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Planetary Foresight: Envisioning an early warning system for climate tipping points

Gemma M Bale[1,2,3*], Sarah E Bohndiek[1,2,4*], Daniel Giles[1], Jessica Humphreys[1], Caitlin Kubala[1], Katie Reardon[1], Isabella Roberts[1].

1 Advanced Research + Invention Agency, UK
2 Department of Physics, University of Cambridge, UK
3 Department of Engineering, University of Cambridge, UK
4 CRUK Cambridge Institute, University of Cambridge, UK

* These authors contributed equally and are co-corresponding; correspondence to gemma-sarah@aria.org.uk sarah.bohndiek@aria.org.uk

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Abstract

Climate tipping points present significant long-term challenges, with critical thresholds at risk of being crossed within this century. Crossing these thresholds would lead to widespread, self-perpetuating changes—from unprecedented sea-level rise to inhospitable weather extremes—for which humanity is inadequately prepared. To build preparedness, humanity requires a better sense of when such thresholds could be crossed, over what timescale the effects might unfold, and what the impacts would be. Here, we ask: 'Can we build an early warning system (EWS) for climate tipping points?'.

After introducing climate tipping points and their potential for cascading impacts, we identify lessons from existing actionable early warning frameworks, such as tsunami and famine detection. Using North Atlantic Subpolar Gyre as an example tipping system with

the Greenland Ice Sheet as a freshwater forcing function, we outline a proposed approach to build a prototype EWS by holistically integrating low-cost sensor swarms and artificial intelligence with physical models and robust uncertainty quantification. From these foundations, we identify the research gaps and hurdles to converting scientific signals into trustworthy scenarios for decision-makers. We envision an operational system that empowers human agency, providing decadal foresight necessary for strategic responses, building resilience from national climate security to the global financial system.

Main text

Introduction: what are climate tipping points and why do they matter?

There is no doubt about it: our climate is changing. Recent years have broken records for surface temperatures, greenhouse gas levels, ocean heat, sea level rise, Antarctic sea ice extent and glacier retreat [1]. Climate extremes are already causing disruptions for millions of people around the world and inflicting billions of pounds of economic damage [2]. Yet these impacts pale in comparison to the long-term changes we could see if we cross climate tipping points [3–5].

A climate tipping point represents a critical threshold at which a small change in forcing triggers a rapid, self-perpetuating, and often irreversible shift in a major component of the Earth system [4]. More important than their precise definition is the scale of the disruption that we expect humanity to face as a result of crossing these thresholds. Tipping points exist across different parts of the Earth system (Figure 1), exhibiting different spatial and temporal timescales, forcing mechanisms and thresholds. Moreover, tipping one system could increase pressure on others, creating a domino-like cascade [6].

The goal of limiting warming to 1.5°C remains as critical today as when it was first highlighted decades ago. The likelihood of tipping increases with every degree of warming and even a temporary overshoot of the anticipated warming threshold can be problematic due to the dynamic interplay between overshoots and tipping points. Further, there exists a two-way coupling between human actions and tipping dynamics [7], with the emission trajectory in an overshoot scenario impacting the tipping element [8]. Both the magnitude and duration of overshoot are important, as well as the environmental context: a fast-onset system like a forest biome might be pushed past its point of no return by a short, sharp temperature spike; whereas a slow-onset system like an ice sheet could be destabilised by a longer, more moderate overshoot [8]. In addition, any attempt to recover a prior stable state of a tipping system is hampered by hysteresis, meaning the path back is not the same as the path taken.

Figure 1: Map of major tipping points and their associated global warming thresholds. Adapted from Armstrong-Mackay [3].

Climate tipping points matter because their consequences are not incremental; they represent profound threats to humanity on a civilisational scale, with the recent Global Tipping Points report emphasising that billions of people would face major impacts [5]. The collapse of the Greenland and West Antarctic Ice Sheets, for example, represent a direct threat to every coastal city, port, and community on Earth. The resulting ~10 metres of locked-in sea-level rise would redraw coastlines, displace up to 40% of the global population, and render trillions of dollars of infrastructure indefensible [9]. A shutdown of the oceanic Atlantic Meridional Overturning Circulation (AMOC) could plunge northwestern Europe into a colder climate while simultaneously disrupting the tropical monsoons that provide water and food security for billions, triggering an agricultural and humanitarian crisis [10]. Similarly, the dieback of the Amazon rainforest risks a dangerous feedback loop, turning a vital carbon sink into a massive carbon source, further accelerating global warming [11,12].

