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ESSAY

Weather Jiu-Jitsu: Prospects for atmospheric nudging to defuse the impact of catastrophic weather extremes

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Abstract

Extreme weather events, e.g., droughts, floods, heatwaves, and freezes, are increasing in frequency and intensity, posing severe socio-economic impacts as growing populations heighten exposure to risks that conventional infrastructure cannot fully address. We propose supplementing disaster management with Weather Jiu-Jitsu: a strategy that exploits the chaotic sensitivity of mid-latitude atmospheric dynamics to redirect destructive weather trajectories through small, precisely timed perturbations guided by Finite-Time Lyapunov Exponent (FTLE) diagnostics and deep learning forecast models. Proof-of-concept experiments using the Aurora deep-learning Earth system model show that FTLE-guided nudges applied days before peak impact can shift a hurricane track to avoid landfall on a major city, weaken the peak intensity of a blocking-driven cold extreme, and reduce atmospheric river moisture transport under favorable upstream conditions. Control inputs remain below 2% of total system energy in idealized models, though real-world implementation will require advances in monitoring, attribution, and international governance. This nature-assisted approach could form a transformative complement to conventional disaster management in the 21st century.

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Main

Floods, droughts and major storms have shaped human history and the march of civilization. They continue to impact societies worldwide. Over the centuries, humans have mastered flight, harnessed the atom, and reached the age of the Anthropocene, a human-dominated planet. Yet, control of extreme weather eludes us. Indeed, it is not even discussed as a national or global priority. Most weather modification applications today involve small-scale operations, such as cloud seeding aimed at improving precipitation locally, typically during droughts [1]. A changing climate, and its control through geoengineering and decarbonization, has been part of a global debate over the last three decades—a discussion where the increasing impact of climate change extremes takes center stage. These discussions focus on managing the global radiation balance, necessitating coordinated efforts on a planetary scale. They do not directly address weather extremes. In this perspective paper, we outline an argument that control over catastrophic weather extremes is imperative to reduce exposure to catastrophic events that are not mitigated by traditional physical, financial or social infrastructure, and explore conditions under which this may be feasible. If such an approach were successful, it could revolutionize hydroclimatic risk mitigation.

We need to understand which weather extremes may be controllable, when, where and how. An interdisciplinary global research agenda is needed to control and avert the impact of weather extremes, as a complement to millennia-old place-based infrastructure strategies such as dams and levees, and century-old strategies for heating and cooling, while addressing social and environmental concerns with both the traditional and the proposed infrastructure. Imagine harnessing the power of nature to help steer hurricanes away from land, redirect atmospheric rivers to spread their rain safely and evenly, or defuse extreme weather patterns like heatwaves, freezes, or prolonged droughts before they take hold. It's a vision where we partner with Earth's own forces to create resilience, rather than reacting to disasters. We call it Weather Jiu-Jitsu.

Climate and weather extremes pose an ever-increasing threat to human societies. Storms, floods, heatwaves, droughts, tornadoes, and freezes are the most prevalent natural hazards. Exposure to these events and their derivative events, such as fires and landslides, is increasing, due in part to climate change and in part to the growing human population and its occupation of vulnerable areas (Fig A in S1 Appendix). The costs of developing physical infrastructure, financial relief (e.g., insurance), and other coping programs at the global scale are large, and traditional physical infrastructure, such as dams, has increased the potential for adverse environmental and social outcomes. The limited ability of these mechanisms to avert disasters manifests as catastrophic or billion-dollar disasters [2]. Can a new approach provide a complementary strategy for averting these disasters globally?

Extreme climate events are largely determined by the dominant modes of atmospheric circulation and the associated thermodynamics and heat transport, which manifest at weather time scales. The underlying equations driving these phenomena are typically nonlinear and chaotic, resulting in varying and limited predictability due to their sensitivity to initial conditions and perturbations. Could this sensitivity be an opportunity? Could a nudge at the right time and place be amplified by natural dynamics in a way that reduces the threat? If such an approach could be developed, it would revolutionize the field of disaster management. The technical and social implications would be far-reaching, and one may require appropriate safeguards to ensure social acceptance. This is the premise of Weather Jiu-Jitsu.

Initially, we consider weather extremes, in particular those associated with mid-latitude atmospheric circulation, rather than the climatic hazards related to sea level rise or tides. This choice is motivated by our understanding of mid-latitude circulation as a nonlinear dynamical system, and that compound climate hazards can be contemporaneously or sequentially associated with these dynamics worldwide. Given the time scales of weather anomaly evolution, there may be opportunities for the preemptive modification of their trajectories, leveraging recent advances in deep learning applications to multi-variable space-time weather prediction. This could be achieved through strategically timed and placed recurrent perturbations that redirect the trajectories of concern.

Growing impacts of extreme hazards and their relation to weather dynamics

Climate extremes caused an estimated $417 billion in total economic costs in 2024, of which insurance entities covered only $154 billion [3]. Hydrometeorological hazards accounted for 74% of losses due to natural hazards over the period from 1970 to 2019 [4]. Hurricanes, extreme rainfall, droughts and floods pose a complex challenge given their spatio-temporal structure and impacts, which often manifest as compound extremes [5]. Many such events are historic, pre-dating significant climate change, and are of concern even if decarbonization efforts are successful. As an example, in the winter of 1861, California was struck by extreme winter storms which submerged large parts of the Central Valley and caused widespread destruction [6]. Looking ahead, the ARkStorm simulation, developed by the U.S. Geological Survey [7], highlights the escalating risk of future flood catastrophes under a warming climate. ARkStorm models the consequences of clustered Atmospheric Rivers (ARs) events, projecting $400 billion in property damages and as much as $325 billion in business interruption losses in California.

