NSF | NCAR OPERATED BY UCAR | High Altitude Observatory

Risk Mitigation and Resiliency Depend on Accurate and Reliable Space Weather Forecasting and Nowcasting

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What is "Space Weather"? Space science research…

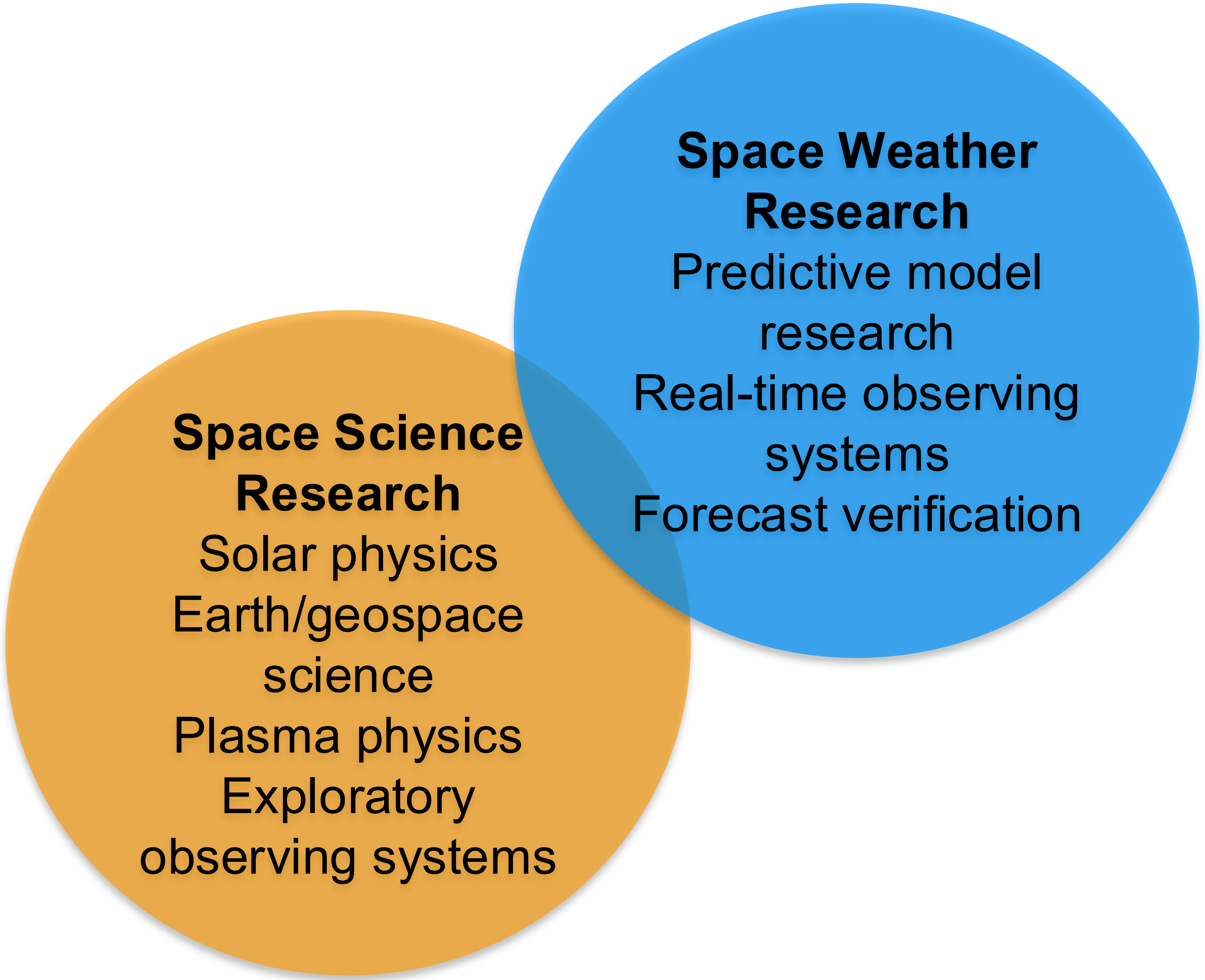
Space Science Research
Solar physics
Earth/geospace science
Plasma physics
Exploratory observing systems

The primary goal of space science research is to **explore the space environment, discover new phenomena, and determine the physical laws governing those phenomena.**

The ***space environment*** could be at Earth ("geospace"), the Moon, Mars, interplanetary space, interstellar space, etc.

Focus on ***phenomena: cause and effect***.

