Alaska Park Science

National Park Service
U.S. Department of the Interior
Region 11, Alaska

Reckoning with a Warming Climate

Volume 22, Issue 1

Alaska Park Science

Volume 22, Issue 1
September 2023

Alaska Park Science is the semi-annual science journal of the National Park Service Alaska Region. Each issue highlights research and scholarship important to the stewardship of Alaska's parks.

Publication in *Alaska Park Science* does not signify that the contents reflect the views or policies of the National Park Service, nor does mention of trade names or commercial products constitute National Park Service endorsement or recommendation.

Table of Contents

Cover photo:The climate station at Howard Pass in Noatak National Preserve in Arctic Alaska.
NPS/KEN HILL

High-Latitude National Parks on the Cusp of Change

Pamela J. Sousanes and Maggie MacCluskie, National Park Service

The wild lands of Alaska national parks are changing at a rapid pace due to the disproportionate increases in temperature at high latitudes. Uncertainty about cumulative climate changes and how they will impact specific regions is one of the greatest challenges facing park managers. Climate has fundamentally shaped the landscape of high-latitude parks, but now climate change is redefining them.

Citation:
Sousanes, P. J. and M. MacCluskie. 2023. High-latitude national parks on the cusp of change. *Alaska Park Science* 22(1): 1-5.

The wild lands of Alaska national parks are changing at a rapid pace due to the disproportionate increases in temperature at high latitudes (Gonzalez et al. 2018). Uncertainty about cumulative climate changes and how they will impact specific regions is one of the greatest challenges facing park managers who are charged with preserving these parks unimpaired for future generations.

Climate has fundamentally shaped the landscape of these high-latitude parks, but now climate change is redefining them. Nothing is static in nature. These parks are continually changing, but what has become so prominent and disconcerting, is the rapid and accelerating rate of change. There is less sea ice, snow seasons are shorter, and temperatures both above and below ground are warmer (IPCC 2021, Markon et al. 2018). The ripple effects of these changes manifest in different ways across park landscapes and scientists and local communities are continuously gathering information and data to aid in climate adaptation planning efforts. Future changes will impact how land stewards will manage natural and cultural resources, food availability, and the fundamental aspects of living on land that is thawing beneath our feet.

High-latitude environments dominated by snow and ice are particularly vulnerable to increases in temperature. Several parks in Alaska have average annual temperatures that hover near 0°C and even small increases in temperatures could mean the difference between rain or snow, permafrost or thawed ground, glaciers or no glaciers. Crossing the 0°C threshold, the difference between liquid water rather than snow or ice, influences the health and abundance of plants and animals that live in the parks and the hydrologic systems that support them.

The flora and fauna of the parks are contending with increases in temperature, shorter snow/ice seasons, longer thaw seasons, and increased disturbance in the form of fire and pests. These changes also impact the communities that call these places home. Parks have boundaries on maps, but nature transcends them. People, who have lived in and around these parks for thousands of years, depend on the caribou, moose, and fish that move across these lands. These people have deep connections to the land and their observations and experiences are critical to understanding local impacts. People who steward these lands and resources are monitoring changes to document and quantify the impacts of climate change. Park managers have prioritized science and climate change action as a top priority for the Alaska parks and use the data, the science, and the results to make informed decisions. The results of park-based science are transferred to

Looking down on the Alatna River, Gates of the Arctic National Park and Preserve.
NPS/KEN HILL

park visitors, local community residents, school kids, and the public generally by the front-line park staff who make the critical connection. The science is gathered locally but applicable globally.

Alaska Climate Beyond Parks

The climate in Alaska varies tremendously, from the maritime parks along the Gulf of Alaska to the continental interior parks, to the Arctic parks along the Chukchi Sea. It is as complex and diverse as the climates of all 48 contiguous states combined (Shulski and Wendler 2007). Multiple mountain ranges, local topographic features, and proximity to the ocean are all factors that influence local temperature and precipitation patterns (Bieniek et al. 2012). Arctic sea ice extent and duration in the north, along with the north Pacific sea surface temperatures to the south, significantly influence the terrestrial air temperatures and weather extremes on adjacent land. There is less sea ice today than there was 30 years ago (NSIDC 2022). Arctic sea ice that lasts through the summer has decreased by 13% per decade since measurements began in 1979 (NOAA 2022a, NSIDC 2022). Ocean temperatures in the North Pacific have increased (NOAA 2022a). This combination leads to warmer air temperatures and increased moisture availability due to the longer ice-free seasons (Gonzalez et al. 2018, Swanson et al. 2021). The darker land and ocean surfaces, now free of ice and snow for longer periods, absorb more of the sun's energy, and amplify the original warming. Alaska temperatures are warming at least twice as fast as the global average and the global climate models project an even warmer future (Markon et al. 2018).

However, atmospheric and oceanic circulation patterns are not static. Extreme weather events, including floods, droughts, heat waves, and cold snaps occur when persistent weather patterns take hold and are slow to move or change. While the overall direction of change is toward warmer and wetter conditions, this does not preclude the possibility of drought in a temperate rain forest (Walston et al. 2023) or consecutive La Niña events that bring colder temperatures to Alaska (2020-2023; NOAA 2022b). Observed changes in temperature and precipitation have been non-monotonic over the last century, linked to atmospheric and oceanic circulation patterns that occur over annual, decadal, and multi-decadal time frames (Markon et al. 2018, Bieniek et al. 2014).

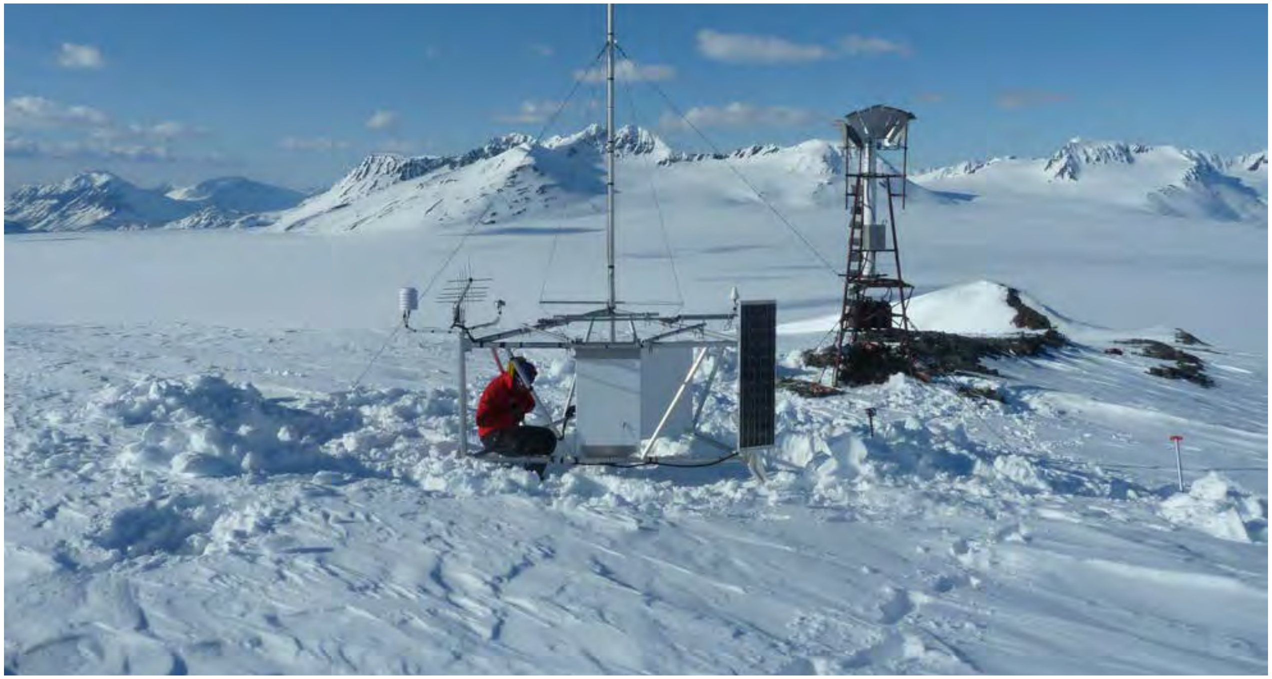
Preservation in Times of Change

Park scientists, research scientists, and local communities are all striving to understand how climate change is playing out across the northern landscape. Future changes will impact how land stewards will manage natural and cultural resources, food availability, and the daunting challenge of living on a thawing landscape. This issue of *Alaska Park Science* will use several themes to present a review of the science and knowledge related to the rapidly changing landscape.

- Crossing the zero-degree threshold: A summary of key findings that focus on how even a small increase in temperature has a profound impact in Alaska parks that are defined by snow and ice.
- What happens when northern oceans get too warm: A collection of studies that couple long-term monitoring data with focused research studies to assess changes over time in marine ecosystems in and adjacent to national parks in Alaska.
- How wildlife are responding to a warming climate: A synthesis of the complex interactions between climate change, habitat, and wildlife across elevational and latitudinal ranges with observations from research and monitoring studies conducted in Alaska parks.
- Alaska's changing vegetation processes and patterns: Plant responses to unprecedented levels of warming in the Far North: A reflective perspective from a park botanist on the observed changes in both the functional and structural changes in landscape level vegetation across park lands, based on decades of monitoring.
- Using satellite imagery to detect the changing seasonality of river ice: River corridors provide access for the traditional harvest of local wild food resources. This research, using remote sensing mapping techniques, suggests that warmer temperatures from October through April are reducing the season of river ice travel on the Copper River in and adjacent to Wrangell-St. Elias National Park and Preserve.
- Traditional knowledge of changes in winter conditions in Alaska's Copper River Basin: In Alaska's Copper River Basin, less reliable snow and ice have presented challenges for traditional wintertime activities such

as trapping, hunting, and gathering firewood. Elders shared their extensive knowledge and experience of change on the Copper River through a series of interviews compiled in this article.

- Stories yet told: Alaska's cultural heritage in a time of unprecedented climate change: A narrative describing some projects and initiatives underway – across parks in Alaska and in partnership with Alaskan communities – that respond to the impact of climate change on heritage sites and cultural resources.
- Responding to the effects of climate change on subsistence in Alaska: This article describes the challenges climate change poses to subsistence harvests, ways subsistence users are adapting to change, and how the National Park Service can support continued subsistence opportunities in Alaska.
- Communicating science and inspiring hope: Relaying the science of climate change to the public is not only about the transfer of information, but also about inspiring the audience to appreciate and care about what the facts represent. The authors lay out a framework of effective communication that can provoke and encourage people to take action.
- Planning for future climates at Wrangell-St. Elias: Mainstreaming park-based actions: Deciding how to act in the face of climate change can be overwhelming. Yet there are actions any park can take to integrate climate change considerations into their operations. This article describes how park managers can understand, adapt to, mitigate the causes of, and communicate with the public about climate change.



The NPS Alaska Inventory and Monitoring climate monitoring program has more than 50 climate stations across 54 million acres of parklands in Alaska. The sites are strategically located at higher elevations to better understand mountain ecosystems.
NPS/PETER KIRCHNER

Our work to understand and manage the effects of a changing climate on natural and cultural resources, infrastructure, and operations are core responsibilities of the National Park Service and rooted in our mission to protect parks and support visitor experience and enjoyment for present and future generations (NPS 2019). This collection of articles provides a glimpse of the science and communication related to climate change in the high-latitude national parks where temperatures are warming fast. It is not comprehensive, nor static, and we learn more each day. We encourage you to explore further.

REFERENCES

Bieniek, P. A., U. S. Bhatt, R. L. Thoman, H. Angeloff, J. Partain, J. Papineau, F. Fritsch, E. Holloway, J. E. Walsh, C. Daly, M. Shulski, G. Hufford, D. F. Hill, S. Calos, and R. Gens. 2012.
Climate Divisions for Alaska Based on Objective Methods. Journal of Applied Meteorology and Climatology 51(7): 1276-1289.

Bieniek, P. A. J. E. Walsh, R. L. Thoman, and U. S. Bhatt. 2014.
Using climate divisions to analyze variations and trends in Alaska temperature and precipitation. Journal of Climate 27(8): 2800-2818.

Gonzalez, P., F. Wang, M. Notaro, D. J. Vimont, and J. W. Williams. 2018.
Disproportionate magnitude of climate change in United States national parks. Environmental Research Letters 13(10): 104001.

Intergovernmental Panel on Climate Change (IPCC). 2021.
Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Markon, C., S. Gray, M. Berman, L. Eerkes-Medrano, T. Hennessy, H. Huntington, J. Littell, M. McCammon, R. Thoman, and S. Trainor. 2018.
Alaska. pp. 1185-1241 In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC.

National Oceanic and Atmospheric Administration (NOAA). 2022a.
National Oceanic and Atmospheric Administration, Global Climate Dashboard. Tracking climate change and variability over time. Available at: https://www.climate.gov/climatedashboard. (accessed October 13, 2022)

National Oceanic and Atmospheric Administration (NOAA). 2022b.
National Oceanic and Atmospheric Administration (NOAA) Physical Sciences Laboratory La Nina Index Dashboard. Available at https://psl.noaa.gov/enso/dashboard.lanina.html (accessed December 5, 2022).

National Park Service (NPS). 2019.
National Park Service Climate Change Response Program Strategic Plan. Available at https://home.nps.gov/orgs/ccrp/upload/CCRP-Strategic-plan-508-smaller.pdf (accessed on July 7, 2023).

National Snow and Ice Data Center (NSIDC). 2022.
Arctic Sea Ice News and Analysis. Available at https://nsidc.org/home (accessed October 13, 2022).

Shulski, M. and G. Wendler. 2007.
The Climate of Alaska. University of Alaska Press. Fairbanks, Alaska.

Swanson, D. K., P. J. Sousanes, and K. Hill. 2021.
Increased mean annual temperatures in 2014–2019 indicate permafrost thaw in Alaskan national parks. Arctic, Antarctic, and Alpine Research 53(1): 1-19.

Walston, J. M., S. A. McAfee, and D. J. McEvoy. 2023.
Evaluating drought indices for Alaska. Earth Interact. 27: e220025.

Imelyak, Noatak National Preserve.
NPS/KEN HILL

RESEARCH REVIEW

Crossing the Zero-Degree Threshold

Pamela J. Sousanes, Kenneth Hill, David Swanson, Jonathan O'Donnell, Peter Kirchner, Deborah Kurtz, Michael Loso, and Andrew Bliss, National Park Service

Alaska, shaped by and dependent on ice and snow, is among the fastest-warming regions on Earth. As the mean annual air temperature warms above the freezing threshold of 0°C, the frozen water of its glaciers, permafrost, and snow will thaw and melt, altering the physical landscape and creating a cascade of effects.

Citation:
Sousanes, P. J., K. Hill, D. Swanson, J. O'Donnell, P. Kirchner, D. Kurtz, M. Loso, and A. Bliss. 2023. Crossing the zero-degree threshold. *Alaska Park Science* 22(1): 6-21.

Alaska is among the fastest-warming regions on Earth. Recent studies show the rate of Arctic-wide warming is almost four times faster in the last four decades than anywhere else on the planet (Rantanen et al. 2022). Alaska national parks are undergoing change in response to disproportionate warming at high latitudes (Gonzalez et al. 2018). As the mean annual air temperature warms above the freezing threshold of 0°C, the frozen water, including glaciers, permafrost, and snow, will melt and thaw, altering the physical landscape. Here we provide a summary of key findings that focus on how even a small increase in temperature has a profound impact in Alaska parks that are defined by snow and ice.

Alaska's Arctic Parks: Approaching Zero-Degree Celsius Threshold

The Arctic national parks have undergone tremendous climate variability over time, but the average temperature conditions we measure are now approaching, and in some cases crossing, the zero-degree threshold, which is unprecedented in modern times. Beyond this threshold, the cold conditions that define the Arctic and organize its landscapes and ecological processes cease, and the transformation to something we have no experience with begins.

Scientific studies in Arctic parks have documented the recent implications of climate change across the landscape as temperatures warm, permafrost thaws, and hydrologic pathways change. The northern regions of Alaska have warmed the most. This includes several parks in northwest Alaska, where the magnitude of temperature change in the past decade was two to three times greater than other parks in Alaska (Swanson et al. 2021). Climate models indicate that Earth's higher latitudes, including Alaska, will continue to warm faster than other parts of the world (IPCC 2021, Lader et al. 2017). The presence of seasonal sea ice and snowpack historically characterized parks in the north and their unique cold climates. Temperatures in the Arctic parks are projected to warm by more than 7°C (on average) by the end of the century, and sea ice duration and seasonal snow cover will become less important defining features of the region (Littell 2023). Ballinger and Overland (2022) highlight the remarkable change that has occurred in Alaskan Arctic weather patterns over the last five years (2017-2021) with shifts in the Aleutian Low and polar jet stream funneling warmer southerly winds towards Alaska resulting in diminished sea ice growth. As warming trends continue, the Arctic will change.

The average annual air temperature of the Arctic parks has been below 0°C for tens of thousands of years. The cold temperature maintains permafrost (perennially frozen

Retrogressive thaw slump in the upper Noatak National Preserve. Retrogressive thaw slumps occur where a cut-bank in ice-rich permafrost advances into undisturbed ground as material thaws in the steep bank, falls or slumps onto the adjacent gentler slope, and then is transported away by water erosion or sliding.
NPS

ground). Every degree of warming brings these frozen soils closer to thawing. Trends in Arctic Alaska's average annual air temperatures in communities near the Arctic parks show a significant increase of more than 2.6°C between 1950 and 2021 (NOAA 2022, Ballinger et al. 2023). In the late 1970s Alaska's statewide temperatures started to increase (Hartman and Wendler 2005). A more recent upward shift in temperatures occurred in 2014 and included the two warmest years on record for Alaska (Figure 1). We compared average annual air temperatures between the 2014 to 2019 period with the preceding 30-year period using weather stations in and around parks. We found that average air temperatures warmed by at least 1°C in most locations and up to 3°C in the northwest Arctic parks. During recent warm winters, the mean annual ground temperature at some of the warmer sites was above 0°C for the first time since we began measuring (Swanson et al. 2021).

Permafrost is an important feature of northern and central Alaska, underlaying large swaths of the landscape (Jorgenson et al. 2008). Permafrost modeling studies indicated that at the start of the current century, permafrost underlaid nearly all of the five Arctic parks, but by the end of the century, about half of the permafrost in the Arctic parks will be thawing as a result of climate warming (Panda et al. 2014a, b, Panda et al. 2016; Figure 2). Thawing permafrost is one of the most impactful and widespread consequences of crossing the 0°C freezing threshold. Permafrost often contains masses of ice that melt when permafrost thaws, causing subsidence of the surface and sometime landslides.

