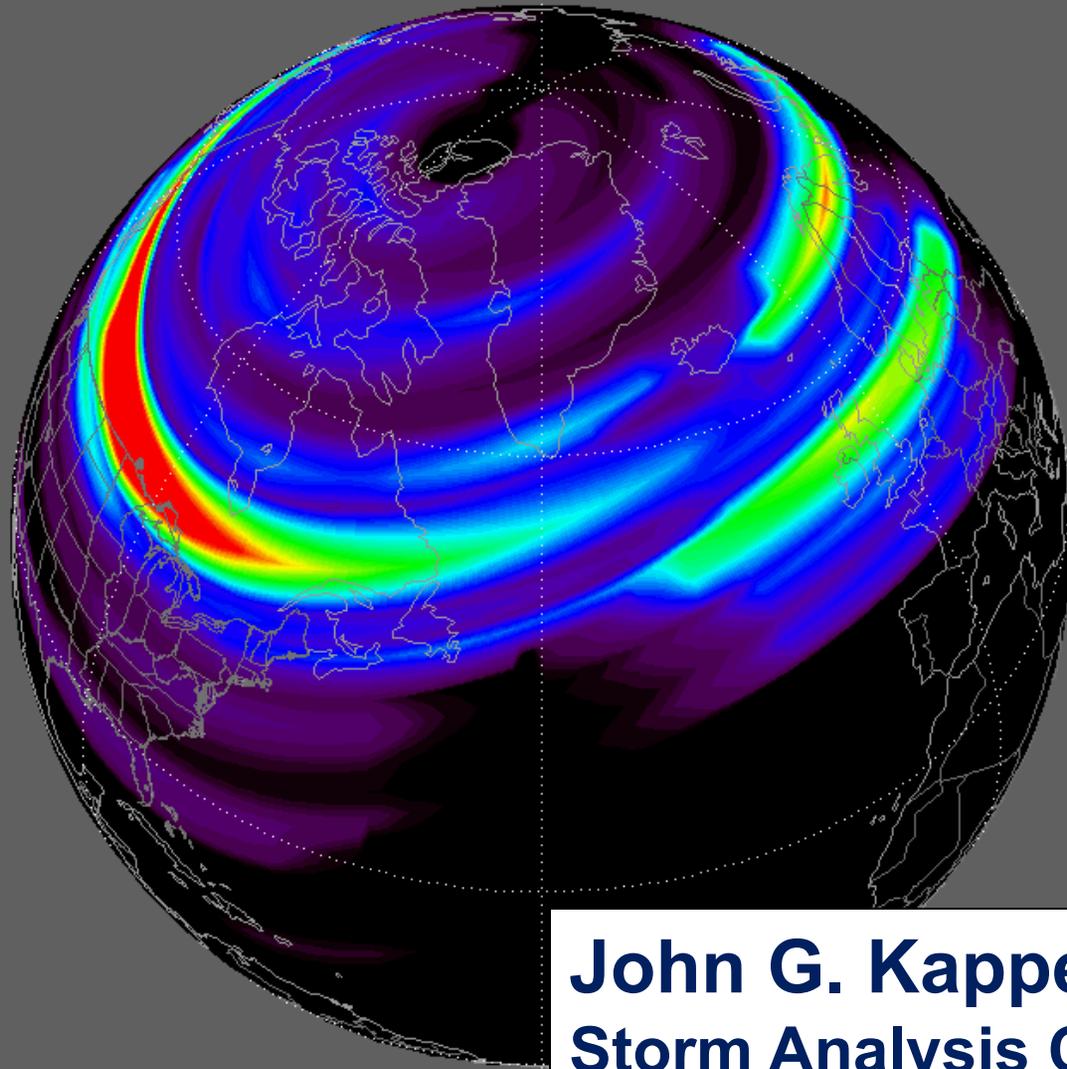


Space Weather and US Electric Power Grid Vulnerabilities:

An Overview of the Risks to this Critical Infrastructure and
Research Necessary to Assess Vulnerability and Mitigate Impacts



