A safe space but not a soft landing: Observation needs for a warming world

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Abstract

Since 2007, the National Academy for Sciences Engineering and Medicine (NASEM) has recommended priorities for Earth Science research and investment every ten years. The Decadal Survey balances the continuation of essential climate variable time series against unmet measurement needs and new Earth Observations made possible by technological breakthroughs. The next survey (2027-2028, DS28) must anticipate the observational needs of the 2030s-2040s, a world increasingly dominated by climate extremes and a rapidly changing Earth system. Here, we identify the critical Earth Observation needs for a hotter, more extreme world where expect challenges in maintaining a safe operating space.

I. *Introduction: The current state of climate scenarios*

Since 2007, the National Academy for Sciences Engineering and Medicine (NASEM) has recommended prioritized directions for Earth Science research and major investments in space every ten years. The next survey (2027-2028, DS28) will begin gathering community inputs circa 2025, but must anticipate the observational needs of the 2030s-2040s, a world increasingly dominated by climate extremes and a rapidly changing Earth system. This world will differ dramatically from any other time in human history.[1] The Decadal Survey guides federally funded research and applications through agencies such as NASA, NOAA, and USGS, and is vital for planning future investments. We argue that this survey must explicitly consider, for the first time, that observations will be made in a world very different from the world in which they are planned.

Historically, the design of Earth observing systems has used the past as an index, fueled by reanalysis or historical data. The missions recommended by the next Decadal Survey (DS28) will encounter an Earth system that is in many ways without direct historical analogs. Global warming is already on the verge of crossing the 1.5°C threshold, and may cross the 2°C threshold even with substantial greenhouse gas mitigation.[1]

Simultaneously, we have witnessed the explosive growth of extreme events. These are statistically rare occurrences found in the long tails of IPCC climate scenarios[2], whose impacts are not fully anticipated by Earth system models focused on average global temperatures and climate patterns. As global temperatures have risen, damages from extremes have increased rapidly (Figure 1). We must anticipate the DS28 world as one where climate change amplifies cascading extremes of heat and drought[3,4] and, counterintuitively, the hydrologic cycle.[5]

