The Potential of Adaptive Chaos Control to Mitigate Climate Extremes

Weather Jiu-Jitsu: Can a mouse's nudge make a lion roar?

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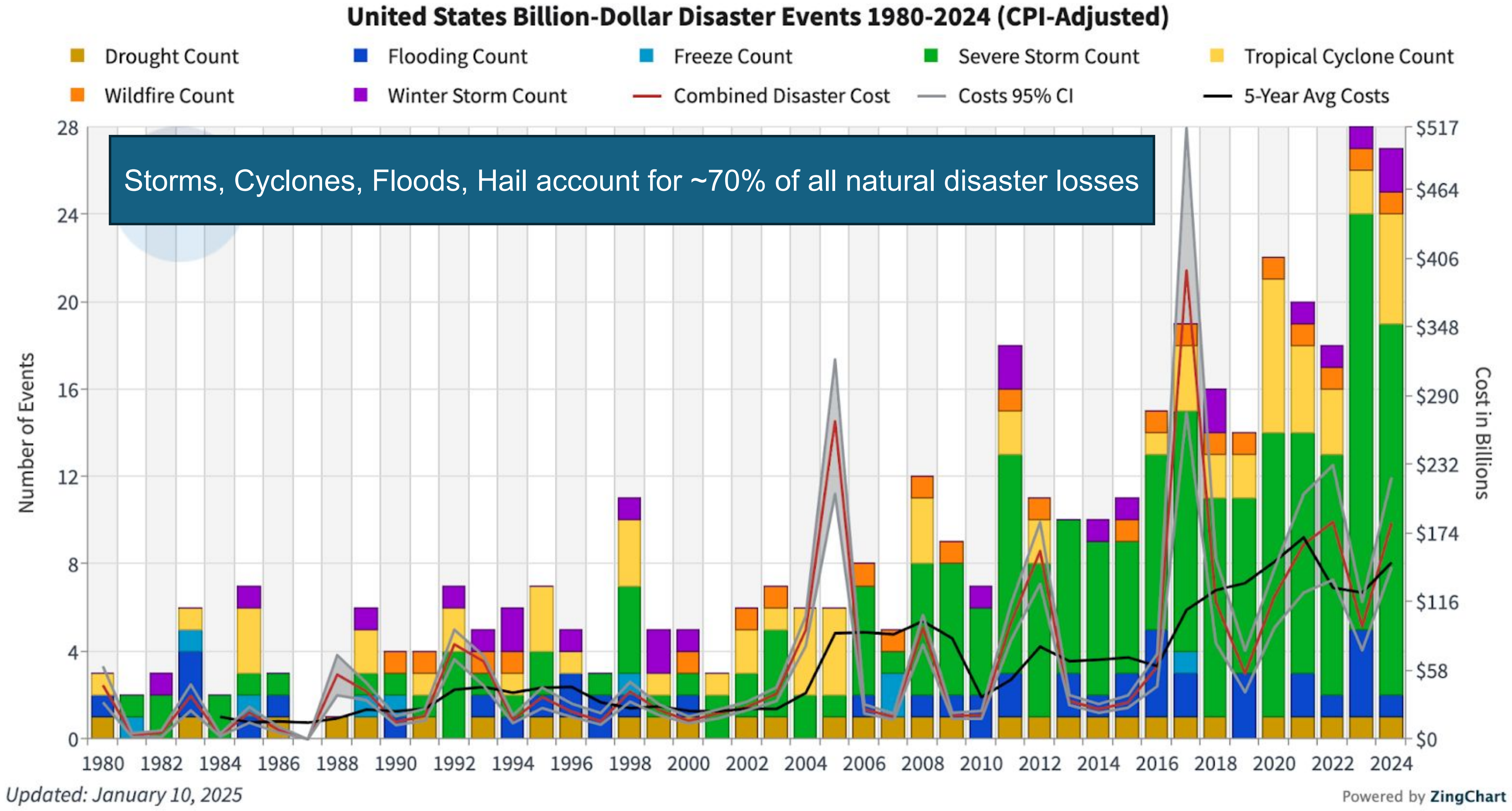
Storms, Cyclones, Floods, Hail account for ~70% of all natural disaster losses



https://www.climate.gov/news-features/blogs/beyond-data/2022-us-billion-dollar-weather-and-climate-disasters-historical

Global Weather Losses as Percent of Global GDP: 1990-2024

(Sources: Munich Re, World Bank & updated from Pielke 2019)

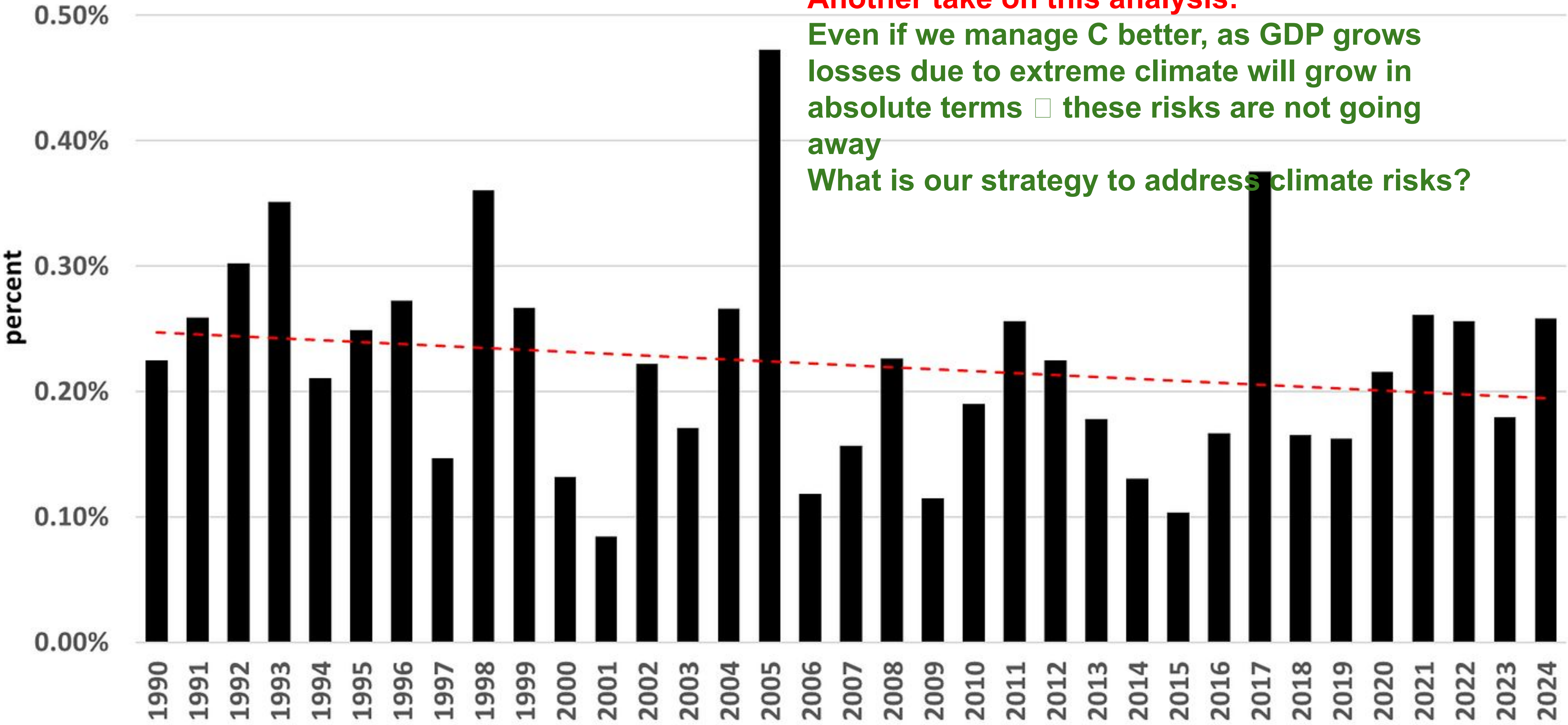
https://rogerpielkejr.substack.com/p/climate-change-is-showing-its-claws