John G. Kappenman
Storm Analysis Consultants

Review of Power Grid Vulnerability to Space Weather

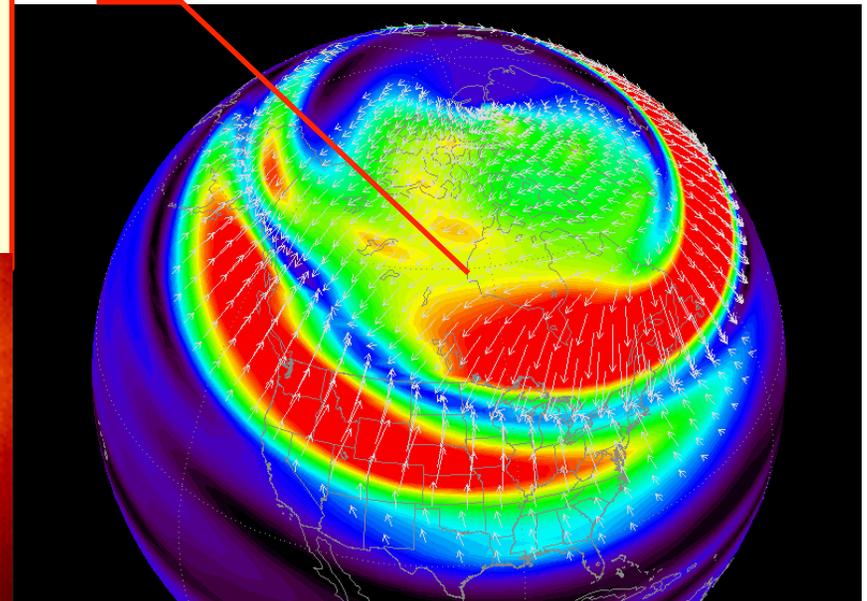
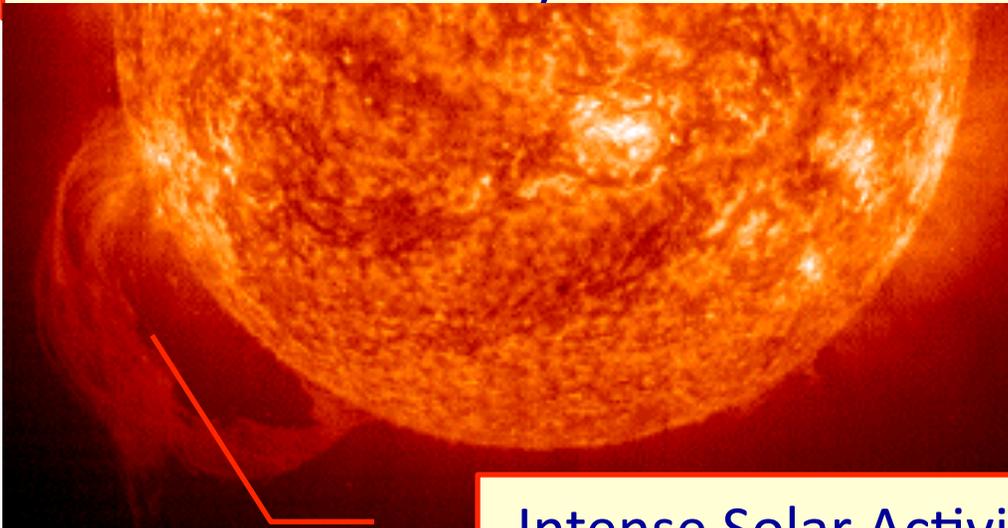
- The US Electric Power Grid is a Critical Infrastructure & Increasingly Vulnerable to Space Weather
 - Electricity is largest energy segment of US ~40% of all energy consumed (petroleum only 22% of current US energy consumption)
- EMP Commission, FEMA Exec Order 1340, National Academy of Sciences Investigation Results Indicate
 - Space Weather Risks have potential to create Large Scale Blackouts,
 - Permanent Damage to Transformer Assets and Lengthy Restoration
- Loss of Electric Supply will Impact all other Interdependent Infrastructures
 - Potable Water distribution, waste treatment impacted within several hours,
 - Loss of perishable foods and medications in about 12-24 hours,
 - Immediate or eventual loss of heating/AC, sewage, phones, transportation, fuel resupply, etc.



A Review of Power Grid Vulnerability to Solar Activity & Geomagnetic Storms

Geomagnetic Storms are disturbances in the Earth's normally quiescent geomagnetic field caused by intense Solar activity

Geomagnetic Storms have Continent-Wide & Planetary Footprints – Threaten Developed Economies on Planetary Scale

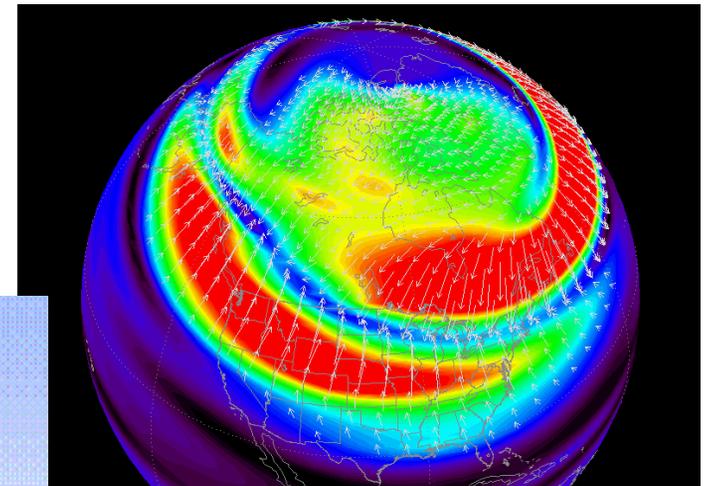
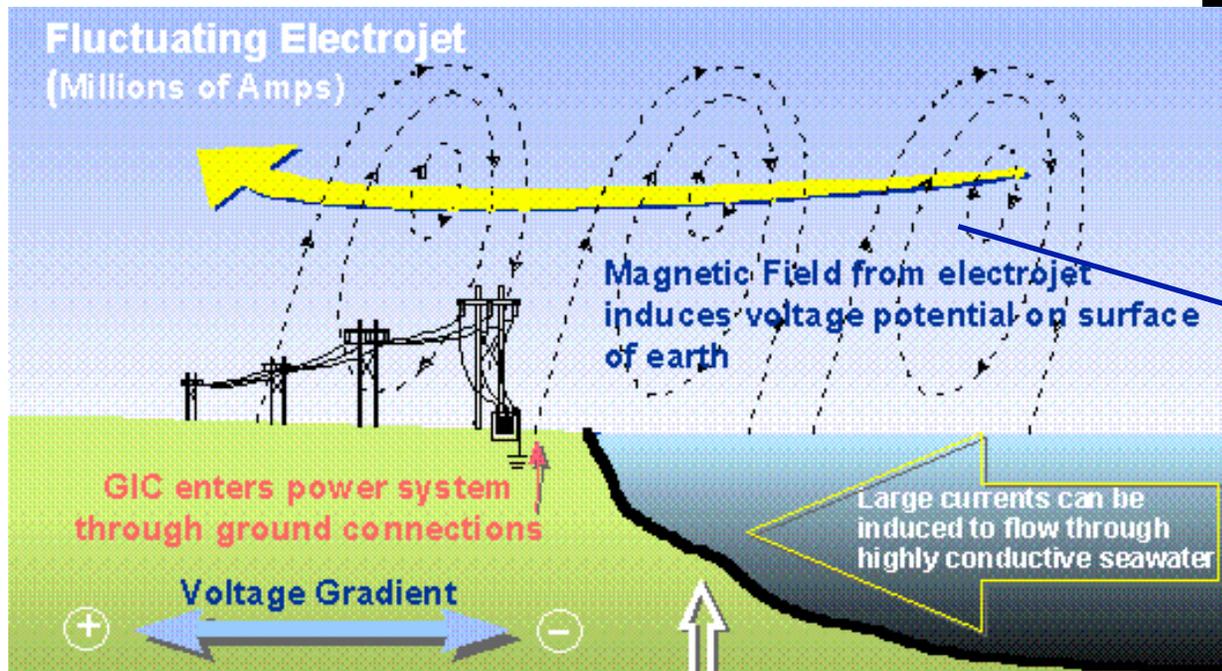


