Predictability of Extreme Space Weather

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UN/USA ISWI 2017 Workshop
Boston College
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Space Weather Events

Extreme events*

September 1859

Extensive impact – worldwide

March 1989

Electric power - Quebec, New Jersey

May 1921

Submarine cables, electric lines, - N. America, Europe

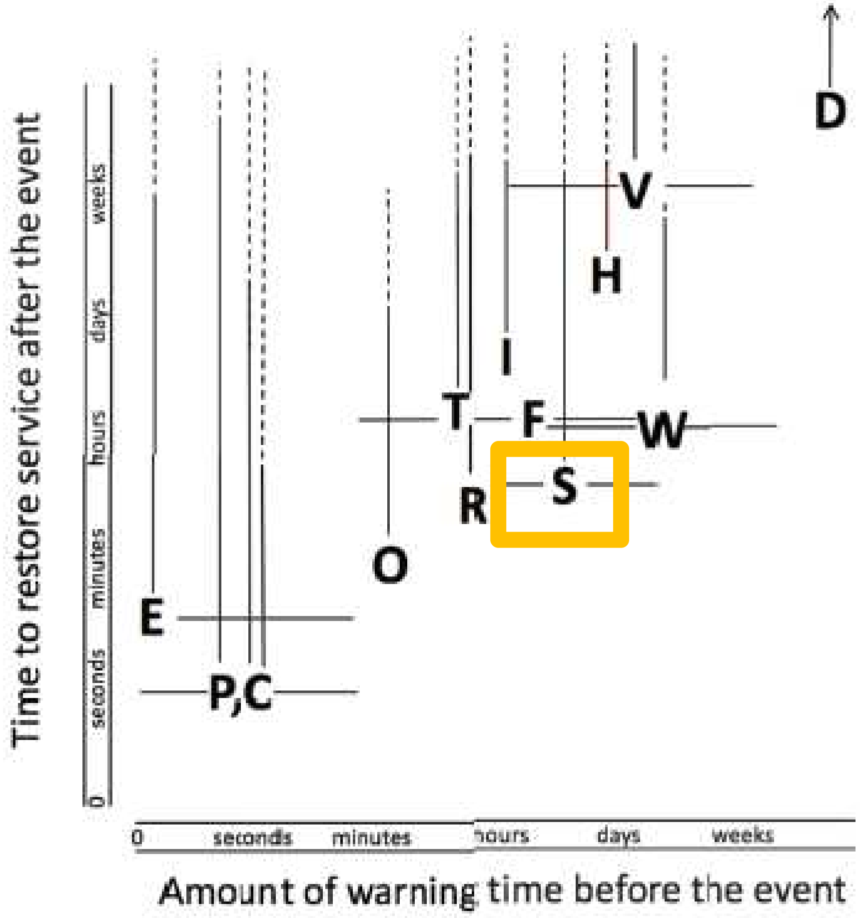
October-November 2003

Satellite anomalies, navigation systems, power grid,..

"…more coordinated international communication and coordination of warnings of extreme space weather events."

* UN CPUOS, Space weather Special report..2017. A/AC.105/1146

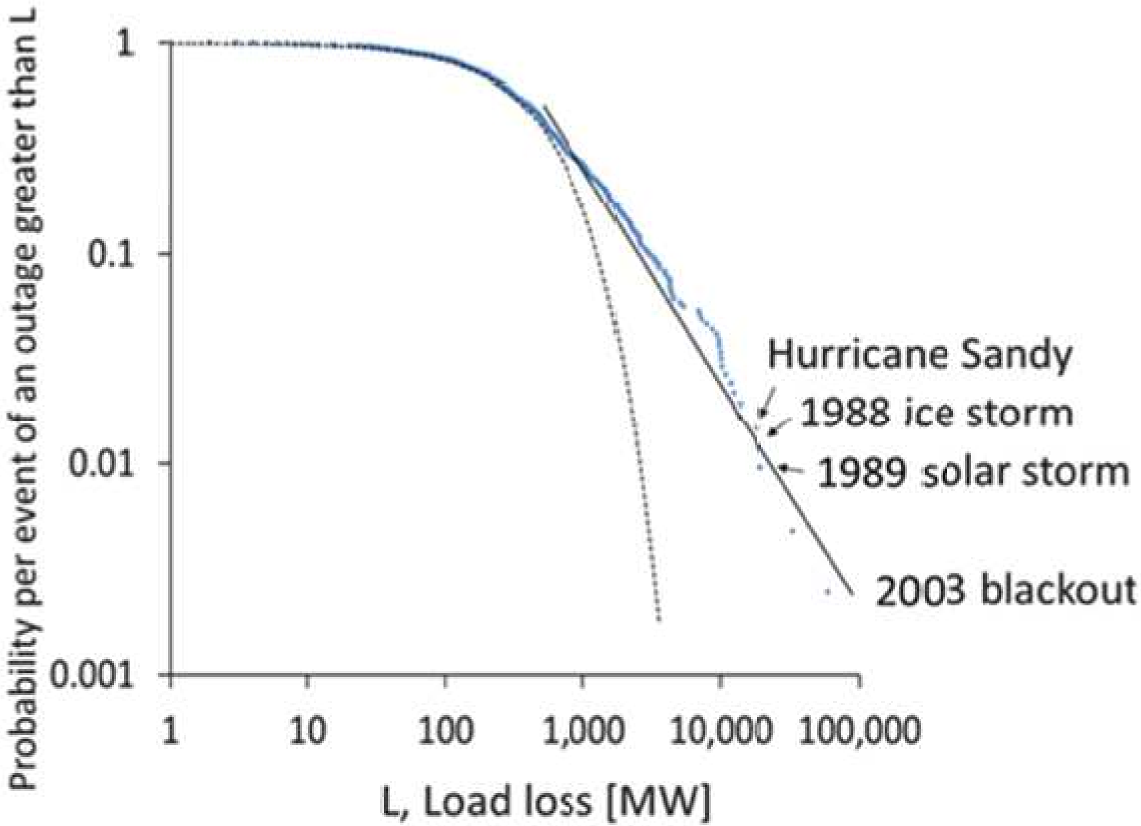
Space Weather Impact on Electric Power System



