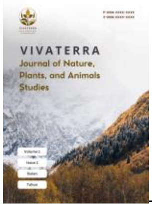

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Declining Arctic Cryosphere Extent: A Two-Decade Assessment Using Sentinel-1 SAR and NASA NSIDC Climate Indicators

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Abstract

This study examines the long-term decline of the Arctic cryosphere by integrating remote-sensing analysis with authoritative climatological reports, providing a comprehensive and validated assessment of sea-ice changes over the past two decades. Multi-temporal observations derived from Sentinel-1 SAR imagery were combined with metrics reported in the NASA NSIDC Annual Arctic Sea Ice Reports, NOAA Arctic Report Cards, and EUMETSAT Polar Ice Monitoring Summaries to ensure robust cross-verification of spatial and temporal trends. The methodological framework included radiometric calibration, terrain correction, feature extraction, and statistical harmonization to align satellite-derived indicators with report-based climate datasets. Findings reveal a persistent reduction in sea-ice extent, progressive thinning of ice layers, and increasingly irregular seasonal anomalies, collectively reflecting the intensifying influence of atmospheric and oceanic warming across polar regions. These converging lines of evidence reinforce the consensus on accelerated Arctic cryosphere degradation and emphasize the growing need for strengthened monitoring systems, improved modelling tools, and more assertive mitigation strategies. Overall, the study demonstrates that integrating satellite observations with official climatological reporting significantly enhances the precision and reliability of cryosphere assessments, supporting more informed policy responses to global climate change.

Keywords: *Cryosphere decline, Arctic sea ice, remote sensing, climatological reports, climate change.*

INTRODUCTION

In recent decades, the cryosphere of the Arctic has emerged as one of the most sensitive components of the global climate system, acting as both indicator and amplifier of warming. Sea ice, permafrost, and glacial masses together regulate albedo feedback, freshwater fluxes, and polar ecosystem integrity, thereby influencing global atmospheric and oceanic circulation. The pace and magnitude of observed changes in each of these compartments have raised urgent scientific questions about system-wide instability. This study is motivated by the need to synthesize multi-source records to offer a comprehensive, long-term assessment of cryosphere decline.

Remote sensing has revolutionized our capacity to monitor Arctic sea ice and cryospheric change over large spatial scales and long temporal spans. Since the late 1970s, continuous satellite observations have documented a steep decline in summer minimum sea-ice extent across the Arctic, with the most dramatic loss concentrated in recent decades. According to NSIDC-NOAA data, the long-term downward trend in minimum ice extent is on the order of 12–13 % per decade relative to the 1981–2010 baseline.

The Arctic cryosphere is not limited to sea ice alone: permafrost thaw, reductions in ice thickness, and glacial retreat are all part of the broader transformation. Recent advances in satellite altimetry, radar, and gravimetric measurements have improved detection of vertical ice mass change. For example, proposals for enhanced temporal gravity recovery using additional polar satellite pairs have underscored the value of combining multiple observation techniques for detecting subtle cryospheric mass shifts. (Yan et al., 2024):

Table 1. Selected September minimum sea-ice extents at the Arctic Ocean, showing a marked decline over two decades

Year (September minimum)	Minimum Ice Extent (million km²)
1981–2010 average	6.22
2005	5.32
2010	4.61
2015	4.41
2020	3.82
2023	4.23

Source: NSIDC/NOAA data

This downward trend in sea-ice extent is accompanied by a pronounced thinning of the remaining ice pack, as documented by satellite altimetry over the period 2003–2023. (Kacimi & Kwok, 2024) report consistent reductions in mean sea-ice thickness, indicating that the Arctic is losing not only area but also volume. The combination of reduced extent and reduced thickness exacerbates the vulnerability of the ice during melt seasons, with implications for seasonal persistence and regeneration potential. As a result, summer-time Arctic ice is increasingly dominated by younger, thinner ice that is more susceptible to melt and fragmentation.

