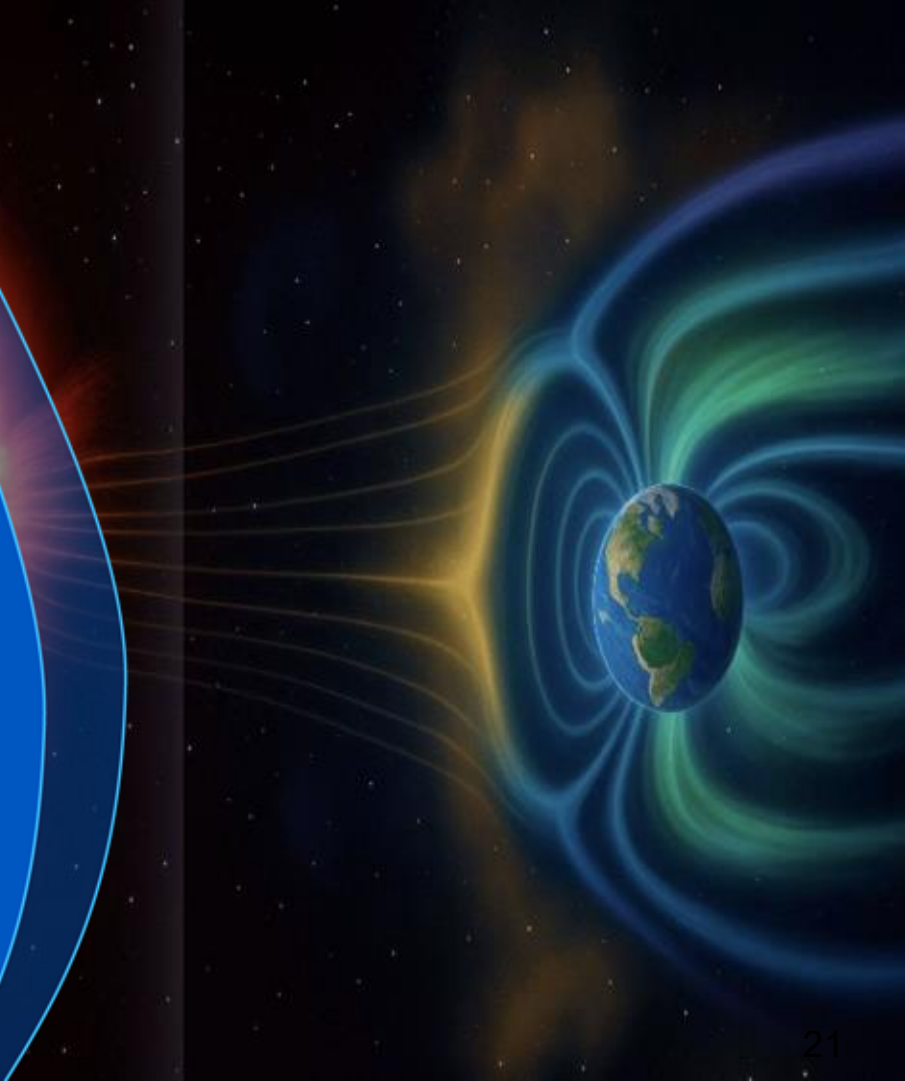
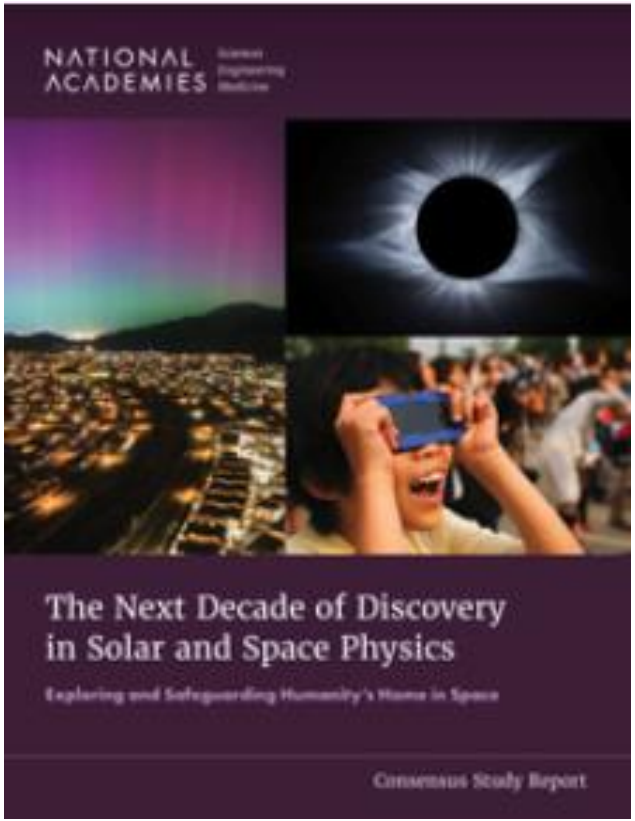
CEDAR Grand Challenge 2026