What is “Space Weather”? …informing Space Weather research…

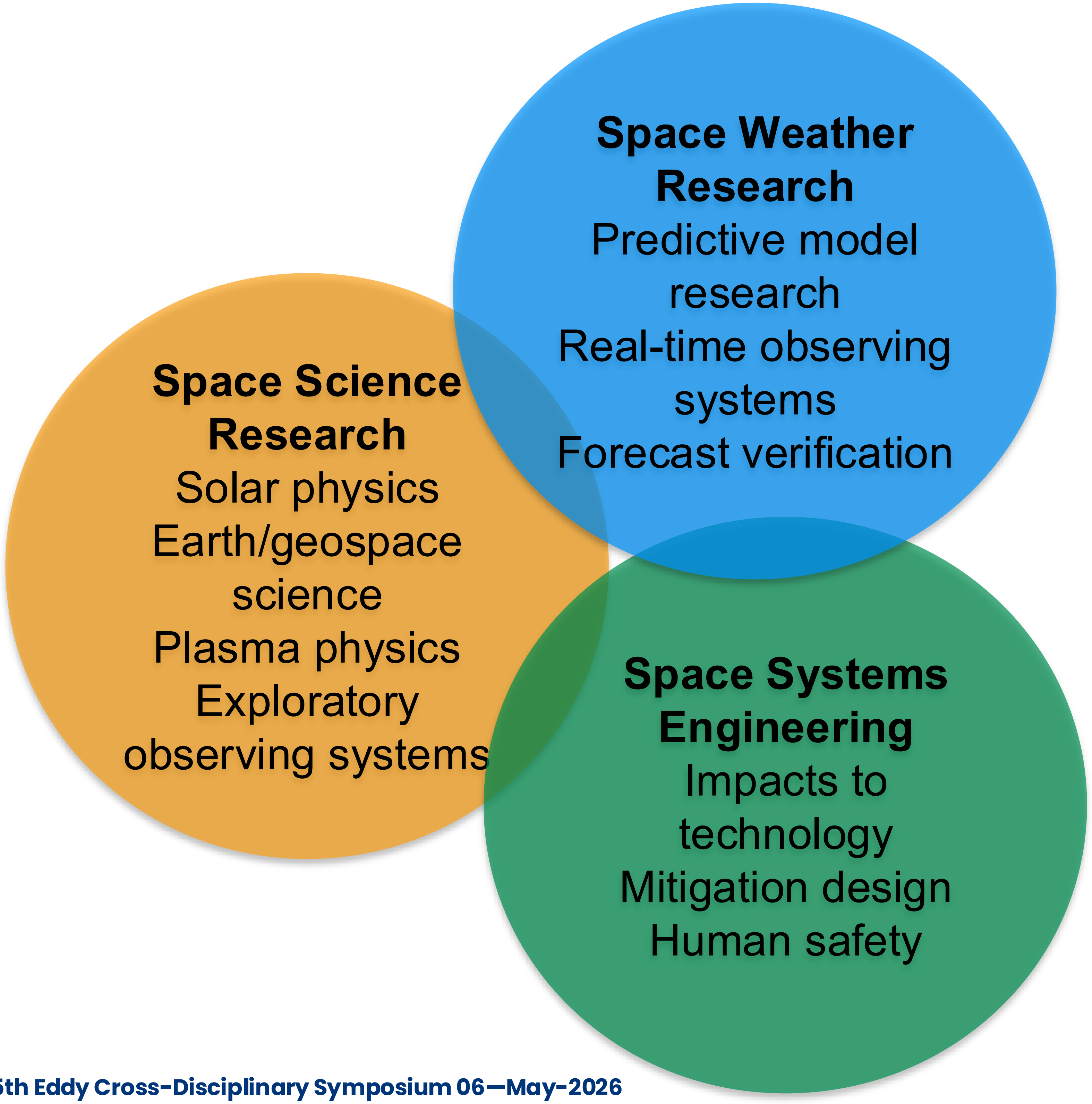


The primary goal of space weather research is to develop models and observing systems to **characterize and predict (“nowcast” and “forecast”) conditions in the space environment for use in operational settings.**

The space environment is complex, nonlinear, multi-scale, and often strongly driven by solar inputs.

Focus on ***characterization and prediction***.

What is “Space Weather”? A human enterprise!



The primary goals of space weather engineering research are to **determine the effect of space weather phenomena on technological systems and human health and to design methods/systems to mitigate those impacts.**

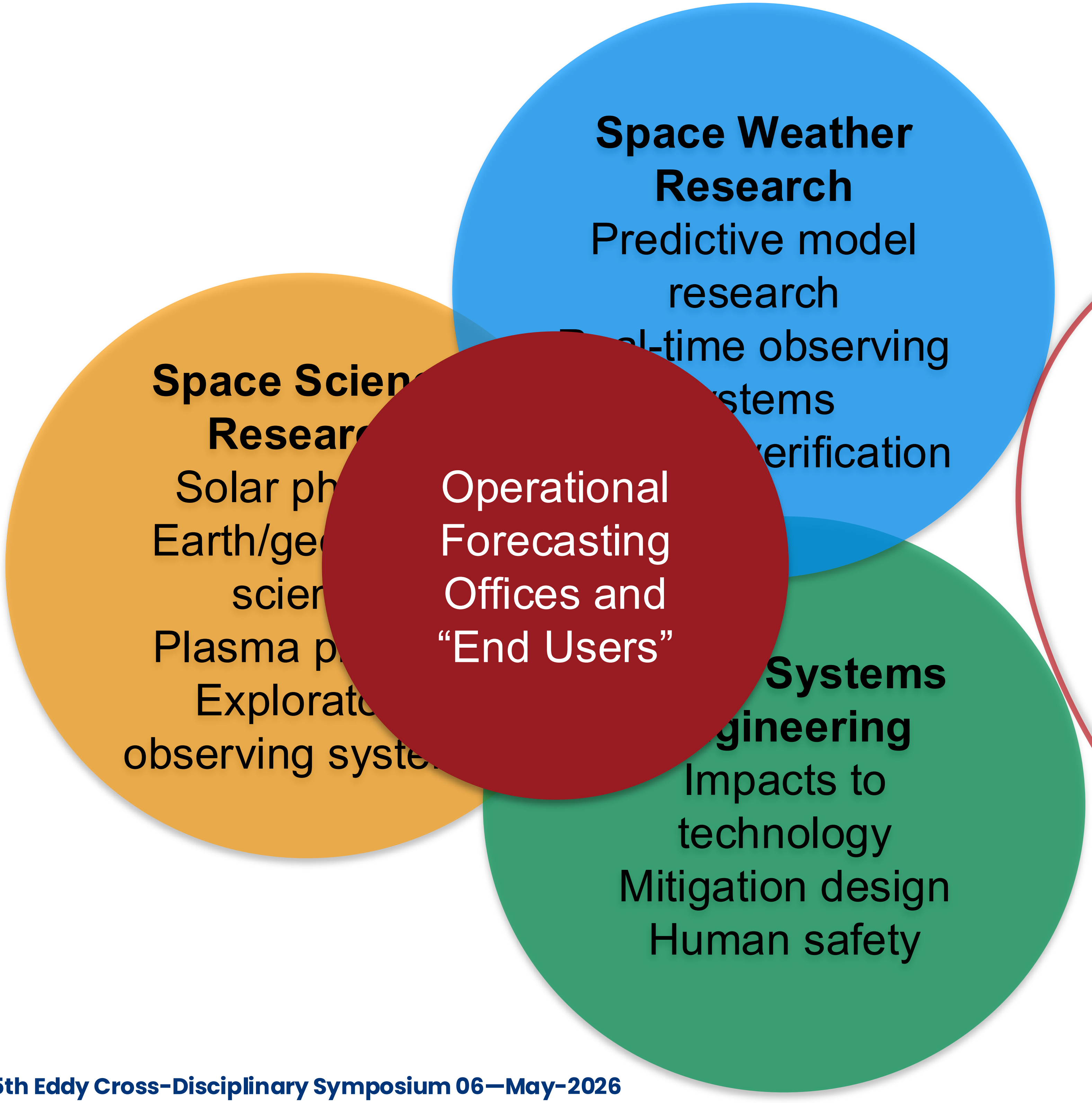
Technological systems:

- Power grid
- Aircraft and spacecraft
- Satellites in Earth orbit
- GNSS navigation & timing systems

Human health:

- Airline crews
- Astronauts in deep space

The Space Weather challenge



Can the space weather enterprise deliver research, nowcasting and forecasting, and protective systems to enable End Users to

- **Safely human exploration of the solar system?**
- **Successfully operation of satellite systems in orbit?**
- **Stably operate power grids during extreme geomagnetic storms?**
- **Ensure reliable GNSS navigation and timing for autonomous systems?**

IMPLICIT RISK

Risk: formal definition

In engineering and safety analysis:

$$\text{Risk} = \text{Impact} \times \text{LikelihoodofOccurence}$$

Impact

	1	2	3	4	5
Fatalities	1-8	9-40	41-200	201-1,000	>1,000
Casualties	1-18	17-80	81-400	400-2,000	>2,000
Economic cost	Millions of £	Tens of millions £	Hundreds of millions £	Billions of £	Tens of Billions £

UK National Risk Register

Impact \ Likelihood	1 <0.2%	2 0.2-1%	3 1-5%	4 5-25%	5 >25%
5 Catastrophic	28, 29		7, 26a	54	
4 Significant	21	24, 38, 56a	10, 27, 49, 51a, 51b, 51c, 61	47, 50, 55, 63	
3 Moderate	17, 32, 33, 34, 35, 36, 56c	23, 52	12, 25, 26b, 31a, 45, 53, 56b, 56d	4, 9, 11, 40, 43, 48, 60	3, 31b, 46, 62
2 Limited	18, 19, 30, 37	5, 16, 41, 42	14, 20, 58, 59	8, 13, 57b	2, 6
1 Minor	44	39		15	1, 57a

Pandemic disease outbreak (54)

Severe space weather (47)

https://assets.publishing.service.gov.uk/media/67b5f85732b2aab18314bbe4/National_Risk_Register_2025.pdf

Space Science research in support of Risk Assessment

Bound the **environmental scenarios** so exploration, infrastructure, and autonomy can design for mitigation and resilience.