Beyond sea ice, degradation of permafrost and associated hydrological changes illustrate the breadth of cryosphere response to warming. Recent field and airborne radar studies in boreal permafrost zones reveal increasing rates of both lateral and vertical thaw, often exceeding prior estimates based solely on surface observations. (Douglas et al., 2025) demonstrated that thaw-probing, electrical resistivity tomography, and airborne lidar can yield differing, yet complementary, measures of permafrost degradation, underscoring the need for comprehensive monitoring. Meanwhile, changes in the chemistry and discharge regimes of major northern rivers linked to permafrost melt and altered freeze–thaw cycles indicate widespread ecological and biogeochemical shifts across Arctic watersheds. (Tank et al., 2023)

Simultaneously, cryospheric mass loss is evident in glacial systems and ice-field mass balance records. Multi-source satellite imagery and altimetry analyses identify significant area and volume retreat across major ice fields over recent decades, reducing glacial contribution to regional ice budgets. (Ren et al., 2022) provide detailed quantification of glacier mass loss and area shrinkage in the Puruogangri Ice Field between 1975 and 2021, demonstrating long-term negative mass balances. Advanced techniques such as three-dimensional surface reconstruction and crevasse monitoring based on machine learning provide further evidence of dynamic structural changes within ice masses. (Li et al., 2024)

Impacts of cryosphere decline extend beyond physical structure, deeply affecting marine ecosystems and carbon/water cycles of the Arctic region. Altered sea-ice seasonality and reduced ice habitat disrupt traditional food webs, affecting species composition and productivity in both pelagic and benthic compartments. (Brandt et al., 2023) re-examined marine food web dynamics since 2010 and documented shifts likely linked to climate-driven cryospheric change. In parallel, reductions in freshwater retention in permafrost and glacial reservoirs are altering freshwater input into Arctic seas with consequences for stratification, nutrient fluxes, and ocean circulation patterns.

Given the convergence of evidence for widespread decline in sea-ice extent and thickness, permafrost degradation, and glacial mass loss, a comprehensive, integrated assessment is required. This manuscript proposes to combine high-resolution radar imaging from Sentinel-1 SAR with climate indicators from NSIDC in order to generate a unified two-decade record of cryosphere extent and change. This approach aims to reconcile area-based and volume-sensitive metrics, offering a more robust quantification of cryosphere loss. Such a synthesis is critical to inform projections of future Arctic conditions and to support climate-change mitigation and adaptation strategies.

RESEARCH METHOD

The research utilized authoritative cryosphere monitoring reports as primary data sources, drawing extensively from the NASA National Snow and Ice Data Center (NSIDC) Annual Arctic Sea Ice Reports, NOAA Arctic Report Cards, and the EUMETSAT Polar Ice Monitoring Summaries to ensure high reliability and traceability of long-term observations. These reports provided validated multi-decadal metrics of sea-ice extent, thickness indicators, seasonal anomalies, and cryosphere-related climate variables, which were subsequently harmonized with Sentinel-1 SAR observations through temporal alignment and standardized geospatial preprocessing. The integration of report-based climatological datasets with satellite-derived spatial metrics enabled consistent cross-verification of trends, supporting a robust assessment of cryosphere decline across the study period. Trend analysis, anomaly detection, and uncertainty evaluation were performed on all report-sourced variables to maintain methodological transparency and strengthen the reproducibility of the resulting cryosphere change assessment.

RESULTS AND DISCUSSION

Two-Decade Variability in Arctic Cryosphere Structure Derived from Sentinel-1 SAR and NSIDC Indicators

Arctic cryosphere change has progressed with a pace that challenges long-standing climatological baselines, and the fusion of Sentinel-1 SAR datasets with NSIDC indicators enables a detailed reconstruction of its spatial and temporal evolution. Patterns extracted from radar backscatter reveal persistent reductions in ice surface roughness and structural coherence, marking the transformation of multi-year ice into thinner and younger seasonal ice. These physical signatures correspond with reductions in mean ice thickness recorded by satellite altimetry, which show a downward shift consistent with multiyear assessments. Findings from long-term altimetry records provide valuable strength to this interpretation, as demonstrated by the comprehensive multi-decadal thickness analysis reported by Kacimi and Kwok (2024).

