AGU Advances

COMMENTARY
10.1029/2023AV001148

A Decadal Survey Without Analogs: Earth Observation Needs for a Warming World

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Peer Review The peer review history for this article is available as a PDF in the Supporting Information.

Key Points:

- Climate change
- Satellite mission priorities
- Decadal survey observable objectives

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Miner, K. R., Braghiere, R. K., Miller, C. E., Schlegel, N., & Schimel, D. (2024). A decadal survey without analogs: Earth observation needs for a warming world. *AGU Advances*, *5*, e2023AV001148. https://doi.org/10.1029/2023AV001148

Received 5 DEC 2023
Accepted 22 FEB 2024

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Abstract Since 2007, the National Academy for Sciences Engineering and Medicine (NASEM) has recommended Earth Science research and investment priorities every 10 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) will be framed by a rapidly changing world, and it will be critical to anticipate the observational needs of the 2030s–2040s, a world increasingly dominated by climate extremes and a rapidly changing Earth system. Here, we highlight some of the changes that factor into a framework for the DS28.

Plain Language Summary Here, we highlight some of the Earth system changes in the 2030–2050 period that factor into a framework for the DS28.

1. Introduction: The Current State of Climate Scenarios

Since 2007, the National Academy for Sciences Engineering and Medicine (NASEM) has recommended directions for Earth Science research and major investments in space every 10 years (National Academies of Sciences, 2018). The Decadal Survey guides federally funded research and applications through agencies such as NASA, NOAA, and USGS and is vital for planning future investments. The next survey (2027–2028, DS28) will begin gathering community inputs in 2025, anticipating the observational needs of the 2030s–2040s. Historically, new Earth observing systems used the past climate as an index, driven by reanalysis or historical data.

The DS28 will chart a course within a world increasingly dominated by extremes and a rapidly changing Earth system. This world will differ dramatically from any other time in human history in a geophysical period without direct historical analogs. From the growth of extreme events (Figure 1), (AghaKouchak et al., 2023; Mukherjee et al., 2023; Tabari, 2020) to imminent ecosystem tipping points (Figure 2), statistically rare occurrences (IPCC, 2021) have a disproportionate impact and are not fully anticipated by Earth system models. Extrapolating today's trajectories of warming, hydrological cycle impacts and cascading events, we expect a world with considerable and still emerging climate tipping points, compounding and cascading impacts, and a rapidly adjusting carbon cycle (Armstrong McKay et al., 2022; Schimel & Miller, 2023). DS28 will be challenged to prioritize aspects of change and import, ensuring we are observing changes at the right cadence and resolution for a non-stationary climate system.

Future science needs could be informed by accurate Earth system model projections, extrapolated from observed trends, or incorporate diverse climate scenarios, across scales (Bettis et al., 2017; Gosling & Arnell, 2016; Kemp et al., 2022; Pörtner et al., 2023). Climate scenarios derived from model projections may include crossing multiple tipping elements (critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system) (Braghiere et al., 2023; IPCC, 2021; Lenton et al., 2008; Ripple et al., 2023), human-managed emissions (L. Bruhwiler et al., 2014; Comyn-Platt et al., 2018; Park et al., 2023), changing carbon cycle feedbacks on land and in the oceans (Lovenduski et al., 2021), numerous emergencies and subsequent migration to cities (Christian et al., 2023; Diffenbaugh et al., 2015; Kuo & Gan, 2015; Meyerson et al., 2009), and risks to water and food security (Redclift & Grasso, 2015; Vörösmarty et al., 2013; White et al., 2007). Scenarios can incorporate diverse stakeholder communities to reflect changes across scales and integrate complimentary modeling, observation and direct experience of all participants and their communities (Cobb & Thompson, 2012;

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Writing – review & editing: K. R. Miner, R. K. Braghiere, C. E. Miller, N. Schlegel, D. Schimel

Kemp et al., 2022). However, in any Earth change scenario, land and ocean ecosystems are dynamic, and they will equilibrate to the magnitude of forcing from anthropogenic emissions.