01 **Deep-space crew radiation**

What is the maximum proton and heavy ion flux and duration from an SEP event experienced beyond Earth's magnetosphere?

02 **LEO satellite collisions**

What is the maximum thermospheric density increase and duration at a given altitude during an extreme geomagnetic storm?

03 **Power-grid disruption**

What is the maximum geoelectric field and duration of peak field expected in any given geographic area during an extreme geomagnetic storm?

04 **GNSS reception loss**

What is the maximum signal degradation or scintillation and duration during an extreme geomagnetic storm?

Research output: credible upper bounds **with uncertainties** for **magnitude and duration** → operational thresholds → decision triggers

Probabilistic risk assessment example

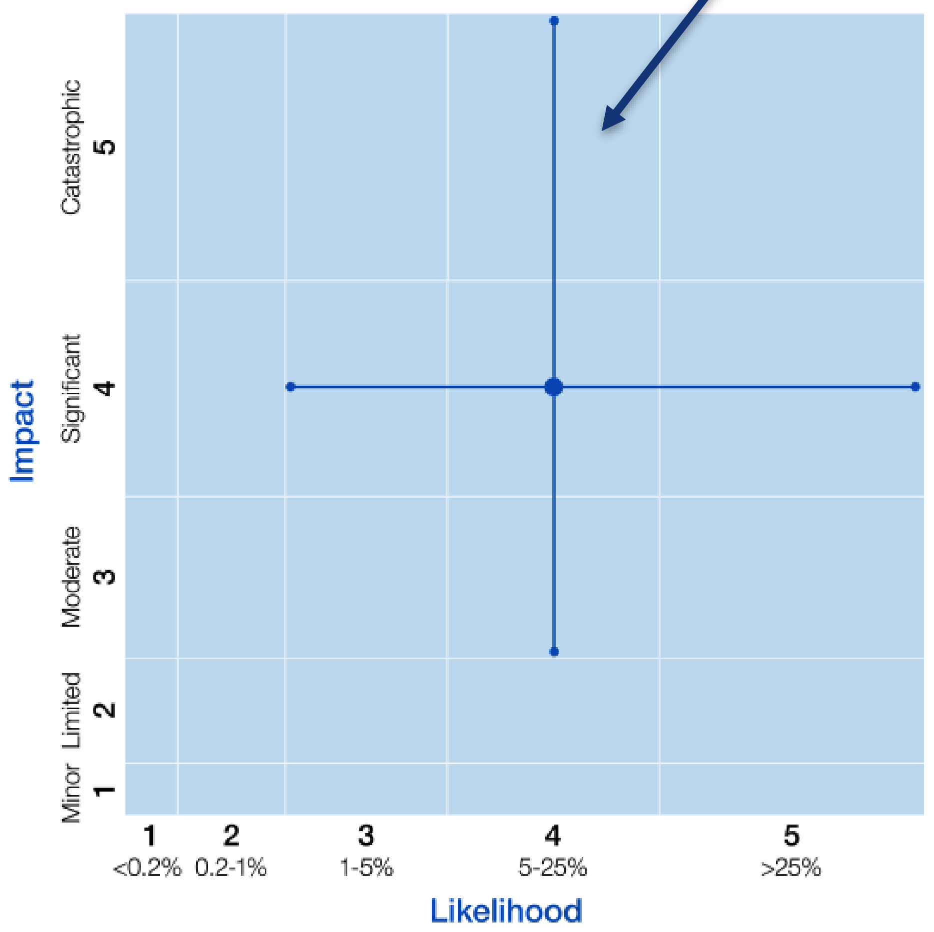
Severe space weather

The term 'space weather' describes a series of phenomena originating from the sun, which include solar flares, solar energetic particles and coronal mass ejections. Day-to-day space weather causes little more than the Aurora Borealis in polar regions, but strong space weather events can bring disruption to many vital technologies. Orbiting satellites are particularly vulnerable to space weather effects, and can be damaged or temporarily disabled.

Scenario

The reasonable worst-case scenario for this risk is based on a severe space weather event, approximately the same scale and magnitude as the Carrington Storm of 1859, lasting for 1-2 weeks. It includes a number of different solar phenomena including coronal mass ejections, solar flares, solar radiation storms and solar radio bursts. Each phenomenon would likely occur several times during a 2-week period, with each varying in magnitude, temporal and spatial extent. Impacts may include regional power disruptions, loss or disruption of Global Navigation Satellite Systems (for example Global Positioning System (GPS)) and some telecommunications (for example satellite communications and high frequency radio), disruption to aviation, an increase in background radiation doses at high altitudes and in space, and possible disruption to ground-based digital components. The catalogue of tracked objects in orbit would be significantly impacted, raising the risk of on-orbit collisions. There may also be second order impacts such as fatalities and casualties (for example, in the event of power disruptions).

Note the error bars!



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Engineering/Social Science Research in support of Risk Assessment

Bound the **infrastructure impact** tails so policy makers can plan for response and recovery.

01 Deep-space crew radiation

What is the expected worst case astronaut health impact and what are the required medical interventions?

02 LEO satellite collisions

What is the worst case collision scenario and which altitudes will be most impacted? How long will it take for the debris to deorbit?

03 Power-grid disruption

What is the expected worst case power outage and system damage and what are the repair requirements and timelines?

04 GNSS reception loss

What is the worst case scenario for a given loss of reception event?

Research output: credible upper bounds on **maximum impact** → mitigation strategies → design margins

Risk Mitigation requires the ART of forecasting

Accurate, **R**eliable, and **T**imely ***forecasts and nowcasts*** are required.