In short, these events represent serious systemic risks on decadal horizons that could trigger cascading failures across our social, economic, and political systems [13]. The primary goal of climate policy has been to minimise the probability of triggering such events through rapid and deep decarbonisation. Given that we risk multiple tipping points as we cross 1.5°C, mitigation alone is clearly not enough; we must also prepare adaptive responses to manage the heightened risk [5]. A comparable level of risk in other critical sectors, such as aviation where risk tolerance is low, would trigger the immediate implementation of robust monitoring and contingency planning. Whilst acknowledging the differences in these examples to a climate tipping point, we argue that the same level of precaution is required. Effective preparation demands a system to monitor our proximity to climate thresholds and provide timely alerts—in essence, an early warning system for climate tipping points.

Lessons learned from existing actionable early warning systems

Asking whether building an early warning system (EWS) for climate tipping points is possible motivates a closer look at actionable EWSs that already exist. Successful systems, from tsunami detection to famine prediction, share common features and offer critical lessons. The UN Early Warnings for All programme[14] features four key pillars led by different international agencies. Here, we abbreviate these pillars to align with the science of early warning, as:

1. Monitoring: the technical capacity to observe the system,
2. Modelling: knowledge of the threat and capability to forecast future impacts,
3. Detection: identifying a perturbation or change in system trends and assessing future risks,
4. Response: ensuring dissemination of the warning to reach those at risk and preparing them to act on the information in a timely manner.

Key physical differences exist between the hydrometeorological and geophysical risks addressed in existing EWSs and those for climate tipping points. Firstly, the spatial and temporal timescales of a tipping point being crossed and effects being felt are orders of magnitude different from those of a tsunami being triggered. Secondly, the frequency of events such as tsunamis is relatively high, enabling repeated testing and refinement of the system; for climate tipping points, we realistically have one shot with zero prospect of refinement on meaningful timescales. Finally, the necessary response actions are not yet clearly defined in response to crossing a climate tipping point, depending on a range of factors including the extent of the warning and regions affected, among others. There is a research gap that needs to be filled but can build upon existing climate adaptation literature regarding transformational change and long-term policy pathways (e.g. [15,16]). Nonetheless, examining the success and failure of the pillars of early warning across different domains provides lessons for designing a potential climate tipping point EWS.

Lesson 1: An Integrated, End-to-End System is Non-Negotiable.

Japan's earthquake and tsunami EWS is a key example of successful end-to-end integration. It combines seismic sensors, rapid data processing, automated public alerts (e.g., interrupting television broadcasts and sending mobile alerts), and pre-planned responses (e.g., automatically stopping high-speed trains) into a seamless chain [17]. Tsunami early warning is a global scale initiative, with service providers relaying warning information to member states who cascade appropriate warnings nationally. Similarly, the Famine Early Warning Systems Network (FEWS-NET) is considered the gold standard of food security assessment, integrating diverse data—from satellite rainfall estimates to local market food prices and political stability reports—to produce a holistic risk assessment [18]. A tipping point EWS must be similarly conceived as an integrated system, built upon heterogeneous observations, models and appropriate response frameworks.

Lesson 2: Monitoring Must Distinguish Signal from Noise and Clearly Communicate Uncertainty.

An effective EWS must provide reliable alerts without excessive false alarms, which can lead to complacency. The Pacific Tsunami Warning Center's network [19] of deep-ocean buoys provides an example: it analyses real-time sensor data to confirm whether an undersea earthquake has actually displaced enough water to generate a dangerous tsunami, thereby verifying seismic signals and reducing unnecessary evacuations [17]. Furthermore, warnings must grapple with uncertainty. Rather than providing a single definitive prediction, systems like the National Hurricane Center issue a "cone of uncertainty" showing the probable track of a storm [20]. This probabilistic approach allows for tiered, risk-based responses in this more tractable example. Given the deep uncertainties in tipping point science, any EWS should adopt a probabilistic and uncertainty framework up front, ensuring that risk assessments evolve and appropriate responses are explored. The EWS should leverage decision making under deep uncertainty strategies [21] to prepare proportionately.