Intense Solar Activity – Carrington Class Solar Events are not Rare – Playing Russian Roulette with the Sun



A Review of Power Grid Vulnerability to Solar Activity & Geomagnetic Storms

A rapidly changing geomagnetic field over large regions will induce Geomagnetically-Induced Currents (i.e. GIC a quasi-DC current) to flow in the continental interconnected Electric Power Grids

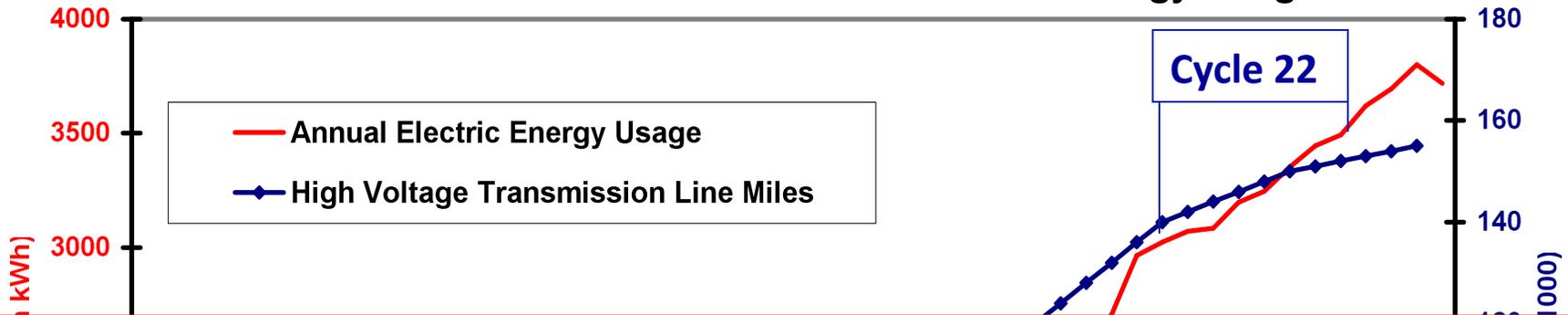


Storm causes Geomagnetic Field Disturbances from Electrojet Current that couple to Power Systems

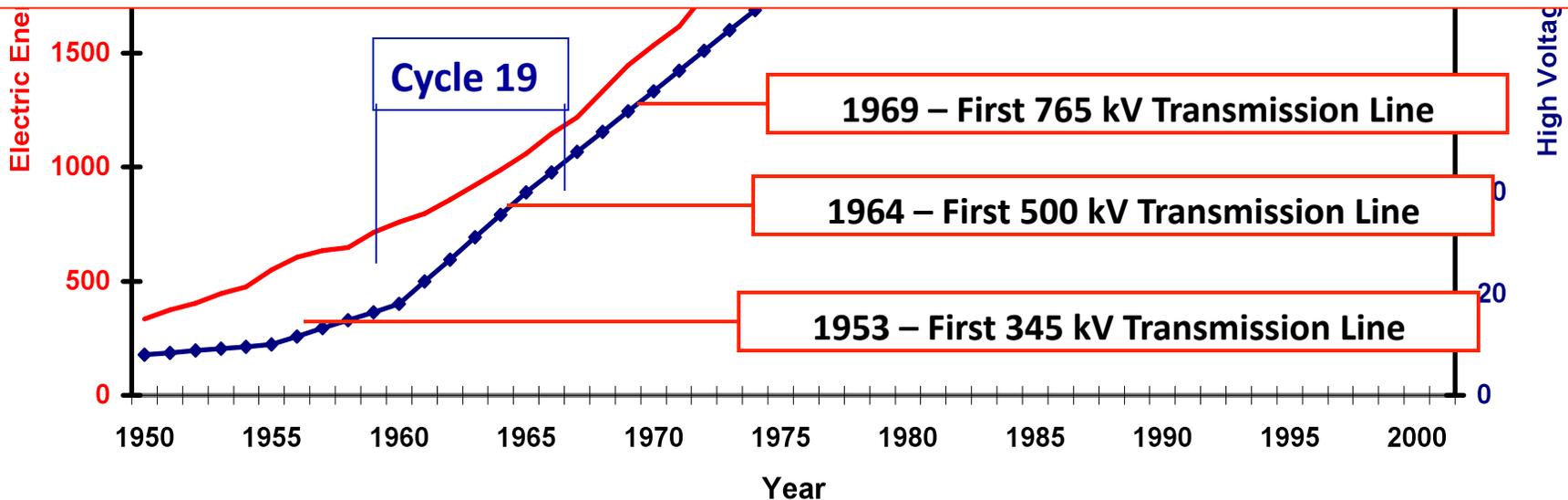
GIC Risk Factor – Growth of Transmission Network

The larger the Grid – the Larger the Antenna to cause GIC

Growth of US Transmission Grid & Electric Energy Usage



**Lacking a Design Code for this Threat Environment
We have been stacking Risk Multipliers On Top of Risk Multipliers
Unknowingly Escalating Risk to Society**



