Anticipating Planetary-scale Surprise: AI to accelerate understanding of climate security, tipping-points and interventions

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Abstract

The Department of Defense has stated in multiple reports that climate change will have measurable impacts on assets in the coming decades. Climate tipping points, sudden shifts in the Earth's climate, may bring about such impacts quickly and with reduced warning. DARPA's AI-assisted Climate Tipping-point Modelling (ACTM) program has demonstrated steps towards developing enhanced climate models and data assimilation techniques which provide a better understanding of climate tipping points, what may cause them, and what the Earth climate system may look like after a tipping point occurs.

Current State of DoD Climate Efforts

There is mounting evidence that climate change will have real, tangible impacts on Department of Defense (DoD) assets. According to an evaluation of the DoD's efforts to address climate resilience of U.S. Military installations in the Arctic and Sub-Arctic conducted by the DoD Inspector General (DoD Inspector General 2022)[1], there has been a large degree of focus on existing weather and energy challenges. There has been less focus on analyzing installation infrastructure, assets, mission exposure, and vulnerability to climate change. There is also a need for additional guidance regarding implementation of military installation resilience assessments, as well as additional resources to analyze and asses climate change.

According to the DoD Climate Risk Analysis 2021 report (DoD Office of the Undersecretary for Policy 2021)[2], extreme weather events have long-term potential to undermine training capability and readiness. Just in recent years it has been reported that there have been billions of dollars in climate related damages to the Tyndall Air Force Base and Marine Corps Base Camp Lejeune. The 2021 report also highlights that climate change is dramatically altering the Arctic environment, creating a new frontier for geostrategic competition. Also highlighted is the strategic importance of U.S. defense assets located in Guam, the Marshall Islands, and Palau, each of which have demonstrated vulnerability to hazards attributable to climate change. There is also the looming risk that China may try to take advantage of climate change impacts in order to gain influence.

U.S. Army[3], Navy[4] and Air Force[5] Climate action plans further outline the need and latest efforts by the DoD to combat the negative effects of climate change. The U.S. Army's plan suggests the incorporation of the latest climate and environmental science into stationing, construction and fielding decisions, to develop predictive logistics that drive more precise and faster decisions, as well as the inclusions of climate change threat mitigation into Army land management decisions. The U.S. Navy plan suggests assessing climate change impacts and threats to be folded into wargames and training exercises. The Navy also suggests that climate change data be embedded in performance management capabilities in order to help leadership understand progress/risks towards accomplishing climate-related outcomes. Finally, the Navy acknowledges that meaningful climate related training/education curricula tied to mission objectives will need to be incorporated. The U.S. Air Force plans to develop a framework for evaluating the effects of climate change at all department installations information resourcing and basing processes by FY24. The Air Force

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[1] Evaluation of the Department of Defense's Efforts to Address the Climate Resilience of U.S. Military Installations in the Arctic and Sub-Arctic (DODIG-2022-083), DoD Inspector General, 2022

[2] Department of Defense Climate Risk Analysis, DoD, 2021

[3] Department of the Army, Office of the Assistant Secretary of the Army for Installations, Energy and Environment. February 2022. United States Army Climate Strategy. Washington, DC.

[4] Department of the Navy, Office of the Assistant Secretary of the Navy for Energy, Installations, and Environment. May 2022. Department of the Navy Climate Action 2030. Washington, DC

[5] Department of the Air Force, Office of the Assistant Secretary for Energy, Installations, and Environment. October 2022. Department of the Air Force Climate Action Plan. Washington, DC.

will also acquire improved extreme weather sensing solutions, develop expertise, analyze authoritative climate and extreme weather data, as well as carry out wargames which factor in environmental risks impacting the U.S.'s ability to win in contested environments.

In addition to the U.S. Army, Navy and Air Force efforts to combat climate change, the Defense Advanced Research Projects Agency (DARPA) has instantiated many programs over the years to do so. One example is the Reefense program[6], which will develop self-healing, hybrid biological and engineered reef-mimicking structures to mitigate the coastal flooding, erosion and storm damage that increasingly threaten DoD infrastructure and personnel. Through these programs, and others like it, DARPA is developing innovative technologies to mitigate the impacts of climate change and enhance resilience in the face of its effects.

