Predictability of Extreme Space Weather

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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

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:
$x_k(t_i) = x(t_i + (k-1)\tau)$

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


“Assessing the magnetosphere's nonlinear behavior:
Its dimension is low, its predictability, high”,
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
\[ F(\tau) \sim \tau^H \]
\[ 0 < H < 1 \]

Relationship with other exponents:

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

**Taqqu’s Theorem**

LRC drives “Heavy tail behavior”

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

\( \delta \) characterizes the “thickness” of the tail of the distribution - *Tail index*.

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 $T_{\text{crossover}}$
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

Data-driven Modeling and Prediction: Intra-seasonal predictability

Phase space reconstruction model (PSRM):
Rainfall data on 0.25 deg longitude \times 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
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