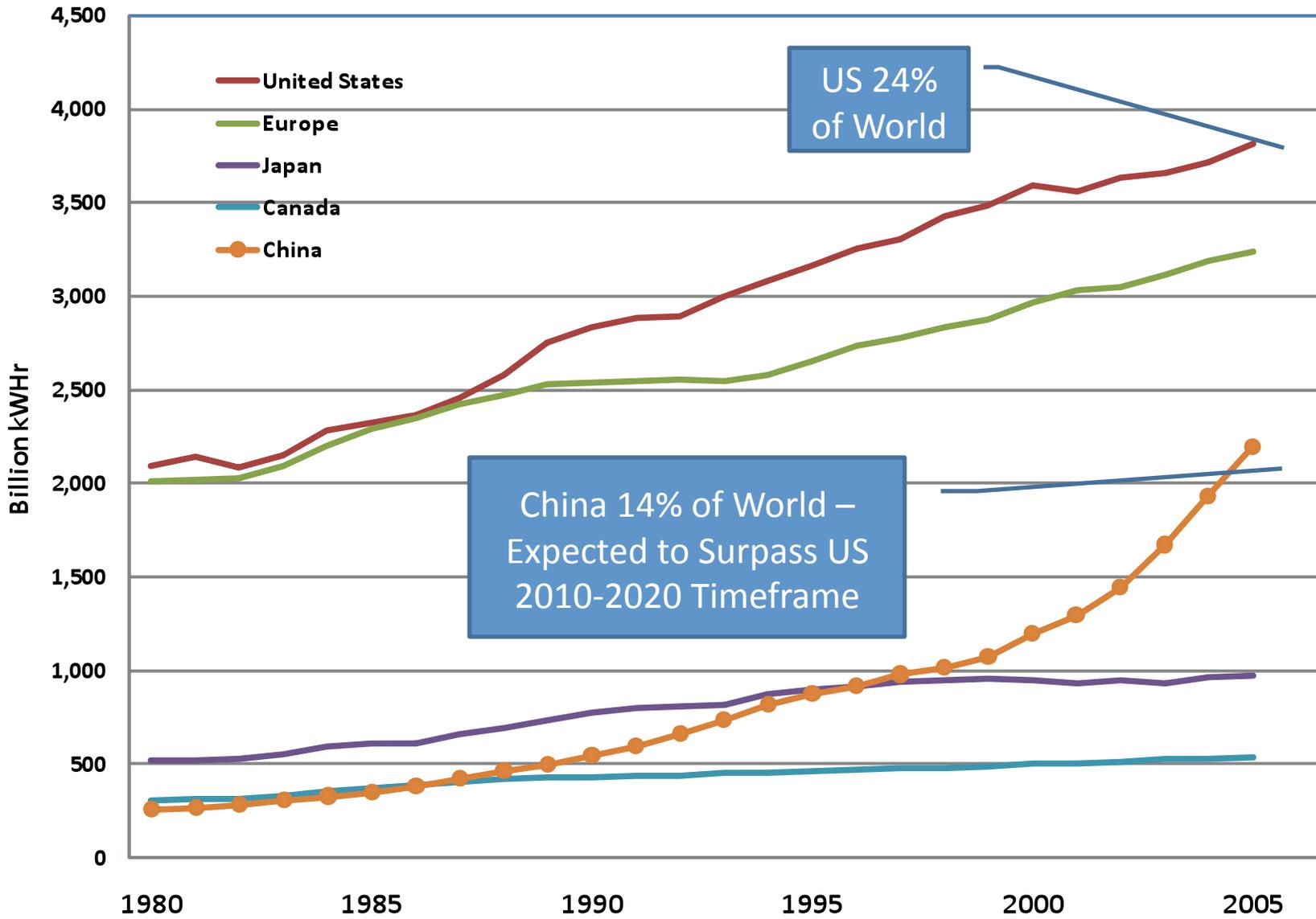
US High-Voltage Transmission Network

500 kV & 765 kV serve ~60% of US geographic territory and ~86% of US population

— 765kV
— 500kV
— 345kV

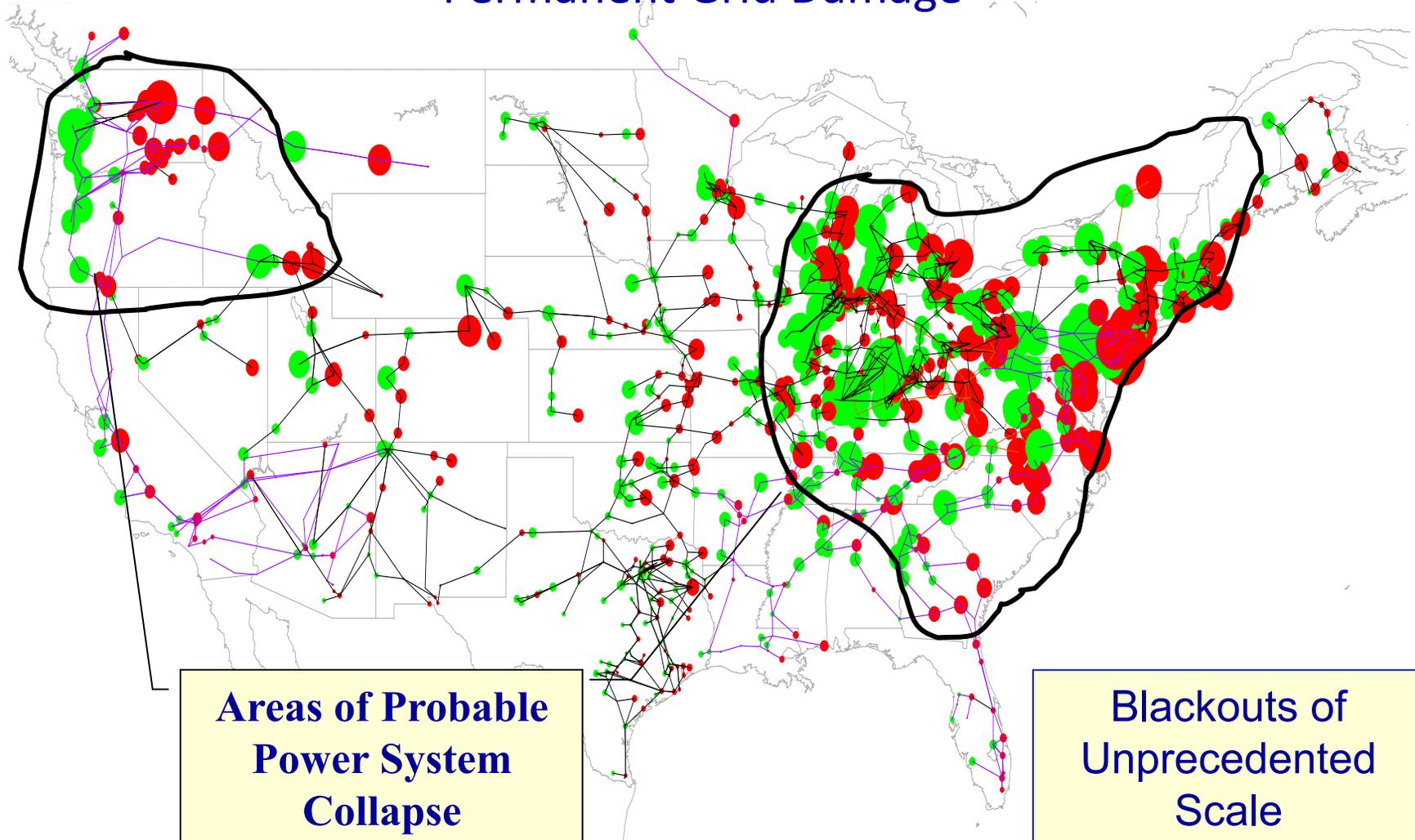
European and Asian Continental Grids are of similar proportions

