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Investigating Adaptive Chaos Control for Mitigating Weather Extremes

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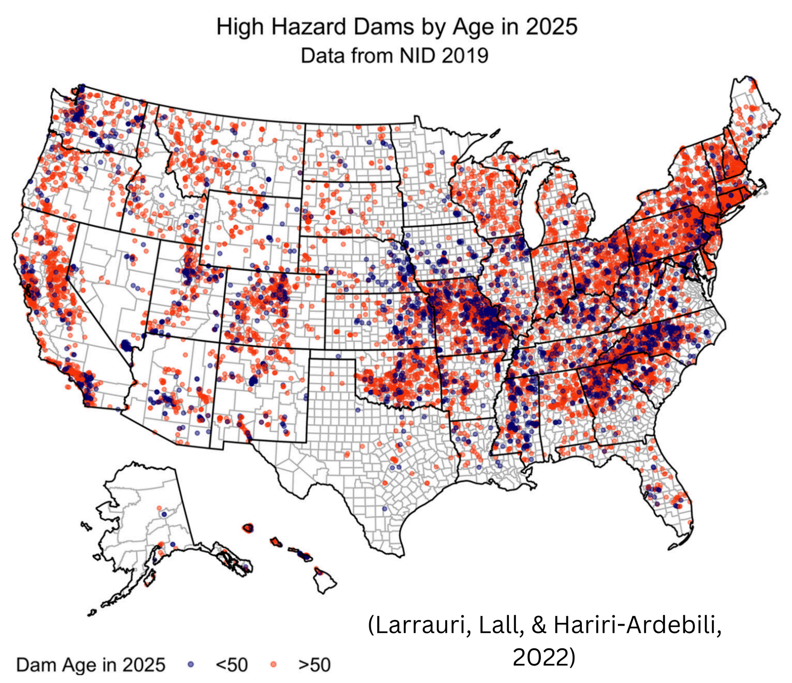
Background

- **Current Issues**
  - Increasing frequency and intensity of floods and droughts under climate change.
  - Traditional infrastructural solutions like dams are now beyond their lifespan and risking failure.
  - Lack of investment makes replacing or repairing aging infrastructure challenging.



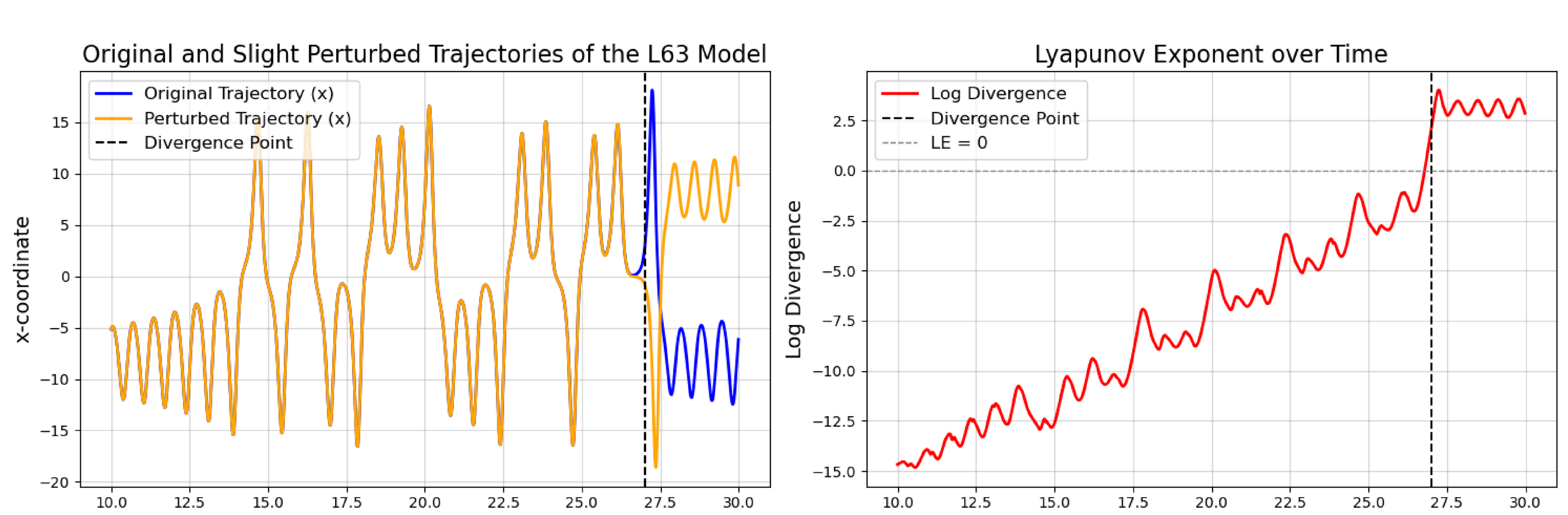
- **Potential Solution: Chaos Control & Weather Modification**
  - Change the structure and trajectory of storms by small perturbations in mid-latitude circulation systems, thereby adaptively reduce the risks of floods and droughts.
- **Previous studies** (Karamperidou, Cioffi, & Lall, 2012)
  - Apply the Lorenz 1984 (L84) model using real-world data.
  - L84 can capture the El Niño-Southern Oscillation (ENSO) dynamic on mid-latitude, and it can guide real-world experiments for altering jet stream and eddy track dynamics.
- **Our Goal**
  - Adaptive chaos control on L84 atmospheric circulation model.
  - Lyapunov Exponents as a guiding method for control strategies.