Persistent atmospheric blocking patterns associated with anomalous jet stream dynamics are implicated for such clustered flood events, and also for concurrent droughts, heatwaves, and freezes in the mid-latitudes [8,9,10]. With global warming, the atmosphere's moisture-holding capacity increases which increases the potential for more frequent and intense events across diverse climate regions [11]. Large scale tropical moisture exports, including but not limited to ARs, are typically associated with fronts or eddies that subsequently interact with the mid-latitude jet stream, and are directed by the persistent high and low pressure centers and traveling waves associated with the jet stream, leading to recurrent high precipitation where they are transported to persistent low pressure centers, and drought where they are diverted away from persistent high pressure centers or atmospheric blocks (8, 10, Video A in S1 Appendix).

The relevance of nonlinear dynamics and chaos theory to weather dynamics was established by idealized models of such eddy-jet stream interactions developed by Saltzman [12], and Lorenz [13,14]. The persistent or semi-permanent features of these systems have been explored extensively since [15,16]. It is remarkable that so many of the climate/weather extremes of concern are associated with these types of interactions of atmospheric Rossby waves with the mid-latitude jet stream [17]. Our thesis is that Weather Jiu-Jitsu, i.e., adaptive chaos control applied to mid-latitude atmospheric dynamics may provide a 21st century approach to managing a range of extreme weather events by nudging the system trajectories. We review some of the traditional climate risk management approaches in use as a precursor to outlining how Weather Jiu-Jitsu could work.

Traditional approaches for hydroclimatic risk management

To mitigate the impacts of extreme weather events, societies have long relied on two risk management strategies: (1) structural solutions (e.g., dams, levees, heating and cooling systems), (2) financial securitization (e.g., insurance or catastrophe bonds). While each plays an important role, these measures are increasingly proving inadequate due to climate volatility, compounding or hyperclustered, persistent, large area risks [18], and vulnerability of the built environment [19,20]. Each is typically designed to cover some level of weather risk, leaving open exposure to more catastrophic events. For instance, flood control measures are designed for a 5- to 10-year return period for urban flooding, or a 100-year return period for regional flooding [21]. Flood insurance, on the other hand, may provide coverage for up to a 100-year event, while catastrophe bonds are designed for rarer events, but with a total cap on the payout [22]. We view Weather Jiu-Jitsu as primarily of interest for events more extreme than those covered by these measures, e.g., potential billion-dollar disasters.

Physical Infrastructure

Many dams and levees in countries like the U.S. are now over 60 years old [23]. More than 552 U.S. dams failed due to hydrologic factors between 2000 and 2023, while experiencing rainfall with an annual probability of about 10–20% (equivalent to a 5–10 year return period), and over 25,000 high-hazard dams remain at risk due to insufficient capacity to withstand rainfall events and systemic deterioration [24]. Even state-of-the-art defenses can be overwhelmed during unprecedented events that exceed their nominal design levels [19], and as conditions change, this may be more frequent.

The 2021 Texas freeze led to cascading failures of electrical and water infrastructure, with nearly $195 billion in damages, 4.5 million customers without electricity and 210 deaths, largely due to a lack of winterization of the electrical and water systems [25]. It was initially argued that it was unprecedented. However, an analysis of the climate data showed that this was the 5th such freeze in the previous 70 years [26]. An extreme southern migration of a weather pattern that often brings Arctic air and freezing temperatures to the Midwestern USA, a region that is prepared for such events with extensive winterization [26], was responsible. This raises the question of whether Weather Jiu-Jitsu could defuse such an extreme event by nudging the atmospheric circulation at the right time and location?

For catastrophic weather extreme events, traditional physical infrastructure solutions offer only a limited solution. From a layered, risk management perspective, these gaps are typically addressed by financial instruments such as insurance, catastrophe bonds, and derivatives.

Financial Instruments: Insurance

Insurance mechanisms, including indemnity-based, index-based, and insurance-linked securities, are designed to pool and transfer risk across populations or financial markets. Insurance-linked securities like catastrophe bonds can distribute risks globally but require advanced financial literacy and strong regulation, often lacking in vulnerable regions [27,28].

In the U.S., climate-linked insurance programs like the National Flood Insurance Program (NFIP) face chronic underfunding, with regulated premiums failing to match payout obligations. Despite past debt forgiveness, the NFIP remains over $20 billion in debt, with major financial stress stemming from catastrophic "hyperclustered" events, large-scale, multi-region floods driven by shared meteorological forces (e.g., hurricanes), that exceed premium recovery capacity. Just eight such events, including Katrina, Sandy, Harvey, and Ian, account for over 50% of total NFIP payouts, each causing damages greater than the annual national premium intake [18]. In parallel, recurrent, low-intensity losses—typically in high-risk areas with repeat claims—generate chronic deficits, costing the NFIP over $2 billion historically and averaging $63 million per year. These losses are not linked to rare events, but rather to frequent precipitation with return periods under 5 years [18,29]. The NFIP could be financially viable with appropriate risk-based premiums, if the catastrophic storm/flood events that cover large areas and persist over several days were excluded. Typically, these events correspond to tropical storms, tropical storm remnants, or recurrent frontal systems associated with persistent atmospheric circulation anomalies.

In summary, physical and financial infrastructure can provide relief from weather extremes but is overwhelmed by catastrophic, persistent, and recurrent events, and addressing these uncovered risks using Weather Jiu-Jitsu would be an attractive possibility.