C = cyber attack (ranging from state/pro on left to good hacker on right)
D = drought and associated water shortage
E = earthquake (in some cases with warning systems)
F = flood/storm surge
H = hurricane
I = ice storm
O= major operations error
P = physical attack
R = regional storms and tornados
S = space weather
T = tsunami
V = volcanic events
W= wild fire

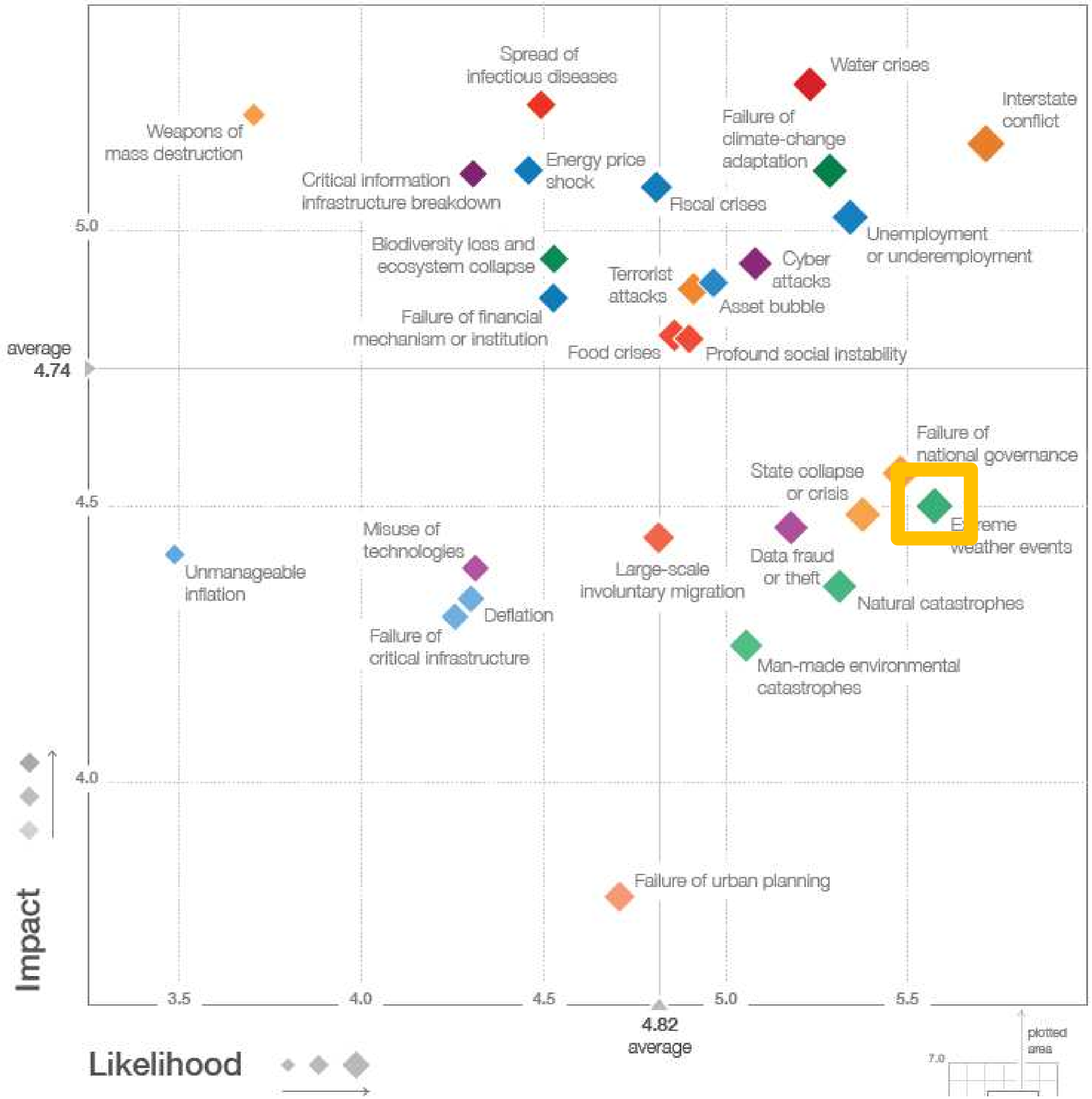
Enhancing the Resilience of the Nation's Electricity System
NASEM, 2017 http://nap.edu/24836