THB

Another take on this analysis:

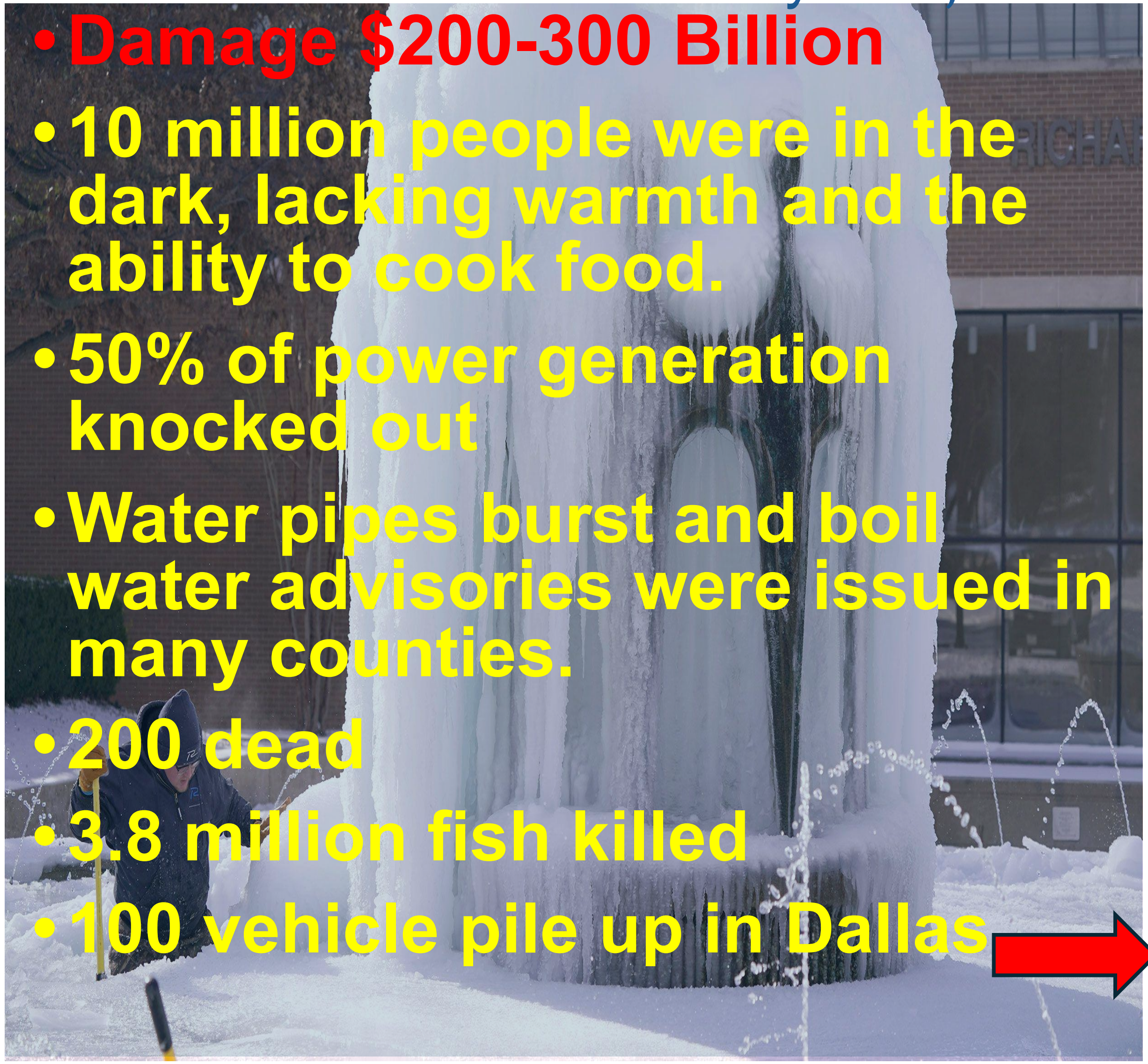
Even if we manage C better, as GDP grows losses due to extreme climate will grow in absolute terms □ these risks are not going away

What is our strategy to address climate risks?

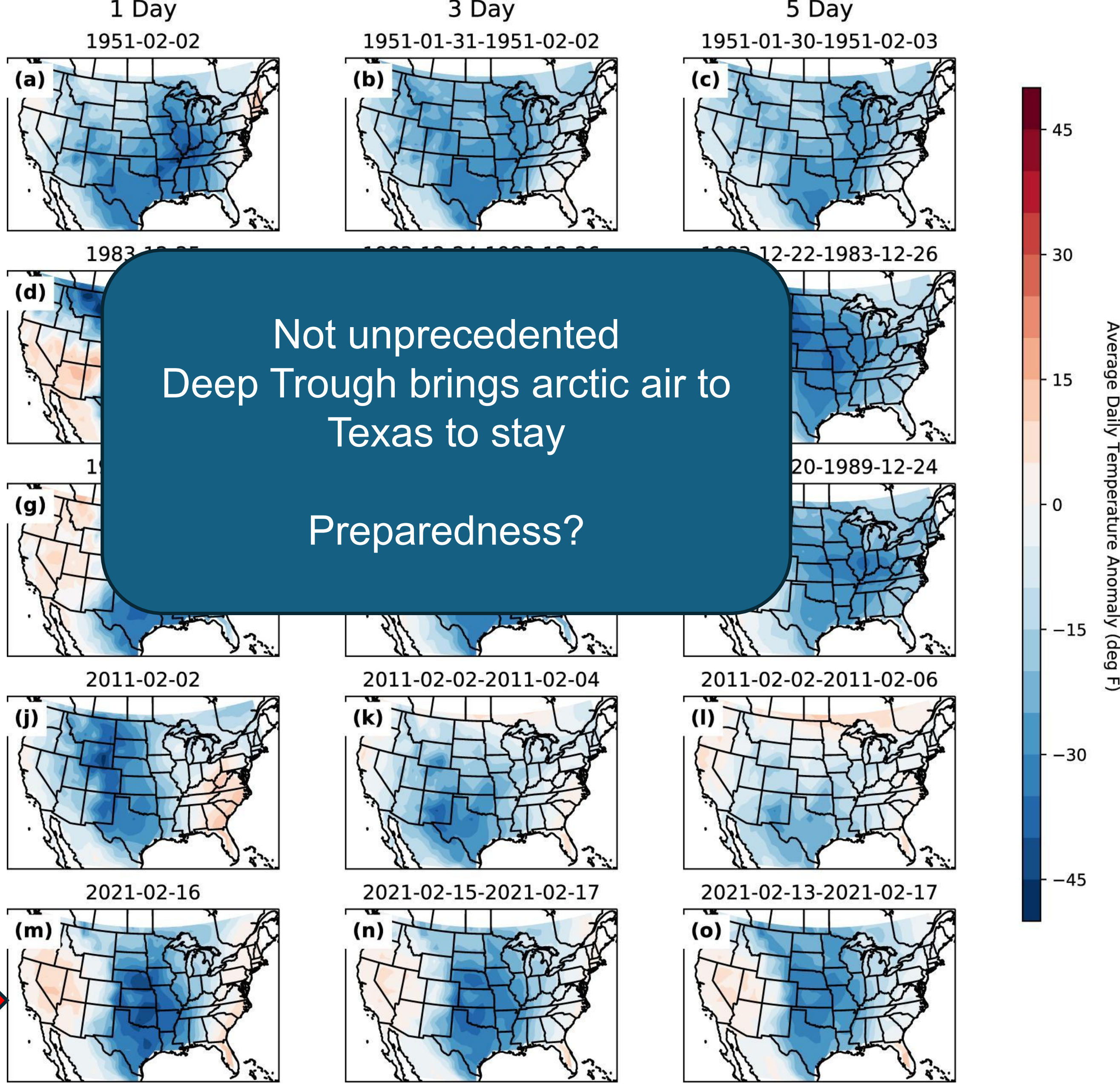


Frozen…………..