Landscape-scale features that are perceptible on the surface are the easiest way to document change. However, the remoteness and sheer size of the northern Alaska parks makes it impossible to do this in person. Instead, images that are gathered from above, through satellites or aerial photography, enable scientists with a discerning eye to look for clues on the landscape that may indicate that the soils are warming. Swanson (2021a) used satellite images to locate numerous small landslides (active-layer detachments and retrogressive thaw slumps) across the Arctic parks that developed during the exceptionally warm summers in the mid-2000s. Swanson

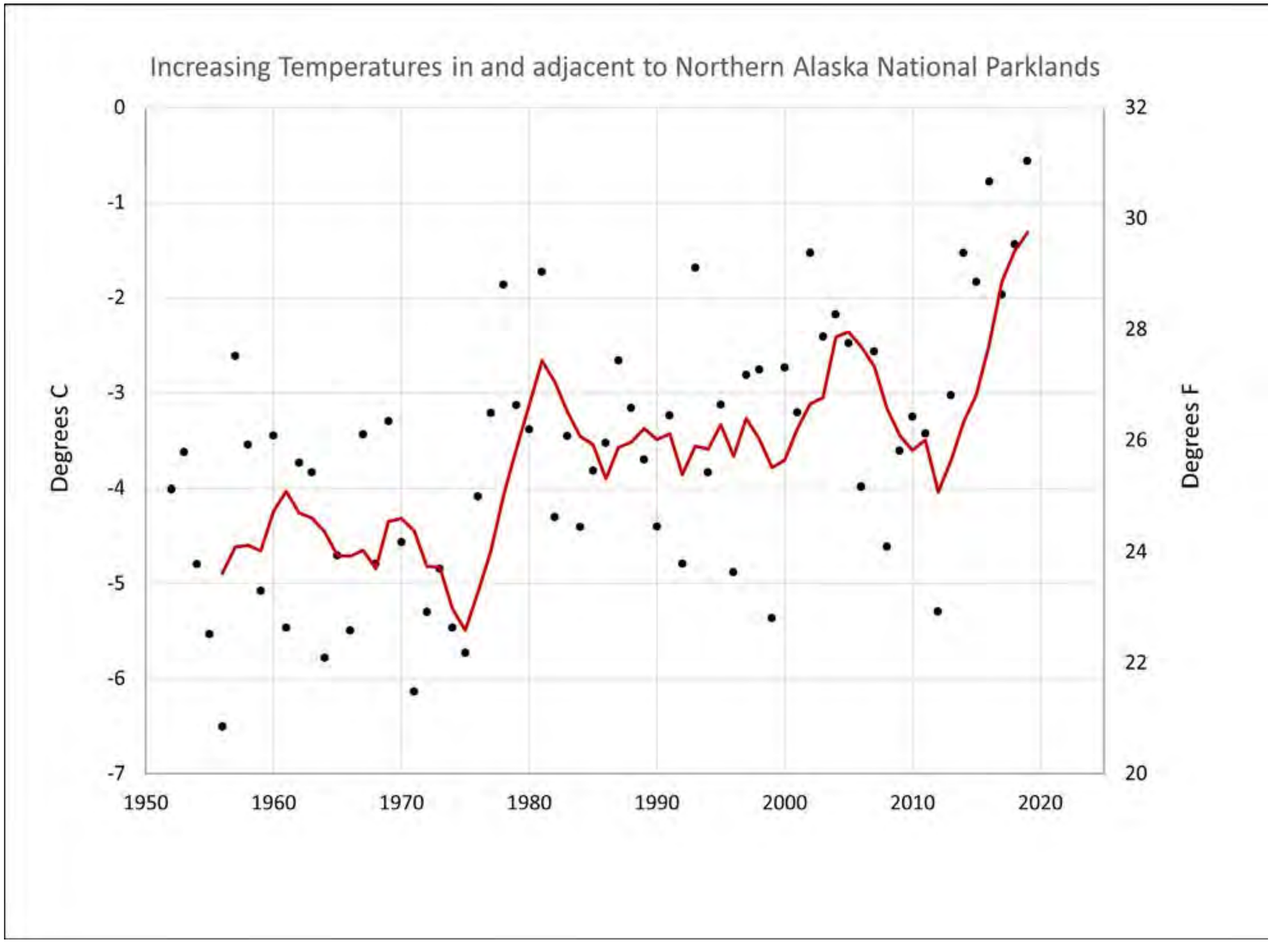


Figure 1. Average annual temperatures from seven long-term weather stations in and around northern Alaska national parks, 1952-2019. The red line shows the 10-year moving average. Notice the upward shift in temperatures in 2014. Also note that the latest increase puts annual temperatures near the 0°C freezing threshold.

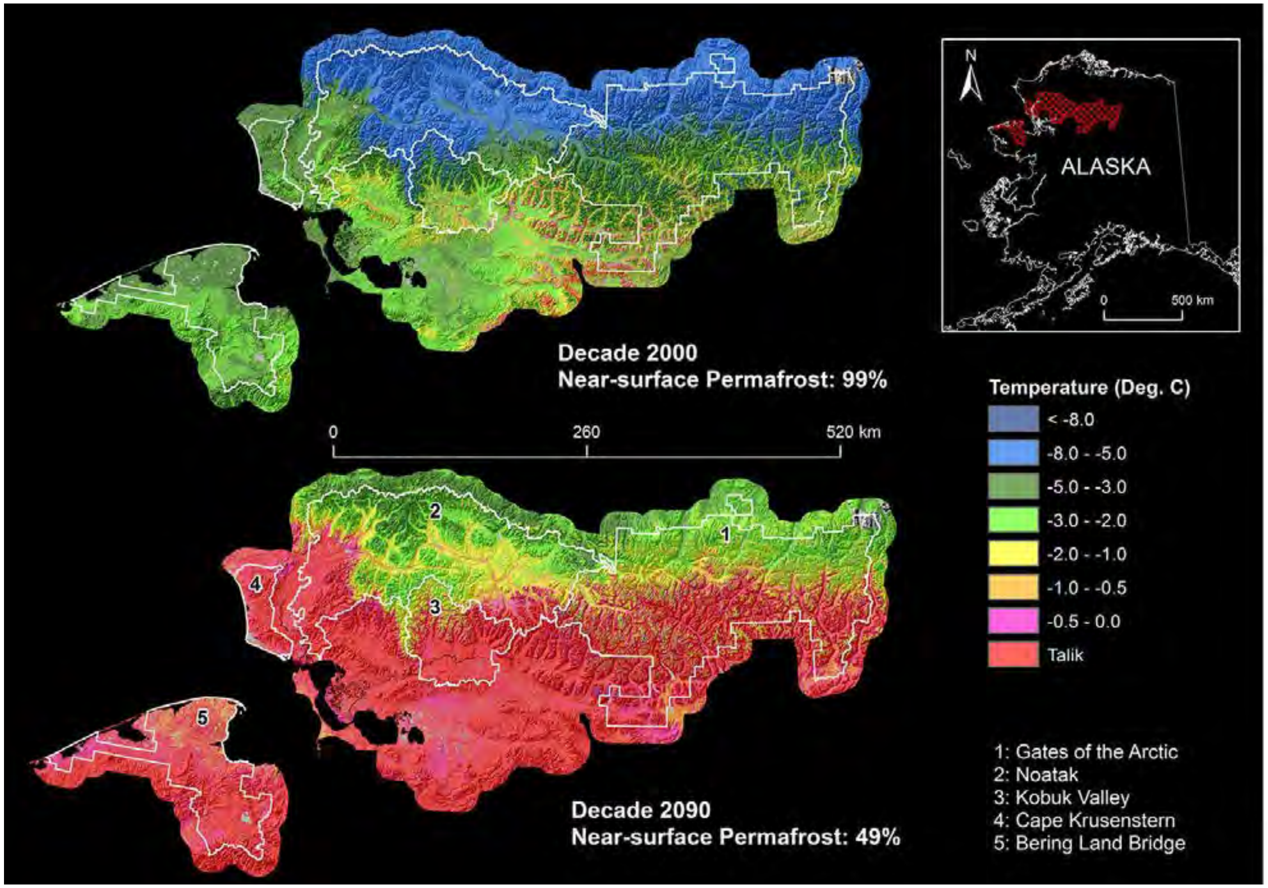


Figure 2. Permafrost maps of the Arctic Network National Parks in the decades 2000 and 2090 from the GIPL 1.0 permafrost model using climate data from CRU (2000s) and a composite of GCMs (2090s). The negative temperature values at the bottom of active layer indicate presence of near-surface permafrost. Temperature above 0 °C at the bottom of active layer indicates presence of unfrozen material (talik), shown in red (Panda et al. 2016).

and Nolan (2018) used aerial photographs to document the continued growth of some of these thaw slumps in the following years.

Other features of these Arctic landscapes include frozen debris lobes, which are masses of frozen material that slowly creep downhill. When warmer temperatures penetrate deeper into these lobes, they destabilize the frozen material, allowing it to move downslope faster. Anything in the path of these debris lobes gets buried (Swanson 2021a). Frozen debris lobes that are just below 0°C are susceptible to run-away sliding with just a degree or two of warming.

Arctic lake drainage is another consequence of warming temperatures. Swanson (2019) found that Arctic coastal parks experienced a major episode of lake drainages following very warm years in 2005-2007 and 2018-2019. As the ground warms and ice melts, the ground surface subsides. When this happens along a lake shore, it opens new pathways for water to drain out of a lake. Deeper snowpacks and high-water levels during the spring melt can also erode the lake shore and carve new lake outlets. Once a new outlet opens, the lake might drain quickly, leaving behind a dry lakebed (Swanson 2019).

Thawing permafrost also affects the hydrology of the northern landscape. Streamflow may be declining in headwater reaches due to the combined effects of vegetation change and permafrost thaw. Koch and others (2022) looked at eleven headwater catchments in northern Alaska parks that varied in forest cover and the degree of permafrost thaw. They identified two main climate change impacts to streamflow. First, climate change allows boreal treeline and shrub line expansion, which results in an increase in evapotranspiration, which is the physical and biological transport of water to the atmosphere. Second, permafrost thaw reroutes rainfall and soil water to deep groundwater aquifers, often bypassing the stream channel. Together, these processes can cause streamflow to decline and may contribute to channel drying. Headwater streams serve as critical habitat for native fish species in the Arctic, and this decline in flow may contribute to a loss of fish habitat (Koch et al. 2022).

Arctic rivers are influenced by permafrost thaw and provide critical nutrients and habitat to fish.
NPS/KEN HILL

Another surprising consequence of permafrost thaw in Arctic parks is that stream water may become cooler (Sjöberg et al. 2021). Model results from this study documented interesting hydrologic flow paths in Arctic systems related to ground thaw. Water that remained on top of continuous permafrost moved through shallow, warmer soil horizons enroute to the stream. In contrast, water that was not restricted by a frozen layer percolated down through unfrozen soils, flowing through deeper and cooler soil horizons, before entering the stream. The results of this study suggest that Arctic summer stream temperatures may decrease as the permafrost thaws and water finds its way through deeper cooler soils (Sjoberg et al. 2021), which can have direct effects on stream productivity and food webs.

Permafrost stores large amounts of organic carbon in frozen soil layers (Hugelius et al. 2014). As ground temperatures cross the zero-degree threshold and permafrost thaws, this carbon can be transformed and released to the atmosphere as the greenhouse gases carbon dioxide and methane (Schadel et al. 2016). Given the large amount of carbon stored in permafrost, its release to the atmosphere has the potential to further warm Earth's climate (Schuur et al. 2013). As described above, permafrost thaw can also alter watershed hydrology and as a result, the transport of carbon from terrestrial to aquatic ecosystems. Not all permafrost soils in Alaska's Arctic parks are the same. Soils vary in texture (silt, sand, gravel, etc.) and in the amount of ground ice within, including massive ice wedges. These soil properties affect groundwater movement and the forms of carbon that get transported to streams and rivers (O'Donnell et al. 2016). These observations suggest that as permafrost thaws, streams and rivers may have different chemical responses to this climate-induced disturbance (Toohey et al. 2016).

Most of the carbon stored in permafrost is very old, ranging from hundreds to thousands of years old (Estop-Aragones et al. 2020). One important question is how this old carbon will impact terrestrial and aquatic ecosystem function when it is released from thawing permafrost. O'Donnell and others (2020) tracked how old carbon was used by stream food webs in Alaska's Arctic parks. They showed that resident fish, like Arctic grayling and Dolly Varden, take up old carbon when they eat stream invertebrates. Fish muscle tissue ranged in radiocarbon age from modern to more than 5,000 years before the present. More research is needed to understand how the use of old carbon affects stream food web function.

The timing of the snow season is closely coupled with air temperature, and as temperatures warm, the snow season is shorter in duration (Pan et al. 2020). A recent study found that Arctic summers are getting longer. Using images from remote cameras in Arctic parks to verify satellite data, one study found that the snow-free season has lengthened over the past 20 years. Vegetation is now greening up a week earlier in the spring and staying green a week later in the fall (Swanson 2021b).

The high-latitude parks in northern Alaska are the coldest in the nation but are at the point of profound change as temperatures warm, permafrost begins to thaw, and hydrologic pathways change. Warmer air temperatures are warming Arctic stream temperatures, causing lakes to drain as the permafrost beneath them melts, and are the catalyst for the release of carbon to the atmosphere and Arctic ecosystems as the ground surface thaws. When the average temperature of these places eventually climbs above freezing, it will be a very different Arctic.

How the National Park Service Contributes to Knowledge of Global Climate Change

Research and monitoring conducted in Alaska parks by the National Park Service and partners has resulted in numerous datasets that are highly valuable to understanding environmental changes from a warming climate in Alaska and beyond. This is because high-latitude regions are seeing changes much faster and Alaska's parks are relatively large and naturally functioning. Large, long-term datasets contribute to greater scientific understanding. The collaboration of NPS scientists in international forums help inform global scientific questions and conservation. Below are some examples of how NPS scientists and datasets have contributed to global knowledge.

Alaska park climate data contribute to the Global Historical Climatology Network to inform climatology maps.

- Global Historical Climatology Network monthly (GHCNm) | National Centers for Environmental Information (NCEI) (noaa.gov)
- PRISM Climate Group at Oregon State University

Permafrost data contribute to Alaska-wide monitoring.

- Arctic Data Center
- Wang, K., E. Jafarov, I. Overeem, V. Romanovsky, K. Schaefer, G. Clow, F. Urban, W. Cable, M. Piper, C. Schwalm, T. Zhang, A. Kholodov, P. Sousanes, M. Loso, and K. Hill. 2018. A synthesis dataset of permafrost-affected soil thermal conditions for Alaska, USA. Earth Syst. Sci. Data 10(4): 2311-2328.

Dissolved organic carbon in Arctic lakes informs global models of carbon's role in climate change.

- PANGAEA
- O'Donnell, J. A., M. P. Carey, J. C. Koch, X. Xu, B. A. Poulin, J. Walker, and C. E. Zimmerman. 2020. Permafrost hydrology drives the assimilation of old carbon by stream food webs in the Arctic. Ecosystems 23: 435-453.
- O'Donnell, J. A., G. R. Aiken, D. K. Swanson, S. Panda, K. D. Butler, and A. P. Baltensperger. 2016. Dissolved organic matter composition of Arctic rivers: Linking permafrost and parent material to riverine carbon. Global Biogeochemical Cycles 30(12): 1811-1826.
- Stolpmann, L., C. Coch, A. Morgenstern, J. Boike, M. Fritz, U. Herzschuh, K. Stoof-Leichsenring, Y. Dvornikov, B. Heim, J. Lenz, A. Larsen, K. Walter Anthony, B. Jones, K. Frey, and G. Grosse. 2021. First pan-Arctic assessment of dissolved organic carbon in lakes of the permafrost region. Biogeosciences 18: 3917-3936.

Boreal-Arctic wetland and lake dataset help improve circumpolar models of current and future methane emissions.

- The Boreal-Arctic Wetland and Lake Dataset (BAWLD) | U.S. Geological Survey (usgs.gov)
- Olefeldt, D., M. Hovemyr, M. A. Kuhn, D. Bastviken, T. J. Bohn, J. Connolly, P. Crill, E. S. Euskirchen, S. A. Finkelstein, H. Genet, G. Grosse, L. I. Harris, L. Heffernan, M. Helbig, G. Hugelius, R. Hutchins, S. Juutinen, M. J. Lara, A. Malhotra, K. Manies, A. D. McGuire, S. M. Natali, J. A. O'Donnell, F. J. W. Parmentier, A. Räsänen, C. Schädel, O. Sonnentag, M. Strack, S. E. Tank, C. Treat, R. K. Varner, T. Virtanen, R. K. Warren, and J. D. Watts. 2021. The Boreal–Arctic Wetland and Lake Dataset (BAWLD). Earth Syst. Sci. Data 13: 5127–5149.

Expert assessment of global peatland vulnerability to climate change.

- Loisel, J., A. V. Gallego-Sala, M. J. Amesbury, ... J. A. O'Donnell, ... et al. 2021. Expert assessment of future vulnerability of the global peatland carbon sink. Nature Climate Change 11: 70-77.

A Climate Change Perspective from Northwest Alaska

The people that live in and around national parks in Alaska are the most important resource. They have the firsthand practical knowledge of changes manifesting across the landscape, and they are also a vital component of that landscape. They are on the front line of climate changes and are acutely affected by what is happening.

Science and data are powerful tools when they are used in conjunction with local knowledge. Ongoing monitoring of weather, animal movements, hydrology, and vegetation patterns contribute to community knowledge. The information is integrated into regional and global analyses and climate models that are key to adaptation and mitigation planning efforts.

The changes to the land and the people are front and center for Bering Land Bridge National Preserve and the Western Arctic Parklands where changes in the timing and extent of sea ice and the ripple effects of a land that is losing its ice are impacting food resources, infrastructure, and livelihoods. Jeanette Koelsch is a tribal member of Nome Eskimo Community, the largest tribe in the Bering Strait Region. She shares her perspective on changes impacting her community and on lands within Bering Land Bridge National Preserve where she serves as the superintendent.

The following excerpts are used with permission from the University of Alaska Fairbanks (UAF) Project Jukebox *Observing Change in Alaska's National Parks* oral history interview conducted by Leslie McCartney, University of Alaska Fairbanks, and Katie Cullen, National Park Service in 2019 (McCartney 2019).

Jeanette Koelsch is Superintendent for Bering Land Bridge National Preserve.

Jeanette Koelsch was born in Anchorage, Alaska to Joe and Grace Cross, and moved to Nome in 1982 when she was about ten years old. Her maternal grandparents were Jane and Jack Antoghame from St. Lawrence Island. From Jeanette's perspective:

> *The continued land use for local people to ensure that lifestyle would continue* [is important]. *One of my main goals is to work with my staff to ensure those values are preserved … and creating stewards of not only the preserve, but everywhere.*

When asked about how climate change impacts Bering Land Bridge, she says:

> *I see climate change as probably the number one threat to park resources. And to manage effectively, we have to be able to adapt to the change and do that in the most responsible way while still allowing for access and working with local people on subsistence.*

One way park staff are interacting with local communities is through conversations:

> *Tribal consultation is something that's taken very seriously here, and the needs and the inputs of the local people … And I see that trend in Alaska as we move forward.*

The interview highlights some of the most significant changes from Jeanette's personal perspective, starting with seasonal changes:

> *When I was a kid growing up here, winter was in September. By the time you went out to do moose hunt, there was usually hard ground and some snow… but now… the ground's not frozen.* [Early fall average temperatures have increased by 0.6°C in Nome (NOAA 2022a).]

> *Winter is the busy time for local people because the main access is by snowmachine. It is the time when locals do a lot of subsistence activities because the whole preserve is accessible.*

Timing is difficult:

When I discuss changes with the local people it makes them sad, they are suffering from the unknown—of not knowing when to go and hunt something or if an animal will be there.

The shorter snow and ice season impacts access to food resources for coastal communities as well. For example, for Shismaref residents:

If the inlet doesn't freeze, they have no access to the preserve, since they are on a barrier island. Even if there are moose, caribou, or musk ox, they can't get to them.

Shorter snow and ice seasons limiting access is a thread running through most of the changes Jeanette described:

[Hunters are] *… also going out farther to find ice to hunt marine mammals, more dangerous to go out five miles than one mile.*

[Since 1980, the amount of sea ice that exists through summer has declined by >13% per decade and the ice that survives year-round is thinner and more fragile (NOAA 2022b).]

Impact of Powerful Autumn Storms on Coastal Western Alaska Communities

A very powerful early autumn storm slammed into the west coast of Alaska in September of 2022. The storm was notable because of the timing, intensity, and sheer size. Although, fall is generally the stormy season, in the past the presence of sea ice along the coast has buffered communities and protected them from powerful storm surges. In the case of remnant Typhoon Merbok, it was early in the season and there was no sea ice. This storm was fueled by anomalously warm water in the North Pacific Ocean southwest of Alaska. Storms usually fizzle when they move over the colder northern waters, but in this case, the warm water enabled it to keep its intensity.

This storm sheds light on how a single extreme event can be devasting for people who subsist off the land and take great care and time to prepare for a long, cold winter. Fish camps were destroyed, boats went missing, and freezers thawed along with a winter's supply of food. Livelihoods were disrupted or upended by this event.

In a warmer world, with warmer oceans and longer ice-free seasons, Alaskan coastal communities will continue to be more vulnerable to intense fall storms. Koelsch adds:

From my observations, storms seem more frequent and stronger, action needs to happen to protect communities and subsistence camps. We need to work with communities and tribes to be more adaptive to climate change impacts.

References

McCartney, L. 2019.
Project Jukebox, Observing Change in Alaska's National Parks, Oral History Interview with Jeanette Koelsch April17-18, 2019. Available at: https://jukebox.uaf.edu/p/3238 (accessed on September 7, 2022).