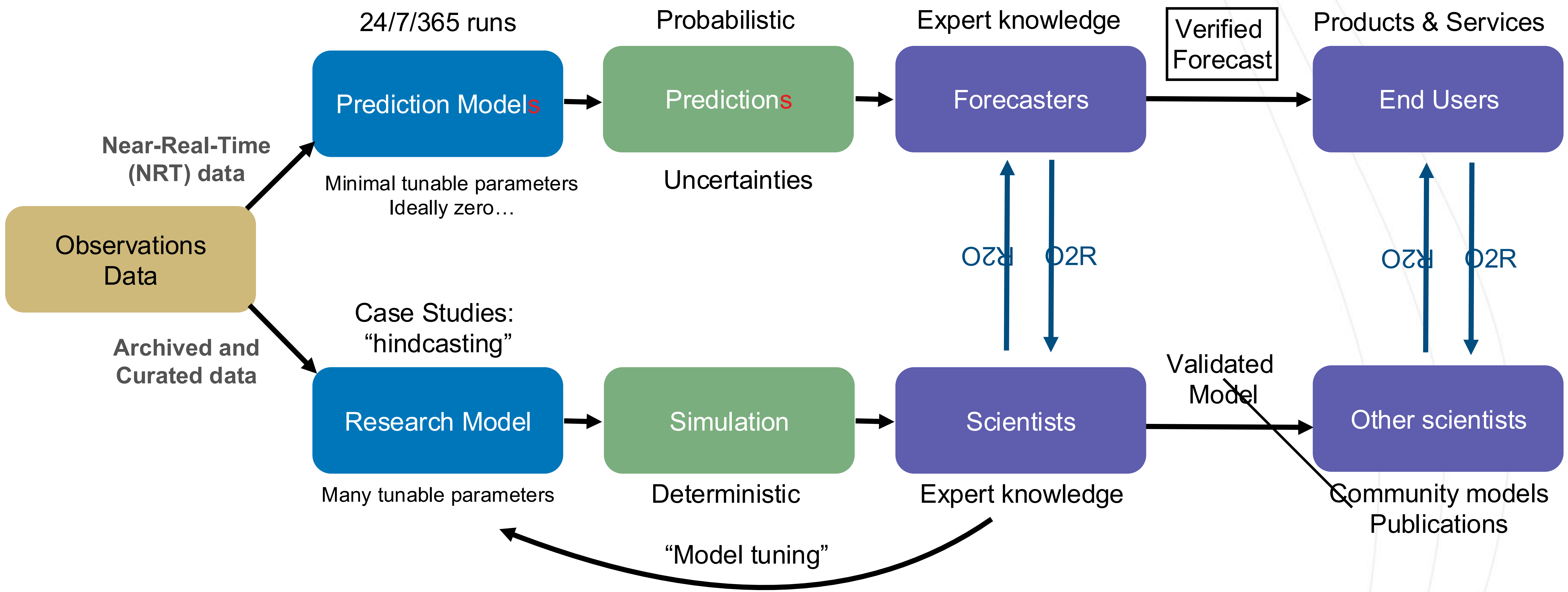
Forecasting and nowcasting models/tools must also be **A**daptable and work with noisy **R**eal-**T**ime data.

"Prediction is hard, especially of the future"
Yogi Bera

Sometimes the A is for "**Actionable**": a forecast must provide information that enables impact-based decision making by the End User.

"There is no value in a forecast. There is only value in how a forecast is used."
Tim Palmer, Royal Society Research Professor, Oxford

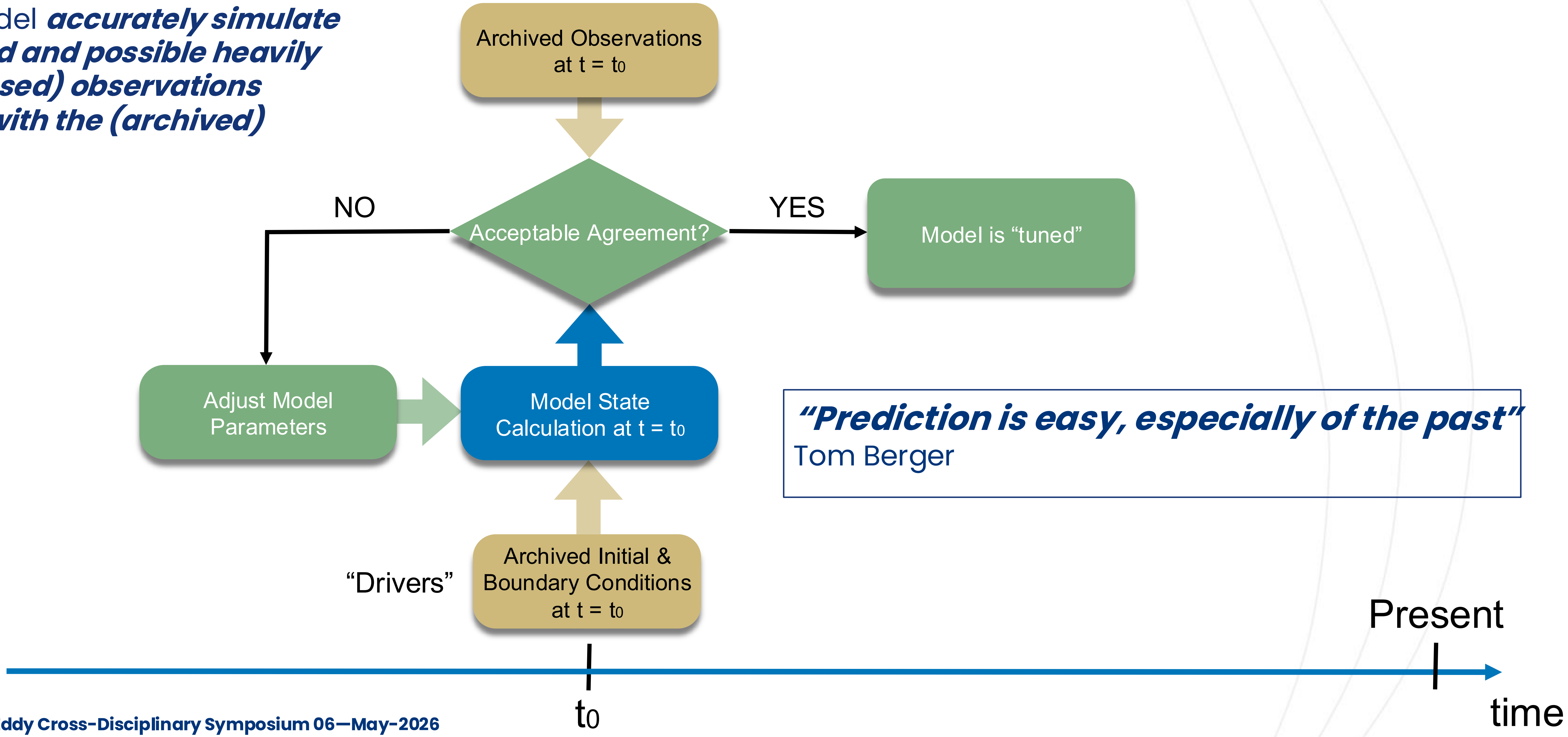
Predicting/Forecasting vs. Simulating



Model validation ≠ Forecast verification

Drivers, model state, and observations typically evaluated concurrently **using archived data**

"Can the model ***accurately simulate the (archived and possible heavily post-processed) observations associated with the (archived) drivers?***"