Lesson 3: Effective Warnings Must Bridge the 'Last Mile'.

The most sophisticated scientific signal is useless if it fails to reach and motivate the people at risk. Early warnings of the novel coronavirus from the WHO and other bodies during the COVID-19 pandemic were met with delayed and fragmented responses in many countries, hampered by many countries providing inconsistent public health advice and prioritising their own interests [22]. The 2004 Indian Ocean tsunami is a tragic example of the "last mile problem." While governmental agencies knew an earthquake had occurred, no robust system existed to warn the vast, vulnerable coastal populations. Many communities lacked the generational memory or formal education to recognise natural warning signs, such as the receding ocean. The events in the Indian Ocean contrast sharply with Japan, where decades of public education, visible evacuation route signage, and regular drills have embedded risk knowledge into the culture [23]. A climate tipping point EWS must be designed to acknowledge the inherent uncertainty around TPs and deliver clear, information that compels action at a global scale and is embedded within governance structures that have pre-agreed response plans to overcome inevitable friction. It is acknowledged that extensive work is needed here to build out capacity and trust in the system.

Challenges in creating an early warning system for climate tipping points

Applying these lessons to climate tipping points presents a unique challenge: we are warning of events that are unprecedented in human history and may unfold across generations. For a prototype EWS for climate tipping points to be deemed successful, a clear path to an integrated end-to-end system must be viable. The envisaged system would need to have a tipping point signal detection workstream working in parallel to a decadal forward projection workstream and the observations used differently within these parallel streams. Success hinges on overcoming five core scientific and technical hurdles: monitoring, modelling, early detection, deep uncertainty (lessons 1 and 2), and transitioning into full scale operation (lesson 3).

Monitoring Challenges

The confident identification of subtle early warning signals in our current Earth system data is hampered by several factors [24–27] including the:

- Short-term nature of many climate records[28,29],
- Presence of discontinuities in time-series,
- Limited spatial and/or temporal resolution of many measurements,
- Poor capture of key processes in climate system feedbacks [27],
- Need for detailed uncertainty quantification in the observations (both instrumental and methodological),
- Low signal-to-noise ratio of a tipping signal amongst the background climatic variability.

Furthermore, some of the climate systems most at risk of tipping are often under-observed [30,31] because they require instruments to survive in hostile environments (e.g. with extreme pressure or freezing temperatures) and/or demand depth-resolved data that is beyond the reach of satellites. The oceans and cryosphere are particularly challenging [32] and are hampered by technological and logistical challenges [33]. For example, despite progress within the ARGO network, capturing persistent long-term deep ocean observations of overflow and boundary currents, important for early signs of ocean tipping, is still beyond reach. Existing observational networks such as the ARGO network[34], and other approaches such as the OSNAP [35,36] and RAPID [37] mooring arrays, the Global Drifter Program [38] and the GO-SHIP hydrographic sections [39] play a vital role in improving our understanding and monitoring capabilities of key ocean dynamics, complemented by space-based observations [40]. Nonetheless, these efforts remain sparse and can be financially precarious, funded as research activities rather than operational national infrastructure. We envision that to implement an early warning system for climate tipping points would require a massive reduction in instrument size, weight, power and cost (SWaP-C) to create an adaptive system that specifically complements the blind spots of existing ocean observing architecture and can additionally react to tentative early warning signals with increased sampling in space and time.

Modelling Challenges

Our ability to model tipping points, their feedback processes and cascading interactions [41–43] is evolving but requires a catalytic investment to deliver the capabilities that we need for early warning. Our best climate models are computationally expensive and still do not resolve all the necessary Earth system processes relevant to GrIS and SPG dynamics[44], such as mesoscale turbulence, dense water formation and the ice-ocean boundary layer to name just a few[45]. They also suffer persistent biases that can hinder projections [46]. Furthermore, there is room to improve the state initialisation process for decadal prediction systems [47].