Lyapunov Exponents (LEs)

- Chaos system in atmospheric circulation: small perturbations will amplify rapidly in mid-latitude circulation systems
- Function of LEs: analyzing the Lyapunov Exponents to identify opportunities to modify and stabilize these chaotic circulation systems through targeted interventions.
- Calculation:

$$\text{LEs:} \quad \lambda = \frac{\log\left(\frac{\|X_{\text{next}}\|}{\|X\|}\right)}{\Delta t}$$

- The plot indicates that two trajectories with close initial condition in the chaotic system will be diverged when LEs >0.



Lorenz Models

Lorenz 1963 (L63)

$$\frac{dx}{dt} = \sigma(y - x),$$
$$\frac{dy}{dt} = x(\rho - z) - y,$$
$$\frac{dz}{dt} = xy - \beta z,$$

Lorenz 1984 (L84)

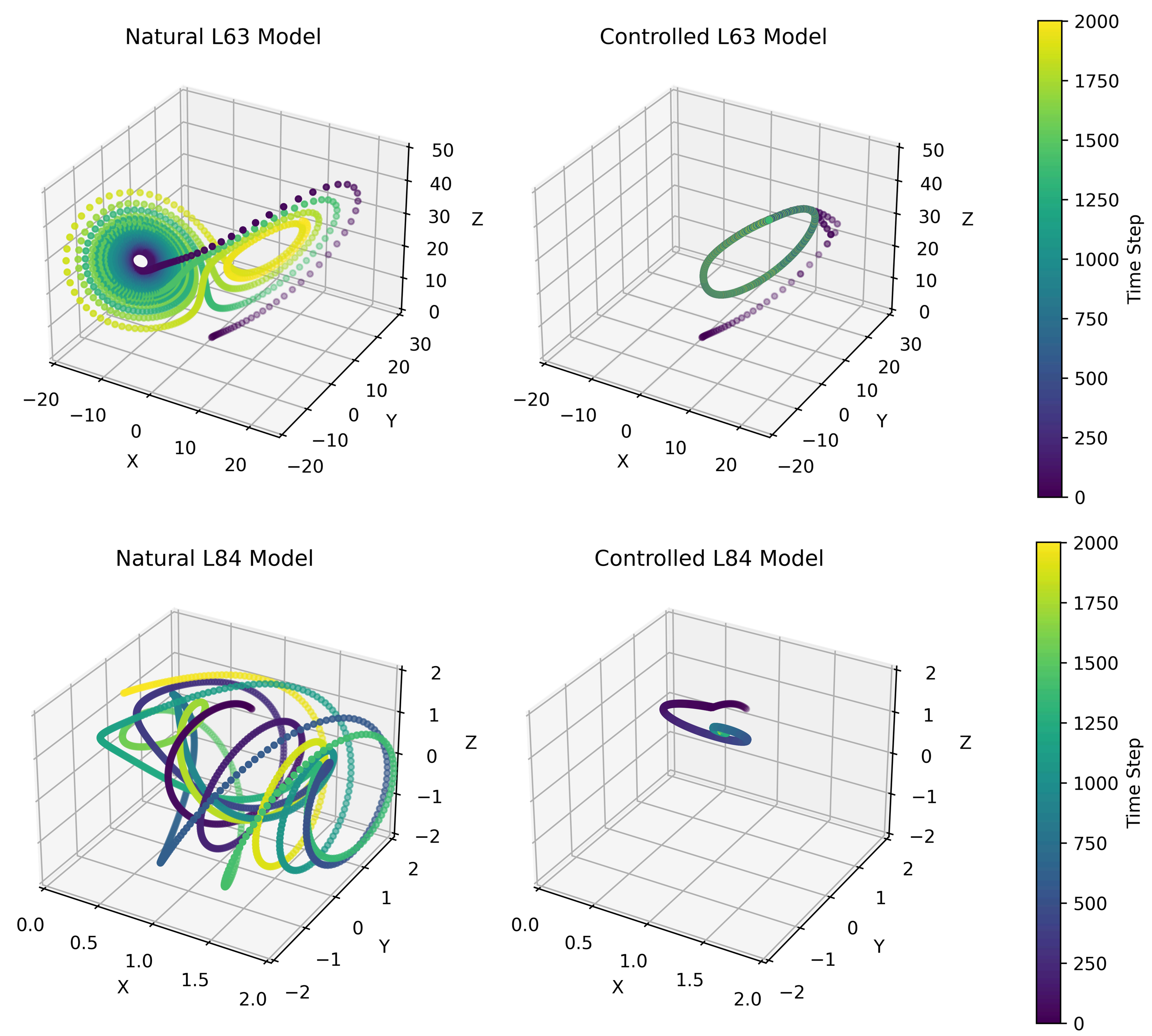
$$\frac{dX}{dt} = -Y^2 - Z^2 - aX + aF,$$
$$\frac{dY}{dt} = XY - bXZ - Y + G,$$
$$\frac{dZ}{dt} = bXY + XZ - Z,$$

- Idealized Model of Mid-Latitude Circulation with External Forcing:
  - F = Equator-to-pole temperature gradient (EPG)
  - G = Ocean-land contrast (OLC)

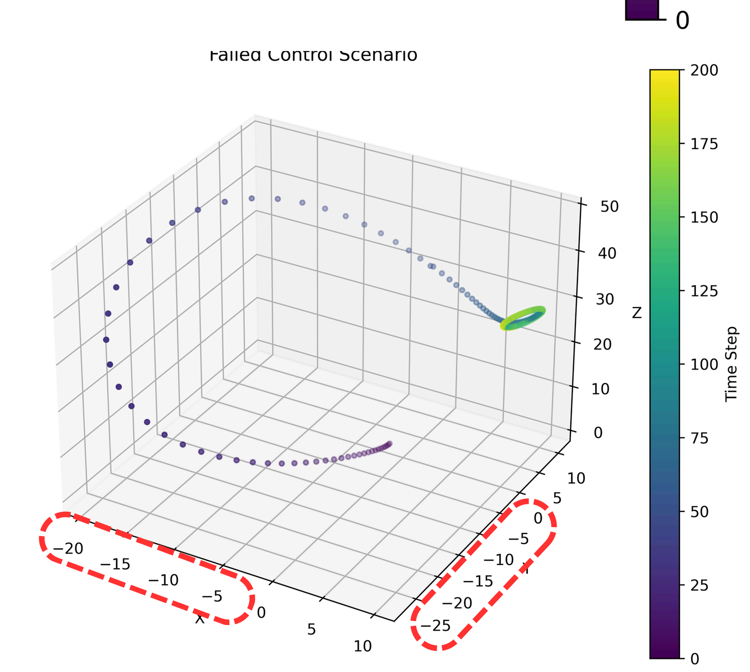
***EPG and OLC are important drivers influencing jet stream and eddy.**

Result

Adaptive Chaos Control on both L63 and L84 model



- **Uncontrolled Condition:**
  - If the initial LEs for applying control is too big that a large amount of perturbation will be required.