Space Weather Impacts:
Disaster Risk Estimation



NASEM, 2017
http://nap.edu/24836

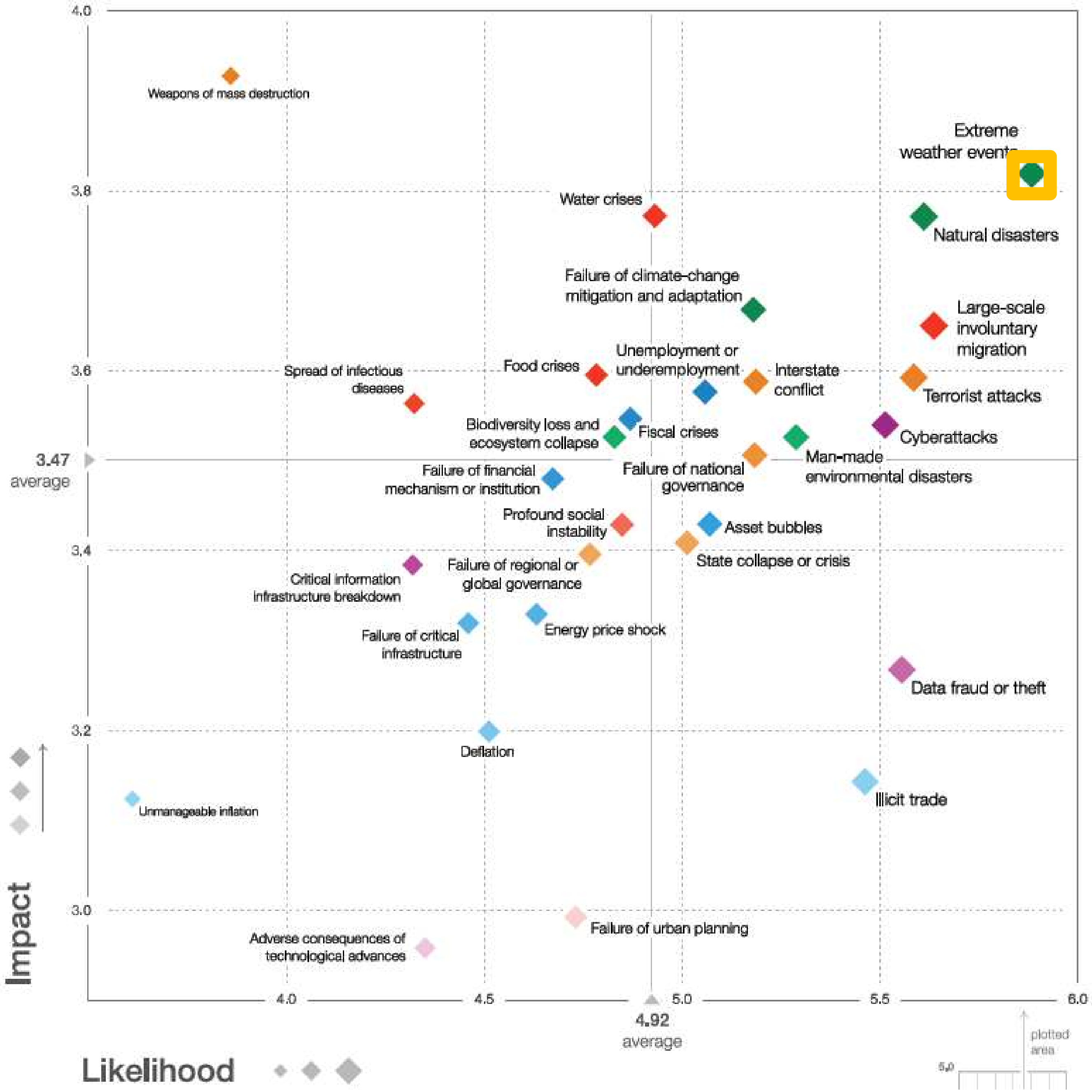
Global Risks Landscape 2015



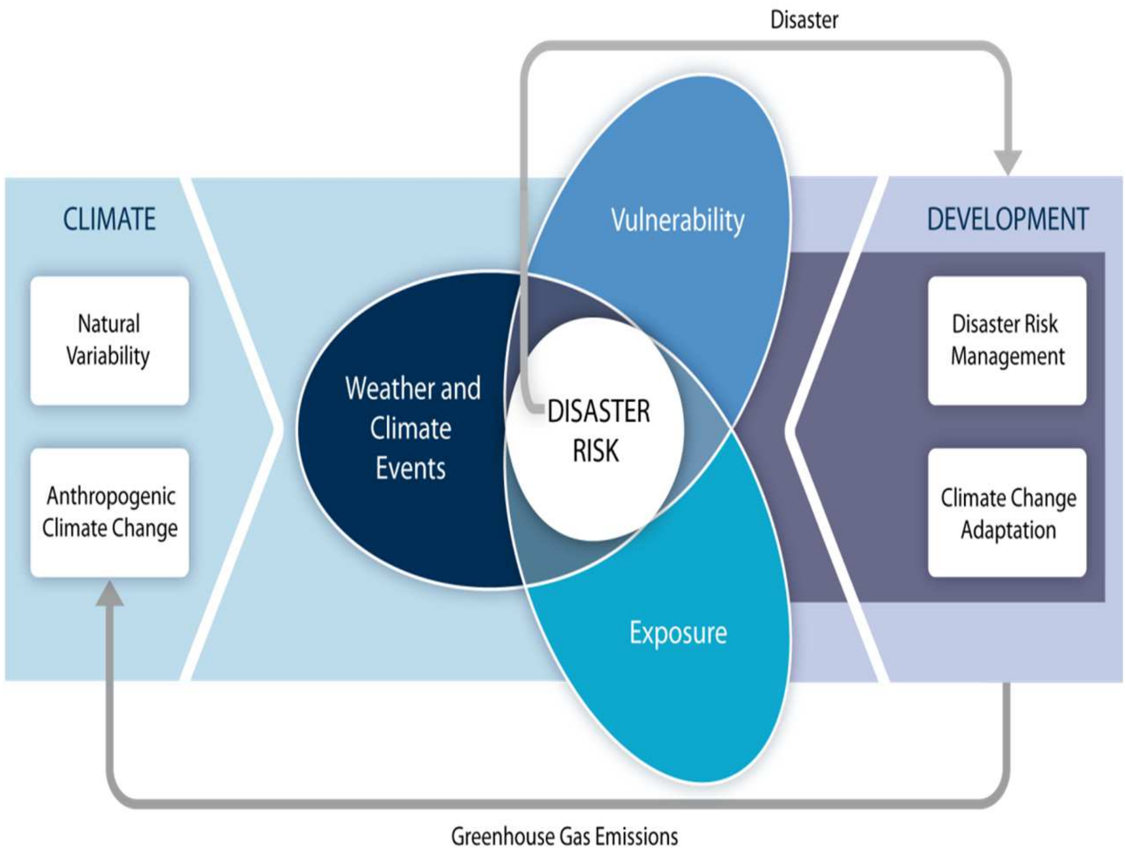
The Global Risks Report 2015, World Economic Forum, Davos

Global Risks Landscape 2017

The Global Risks Report 2015, World Economic Forum, Davos



Disaster Risk Estimation



Disaster Risk Management and Climate Change Adaptation (IPCC SREX 2012)