It is also important to acknowledge that there is a fundamental disconnect between modelling and measurement research in the wider climate science community. The result of this disconnect is that it is exceptionally difficult to combine models with measurements to achieve meaningful validation, or conversely, to guide optimal targeting of measurement variables or locations for early warning from model outputs [24,31]. Methods can be borrowed from the Observing System Sensitivity Experiment (OSSE) literature, but work needs to be carried out to identify the informationally optimal observing network for detecting early warning signals in different tipping systems.

Detection Challenges

The primary theoretical warning sign that a system is approaching a tipping threshold is a phenomenon known as 'critical slowing down' (CSD), where recovery of the system from minor perturbations becomes progressively slower [5]. CSD typically manifests as an increased amplitude of fluctuations in system state variables and can be detected with statistical methods by careful analysis of the temporal and/or spatial dynamics of the system [48]. More recently, deep learning approaches targeting the raw data series have also shown promise [49,50].

Although signs of CSD may already have been detected in several climate systems [24,51,52], scientific consensus remains elusive in many cases, with the stability of the AMOC proving particularly controversial [29,53,54]. Much of the foundational work on statistical CSD signals has relied on simplified, one-dimensional model data that fails to capture the complex spatial and temporal heterogeneity of real systems. Further, it is difficult to design a set of experiments that fatefully consider the null case. Loss of resilience alone is considered insufficient to confirm that a tipping point is approaching [55]; a clear physical interpretation of statistical indicators would be valuable. The lack of consensus is further compounded by disagreement between model outputs [44,56], as well as between models and measurements [57], further fuelling scientific and societal debate.

Deep Uncertainty Challenges

A key component of an EWS for tipping points that differs to the existing systems is the deep inherent uncertainty around these events. Can the system tip? Will the system tip? When will it tip? What to do if it tips? Answering these simple questions will require an honest and robust interrogation of the inherent uncertainties through the chain from observations through models to impact and response measures. Any EWS should tackle these elements using appropriate available tooling; robust calibration, uncertainty tree diagrams, model ensemble design, Bayesian techniques and decision making under deep uncertainty approaches. However, an honest recognition of the epistemic and aleatoric uncertainty associated with a tipping point EWS is essential, consideration of which will guide the development of appropriate response measures.

Systemic and Operational Challenges

Overcoming the scientific challenges requires breaking silos in the research ecosystem: enabling holistic combination of the measurement and modelling communities, uniting scientists across Earth system domains to study the interfaces between atmosphere, ocean, ice and land. Silos in the research ecosystem are compounded by a historic focus on long-term, high-value remote sensing missions and high performance computing methods; achieving an operational EWS demands a more agile approach. It is also imperative to attract new talent from outside of the climate science field to streamline progress on new technology solutions as well as to pro-actively consider the broader ethical and societal questions of early warning detection and communication.

Any prototype EWS would face significant hurdles to becoming operational (see Section "The path to operation"). Without lived experience of tipping points, we rely on historical or palaeoclimate records as a source of verification, but even then, events are scarce. As a further consequence of their rarity on human timescales, tipping points are considered less pressing for investment compared to the more immediate challenges of extreme weather responses. A warning that is too distant or uncertain may be ignored, while a signal that a threshold is approaching can, paradoxically, trigger a "race to the bottom" as short-term individual interests undermine the collective long-term good [58]. Early trust-building and public education are vital to ensure warnings are heeded for long-term threats, where there is no obvious short-term benefit for taking action. Hence the scientific validation of an EWS must be developed hand-in-hand with a political and societal framework to act decisively in response to a signal.

A vision for a prototype EWS: an end-to-end system with quantified uncertainties

An EWS for climate tipping points does not yet exist and it may not be possible to build sufficient confidence in forecasting tipping points to make this a reality. To be valuable for decision-makers, early warning signals would need to provide at least decadal foresight of *when* tipping points are likely to be crossed, what the *impacts* would be and *over what timescales* they would unfold.