Systems and team based approaches

Presenter: Soudeh Kamali



The call for taking a systems approach

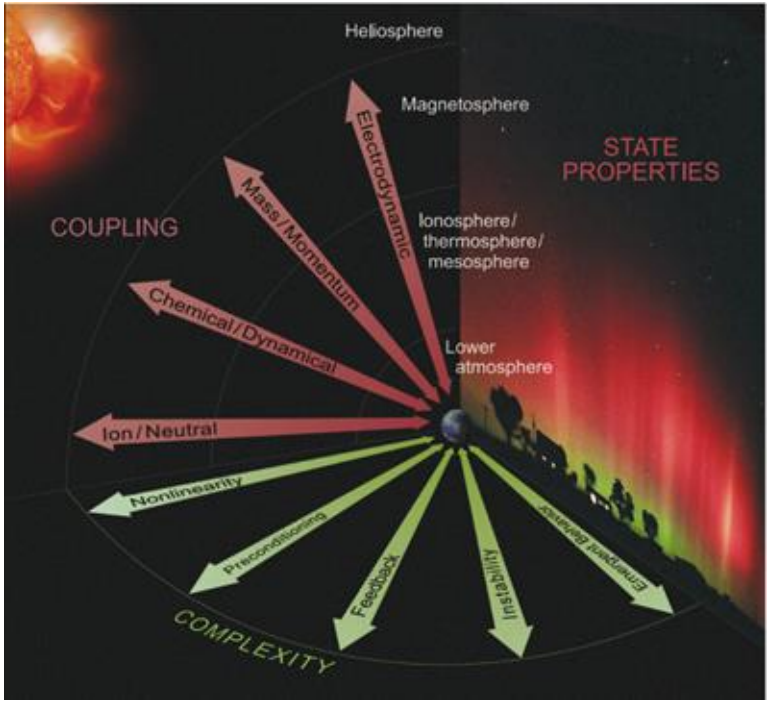


The Heliophysics Decadal Survey (2024-2033)

*"The heliosphere as a whole, and its various parts, behave as a complex **system of systems**. To understand its behaviour it is imperative to understand how each of these **systems function** and how they interact with each other."*

The Space weather system of systems- natural systems

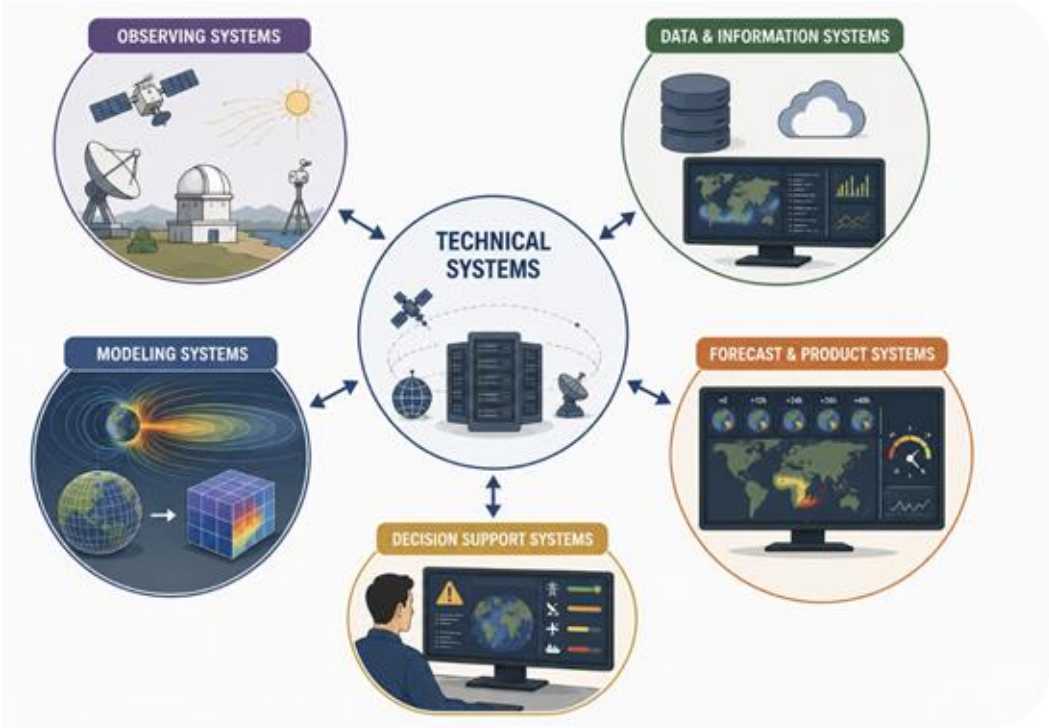
The dynamic sun-earth system we seek to understand and predict.