National Oceanic and Atmospheric Administration (NOAA) 2022a.
National Centers for Environmental Information, Climate at a Glance: City Time Series, Average Temperature, published August 2022. Available at: https://www.ncdc.noaa.gov/cag/ (accessed on September 7, 2022)

National Oceanic and Atmospheric Administration (NOAA). 2022b.
National Oceanic and Atmospheric Administration (NOAA) Climate.Gov, Science and Information for a Climate Smart Nation. September 2022. Available at: https://www.climate.gov (accessed on September 20, 2022)

Also See

Observing Change in Alaska's National Parks

Capturing the effects of change on cultural and natural resources at these coastal parks, and hearing about the effects on the human connection to those resources allows audiences to gain first-hand understanding of a changing environment and provides the opportunity to draw comparisons between two distinct regions of Alaska.

Alaska's Interior Parks: At the Zero-Degree Celsius Threshold

Parks in the central and southwest Alaska interior are in a more precarious position than the Arctic when it comes to nearing the 0°C threshold. A temperature increase of just a few degrees could alter the landscape. Many Interior Alaska parks have an annual average air temperature just below the freezing threshold. Temperatures increased abruptly in 2014 and many of the locations in and adjacent to Denali National Park and Preserve, Wrangell-St. Elias National Park and Preserve, and Yukon-Charley Rivers National Preserve experienced average annual temperatures at or above the freezing threshold of 0°C (Swanson et al. 2021). Permafrost extent maps show that about half of Denali and three-fourths of Wrangell-St. Elias had permafrost around the year 2000, but that it was susceptible to thaw because ground temperatures were at or just below 0°C (Panda et al. 2014a, b). Modeling by Panda and others (2014a, b) predict that most of the permafrost in these two parks will start to thaw by the end of the current century. The implications of thawing permafrost are more immediate and widespread in this region. Large swaths of parklands and communities are at the precipice of melt, with immediate and visible changes to the physical landscape and costly impacts to park infrastructure.

Permafrost landscapes in Interior Alaska parks are already experiencing dramatic changes in response to climate, ecological succession, and fire (Jorgenson et al. 2020). Fire history, soil properties, hydrology, air temperature, and snow cover all interact and affect ground temperatures and the potential for permafrost degradation in boreal peatlands which are common throughout Interior Alaska. Long-term monitoring at Gosling Lake, near Lake Minchumina in Denali National Park and Preserve, showed increasing permafrost degradation in recent decades in response to long-term warming, recent warm and wet summers, and low-severity fire (Jorgenson 2022). However, short-term variability also plays a key role. Snow acts as a blanket, insulating the permafrost from frigid winter air temperatures. Extreme seasonal weather with cold winters and little snow resulted in the temporary recovery of permafrost in some bog landscapes. This shows that when ground temperatures are near zero, relatively small changes in temperature can result in large landscape changes.

Climate warming is thawing permafrost, which can weaken earth materials and increase the occurrence of landslides (Patton et al. 2019, Lader et al. 2023). There are numerous landslides in the vicinity of the Denali Park Road that were initiated or aggravated by permafrost thaw, leading to road closures and costly repairs (Capps et al. 2017, Patton et al. 2020, 2021). Patton and others (2021) looked at three shallow-angle, thaw-initiated landslides in Denali to quantify the deformation and movement. The authors found that there was no evidence of shallow permafrost within a recent landslide, indicating that when the surface was disturbed there was an increase in the amount of heat available to thaw soils below the surface. This is an example of a positive feedback loop where warming temperatures lead to an acceleration of permafrost thaw in recent landslides (Patton et al. 2021).

Snow cover plays an important role on the landscape; it regulates local and regional temperatures by reflecting incoming solar radiation and controlling evaporation, condensation, and sublimation of water. Snow cover also protects vegetation and wildlife that lives under the snow from sub-zero air temperatures and opens the landscape to snow travel for transportation and subsistence activities. When temperatures exceed 0°C, precipitation falls more frequently as rain rather than snow, which can impact wildlife, plants, and people. This temperature and rain-versus-snow threshold also dictates the duration of the snow cover season, with warming temperatures changing the timing (phenology) of the seasons.

A recent study showed that the amount of sunlight that is reflected by the ground (known as *albedo*) declined by 79% when dry winter snow melted in the spring (Kim et al. 2018). Along the way from snow to no-snow, the study found that when the snowpack starts to thaw and refreeze each day in the spring, there is a 25% decrease in snow cover albedo in Alaska. As albedo goes down, the surface absorbs more energy from the sun, reinforcing snowmelt and surface warming. This contributes to an earlier growing season onset and activation of seasonal biological and hydrological processes (Kim et al. 2018).

As temperatures increase and influence other processes like snow melt and albedo, the number of snow-free days is increasing. Earlier snow-off dates (date when the seasonal snowpack melts in the spring) lead to longer growing seasons, permafrost degradation, changes in hydrology, and a host of other ecosystem processes. Using remote sensing, Pan et al. 2020, 2021 found a trend toward earlier snow-off timing from 1988-2018 across Alaska. The average trend was 0.39 days per year or 12 days over the study period, but the trend varied from 0.11 to 1.31 days per year depending on the location. Snow-off was markedly earlier in warm years and more variable in recent years.

Rain-on-snow (ROS), or "wet" snow events affect the hydrology, wildlife, and human activity in and around Alaska's parks. ROS events can influence caribou movement during the winter season (Loe et al. 2016) and reduce caribou's access to forage under the snow. The rain freezes on top of the snow creating a hard crust and a barrier to the lichens on the ground below. Projections indicate an increased likelihood of ROS events across caribou ranges in northern Alaska (Bieniek et al. 2018). ROS events are most common during autumn and spring months along the maritime Bering Sea coast and boreal interior regions but are infrequent on the colder Arctic North Slope. Their frequency and extent coincide with greater climate variability and warmer temperatures regionally (Figure 3). While further study of ROS is needed, initial modeling results suggest that as high-latitude temperatures increase, wet snow events will also increase in frequency and extent, particularly in the southwestern and interior regions of Alaska (Pan et al. 2018a, b).

Littell and others (2018) looked at the statewide snow response to climate change using historical data and global climate models. As more locations in Alaska transition across the 0 °C threshold, the number of months with reliable snow cover decreases, mainly at lower elevations and lower latitudes. Littell (2023) recently mapped climate change and impact projections for the national parks in Alaska. The future scenarios for snowfall included both a mid- and late-century time frame, and both a medium and high range of warming. In all scenarios and at all parks temperatures warmed and total annual precipitation increased. The snowfall trajectories vary by location and depend on the annual temperature of the region. Higher latitudes and higher elevations will stay colder longer, and the increase in winter precipitation will be in the form of snow.

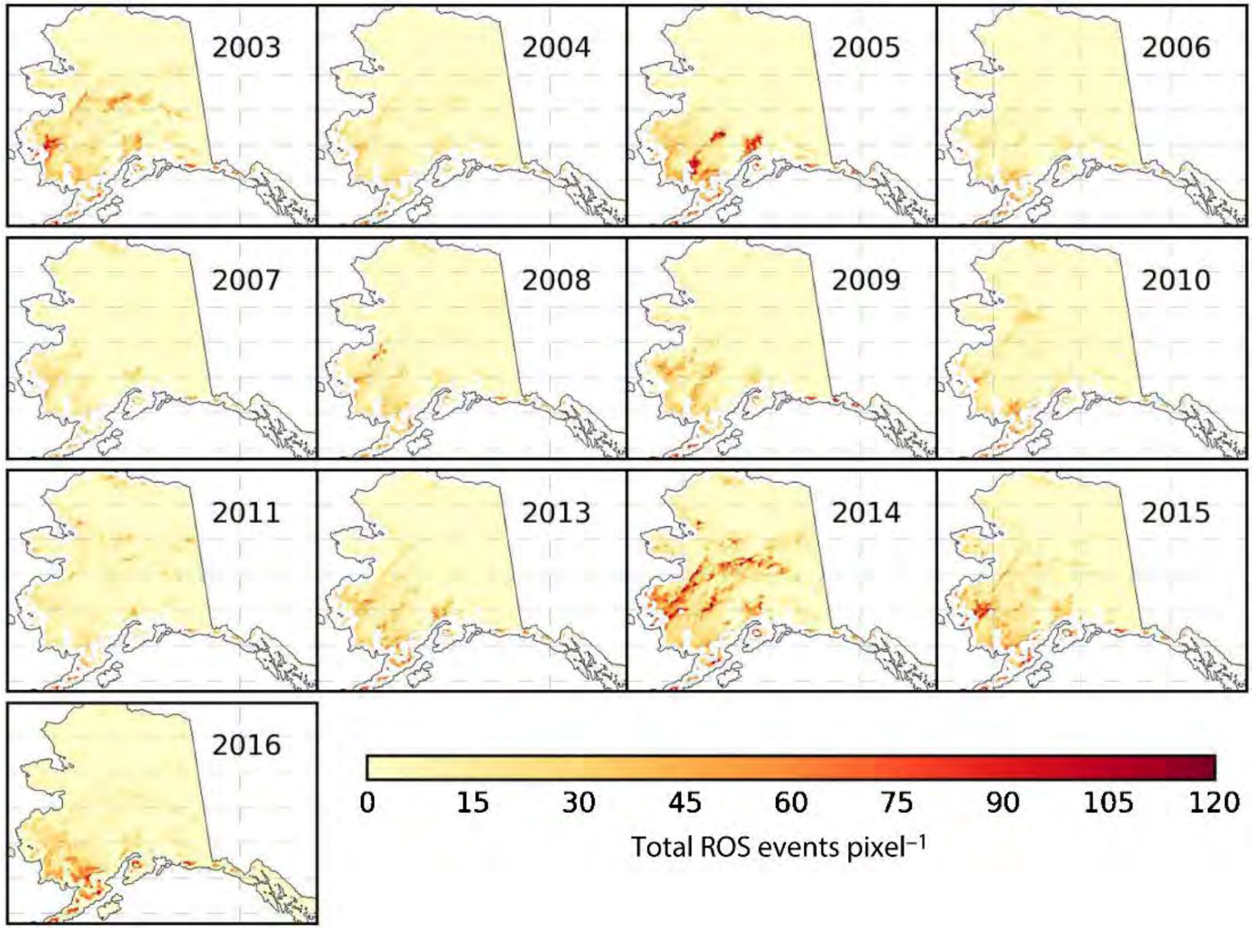


Figure 3. This figure shows the number of rain-on-snow (wet snow) days per year across Alaska. Southwest and central Alaska experience the most rain-on-snow days mostly in November and December. But they can occur anywhere, even in the high Arctic, with above normal temperatures.

Alaska's Coastal Mountain Parks: Straddling the Zero-Degree Celsius Threshold

Alaska parks along the southern coast have the largest proportion of glaciers and ice fields of any in the country—they are high enough in latitude and have high-elevation mountain ranges that capture moisture spinning off the Pacific Ocean as snow. Glaciers and glacier systems are the dominant physical features in these parks and are inextricably linked to climate fluctuations.

Delineation of glacier-covered area in the state of Alaska indicates overall glacier-covered area decreased by 13% (3,253 square miles or 8,425 km^2) between 1985 and 2020 (Roberts-Pierel et al. 2021). During the same period supraglacial debris expanded by 64% (1,081 square miles or 2,799 km^2) suggesting a significant loss in volume as well. This study also shows a clear and ongoing trend of reduced area, especially at the mid and lower elevations, where the 0-degree isotherm is changing most rapidly. Furthermore, an earlier study showed the glacier-covered area in the Alaskan parks decreased by 8% between the 1950s and the early 2000s suggesting that the rate of loss is also increasing (Loso et al. 2014).

As temperatures warm and glaciers retreat, what was recently covered in ice becomes newly exposed land or water with implications for surface albedo, ecosystems and downstream hydrologic conditions. A recent study in Kenai Fjords National Park documented rapid maritime glacier retreat and terminus change at 19 glaciers between 1984-2021 that resulted in a cumulative loss of 16 square miles (42 km^2) of ice (Black and Kurtz 2022; Figure 4). As glaciers melt, new habitats form in their wake. In some

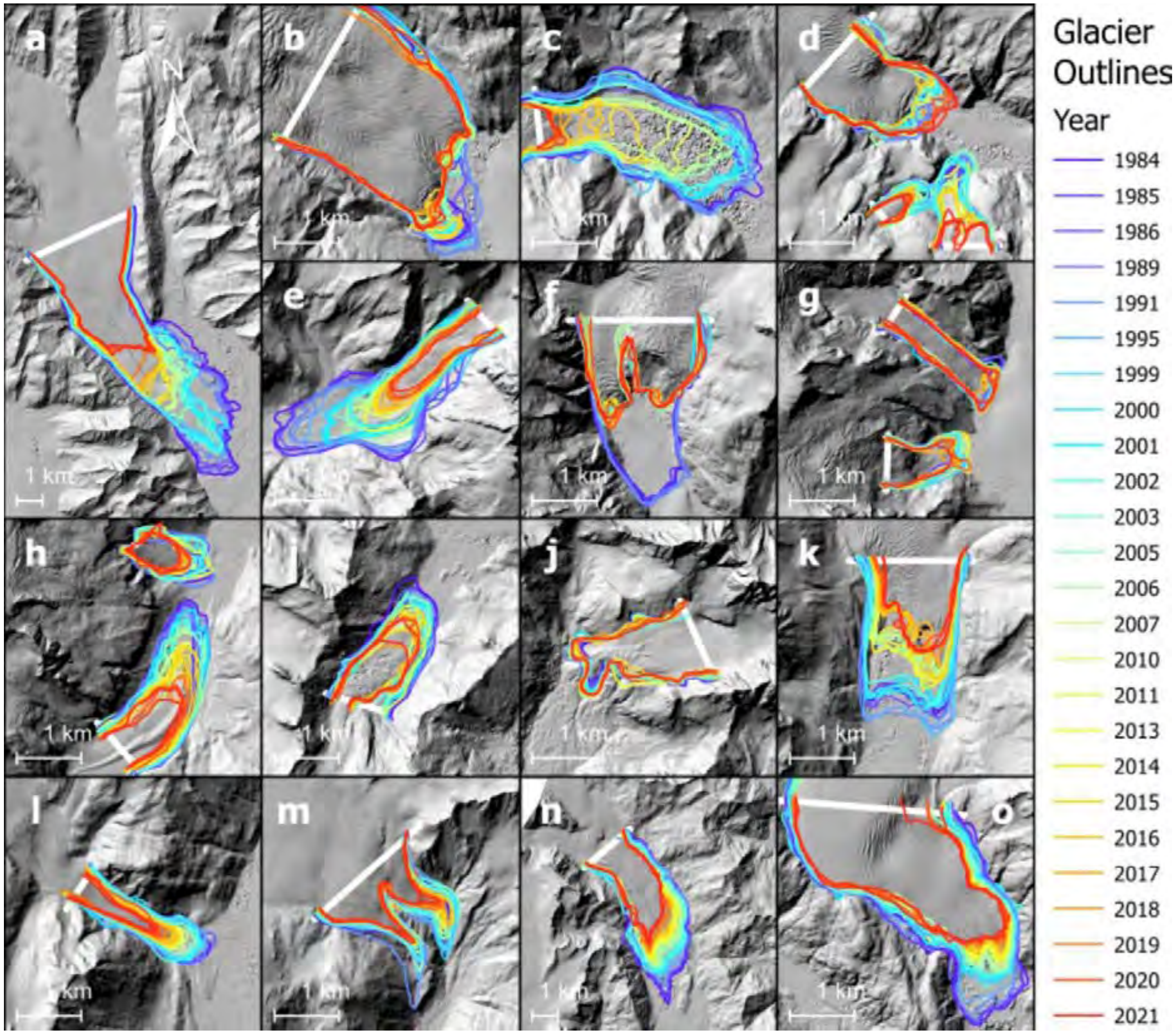


Figure 4. Kenai Fjords National Park seasonal glacier outlines traced for (a) Bear Glacier; (b) Aialik Glacier; (c) Pedersen Glacier; (d) Holgate Glacier (top), South Holgate Glacier – West (bottom left) and South Holgate Glacier – East (bottom right); (e) Northeastern Glacier; (f) Northwestern Glacier; (g) Ogive Glacier (top) and Anchor Glacier (bottom); (h) Reconstitution Glacier (top) and Southwestern Glacier (bottom); (i) Sunlight Glacier; (j) Paguna Glacier; (k) McCarty Glacier; (l) Dinglestadt Glacier; (m) Split Glacier; (n) Yalik Glacier; and (o) Petrof Glacier. The color scale ranges from purple as the oldest (1984) to red as the youngest (2021). Glacier reference lines are shown in white. Maps (a) and (n) are shown at 1:250 000 scale, and all others are at 1:100 000 scale. The base image is a hillshade of a DEM from a U.S. Fish and Wildlife Service-led structure-from-motion data acquisition in 2016. From Black and Kurtz 2022.

cases, new recreation opportunities develop, too, such as at the expanded proglacial lake at Kenai Fjords' Bear Glacier where visitation has increased in the past decade.

Recent monitoring efforts in Glacier Bay National Park and Preserve found that, in some cases, glacier retreat can reroute the outlet of a major river, resulting in not only ecological impacts, but significant socioeconomic impacts as well. Loso and others (2021) predict that due to thinning glacier termini, the Alsek River will abandon its present Dry Bay outlet channel in favor of the much steeper outlet of Grand Plateau Lake, more than 17 miles (28 km) to the southeast in the federally designated wilderness of Glacier Bay National Park (Figure 5). Traditional and modern human activities dependent on the Alsek River in Dry Bay include commercial fishing, subsistence and sport hunting and fishing, and world-renowned wilderness rafting expeditions.

Figure 5. Overview of the lower Alsek River/Grand Plateau Glacier study area. On main map, yellow dashed line is possible new outlet of Alsek River. GPG is Grand Plateau Glacier; -AL and -GPL are its Alsek and Grand Plateau distributary lobes, respectively. AG is Alsek Glacier, GK is Gateway Knob, and N is an unnamed nunatak. Red lines show extent of Alsek and Grand Plateau lobes in 1958; both lake basins were completely occupied by glacier ice in 1928 International Boundary Commission map. Inset shows location of the main map (red rectangle) in southern Alaska and adjacent Canada. Blue line is Alsek River, red line is Alsek watershed boundary, and light blue polygons are glacier cover from RGI 6.0. Green polygon is Glacier Bay National Park, and the yellow polygon is Glacier Bay National Preserve, centered over the lower Alsek River and Dry Bay. Base is Sentinel-2 image acquired September 10, 2018; Albers equal area projection. From Loso et al. 2021.

The Phase Shift

Alaska parks are in a state of change as the frozen components of the landscapes warm. As average annual temperatures climb above 0 °C, permafrost has begun to thaw and, with this phase shift, there has been a myriad of changes. Thawing ground increases landslide risks and erosion along park roads and rivers and wreaks havoc on infrastructure that has been designed for frozen soils. Warming temperatures are affecting snow cover, increasing the length of the snow-free season, decreasing surface albedo and increasing the frequency of rain-on-snow or wet snow events with cascading impacts to park resources. Glaciers, while retaining snow up high, are receding and thinning at lower elevations and this has significant impacts for subsistence, park management, and recreational pursuits in the parks. This critical phase shift from frozen to unfrozen is happening now and will continue into the future, impacting all Alaska parks.

REFERENCES

Ballinger, T. J. and J. E. Overland. 2022.
The Alaskan Arctic regime shift since 2017: A harbinger of years to come? Polar Science 32: 100841.

Bieniek, P. A., U. S. Bhatt, J. E. Walsh, R. Lader, B. Griffith, J. K. Roach, and R. L. Thoman, 2018.
Assessment of Alaska rain-on-snow events using dynamical downscaling. J. Appl. Meteor. Climatol. 57: 1847-1863.

Black, T. and D. Kurtz. 2022.
Maritime glacier retreat and terminus area change in Kenai Fjords National Park, Alaska, between 1984 and 2021. Journal of Glaciology 1-15.