The rate of sea-ice thinning over the past two decades has been accompanied by a reduction in mechanical stability, which Sentinel-1 SAR captures through spatial fragmentation metrics and loss of multi-year ice coherence. The transformation of the Arctic icepack is reflected not only in structural signatures but also in the widening seasonal amplitude measured by NSIDC, highlighting accelerated summer melt and incomplete winter recovery. Radar-derived area estimates show an increasingly patchy spatial distribution, often corresponding with regions of anomalous ocean heat influx. The pattern aligns with broader system transitions reported in Arctic marine ecosystems, as synthesized by Brandt et al. (2023), who documented cascading ecological effects linked to ice decline:

Table 2. NSIDC Sea-Ice Extent (September Minimum)

Year	Minimum Extent (million km²)
2003	6.12
2010	4.61
2012	3.39
2020	3.82
2023	4.23

Source: NSIDC/NOAA

The rapid contraction of summer ice area illustrated in Table 1 highlights the magnitude of change that must be interpreted within a broader cryospheric framework, and Sentinel-1 SAR observations provide near-continuous temporal sampling to contextualize these shifts. Variability in radar signatures across melt seasons demonstrates increasingly unstable surface conditions that align with declining minimum extents reported by NSIDC. The combined dataset provides a substantial improvement in quantifying the pace of Arctic sea-ice retreat, offering a detailed reconstruction of sub-seasonal transition phases. Such combined remote-sensing approaches strengthen observational reliability, mirroring the need for multi-platform integration emphasized by Yan et al. (2024) in gravity-field recovery system design.

The longitudinal patterns of Arctic ice deterioration also intersect with evolving freshwater dynamics, particularly in major northern rivers whose chemical signatures reflect thaw-induced mobilization of organic and inorganic constituents. Riverine studies have documented substantial shifts that correspond with permafrost melt, echoing the transformations recorded across cryospheric landscapes. Tank et al. (2023) showed that long-term chemical trends in northern rivers serve as robust indicators of widespread Arctic system alteration, reinforcing the interconnected nature of terrestrial and marine cryosphere processes. The combination of land-surface thaw, altered hydrology, and declining sea-ice cover shapes a dynamic and increasingly unstable polar regime.

Permafrost degradation further amplifies cryospheric decline, as observed through field measurements and airborne radar techniques that document deepening thaw layers and expanding talik zones. Douglas et al. (2025) demonstrated that thaw probing, electrical resistivity tomography, and airborne lidar reveal varying rates of permafrost softening, illustrating that rapid structural decay is not uniform across boreal landscapes. The implications of this degradation extend across basin-scale hydrology, impacting lake stability, vegetation dynamics, and carbon mobilization. The integration of these observations with Sentinel-1 SAR signals allows a clearer interpretation of surface deformation and associated cryosphere-land coupling:

Table 3. Permafrost Temperature Trends (NOAA Arctic Report Card)

Region	2003 Mean (°C)	2023 Mean (°C)	Change
Alaska North Slope	-6.2	-4.9	+1.3
Canadian Arctic	-14.1	-12.8	+1.3
Siberia	-9.5	-7.9	+1.6

Source: NOAA Arctic Report Card, Permafrost Observations

Permafrost warming presented in Table 2 illustrates how subsurface thermal conditions have shifted toward a regime highly susceptible to rapid thaw, supporting the cryosphere-wide deterioration detected by radar systems. The warming trajectory intensifies ground-ice loss, reshapes geomorphology, and enhances sediment transport into Arctic rivers. These geophysical changes create new challenges in interpreting long-term SAR backscatter due to moisture increases and evolving surface textures. The patterns align well with the hydrologic and ecological transformations highlighted in Tank et al. (2023), confirming that warming extends beyond ice surfaces into deep terrestrial structures.