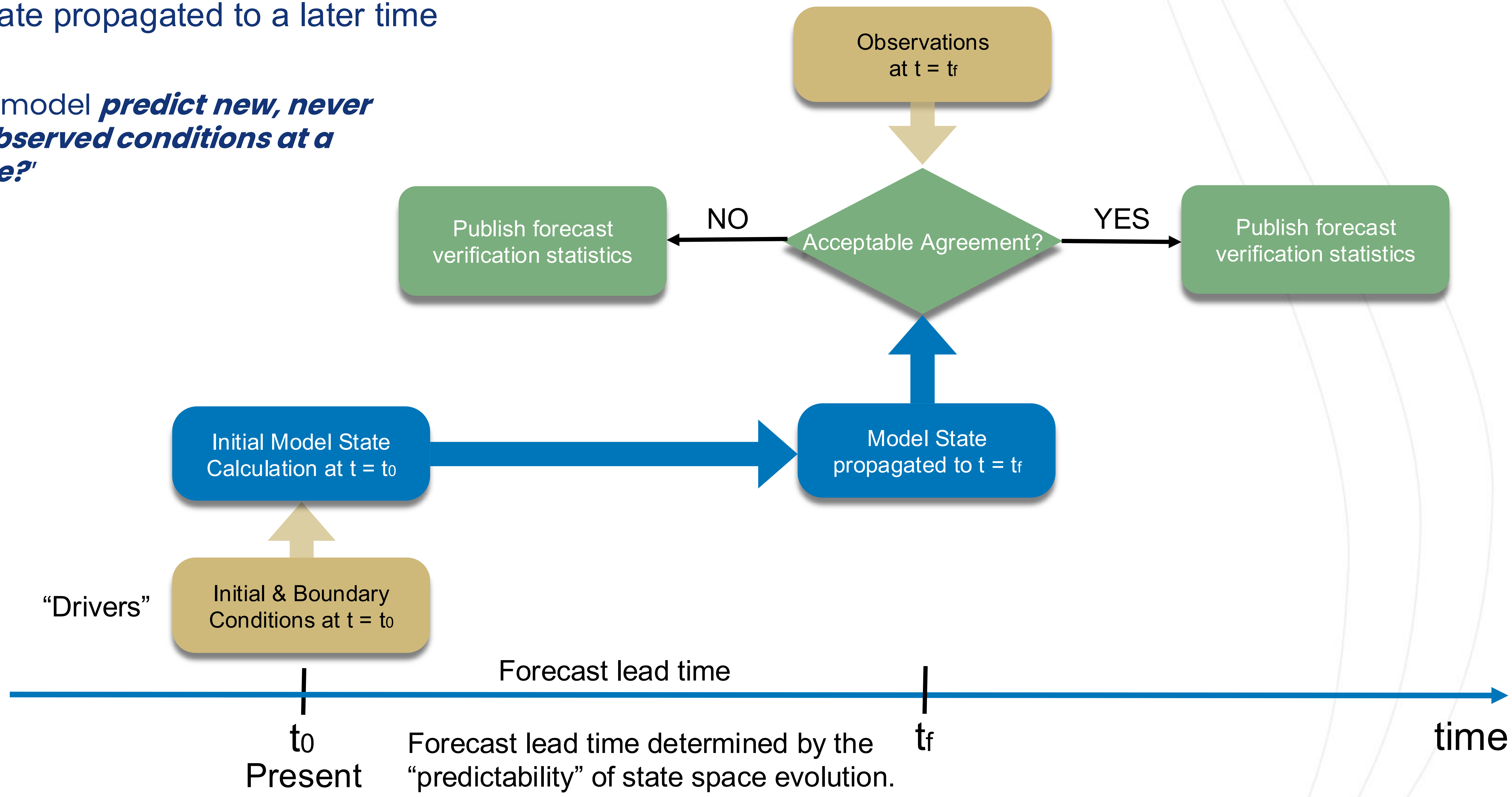


"Prediction is easy, especially of the past"
Tom Berger

Forecast verification ≠ Model validation

Model state propagated to a later time

“Can the model ***predict new, never before observed conditions at a later time?***”



Deterministic vs. Probabilistic forecasts

Deterministic

Single scalar value or category

Answers: what value or category should we expect?

SWPC example: The greatest expected 3 hr Kp for May 06-May 08 2026 is 4.33

Interpretation: below NOAA geomagnetic storm scale levels.

Probabilistic

Likelihoods across outcomes

Answers: how likely is each threshold or impact level?

SWPC examples: R1–R2 radio blackout for next three days = 25%, 25%, 35%

G1 minor storm probability for next three days = 10%, 25%, 25%

Easier for physics-based models to produce

More useful for End User downstream impact models

Deterministic forecasts simplify modeling and action decisions ; probabilistic forecasts expose uncertainty and risk tolerance.

Example forecast verification: NOAA/SWPC Solar F10.7 accuracy

3-day forecast from daily RSGA files: 1988-2025

- **Annual average** of N = 13,551 daily forecasts.

Symbols: results from SWPC 2013 verification report.

Correlation is Pearson correlation coefficient

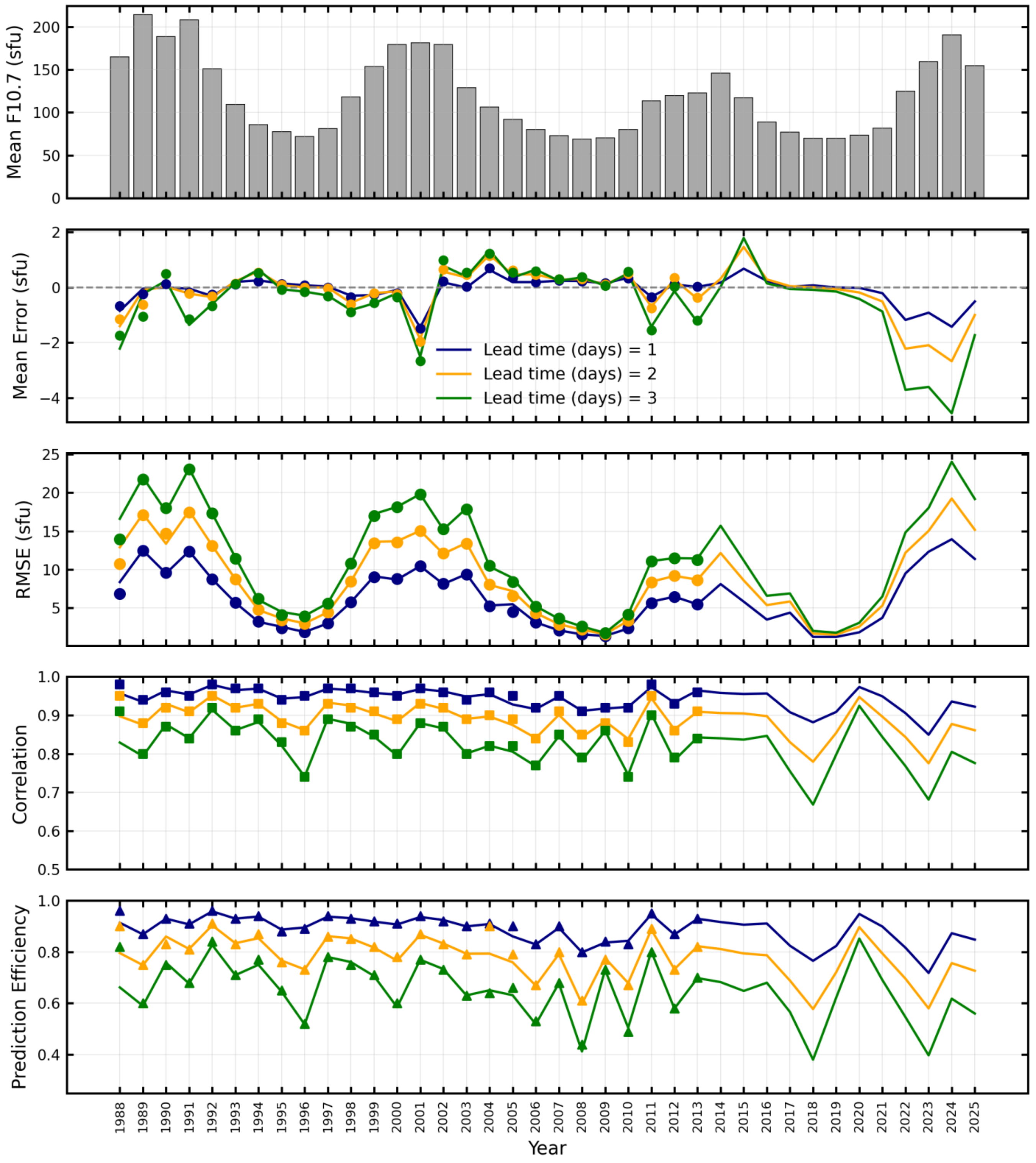
$$r = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2 \cdot \sum_{i=1}^{n}(Y_i - \overline{Y})^2}}$$