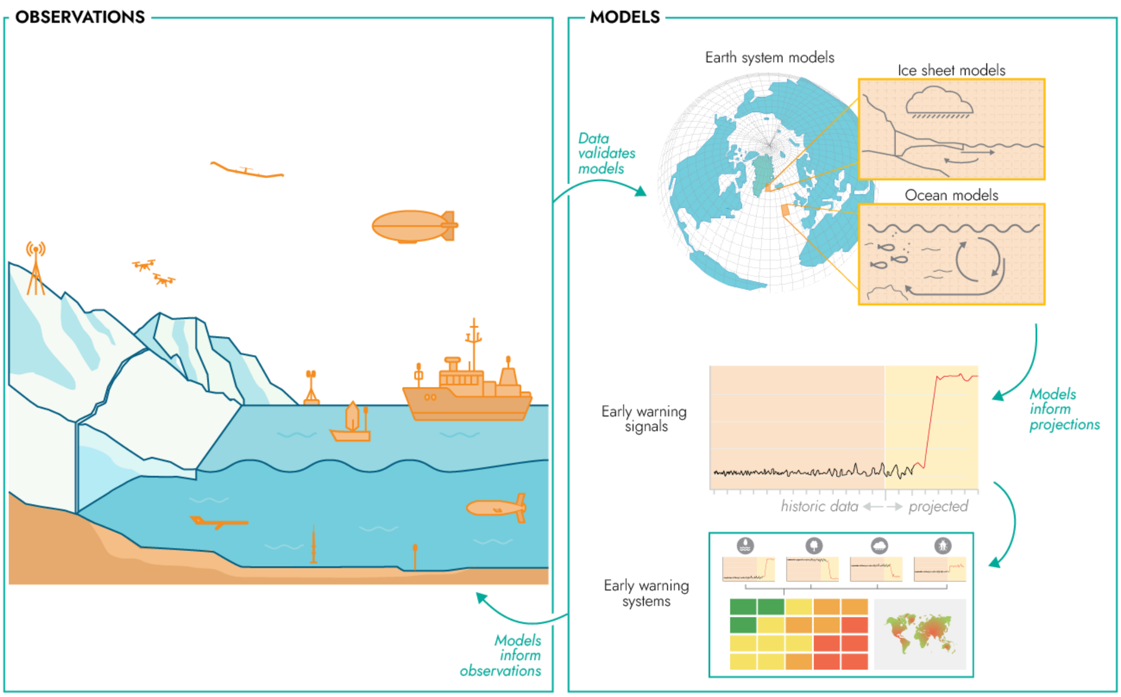

Figure 2: High level schematic illustrating how a distributed sensing network could combine with a hierarchy of models and early warning signal quantification to deliver a signal detection system for climate tipping points. Examples drawn from North Atlantic tipping systems.

Considering the first lesson from successful EWSs, any approach for climate tipping points clearly needs an integrated system. The core signal detection component (Figure 2) of such a system includes a distributed network of sensors that can form a long-term record of key climate variables with well quantified uncertainties [59]. A cost effective observing network is vital to enable long-term sustainability and requires innovation in sensing systems for harsh environments to overcome traditional performance / portability trade-offs. New systems require benchmarking against reference measurements and appropriate uncertainty quantification before delivery into sustained deployment. A core need for a tipping point EWS infrastructure is adaptability: sensing systems should be reactive to the current state of the system, where if an instability is detected, additional systems can be deployed to interrogate with greater spatio-temporal resolution.

Akin to observing system simulation experiments, improved model projections are then needed to define the ideal variables and locations for measurement, to directly evaluate drivers of tipping behaviour, and infer the current health and future trajectory of the tipping systems. The current state of knowledge about what should be measured and where is limited. Harmonised and intelligent ensemble design is vital to guide sensing network design and deployment. The resulting observational data can then validate physical process representation in models, building trust as the duration of the observational record extends. A key enabler of this activity is interoperability of data formats and standards for seamless data sharing, assimilation and fusion.

Effectively distinguishing signal from noise is the second lesson and requires new mathematical, physical and AI methods. Enhanced forecasting requires better representation of tipping dynamics and temporal evolution of tipping scenarios across the range of model implementations, from local physical models, to regional systems models, through to Earth systems models. Mapping out the domain of possibilities from models and improving ensemble techniques to better explore low likelihood but high impact events will help to better capture tail risks and identify areas of deep uncertainty where models disagree wildly [60].