Potentially Irreversible Changes to Climate Systems

Of the many threats posed by climate change, one of the more concerning involves the crossing of what are thought to be climate tipping points. A tipping point is a critical threshold that, when crossed, leads to large and often irreversible changes in the climate system. Some examples of major, land, ocean and atmospheric environmental features that are being monitored for tipping points include:

- The Greenland ice sheet (*ice loss accelerating*)
- Atlantic Circulation (*15% slowdown since the 1950s*)
- The Boreal Forest (*fire regime changing*)
- Amazon rainforest (*unprecedented droughts in the last 15 years*)
- Australian great barrier reef (*massive die offs in recent years*)

A survey of the latest literature in the community indicates that large uncertainties exist on the timing and thresholds to reach tipping-points on top of the existing uncertainties from Greenhouse Gas Emission (GHG) trajectories and climate sensitivity. Many of the tipping-points of immediate concern involve large increases in GHG emissions (particularly methane) or large decreases in natural CO2 removal, which could lead to further tipping-points (so-called tipping-point cascade scenarios) (McKay et al. 2022). Additionally, while computer performance has been increasing exponentially over the past 70 years, its estimated that 100 billion times currently available computing resources would be required to fully resolve multi-scale cloud phenomena in a global earth system model, just one example of a key model inadequacy limiting our ability to understand climate tipping-points. Even for climate tipping-points that are represented to varying degrees of fidelity in present-day models, very large ensemble runs are needed to study them, dramatically increasing the necessary computation.

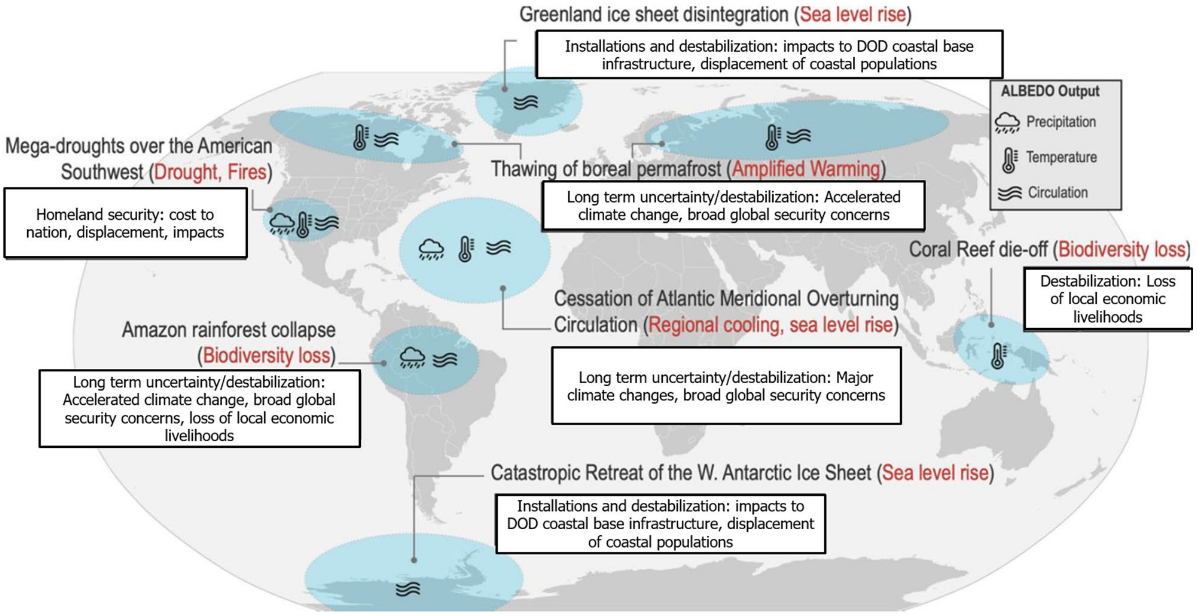

Figure 1: Potential climate tipping-point events and related national and global security concerns.