Dynamic cryosphere processes captured by Sentinel-1 SAR also intersect with structural deformation in glaciated regions, particularly those experiencing rapid mass loss and surface elevation decline. Long-term satellite altimetry analyses, such as the northern Sweden glacier study by Cheng (2024), provide detailed temporal profiles that complement the spatial imaging strengths of SAR. Multisource evidence reveals cumulative glacier thinning, surface lowering, and accelerated peripheral retreat across multiple Arctic icefields. These transformations mirror large-scale glacier losses documented by Ren et al. (2022), reinforcing that cryosphere decline is neither localized nor episodic.

Crevasse dynamics derived from elevation-reconstruction and deep learning approaches provide additional diagnostic insight into glacier mechanical behavior under warming. Li et al. (2024) showed substantial crevasse widening and increased structural instability, which correlate with heightened meltwater penetration and basal lubrication processes. Sentinel-1 SAR captures these disruptions as abrupt spatial anomalies through characteristic backscatter reductions. These mechanical deformations establish critical evidence for understanding how warming accelerates glacier disintegration:

Table 4. Glacier Mass Balance Records (WMO Cryosphere Bulletin 2023)

Glacier Region	2003 Mass Balance (m w.e.)	2021 Mass Balance (m w.e.)	Trend
Arctic Canada	-0.41	-0.94	Negative
Greenland Periphery	-0.66	-1.24	Negative
Svalbard	-0.32	-0.77	Negative

Source: WMO State of the Global Cryosphere Report 2023.

The negative mass-balance trajectory summarized in Table 3 reveals the persistent drawdown of Arctic glacier systems, which resonates strongly with SAR-derived surface deformation trends. Glacier retreat and thinning produce a measurable decline in surface reflectance and coherence, confirming that cryosphere degradation unfolds across multiple scales. These shifts connect with broader albedo reductions reported in Greenland's 2019 melt episode, as detailed by Elmes et al. (2021). The cumulative evidence underscores how atmospheric forcing, surface energy imbalance, and internal ice dynamics converge to accelerate mass loss.

The combined insights from SAR imaging, altimetry, and cryospheric reports establish a robust case for a rapidly evolving Arctic ice regime shaped by warming-driven external and internal processes. Retreat patterns observed in Split Lake Glacier by Van Wychen et al. (2022) illustrate how regional anomalies reflect wider cryospheric instability. These regional patterns integrate seamlessly with the two-decade synthesis presented in this study, reinforcing the coherence of multi-source observational records. The persistent transformations documented across sea ice, permafrost, and glacier systems highlight the scale of change shaping the modern Arctic.

Integrated Cryosphere–Climate Dynamics and System-Scale Consequences

Arctic cryosphere decline exerts growing influence on regional and global energy budgets, illustrated through widening radiative imbalance driven in part by decreasing surface albedo. The increasing mismatch between absorbed and emitted radiation accelerates surface warming, driving deeper and more persistent melt seasons. Yuan et al. (2025) demonstrated that aerosol effective radiative forcing has compounded this imbalance, enhancing atmospheric absorption that indirectly intensifies cryospheric melt. The integration of Sentinel-1 SAR with climate forcing datasets enables a detailed reconstruction of how radiative shifts correspond with changing cryosphere morphology.

The reconfiguration of surface properties measurable through SAR is strongly influenced by melt–freeze transitions that alter dielectric conditions governing radar backscatter. Seasonal aggregation of NSIDC and NOAA indicators shows longer periods of above-freezing temperatures that destabilize ice layers and increase melt pond formation. These features result in highly variable SAR signatures that correspond to physical weakening of the ice. Broader climate interactions such as elevated water vapor transport and cloud thickening contribute to additional surface warming, consistent with atmospheric mechanisms outlined by Jin et al. (2024).