World Electric Energy Usage



A Review of Power Grid Vulnerability to Solar Activity & Geomagnetic Storms

GIC flow in transformers can cause Power Grid Blackouts & Permanent Grid Damage



A Review of Power Grid Vulnerability to Solar Activity & Geomagnetic Storms

GIC flow can also has potential to cause wide-spread catastrophic damage to key Power Grid Transformers
Causing Restoration Problems

These Key Assets may take a
Year or More to Replace



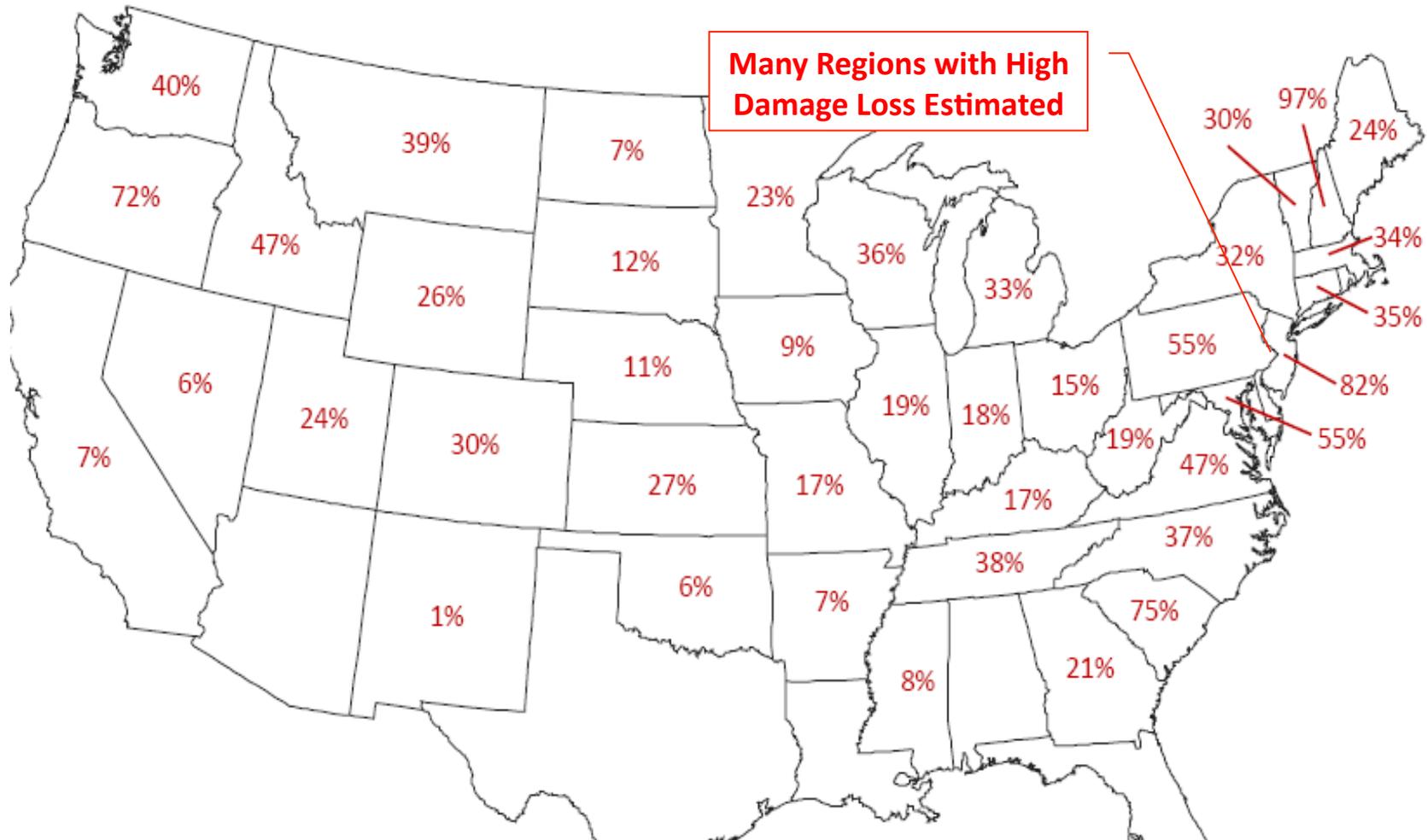
Salem Nuclear Plant
GSU Transformer
Failure, March '89