Boelman, N. T., G. E. Liston, E. Gurarie, A. J. H. Meddens, P. J. Mahoney, P. B. Kirchner, G. Bohrer, T. J. Brinkman, C. L. Cosgrove, J. U. H. Eitel, M. Hebblewhite, J. S. Kimball, S. LaPoint, A. W. Nolin, S. H. Pedersen, L. R. Prugh, A. K. Reinking, and L. A. Vierling. 2019.
Integrating snow science and wildlife ecology in Arctic-boreal North America. Environmental Research Letters 14(1): 010401.

Gonzalez, P., F. Wang, M. Notaro, D. J. Vimont, and J. W. Williams. 2018.
Disproportionate magnitude of climate change in United States national parks. Environmental Research Letters 13(10): 104001.

Estop-Aragonés, C., D. Olefeldt, B. W. Abbott, J. P. Chanton, C. I. Czimczik, J. F. Dean, J. E. Egan, L. Gandois, M. H. Garnett, I. P. Hartley, A. Hoyt, M. Lupascu, S. M. Natali, J. A. O'Donnell, P. A. Raymond, A. J. Tanentzap, S. E. Tank, E. A. G. Schuur, M. Turetsky, and K. Walter Anthony. 2020.
Assessing the potential for mobilization of old soil carbon after permafrost thaw: A synthesis of 14C measurements from the northern permafrost region. Global Biogeochemical Cycles 34(9): e2020GB006672.

Ewing, S. A., J. A. O'Donnell, G. R. Aiken, K. Butler, D. Butman, L. Windham-Myers, and M. Z. Kanevskiy. 2015.
Long-term anoxia and release of ancient, labile carbon upon thaw of Pleistocene permafrost. Geophysical Research Letters 42(24): 10,730-10,738.

Hartman, B. and G. Wendler. 2005.
The significance of the 1976 Pacific climate shift in the climatology of Alaska. Journal of Climate, 18 (22): 4824-4839.

Hugelius, G., J. Strauss, S. Zubrzycki, J. W. Harden, E. A. G. Schuur, C.-L. Ping, L. Schirrmeister, G. Grosse, G. J. Michaelson, C. D. Koven, J. A. O'Donnell, B. Elberling, U. Mishra, P. Camill, Z. Yu, J. Palmtag, and P. Kuhry. 2014.
Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. Biogeosciences 11 (23): 6573-6593.

Intergovernmental Panel on Climate Change (IPCC). 2021. [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]
Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental

Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jorgenson, M. Torre, Thomas A. Douglas, Anna K. Liljedahl, Joanna E. Roth, Tim C. Cater, Wendy A. Davis, Gerald V. Frost, Patricia F. Miller, and Charles H. Racine. 2020.
The roles of climate extremes, ecological succession, and hydrology in repeated permafrost aggradation and degradation in fens on the Tanana Flats, Alaska. Journal of Geophysical Research: Biogeosciences 125 (12): e2020JG005824.

Jorgenson, M.T., M. Kanevskiy, C. Roland, K. Hill, D. Schirokaer, S. Stehn, B. Schroeder, and Y, Shur. 2022.
Repeated permafrost formation and degradation in boreal peatland ecosystems in relation to climate extremes, fire, ecological shifts, and a Geomorphic legacy. Atmosphere 13: 1170.

Kim, Y., J. Kimball, J. Du, C. Schaaf, and P. Kirchner. 2018.
Quantifying the effects of freeze-thaw transitions and snowpack melt on land surface albedo and energy exchange over Alaska and Western Canada. Environmental Research Letters 13: 075009.

Koch, J. C. Y. Sjoberg, J. O'Donnell, M. Carey, P. F. Sullivan and A. Terskaia. 2022.
Sensitivity of headwater streamflow to thawing permafrost and vegetation change in a warming Arctic. Environmental Research Letters 17(4): 044074.

Lader, R., J. E. Walsh, U. S. Bhatt, and P. A. Bieniek. 2017.
Projections of twenty-first-century climate extremes for Alaska via dynamical downscaling and quantile mapping. Journal of Applied Meteorology and Climatology 56(9): 2393-2409.

Lader, R. J., P. Sousanes, U. S. Bhatt, J. E. Walsh, and P. A. Bieniek. 2023.
Climate Indicators of landslide risks on Alaska national park road corridors. Atmosphere 14 (1).

Littell, J., S. McAfee, and G. Hayward. 2018.
Alaska snowpack response to climate change: Statewide snowfall equivalent and snowpack water scenarios. Water 10(5): 668.

Littell, J. S. 2023.
Alaska climate futures (mid and late 21st century) and historical references (20th century): U.S. Geological Survey Data Release.

Loe, L.E., B.B. Hansen, A. Stien, S.D. Albon, R. Bischof, A. Carlsson, R.J. Irvine, M. Meland, I.M. Rivrud, E. Ropstad, V. Veiberg and A. Mysterud. 2016.
Behavioral buffering of extreme weather events in a high-Arctic herbivore. 2016. Ecosphere 7(6): e01374.

Loso, M. G., C. F. Larsen, B. S. Tober, M. Christoffersen, M. Fahnestock, J. W. Holt, and M. Truffer. 2021.
Quo vadis, Alsek? Climate-driven glacier retreat may change the course of a major river outlet in southern Alaska. Geomorphology 384: 107701.

Markon, C., S. Gray, M. Berman, L. Eerkes-Medrano, T. Hennessy, H. P. Huntington, J. S. Littell, M. McCammon, R. Thoman, and S. Trainor. 2018.
Alaska. pp. 1185–1241 In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. Washington, D.C.: U.S. Global Change Research Program.

NOAA Regional Climate Centers. 2022.
XmACIS2.

O'Donnell, J. A., G. R. Aiken, D. K. Swanson, S. Panda, A. P. Baltensperger, and K. D. Butler. 2017.
Dissolved organic matter composition of Arctic rivers: Linking permafrost and parent material to riverine carbon. Global Biogeochemical Cycles 30 (12): 1811-1826.

O'Donnell, J. A., M. P. Carey, J. C. Koch, X. Xu, B. A. Poulin, J. Walker, and C. E. Zimmerman. 2020.
Permafrost hydrology drives the assimilation of old carbon by stream food webs in the Arctic. Ecosystems 23(2): 435-453.

Pan, C. G., P. B. Kirchner, J. S. Kimball, J. Du, and M. A. Rawlins. 2021.
Snow phenology and hydrologic timing in the Yukon River Basin, AK, USA. Remote Sensing 13(12): 2284.

Pan, C. G., P. B. Kirchner, J. S. Kimball, and J. Du. 2020.
A long-term passive microwave snowoff record for the Alaska region, 1988-2016. Remote Sensing 12(1): 153.

Pan, C. G., P. B. Kirchner, J. S. Kimball, Y. Kim, and J. Du. 2018a.
Rain-on-snow events in Alaska, their frequency and distribution from satellite observations. Environmental Research Letters 13(7): 075004.

Pan, C. G., P. B. Kirchner, J. S. Kimball, Y. Kim, and J. Du. 2018b.
ABoVE: Rain-on-snow frequency and distribution during cold seasons, Alaska, 2003-2016. ORNL DAAC, Oak Ridge, Tennessee, USA.

Panda, S. K., S. S. Marchenko, and V. E. Romanovsky. 2014a.
High-resolution permafrost modeling in Denali National Park and Preserve. Natural Resource Report NPS/CAKN/NRTR—2014/858. Fort Collins, Colorado: National Park Service.

Panda, S. K., S. S. Marchenko, and V. E. Romanovsky. 2014b.
High-resolution permafrost modeling in Wrangell-St. Elias National Park and Preserve. Natural Resource Report NPS/CAKN/NRTR—2014/861. Fort Collins, Colorado: National Park Service.

Panda, S. K., S. S. Marchenko, and V. E. Romanovsky. 2016.
High-resolution permafrost modeling in the Arctic Network of national parks, preserves and monuments. Natural Resource Report NPS/ARCN/NRR-2016/1366. Fort Collins, Colorado: National Park Service.

Patton, A. I., S. L. Rathburn, D. M. Capps, D. McGrath, and R. A. Brown. 2021.
Ongoing landslide deformation in thawing permafrost. Geophysical Research Letters 48(16): e2021GL092959.

Rantanen, M., A. Y. Karpechko, A. Lipponen, K. Nordling, O. Hyvärinen, K. Ruosteenoja, T. Vihma, and A. Laaksonen. 2022.
The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment 3(1): 168.

Roberts-Pierel, B. M., P. B. Kirchner, J. B. Kilbride, and R. E. Kennedy. 2022.
Changes over the last 35 years in Alaska's glaciated landscape: A novel deep learning approach to mapping glaciers at fine temporal granularity. Remote Sensing 14(18): 4582.

Schuur, E. A. G., B. W. Abbott, W. B. Bowden, V. Brovkin, P. Camill, J. G. Canadell, J. P. Chanton, F. S. Chapin III, T. R. Christensen, P. Ciais, B. T. Crosby, C. I. Czimczik, G. Grosse, J. Harden, D. J. Hayes, G. Hugelius, J. D. Jastrow, J. B. Jones, T. Kleinen, C. D. Koven, G. Krinner, P. Kuhry, D. M. Lawrence, A. D. McGuire, S. M. Natali, J. A. O'Donnell, C. L. Ping, W. J. Riley, A. Rinke, V. E. Romanovsky, A. B. K. Sannel, C. Schädel, K. Schaefer, J. Sky, Z. M. Subin, C. Tarnocai, M. R. Turetsky, M. P. Waldrop, K. M. Walter Anthony, K. P. Wickland, C. J. Wilson, and S. A. Zimov. 2013.
Expert assessment of vulnerability of permafrost carbon to climate change. Climatic Change 119(2): 359-74.

Schädel, C., M. K. F. Bader, E. A. G. Schuur, C. Biasi, R. Bracho, P. Čapek, S. De Baets, K. Diáková, J. Ernakovich, C. Estop-Aragones, D. E. Graham, I. P. Hartley, C. M. Iversen, E. Kane, C. Knoblauch, M. Lupascu, P. J. Martikainen, S. M. Natali, R. J. Norby, J. A. O'Donnell, T. Roy Chowdhury, H. Šantrůčková, G. Shaver, V. L. Sloan, C. C. Treat, M. R. Turetsky, M. P. Waldrop, and K. P. Wickland. 2016.
Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. Nature Climate Change 6(10): 950-53.

Swanson, D. K., P. J. Sousanes, and K. Hill. 2021.
Increased mean annual temperatures in 2014-2019 indicate permafrost thaw in Alaskan national parks. Arctic, Antarctic, and Alpine Research 53(1): 1-19.

Swanson, D. K. and M. Nolan. 2018.
Growth of retrogressive thaw slumps in the Noatak Valley, Alaska, 2010-2016, measured by airborne photogrammetry. Remote Sensing 10(7): 983.

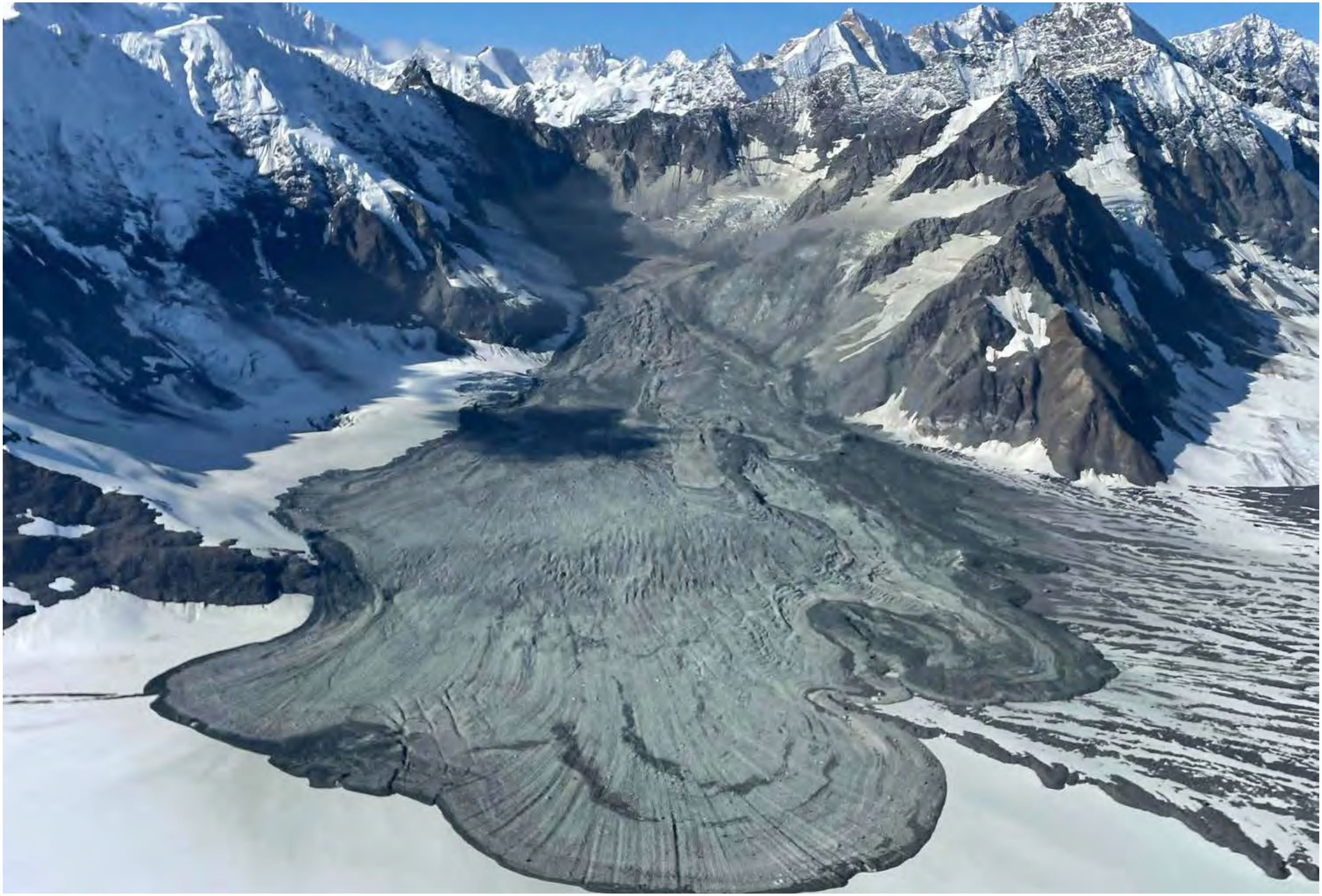
Swanson, D. K. 2019.
Thermokarst and precipitation drive changes in the area of lakes and ponds in the National Parks of northwestern Alaska, 1984-2018. Arctic, Antarctic, and Alpine Research 51(1): 265-279.

Swanson, D. K. 2021a.
Permafrost thaw-related slope failures in Alaska's Arctic National Parks, c. 1980-2019. Permafrost and Periglacial Processes 32(3): 392-406.

Swanson, D. K. 2021b.
Vegetation and snow phenology monitoring in the Arctic Network through 2020: Results from satellites and land-based cameras. Natural Resource Report NPS/ARCN/NRR—2021/2337. Fort Collins, Colorado: National Park Service.

Sjöberg, Y., A. Jan, S. L. Painter, E. T. Coon, M. P. Carey, J. A. O'Donnell, and J. C. Koch. 2021.
Permafrost promotes shallow groundwater flow and warmer headwater streams. Water Resources Research 57(2): e2020WR027463.

Toohey, R. C., N. M. Herman-Mercer, P. F. Schuster, E. A. Mutter, and J. C. Koch. 2016.
Multidecadal increases in the Yukon River basin of chemical fluxes as indicators of changing flowpaths, groundwater, and permafrost. Geophysical Research Letters 43 (23): 12,120-12,130.



Thawing permafrost creates instability and can lead to geohazards such as landslides, like this massive one that occurred on September 17, 2022 and covered almost 2,000 acres (8 km^2) of Lamplugh Glacier in Glacier Bay National Park and Preserve.
MOUNTAIN FLYING SERVICE/PAUL SWANSTROM

Stories Yet Told: Alaska's Cultural Heritage in a Time of Unprecedented Climate Change

Shina duVall, National Park Service

Within the modern boundaries of Alaska are some of the oldest-dated archeological sites in the Americas. An understanding of the depth and breadth of human history in Alaska informs our global understanding of human evolution, migration, occupation, adaptation, and cultural change around the planet. Climate change is threatening irreplaceable archeological sites, historical sites, and modern communities.

Citation:
duVall, S. 2023. Stories yet told: Alaska's cultural heritage in a time of unprecedented climate change. *Alaska Park Science* 22(1): 22-33.

This article presents a select review of some National Park Service (NPS) projects and initiatives underway across parks in Alaska and in partnership with Alaskan communities that endeavor to respond to the impact of climate change on heritage sites and cultural resources.

Alaska is Vast and Extraordinary

The state of Alaska encompasses over 663,000 square miles (an almost-unfathomable 365 million acres) and has more miles of coastline than the entire lower-48 coastline combined. There are over 54.6 million acres within the exterior boundaries of the National Park System units in Alaska, which together constitute 65% of the entire system. Most of these lands are in federal ownership, but there are also private, state, borough, and municipally owned lands therein. Private lands include those held by Alaska Native Corporations, which are the largest non-federal landowner of lands within the boundaries of NPS units in Alaska. At 13.2 million acres, Wrangell-St. Elias National Park and Preserve is the largest unit in the system. On top of this, Alaska has seven of the ten largest national parks in the system, which in addition to Wrangell-St Elias, include Gates of the Arctic, Denali, Katmai, Glacier Bay, and Lake Clark national parks and preserves, and Kobuk Valley National Park.

Alaska's Cultural Heritage is Irreplaceable

The archeological record is catching up with Alaska Native oral history and traditional knowledge, which maintains that people have been here since time immemorial. Contemporary and historical data compiled by Indigenous Elders, scholars, and scientists, combined with data gathered from the archeological record, paleogenomics, linguistics, and related disciplines, all indicate that Alaska is perhaps more accurately the First Frontier (not the "Last") in the peopling of the Americas and the Western Hemisphere (e.g., Amos 2018, Aquino 2022, Keats 2021, Nicholas 2018, Taylor and Running Horse Collin 2023). Within the modern boundaries of the state are some of the oldest dated archeological sites in the Americas. An understanding of the depth and breadth of human history in Alaska informs our global understanding of human evolution, migration, occupation, adaptation, and cultural change around the planet.

In addition to the deep Indigenous past in Alaska as well as contemporary sites and landscapes of continuing cultural significance to Tribes, the state also holds innumerable stories to be told through the cultural heritage sites of a more recent past. These include the material and structural remains of exploration and colonization by Russian America and the

Archeological excavation units at the historic gold rush townsite of Dyea were lost within one week of excavation, destroyed by the Taiya River. Emergency archeological data recovery is ongoing at the site to document and preserve cultural materials before they are lost due to severe riverbank erosion.
NPS/SHINA DUVALL

Alaska is Indigenous Land

Any conversation about the impacts of climate change on places of cultural significance —particularly in Alaska—should begin by centering the experience of Indigenous people. Alaska is the current and traditional homeland of hundreds of Indigenous cultures and language groups. The state has 228 federally recognized Tribes, numerous non-federally recognized Tribal entities, 12 Alaska Native Regional Corporations, 11 Alaska Native Regional Non-Profit Organizations, and over 200 Alaska Native village corporations. Every action taken on these lands impacts Indigenous lands, resources, and values. Cultural resources spanning more than 10,000 years within national parks in Alaska are affected by a broad range of climate-related stressors, some of which are shared with other places around the world, and some of which are unique to Alaska.

As noted by the United Nations Department of Economic and Social Affairs (n.d.):

> *Indigenous peoples are among the first to face the direct consequences of climate change, due to their dependence upon, and close relationship with, the environment and its resources. Climate change exacerbates the difficulties already faced by Indigenous communities including political and economic marginalization, loss of land and resources, human rights violations, discrimination, and unemployment.*

Furthermore,

> *Climate change poses threats and dangers to the survival of Indigenous communities worldwide, even though Indigenous peoples contribute the least to greenhouse emissions. In fact, Indigenous peoples are vital to, and active in, the many ecosystems that inhabit their lands and territories and may therefore help enhance the resilience of these ecosystems. In addition, Indigenous peoples interpret and react to the impacts of climate change in creative ways, drawing on traditional knowledge and other technologies to find solutions which may help society at large to cope with impending changes.*

The history of colonization, modern industrialization, land and resource extraction, use, and management in Alaska, has at times exploited, harmed, and marginalized Indigenous People (Scheidel et al. 2023)—the original stewards of the lands, plants, animals, ecosystems, and sacred sites since time immemorial. Here at the National Park Service in Alaska, we are committed to reflecting on this history and its legacy so as not to repeat the mistakes of the past.