Driving questions for Earth observations in the DS28 era include identifying detectable signals of Earth System tipping points (Bury et al., 2021) and considering how these signals can be observed. What observations are necessary to detect change in a transitional, more extreme world, and what is still missing in our understanding?

2. State of the Science: Gaps and Uncertainties

Identifying the needs for future Earth observing systems requires understanding how Earth science could answer questions about risks to the stability of the Earth system. Regions key to ongoing Earth system stability, such as the Arctic, Antarctic, and Amazon, are remote, vast, poorly observed, and will remain a high priority (Gatti et al., 2021; Jansen et al., 2020; Lovejoy & Nobre, 2018; Overland et al., 2019). As the forcings and feedbacks of the Earth change with a warming atmosphere, the water and carbon cycles, atmospheric processes and air-sea exchanges will require rapid monitoring and response.

One critical uncertainty is how and when global tipping points may be crossed and whether cascading tipping points lower the threshold to tipping point events (Ripple et al., 2023). We lack both complete theory and observations to inform predictions and risk assessment. Different processes within the Earth System operate on different spatiotemporal scales, requiring focused observing system strategies. For example, measurements with a weekly to bi-weekly frequency are required to avoid confusing phenological changes to vegetation with longer term trends (Chadwick et al., 2022; Raiho et al., 2023), while global land surface temperature trends requires a 1–3 days revisit to avoid aliasing synoptic and longer time scales (Cawse-Nicholson et al., 2022). Similarly, glacier and sea level change dynamics occur over large spatial scales but require input data with <100 m spatial resolution to drive state-of-the-art models (Dozier et al., 2022; Fisher et al., 2018). Identifying and observing critical spatial scales and temporal revisit frequencies are key considerations for forecasting Earth System change (Diffenbaugh & Barnes, 2023).

3. Cross-Scale Changes Drive Future Research

DS28 would benefit from considering a non-stationary Earth System in the 2030–2050 time period (Armstrong McKay et al., 2022; Ripple et al., 2023; Schimel & Miller, 2023). Observations can be prioritized to observe large-scale climate, cryosphere or ocean tipping points and carbon cycle shifts (Bruhwiler et al., 2021; Lenton et al., 2024). Integrating the global vantage of satellite remote sensing, the intermediate space-time scales of airborne surveys, and the detailed local information delivered by in situ sampling will be important for charting the course through challenging climate changes. This also necessitates collaboration, cooperation, and coordination across diverse monitoring networks, agencies, and communities.

As climate changes mount, year over year, the conditions in model forecasts for the late 2050–2100s seem likely to occur, at least regionally, sooner (Armstrong McKay et al., 2022; Randers & Goluke, 2020). Extreme events are driving change faster than predictions (Almazroui et al., 2021; Tabari, 2020) and as a result, tipping points forecast for later in the century may be on the verge of breach. Already the increase of fires worldwide (Clarke et al., 2022; Pandey et al., 2023), and in the previously frozen Arctic Boreal forest (Dieleman et al., 2020, p. 202; Kim et al., 2020; Veraverbeke et al., 2017), the change in ocean salinity and overturning as a consequence of ice melt (Almeida et al., 2023; Boers, 2021; Ditlevsen & Ditlevsen, 2023; Fournier et al., 2023), and the switch of carbon sequestration to emission of the Amazon (Gatti et al., 2021; Lovejoy & Nobre, 2018) and Arctic tundra (de Vrese & Brovkin, 2021; Heffernan et al., 2020; Hugelius et al., 2020) have been reported (Figure 2).