Internal
Damage due
to one storm

Severe Geomagnetic Storm Scenario

At-Risk 345kV, 500kV, & 765kV Transformers



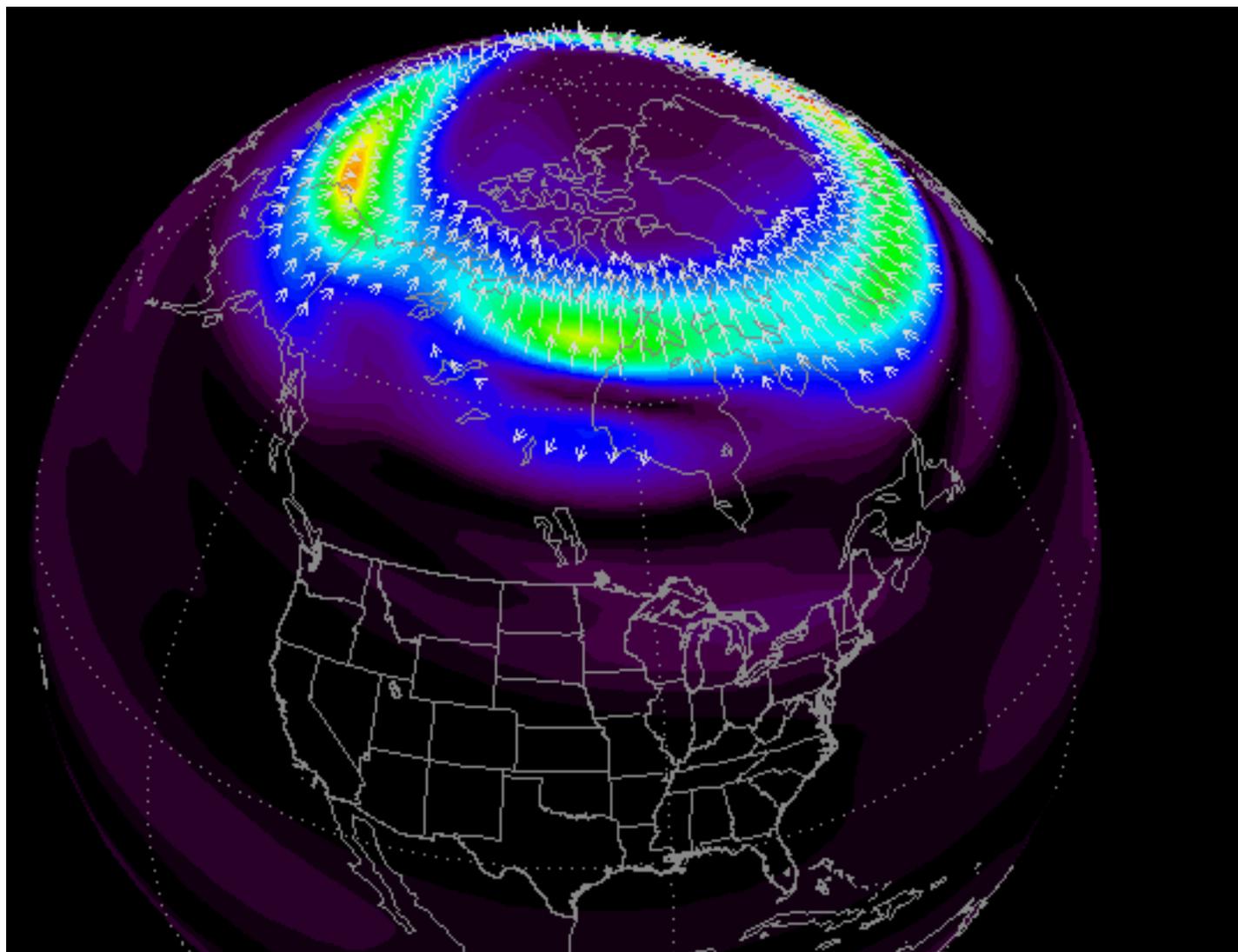
Estimated that many large EHV Transformers would have sufficient GIC exposure to be At-Risk of Permanent Damage & Loss – Replacement could extend into 4-10 years at current world production rates

Great Geomagnetic Storms

US Electric Grid Vulnerability Trends and Preparedness

- **Threat**
 - New Awareness that Geomagnetic Storm Severity is 4 to 10 Times larger than previously understood – Past NOAA Metrics did not measure risks correctly for power industry
- **Vulnerability**
 - Power Grid infrastructures have experienced a “Design Creep” over past few decades that have unknowingly escalated vulnerability to these threats – No Design Code Yet Exists
- **Consequences**
 - Power Supply is an essential scaffolding of modern society – a process of “Interdependency Creep”
 - All other Critical infrastructures will also collapse with long-term loss of Electricity
- **Risk** – Events have catastrophic potential, the ability to take the lives of hundreds of people in one blow, or to shorten or cripple the lives of thousands or millions more, impact future generations of society

March 13, 1989 – Storm 7:39UT



Time 2:39-2:58 EST (7:39-7:58 UT)