The Great Texas Freeze: February 11-20, 2021



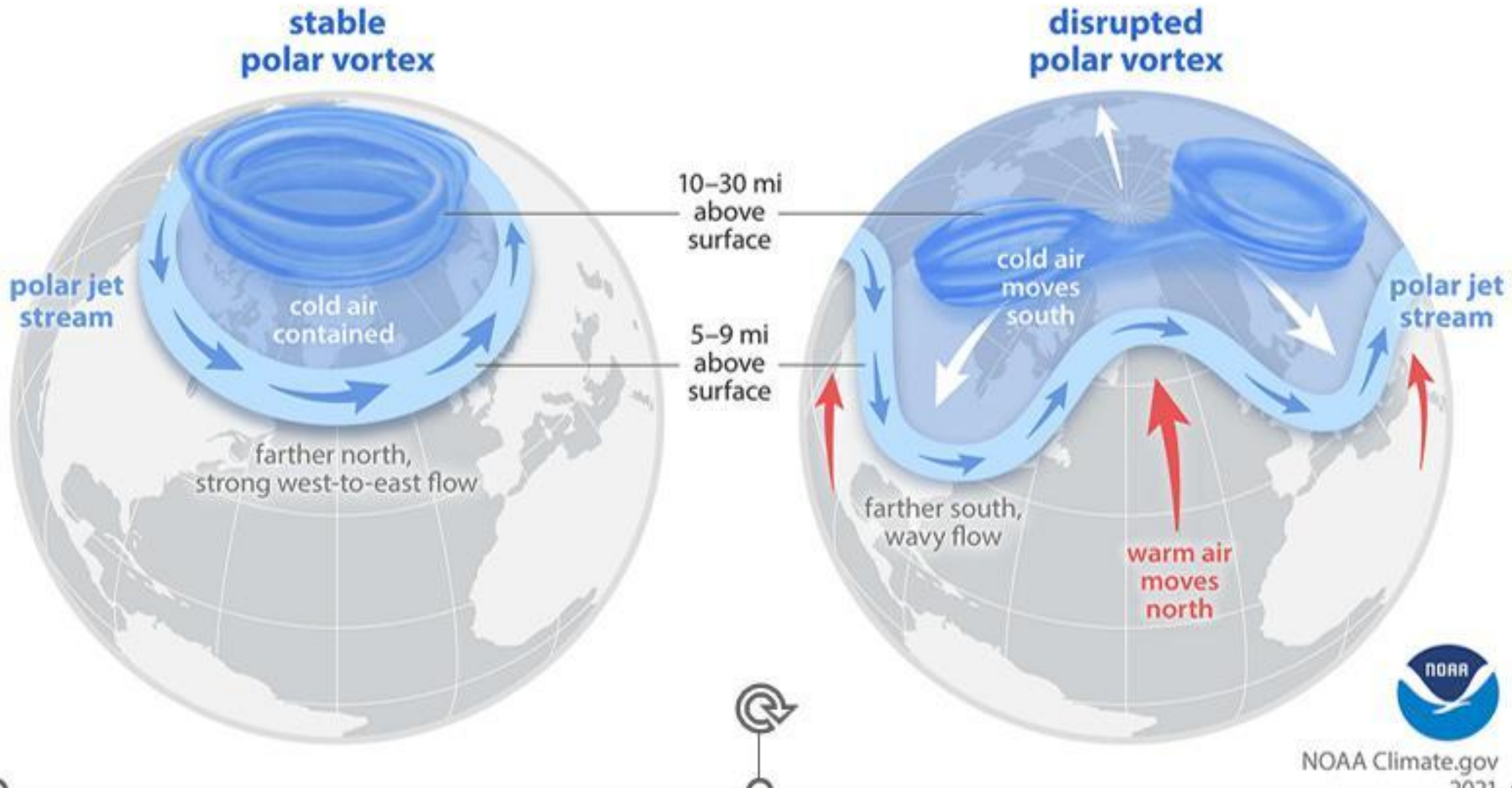
- **Damage $200-300 Billion**
- **10 million people were in the dark, lacking warmth and the ability to cook food.**
- **50% of power generation knocked out**
- **Water pipes burst and boil water advisories were issued in many counties.**
- **200 dead**
- **3.8 million fish killed**
- **100 vehicle pile up in Dallas**



Not unprecedented
Deep Trough brings arctic air to Texas to stay

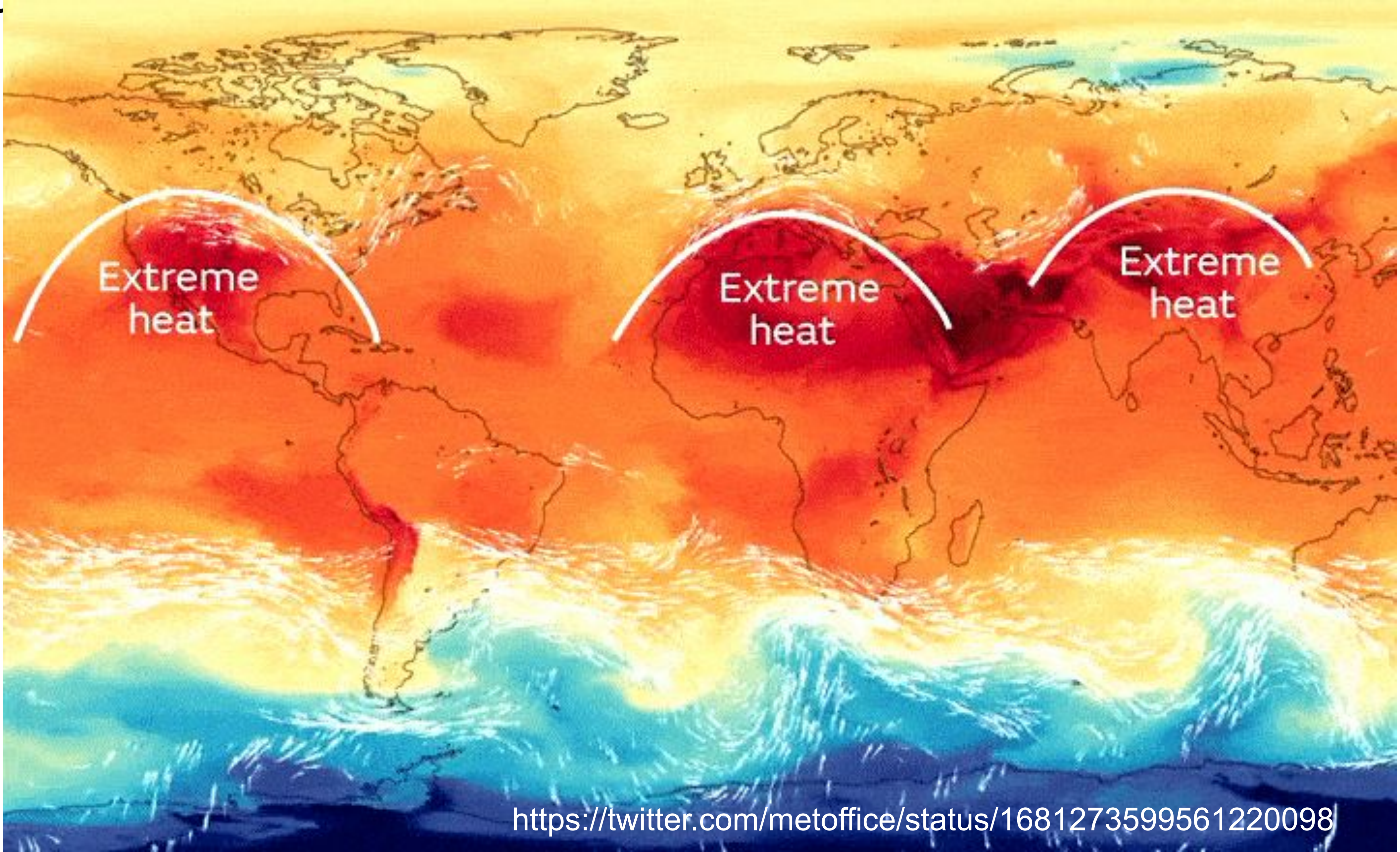
Preparedness?