As we now consider together how we will face climate change, we would do well to first listen to Indigenous communities, scholars, and experts and second, take their lead on adaptive response, resiliency, ecological health, and wellbeing. Particularly when Indigenous communities have relied on traditional knowledge and adaptive technology for millennia, which has allowed for sustainable interactions with the environment, and effective methods for coping with and adapting to environmental change (Braje et al. 2023).

We must endeavor to develop more holistic and inclusive approaches to climate response and adaptation work. To accomplish problem-solving in a more thoughtful, respectful, and collaborative way in all aspects of our work. Indigenous leadership and knowledge systems have much to teach us about moving from the more extractive, exclusive, and burdensome practices of the past to a healthier and more holistic systems approach. Under the leadership of Secretary Haaland and Director Sams (Haaland 2021, Sams 2022, Stoddart et al. 2021), it seems that there is no better time than now to genuinely transform the way that we do our work. We must welcome and value the expertise and input of our Indigenous colleagues, partners, fellow governmental representatives, community members, friends, and relatives in helping us shape the critical decades that lie ahead.

United States, the spread of Russian Orthodoxy and other denominations of Christianity, a long history of military activity and resource extraction, settlement, transportation, fishing and the cannery industry, the gold rush, reindeer and fox farming, the fur industry, forestry, voting rights, statehood, the impacts of earthquakes and other natural disasters, ANCSA, ANILCA and conservation lands, subsistence, wilderness, the Trans-Alaska Pipeline, the Exxon-Valdez Oil Spill, tourism, dog mushing and the Iditarod, and more.

The significance of heritage and history in Alaska cannot be overstated. The Alaska Office of History and Archaeology/State Historic Preservation Office maintains a statewide data repository called the Alaska Heritage Resources Survey (AHRS). The AHRS is a primary source of cultural resources data in the State of Alaska. The database contains information on approximately 45,000 reported cultural resources (archeological sites, buildings, structures, objects or locations, and some paleontological sites) within the state. While this number of records may seem like a lot, it is estimated that only 5% of the state has been inventoried for the presence of cultural resources, which means that we simply do not know the number or density of cultural resource localities for the remaining 95%. The profoundly dynamic nature of environmental and depositional processes in Alaska, as well as obstacles to pedestrian terrestrial access further limit our ability to gain a complete understanding of the presence of cultural resources on the landscape in this state.

Climate Change and Cultural Heritage in Alaska

We know that the size and scale of Alaska is immense and the significance of Alaska's cultural heritage to our understanding of the human experience is unparalleled. Equally astounding are the current statistics about the rate of climate-influenced change that the state is facing. According to the *Fourth National Climate Assessment* (USGCRP 2017), Alaska has been warming twice as quickly as the global average since the middle of the 20th century. Alaska is also warming faster than any U.S. state (Llanos 2007).

A report entitled, *Alaska's Changing Environment* (Thoman and Walsh 2019) observes that climate change threatens dire consequences for many Alaska Native villages in remote areas, where subsistence hunting, fishing, and gathering are critical to livelihoods. The report states that since 2014, there have been 5 to 30 times more record-high temperatures set than record lows.

As noted by Holtz and others in 2014:

> *Climate change is threatening not only native Alaskan communities—many of which go back thousands of years—but also some of the oldest archaeological sites in the Western Hemisphere.*

Most of the work highlighted in the remainder of this article focuses on archeological resources, but similar efforts are underway at other sites of cultural significance, including historic built environment resources (buildings, structures, monuments), cultural landscapes, and ethnographic and subsistence resources (see Mason and Craver, this issue).

Cultural Resources in Alaska's National Parks are Threatened by Climate Change Impacts Now

It is crucial to note that—as with the rest of the planet—all areas of Alaska are experiencing a remarkable range of climate-related impacts from many stressors. These stressors include, but are not limited to: temperature change, increasing freeze-thaw cycles, permafrost melt, higher relative humidity, increased wind, increased wildfire, changes in seasonality and phenology, species shift, invasive species/pests, increased precipitation, drought, increased flooding, inundation, storm surges, coastal and riverine erosion, higher water tables, salt water intrusion, extreme weather events, pollution, development pressures, and ocean acidification (Rockman et al. 2016). There is considerable overlap in the types of stressors as well as the approaches that park cultural resource managers and staff take toward response, treatment, and adaptation to these stressors across national parks in Alaska.

Bering Land Bridge National Preserve and Cape Krusenstern National Monument

NPS staff and researchers have long been monitoring the impact of erosion on archeological sites at Bering Land Bridge National Preserve. Most recently, between 2012 and 2016, a multi-year survey documenting climate change impacts at coastal archeological sites was initiated in Bering Land Bridge National Preserve. Thus far, the research has identified severe threats to sites located along the coasts, most of which are extremely vulnerable to coastal erosion. Beginning in 2024, park staff will undertake an important project that builds upon this past work. The ensuing project represents a collaborative effort among NPS, Portland State University, Kawerak (a regional non-profit organization), and other cultural resource management groups. Previously inventoried threatened coastal sites will be revisited for limited testing and non-invasive documentation. The goal of the project is to assess site condition, to establish site significance, to continue monitoring the impacts of coastal erosions upon the sites, and to proactively work with local communities to help prioritize site mitigation.

Similarly, for the past several years, researchers at Cornell University have been collecting permafrost depth data at two study locations in Bering Land Bridge National Preserve and Cape Krusenstern National Monument. Researchers are concerned that impacts to buried cultural material resulting from changing permafrost in the region is worse than originally expected and is likely accelerating to a point or irreparable damage or loss. In the coming years, NPS staff at these Western Arctic Parklands will collaborate with Cornell to support ongoing research to further develop an understanding of the extent of permafrost loss and its impact upon buried cultural features at these sites. Several additional study locations will be established to monitor seasonal (early summer and early fall) and annual permafrost depths and to quantify the rates and levels of permafrost change. Many of the subject sites have already indicated signs of impacts to buried cultural resources resulting from changing permafrost (Junge 2022). The goals of the project will be to develop a management plan for archeological resources located in areas where permafrost is changing and to develop measures to mitigate effects.

Denali National Park and Preserve

As in other parks in Alaska and the lower-48, archeologists at Denali have observed artifacts that have likely eroded out of permafrost or ice patches due to overall warming. As these frozen contexts melt, we risk the permanent loss of highly significant artifacts, such as these organic tools (pictured below), believed to be around 1,000 years old (Gilbert 2022). The top artifact was found floating in a river and the bottom one was found in a high mountain pass. It was extremely fortunate that they were observed and collected as they have the potential to inform us about past human behavior in the region. When artifacts like this are found in this manner, we've already lost the most significant archeological data, which is the context in which the artifact was originally located.

Undated bone and antler arrow shafts found in Denali National Park and Preserve. They most likely melted out of an ice patch. Ice patches often protect cultural artifacts and keep them from exposure and degradation, that is, until the ice patches melt.
NPS/PHOEBE GILBERT

Another highly publicized issue in Denali, which has caused an enormous impact on visitor use, the natural environment, and to cultural resources in the vicinity, is the Pretty Rocks Landslide. This epic landslide intersects the Denali Park Road at Mile 45.4. It has completely covered a 90 m-long stretch of the road and caused the park to close road access to the park past Mile 43 at least through the summer of 2024. As stated by NPS:

> *The Pretty Rocks landslide has been active since at least the 1960s, and probably since well before the Denali Park Road was built through this area in 1930. Before 2014, the landslide only caused small cracks in the road surface and required moderate maintenance every 2–3 years. Prior to 2014, road maintenance crews noticed a substantial speed up. By 2016 the movement had increased further, a slump had developed in the road, and a monitoring program was begun. The rate of road movement within the landslide evolved from inches per year prior to 2014, to inches per month in 2017, inches per week in 2018, inches per day in 2019, and up to 0.65 inches per hour in 2021.*

Based on climate data from 1950 to 2010, Denali has experienced an overall average temperature increase of more than 7°F, which is the highest of all national parks.

The impacts of the Pretty Rocks Landslide to the visitor experience, as well as to the geology and other natural resources of the area are perhaps obvious. Less obvious however, is the impact of this and similar events to cultural resources. The Denali Park Road is a unique and highly significant linear cultural resource that is listed on the National Register of Historic

Places. At 92.5 miles long, it has served as the backbone of the park's circulation system since construction began in 1922. It is historically significant for its association with the period of scenic road development in national parks in the 1920s and 1930s, and with the Mission 66 park development program in the 1950s and 1960s. The road is also a rustic example of landscape engineering combining NPS aesthetic road design principles with the Alaska Road Commission's experience constructing roads in harsh environments.

Dramatic and monumental events like the Pretty Rocks landslide have an enormous effect on the places that make up historic and cultural fabric of our parks. In this instance, the landslide has resulted in irreversible damage to the integrity of the historic Denali Park Road.

Heritage Assistance Program

The Heritage Assistance Program within the Cultural Resources Program at the Alaska Regional Office allows for NPS staff to provide technical support and assistance on projects outside of parks, often in collaboration with communities and partners. A group of concerned individuals and organizations, including NPS, have been monitoring the condition and integrity of the Ascension of Our Lord Church in Karluk, Alaska since at least 2002 when a non-profit organization called Russian Orthodox Sacred Sites of Alaska (ROSSIA) was formed to maintain and preserve the portfolio of historic orthodox churches in Alaska. The bluff upon which the Karluk church was constructed has been eroding rapidly for decades.

The church was built in 1888. The churchyard also contains associated outlying structures, archeological remains associated with the 6,000+ year occupation of the area, and the community cemetery. In March of 2020, the partners monitoring the church, including the community of Karluk, ROSSIA, NPS, and others, realized that the situation had become dire. A huge consortium of partners and supporters joined forces to save the church, and in August of 2021, the church building was physically moved approximately 80 feet inland, away from the bluff edge (duVall 2021).

As technical support partners on the effort, NPS has provided guidance to the community and ROSSIA on site planning, architectural documentation, and historic preservation, as well as archeological monitoring during the move to ensure no disturbance to burials or other cultural deposits located on the church grounds. We continue to support the project partners as they work to identify a new, permanent location for the church and community cemetery.

The Ascension of Our Lord Church, listed on the National Register of Historic Places, was in danger of falling into the Karluk River where it meets Shelikof Strait. It was moved inland to save it.
NPS/DUSTIN REFT

Klondike Gold Rush National Historical Park

At Klondike Gold Rush National Historical Park, park archeologists are collaborating with community and Tribal cultural resource specialists at the Skagway Traditional Council to swiftly but methodically complete emergency salvage excavation at the historic Townsite of Dyea. A hallmark site that contributes greatly to the significance of the Chilkoot Trail and Dyea National Historic Landmark (NHL), this once-booming gold rush townsite (1897-1898) is threatened by erosion caused by severe flooding and aggressive course changes along the Taiya River since it was largely abandoned in the early 1900s. The townsite and vicinity are also the traditional homelands of the Chilkoot and Chilkat Tlingit, who call the area *Skaqua* or *Shgagwéi*, which means a windy place with "white caps on the water" (Brady 2013).

Within the last couple of years, the cutbank bordering the north edge of Dyea began to erode at a rate exponentially faster than at any time since the townsite was occupied. In 2021, 125 linear feet and 64,000 square feet of land was lost to the river. In 2022, an additional 235 linear feet and over 97,000 square feet of land was lost. It is conservatively anticipated that the park will lose an additional 125-150 linear feet in 2023. By comparison, prior to 2021, the average annual cutbank loss was 66 linear feet per year. To demonstrate the pace of loss, during active data recovery in the 2022 field season, 1x2 meter excavation units were obliterated by the unceasing cutbank loss within days of having been dug.

In addition to the accelerated efforts to recover archeological data at the Dyea Townsite, relentless flooding is severely and adversely affecting known and as-yet undocumented cultural resources as well as modern park infrastructure all along the Chilkoot Trail. The current Taiya River flooding and channel migrations are a result of:

1. an increase in overall discharge related to climate change (higher precipitation as well as glacial melt),
2. the shift of a braided channel system into a single powerful channel (related to reforestation post-gold rush as well as climate change), and
3. bank modifications in the lower reaches (namely the bank armoring the dike at Taiya River bridge).

Excavation units were washed away by the raging Taiya River, eroding away irreplaceable cultural artifacts and context.
NPS/SHINA DUVALL

Lake Clark National Park and Preserve

Archeologists and cultural resource staff at Lake Clark National Park and Preserve are working to document the Clam Cove Pictograph Site, which is one of only two pictograph sites in Lake Clark (Baird et al. 2022). The Clam Cove site was listed on the National Register of Historic Places in 2017.

Archeological research and Carbon-14 dates obtained from organic artifacts collected from the site in the late 1960s suggests a late Holocene occupation at the site (c. 1,700 radiocarbon years ago; Baird et al. 2022). The pictographs consist of anthropomorphic body shapes, zoomorphic images (mainly sea mammals), boats, and abstract markings. The pictograph site is presently threatened by generally warmer temperatures in the region, which is causing increased water runoff, increased vegetation growth in the immediate vicinity of the site, spalling of the rock face, increased lichen growth on the surface, and water percolating directly through the sandstone substrate of the rock upon which the pictographs are located. The stressors present at the site, which are a direct result of climate change effects, have been quantified over the past 15^{+} years by park staff through both anecdotal and photographic evidence.

Although park staff can do little to ameliorate conditions or mitigate the threats at the site, a conservation plan was developed for the site (Shah 2006), and the park continues to document existing conditions and the ongoing changes at the site, while also keeping Tribal groups and gateway communities informed of the site conditions.

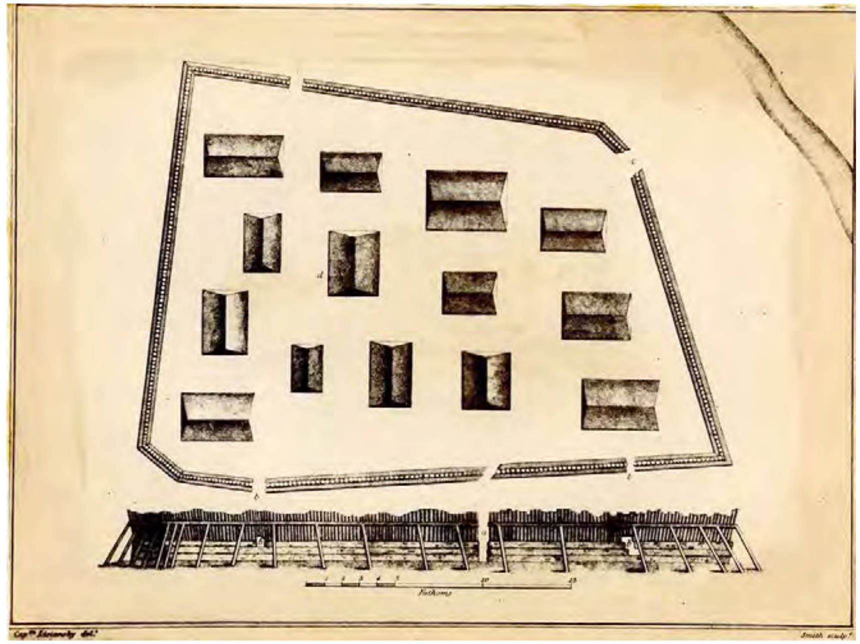
A warming climate that brings more rain can damage pictographs. On the left, surface runoff, lichen, and vegetation growth are eroding and obscuring the pictographs. On the right, weather conditions have caused spalling and exfoliation of the rock surface.
NPS/JASON ROGERS

Sitka National Historical Park

The Kiks.ádi Fort Site, or *Shís'gi Noow*, is the location of the Battle of 1804, a "watershed moment in the history of Alaska and Russian America" (Hope 2008). Named for the most powerful of the Sitka Tlingit clan houses, the Kiks.ádi successfully fought off a Russian advance on the territory at this location. The Fort Site is also directly associated with the Survival March, which resulted in the loss of land, homes, possessions, and clan regalia by the Kiks.ádi Tlingit and caused them to remain away from their home for 18 years.

The Kiks.ádi Fort Site and Battleground has been archeologically documented intermittently over the years since the park was established, but a current project is underway to confirm past survey findings in order to more confidently affirm the exact location of the fort walls. This effort is critical now as the fort site is threatened by erosion and an existing revetment repair project is planned at the site.

The Kiks.ádi Fort Site and battleground has been protected from erosion by a riprap revetment since 1985, when it was determined that the natural course of the Indian River would continue to erode at a rate of 3-6 meters per year, destroying the historic cultural landscape (Perkins 2022). The revetment remained undamaged until a huge rain event in 2015, which raised the river level significantly above flood levels and caused substantial damage to the revetment. Extreme increases in rainfall and extraordinary precipitation events are significant climate stressors in the region. Park staff plan to completely reconstruct approximately 150 feet of the revetment along the river. The Park continues to consult with the Sitka Tribe of Alaska and other potential consulting parties regarding the design and implementation of the project, which is scheduled to be completed in 2027.



Map of the Sitka Fort, drawn by Lisiansky in 1814.
NPS

Alaska's Cultural Heritage Challenges Going Forward

Despite the commendable work that is occurring now at parks in Alaska, considerable obstacles and deficiencies persist that prohibit us from assuming a greater lead in areas of assessment, treatment, and adaptive response to climate impacts on our cultural heritage.

To get out ahead of the changes we are experiencing in the region—to be proactive instead of reactive—our needs are numerous. And they must be coordinated with other regions and at the service-wide level to be effective. We simply cannot accomplish meaningful progress —which is difficult in and of itself to define given the rate and extent of change—without a wholesale commitment of resources and energy toward these ends: partner engagement and collaboration, condition and vulnerability assessments, prioritization of needs, resource documentation, and where necessary, mitigation of loss.

To complete this work in Alaska, we need to be able to access remote field locations where limited to no road access is available. This means travel via helicopter, small plane, or by watercraft. We must continue and build upon existing climate futures planning efforts to anticipate and visualize response, build resiliency, and maintain continuity of operations in the face of increasing and overlapping climate stressors and threats. We desperately need improved spatial modeling, data management, and digitization tools that allow us to conduct robust risk analysis and ranking of need, both in the field and within our collections. In collections and facilities, we need improved and more routine emergency response and evacuation training, including inter- and intra-regional disaster response and recovery solutions for cultural resources staff. We need to integrate even more closely with our community and Tribal partners, as well as our NPS colleagues in subsistence, natural resources, law enforcement, environmental planning and compliance, interpretation and education, and other departments to move forward toward shared goals, and to generate meaningful outcomes in collaboration and co-stewardship. Sadly, we must also learn together when and where it will be necessary to accept the inevitability of loss.

We are not just cultural heritage professionals. We are also residents and responsible caretakers of this place which is steeped in extraordinary history and culture. We care deeply about the places and cultural practices that together form the fabric of this unique state. As we face the enormous test that is climate change in the 21st century, may we keep in mind the words of Katie John (1915-2013), a beloved Ahtna Athabascan Elder and champion of Alaska Native rights:

I don't know if any of us really know what we are capable of until it comes to it.

—Katie M. John

REFERENCES

Amos, J. January 3, 2018.
Alaskan infant's DNA tells story of 'first Americans.' Available at: Alaskan infant's DNA tells story of 'first Americans' - BBC News (accessed June 2023)

Aquino, L. October 28, 2022.
Community Archeology Helps Bridge Gap Between Science and Tradition. Available at: Community Archeology Helps Bridge Gap Between Science and Tradition | Smithsonian Voices | National Museum of Natural History Smithsonian Magazine (accessed June 2023)

Baird, M. F., M. L. Moss, S. Perrot-Minnot, and J. Rogers. 2022.
The Archaeology of Clam Cove, Lake Clark National Park and Preserve, Southcentral Alaska. Alaska Journal of Anthropology 20(1-2): 85-102.