Towards weather Jiu-Jitsu

Efforts to explore weather control at broader spatiotemporal scales are already underway. Japan's Moonshot Goal 8 aims to demonstrate weather-modification feasibility by 2050 [30], while China operates the world's largest national weather-modification program, conducting large-scale cloud seeding for precipitation enhancement and hail suppression [31], and the United Arab Emirates runs sustained rain-enhancement operations to increase rainfall in arid regions [32]. Beyond these national programs, a substantial history of weather modification research—from early cloud seeding experiments to hurricane mitigation studies—has established both the physical plausibility of small-scale atmospheric interventions and the governance challenges that any operational system must confront [33,34,35]. These emerging initiatives motivate a deeper examination of the underlying physics: what aspects of the atmospheric circulation are potentially controllable, over which time scales, and by what mechanisms?

A common perception is that vast amounts of energy would be needed to induce changes in atmospheric circulation, i.e., nudging the system with small amounts of energy is not feasible. To move from this perception towards Jiu-Jitsu, we consider mid-latitude phenomena whose physics and nonlinear dynamics are relatively well understood, and whose chaotic dynamics at the time scales of interest suggest that there is an opportunity to intervene, at least for some of the extremes that would otherwise have catastrophic impacts. The open technical questions are (a) whether appropriately timed and placed small nudges can indeed allow controls of the trajectories of weather systems of concern, (b) how these nudges would be applied in practice, and (c) how the system would be monitored and predicted to assure that the emerging trajectories are working as intended or are updated with new nudges. These are the main elements of adaptive control (Fig 1).

The concept of Weather Jiu-Jitsu leverages the nonlinear and chaotic nature of the atmosphere, inspired by Edward Lorenz's seminal work on idealized systems such as the Lorenz 63 (L63) and Lorenz 84 (L84) models [13,14,36]. His work revealed two key features of atmospheric dynamics: intransitivity, or the existence of multiple coexisting flow regimes, and chaos, which refers to the extreme sensitivity of the system to initial conditions. The typical application of these ideas has been to speak of the limits of forecast predictability. However, sensitivity to initial conditions also implies that small, well-timed perturbations may be able to steer the atmosphere toward desirable regimes. This idea forms the foundation of Weather Jiu-Jitsu: a paradigm that exploits the natural instabilities and bifurcations in the climate system to gently "nudge" it away from harmful trajectories using minimal energy input.

The L63 and L84 models have been popular with dynamicists to explore attractor structure, predictability, prediction using machine learning tools, and means for control. These are "toy models" of convection in an asymmetrically heated rotational system (L63), and of the interaction between the atmospheric jet stream and the eddies that are coupled to it (L84). For L63, a number of chaos-control strategies have been shown to be numerically and physically feasible for both regime switching and trajectory stabilization [37,38]. Recent advances have integrated deep learning to approximate system dynamics and guide interventions, while Lyapunov Exponents (LEs), which quantify sensitivity to initial conditions, are used to identify where and when to apply perturbations [39,40]. Researchers have also used Data Assimilation (DA) and Model Predictive Control (MPC) to steer chaotic systems like L63 toward specific attractor basins [41,42]. Similar results

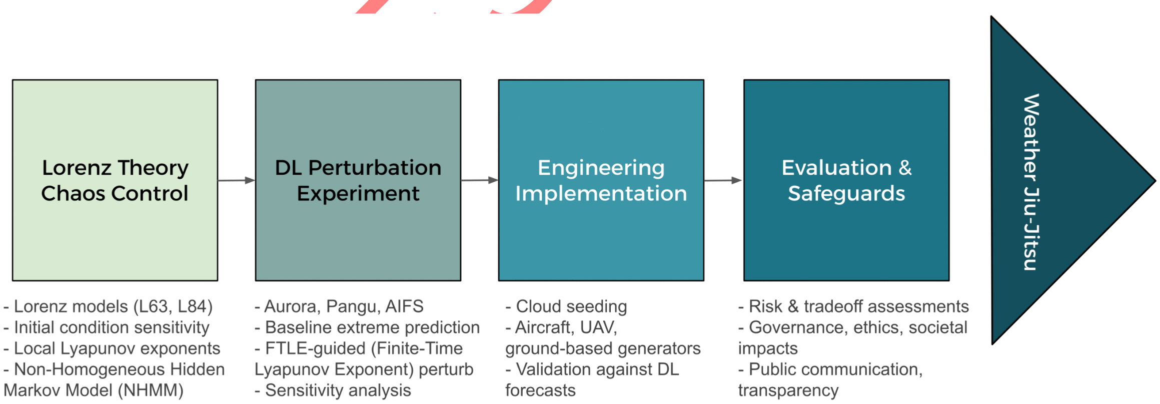

Fig 1. Weather Jiu-Jitsu Framework Overview. The framework progresses from nonlinear dynamical theory and chaos-control concepts (Lorenz models, sensitivity diagnostics, NHMM triggers) to deep-learning-guided perturbation experiments, followed by engineering implementation pathways for applying small interventions in the atmosphere, and finally evaluation, risk assessment, and governance safeguards. Together, these components outline a potential research agenda for low-energy, adaptive control of extreme weather trajectories.

https://doi.org/10.1371/journal.pwat.0000562.g001 are being achieved for L84, which has a more complex attractor, and has been explored with seasonal variations [43,44] in the forcings provided by the equator-to-pole and land-ocean temperature gradients, as well as ENSO forcings [45]. In noise-perturbed L63 and L84 systems, our studies show that adaptive chaos control requires only very small relative energy: control inputs in L63 remain <0.03% of total system energy in typical runs, while L84 requires <2% for most of the simulation [38,44].