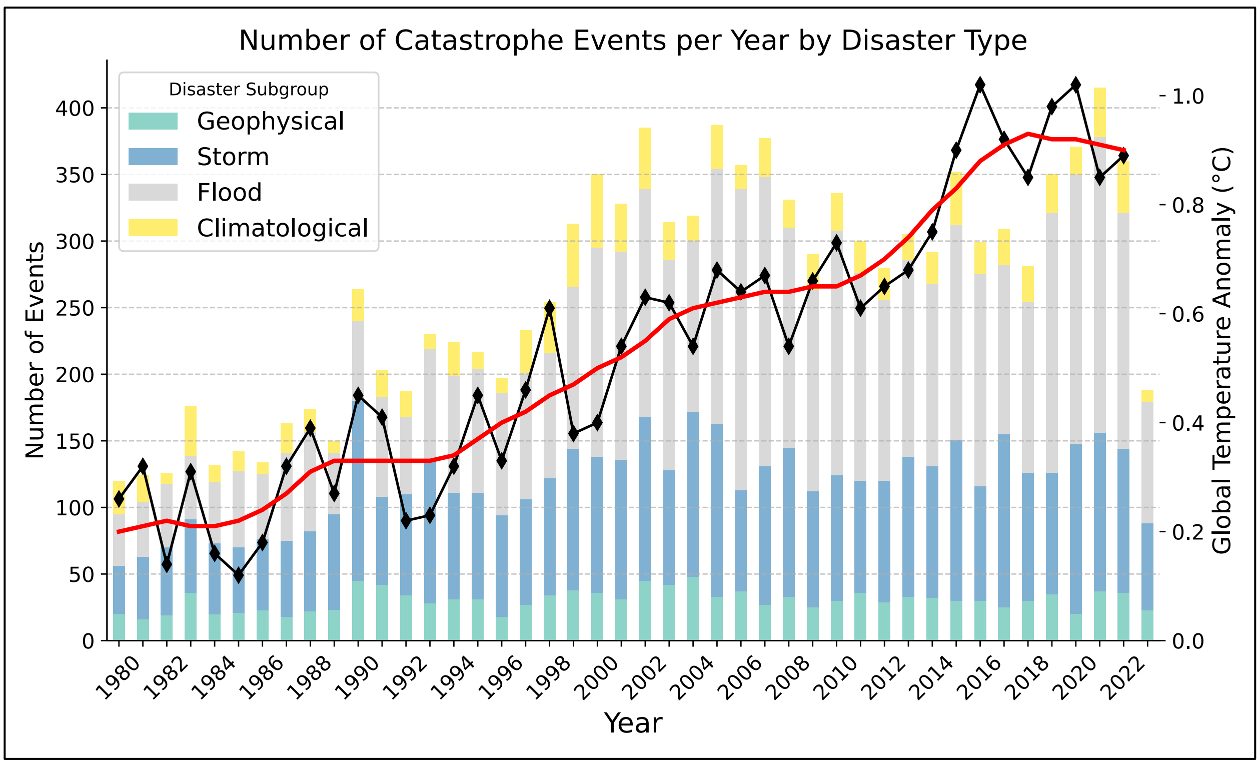

Figure 1. Yearly warming (black) and warming trends (red) superimposed with select natural disasters, graphically illustrating the increasing number of compounding impacts (as reported by MunichRE).

The scientific community must integrate climate scenarios across scales to forecast and plan for a warmer, more volatile world. For example, what will the world be in the 2035-2050 timeframe if we achieve stabilization at the agreed upon "safe operating space" of ~1.5°C? Extrapolating today's observed changes, we expect a world with considerable and still emerging climate challenges (Figure 1), compound and cascading impacts (Box 1), and a rapidly adjusting carbon cycle.[6,7]

Future science needs could be derived from Earth system model projections, extrapolated from observed trends, or incorporating worst-case scenarios.[8–11] These scenarios may include crossing multiple tipping points,[12–14] human managed emissions,[15–17] changing carbon cycle feedbacks on land and in the oceans[18] numerous emergencies and subsequent migration,[19–22] and risks to water and food security.[23–25] However, in any emissions scenario, land and ocean ecosystems are dynamic, and will equilibrate to the magnitude of forcing from anthropogenic emissions.

The driving questions for Earth observations in the DS28 era are: Is the Earth system behaving as our models project for the observed anthropogenic emissions pathway?[26] Are there signals that the Earth System is approaching a critical climate tipping point?[27] In a warming world, what observation duration, resolution, and foci are necessary to detect change?

Compound impacts: The consequences of multiple extremes (e.g., temperature and hydrological extremes) overlapping in one time and space

Cascading Impacts: A chain of consequences triggered by an extreme situation, such as extreme montane rain causing glacier lake outburst flooding

Compound or cascading impacts can lower the thresholds for critical Earth system tipping points.

Box 1. Definition box

II. *Assessment of the science: Change is the new constant*

Identifying the needs for future Earth observing systems requires understanding how mission continuity, observational gaps, and science requirements map onto the likelihood and severity of future risks to the Earth system (Figure 2). Regions key to ongoing Earth system functions, such as the Arctic and Amazon, are remote, vast, poorly observed and will remain a high priority.[28–31] Both the cryosphere and tropical forests drive tipping points where the consequences of warming are generally understood, but their spatiotemporal constraints on carbon, water, and energy fluxes are not. One of the critical uncertainties is how and when these global tipping points could trigger each other.[13] The dynamics for each system operate on different spatiotemporal scales, requiring various observing system strategies. For example, a weekly or bi-weekly revisit is required to understand seasonal changes in vegetation,[32,33] while global land surface temperature variability requires a 1-3 day revisit.[34] Similarly, glacier and sea level change dynamics occur over large spatial scales but require input data with 10-60m resolutions to drive state-of-the-art models.[35,36]

Identifying and observing critical regions will become increasingly important as change across scales becomes the new constant. If ecosystem destabilization occurs sooner than models forecast, tipping points could be crossed within the next decade (Figure 2).[1] While some dynamics are not well constrained spatiotemporally, likely changes include:

- More frequent and more intense extremes, including compound extremes with cascading consequences
- Amplification of the hydrologic cycle, with consequences for weather and climate extremes, drought, and floods
- Changing carbon-climate feedbacks and increasing extremes leading to reduced ocean and biosphere uptake
- Human mitigation efforts modify land and ocean carbon exchange

Clearly, a mitigated world with warming stabilized near 1.5°C would be the best of all scenarios, but it won't be a soft landing.