Risk=Rate x Vulnerability x Consequence

Extreme Events

- Extreme events in highly correlated system with multiple components
- Emergence from
  - gradual evolution (long-range correlations) or
  - triggered (directly driven)
- Identification of processes that can trigger
- Space weather multiple components that require different physics
- Integrative modeling

Extreme Space Weather

Fundamental Processes in Space Weather

- Multiple components that require different physics
- Plasma processes of relevant phenomena – essential for numerical simulations

  (first-principle : plasma physics)
- Statistical nature – essential to predictability of extreme events

  (first-principle : nonequilibrium statistical physics)
- Data-driven modeling – effective tools for quantitative predictions

  (first-principle: complexity science)

Integrative modeling

Reconstruction of Dynamics

"Geometry from a time series"

(Packard et al., PRL, 1980)

Embedding theorem (Takens, 1981)

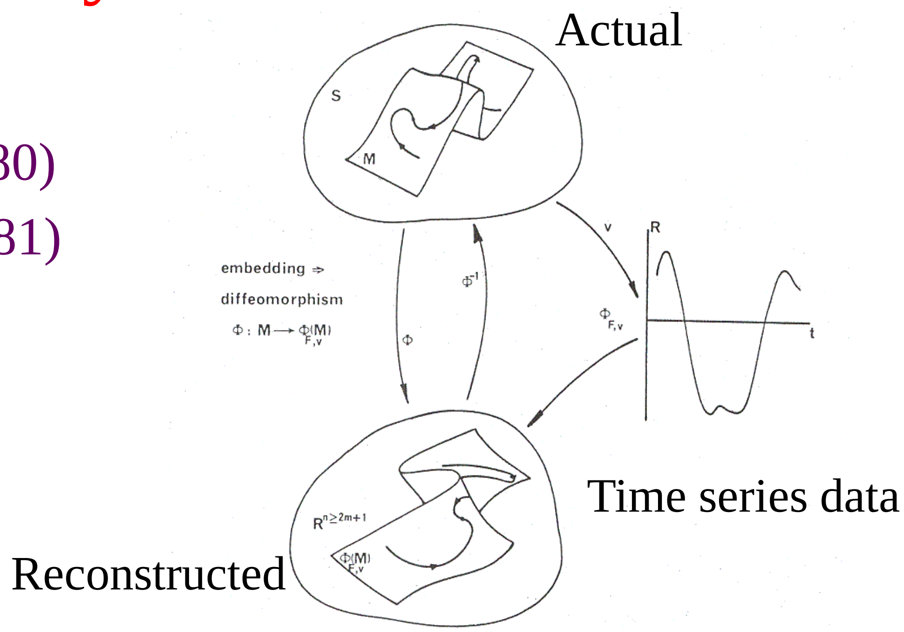
Time series data: $x(t)$

Time-delay embedding:

$$x_k(t_i) = x(t_i + (k\text{-}1)\tau)$$

Reconstructed space:

$$X_i = \{x_1(t_i), x_2(t_i), x_3(t_i), ..\}$$



(Broomhead and King, Phys. A, 1986)

First prediction of space weather

US National Report to IUGG 1991 - 1994

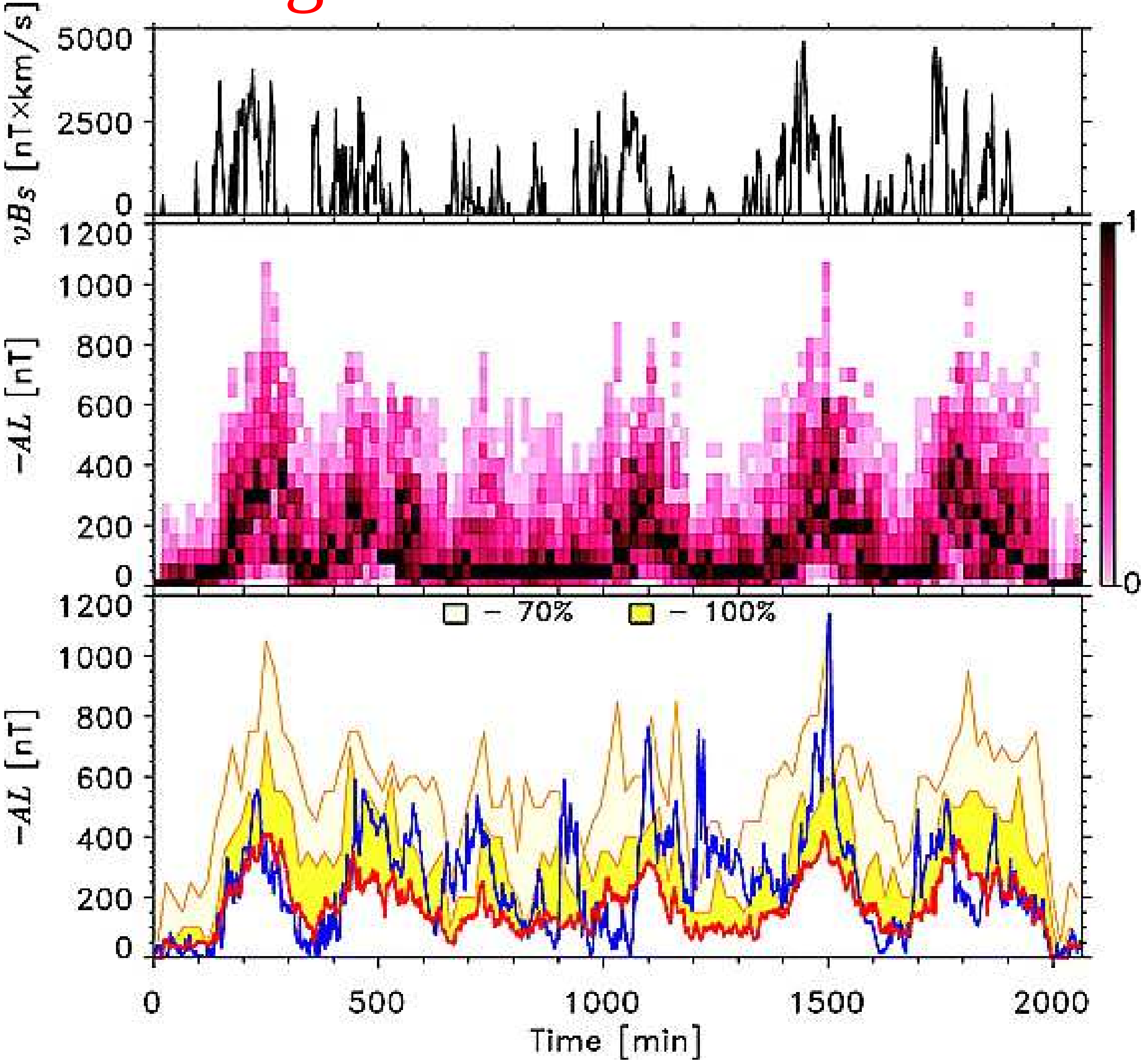
"Assessing the magnetosphere's nonlinear behavior: Its dimension is low, its predictability, high", Sharma, Rev Geophys., 1995.