Brady, J. 2013.
Skagway: City of the New Century. Lynn Canal Publishing.

Braje, T. E. Elliott Smith, J. Meling, and T. Rick. 2023.
Can archaeology help restore the oceans? Sapiens. Available at: https://www.sapiens.org/archaeology/archaeology-sustainability-channel-islands/ (accessed August 30, 2023)

duVall, Shina. 2021.
How We Rescued the Ascension of Our Lord Church in Karluk, Alaska, from Falling off a Cliff. Park Science 35(1).

Gilbert, P. November 2022.
Presentation to NPS Alaska Cultural Resources Advisory Committee on ongoing projects in Denali National Park & Preserve.

Haaland, D. 2021.
Department-Wide Approach to the Climate Crisis and Restoring Transparency and Integrity to the Decision-Making Process. Secretarial Order 3399. Available at: SO 3399 Climate Crisis Transparency and Integrity to Decision-Making Processes (doi.gov) (accessed June 2023).

Holtz, D., A. Markham, K. Cell, and B. Ekwurzel. 2014.
Native Villages and Ancestral Lands in Alaska Face Rapid Coastal Erosion. Pages 47-49 in National Landmarks at Risk: How Rising Seas, Floods, and Wildfires Are Threatening the United States' Most Cherished Historic Sites. Union of Concerned Scientists.

Hope, H. 2008.
The Kiks.ádi Survival March of 1804. Pages 273-285 in N. Marks Dauenhauer, R. Dauenhauer, and L. T. Black, eds. Anóoshi Lingít Aaní Ká/Russians in Tlingit America: The Battles of Sitka, 1802 and 1804. Seattle: University of Washington Press.

Junge, J. November 2022.
Presentation to NPS Alaska Cultural Resources Advisory Committee on ongoing projects in Bering Land Bridge National Preserve and Cape Krusenstern National Monument.

Keats, J. February 8, 2021.
How Indigenous Oral Tradition Is Guiding Archaeology and Uncovering Climate History in Alaska. Available at: How Indigenous Oral Tradition Is Guiding Archaeology and Uncovering Climate History in Alaska | Discover Magazine (accessed June 2023).

Llanos, M. July 6, 2007.
Alaska, the first frontier for warming in U.S. Available at: Alaska, the first frontier for warming in U.S. (nbcnews.com) (accessed June 2023).

Nicholas, G. February 21, 2018.
When Scientists "Discover" What Indigenous People Have Known For Centuries. Available at: When Scientists "Discover" What Indigenous People Have Known For Centuries | Science| Smithsonian Magazine (accessed June 2023).

Perkins, J. November 2022.
Presentation to NPS Alaska Cultural Resources Advisory Committee on ongoing projects in Sitka National Historical Park.

Rockman, M., M. Morgan, S. Ziaja, G. Hambrecht, and A. Meadow. 2016.
Cultural Resources Climate Change Strategy. Washington, DC: Cultural Resources, Partnerships, and Science and Climate Change Response Program, National Park Service.

Sams III, C. F. 2022.
Statement of Charles F. Sams III Director, National Park Service, U.S. Department of the Interior Before the Subcommittee on Interior, Environment, and Related Agencies of the Committee on Appropriations, U.S. House of Representatives. May 18, 2022. Available at: HHRG-117-AP06-Wstate-SamsC-20220518.pdf (house.gov) (accessed June 2023).

Scheidel, Arnim, et al. 2023.
Global impacts of extractive and industrial development projects on Indigenous Peoples' lifeways, lands, and rights. Science Advances 9(3): eade9557.

Shah, M. 2006.
Preservation Plan for Tuxedni Bay and Clam Cove Pictograph Sites, Lake Clark National Park and Preserve. Report on file at the National Park Service / Lake Clark National Park and Preserve, Alaska Association for Historic Preservation, Anchorage.

Stoddart, M., J. Cherner, and D. Dwyer. 2021.
Haaland embraces 'indigenous knowledge' in confronting historic climate change impacts. Available at: Haaland embraces 'indigenous knowledge' in confronting historic climate change impacts - ABC News (go.com) (accessed June 2023).

Taylor, W. and Y. Running Horse Collin. March 30, 2023.
Archaeology and genomics together with Indigenous knowledge revise the human-horse story in the American West. Available at: Archaeology and genomics together with Indigenous knowledge revise the human-horse story in the American West (theconversation.com) (accessed June 2023).

Thoman, R. and J. E. Walsh. 2019.
Alaska's changing environment: Documenting Alaska's physical and biological changes through observations. H. R. McFarland, Ed. International Arctic Research Center, University of Alaska Fairbanks.

United Nations Department of Economic and Social Affairs. n.d.
Statement on the effects of climate change on Indigenous peoples. Available at: Climate Change | United Nations For Indigenous Peoples) (accessed June 2023).

U.S. Global Climate Research Program (USGCRP). 2017.
Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D. J., D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, eds.]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp.

SELECT CRITICAL READING

Daly, C. 2014.
A Framework for Assessing the Vulnerability of Archaeological Sites to Climate Change: Theory, Development, and Application. Conservation and Management of Archaeological Sites 16(3): 268-282.

Dawson, T., C. Nimura, E. López-Romero, and M. Daire, eds. 2017.
Public Archaeology and Climate Change, 1st edition. Oxbow Books, United Kingdom. 208 pp.

Jarvis, J. B. 2014.
Policy Memorandum 14-02, Climate Change and Stewardship of Cultural Resources. National Park Service. Available at: https://www.nps.gov/policy/PolMemos/PM-14-02.htm (accessed June 2023)

National Park Service. 2010.
National Park Service Climate Change Response Strategy. National Park Service Climate Change Response Program, Fort Collins, Colorado.

Wright, J. P. and Morris Hylton III. 2022.
Plan the work, work the plan: An introduction to the National Park Service Climate, Science, and Disaster Response Program. Parks Stewardship Forum 38(3): 389-411.

Xiao, X., P. Li, and E. Seekamp. 2023.
Sustainable adaptation planning for cultural heritage in coastal tourism destinations under climate change: A mixed-paradigm of preservation and conservation optimization. Journal of Tourism Research.

At Kennecott Mines National Historic Site, people who lived in the village when the mine was active couldn't see across the valley because the Kennicott Glacier blocked their view with a wall of ice. Now the rocky terminal moraine blends in with the river valley and you have to hike a mile out of town to reach exposed glacier ice. What will it be like in another 100 years?
NPS/KEN HILL

RESEARCH REVIEW

Alaska's Changing Vegetation Processes and Patterns: Plant Responses to Unprecedented Levels of Warming in the Far North

Carl Roland, National Park Service

Climate is a fundamental driver of the character, structure, and distribution of plant communities in the Far North. Periodic and massive change is deeply woven into the fabric of Alaska's ecosystems, which have been subject to repeated, dramatic shifts precipitated by disturbance and changing climatic conditions, among other drivers. We are just starting to see the earliest results of a huge experiment playing out on northern ecosystems.

Citation:
Roland, C. 2023. Alaska's changing vegetation processes and patterns: Plant responses to unprecedented levels of warming in the Far North. *Alaska Park Science* 22(1): 34-47.

In one sense, the vegetation of Alaska is in a constant state of flux, with the individual plants that make up familiar vegetation types that we see while traversing Alaska's landscapes (e.g., forest, tundra, meadows) all busy with the processes of establishment, growth, reproduction, senescence, and decay, with each plant constantly responding to its environment during the growing season. In another sense, there is considerable stability in Alaska's hardy vegetation. We can recognize clear, repeating patterns that reflect the varying conditions (including temperature, precipitation, solar energy, drainage, soil factors, and disturbance, among others) that influence the structure of plant communities discernible as we move through these northern landscapes.

For example, while traversing a river valley in Alaska, adjacent to each stream you will find open, gravelly soils deposited by flowing water and dotted with scattered colonizing plants including legumes. These open areas give way to a lining of willow thickets and then successively grade into stands of poplars, and then into spruce forest in places that have not been disturbed by flowing water in many decades. Similarly, as you ascend a mountainside from the forested lowlands, you soon emerge from under the forest canopy into shrubby treeline areas where shorter seasons, cold temperatures, and thin soils may inhibit the growth of trees thereby allowing more space and light so that smaller members of the plant kingdom can thrive there. Ultimately, if you climb high enough, you will traverse low tundra with its scattered cushion plants, mosses, lichens, and dwarfed plant species to reach the outer limits of plant growth in these cold, rocky high alpine areas. There are occasional splashes of green—the small alpine plants adapted to harsh conditions nestled among the slide rock and snow patches that dominate Alaska's high mountain landscapes. These sorts of clear, reliable, and repeating structural patterns in the vegetation all reflect the strong control of plants by their environment in high-latitude areas such as Alaska.

A Brief Ecological History of Alaska

On a different timescale altogether, the science of paleoecology (which is concerned with the dynamics of ecological history going back thousands of years) gives us insights into another realm of stability and change—the massive ecological perturbations associated with the repeated epochs of advance and retreat of continental-scale sheets of ice hundreds of meters thick in Alaska: the ice ages! During the cold-phase periods of the Pleistocene Epoch, when Earth's climate cooled, the accumulation of large snowpacks that failed to melt fully each summer steadily built gargantuan ice sheets that

Looking north to Kankone Peak, a shrubline-tundra ecotone, Denali National Park and Preserve. Since 2001 (or 1992 in Denali), more than 2,250 monitoring plots have been installed across three parks and almost 40 peer-reviewed journal articles published.
NPS/CARL ROLAND

isolated Alaska from the rest of North America (what is now Canada was fully blanketed by glacial ice). At the same time, a good portion of Earth's water was tied up in ice sheets in Earth's high latitudes and mountains, which drew down sea levels, and consequently exposed many land bridges around the world. This is how the shallow continental shelf between Alaska and northeastern Asia (the Bering platform) was exposed and became the Bering Land Bridge creating Beringia—a large terrestrial ecosystem occupying areas formerly lying beneath the waves and adjacent areas of North America and Asia (Hopkins 1982).

During periodic glacial advances, forests and associated boreal woody vegetation types mostly vanished from Alaska's landscapes (Matthews 1982, Edwards et al. 2000, Blinnikov et al. 2011), replaced by an open vegetation mosaic that included steppe-tundra, tundra, meadows, and shrublands in tune with the prevailing cooler, drier climatic conditions of the era. Ice-age eastern Beringia (what is now Alaska) was a refuge for biota surrounded by massive ice sheets to the south and east and the Bering Land Bridge to the west northward to the Arctic Ocean, which had receded toward the pole with the falling sea levels. The huge amounts of silt and other sediments ground up and transported by the icefields was another prominent feature of Alaska's ice-age landscape—deep blankets of silt were deposited by running water and the fierce winds that blew across the open, treeless landscapes far from any ocean. Periodically, as the climate warmed again, the glaciers and ice fields once again shrank, revealing newly exposed and deeply gouged, barren landscapes as the copious meltwaters flowed down to the sea to refill the ocean basins and again flood the Bering platform and other land bridges as warmer and wetter inter-glacial conditions returned to the Far North.

In addition to shrinking the glaciers, conditions in these relatively warm and wet interglacial periods also prompted the expansion of trees and shrubs across the landscape of Alaska as boreal forest and other taller-statured woody vegetation types formerly confined south of the icesheets migrated in and displaced the relatively open and low plant communities characteristic of the ice age intervals in Beringia (Matthews 1982, Edwards et al. 2000, Blinnikov et al. 2011). Thus, the recognizable and widespread boreal forests that we now experience as Alaska's vegetation are, in reality, relative newcomers that were mostly absent from these landscapes prior to the onset of our current interglacial period, the Holocene, starting about 12,000 years ago.

Beringia during the last glacial maximum when Asia and North America were connected by the Bering Land Bridge.
NPS MAP

A brief consideration of the ecological history of what is now Alaska yields two clear conclusions. The first is that climate is an overarching and fundamental driver of the character, structure, and distribution of plant communities in the Far North. Secondly, periodic and massive change is deeply woven into the fabric of Alaskan ecosystems, which have been subject to repeated, dramatic shifts precipitated by disturbance and changing climatic conditions, among other drivers.

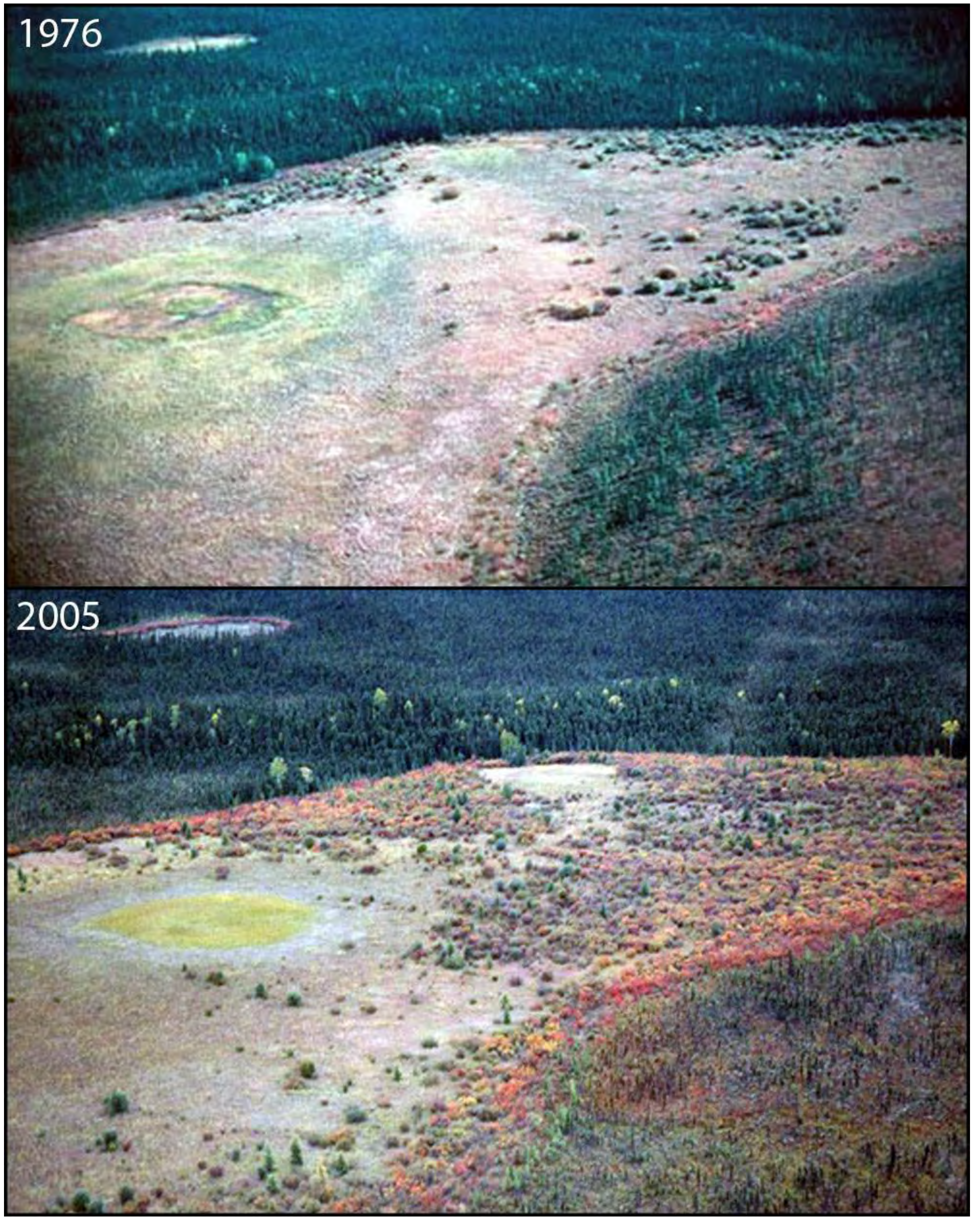
A Time of Unprecedented Change

The climate of Alaska is changing very rapidly. Startling levels of warming are being driven primarily by heat-trapping gases released by processes associated with industrialized human activities, which are predicted to intensify in coming decades (Box et al. 2019, Ballinger and Overland 2022). Based on what we know of Alaska's ecosystems, it is likely that rapid warming and the associated changes in various atmospheric properties and processes (including humidity, precipitation, windiness, and other dynamics that directly affect biota) will have profound consequences for all life that resides here. Indeed, given the precipitous current rate of climate change, it seems increasingly likely that the transformations occurring in our lifetimes may render much of Alaska almost unrecognizable to us in what is, geologically speaking, the blink of an eye. Indeed, it seems likely that for many species of animals and plants, dependent solely on the legacy of their adaptations to heretofore 'normal' local conditions and relatively predictable (in both space and time) variation in the ecosystems of the Far North will face many arduous and difficult circumstances trying to cope with the unprecedented cascading changes that may be precipitated by rapid climate change. At the same time, some species (especially those with ranges extending to more southerly regions) may thrive in the new and unfamiliar warmed conditions spreading across the region.

There are a variety of ways to evaluate and categorize the types of changes that occur in ecosystems that help us to understand the biological significance and ramifications of such change. One useful way to do this is to distinguish process-related changes in an ecosystem (those that primarily occur in the moment in response to stimuli) from changes that are related to alterations in the structure or composition of the ecosystem (which usually integrate changes happening over longer intervals, such as a site changing from tundra to a forested condition). An easy way to think about this is that process-related changes are equivalent to individual plants and populations responding to weather events—for example, how warm or wet or sunny it is today or over this growing season. In contrast, structural changes in plant communities generally reflect modifications in response to climate—the prevailing norms such as long-term averages and extremes experienced at a site. These structural changes in ecosystems also most often reflect changes on the part of multiple interacting sets of organisms. In other words, one hot day or even a particularly warm summer will not convert tundra into forest, but a span of 50 summers with increasing warming combined with the availability of tree seeds, may do so.

While process-related and structural changes are closely inter-related (and not mutually exclusive) this framing does offer a useful template for us to think about how unprecedented warming is exerting various and transformative pressures on Alaska's plant life. Some examples of important plant processes include phenology (the timing of biological events such as green-up in the spring), the rate and manner of uptake of water and nutrients, rates of vegetative growth, reproductive effort (the production of flowers and fruits, etc…), the effects of plant-eating insects on growth and development, and the germination and establishment of seedlings and related processes. These are processes that may be affected in a continuous way, as temperature, available moisture, or incident light changes through the course of a day or a growing season continuously affects the instantaneous rates of growth and respiration of plants, for example.

Structural or compositional changes in an ecosystem are transformations that involve changes in the species or growth forms of the organisms that make up a plant community. Such changes often result in very different spatial arrangements of the biomass in an ecosystem. For example, forested areas are structurally complex and have biomass arranged in multiple vertical layers (ground-level, sub-canopy, tree canopy), including high above the soil surface, whereas tundra areas are structurally simpler and all plant tissues occur quite close to the ground. For obvious reasons, then, structural changes usually require longer intervals of time to occur as (for example) one set of organisms replace another in response to altered conditions. Changes in plant process and function in the moment, if sufficiently pronounced and long term, will ultimately lead to changes in the structure and composition of plant communities. For example, if photosynthesis in a single spruce tree shuts down during a warm and dry afternoon, that is a



As wetlands dry, they will gradually be taken over by new assemblages of (non-wetland) plant species. The area shown here was once a shallow lake, which was colonized by a sedge wetland as it dried, and is now rapidly being colonized by trees and shrubs with further drying. This is an example of a gradual ecosystem process change that is dramatically altering vegetation structure of the site.
NPS/CARL ROLAND

transitory change that occurs in the moment and is physiological in nature. If this circumstance repeats itself over long periods of time and in many trees over large areas of the landscape, resulting in reduced wood production, then over time this will ultimately result in structural changes to the vegetation (reduced biomass of spruce). The distinction between the two types of change, then, is a matter of temporal and spatial scale of a change dynamic.