where X is the observed F10.7 and Y is the prediction.

Prediction Efficiency is

$$\mathrm{PE} = 1 - \frac{\sum_{i=1}^{N}(f_i - o_i)^2}{\sum_{i=1}^{N}(o_i - \overline{o})^2}$$

where f_i = forecast, o_i = observed, and $\overline{o}$ = climatological mean (e.g., 30-day mean F10.7).



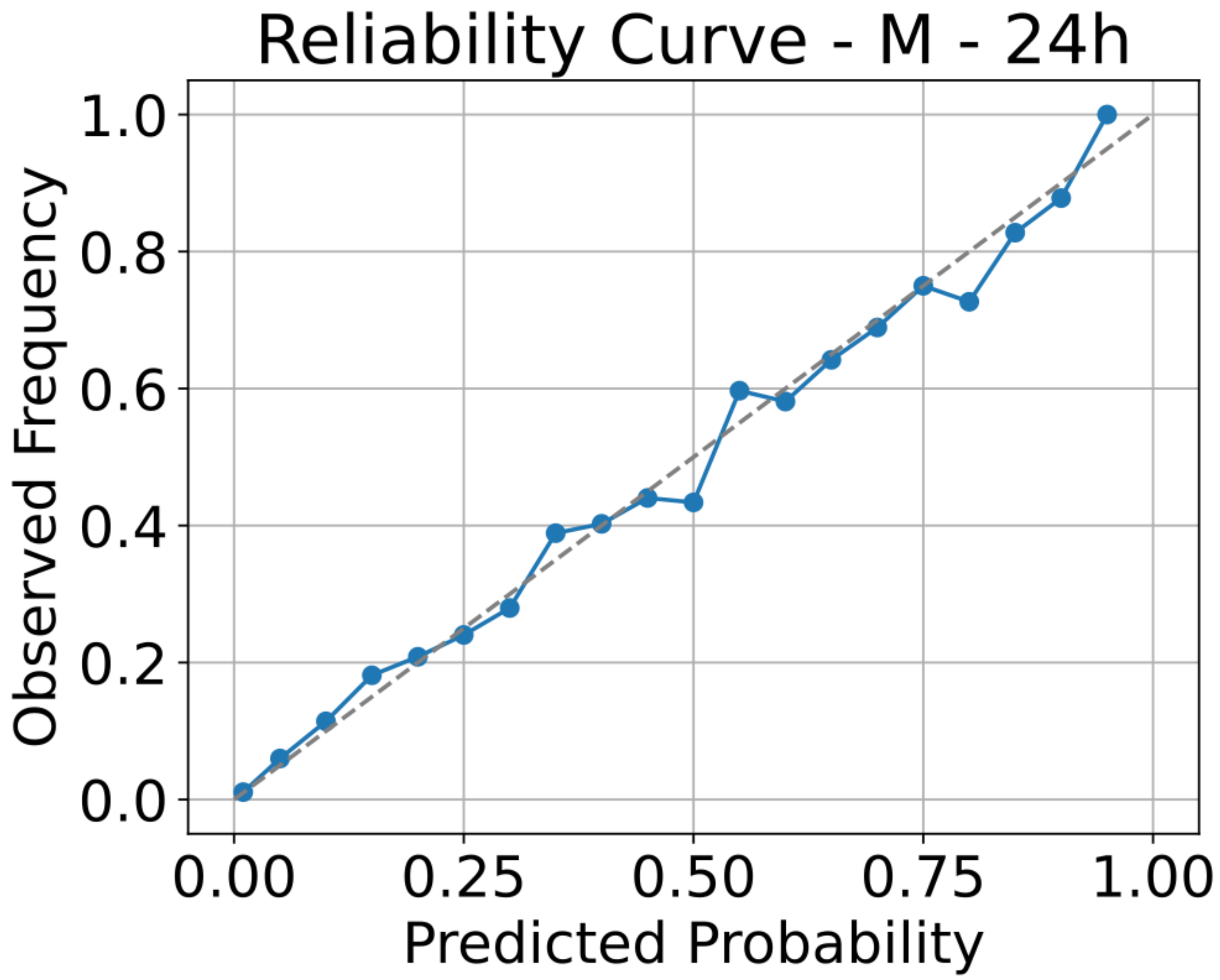
Example forecast verification: NOAA/SWPC Solar flare reliability

Reliability is usually applied to probabilistic forecasts only

Definition of **Reliability**

For all events forecast to occur at probability *p%*, the event should occur about *p%* of the time.

Example: among all “70% chance of rain” forecasts, rain occurred on ~70% of those cases.



Camporeale, E. and Berger, T.E. (2025) “Verification of the NOAA Space Weather Prediction Center Solar Flare Forecast (1998–2024),” *Space Weather*, 23(10), p. e2025SW004546. https://doi.org/10.1029/2025SW004546.