Space Weather Forecasting

Solar wind conditions

Distribution of past events

Predicted and actual AL; Conditional probabilities
Ukhorskiy et al., 2004



Near-real time forecasts using Solar wind data at L1 (ACE, DSCOVR):
www.astro.umd.edu/spaceweather

Long Range Correlations (LRC): Hurst Exponent

LRC and power law :

Fluctuation functions

$$F(\tau) \sim \tau^{H}$$

$$0 < H < 1$$

$H = 0.5$: Uncorrelated

$H > 0.5$: Persistence

$H < 0.5$: Anti-persistence

Relationship with other exponents:

- Auto-correlation: $C(\tau) \sim \tau^{-\gamma}, \quad H = 1 - \frac{\gamma}{2}$
- Spectral density: $PSD(f) \sim f^{-\beta}, H = \frac{(\beta - 1)}{2}$

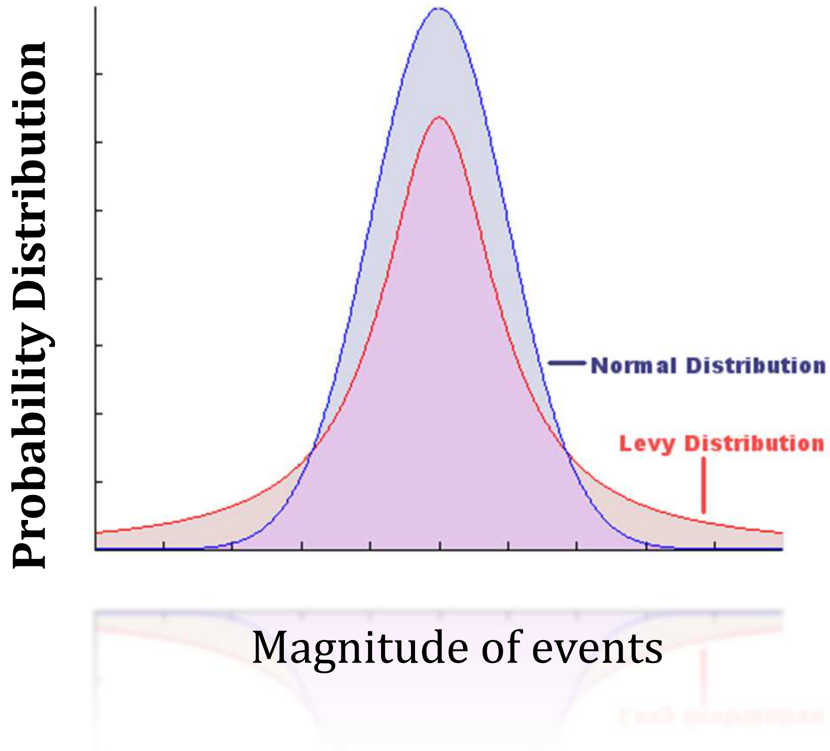
LRC and Extreme Events

Taqqu's Theorem

LRC drives "Heavy tail behavior"