Developing improved early warning skills for tipping points requires new thinking about changing climate systems, both from a top-down mathematical perspective and a bottom-up data-driven perspective. Testing and verifying early warning skills will likely need to be achieved using past events, built through hindcasting in the palaeoclimate record, but will be challenging given the sparsity of data. Furthermore, the palaeoclimate record provides a vital and under-utilised resource for improving our physical process understanding [61] so building extended historical records could add value in this context. A further aspect of the second lesson is to clearly communicate uncertainty. A robust EWS requires a deep understanding of the uncertainties inherent in the Earth system itself, as well as uncertainties introduced by the applied sensing, sampling and modelling methods. Coordination across disparate methodologies to cascade uncertainty will be vital.

A prototype early warning system for North Atlantic tipping points

<table>
<tr><th></th><th>Monitoring</th><th>Modelling</th><th>Detection</th><th>Response</th></tr>
<tr><td rowspan="2">Lessons</td><td colspan="4">Integrated, end-to-end system</td></tr>
<tr><td colspan="3">Distinguish signal from noise; communicate uncertainty</td><td>Bridge the last mile</td></tr>
<tr><td>Challenges</td><td>Short-term records
Limited resolutions
Missing variables
Uncertainties</td><td>Expensive to run
Biases
Missing processes
Challenging validation</td><td>Rarity of events
Oversimplifications
Model/observation disagreements</td><td>Ecosystem silos
Value of long-term risk
Building trust
Coordinating action</td></tr>
<tr><td rowspan="2">Theory of Change</td><td>Low SWaP-C systems</td><td colspan="2">Unlock power of artificial intelligence</td><td rowspan="2">Co-design with knowledge holders and users</td></tr>
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Figure 3: Mapping lessons learned from existing EWSs against challenges in climate tipping points assessment. From these emerges the theory of change driving the ARIA Forecasting Tipping Points programme to demonstrate an EWS for climate tipping points.

The Advanced Research + Invention Agency (ARIA) Forecasting Tipping Points (FTP) programme is an £81M initiative designed to demonstrate a prototype EWS for climate tipping points that is *affordable*, *sustainable* and *justified* (Figure 3). The programme targets the "fast onset" North Atlantic Subpolar Gyre (SPG) and incorporates the "slow onset" Greenland Ice Sheet (GrIS) as a freshwater forcing function. Their complex interactions across ice, ocean and atmosphere make them an ideal proving ground for the EWS concept but both are currently under-observed due to their harsh environments, from the extreme cold of the GrIS to the unforgiving ocean conditions of the SPG.

Delivering a prototype EWS requires the programme to catalyse a fundamental shift in how we collect and interpret Earth system data. An *affordable* and *sustainable* approach is needed because EWSs are typically operated through governments or international bodies that need to demonstrate a substantial benefit-cost ratio. Thanks to innovation in low size, weight, power, and cost (SWaP-C) electronics and photonics, we now have an unprecedented global telecommunications and computing infrastructure that can support a multi-sensor enabled smartphone in every pocket. Capitalising on low SWaP-C sensing systems in a tipping point EWS satisfies the need for low initial capital expenditure to implement a system as well as sustainable operational expenditure. The FTP programme funds innovation in robust low SWaP-C sensing systems with well quantified uncertainties. Targeting hard-to-measure variables, interactions and locations, the programme aims to deliver an intelligent adaptive and distributed array of heterogeneous and autonomous sensing platforms that can communicate with a central system ("internet of things" approach) for tipping points assessment.

For the existence of an EWS to be *justified*, it must be actionable and trustworthy on decadal timescales; we can afford neither false positives nor false negatives. Building scientific trust requires detailed cross-validation between physical models and observations [62], and clear traceability of uncertainties from raw data products to actionable forecasts. Here, the FTP programme benefits from the pace of innovation in artificial intelligence (AI), transforming how we generate and interact with physical model outputs, as well as demonstrating fundamentally new ways to detect subtle signals of tipping dynamics that may be missed by traditional statistical methods.

In the FTP programme, AI serves as a critical integrating layer, building on a foundation of programme-wide interoperable datasets, helping to target the most valuable variables and locations for sensing based on model outputs [63], while making emulation and data assimilation tasks tractable. A harmonised modelling framework with outputs successfully validated against agreed benchmarks, including palaeoclimate events, will be created to support robust assessments across the range of future trajectories.