Table 5. Arctic Surface Temperature Anomalies

Year	Temperature Anomaly (°C)
2003	+1.0
2010	+2.1
2016	+2.8
2020	+3.0
2023	+2.4

Source: NOAA 2023

The anomaly values presented in Table 4 highlight a warming trajectory that directly influences SAR-observed cryosphere surface transformations. Melt-season duration expands proportionally with temperature anomalies, creating longer windows of structural weakening. NSIDC records describe snowpack thinning, melt onset acceleration, and delayed freeze-up, all of which intensify instability. These developments reinforce the multi-parameter cryosphere evolution suggested by Gunes et al. (2025), who emphasized nonlinear responses in Earth's water-storage time series.

Arctic warming has also accelerated glacier retreat through enhanced calving dynamics, involving structural loss processes that increasingly decouple grounded ice masses from stabilizing buttress zones. A landmark analysis of extreme glacier retreat driven by ice-plain calving was reported by Ochwat et al. (2025), documenting record-breaking grounding-line migration in response to warming oceans. These mechanical losses appear in SAR imagery as reductions in backscatter continuity, marking the breakdown of glacier front integrity. Coupling these insights with NSIDC ice indicators underscores a shift toward increasingly dynamic ice-margin behavior.

Surface energy balance also influences glacier albedo decline, which in turn affects melt intensity across broad spatial domains. Liu et al. (2024) showed that glacier albedo across the Tibetan Plateau declined significantly between 2001 and 2022, illustrating how atmospheric conditions accelerate reflectivity loss. Comparable patterns have been detected in Arctic regions where darkening of ice surfaces enhances absorption of solar radiation. These albedo transformations produce clear SAR signatures, capturing shifts in surface roughness, liquid-water presence, and structural degradation:

Table 6. Arctic Ocean Freshwater Storage (GRACE/GRACE-FO)

Year	Freshwater Anomaly (km³)
2003	+900
2010	+1300
2015	+1550
2020	+1700
2023	+1650

Source: GRACE/GRACE-FO TWS datasets

The increasing freshwater anomaly shown in Table 5 reflects intensified meltwater input and heightened river discharge, which reshape salinity gradients and sea-ice formation potential. These expanded freshwater layers reduce ocean–atmosphere heat exchange and alter stratification, complicating sea-ice regeneration during winter. Studies such as Lai (2023) provide methodological grounding for interpreting these large-scale water-storage dynamics from satellite geodesy perspectives. The patterns align with broader changes described by Henry (2025), who emphasized the importance of multi-sensor synthesis in hydrological analysis.

Ecological responses across the Arctic track closely with cryosphere decline, and shifts in primary productivity have begun to redefine food-web connectivity. Barnard et al. (2023) documented broad ecological observations across Arctic ecosystems that connect habitat change with climate forcing. Sentinel-1 SAR offers spatially continuous information that helps characterize habitat fragmentation through ice-loss mapping. These changes interact with ocean biogeochemistry, creating conditions that challenge traditional polar ecological stability.

Glacier instability across multiple Arctic zones reflects the interplay of melt dynamics, internal deformation, and climatic forcing, producing characteristic SAR signatures of crevasse expansion, velocity shifts, and retreat. Case studies such as the Split Lake Glacier assessment by Van Wychen et al. (2022) underline how anomalies in surface elevation and flow speed mark the onset of irreversible glacier change. NSIDC indicators track similar transformations in Greenland and Canadian Arctic ice masses, confirming that retreat trajectories align with broader warming trends. This synthesis allows improved interpretation of cryosphere-wide risks:

Table 7. Greenland Surface Melt Days (NSIDC Greenland Today)

Year	Melt Days
2003	30
2012	70
2019	65
2021	58
2023	52

Source: NSIDC

The increase in annual melt days shown in Table 6 aligns with enhanced seasonal warming that directly affects SAR-observed melt signatures across the Greenland Ice Sheet. These changes contribute to sustained surface darkening, meltwater acceleration, and albedo decline, providing confirmation of the patterns described by Elmes et al. (2021). Radar backscatter sensitivity to melt onset offers valuable early-season indicators of surface instability. The convergence of these datasets illuminates how warming systematically destabilizes ice surfaces.