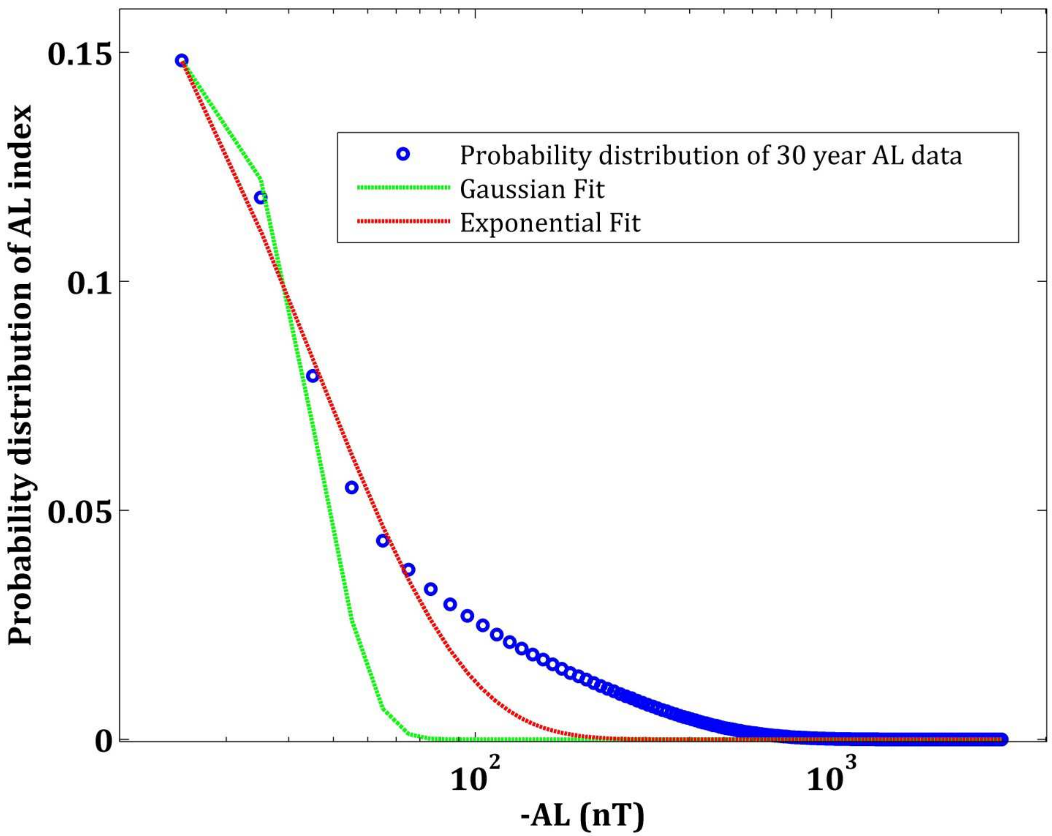
$$H = \frac{(3-\delta)}{2},$$

δ characterizes the "thickness" of the tail of the distribution - *Tail index.*



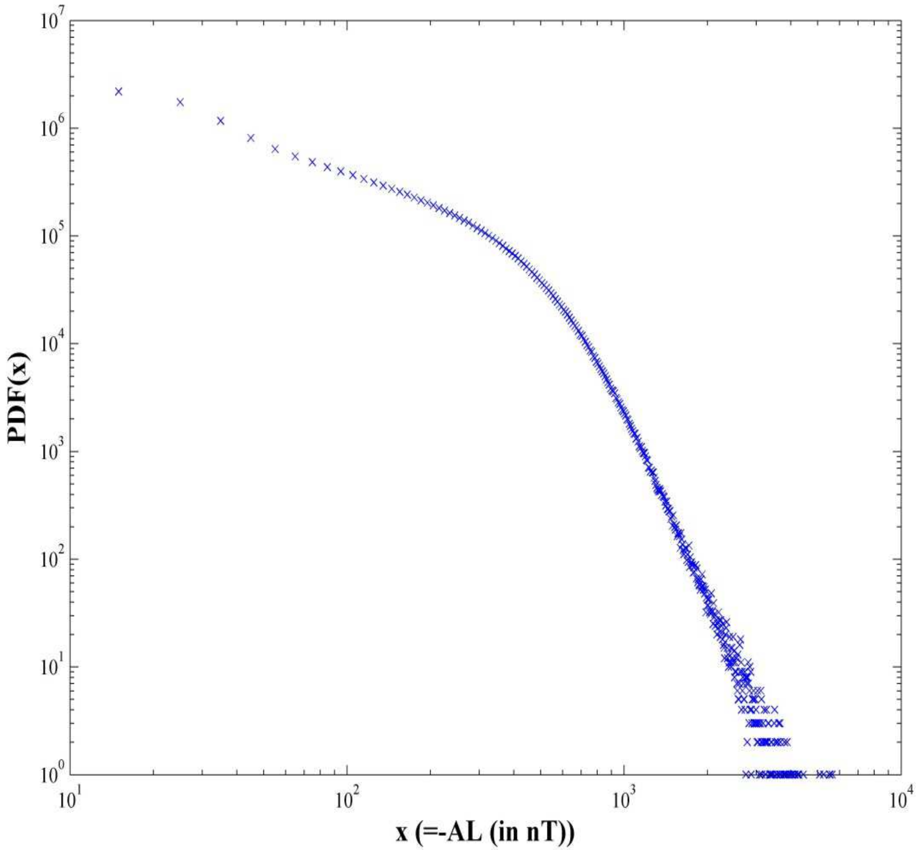
Taqqu et al., (1986) 73-89. *Birkhäuser*: Boston.

Geomagnetic Disturbance:
Probability Distribution Function



Heavy-tail distribution of frequency vs. event size for 1-min AL data

Geomagnetic Disturbance: AL Index



Distribution of frequency vs. event size for 1-min AL data for 30 years.

Estimates on Large Events?

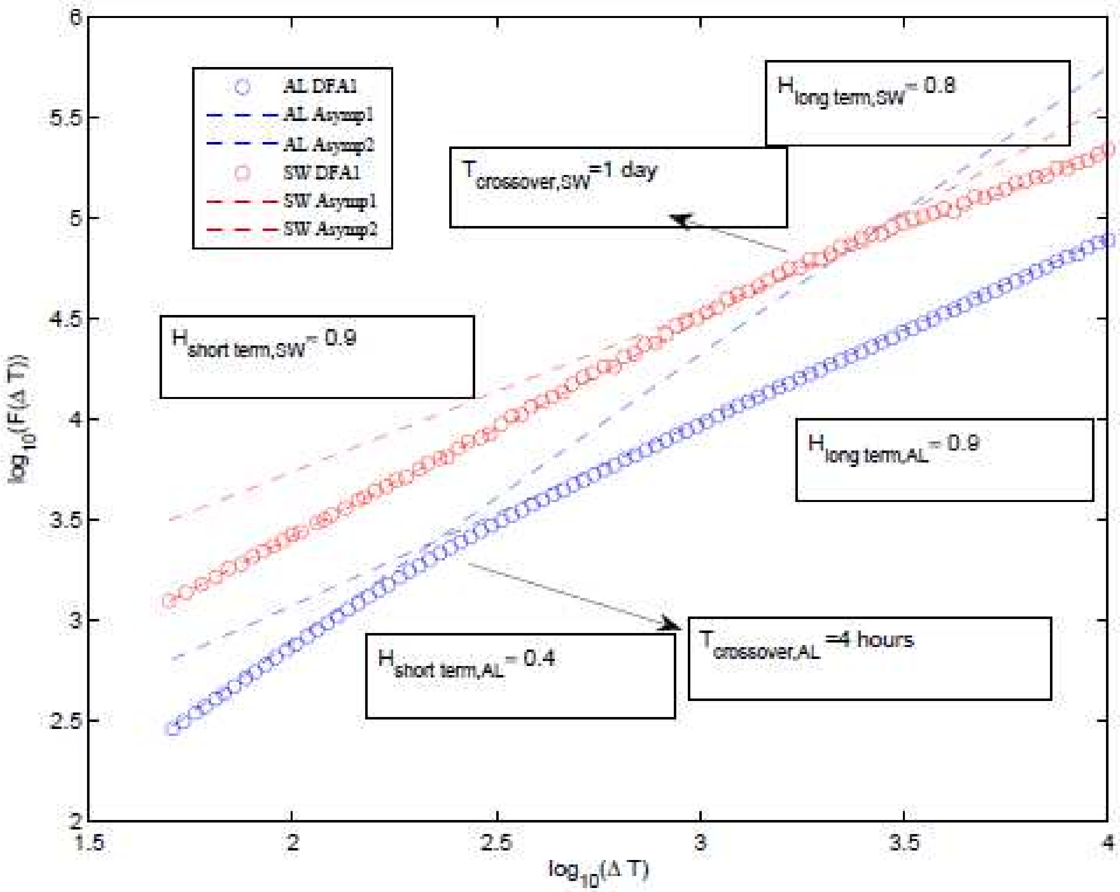
Crossover Analysis - Hyperbolic Regression
AL Index & Solar Wind