How can one transition from controlling chaos in toy mathematical models of the atmosphere to controlling atmospheric circulation in the real world with small perturbations? Which features are likely to be most or least tractable and over which space and time scales? In the mid-20th century, the USA pursued Project Stormfury [33,34], whose goal was to weaken hurricanes using a variety of possible weather control methods. One of the hypotheses was to modify the convective cloud properties through cloud seeding or other means, resulting in a weakening of the winds and the associated rainfall. The number of actual experiments was few, and the results were deemed inconclusive regarding hurricane modification, although the effects of seeding were noted in at least one of the experiments. We reframe the question of hurricane modification by asking whether it could be more effective to modify the steering winds of a hurricane than to modify the hurricane's power. A substantial literature discusses the role of the jet stream and associated wave dynamics in determining the hurricane tracks, especially as the tropical cyclones enter the mid-latitude [46,47,48]. Poor predictions of the jet stream in the vicinity of the evolving hurricane have been shown to be a significant factor in poor hurricane track prediction. Can the jet stream dynamics sufficiently upstream of the hurricane be adaptively perturbed in a way that favorably impacts the resulting hurricane track? We performed a proof-of-concept test using the Aurora deep-learning forecast system to evaluate whether such upstream perturbations can produce measurable effects on a real hurricane (Fig 2).

A related question is whether one could perturb the trajectories of Atmospheric Rivers, or large-scale Tropical Moisture Exports that translate into extreme regional floods? In the mid-latitudes, these features connect to the stationary and traveling waves associated with the jet stream and eddies or fronts that bring latent and sensible heat from the tropics. These are essentially the dynamics represented in the L84 model at a highly idealized level.

The atmospheric blocking patterns and associated troughs that set up persistent high- and low-pressure centers, often associated with concurrent heatwaves (Video A in S1 Appendix)/ droughts, or freezes/ recurrent floods, are another interesting target. Recent research [54,55,56] using Lyapunov exponents as a diagnostic tool has identified that these phenomena are marked by particularly high instability or low predictability as the system transitions in or out of a block, while predictability increases as the block persists. The implication is that if a prediction system could detect an impending state transition into a blocking setting, early action on appropriate nudging could avert that situation.

To adaptively control weather extremes, we can consider two settings. The first considers conditional perturbation based on near-term prediction, e.g., as a hurricane or an atmospheric river is in place, and we wish to change its trajectory with a finite set of monitored nudges. The second condition would be one where the system is regularly nudged, perhaps at sub-seasonal time scales, to reduce the potential for undesirable weather regimes, such as atmospheric blocking patterns that lead to persistent heatwaves, freezes, droughts, and floods. In this setting, one may need an identification of the latent states of the atmospheric circulation that include these regimes, and their transition probabilities, to decide when to nudge and change the probabilities of regime transition. In both situations, a deeper understanding of the circulation dynamics, its predictability, and regime dynamics is needed. We consider low-order models, like Lorenz's, to be useful for building such intuition and emerging spatio-temporal deep learning models as operationally useful for developing these ideas.

One would need to explore methods to explore the stable and unstable manifolds of the spatio-temporal dynamics to identify feasible or optimal solutions to when or where or how often to perturb and how this can be done. Given the recent advances in multiscale deep learning models of the atmosphere [57,58,59], the question is ripe for study, and we propose that an inter-disciplinary group take this on as a fundamental challenge.