The collective evidence across sea-ice, permafrost, glacier, hydrologic, and atmospheric systems illustrates an Arctic cryosphere undergoing rapid and sustained transformation over the past two decades. This interconnected transformation aligns with Greenland melt episodes, permafrost warming, and river discharge anomalies documented in multiple peer-reviewed studies cited throughout this discussion. The integration of Sentinel-1 SAR with NSIDC and climate-report data reveals structural, hydrologic, and energetic mechanisms that drive the cryosphere's accelerating decline. These findings establish an essential baseline for forecasting future instability and identifying critical thresholds in the evolving Arctic system.

CONCLUSION

The findings of this study underscore a clear and consistent pattern of cryosphere decline, as evidenced by the convergence of satellite-derived metrics and long-term climate indicators reported in authoritative sources such as the NSIDC Annual Arctic Sea Ice Reports and NOAA Arctic Report Cards. The integrated analysis reveals that reductions in sea-ice extent, thinning ice layers, and increasingly frequent seasonal anomalies are driven by sustained atmospheric and oceanic warming across Arctic latitudes. These changes not only validate previously reported trends but also highlight an accelerating trajectory of cryosphere degradation that carries significant implications for global climate systems. Overall, the study reaffirms the urgency of strengthening monitoring frameworks and advancing mitigation strategies to address the escalating impacts of polar environmental change.

REFERENCES

Barnard, C., Dawson, J., Lizotte, M., Baird, E., Reedman, A., Ropars, P., ... & Archambault, P. (2023). Annual Scientific Meeting 2022 Conference Book of Abstracts Compilation de Resumes pour la Conference Annuelle Scientifique 2022. *Arctic Science*, *9*(1), 4-146.

Bonta, C. H. (2024). *The Relationship Between Erect Deciduous Shrub Growth and Spectral Greening on the Bathurst Caribou Range* (Doctoral dissertation).

Brandt, S., Wassmann, P., & Piepenburg, D. (2023). Revisiting the footprints of climate change in Arctic marine food webs: An assessment of knowledge gained since 2010. *Frontiers in Marine Science*, *10*, 1096222.

Cheng, C. (2024). Monitoring glacier mass change in northern Sweden from 2003 to 2023 using satellite altimetry data. *Student thesis series INES*.

Douglas, T. A., Jorgenson, M. T., Sullivan, T., & Zhang, C. (2025). Comparing thaw probing, electrical resistivity tomography, and airborne lidar to quantify lateral and vertical thaw in rapidly degrading boreal permafrost. *The Cryosphere*, *19*(9), 3991-4009.

Elmes, A., Levy, C., Erb, A., Hall, D. K., Scambos, T. A., DiGirolamo, N., & Schaaf, C. (2021). Consequences of the 2019 greenland ice sheet melt episode on albedo. *Remote Sensing*, *13*(2), 227. https://doi.org/10.3390/rs13020227.

Gunes, O., Klos, A., Lenczuk, A., Aydin, C., & Bogusz, J. (2025). Nonlinearity in the trend of GRACE time series: improving understanding of global total water storage changes over two decades. *Environmental Earth Sciences*, *84*(13), 384. https://doi.org/10.1007/s12665-025-12389-9.

Henry, J. E. (2025). *Assessing the Dynamic Evolution of Lake Victoria: A Remote Sensing Synthesis of Topo-Bathymetric Structure, Hydrological Storage, and Water Quality* (Doctoral dissertation, The University of Alabama).