Doss-Gollin, James, David J. Farnham, Upmanu Lall, and Vijay Modi. "How unprecedented was the February 2021 Texas cold snap?." *Environmental Research Letters* 16, no. 6 (2021): 064056.



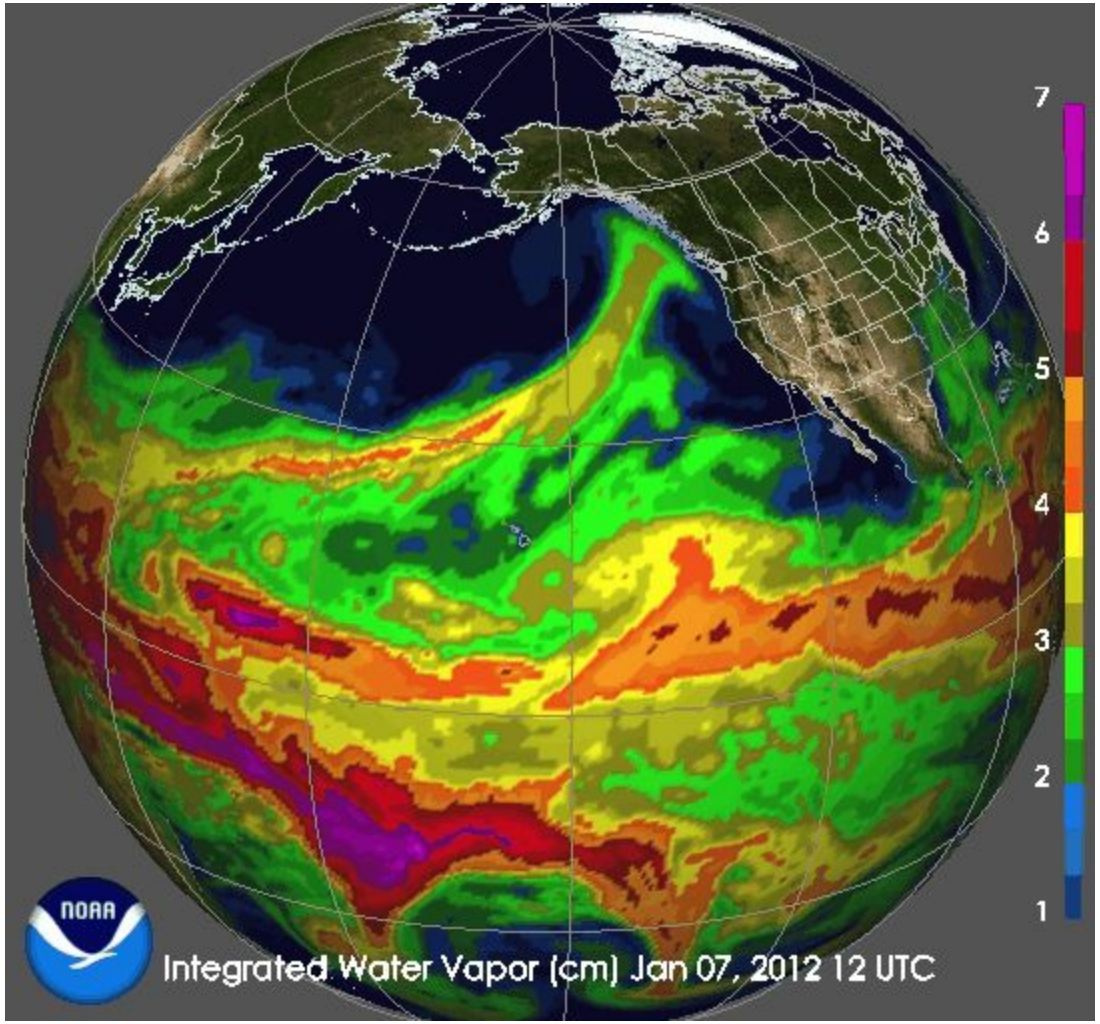
A stable or normal polar vortex traps frigid air over the north pole. When the vortex breaks down or is disrupted, the polar jet becomes less well defined and cold air escapes to the south.

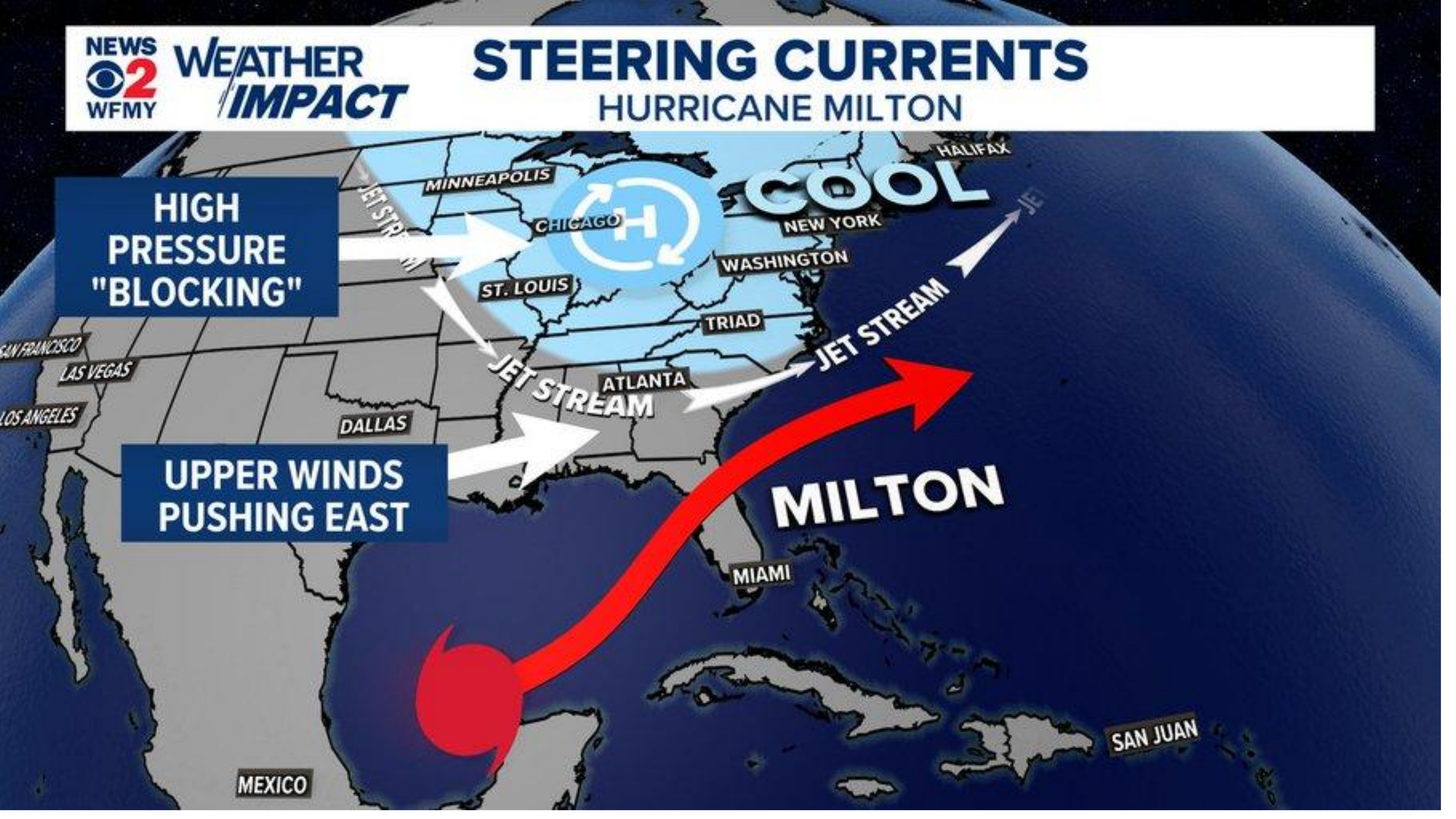
Jet stream dynamics: persistence with surface feedback