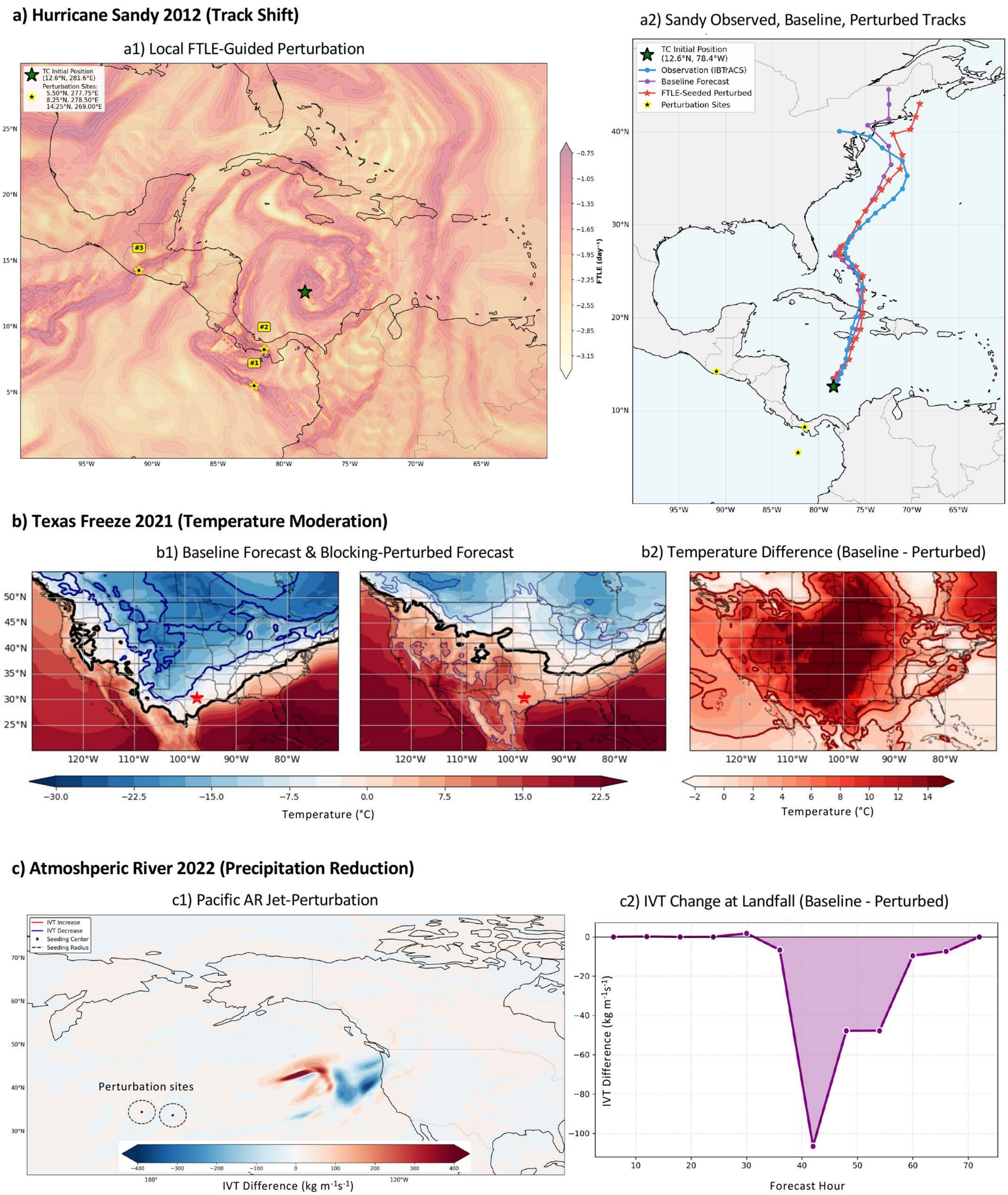

Fig 2. Weather Jiu-Jitsu perturbation experiments for three extreme events using the Aurora [49] deep-learning Earth system model. Perturbations are applied once, several days before peak impact, at 2−3 locations and atmospheric levels identified using Finite-Time Lyapunov Exponent (FTLE) diagnostics [50], which highlight upstream regions of maximal sensitivity in the flow. At each site, a small, localized cloud-seeding-simulated microphysical perturbation (latent-heating and humidity anomaly; $\Delta T \approx 6.7\text{-}10.4$ K, $\Delta q \approx 2.3\text{-}3.4$ g kg^{-1}) is introduced into Aurora's forecast to modify downstream

evolution [51]. **a)** Hurricane Sandy (2012): FTLE-guided nudges applied 7 days before landfall shift the simulated track by ~322 km [52]. **b)** Texas Freeze (2021): Upstream perturbations weaken Arctic blocking, reducing the minimum temperature anomaly by ~10°C [51]. **c)** Atmospheric River (2022): Targeted jet-wave interference shifts AR trajectory, reducing integrated vapor transport (IVT) by approximately 5% in a one-time perturbation under favorable upstream kinematic conditions [53]. Basemap boundaries were generated using Natural Earth public-domain shapefiles, including Admin 0 country boundaries and Admin 1 state/province boundaries (Natural Earth, https://www.naturalearthdata.com/). Data are in the public domain; terms of use available at https://www.naturalearthdata.com/about/terms-of-use/.

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The practical challenge is how to physically perturb the atmospheric circulation. This comes down to identifying feasible ways of delivering the energy of perturbation such that the flow is perturbed in the right way, i.e., the perturbation is amplified by natural dynamics. Weather Jiu-Jitsu interventions would target synoptic-scale weather features at weather timescales of days to weeks, with perturbation sites located upstream of the evolving event as identified by FTLE diagnostics, consistent with the proof-of-concept experiments in Fig 2 [52,53]. The Stormfury cloud seeding experiments demonstrated that silver iodide as well as salt provided the nucleation necessary for precipitation and hence the thermodynamic agency for changing the energetics [33,34,35]. More recently, the SNOWIE field experiments (2017) provided the first unambiguous physical evidence of the complete chain from silver iodide release through ice nucleation to surface precipitation, and demonstrated that seeding-induced snowfall can be quantified and directly attributed using radar, airborne probes, and chemical tracers [60,61]. Laser lightning control has emerged [62] as an interesting research area, where lightning goes to a cloud level focal point created by multiple ground-based lasers, rather than to the ground, leading to a significant concentration of heating at the focal point. Other ideas as to how to accomplish perturbations with low energy inputs need to be explored and tested.

Finally, multiple algorithms for adaptive stochastic or chaos control have been applied to a number of problems [63,64], including spatio-temporal dynamics. Consequently, the literature on appropriate algorithms is accessible, and the challenge is the acquisition of and access to real time data on the evolving systems and its assimilation into the state space for adaptive control. The minimum set of observables that is necessary for this exercise, drawing on real-time satellite wind retrievals, radiosonde profiles, aircraft reconnaissance data, and potentially drone-based in-situ measurements at perturbation sites, needs to be identified and integrated into a data assimilation framework purpose-built for adaptive control.

We recognize that there are numerous legal, social, and environmental challenges posed by our proposal. Targeted atmospheric interventions can create winners and losers across national boundaries, raising critical questions of transboundary liability, consent, and equitable risk distribution [31]. International frameworks, including the UN Environmental Modification Convention [65] and WMO protocols for weather modification activities [66], offer relevant precedents, but their adaptation to synoptic-scale adaptive interventions will require new governance structures developed in consultation with affected states and international scientific bodies. Transparent stakeholder engagement and proactive public communication are preconditions for the social legitimacy of any operational program; lessons from the broader geoengineering governance literature suggest that deliberative, multi-stakeholder processes must be embedded from the earliest stages of research [67], long before any operational deployment is contemplated. Weather Jiu-Jitsu focuses on subtle, adaptive intervention, integrated with real-time forecasts and physical constraints, and its potential risks may prove more manageable and its benefits more precisely targeted than those of conventional geoengineering or hard infrastructure.