Cross-scale changes are already occurring. For the past century, forests have consistently been, on balance, sinks for anthropogenic CO_2, but studies show regions transitioning to sources due to more frequent and intense drought, warming and fire (Alves de Oliveira et al., 2021; Braghiere et al., 2023; Dieleman et al., 2020; Gatti et al., 2021; Lovejoy & Nobre, 2018; Massey et al., 2023; Wang et al., 2021). The stability of the Arctic and Antarctic regions are critical for global ocean and atmospheric circulation, and melting ice has already begun to shift ocean and atmospheric circulation (Almeida et al., 2023; Boers, 2021; Ditlevsen & Ditlevsen, 2023; Fournier et al., 2023). The thawing Arctic also has vast stores of at-risk carbon that could result in significant carbon emissions (Comyn-Platt et al., 2018; Dean et al., 2018; K. R. Miner et al., 2022; de Vrese & Brovkin, 2021).

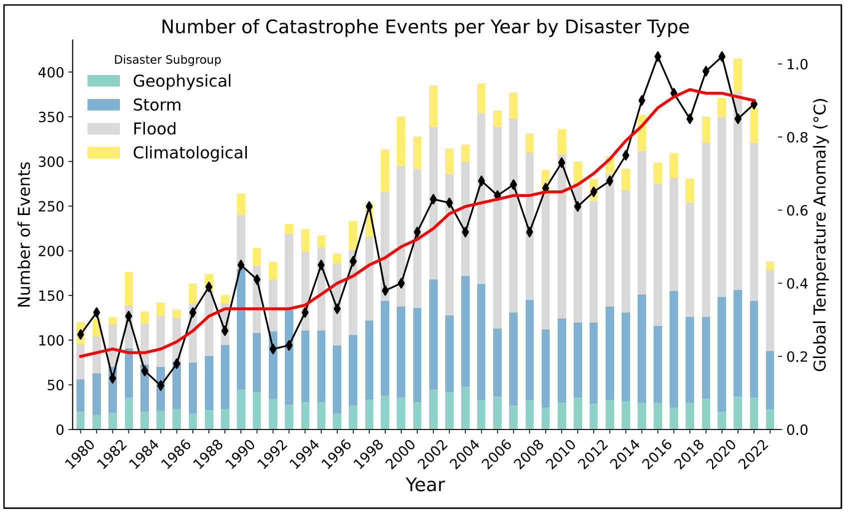

Figure 1. Yearly warming (black) and warming trends (red) superimposed with select natural disasters, graphically illustrating the increasing number of compounding impacts (as reported by MunichRE).

As the climate and socio-political conditions change, a growth in "megacities" creates unique opportunities for localized carbon emission management and, perhaps, sequestration in urban forests (Dodman et al., 2022; Wei et al., 2021). Observing these changes and managing compliance with carbon emission policy agreements will be important politically and scientifically.

There is a growing urge to accelerate the transition of discovery to actionable information. Government and public partners can be engaged early and often to help refine data and observation needs, enabling rapid decision making.

Figure 2. Plausible transitions in a non-stationary world, 2035–2050. Potential tipping elements for the DS28 period suggested by ongoing behavior of the climate, the hydrological cycle and the carbon cycle. Figure adapted from Lenton (2012) and Lenton et al. (2008, 2019, 2024).

As regional changes increase, local governments will continue to manage regional impacts-monitoring and mitigating wildfires, sea level rise, biodiversity, and air quality (Abatzoglou & Williams, 2016; Hamlington et al., 2022; Schimel & Schneider, 2019; Veefkind et al., 2012). These communities' capacity and needs can be incorporated in the DS28 with stakeholders as critical partners in the changing global system (Ermine, 2007; K. Miner et al., 2023).

4. Conclusions

The climate is changing in both predicted and unexpected ways, and it is challenging to project observing needs for the climate future. Likely changes include more frequent and intense extremes, the potential to cross multiple tipping points, amplifying hydrologic extremes, as well as changing carbon fluxes across ecosystems. The DS28 requires a novel, forward-thinking approach to create an Earth observing system for priorities in the 2030s–2050s. To understand a world increasingly dominated by extremes, the next Decadal Survey will strive to project an unpredictable future.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data were not used, nor created for this research.

Acknowledgments
A portion of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). JPL is within the unceded land of the people known as the Tongva (Gabrielieño) within the limits of the Kizh Nation. This paper was the result of a NASA JPL workshop on decadal survey planning.

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