20 Minutes of Bad Space Weather

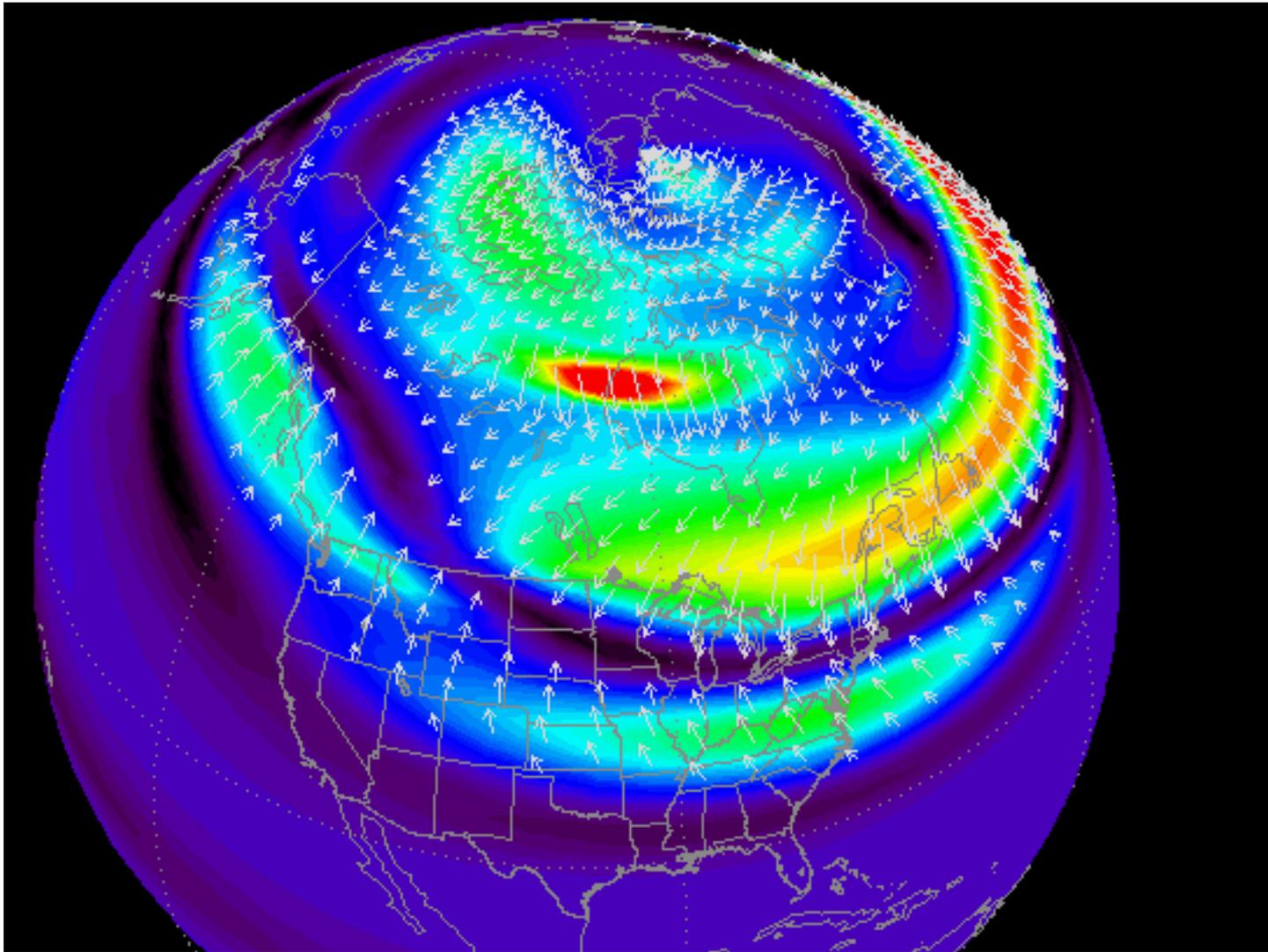
Reported Power System Events – March 13, 1989



Time 2:39-2:58 EST (7:39-7:58 UT)

Quebec Blackout in 92 Seconds at
Intensity of ~ 480 nT/min

March 13, 1989 – Storm 21:40UT



Time 4:40-5:30 PM EST (21:40-22:30 UT)

Reported Power System Events – March 13, 1989

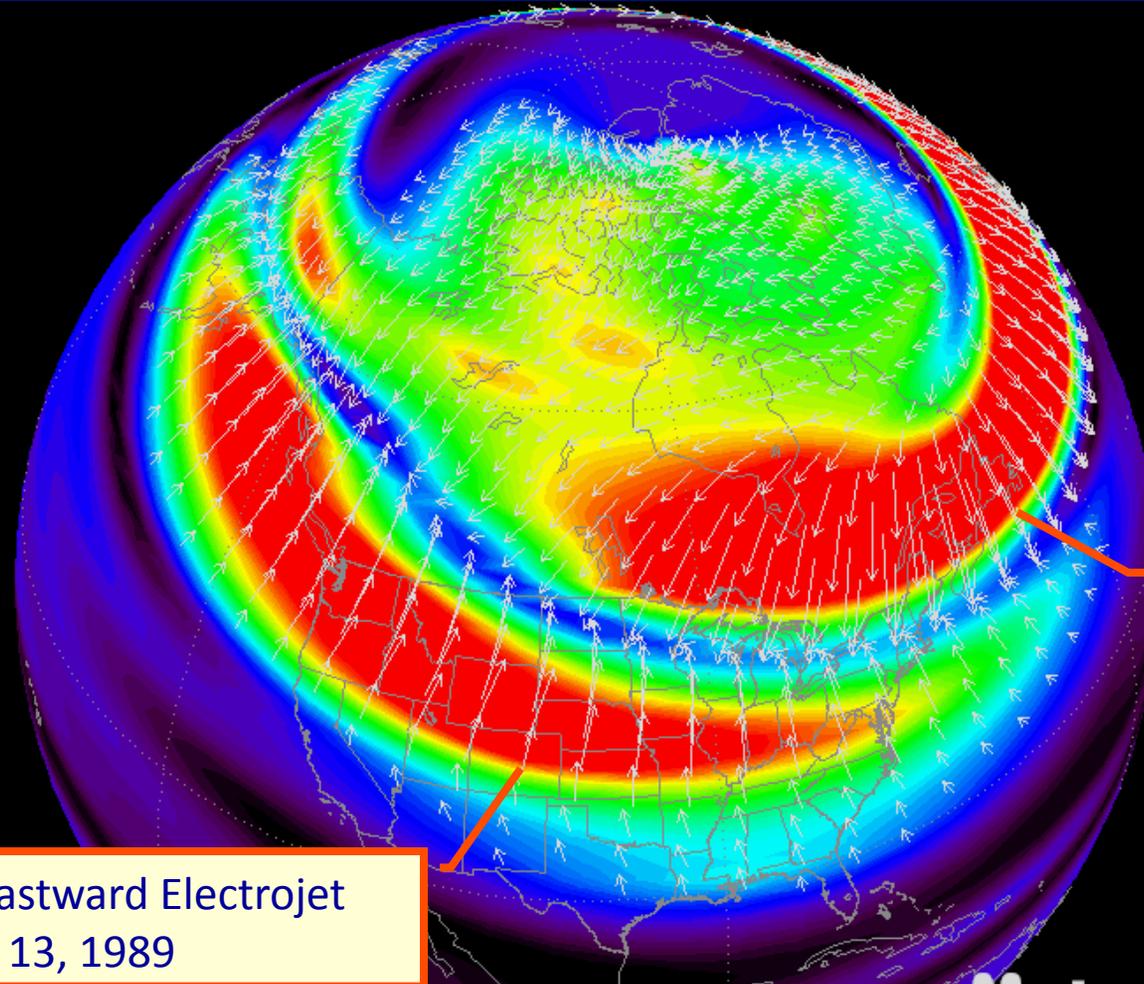


Time 16:03-17:30 EST (21:03-22:30 UT)