Demonstrating these benefits will require concrete evaluation metrics, such as reductions in peak precipitation intensity, flood inundation extent, and insured economic losses, assessed through counterfactual ensemble experiments that compare large sets of perturbed and unperturbed simulations to attribute outcomes to interventions rather than natural variability [53]. We envision a staged research agenda: in the near term, controlled deep-learning perturbation experiments for historical extreme events paired with observational system design; in the medium term, scaled regional pilot studies and governance framework development with WMO and UNEP; and in the longer term, limited operational pilots under formal international oversight with systematic outcome monitoring. By leveraging the atmosphere's inherent sensitivity, Weather Jiu-Jitsu seeks not to overpower nature, but to collaborate with it: nudging storm tracks, influencing jet stream meanders, and possibly mitigating compound extremes before they fully develop. We invite discussion and collaboration to develop and evaluate the ideas.

Supporting information

S1 Appendix. Appendix for Weather Jiu-Jitsu: prospects for atmospheric nudging to defuse the impact of catastrophic weather extremes.
(DOCX)

Author contributions

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Validation: Qin Huang, Moyan Liu.

Visualization: Qin Huang, Moyan Liu.

Writing – original draft: Qin Huang, Upmanu Lall.

Writing – review & editing: Qin Huang, Moyan Liu, Upmanu Lall.

References

1. Utah Division of Water Resources. Why Utah cloud seeds. https://water.utah.gov/cloudseeding/ Accessed 2025 August 25.
2. Munich Re. Natural disasters in 2024: climate change is showing its claws. https://www.munichre.com/en/company/media-relations/media-information-and-corporate-news/media-information/2025/natural-disaster-figures-2024.html. 2025. Accessed 2025 August 25.
3. Gallagher R. Natural catastrophe and climate report: 2024. https://www.ajg.com/gallagherre/news-and-insights/gallagherre-natural-catastrophe-and-climate-report-2024/ 2024. Accessed 2025 August 25.
4. World Meteorological Organization. WMO atlas of mortality and economic losses from weather, climate and water extremes (1970-2019). Geneva: WMO. 2021. https://wmo.int/publication-series/wmo-atlas-of-mortality-and-economic-losses-from-weather-climate-and-water-extremes-1970-2019
5. Zscheischler J, Martius O, Westra S, Bevacqua E, Raymond C, Horton RM, et al. A typology of compound weather and climate events. Nat Rev Earth Environ. 2020;1(7):333–47. https://doi.org/10.1038/s43017-020-0060-z
6. Dettinger MD, Martin Ralph F, Abel MR, Das T, Neiman P, Cox D, et al. Correction to: Design and quantification of an extreme winter storm scenario for emergency preparedness and planning exercises in California. Nat Hazards. 2024;120(13):12571–12571. https://doi.org/10.1007/s11069-024-06865-x
7. Porter K, Wein A, Alpers C, Baez A, Barnard P, Carter J. Overview of the ARkStorm scenario. Reston (VA): US Geological Survey. 2011. http://pubs.usgs.gov/of/2010/1312/
8. Stendel M, Francis J, White R, Williams PD, Woollings T. The jet stream and climate change. Climate Change. Elsevier. 2021:327–57. https://doi.org/10.1016/b978-0-12-821575-3.00015-3
9. Kautz L-A, Martius O, Pfahl S, Pinto JG, Ramos AM, Sousa PM, et al. Atmospheric blocking and weather extremes over the Euro-Atlantic sector – a review. Weather Clim Dynam. 2022;3(1):305–36. https://doi.org/10.5194/wcd-3-305-2022
10. Lau WKM, Kim KM. The 2010 Pakistan flood and Russian heat wave: teleconnection of hydrometeorological extremes. J Hydrometeorol. 2012;13:392–403. https://doi.org/10.1175/JHM-D-11-016.1
11. Tabari H. Climate change impact on flood and extreme precipitation increases with water availability. Sci Rep. 2020;10(1):13768. https://doi.org/10.1038/s41598-020-70816-2 PMID: 32792563

12. SALTZMAN B. On the Maintenance of the Large-Scale Quasi-Permanent Disturbances in the Atmosphere. Tellus. 1959;11(4):425–31. https://doi.org/10.1111/j.2153-3490.1959.tb00052.x

13. Lorenz EN. Deterministic nonperiodic flow. J Atmos Sci. 1963;20:130–41. https://doi.org/10.1175/1520-0469(1963)020<0130:DNF>2.0.CO;2

14. Lorenz EN. Irregularity: a fundamental property of the atmosphere. Tellus A. 1984;36A:98–110. https://doi.org/10.1111/j.1600-0870.1984.tb00230.x

15. Maasch KA, Oglesby RJ, Fournier A. Barry Saltzman and the theory of climate. J Clim. 2005;18:1073–85. https://doi.org/10.1175/JCLI3383.1

16. Lewis JM, Lakshmivarahan S. The Saltzman-Lorenz exchange in 1961: bridge to chaos theory. Bull Am Meteorol Soc. 2024;105. https://doi.org/10.1175/BAMS-D-23-0157.1

17. Aemisegger F, Vogel R, Graf P, Dahinden F, Villiger L, Jansen F, et al. How Rossby wave breaking modulates the water cycle in the North Atlantic trade wind region. Weather Clim Dynam. 2021;2(1):281–309. https://doi.org/10.5194/wcd-2-281-2021

18. Nayak A, Zhang M, Gentine P, Lall U. Catastrophic "hyperclustering" and recurrent losses: diagnosing U.S. flood insurance insolvency triggers. npj Nat Hazards. 2025;2(1). https://doi.org/10.1038/s44304-025-00136-w

19. Kreibich H, Van Loon AF, Schröter K, Ward PJ, Mazzoleni M, Sairam N, et al. The challenge of unprecedented floods and droughts in risk management. Nature. 2022;608(7921):80–6. https://doi.org/10.1038/s41586-022-04917-5 PMID: 35922501

20. Ward PJ, Jongman B, Aerts JCJH, Bates PD, Botzen WJW, Diaz Loaiza A, et al. A global framework for future costs and benefits of river-flood protection in urban areas. Nature Clim Change. 2017;7(9):642–6. https://doi.org/10.1038/nclimate3350

21. Ponce VM. On the return period to be used for design. https://ponce.sdsu.edu/return_period.html Accessed 2025 August 27.