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[6] https://www.darpa.mil/program/reefense

AI-assisted Climate Tipping-point Modelling

Current climate models of highly complex underlying physical processes lack the fidelity to resolve key processes, are too computationally intensive to run in sufficiently large ensembles, and have limited capacity for causal explainability and so provide limited actionable guidance to policy makers on the risks and causes of sudden tipping points. To this end, DARPA has funded the AI-assisted Climate Tipping-point Modelling (ACTM) program[7] whose primary goal is to explore many key application domains (ocean, ice, clouds, etc.), potential strategic tipping-point events, and emerging AI methods to identify areas where hybrid (AI and process) modeling approaches are likely to have the most impact on our understanding of future climate-induced planetary-scale surprise.

The program started in December of 2021 and is structured in two Phases. Phase 1 was 12 months and completed in December 2022. It explored the use of 3rd wave AI methods to enhance models of complex interconnected processes with the goal of improving modeling, understanding, and characterization of possible environmental tipping-points that pose critical strategic challenges. Running from January 2023 – July 2023, Phase 2 of the ACTM program will develop methods to assimilate diverse data into models and estimate the "value of new data" to enhance confidence in target-specific forecasts relative to state-of-the-art (SOTA) techniques. DARPA hopes to make critical progress and identify opportunities for future programs to develop new methods and sensors to better understand the risks of tipping-points events and cascades, what climate conditions following tipping-point events may be, data, and indicators that can provide actionable early warning, and possible intervention options.

ACTM is investigating several questions regarding how these systems change including how can we improve understanding of tipping-point phenomena and risk (e.g., causal neuro-symbolic simulators for better understanding of AMOC system dynamics). Performers working on the ACTM program are also working to understand how much early warning can we get that tipping-points are occurring (e.g., hybrid deep learning classifiers to characterize approaching tipping-points). ACTM also seeks to understand that if tipping-points do happen, what does the climate look like on the other side (e.g., physics-informed, biologically-inspired AI for fast/accurate climate models). Lastly, the program also seeks to illuminate if adversaries might leverage interventions and how would we know (e.g., use AI to detect, attribute and quantify Solar Climate Intervention effects/risks under a range of geopolitical scenarios).

ACTM is tackling several modelling challenges directly related to tipping-points. For example, climate models currently lack fidelity for key processes related to tipping points. Model ensembles needed to understand likelihoods are too expensive to run, so there is a need to make such ensembles more computationally efficient. The science of tipping point early-warning is currently based on very simple systems and data/modeling for climate interventions and provides limited guidance on potential or adversarial application. ACTM's approach to these challenges is to improve tipping point understanding over multiple time-scales, enable large ensemble studies to understand uncertainty, and study the time-scales of tipping-point early warning signals. The program also aims to create a basis for understanding climate conditions on the other side of tipping points for planning triage and adaption mechanisms, studying climate intervention to better understand the potential impact of adversarial applications, and monitoring strategies. The ACTM program is also creating useful, open, well documented, and reproducible machine learning tools and data readily adoptable by the climate science community.

Approaches in the ACTM program

ACTM performers are building a new climate tipping point dataset for AI exploration, reducing computation for large climate models and creating neuro-symbolic language to represent model-specific questions for causality exploration. This methodology is being applied to the Atlantic Meridional Overturning Circulation (AMOC) to improve understanding of ocean operations, as well as to increase explainability and accuracy of climate and tipping point models to enable improved adaptation strategies.

Performers have built a hybrid AI framework to capture the effects of cloud properties on global circulation (atmospheric and ocean), and regional climate patterns (temperature and precipitation). The framework runs multi-decadal climate scenarios that obviates the need to run full earth models, saving millions of core computing hours. This tool can be used for rapid generation of scenario analysis and for preparedness and climate resilience planning. This work explores if marine cloud brightening interventions can yield specific, targeted climate outcomes.