An example of this dynamic that is directly relevant to Alaska is the process of wetland conversion. In this process, plants growing within a formerly submerged, but gradually drying wetland will suffer increasing drought stress and will thus grow and reproduce more slowly. Over time, seedlings of wetland plants will not be able to establish in periodically dry conditions, and gradually as members of these species perish due to altered conditions, they will be replaced by more drought-tolerant species that had previously been excluded from the site by their inability to establish or grow in saturated soils or standing water, thus eventually completing the transformation of the vegetation structure of the site over time. Ultimately, this process can inexorably lead to the transition of herbaceous sedge-dominated wetlands comprised of plants adapted to growing in saturated substrates into a shrub or tree-dominated woody terrestrial plant community with plants adapted to well-drained soils that periodically dry out. Such a transformation would represent an important structural change in the vegetation mosaic with many consequences for other members of the ecosystem, likely precipitating a transformation in the animal communities inhabiting the site. For example, insects, birds, and other animal species that nest among open wetlands or subsist upon herbaceous wetland plants for their diets likely do not also use shady, well-drained forested habitats or consume woody shrub plant tissues as a regular part of their diet.

While most process-related changes in plant function require sustained time periods to affect ecosystem structure and composition, major disturbances are an example of processes that frequently have immediate and important structural implications for vegetation patterns. For example, when a crown fire consumes a forested site and eliminates the vegetation, leaving behind an ashy plain, or when floodwaters erode away an intact stand of vegetation, replacing the plant community with newly deposited barren silt and gravel. Similarly, the catastrophic draining of a lake due to permafrost thaw, which is a phenomenon being observed repeatedly in Alaska of late (Swanson 2019) may result in a much faster conversion of lakeshore strand wetlands to upland vegetation than gradual drying related to increased evapotranspiration.

A survey of the recent ecological literature reveals that Alaska's vegetation is already responding in myriad ways to our changing climate with profound consequences for resident biota. There is copious evidence for both process-related and structural changes being manifested with important and lasting implications for both humans and Alaska's ecosystems. I discuss a selection of some of the most important changes that have been observed below, organized in terms of the two types of change—process-related or functional change, and change manifested by altered structure or composition of Alaskan plant communities.

Longer and warmer growing seasons are stimulating myriad changes in vegetation patterns, including the expansion of trees and shrubs into tundra areas.
NPS/CARL ROLAND

Examples of process- and disturbance-related dynamics relating to climate change that have been observed and published for Alaska:

1. Researchers have documented geographically variable trends in Normalized Difference Vegetation Index (the relative greenness of the vegetation in summer associated with varying levels of annual productivity) across Alaska with some areas in colder and/or moister regions of the state showing trends of increasing summer greenness (reflecting greater productivity with warming) and some warmer, drier regions showing a "browning" trend over time related to heat and drought stressors on plant life (Jia et al. 2003, 2006, Verbyla 2008, Beck and Goetz 2011, Epstein et al. 2012, Pastick et al. 2018);

2. Researchers have shown that changes in vegetation phenology have been observed at very large spatial scales, which include evidence of longer growing seasons that follow from earlier snowmelt and warmer early season temperatures (Potter and Alexander 2020, Chen et al. 2022, Zheng 2022);

3. Changes in reproductive effort and output of plants have been related to increasing productivity or changes in growing season conditions (for example, longer and warmer growing seasons (e.g., Roland et al. 2014, Barrett et al. 2015);

4. Ecological studies including many areas of Alaska have shown plant responses to warming soils and thawing permafrost with examples that include localized landscape "wetting" from ice-wedge degradation (Jorgenson et al. 2001, 2018) and effects of soil active layer depth and air temperature on tree growth (Nicklen et al. 2016, 2019, 2021);

5. In many areas of Alaska, there have been widespread or severe insect outbreaks that are likely enhanced by climate warming and have resulted in plant damage and mortality (see Berg et al. 2006, Verbyla 2008, Parent and Verbyla 2010, Wagner and Doak 2013, Cahoon et al. 2018);

6. Researchers have documented changes in the frequency and severity of fire disturbance over time in Alaska (Kasischke et al. 2010) as well as the consequences of these changes in generating novel post-fire successional trajectories and changes in forests (Hu et al. 2015, Johnstone et al. 2006 a,b, Johnstone et al. 2010, Shenoy et al. 2011).

7. Trends in annual tree growth in response to variations in temperature and precipitation over long spans of time as encoded in tree rings (e.g., Walker and Johnstone 2014, Sullivan et al. 2017, Nicklen et al. 2021) resulting in changes in tree productivity across the Alaskan landscape.

8. Changing seasonal dynamics relating to the timing and establishment of an insulating layer of snow in forested areas of Southeast Alaska due to changing winter precipitation regimes has left tree roots (such as those of yellow cedar) vulnerable to thaw-freeze events and in combination with multiple stressors relating to a changing climate, is causing substantial tree decline and mortality in the region (Hennon et al. 2012, Comeau and Daniels 2022).

Widespread and severe insect outbreaks have recently occurred across southcentral Alaska, enhanced by climate warming. Insect damage in forests and shrublands is likely to accelerate in the future in response to additional warming.
NPS/SARAH STEHN

Examples of warming-driven changes in vegetation structure and composition recorded in Alaska's ecosystems:

1. A group of Alaskan researchers recently published an extraordinary description of rapid northward expansion of white spruce trees into tundra in areas of northwestern Alaska in the journal Nature, which has major implications for the future (Dial et al. 2022). Far to the south, another group of Alaskan researchers showed that warming along the southern coastal region has driven a wave of spruce seedling establishment there as well (Miller et al. 2017);

2. Diverse studies from widely scattered locations across Alaska have documented the expansion of woody and other vegetation on floodplains and similar early successional environments (including recently deglaciated sites) resulting in conspicuous increases in the stature and density of vegetation and reducing the extent of these heretofore open areas of the landscape over recent decades (Klaar et al. 2015, Roland et al. 2016, Brodie et al. 2019, Pastick et al. 2018, Frost et al. 2023, Tape et al. 2016, Fryday and Dillman 2022);

3. Examinations of extensive-scale long-term patterns in the growth-form cover attributes of Alaska's vegetation using remotely sensed imagery have revealed a variety of changes occurring over time, including net increases in deciduous shrubs, evergreen shrubs, broadleaf trees, and conifer trees with concomitant decreases in moss, lichen, and graminoid cover, among others (e.g., Cornliessen 2001, Macander et al. 2022, Pastick et al. 2018, Bao et al. 2022),

Warming has been shown to be a driver of shrinking surface area of lakes and ponds. Alaska is becoming a much woodier place as lakes and ponds are being encroached upon or replaced by shrubs and trees.
NPS/CARL ROLAND

4. Researchers predict that one important consequence of increases in the amount of forested area burned and shrinking time intervals between fires associated with a warming boreal zone is the possible widespread conversion of areas that have long been dominated by coniferous species to deciduous woodlands and forest dominated by birch, aspen, and balsam poplar. These broadleaved species produce huge, easily dispersed seed crops that thrive in recently burned terrain, where these rapidly growing species can thrive in the relatively nutrient rich, warm soils after high-severity fires (Johnstone et al. 2006 a, b, 2010).

5. Another active area of research has focused on the spatial and temporal patterns of surface water fraction on the landscape of Alaska. This body of work

has identified warming as one driver of the shrinking surface area occupied by lakes and ponds in recent in parts of Alaska (Yoshikawa and Hinzman 2003, Roach et al. 2013, Rupp and Larsen 2022). Associated with shrinking of surface waters, the (perhaps related) drying of wetland areas has catalyzed invasions of herbaceous wetland areas by shrubs in parts of Alaska (Klein et al. 2006, Berg et al. 2009).

6. Researchers working in the Chugach Mountains and Kenai Mountains of Southcentral Alaska have found that tall shrubs are moving upslope into tundra at a faster rate than the treeline (Dial et al. 2015). Similar ecological dynamics of woody plants encroaching into tundra have been observed in other regions of Alaska as well, including the North Slope (Sturm et al. 2001) and areas of western Alaska (Terskaia et al. 2020) not to mention floodplains across large areas (Frost et al. 2023). Overall, Alaska has likely become a much woodier place over time as the climate has warmed, with many important consequences for the human cultures and animals that live here.

7. There are other, perhaps less dramatic, but still important changes that botanists have forecasted given the various processes related to the development of a warmer, woodier, and more fire-prone Alaskan landscape (Roland and Schmidt 2015, Roland et al. 2017, Roland et al. 2019, Roland et al. 2021). For example, we can expect the gradual displacement of many of the endemic plant species and wildflowers that are unique to eastern Beringia and neighboring areas by more widespread, larger boreal plant species that will likely outcompete the endemic flora in a changed northern world. These endemic species have persisted over millennia in this region and reflect the long-term evolution of Alaska's flora in relation to climate—they persist in areas with open vegetation, often very cold areas in high-elevation sites, refugees from the expanding woody vegetation types in the valleys below. While this change may not be as significant from an ecological point of view, in terms of changing bird and wildlife habitats or causing infrastructure issues for humans, it could represent another kind of loss—the further contracting of the superbly cold-adapted biota that has witnessed many changes over the millennia, including the comings and goings of vast icesheets across our northern homelands.

The cold-adapted ecosystems that have persisted over millennia in high-elevation sites are in danger of being replaced by boreal forest species as a warmer climate allows the spread of shrubs and other woody species.
NPS/CARL ROLAND

As the selection of examples I have described above reveals, the cumulative scope and scale of the changes described in the scientific literature thus far are a harbinger of profound alteration of Alaska's vegetation mosaic, especially given the strong likelihood that such changes will continue apace and even intensify in the future. However, the changes being observed are not evenly distributed across the landscape and certain areas, species, and plant communities are more or less sensitive to certain types of changes (e.g., Swanson 2015, Roland et al. 2016, Raiho et al. 2022). One source of resilience is that the dominant boreal forest species are, for the most part, quite widespread and occur over large gradients of climate and site conditions thus possessing relative wide ecological tolerances and plasticity to endure different sets of conditions. Additionally, site factors may also provide some resistance to rapid changes (Swanson 2015, Roland et al. 2016, Raiho et al. 2022), such as conditions associated with well-insulated and thus-far undisturbed permafrost being more resistant to observable structural vegetation change even over long spans of time. However, the redoubts where vegetation may be currently protected by the "inertia" afforded by substantial frozen ground and thus slower rates of change (Swanson 2015, Roland et al. 2016, Brodie et al. 2019) are not permanently protected given the current projections for disappearance of permafrost in large areas of Alaska in the coming decades (e.g., Panda 2014, Ballinger and Overland 2022).

One thing is certain, however, the vegetation changes instigated by a warming and changing climate will exert consequential and far-reaching influences on most of Alaska's biota including invertebrates, birds, mammals, and humans, among others. This is because plants form the energetic foundations of terrestrial ecosystems (they are the primary base of all food webs) and define the primary structural elements of habitat for most animal species. For example, the insect and avifauna of tundra and other open habitats differs markedly from that of neighboring spruce forests and while there are many moose traversing the boreal forested lowlands of Alaska, it is much rarer to find caribou in these dense, taller-statured vegetation types in any numbers (and vice versa). Indeed, most animals, and particularly herbivores, are creatures of particular habitats that are primarily defined jointly by vegetation and associated physical factors of the environment. For this reason, we can expect what are referred to as "cascading" ecological effects following from vegetation change. That is, there are second-, third-, and fourth-order effects that may be set in motion, some of which will be difficult, if not impossible, to predict with confidence.

One example of this kind of complicated and multilayered ecological interaction was recently demonstrated by a group of Alaskan researchers working on beaver ponds in far Northwestern Alaska (Tape et al. 2022). Using aerial images, they found that (consistent with Indigenous knowledge and local observations) a conspicuous proliferation of beaver ponds has occurred in this huge area during the period 1949 to 2019. In fact, they estimated it's likely that the construction of 10,000 beaver ponds in tundra-dominated areas has occurred in recent decades synchronously with the onset of considerable warming in the region, resulting in many and various downstream ecological consequences. This process may have a positive feedback element with warming as it is likely that the impounding of so much surface water by these ecosystem engineers is resulting in considerable thawing of permafrost as shallow surface waters absorb heat and transfer it to thawing submerged permafrost, thus releasing additional carbon into the atmosphere as peat and other organic sediments decompose as they thaw (Tape et al. 2018). While this study does not pinpoint the reasons for this apparent explosion in beaver distribution across the landscape, one likely contributing factor is the increasing availability of their preferred woody forage species, which are known to be expanding in response to rapid warming across these tundra regions. So, a warming world is prompting increased shrub growth, which, in turn, may be drawing in beavers whose engineering may be further exacerbating permafrost thaw and thus instigating further changes in a widening cascade of effects.

These ecological effects of humanity's warming of the global climate represent some of the initial results of a huge experiment from which we are likely only starting to witness the outcomes. The ultimate complexity and reach are likely beyond our current comprehension. For example, the scope and scale of just the few examples of how the vegetation is changing in Alaska that I have described above would have likely been unfathomable even to very experienced and knowledgeable ecologists working in the state just 50 years ago. Indeed, these are unprecedented changes happening at a speed and scale with no analog in our collective history. For a thinking person, a consideration of the changing ecological dynamics occurring in the Far North inevitably begs the question: *What further changes will befall Alaska in fifty years that we are currently unable to fathom, that will be wrought by this ongoing colossal and uncontrolled experiment?*

REFERENCES

Ballinger, T. K. and J. E. Overland. 2022. The Alaskan Arctic regime shift since 2017: A harbinger of years to come? Polar Science 32: 100841.

Barrett, R. T., R. D. Hollister, S. F. Oberbauer, and C. E. Tweedie. 2015. Arctic plant responses to changing abiotic factors in northern Alaska. American Journal of Botany 102(12): 2020-2031.

Bao, T., G. Jia, and X. Xu. 2022. Warming enhances dominance of vascular plants over cryptogams across northern wetlands. Global Change Biology 28(13): 4097-4109.

Beck, P. S. A. and S. J. Goetz. 2011. Satellite observations of high northern latitude vegetation productivity changes between 1982 and 2008: Ecological variability and regional differences. Environ. Res. Lett. 6: 045501.

Berg, E. E., J. D. Henry, C. L. Fustier, A. D. De Volder, and S. M. Matsuoka. 2006. Spruce beetle outbreaks in spruce forests on the western Kenai Peninsula, Alaska, and Luanne National Park and Reserve, Yukon Territory: relationships with summer temperature and regional differences in disturbance regimes. For. Ecol. Manage. 227: 219-232.

Berg, E. E., K. McDonnell Hillman, R. Dial, and A. DeRuwe. 2009. Recent woody invasion of wetlands on the Kenai Peninsula Lowlands, south-central Alaska: A major regime shift after 18,000 years of wet Sphagnum–sedge peat recruitment. Can. J. For. Res. 39: 2033-2046.

Blinnikov, M. S., B. V. Gaglioti, D. A. Walker, M. J. Wooller, and G. D. Zazula. 2011. Pleistocene graminoid-dominated ecosystems in the Arctic. Quaternary Science Reviews 30: 2906-2929.

Box, J., W. T. Colgan, T. R. Christensen, N. M. Schmidt, M. Lund, F. W. Parmentier, R. Brown, U. S. Bhatt, E. S. Euskirchen, V. E. Romanovsky, J. E. Walsh, J. E. Overland, M. Wang, R. W. Corell, W. N. Meier, B. Wouters, S. Mernild, J. Mard, J. Pawlak, and M. S. Olsen. 2019. Key indicators of Arctic climate change: 1971–2017. Environ. Res. Lett. 14: 045010.

Brodie, J. F., C. A. Roland, S. E. Stehn, and E. Smirnova. 2019. Variability in the expansion of trees and shrubs in boreal Alaska. Ecology 100: e02660.

Cahoon, S. M. P., P. F. Sullivan, A. H. Brownlee, R. R. Pattison, H. E. Andersen, K. Legner, and T. N. Hollingsworth. 2018. Contrasting drivers and trends of coniferous and deciduous tree growth in interior Alaska. Ecology 99: 1284-1295.

Chen, X., Y. Yang, and J. Du. 2022. Distribution and attribution of earlier start of the growing season over the Northern Hemisphere from 2001-2018. Remote Sens. 14: 2964.

Comeau, V. M. and L. D. Daniels. 2022. Multiple divergent patterns in yellow-cedar growth driven by anthropogenic climate change. Climatic Change 170: 22.

Cornelissen, J. H. C., T. V. Callaghan, J. M. Alatalo, A. Michelsen, E. Graglia, A. E. Hartly, D. S. Hik, S. E. Hobbie, M. C. Press, C. H. Robinson, G. H. R. Henry, G. R. Shaver, G. K. Phoenix, D. Gwynn Jones, S. Jonasson, F. S. Chapin III, U. Molau, C. Neill, J. A. Lee, J. M. Melillo, B. Sveinbornsson, and R. Aerts. 2001. Global change and arctic ecosystems: Is lichen decline a function of increases in vascular plant biomass? Journal of Ecology 89(6): 984-994.

Dial, R. J., T. S. Smeltz, P. F. Sullivan, C. L. Rinas, K. Timm, J. E. Geck, S. C. Tobin, T. S. Golden, and E. C. Berg. 2015. Shrub-line but not treeline advance matches climate velocity in montane ecosystems of south-central Alaska. Global Change Biology 22(5): 1841-1856.

Dial, R. J., C. T. Maher, R. E. Hewitt, and P. F. Sullivan. 2022. Sufficient conditions for rapid range expansion of a boreal conifer. Nature 608: 546-551.

Epstein, H. E., M. K. Raynolds, D. A. Walker, U. S. Bhatt, C. J. Tucker, and J. E. Pinzon. 2012. Dynamics of aboveground phytomass of the circumpolar arctic tundra over the past three decades. Environ. Res. Lett. 7: 015506.

Edwards, M. E., P. M. Anderson, L. B. Brubaker, T. A. Ager, A. A. Andreev, N. H. Bigelow, L. C. Cwynar, W. R. Eisner, S. P. Harrison, F. S. Hu, D. Jolly, A. V. Lozhkin, G. M. MacDonald, C. J. Mock, J. C. Ritchie, A. V. Sher, R. W. Spear, J. W. Williams, and G. Yu. 2000. Pollen-based biomes for Beringia 18,000, 6000 and 0 14C yr bp. Journal of Biogeography 27: 521-554.

Frost, G. F., C. A. Roland, and J. H. Schmidt. 2023. Dynamic disequilibrium: Recent widespread increases in vegetation cover on subarctic floodplains of Interior Alaska. Ecosphere 14(1): e4344.

Fryday, A. M. and K. L. Dillman. 2022.
A preliminary investigation of the lichen biota associated with recently deglaciated terrain in southeastern Alaska. Botany 100: 313-328.

Hennon, P. E., D. V. D'Amore, P. G. Schaberg, D. T. Wittwer, and C. S. Shanley. 2012.
Shifting climate, altered niche, and a dynamic conservation strategy for yellow-cedar in the North Pacific Coastal Rainforest. Bioscience 62: 147-158.

Hopkins, D. M. 1982.
Aspects of the paleogeography of the Bering Land Bridge during the late Pleistocene. pp. 3-28 In D. M. N. Hopkins, et al. (eds) Paleoecology of Beringia. Academic Press, New York, NY.

Hu, F. S., P. E. Higuera, P. Duffy, M. L. Chipman, A. V. Rocha, A. M. Young, R. Kelly, and M. C. Dietze. 2015.
Arctic tundra fires: Natural variability and responses to climate change Front. Ecol. Environ. 13: 369-377.

Jia, G. J., H. E. Epstein, and D. A. Walker. 2003.
Greening of Arctic Alaska, 1981-2001. Geophysical Research Letters 30: 2067.

Jia, G. J., H. E. Epstein, and D. A. Walker. 2006.
Spatial heterogeneity of tundra vegetation response to recent temperature changes. Global Change Biology 12: 42-55.

Johnstone, J. F. and F. S. Chapin III. 2006a.
Effects of soil burn severity on post-fire tree recruitment in boreal forest. Ecosystems 9: 14-31.

Johnstone, J. F. and F. S. Chapin III. 2006b.
Fire interval effects on successional trajectory in boreal forests of Northwest Canada. Ecosystems 9: 268-277.

Johnstone, J. F., F. S. Chapin III, T. N. Hollingsworth, M. C. Mack, V. Romanovsky, and M. Turetsky. 2010.
Fire, climate change, and forest resilience in interior Alaska. Canadian Journal of Forest Research 40: 1302-1312.