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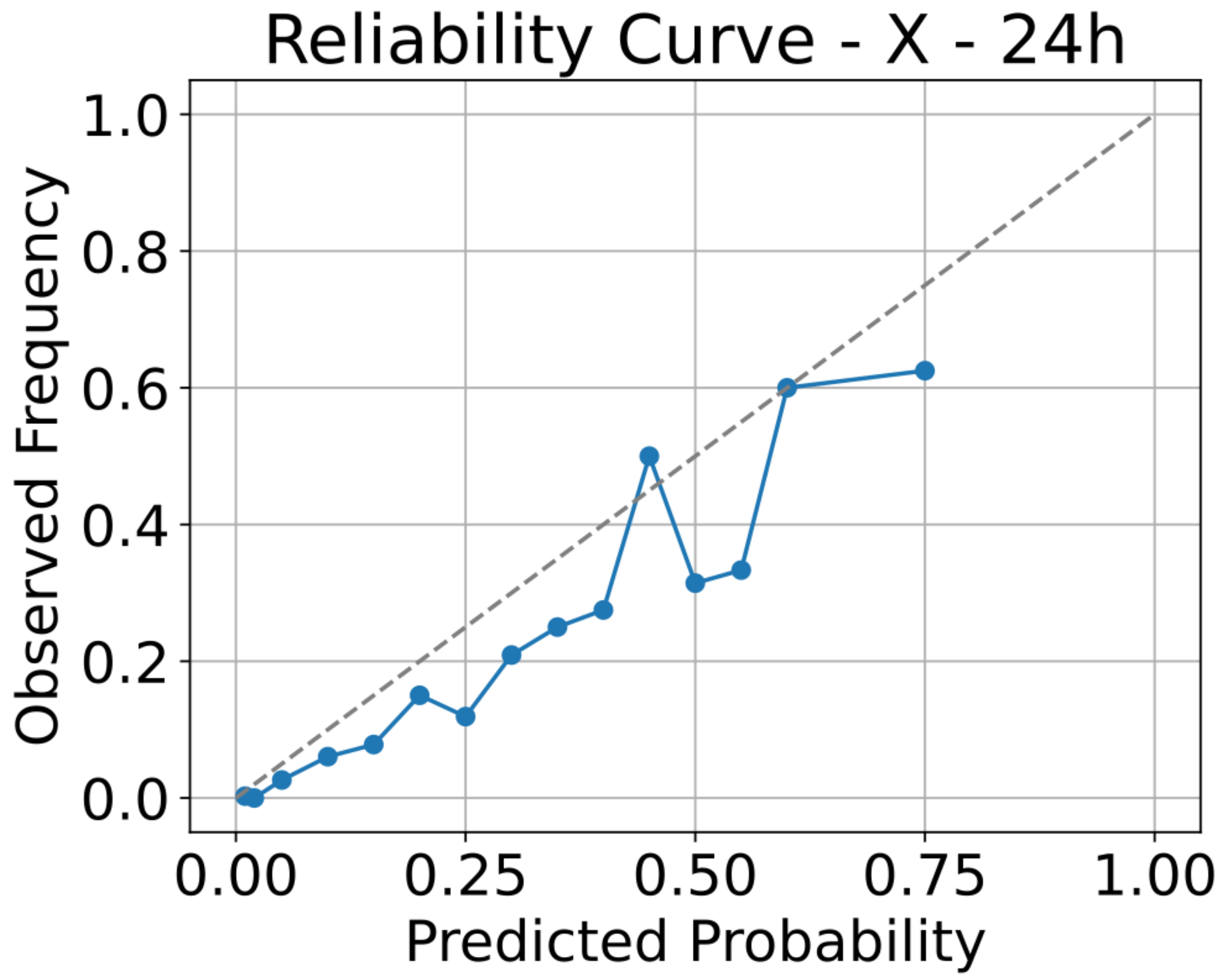

Reliability is about trust in the probabilities — not whether each individual forecast is right or wrong.

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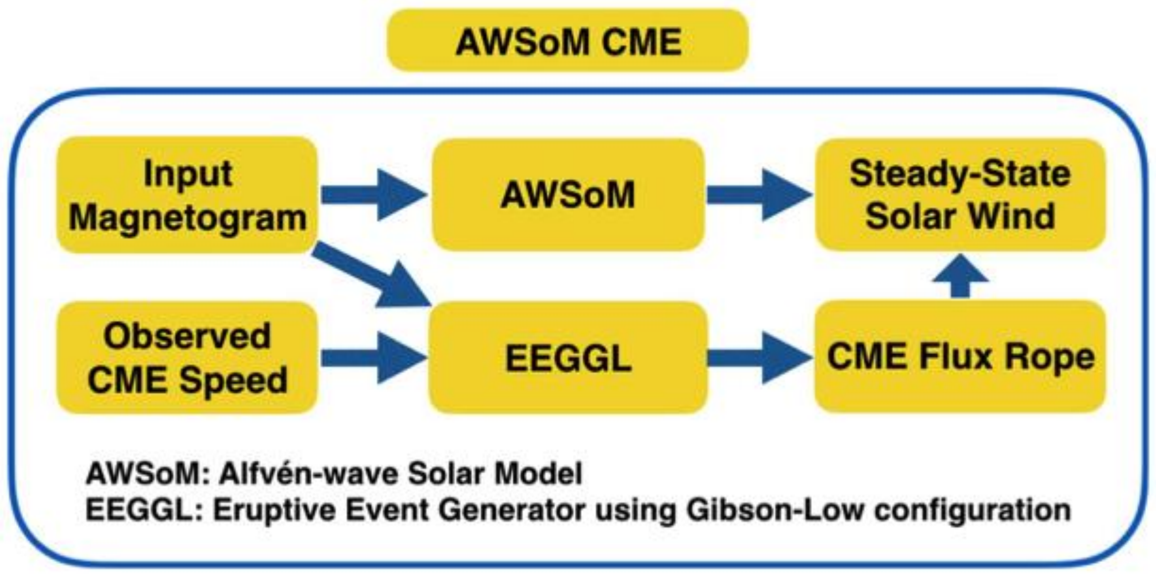
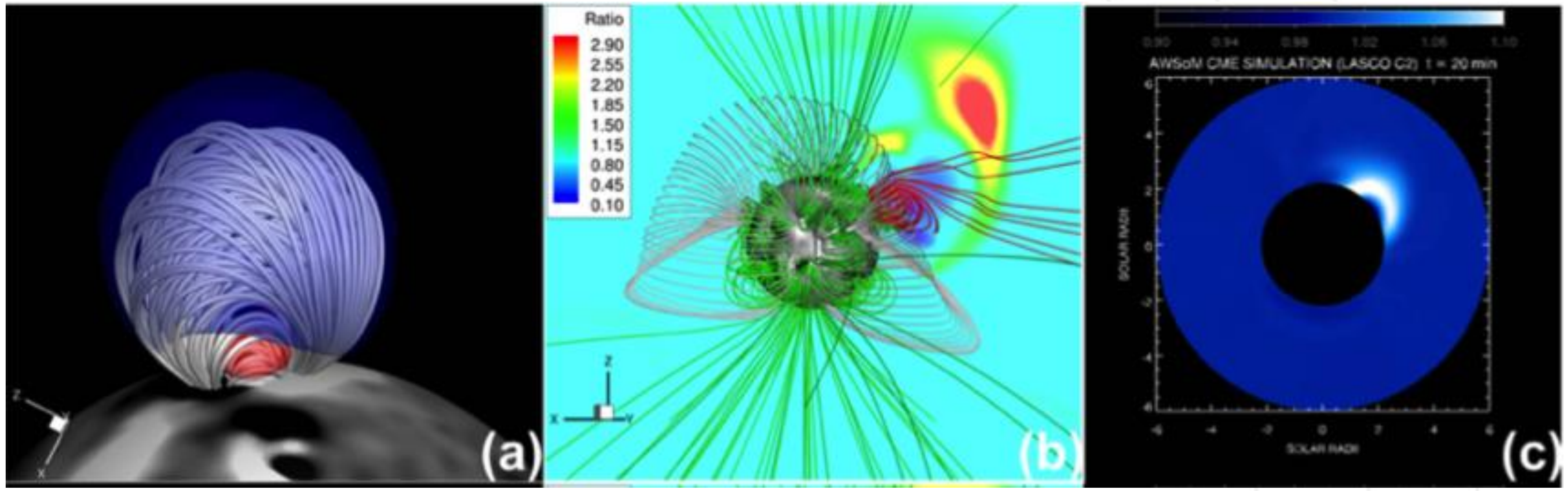
Definition of Timeliness in forecasting