22. Polacek A. Catastrophe bonds: a primer and retrospective. Chicago Fed Lett. 2018;(405). Available from: https://www.chicagofed.org/publications/chicago-fed-letter/2018/405

23. Ho M, Lall U, Allaire M, Devineni N, Kwon HH, Pal I, et al. The future role of dams in the United States of America. Water Resources Research. 2017;53:982–98. https://doi.org/10.1002/2016WR019905

24. Hwang J, Lall U. Increasing dam failure risk in the USA due to compound rainfall clusters as climate changes. npj Nat Hazards. 2024;1(1). https://doi.org/10.1038/s44304-024-00027-6

25. Lee CC, Maron M, Mostafavi A. Community-scale big data reveals disparate impacts of the Texas winter storm of 2021. Humanit Soc Sci Commun. 2022;9:335. https://doi.org/10.1057/s41599-022-01353-8

26. Doss-Gollin J, Farnham DJ, Lall U, Modi V. How unprecedented was the February 2021 Texas cold snap?. Environ Res Lett. 2021;16:064056. https://doi.org/10.1088/1748-9326/ac0278

27. Kraehnert K, Doetsch J, Barham B, Carter M, Flechtner I, Guenther I. Insurance against extreme weather events: an overview. Rev Econ. 2021;72:71–95. https://doi.org/10.1515/roe-2021-0024

28. Kron W. Flood insurance: from clients to global financial markets. J Flood Risk Management. 2009;2(1):68–75. https://doi.org/10.1111/j.1753-318x.2008.01015.x

29. Nayak A, Gentine P, Lall U. Financial losses associated with US floods occur with frequent low-return-period precipitation. Nat Water. 2025;3(11):1256–67. https://doi.org/10.1038/s44221-025-00506-8

30. Japan Science and Technology Agency (JST). Goal 8: controlling and modifying the weather. https://www.jst.go.jp/moonshot/en/program/goal8/index.html Accessed 2025 June 10.

31. Simon M, McDonald J, Brent K. Transboundary Implications of China's Weather Modification Programme. TEL. 2023;12(3):594–622. https://doi.org/10.1017/s2047102523000146

32. UAE Research Program for Rain Enhancement Science. Overview of UAE cloud-seeding operations. https://www.uaerep.ae/ Accessed 2025 October 10.

33. Willoughby HE, Jorgensen DP, Black RA, Rosenthal SL. Project STORMFURY: A Scientific Chronicle 1962-1983. Bulletin of the American Meteorological Society. 1985;66:505–14. https://doi.org/10.1175/1520-0477(1985)066<0505:PSASC>2.0.CO;2

34. Sheets RC. Tropical cyclone modification: the Project Stormfury hypothesis. Miami (FL): NOAA. 1981. https://repository.library.noaa.gov/view/noaa/11351/noaa_11351_DS1.pdf

35. National Research Council. Critical issues in weather modification research. Washington (DC): National Academies Press. 2003. https://doi.org/10.17226/10829

36. Lorenz EN. Computational periodicity as observed in a simple system. Tellus A: Dynamic Meteorology and Oceanography. 2006;58(5):549. https://doi.org/10.1111/j.1600-0870.2006.00201.x

37. Yang S-K, Chen C-L, Yau H-T. Control of chaos in Lorenz system. Chaos, Solitons & Fractals. 2002;13(4):767–80. https://doi.org/10.1016/s0960-0779(01)00052-2

38. Liu M, Huang Q, Lall U. Weather Jiu-Jitsu: Towards Adaptive Chaos Control of Weather Extremes. ESS Open Archive. 2025. https://doi.org/10.22541/essoar.176617236.67354673/v1

39. Li R, Zheng F, Zhu J, Huo Z, Chen Y, Ying J. Estimating the decadal-scale climate predictability limit using nonlinear local Lyapunov exponent with optimal dynamic analogues. Clim Dyn. 2025;63:85–102. https://doi.org/10.1007/s00382-024-07573-9

40. Dong C, Faranda D, Gualandi A, Lucarini V, Mengaldo G. Revisiting the predictability of dynamical systems: a new local data-driven approach. 2024. https://doi.org/10.48550/arXiv.2409.14865