Another atmospheric river will thrash storm-ravaged California, threatening more flooding and hurricane-force wind gusts

By Nouran Salahieh, Rob Shackelford and Holly Yan, CNN
4 minute read · Updated 7:12 PM EDT, Mon March 20, 2023





NEWS 2 WFMY
WEATHER IMPACT
STEERING CURRENTS
HURRICANE MILTON
HIGH PRESSURE "BLOCKING"
UPPER WINDS PUSHING EAST
COOL
MILTON
JET STREAM
JET STREAM
JET STREAM
JET STREAM
H
MINNEAPOLIS
CHICAGO
ST. LOUIS
NEW YORK
WASHINGTON
TRIAD
ATLANTA
HALIFAX
SAN FRANCISCO
LAS VEGAS
LOS ANGELES
DALLAS
MIAMI
SAN JUAN
MEXICO

Climate Adaptation = Reducing Risks of Climate induced Loss Events?

- What about traditional or “natural” infrastructure solutions?
  - Dams, Levees, Insurance: Aging and Failing
  - Warning and early action: Seasonal forecasts lack specificity and skill
  - Weather time scale: Reasonable predictive skill but limited response time
  - Cooling/Heating Stations? Making people live underground?

We need a new 21st century approach for planetary security

Weather Jiu Jitsu: Use Nature’s Power to shape the weather

Chaos and Intransitivity in Toy Models of the Jet stream-eddy interaction:
1. Lorenz (1963) implementation of Saltzman (1962)

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \sigma(y - x),$$

$$\frac{\mathrm{d}y}{\mathrm{d}t} = x(\rho - z) - y,$$

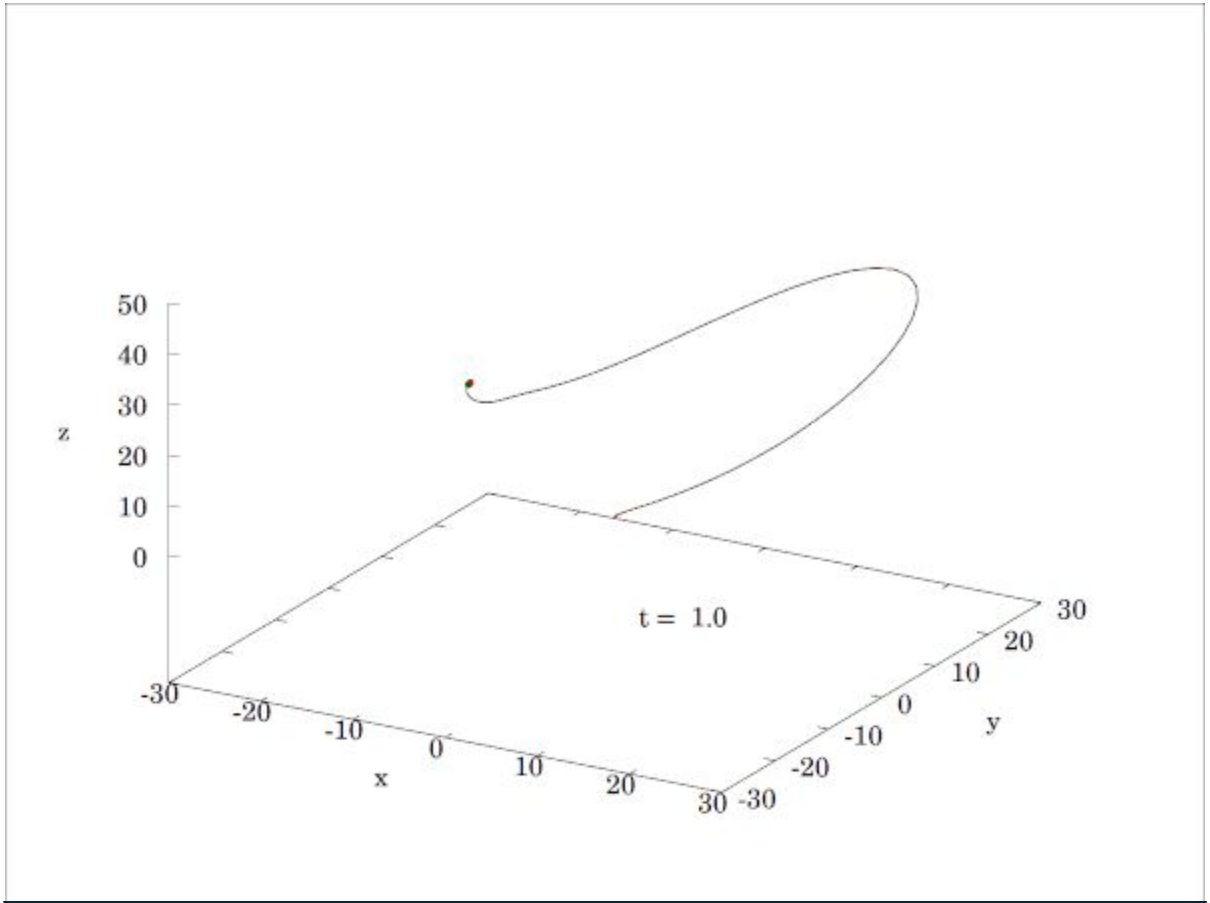
$$\frac{\mathrm{d}z}{\mathrm{d}t} = xy - \beta z.$$

x=extratropical jet energy

y and z are phases of wave transient eddies interactions with the jet

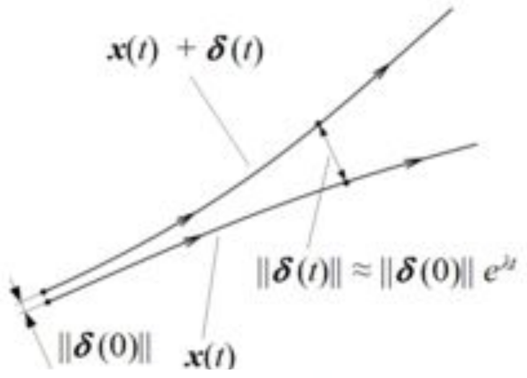
x is dissipative but gains energy from the eddies