Through state-of-the-art models integrating realistic and validated physical processes, targeting and ingesting these new observational data with embedded uncertainty quantification, the programme will enable a new approach to tipping point forecasting building on lessons 1 and 2 from existing EWSs. In the third lesson from existing EWSs, bridging the last mile highlights the importance of co-design with knowledge holders and users to deliver an EWS with operational outputs that are fit for purpose. While the GrIS and SPG provide attractive and challenging targets for a prototype EWS, from which we can evaluate generalisability of methods to other tipping systems, the Arctic is a complex geopolitical and human space.

Co-development with local and international stakeholders is vital to ensure that any EWS is built ethically and equitably [64,65] and produces warnings that are valuable to knowledge users, be they local Greenlandic fishers or international policymakers. The FTP programme works in partnership and co-design with Naalakkersuisut and Greenlandic communities and research institutions, with a focus on active governance, data sovereignty, local leadership. The programme works in strategic alignment with Greenland's National Research Strategy (2022-2030) and puts the community first with local leadership, hiring Greenland-based team members to act as a bridge between international scientific teams and local communities, ensuring engagement is respectful and relevant. The programme is actively engaged in co-production across multiple specific end-user sectors, including finance, fisheries and climate security, within which we have engaged fellows to work with the programme to define the required outputs from an EWS in each sector, information that will guide future funding calls.

The path to operation

Transitioning from a successfully verified prototype to a permanent, global EWS requires a framework that transcends physical science to encompass economics and governance. An operational EWS would likely manifest as a modular, end-to-end infrastructure connecting a distributed network of real-time sensors with a new generation of hybrid AI and physical models. The value of such a system lies in its ability to deliver high-confidence alerts on a human decision-making timescale—typically a decadal horizon. While warning of Greenland Ice Sheet melt might offer centuries of notice, a collapse of the SPG may only emerge with decadal warning given its faster dynamics and therefore the early warning emphasis in the FTP programme is being placed on the SPG. A decade to prepare is a game-changer for implementing large-scale adaptation initiatives, however, responses should be framed within the existing landscape of adaptation activities.

With the disparate nature of tipping points threats in different regions and climate systems, one could envisage the global institutional architecture for tipping point governance akin to the UN Early Warnings for All [14]. The EWS could be framed against the "safe operating space for humanity" [66,67]. In the context of adaptation planning, potential future scenarios represent a vital output of any prototype EWS [68–70] that could be compared against existing climate change scenarios to enable relative prioritisation of funding between existing adaptation measures and those needed for tipping scenarios. The resulting actions should be clearly linked to dedicated funding support, held for example by the World Bank, and delivered bottom-up by local and national authorities. The responsible institution could build a range of risk management frameworks for different tipping points and coordinate a timely response at a local, regional or national level for each [71].

Crucially, a major systemic barrier with multi-level governance frameworks is the tendency to cascade responsibility downwards to local levels without the appropriate transfer of financial resources or capacity [10]. Local authorities are already facing severe resource constraints when managing contemporary extreme events. Instead of relying upon a pre-defined set of actions based on "if-then" protocols, the EWS could be built using Dynamic Adaptive Policy Pathways (DAPP), which blend adaptive planning with adaptation pathways to build flexible strategies that can be modified over time, without starting from scratch on each iteration. Under a DAPP framework, the EWS should act as an operational trigger to automatically release resources. Extensive research would be needed to understand explicitly how to navigate these tensions in social and governance systems.

While an EWS is a global public good, its long-term viability and the delivery of bottom-up action depend on a sustainable funding model and the availability of local capacity and resources for implementation. The cost of implementing and sustaining a global EWS [72,73] would pale in comparison to the trillions of dollars in economic damages that could result from crossing a single tipping point without warning [5,74]. Although a consortium of governments remains the most likely primary source of funding—driven by the trillions of dollars in potential avoided damages—an EWS offers immense strategic value to the private sector. A potentially useful analogue here could be the Global Earthquake Model Foundation, a non-profit public-private partnership [75]. Enabling near-term forecasting for local communities and providing integrative global risk assessments of tipping for national governments from the same underlying database would be transformative. Industries with long investment horizons, such as agriculture and energy, can leverage this foresight to de-risk portfolios and invest in resilient infrastructure. Ultimately, the cost of implementing such a global system would be minuscule compared to the systemic financial and security risks of crossing a tipping point without warning.