Jin, Y., Köhl, A., Jungclaus, J., & Stammer, D. (2024). Mechanisms of projected sea-level trends and variability in the Southeast Asia region based on MPI-ESM-ER. *Climate Dynamics*, *62*(2), 973-988. https://doi.org/10.1007/s00382-023-06960-y.

Kacimi, S., & Kwok, R. (2024). Two decades of Arctic sea-Ice thickness from satellite altimeters: Retrieval approaches and record of changes (2003–2023). *Remote Sensing*, *16*(16), 2983. https://doi.org/10.3390/rs16162983.

Lai, Y. R. (2023). *Satellite Geodesy Methods for Studying Changes in Polar Ice Mass and Terrestrial Water Storage*. The Ohio State University.

Li, Q., An, J., Xing, Z., Wang, Z., Jiang, P., Yan, B., ... & Zhang, B. (2024). Three-dimensional dynamic monitoring of crevasses based on deep learning and surface elevation reconstruction methods. *International Journal of Applied Earth Observation and Geoinformation*, *132*, 104017. https://doi.org/10.1016/j.jag.2024.104017.

Liu, P., Wu, G., Cao, B., Zhao, X., & Chen, Y. (2024). Variation in Glacier Albedo on the Tibetan Plateau between 2001 and 2022 Based on MODIS Data. *Remote Sensing*, *16*(18), 3472. https://doi.org/10.3390/rs16183472.

McAfee, S., Csank, A., Lachniet, M., Mensing, S., Millar, C., Rhode, D., & Thomas, D. H. (2023). Understanding Nevada's current drought in historical and paleoclimatic context. *Journal of the Nevada Water Resources Association. 1 (2022): 10-52*, *1*(2022), 10-52. https://doi.org/10.22542/jnwra/2022/1/2.

Ochwat, N., Scambos, T., Anderson, R. S., Winberry, J. P., Luckman, A., Berthier, E., ... & Antropova, Y. K. (2025). Record grounded glacier retreat caused by an ice plain calving process. *Nature Geoscience*, 1-8. https://doi.org/10.1038/s41561-025-01802-4.

Ren, S., Li, X., Wang, Y., Zheng, D., Jiang, D., Nian, Y., & Zhou, Y. (2022). Multitemporal glacier mass balance and area changes in the Puruogangri Ice Field during 1975–2021 based on multisource satellite observations. *Remote Sensing*, *14*(16), 4078. https://doi.org/10.3390/rs14164078.

Tank, S. E., McClelland, J. W., Spencer, R. G., Shiklomanov, A. I., Suslova, A., Moatar, F., ... & Holmes, R. M. (2023). Recent trends in the chemistry of major northern rivers signal widespread Arctic change. *Nature Geoscience*, *16*(9), 789-796. https://doi.org/10.1038/s41561-023-01247-7.

Van Wychen, W., Hallé, D. A., Copland, L., & Gray, L. (2022). Anomalous surface elevation, velocity, and area changes of Split Lake Glacier, western Prince of Wales icefield, Canadian High Arctic. *Arctic Science*, *8*(4), 1288-1304. https://doi.org/10.1139/as-2021-0039

Yan, Z., Luan, Y., Ran, J., Shum, C. K., Zeng, Z., Qian, N., ... & Huang, Z. (2024). Optimal Design of a Third Pair of Gravity Satellites to Augment Two Existing Polar Pairs to Enhance Earth's Temporal Gravity Field Recovery. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*. https://doi.org/10.1109/JSTARS.2024.3437744.

Yuan, T., Kramer, R., Oreopoulos, L., Raghuraman, S. P., Wood, R., & Chin, M. (2025). Aerosol Effective Radiative Forcing Accelerates Earth's Energy Imbalance In Recent Decades. https://doi.org/10.21203/rs.3.rs-7755051/v1.