y and z are dissipative but can gain energy from the jet



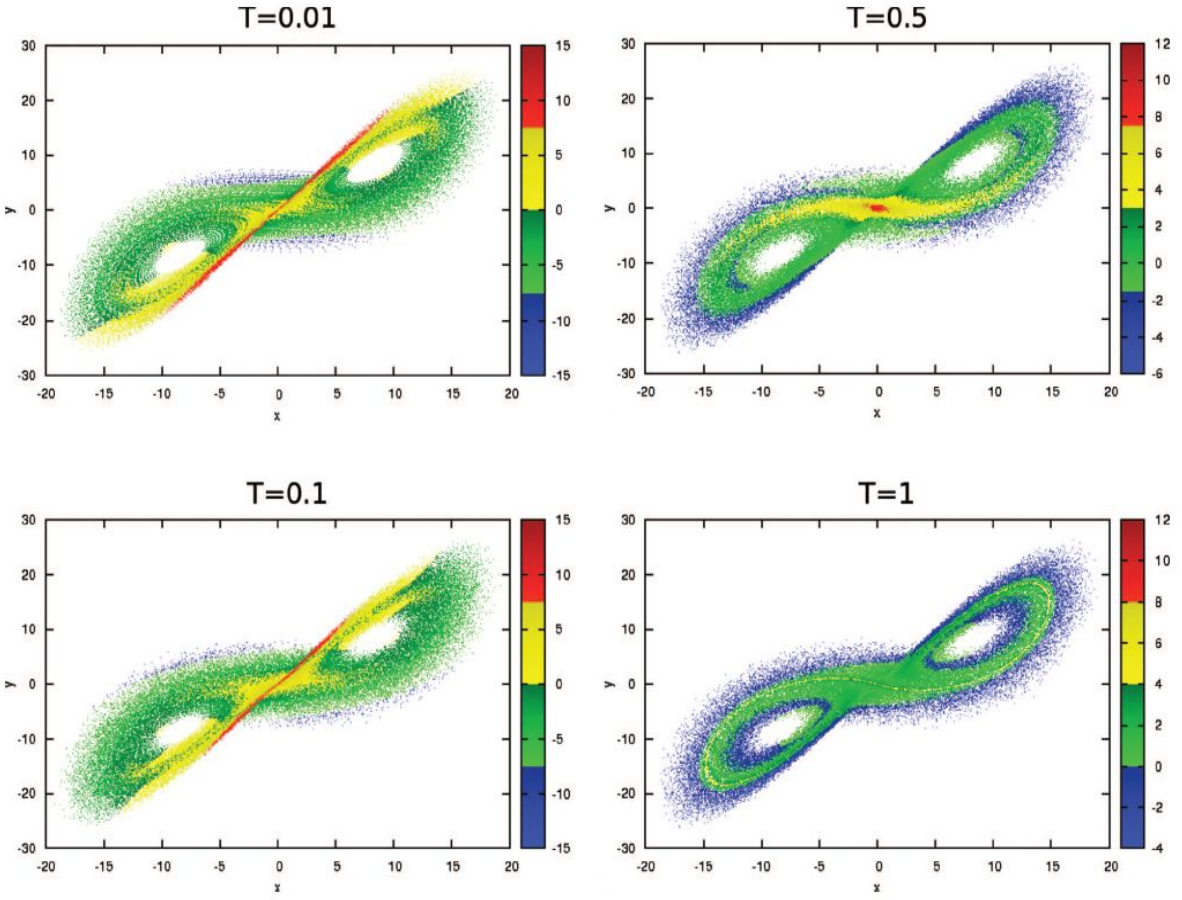
Sensitivity to initial conditions
Global & Local Lyapunov Exponents

Lyapunov Exponents



The average exponential rate of divergence of state with time

Local Lyapunov Exponent: Computed as varying over the phase space



Note the example on right for the Lorenz Model. **LLE's vary from negative to positive over phase space and over time**

Finite Time Lyapunov Exponent (over a predefined time horizon)

Deremble, Bruno & D'Andrea, Fabio & Ghil, Michael. (2009). Fixed points, stable manifolds, weather regimes, and their predictability. Chaos (Woodbury, N.Y.). 19. 043109. 10.1063/1.3230497.

Lorenz (1984) Model

$$\frac{dx}{dt} = -y^2 - z^2 - ax + a(F + \varepsilon)$$

$$\frac{dy}{dt} = xy - bxz - y + G + \tau$$

$$\frac{dz}{dt} = bxy + xz - z\,.$$

Accounts for forcing

F= equator to pole temperature gradient

G= Land Ocean temperature contrast

For adaptive control, F and G are parameters we can "nudge" to gain control over the solution space – i.e. jet and eddies evolution

Can we control the Lorenz (63 or 84) Trajectories?

Add small perturbations δx_t, δy_t, δz_t, starting at t=i, to control x_t, t=i+1, ...i+T.

$$\underset{\partial \boldsymbol{x_t}}{Minimize} \sum_{t=1}^{T} \left(u_t + \lambda \sum_{i=1}^{3} penalty_{ti} \right)$$

Subject to

$$\mathbf{x}_t = f(\mathbf{x}_{t-1}, \partial \mathbf{x}_{t-1}) \qquad t=1\ldots T$$

$$u_k \leq D_{max} \qquad t=1\ldots T$$

Where

$$u_t = ||\partial \mathbf{x}_t||_2$$

$$\text{penalty}_{k,i} = \begin{cases} l_i - x_{k,i}, & \text{if } x_{k,i} < l_i, \\ x_{k,i} - h_i, & \text{if } x_{k,i} > h_i, \\ 0, & \text{otherwise.} \end{cases}$$

Triggered by Local Lyapunov Exponents >Threshold at t=i

Adaptive Control:

The optimization problem is repeatedly solved for a T step look ahead at every time step after updating Multiplicative noise and ensembles are considered

L63

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \sigma(y - x),$$

$$\frac{\mathrm{d}y}{\mathrm{d}t} = x(\rho - z) - y,$$

$$\frac{\mathrm{d}z}{\mathrm{d}t} = xy - \beta z.$$

L84

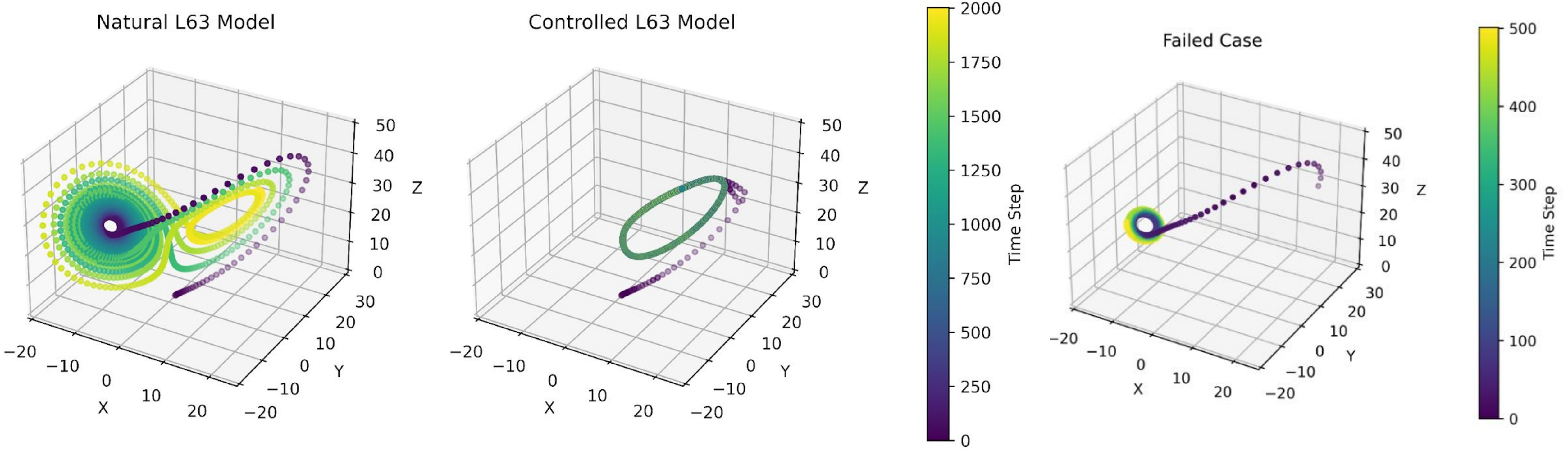
$$\frac{dx}{dt} = -y^2 - z^2 - ax + aF$$

