Beyond averages: Why Arctic extremes matter

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Abstract

Arctic extremes—not only gradual trends—are reshaping ecosystems. Sustained monitoring is vital to detect, understand, and respond to these transformative events.

The Arctic is warming faster than any other region on Earth (*1*), a fact that has dominated headlines and scientific focus for decades. Most studies and models have focused on gradual changes in mean temperature and precipitation (*2*). These averages underpin narratives of "Arctic greening," permafrost thaw, and shifting species ranges (*3*). Yet, as the paper by Aalto and colleagues in this week's issue of *Science Advances* reveals, this perspective misses a critical dimension: extreme events (*4*).

The authors show that the Arctic has entered a new era of bioclimatic extremes; heatwaves, droughts, rain-on-snow, and winter-warming events are increasing in frequency and spatial extent (*5*, *6*). These events are not mere anomalies; they are ecological disruptors capable of triggering cascading impacts that dwarf decades of incremental change (*7*). Understanding this shift is essential for predicting ecosystem responses, safeguarding biodiversity, and informing adaptation strategies for Arctic communities.

Aalto *et al*. (*4*) move beyond coarse climatologies and annual means to examine seven decades of high-resolution data from the ERA5-Land reanalysis, synthesized in the ARCLIM dataset (*4*). This approach enables detection of short-lived but biologically consequential extremes, events that traditional 30-year averages obscure.

Although long-term warming trends are widespread, extremes show striking spatial heterogeneity. Heatwaves have surged in the Canadian High Arctic Archipelago (*5*), droughts in continental Siberia, and rain-on-snow events in northern Europe (*6*). Nearly one-third of Arctic land now experiences extremes that were absent in the mid-20th century (*4*).

Extreme events push organisms beyond physiological thresholds, causing vegetation dieback, altered carbon fluxes, and wildlife mortality (*3*, *8*, *9*). A single winter rain-on-snow event can devastate ungulate populations by encasing forage in ice (6, 8), whereas heatwaves combined with drought accelerate shrub mortality and soil desiccation (5). These impacts unfold in days yet reverberate for decades (7).

Detecting and interpreting extremes requires sustained, fine-scale observation. Several studies now such as Aalto *et al.* (4) leverage reanalysis data, but field measurements remain sparse and uneven (4). Without robust long-term monitoring, we risk blind spots in understanding ecological tipping points and fail to anticipate feedback to the global climate systems (8). The monitoring needs to be simultaneously connecting components in the Arctic landscape, glaciers, fresh water, and terrestrial and coastal ecosystems.<< Q1 - Query: Please check if the sentence is correct as edited. Ans: **torben.christensen@ecos.au.dk:** The edit is fine. >> These may affect each other when extreme events happen (7) as they do as more gradual changes develop (8).

A connecting element between landscapes is the delicate balance of carbon exchange within ecosystems. A solid understanding of these interconnections as they are affected by climate and extreme events has profound implications for understanding and mitigating the impacts of climate change. The Net Ecosystem Carbon Balance (NECB) accounts for all carbon fluxes, encompassing both vertical and lateral exchanges of carbon between ecosystems and the atmosphere (9). NECB integrates processes such as photosynthesis, autotrophic and heterotrophic respiration, and lateral carbon transport. However, these components have often been considered in isolation. For example, land-atmosphere exchanges, lateral fluxes of dissolved organic carbon, and their links to hydrological pathways or grazing impacts are typically treated separately.

Addressing all flux components, i.e., compiling NECB, provides a comprehensive measure of an ecosystem's capacity at the landscape level to function as either a carbon sink or a source. The interconnected responses can be deeply affected by both slow and abrupt changes in driving climate drivers. Monitoring and understanding all individual components are essential for assessing ecosystem health, defined by its resilience and functional stability, and for understanding its role in combined long-term response to extreme events (9).

Why does this matter beyond the Arctic? Because, through these interconnected processes, extremes amplify feedback that influences global climate. Vegetation dieback reduces carbon uptake (3); permafrost thaw releases greenhouse gases (7); altered snow regimes affect albedo. These processes are sensitive to short-lived events, not just slow trends (4, 7).

Moreover, extremes challenge adaptation strategies. Infrastructure designed for gradual warming may fail under sudden thaw or flooding (9). Indigenous communities reliant on predictable seasonal cycles face heightened risks from erratic weather. Conservation planning must account for variability, not just averages (3).

Further research should follow several avenues. Current Earth system models, long analyzed in terms of mean-state changes, need focused calibration for extreme-event dynamics, frequency, intensity, and compound events to improve projections of ecosystem resilience and carbon feedback (*4*, *7*).

Reanalysis products are invaluable, but ground truthing remains essential. Investments in Arctic weather stations, remote sensing, and ecological monitoring will reduce uncertainties and enhance early-warning systems (*4*). It is important to couple bioclimatic extremes with biological responses at multiple scales, from gene expression to biome shifts (*3*). Understanding thresholds will inform risk assessments for greenhouse gas emissions, biodiversity, and livelihoods (*7*).

Policy-makers must recognize extremes as drivers of change. Adaptation strategies, from infrastructure design to wildlife management, should incorporate scenarios of acute disturbance, not just gradual trends (*10*). The Arctic is not simply warming; it is becoming more volatile. Extremes are the new normal, and their ecological consequences are profound. Sustained monitoring and a paradigm shift, from averages to variability, are imperative for science and society alike.

Fig. 1. Arctic fox contemplates a meal.
Extreme snow conditions in a particular year may affect mortality of ungulate populations, affecting ecosystem dynamics strongly in a single year, which, in turn, affects multiple years to follow. The muskoxen population in northeast Greenland is an example of a sensitive key species in an ecosystem with complex interactions in a highly variable climate. CREDIT: L. H. HANSEN/*AARHUS UNIVERSITY*.

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Queries

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