Accurate, **R**eliable, and **T**imely…

Example of what is ***not*** a timely operational forecasting model: AWSoM + EEGL CME propagation model





Jin, M. *et al.* (2017) "DATA-CONSTRAINED CORONAL MASS EJECTIONS IN A GLOBAL MAGNETOHYDRODYNAMICS MODEL," *The Astrophysical Journal*, 834(2), p. 173. https://doi.org/10.3847/1538-4357/834/2/173.

Sun-to-Earth CME simulation: **35 hours** on 1,800 CPU cores for a single CME (add 4 hours for background solar wind if not already supplied). Fast CMEs arrive at Earth in **14–24 hours**.

A reminder on forecast models:

"All models are wrong…"
George Box

"…but some can be made useful with data assimilation."
Tom Berger

There is no such thing as an ARTful, useful, forecast or nowcast without ARTful observations and data to correct model deficiencies.

Resilience = response and recovery

Severe space weather

Key assumptions for this scenario

The impacts of severe space weather would be global, although the magnitude would vary, with the key dependencies being latitude, reliance on access to space for the operation of key services and the resilience of engineered and digital infrastructure.

Variations of this scenario

Notable variations are possible in the timescale, type and magnitude of driving solar activity. Therefore, significant events with lesser or greater overall and/or differential impact spectra should be anticipated. This could lead to greater disruption in some sectors, such as aviation and the emergency services.

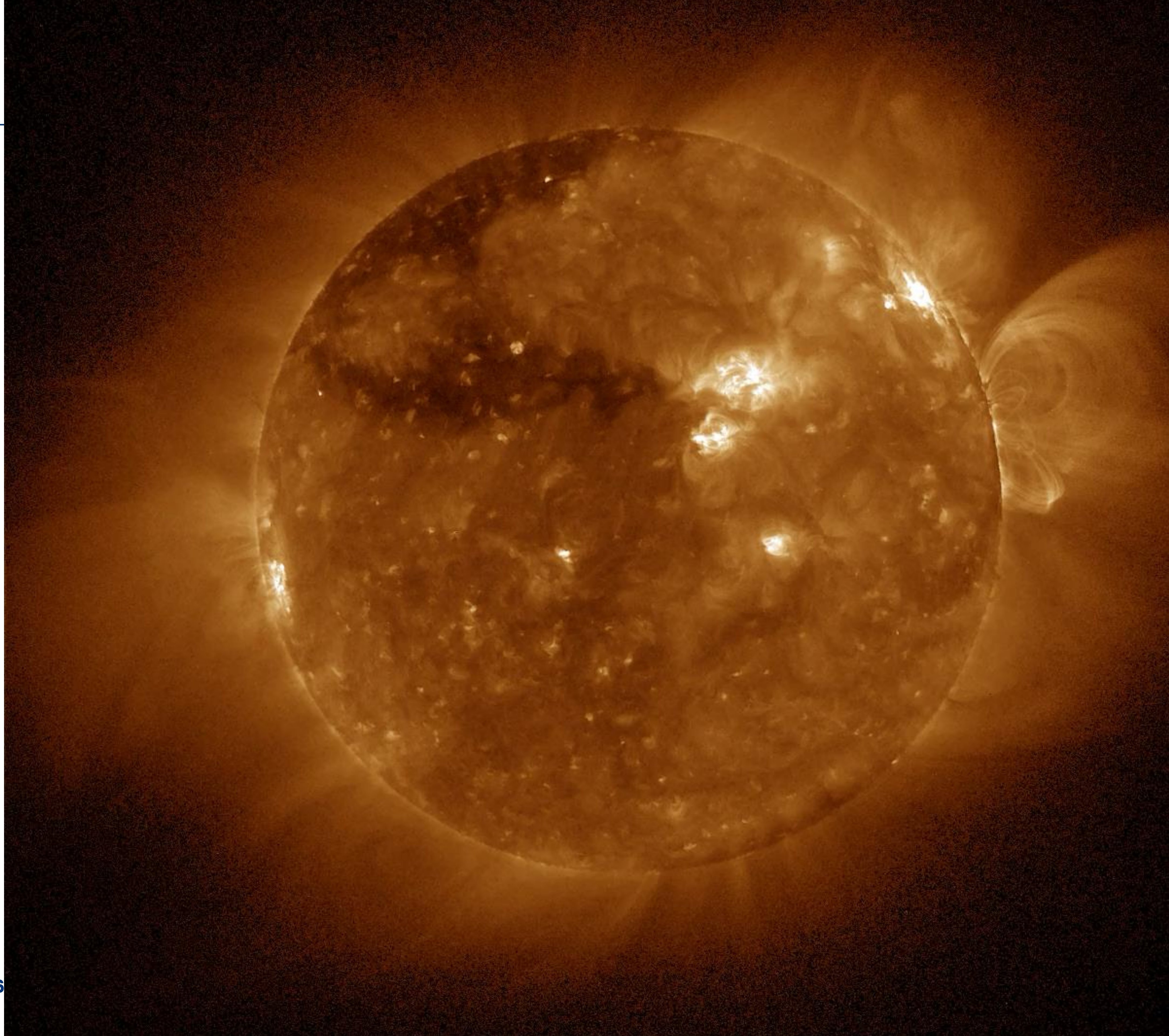
Response capability requirements

Mobile back-up power generation would be required in some areas for a sustained period, while damaged electricity transformers are replaced, which could take several months. Additionally, resilient communications systems and support for local emergency services and vulnerable members of these populations will be needed.

Recovery

Loss of power due to safety system trips in urban areas could be recovered in a matter of hours. In the event of electricity transformers needing to be replaced in remote coastal areas, recovery could take several months based upon current replacement transformer availability. Loss of, or disruption to, satellite based services and Global Navigation Satellite Systems (for example GPS) has a recovery time of several days, with a small number of satellites non-recoverable. It could take weeks for flight schedules (especially long-haul carriers) to fully return to normal. The catalogue of tracked objects on-orbit (satellites and debris) could similarly take weeks to re-establish, with this temporarily raising the risk of collisions.

Questions? Comments?



Forecasting a strongly driven system

- Does the driver become the primary system to forecast?
- Is the model essentially a "nowcast" model of the given driver state?
  - In the case of empirical models like MSIS, yes.