41. Miyoshi T, Sun Q. Control simulation experiment with Lorenz's butterfly attractor. Nonlin Processes Geophys. 2022;29(1):133–9. https://doi.org/10.5194/npg-29-133-2022
42. Kawasaki F, Kotsuki S. Leading the Lorenz 63 system toward the prescribed regime by model predictive control coupled with data assimilation. Nonlin Processes Geophys. 2024;31(3):319–33. https://doi.org/10.5194/npg-31-319-2024
43. Broer H, Simó C, Vitolo R. Bifurcations and strange attractors in the Lorenz-84 climate model with seasonal forcing. Nonlinearity. 2002;15(4):1205–67. https://doi.org/10.1088/0951-7715/15/4/312
44. Liu M, Huang Q, Lall U. Controlling eddies in the non-autonomous Lorenz-84 model. 2025. https://doi.org/10.48550/arXiv.2510.26005
45. Karamperidou C, Cioffi F, Lall U. Surface temperature gradients as diagnostic indicators of midlatitude circulation dynamics. J Clim. 2012;25:4154–71. https://doi.org/10.1175/JCLI-D-11-00067.1
46. Finocchio PM, Doyle JD. How the Speed and Latitude of the Jet Stream Affect the Downstream Response to Recurving Tropical Cyclones. Monthly Weather Review. 2019;147(9):3261–81. https://doi.org/10.1175/mwr-d-19-0049.1
47. Becker S, Becker T. The impact of changes in steering patterns on the probability of hurricanes making landfall in the New York City area. Int J Climatol. 2023;43:4590–602. https://doi.org/10.1002/joc.8104
48. Barnes EA, Polvani LM, Sobel AH. Model projections of atmospheric steering of Sandy-like superstorms. Proc Natl Acad Sci U S A. 2013;110(38):15211–5. https://doi.org/10.1073/pnas.1308732110 PMID: 24003129
49. Bodnar C, Bruinsma WP, Lucic A, Stanley M, Allen A, Brandstetter J, et al. A foundation model for the Earth system. Nature. 2025;641(8065):1180–7. https://doi.org/10.1038/s41586-025-09005-y PMID: 40399684
50. Garaboa-Paz D, Eiras-Barca J, Perez-Munuzuri V. Climatology of Lyapunov exponents and atmospheric rivers. Earth Syst Dynam. 2017;8. https://doi.org/10.5194/esd-8-865-2017
51. Lall U, Huang Q, Liu M, Kwon HH, Kwon Y. Weather Jiu-Jitsu: adaptive chaos control with deep learning of atmospheric dynamics to leverage large-scale circulation for storm steering and flood risk reduction. In: New Orleans, Louisiana. https://agu.confex.com/agu/agu25/meetingapp.cgi/Paper/1926148
52. Huang Q, Liu M, Lall U, Kwon Y, Kwon HH, Liu Y. Weather Jiu-Jitsu: Steering Tropical Cyclones with Small Perturbations of the Jet Stream in Experiments with Deep Learning Foundation Models. In: New Orleans, Louisiana, 2025. https://agu25.ipostersessions.com/?s=80-79-CE-89-5E-5F-05-4E-D0-B7-7C-4F-EE-84-B0-CE
53. Liu M, Huang Q, Lall U. Instability-aware steering of an extreme atmospheric river in an AI weather foundation model. arXiv. 2026. https://doi.org/10.48550/arXiv.2604.18906
54. Schubert S, Lucarini V. Dynamical analysis of blocking events using covariant Lyapunov vectors. Q J R Meteorol Soc. 2016;142:2143–58. https://doi.org/10.1002/qj.2808
55. Lucarini V, Gritsun A. A new mathematical framework for atmospheric blocking events. Clim Dyn. 2020;54:575–98. https://doi.org/10.1007/s00382-019-05018-2
56. Faranda D, Messori G, Yiou P. Dynamical proxies of North Atlantic predictability and extremes. Sci Rep. 2017;7:41278. https://doi.org/10.1038/srep41278 PMID: 28120899
57. Lai C-Y, Hassanzadeh P, Sheshadri A, Sonnewald M, Ferrari R, Balaji V. Machine Learning for Climate Physics and Simulations. Annual Review of Condensed Matter Physics. 2025;16(1):343–65. https://doi.org/10.1146/annurev-conmatphys-043024-114758
58. Zhang L, Zhao Y, Cen Y, Lu M. Deep learning-based precipitation simulation for tropical cyclones and atmospheric rivers. J Geophys Res Atmos. 2024;129:e2024JD041914. https://doi.org/10.1029/2024JD041914
59. Mu B, Qin B, Yuan S, Qin X. A climate downscaling deep learning model considering multiscale spatial correlations and chaos. Math Probl Eng. 2020;2020:7897824. https://doi.org/10.1155/2020/7897824
60. French JR, Friedrich K, Tessendorf SA, Rauber RM, Geerts B, Rasmussen RM, et al. Precipitation formation from orographic cloud seeding. Proc Natl Acad Sci U S A. 2018;115(6):1168–73. https://doi.org/10.1073/pnas.1716995115 PMID: 29358387
61. Friedrich K, Ikeda K, Tessendorf SA, French JR, Rauber RM, Geerts B, et al. Quantifying snowfall from orographic cloud seeding. Proc Natl Acad Sci U S A. 2020;117(10):5190–5. https://doi.org/10.1073/pnas.1917204117 PMID: 32094189
62. Houard A, Walch P, Produit T, Moreno V, Mahieu B, Sunjerga A, et al. Laser-guided lightning. Nat Photonics. 2023;17(3):231–5. https://doi.org/10.1038/s41566-022-01139-z PMID: 36909208
63. Scholl E, Schuster HG. Handbook of chaos control. Scholl E, Schuster HG, editors. Weinheim: Wiley-VCH. 2008.
64. Boccaletti S, Grebogi C, Lai YC, Mancini H, Maza D. The control of chaos: theory and applications. Phys Rep. 2000;329:103–97. https://doi.org/10.1016/S0370-1573(99)00096-4
65. United Nations. Convention on the prohibition of military or any other hostile use of environmental modification techniques (ENMOD). New York: United Nations. 1977. https://treaties.un.org/pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVI-1&chapter=26
66. World Meteorological Organization. WMO statement on weather modification. Geneva: WMO. 2025. https://wmo.int/content/wmo-statement-weather-modification
67. National Academies of Sciences, Engineering, and Medicine. Reflecting sunlight: recommendations for solar geoengineering research and research governance. Washington (DC): National Academies Press. 2021. https://doi.org/10.17226/25762