AL and Solar wind data (2000-2013)

H values and $T_{crossover}$ from Hyperbolic regression

Crossover in H for AL not of solar wind origin

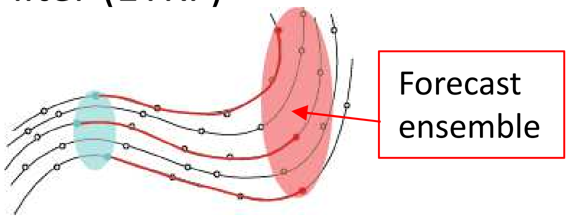
Need a model for crossover in AL



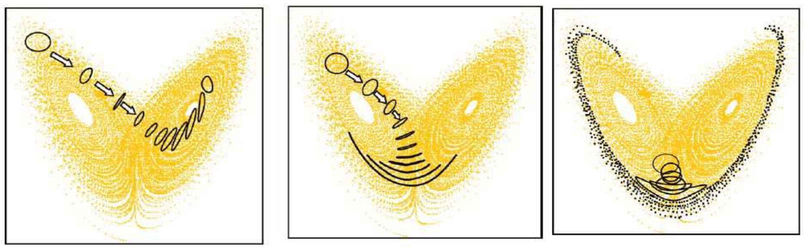
Sharma and Veeramani, 2011
Setty, *Ph. D. thesis., UMD* 2014

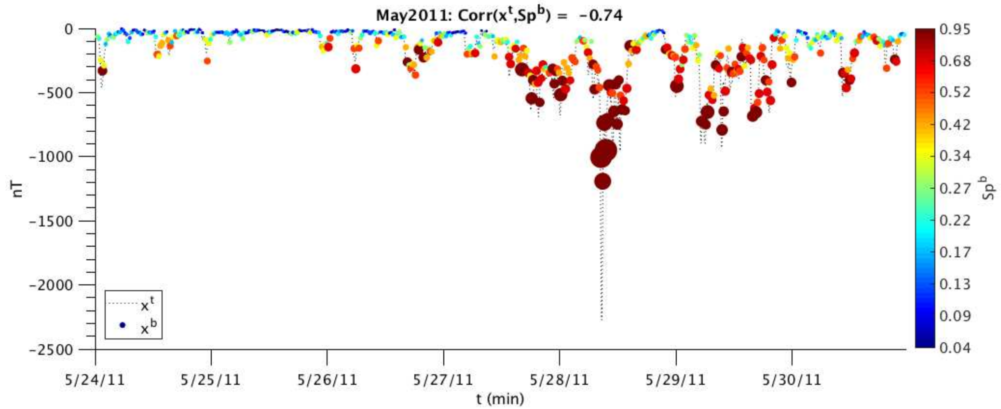
Extreme events and Ensemble forecasting

- Data-driven models without governing equations
- Forecasts using Ensemble Transform Kalman Filter (ETKF)



- Ensemble spread as an indicator of extreme events





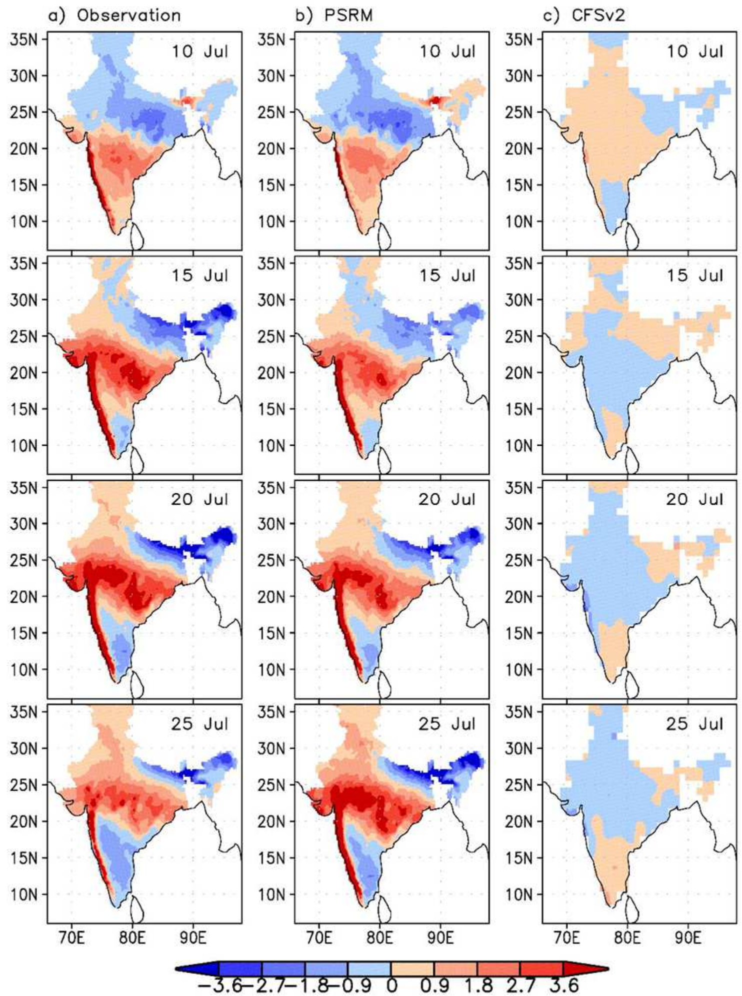
Erin Lynch, Ph. D. thesis (2017)