Intensity over Mid-Atlantic Region
~300 nT/min

Great Geomagnetic Storms

March 1989 Superstorm & May 1921 Storm Comparisons



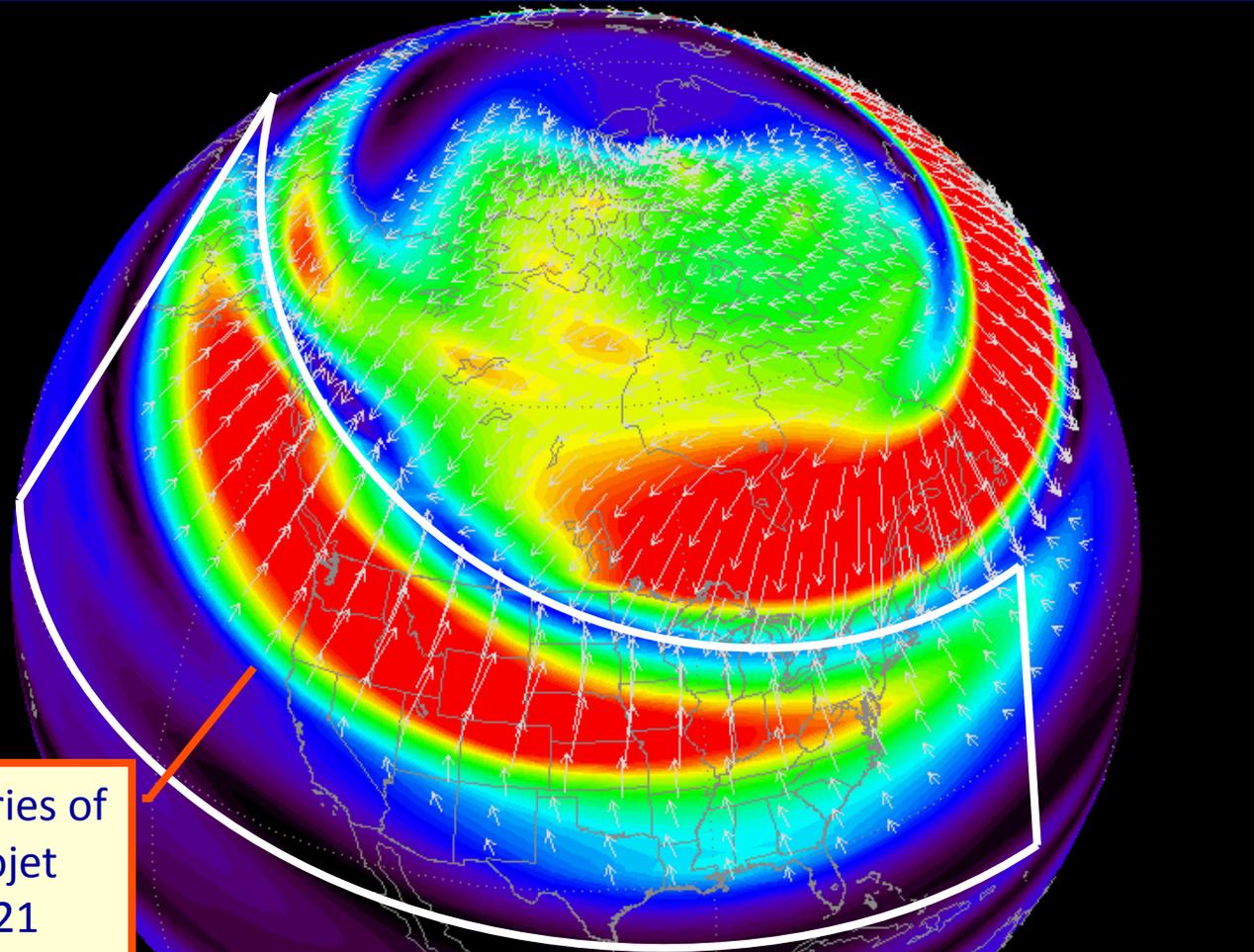
Position of
Westward
Electrojet

Boundaries of Eastward Electrojet
March 13, 1989



Great Geomagnetic Storms

March 1989 Superstorm & May 1921 Storm Comparisons



Estimated Boundaries of
Eastward Electrojet
May 14-15, 1921
Larger & More Intense than
March 1989



A Review of Power Grid Vulnerability to GIC Events

- GIC driven by fast changes in geomagnetic field (need data and forecasting from 1 second to 1 minute cadence)
- GIC in Power Grids can be driven by a number of diverse Magnetospheric/Ionospheric Processes, Including
 - Electrojet Intensifications –Threatening to Power Grids at High to Mid-Latitude Locations
 - Equatorial Current System Intensifications – Threatening to Power Grids at Low to Equatorial Latitude Locations
 - SSC/Shock Events – Threatening to Power Grids at all Latitudes
 - Suspect Kelvin/Helmholtz Shearing arising from Extreme Solar Wind Conditions
 - All of Above have been Observed in Contemporary Storms
 - Very Little is Yet Known about the Possible Extremes of these Storm Processes
- With each new Major Storm we have Learned New and Unpleasant Surprises on ways that our Infrastructure can Fail



Wrap-Up

The Nation has experienced a Several Decade Long Failure to Understand how Risk has Migrated into our Electric Grid Infrastructures from Space Weather Threats

This Failure has been Collective - Spanning Space Weather Community to Power Grid Infrastructure Operators

What are the Issues We should Understand Going Forward

- The Sun, Magnetosphere remain fully Capable of Producing Historically Large Geomagnetic Storms in the Future
- Grid Design Evolutions have unknowingly Escalated GIC Risks and Potential Impacts
 - Un-Recognized Systemic Risk** – No Design Code Yet to minimize this Threat
- Given Sufficient Time the Reoccurrence of Large Storm Event is a Certainty – Only with Much more Serious Consequences**