(CEDAR, 2011)

Space weather system of systems - technical systems

The systems we build to observe, model, predict, and understand the natural system.



Space weather system of systems - human/social systems

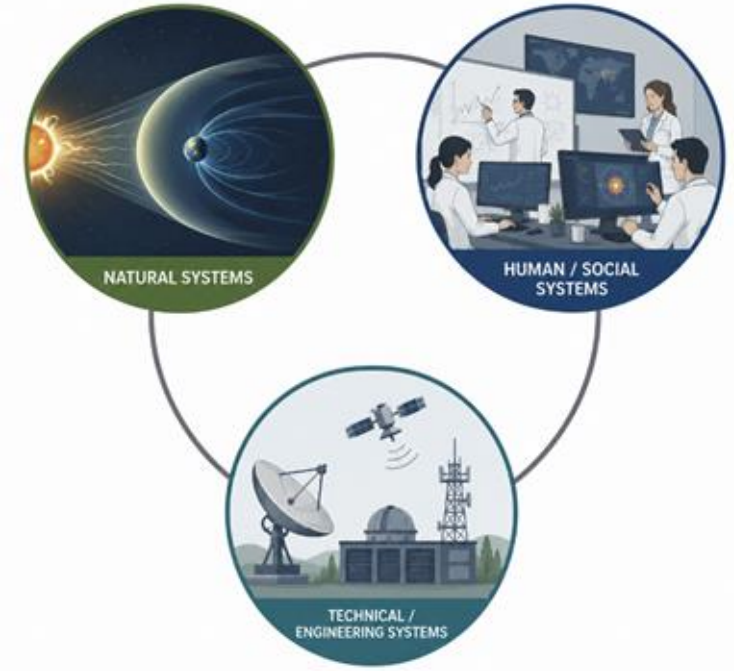
The experts and organizations designing and using the technical systems to study the natural system, as well as the end users being impacted by space weather.

Space weather system of systems - a sociotechnical system of system

A socio-technical system that connects human, technical, and natural systems to advance knowledge, inform decisions, and build societal resilience.

Conway's Law

Organizations which design systems (in the broad sense used here) are constrained to produce designs which are copies of the communication structures of these organizations.
—Melvin E. Conway



The need for team-based approaches if we are to take a systems perspective

Team-science - A collaborative effort to address a scientific challenge that leverages the strengths and expertise of professionals often times trained in different fields (NASEM 2015).

A call to participate

- **In Summary:** CEDAR community holds the expertise and ESPAT can provide a proven team-based approach.

- **Our Goal:** Working collaboratively towards improving our understanding of space weather predictability to protect technological infrastructure and meet the needs of the society.

- **Next Steps:** Join us in the coming days as we work together to refine the science questions, discuss better ways to collaborate, and initiate formation of working groups.

Upcoming breakout sessions

Breakout session #1: Wednesday June 24th 10:00-12:00 CDT

- Cross Disciplinary Panel Discussion: Fundamental Science for Pathways to Improved Space Weather Predictability
- Small Group Conversations: Initial Conversation around the 3 High Level Science Questions of the Grand Challenge

Breakout session #2: Wednesday June 24th 13:30-15:30 CDT

- Cross Sector Panel Discussion: Cross Sector Perspective on Pathways to Improved Space Weather Predictability
- Small Group Conversations: Relay Races and Batons!!
- CEDAR Grand Challenge 2026: Closing Remarks and Next Steps

Thank you and hope you can join us on Wednesday!!