Data-driven Modeling and Prediction: Intra-seasonal predictability

Phase space reconstruction model. (PSRM):
Rainfall data on 0.25 deg longitude × 0.25 deg latitude grid for 1901-2009 (1800 stations)

Climate Forecasting System (CFS)
State of the art numerical model (NOAA)

Modeling by Reconstruction using Rainfall and CFSv2 data.
Improvement of predictability



Comparison of predictions of PSRM and CFSv2

Key results and conclusions:

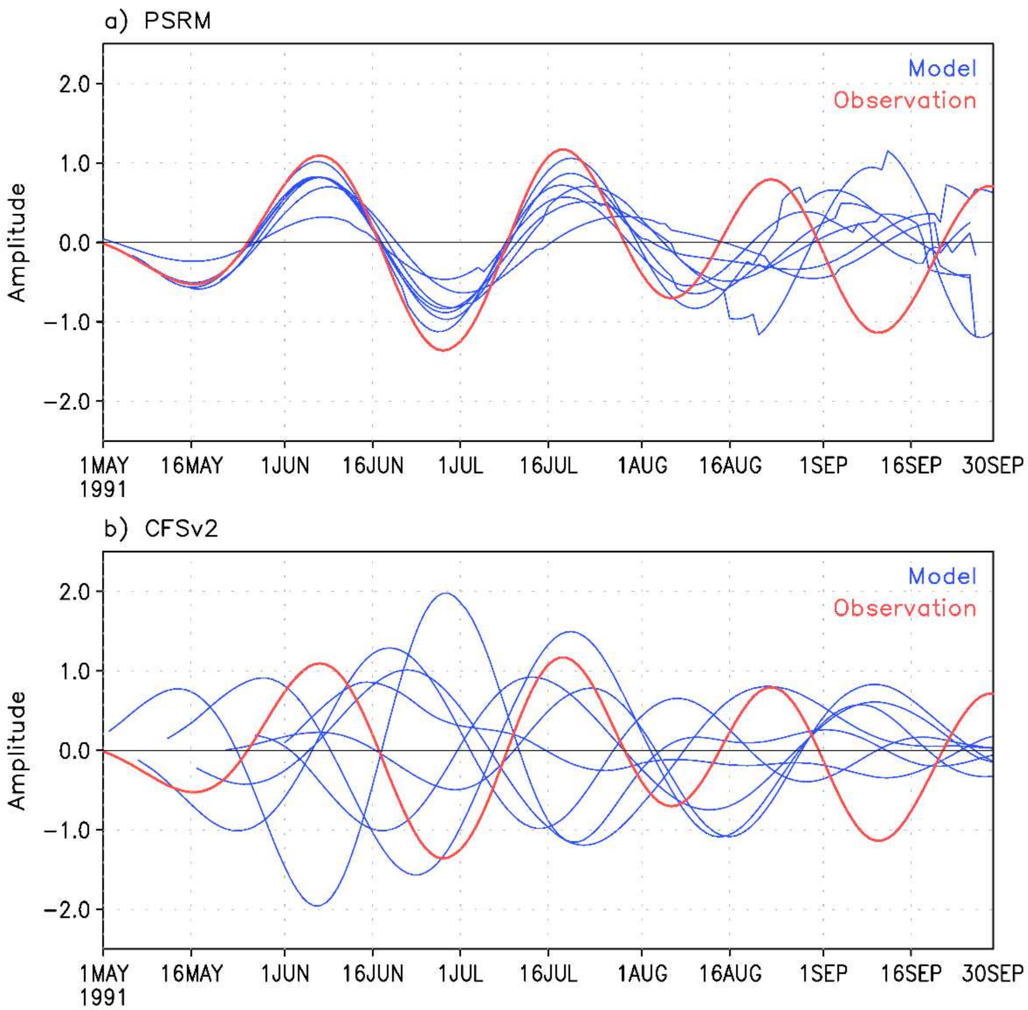
Intraseasonal oscillations are predictable

Predictability of intraseasonal phenomena such as MJO and midlatude processes

Data-driven modeling provides higher predictability

Modeling and prediction of spatio-temporal structure of space weather

Need for networks of monitoring stations



Krishnamurthi and Sharma, 2017

Confluence of Extreme Events

- Most extreme events are isolated
- Extreme space weather can have confluence with another event
- Spread weather related disruption during
- 2011 Japan Earthquake
- Hurricane Sandy
- Integrated effects study and analysis needed
- Low probability – high risk
- Worst case scenario

Space Weather Workshops
at University of Maryland, College Park

Space Weather Impacts on Economic Vitality and National Security,

October 2015 (NSF, NASA, NOAA)

Extreme Space Weather

July 2016 (NSF) Report (Eos, July 2017)*

Next meeting planned Spring 2018

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Predictive Capability
for Extreme Space Weather Events

Workshop on Modeling and Prediction of Extreme Space Weather Events
College Park, Maryland, 22–24 August 2016