Fail to Control
Initial LEs: 8.8752

Control Methods

- Chaos control on both L63 and L84 model:
  - **Involving the LEs for the control process.**
    - if LEs >0, the system is in a chaotic region, and control is applied by perturbing the current state.
  - **Optimizing the perturbation (u) for reducing energy usage.**
    - Objective function:

$$\text{Minimize:} \quad \sum_{i=1}^{n} u_i^2$$

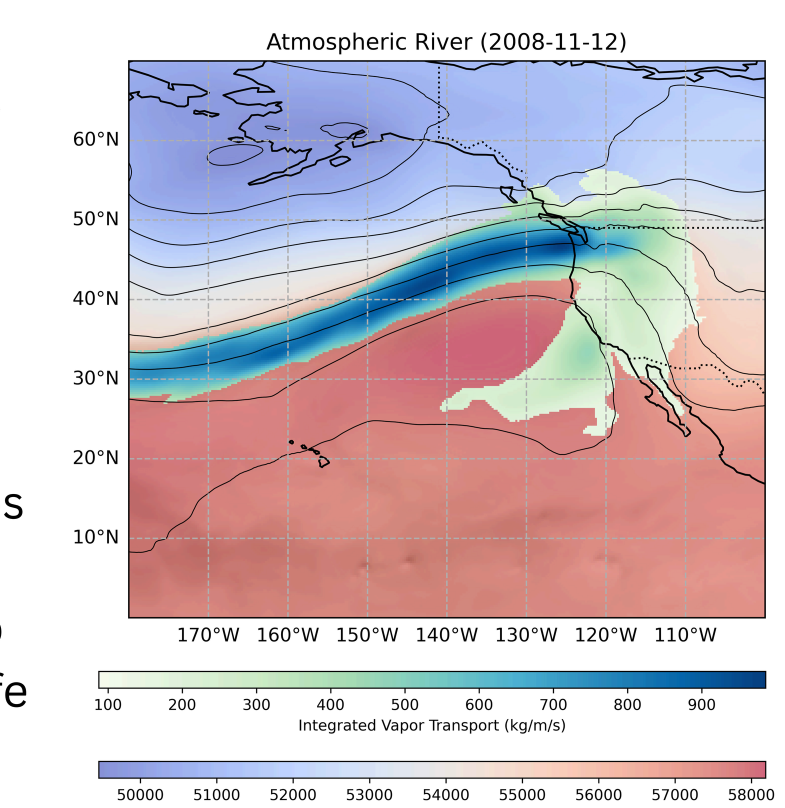
    - Constraints (Boundary Constraint and Perturbation Magnitude Constraint:):

$$\text{lower}_i \leq X_{t+k}[i] \leq \text{upper}_i, \quad \forall i \in \{1, 2, \ldots, n\}$$
$$\|\mathbf{u}\| \leq u_{\max}$$

    - Solver: Sequential Least Squares Programming (SLSQP)
- Settings:
  - Steps: 2000
  - Look ahead steps: 5
  - Boundary: trajectory remain at specific regimes

Atmospheric Rivers (ARs)

- ARs: key drivers of floods at western US.
- Managing ARs:
  - Applying LEs to identify unstable states.
  - Adding adaptive chaos control to optimize perturbations to keep trajectories within safe bounds.



Future Work

- Use deep learning method with high-resolution weather forecast models to build prediction engine for ARs.
- Data assimilation to refine ARs condition.
- Extend LEs-based optimal control to modify the ARs trajectory.

References

1. Concha Larrauri, P., Lall, U., & Hariri-Ardebili, M. A. (2022). Needs for portfolio risk assessment of aging dams in the United States. Journal of Water Resources Planning and Management, 149(1), 04022088.
2. Karamperidou, C., Cioffi, F., & Lall, U. (2012). Surface temperature gradients as diagnostic indicators of midlatitude circulation dynamics. Journal of Climate, 25(12), 4154–4171.