ACTM is also creating a hybrid AI model to identify early-warning systems for tipping points using an improved deep learning classifier to better understand tipping point features, extensively test its skill on complex climate model output and paleo/observational data, and combine this with considerations of DoD strategic/operational relevance.

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[7] https://www.darpa.mil/program/ai-assisted-climate-tipping-point-modeling

Regarding Solar Climate Intervention (SCI) ACTM performers are developing and applying novel AI algorithms to detect, attribute, and quantify effects of SCI on climate, quantify the risks and uncertainties of Earth system impacts under different SCI scenarios. Performers have designed, simulated and analyzed plausible geopolitically-motivated SCI deployment scenarios.

ACTM performers are applying a hybrid parallel weather prediction model on a realistic 3-dimensional atmospheric global circulation model. They are using reservoir computing to train in parallel to increase computational efficiency in modeling large datasets. Though the models cannot be directly validated, the team is generating probabilistic forecasts of extreme events and tipping points and identify high-value data collection opportunities.

Work carried out under the program has been done on previously un-modeled dynamics of earth climate models using Koopman operator theory (data-driven approach for studying nonlinear dynamical systems). This enabled models to produce causal discovery, tipping point identification and explanations. The work concluded using arctic sea ice variability as proof of concept.

ACTM performers have combined new AI methods with new physical models for turbulence, convection, and clouds using large eddy simulation (LES) data. This has improved modeling of clouds and other small-scale processes for more accurate, interpretable and generalizable climate predictions with quantified uncertainties.

Regarding Madden Julian Oscillations (MJOs), performers have developed new hybrid AI methods to accelerate models with improved cloud-resolving physics surrogates; test tipping point hypotheses, with focus on an intraseasonal atmospheric MJO variability in the tropics. ACTM performers implemented hypothesis-directed methodology for AI-supported scientific discovery near the limits of available computation.

Lastly, ACTM performers are also currently studying storm relevance (AMOC, monsoons) to tipping points using a physically-informed, biologically-inspired machine learning framework to produce fast and accurate climate models, where accuracy has been tested against past observational data (e.g., El Nino cycles) and the latest state-of-the-art climate models (e.g., E3SM). This work focuses on enabling quantification of prediction uncertainty, and climate risks associated with changing storms that threaten regional stability for a range of scenarios.

Conclusions

Climate change, whether natural or human-driven, has huge impacts on geopolitical and economic stability, food and water security, and DoD missions and operations. Modeling of “slow” long-term climate change is relatively robust and has reached something approaching a global consensus. However, the risks and causes of sudden tipping points (in which one or more key parts of the Earth System, such as ocean circulations or ice sheets, transition to a new state in an irreversible way with unpredictable consequences), runaway feedback loops, and the strategic implications of potential adversarial intervention activities, are poorly understood. Current climate models of highly complex underlying physical processes provide limited actionable guidance to policy makers on these critical planetary-scale “strategic surprises”, partly due to the computational cost to run in sufficiently large ensembles in order to test a large diversity of scenarios.

There are inherent limitations to how much confidence we can derive from AI modelling of climate tipping points, primarily because we are examining irreversible events for which we – by definition – have limited direct observational data. While we have learned a lot about the nature of tipping points more generally, validation for predicting future events in any one of the areas studied on this program is not possible based on current data limitations. Also, machine learning models over the course of the program have demonstrated some bias influenced by the data it has been trained on, leading to inaccuracies in some test scenarios. Finally, there is still much work left to be done to make machine learning models more human interpretable in order to further explore how AI driven climate models make their decisions.

The goal of the ACTM program has been and continues to be the enhancement of climate models so we can begin to explore a range of possible scenarios, such as those related to DoD planning and decision support (e.g., arctic strategy/defense, regional destabilization, global power/economic realignment, base/force locations, and extreme weather threats) and to identify new potential high-value observations (e.g., stratospheric vs. ocean surface vs. deep ocean vs. arctic, etc.) to enhance confidence in forecasts.

References

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