Risk Matrix		Severity				
		Insignificant	Minor	Moderate	Major	Severe
Likelihood	Almost Certain			Sea Level Rise; Seasonality shifts	Global glacier loss; Increased extreme weather and fire	Urban heat; Biogeochemical and resource changes
	Likely			Increased zoonotic diseases	Higher PH ocean; Warmer ocean	Changing atmospheric and ocean circulation
	Possible				Megacities expanding at coasts; Soil microbe changes	Accelerated water cycle; Permafrost carbon feedback
	Unlikely					
	Rare					

Figure 2. Example of a risk matrix characterizing likelihood and severity for select Earth system dynamics facing destabilization.

I. Actionable Recommendations: Observation Needs for the DS28 Era

Remote sensing is unparalleled for determining large-scale trends and is a critical tool in understanding the trajectory of the climate crisis.[37,38] Space-based Earth observations provide a global perspective to monitor system change, including tipping points and emergent processes across scales. This is essential for characterizing and resolving deep uncertainties in physical processes, especially in areas of the world that are sparsely populated. For example, the rate of ice sheet loss is a large uncertainties in projections of sea-level rise, but is driven by complex interactions between the cryosphere, atmosphere, land, oceans, temperature, and precipitation.[39,40]

Earth system models must also have the most up-to-date and high-resolution information to understand changing biospheres (e.g., 10-60m and bi-weekly). Input data must include clouds, aerosols, precipitation, ocean circulation, sea ice, vegetation dynamics, soil hydrological and thermal features, carbon and biogeochemical cycles, and feedback mechanisms. In addition to high-resolution needs, pointing capabilities and a high signal-to-noise would be required. A better representation of these changing processes will lead to more realistic climate simulations and increase confidence in model outputs. To achieve these results, satellite coverage throughout the mid and upper latitudes, in collaboration with airborne and in-situ research, is necessitated.

The resolution of airborne retrievals and in-situ networks lies below satellite monitoring, with the ability to sample at 0.1 – 10 m scales.[43] However, airborne campaigns are of limited duration and spatial extent. Even airborne campaigns which sample from pole to pole, represent seasonal transects and not continuous global sampling - leaving large areas unmonitored over time. A growth of in-situ observing networks in the past decade facilitates data sharing but requires calibration and validation support from satellite networks. Prioritizing synergistic data across scales is required to observe climate change risks and mitigate it's impacts.

As needs increase for climate change research and monitoring, work across Federal Agencies focuses on ethically coproducing regional research.[44,45] NASA airborne[36] and satellite missions[38] have prioritized engagement with regional collaborators. This includes integrating local information into models, sharing downscaled models with community planners and decision-makers, and providing actionable, coproduced data across scales.[45] Regional governments and NGOs are increasingly tasked with monitoring and mitigating wildfires, sea level rise, biodiversity, and air quality.[40,42,46,47] These governments require tools that span scales and are easy to integrate into management plans. Combining the abilities and products of satellite remote sensing, airborne retrievals across instruments, and in-situ collaboration will be critical for charting the course through challenging climate changes.

II. Conclusions

The climate is changing in ways both predicted and unexpected. Each day brings a new record-shattering extreme or biosphere emergency. Whether it is the global temperature extremes experienced during the summer of 2023 or the loss of 10 billion snow crabs in the Bering Sea,[48] challenges to forecasting and planning for climate futures will continue. Precision tools for ecosystem management will continue to be of critical importance, and charting a course for future science and observations is the first step. The DS28 requires a novel, forward-thinking perspective to create an Earth observing system for priorities in the 2030s and 2040s. To understand a world increasingly dominated by extremes, the next Decadal Survey must strive to predict an unpredictable future.

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Competing interests

The authors have no competing interests to declare

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