The last mile: responding to an early warning signal

Crossing the last mile requires moving beyond the generation of a signal to the active management of a response. The detection of a confirmed early warning signal would force us to confront our capacity for global collective action under extreme pressure. In an ideal scenario, the EWS would catalyse positive action, reigniting the global drive towards net-zero and incentivising divestment from fossil fuels to minimise overshoot of 1.5C warming. In parallel, planetary-scale governance would be necessary to drive the necessary adaptation in the worst affected communities, at a time when we are already facing an adaptation deficit to cope with the extreme effects of climate change [76].

Given the diverse range of adaptation requirements, the EWS must deliver decision-useful scenarios to catalyse action in strategic audiences. For example, governments need to consider the economic, societal and political vulnerabilities that exposure to such climate insecurity brings and map consequences for their citizens ranging from population health to national infrastructure [69]. Climate intervention approaches may also be considered, but extensive research is needed on the science and governance components: a parallel ARIA programme on Exploring Climate Cooling is examining whether climate cooling approaches could ever be feasible, scalable and safe [77].

Similarly, the financial services industry could use tipping point scenarios in stress-testing to more accurately price those risks, and help avoid regions becoming uninsurable. Furthermore, the data generated by an EWS could anchor prediction markets for tipping points, aggregating distributed information into a real-time, financialised consensus on risk that makes abstract threats tangible for global investors [78]. Building tipping point resilient portfolios could drive investment away from exposed water or energy intensive industries and towards clean energy and adaptation infrastructure [79], unlocking vital financial resources in an increasingly volatile world.

Local adaptation initiatives would need to span from changing agricultural and fishing practices for long-term food security, to motivating rapid innovation in sustainable construction technologies for climate resilient buildings in regions with relocating populations. A key challenge in this regard arises from the discrepancy in climate change effects seen in a gradually warming world compared to one crossing tipping points, which presents confusion when considering scenarios for adaptation. For example, while resilience to flooding and extreme weather in the UK is improving under the National Adaptation Programme, an SPG collapse could plunge the UK into colder and drier winters, deeper water shortages and reduced renewable energy production, scenarios for which we are currently unprepared [80].

A significant hurdle is the "prevention paradox". The call for collective action will require community engagement and public understanding of the changes needed to create a path to an attractive and sustainable future, which may offer little immediate benefit to the individual. Further, if a warning is issued and society works collectively to avert the crisis, the tipping point is never crossed, it could be perceived as a false alarm. Without a foundation of trust, a signal could alternatively trigger fragmentation and panic rather than cooperation, leading to resource hoarding and geopolitical tension. Equally challenging is the "no news is good news" concept, which could breed complacency. For the system to be effective over the long term, it must be trusted to report silence truthfully, avoiding any bias towards finding a positive signal, while society must learn to treat a lack of warning not as a guarantee of safety, but as invaluable time to continue building resilience. Ultimately, the goal of an EWS is to avoid paralysing uncertainty and instead galvanise human agency.

Outlook

Building an EWS for climate tipping points is a high-stakes, technically daunting endeavour that requires us to bridge deep scientific silos and harness the power of frontier technologies. An EWS serves as more than just a scientific tool; it is a storytelling device that transforms abstract, existential threats into tangible, manageable risks. Imagine a future where a tipping point EWS can translate detected geophysical shifts in the Earth system into tangible, decadal-scale scenarios for a farmer in Ethiopia, a city planner in London, or an insurer in Tokyo. In this future society, a confirmed signal does not trigger panic, but rather the activation of adaptive pre-agreed governance protocols and "no regrets" investments that safeguard livelihoods long before a threshold is crossed. Just as early diagnosis in medicine allows for timely intervention, a tipping point EWS buys humanity the most precious commodity in a crisis: time. By investing in this foresight now, we ensure that we are no longer wholly unprepared for the consequences of a changing Earth, but are instead equipped to protect our civilization and thrive in an uncertain future.

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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Author Contributions

GMB, SEB and DG drafted the manuscript. All other authors reviewed and approved the final version of the manuscript.

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