$$\frac{dy}{dt} = xy - bxz - y + G$$

$$\frac{dz}{dt} = bxy + xz - z\ .$$

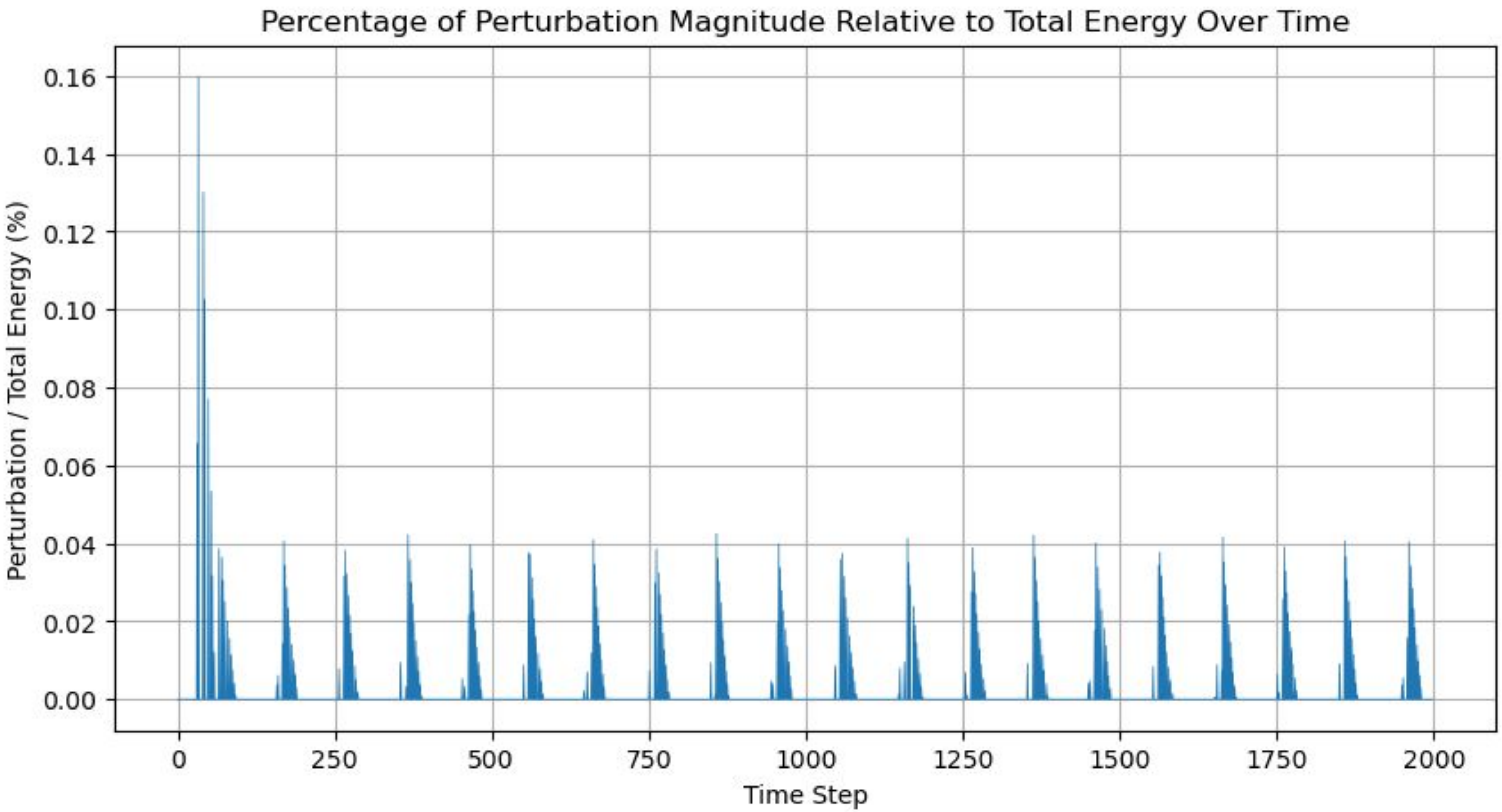
Examples

Lorenz 63

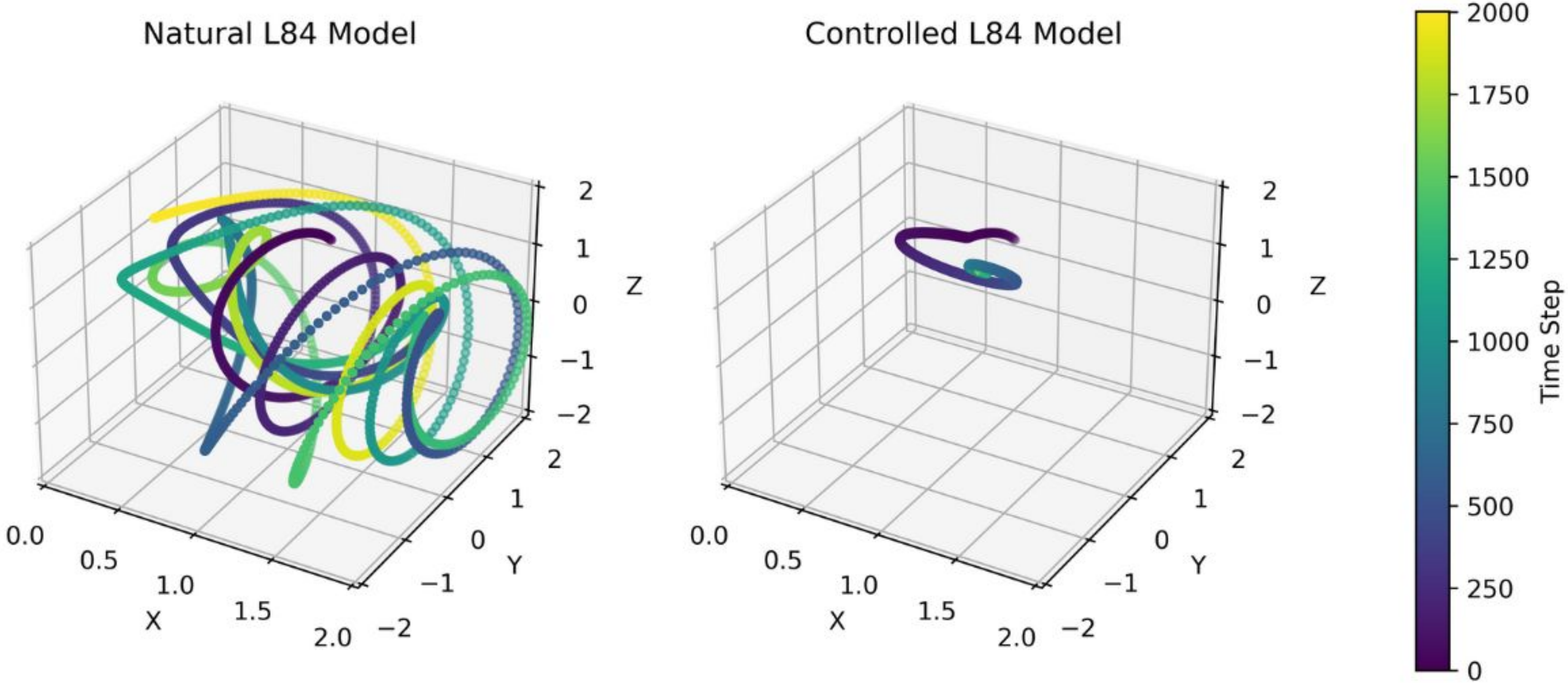


Goal: Restrict Trajectories to stay in the positive quadrant

Lorenz 63 Perturbation Magnitudes

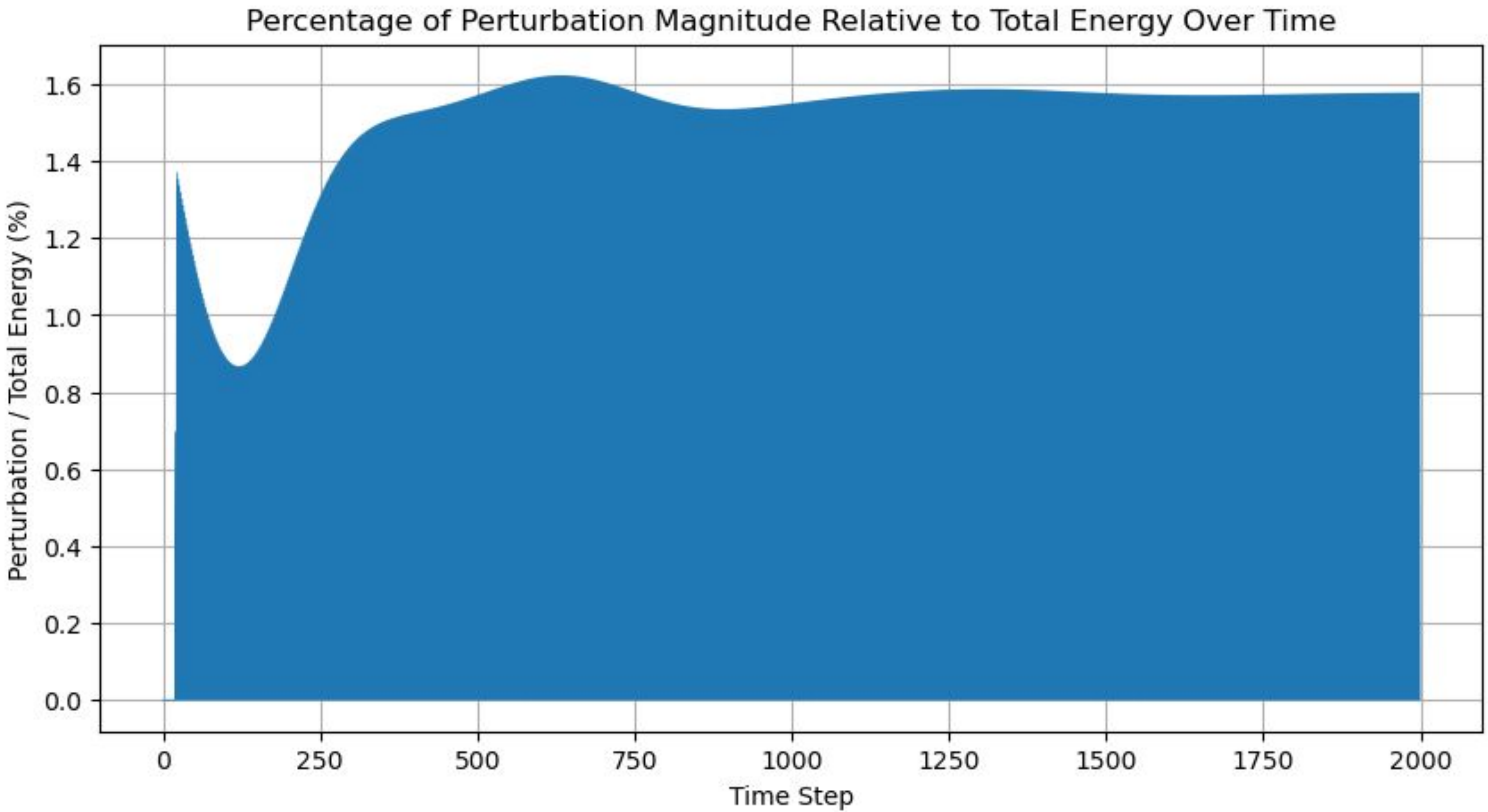


Lorenz 84

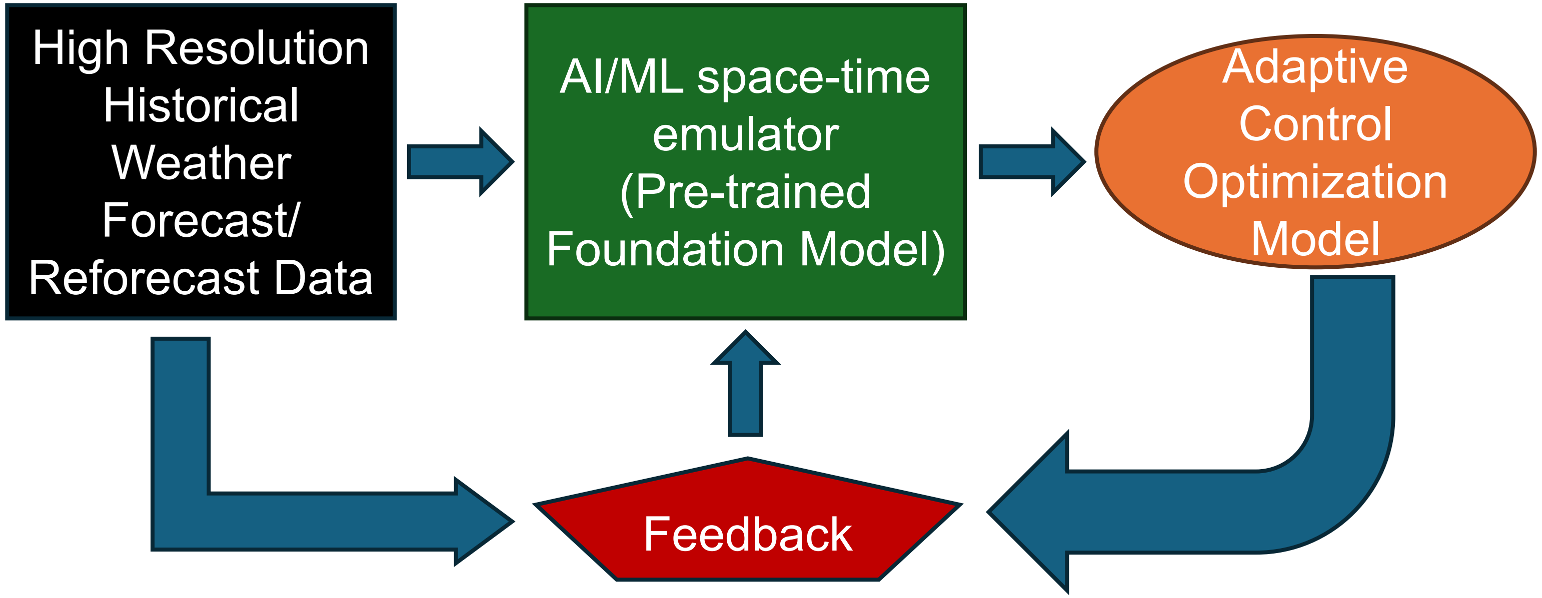


Goal: Restrict Trajectories to stay in the positive quadrant

Lorenz 84 Perturbation Magnitudes



Potential Modeling Strategy



Solve for strength, location and timing of perturbation

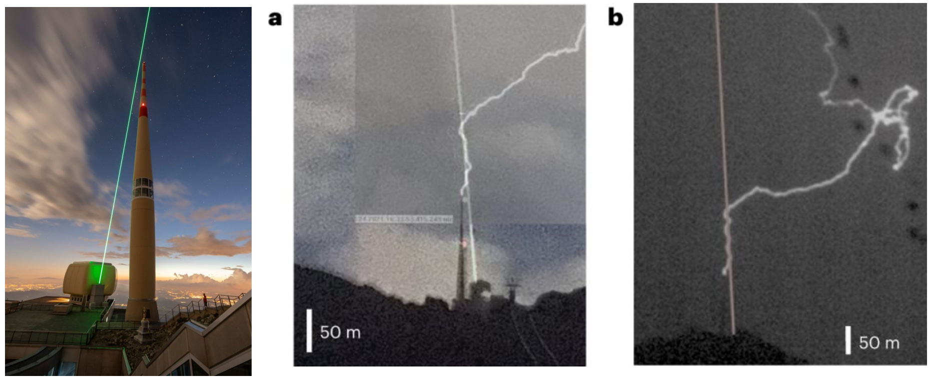
Adaptive update frequency for optimization based on trajectory divergence (finite time Lyapunov exponents -FTLE)

Pre-identify FTLE as part of deep learning foundation model

How to intervene?

- Thermodynamic triggers
  - A typical thunderstorm can release as much as10 GWH of energy, primarily via latent heat of condensation
  - [Laser-induced water condensation in air]

- Cloud seeding
- Focused Lasers for localized heating anomaly and lightning convergence
- Space-based microwave



Houard, A., Walch, P., Produit, T., Moreno, V., Mahieu, B., Sunjerga, A., ... & Wolf, J. P. (2023). Laser-guided lightning. *Nature photonics*, *17*(3), 231-235.