Jorgenson, M.T., C. H. Racine, J. C. Walters, and T. E. Osterkamp. 2001.
Permafrost degradation and ecological changes associated with a warming climate in central Alaska. Clim. Chang. 48: 551-579.

Jorgenson, J. C., M. T. Jorgenson, M. L. Boldenow, and K. M. Orndahl. 2018.
Landscape change detected over a half century in the Arctic National Wildlife Refuge using high-resolution aerial imagery. Remote Sens. 10(8): 1305.

Kasischke, E. S., D. L. Verbyla, T. S. Rupp, A. D. McGuire, K. A. Murphy, R. Jandt, J. L. Barnes, E. E. Hoy, P. A. Duffy, M. Calef, and M. R. Turetsky. 2010.
Alaska's changing fire regime—implications for the vulnerability of its Boreal forests. Canadian Journal of Forest Research 40: 1313-1324.

Klaar, M. J., C. Kidd, E. Malone, R. Bartlett, G. Pinay, F. S. Chapin, and A. Milner. 2015.
Vegetation succession in deglaciated landscapes: Implications for sediment and landscape stability. Earth Surface Processes and Landforms 40(8): 1088-1100.

Klein, E., E. E. Berg, and R. Dial. 2005.
Wetland drying and succession across the Kenai Peninsula Lowlands, south-central Alaska. Can. J. For. Res. 35: 1931.1941.

Macander, M. J., P. R. Nelson, T. W. Nawrocki, G. V. Frost, K. M. Orndahl, E. .C Palm, A. F. Well, and S. J. Goetz. 2022.
Time-series maps reveal widespread change in plant functional type cover across Arctic and boreal Alaska and Yukon. Environmental Research Letters 17: 054042.

Matthews, J. J. V. 1982.
East Beringia during late Wisconsin time: A review of the biotic evidence. pp. 307-326 In D. M. N. Hopkins, et al. (eds) Paleoecology of Beringia. Academic Press, New York, NY.

Miller, A., T. Wilson, R. Sherriff, and J. Walton, J. 2017.
Warming drives a front of white spruce establishment near western treeline, Alaska. Global Change Biology 23: 5509-5522.

Nicklen, E. F., C. A. Roland, R. A. Ruess, J. H. Schmidt, and A. H. Lloyd. 2016.
Local site conditions drive climate-growth responses of Picea mariana and Picea glauca in interior Alaska. Ecosphere 7: 1-17.

Nicklen, E. F., C. A. Roland, A. Z. Csank, M. Wilmking, R. W. Ruess, and L. A. Muldoon. 2019.
Stand basal area and solar radiation amplify white spruce climate sensitivity in interior Alaska: Evidence from carbon isotopes and tree rings. Global Change Biology 25(3): 911-926.

Nicklen, E. F., C. A. Roland, R. W. Ruess, T. Scharnweber, and M. Wilmking. 2021.
Divergent responses to permafrost and precipitation reveal mechanisms for the spatial variation of two sympatric spruce. Ecosphere 12(7): e03622.

Panda, S., S. Marchenko, and V. Romanovsky. 2014.
High-resolution permafrost modeling in Denali National Park and Preserve. Natural Resource Technical Report NPS/CAKN/NRTR–2014/858. National Park Service, Fort Collins, Colorado, USA.

Parent, M. B. and D. Verbyla. 2010.
The Browning of Alaska's Boreal Forest. Remote Sensing, 2 (12): 2729-2747.

Pastick, N. J., M. T. Jorgenson, S. J. Goetz, B. M. Jones, B. K. Wylie, B. J. Minsley, H. Genet, J. F. Knight, D. K. Swanson, and J. C. Jorgenson. 2018.
Spatiotemporal remote sensing of ecosystem change and causation across Alaska. Global Change Biology 25(3): 1171-1189.

Potter, C. and O. Alexander. 2020.
Changes in vegetation phenology and productivity in Alaska over the past two decades. Remote Sens.12 (10): 1546.

Raiho, A. M., H. R. Scharf, C. A. Roland, D. K. Swanson, S. E. Stehn, and M. B. Hooten. 2022.
Searching for refuge: A framework for identifying site factors conferring resistance to climate-driven vegetation change. Diversity and Distributions 28: 1-17.

Roach, J. K., B. Griffith, and D. Verbyla. 2013.
Landscape influences on climate-related lake shrinkage at high latitudes. Global Change Biology 19(7): 2276-84.

Roland, C. A., J. H. Schmidt, and J. F. Johnstone. 2014.
Climate sensitivity of reproduction in a mast-seeding boreal conifer across its distributional range from lowland to treeline forests. Oecologia 174: 665-677.

Roland, C. A. and J. H. Schmidt. 2015.
A diverse alpine species pool drives a "reversed" plant species richness-elevation relationship in interior Alaska. Journal of Biogeography 42: 738-750.

Roland, C. A., S. E. Stehn, J. H. Schmidt, and B. Houseman. 2016.
Proliferating poplars: the leading edge of landscape change in an Alaskan subalpine chronosequence. Ecosphere 7(7): e01398.

Roland, C. A., S. E. Stehn, and J. H. Schmidt. 2017.
Species richness of multiple functional groups peaks in alpine tundra in subarctic Alaska. Ecosphere 8: e01848.

Roland, C. A., G. Sadoti, E. F. Nicklen, S. A. McAfee, and S. E. Stehn. 2019.
A structural equation model linking past and present plant diversity in Alaska: a framework for evaluating future change. Ecosphere 10: e02832.

Roland, C. A., J. H. Schmidt, S. E. Stehn, C. Hampton-Miller, and E. F. Nicklen. 2021.
Borealization and its discontents: Drivers of regional variation in plant diversity across scales in interior Alaska. Ecosphere 12(5): e03485.

Rupp, D. L. and A. S. Larsen. 2022.
Surface water area in a changing climate: Differential responses of Alaska's subarctic lakes. PLOS Clim 1(6): e0000036.

Shenoy, A., J. F. Johnstone, E. S. Kasischke, and K. Kielland. 2011.
Persistent effects of fire severity on early successional forests in interior Alaska. Forest Ecology and Management 261: 381-390.

Sturm, M., C. Racine, and K. Tape. 2001.
Increasing shrub abundance in the Arctic. Nature 411: 546-547.

Sullivan, P. F., R. R. Pattison, A. H. Brownlee, S. M. P. Cahoon, and T. N. Hollingsworth. 2017.
Limited evidence of declining growth among moisture-limited black and white spruce in interior Alaska. Scientific Reports 7: 15344.

Swanson, D. K. 2015.
Environmental limits of tall shrubs in Alaska's Arctic national parks. PLoS One 10: e0138387.

Swanson, D. K. 2019.
Thermokarst and precipitation drive changes in the area of lakes and ponds in the National Parks of northwestern Alaska, 1984-2018. Arctic, Antarctic, and Alpine Research 51(1): 265-279.

Tape, K. D., D. D. Gustine, R. W. Ruess, L. G. Adams, and J. A. Clark. 2016.
Range expansion of moose in Arctic Alaska linked to warming and increased shrub habitat. PLoS One 11: e0152636.

Tape, K. D., B. M. Jones, C. D. Arp, I. Nitze, and G. Grosse. 2018.
Tundra be dammed: Beaver colonization of the Arctic. Glob. Change Biol. 24: 4478-88.

Tape, K. D., J. A. Clark, B. M. Jones, S. Kantner, B. V. Gaglioti, G. Grosse, and I. Nitze. 2022.
Expanding beaver pond distribution in Arctic Alaska, 1949 to 2019. Sci Rep 12(1): 7123.

Terskaia, A., R. J. Dial, and P. F. Sullivan. 2020.
Pathways of tundra encroachment by trees and tall shrubs in the western Brooks Range of Alaska. Ecography 43: 769-78.

Verbyla, D. 2008.
The greening and browning of Alaska based on 1982-2003 satellite data. Global Ecology and Biogeography 17: 547-555.

Wagner, D. and P. Doak. 2013.
Long-term impact of a leaf miner outbreak on the performance of quaking aspen. Canadian Journal of Forest Research 43(6): 563-569.

Walker, X. and J. F. Johnstone. 2014.
Widespread negative correlations between black spruce growth and temperature across topographic moisture gradients in the boreal forest. Environmental Research Letters 9: 064016.

Yoshikawa, K. and L. D. Hinzman. 2003.
Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska. Permafrost and Periglacial Processes 14(2): 151-60.

Zheng, J., G. Jia and X. Xu. 2022.
Earlier snowmelt predominates advanced spring vegetation green-up in Alaska. Agricultural and Forest Meteorology 315: 108828.

The NPS is actively engaged in monitoring and studying changes to park vegetation and other ecosystem components occurring over time across large spatial scales. The technician seen here is installing a permanent vegetation plot in a remote corner of the Ogilvie Mountains in Yukon-Charley Rivers National Preserve near the Alaska-Canada border that will be remeasured in future years to document any changes.
NPS/CARL ROLAND

RESEARCH REVIEW

What Happens When Northern Oceans Get Too Warm

Heather Coletti, Nina Chambers, Jamie Womble, and Chris Gabriele, National Park Service

Oceans have always been integral to the people inhabiting Alaska, driving culture and economics for thousands of years. Ecologically, productive northern oceans and seas provide abundant and commercially important fisheries and habitat for marine mammals, seabirds, shorebirds, and many other species. Recent marine heatwaves provide a window into what may happen to ocean life in a warming world.

Citation:
Coletti, H., N. Chambers, J. Womble, and C. Gabriele. 2023. What happens when northern oceans get too warm. *Alaska Park Science* 22(1): 48-55.

Alaska is surrounded on most of its border by oceans, with an estimated length of coastline likely exceeding 33,904 miles. These oceans have been integral to the lifeways of people for hundreds of generations. Ecologically, Alaska's productive northern oceans and seas provide abundant and commercially important fisheries and habitat for marine mammals (whales, polar bears, seals), seabirds, shorebirds, and many other species. In addition, much of Alaska's weather, exceeding over a thousand miles inland, is influenced by the ocean, including the severity of storm fronts, precipitation patterns, and rapid temperature flux.

Marine Heatwaves and How They Impact Ecosystem Components

Marine heatwaves are a consequence of changing ocean conditions and have increased globally in recent years (Gruber et al. 2021). They are abrupt, extreme events that are likely to occur more frequently and across larger areas than in the past due to a warming climate (Frölicher et al. 2018). In 2013, researchers noticed ocean temperatures were rising across the North Pacific Ocean, which represented the onset of a marine heatwave. The Pacific Marine Heatwave (PMH) persisted for more than three years and had profound and lasting effects on everything from phytoplankton to whale watching in Hawaii, to trawl fisheries in northern Alaska. It was the most impactful heatwave owing to its spatial extent, magnitude, and duration. For example, persistent high ocean temperatures of 5-11 degrees Fahrenheit (3-6 degrees Celsius) above average were recorded from Southern California to the Gulf of Alaska (Piatt et al. 2020, Bond et al. 2015).

Thanks to a suite of studies, informed by long-term monitoring and research conducted by scientists and resource managers at Alaska parks in collaboration with university and agency partners, we now have a better understanding of how marine food webs, fish, marine mammals, and seabirds responded to the profound changes during and after the heatwave. Climate projections predict more marine heatwaves, and questions persist as to how, when, and why species may (or may not) recover from these large-scale perturbations.

The Pelagic Food Web Response was Severe

When marine heatwaves occur in normally cold water off the coast of Alaska, primary productivity goes down.

Everything from small fish to seabirds to whales rely on plankton. Plankton is made up of phytoplankton (tiny plants that are the primary producers in the pelagic ecosystem) and zooplankton (small animals that can be primary consumers of phytoplankton). Zooplankton, such as copepods, were smaller and less

A murre carcass on a rocky beach. A massive seabird die-off occurred with the Pacific Marine Heatwave.
USGS/SARAH SCHOEN

nutritious during the heatwave. Certain species of copepods became more prevalent, and these warm-water species tended to be smaller and lipid-poor (less fatty) than the larger, lipid-rich (fattier) copepods generally found in cold water. This translates to lower-quality food for animals that feed on zooplankton (Arimitsu et al. 2021).

Forage fish populations collapsed.

Small, cold-water fish that feed on plankton are collectively (and appropriately) termed forage fish. They are important food sources for larger fish and other marine animals. In normal conditions, different species of forage fish have diverse life histories resulting in variability in timing of life stages such as larvae, juveniles, and spawning. This diversity in life history strategies varies their abundance across space and time, providing a buffer against low availability to marine mammals and seabirds. In this case, the heatwave was so large that multiple forage fish species concurrently collapsed (Arimitsu et al. 2021). The result was large-scale starvation of many seabirds, marine mammals, and other fishes.

What forage fish remained were smaller and in poorer condition due to a lack of nutrients and metabolic stress.There was likely more competition for these dwindling numbers of forage fish, too, because both seabirds and larger fish needed more of the smaller forage fish for food. When the water warmed, the fish warmed with it, and a warmer fish is a more active fish—and a hungrier one. This meant that neither pelagic fish nor seabirds could meet their metabolic needs (Arimitsu et al. 2021, Piatt et al. 2020).

With the collapse in forage fish populations, seabirds, especially common murres, died of starvation (above).
USGS/TONY DEGANGE

Small, forage fish (left) depend on plankton and are important food sources for many species. Normally, their populations have staggered life histories so that not all populations boom and bust at the same time and food sources are readily available throughout the year. But during the PMH, multiple species collapsed at the same time. Those that were left, were smaller and in poor condition due to stress.
NOAA

With little to eat and mostly low-quality forage available, there was a massive seabird die-off.

The 2014-2016 marine heatwave resulted in a wide-spread common murre die-off and repeated nesting failure of breeding colonies from the southern Bering Sea to the south coast of California. At least 500,000 and perhaps as many as just over 1 million seabirds, most of them common murres, died in the Gulf of Alaska and all along the west coast of the U.S. Seabird die-off events are not unusual; they occur on an irregular basis throughout the world's oceans when food supplies are depleted or otherwise unavailable. But what made this die-off globally unprecedented was the extreme extent—the large geographic area that was impacted, how long it lasted, and the vast number of dead birds. They starved because their food source changed; prey became less available and what was available was smaller, leaner, and less nutritious than usual (Piatt et al. 2020, also see How Marine Heatwaves are Changing Ocean Ecosystems).

Population declines, reduced survival, and unusual mortality events occurred in marine mammals.

Across the Gulf of Alaska, population declines, reduced survival, and unusual mortality events were also documented for whales and pinnipeds. For example, higher whale mortality was reflected in Glacier Bay National Park's long-term monitoring of humpback whales; their abundance declined by 56% between 2013 and 2018, followed by increases in 2019-2020 (Gabriele et al. 2022). Calf survival dropped by a factor of ten (from 39% down to 3%) during and after the heatwave. Females also began having calves much less frequently. For a five-year period during and after the PMH (2015-2019) there was about one calf born for every 25 adult females (0.041 calves per adult female) in contrast to one calf per three females (0.27 calves per adult female) prior to the PMH.

Even long-lived animals like humpback whales were affected by the PMH, with poor body condition and lower reproduction rate due to the stress of the heatwave and poor-quality, low abundance of food sources.
NPS

Long-term monitoring of pinniped populations in Glacier Bay documented declines in Steller sea lions at the primary haul-out site at South Marble Island (Whitlock et al. 2020). The number of harbor seals also declined in Johns Hopkins Inlet, a tidewater glacier fjord in Glacier Bay (Womble et al. 2020), but seal abundance in fjords is also influenced by the availability of ice habitat and changing tidewater glaciers (Womble et al. 2021). Studies across the broader region of the Gulf of Alaska also demonstrated declines in abundance, changes in diet, and reduced survival of Steller sea lions

Seals (above, left) and sea lions (above, right) were also impacted by the PMH. Steller sea lions showed declines in abundance, changes in diet, and reduced survival following the PMH.
NPS/JAMIE WOMBLE

following the marine heatwave (Sweeney et al. 2022, Hastings et al. 2023, Maniscalco et al. 2023).

Unusual mortality events (UMEs) are defined as a significant die-off of any marine mammal population as described under the Marine Mammal Protection Act. Hundreds to thousands of sea lion pups died in 2015 off the California coast and fur seals died in large numbers and experienced reproductive failures in the North Pacific. During the 2015 Large Whale UME in the Gulf of Alaska, a record number of humpback and fin whales were found dead in 2015-2016 along the Alaska and British Columbia coasts (Gabriele et al. 2022). The timing and location of these events coincided with warm-water conditions and forage depletion, further demonstrating the far-reaching impacts of the marine heatwave through all levels of the food chain.

Nearshore Food Web Responses Were Mixed

The nearshore is defined as the relatively shallow waters that run along the coastlines and, in the North Pacific, is constrained by light-level penetration. Hence, the food web is primarily driven by kelps and seagrasses with higher trophic-level consumer species that include invertebrates (for example, clams and mussels), nearshore sea birds, and sea otters. Primary consumers (macroinvertebrates) like mussels, clams, and sea urchins act as conduits of energy from the primary producers to the higher trophic-level consumers. Sea stars and sea otters, both keystone predators in the nearshore, shape the ecosystem in which they reside through their foraging behaviors by consuming a large variety of macroinvertebrates. Black oystercatchers, a charismatic shorebird that feeds on mussels and other intertidal macroinvertebrates, resides in the nearshore and nests in the intertidal (Dean et al. 2014).

The physical environment of the nearshore is also important. The intertidal zone (the area exposed to air at low tide and covered by water at high tide), within the nearshore ecosystem, experiences a wide range of extreme physical conditions due to the daily rising and falling tides. Low tides expose organisms to air, which could mean desiccation or freezing depending on the local conditions. While submerged during low tides, changes in water chemistry, such as decreased salinity or rising water temperatures, may stress organisms as well. Space is also a limiting factor in the intertidal, so large-scale disturbances that open up space generally result in competition between species for which ones can settle first. The species that reside in the nearshore are well adapted to these extremes.

Diverse rocky intertidal communities became more similar across the Gulf of Alaska.

Responses to the marine heatwave at rocky intertidal sites indicated major changes in community structure. Sites monitored from Prince William Sound west to Kenai Fjords National Park, Kachemak Bay, and Katmai National Park and Preserve have historically been very different from each other, with measurable differences between species composition and abundance across sites, likely driven by the local-scale conditions of each site. However, these sites became more similar with similar species composition and abundance than in years prior to the heatwave. This homogenization manifested itself as a shift from communities dominated by macroalgae (kelps and seaweeds) to communities dominated by mussels and barnacles, essentially indicating a decline in the primary producers at the base of the nearshore food web concurrent with the PMH. The decline in macroalgae also likely created open space for mussels and barnacles to settle (Weitzman et al. 2021).

Intertidal areas became more homogenous in species composition after the heatwave, with a shift from kelp and seaweed to more mussels and barnacles.
NPS

Sea stars declined, but mussels increased.

Sea stars, a top-level predator and keystone species in the intertidal, suffered significant population declines likely due to increased prevalence of sea star wasting (SSW; Konar et al. 2019), a phenomenon thought to be exacerbated by warm water temperature anomalies (Eisenlord et al. 2016). Due to the decline in macroalgae (described above), the increase in available space and decrease in predation pressure from the decline in sea stars likely allowed mussel populations to flourish (Traiger et al. 2022). In general, we also found that other benthic invertebrate prey species remained relatively stable (Robinson et al. in press).

A variable upper trophic-level response to changing prey availability.

Even with a general increase in mussel abundance, sea otter populations did not seem to change with the increased availability of mussels, a common prey item. However, preliminary analysis of diet and foraging effort indicates that there was a shift in the sea otter diet to one consisting of a higher proportion of mussels (Traiger et al. 2022). Another mussel-eating predator in the nearshore, the black oystercatcher, had a different response than sea otters. The abundance of black oystercatchers increased sharply in the eastern and western Gulf of Alaska concurrent with an increase in mussels, however, there was no observable response in the productivity of black oystercatchers (Suryan et al. 2021). Nearshore marine birds that rely on benthic prey (mussels, clams, and other intertidal invertebrates) also did not show a strong response to the PMH. This is in contrast to the forage-fish reliant seabirds such as the common murre, which collapsed during the PMH.

The stark differences in prey availability and predator response between the pelagic and nearshore ecosystems during the PMH indicates that a large-scale perturbation, such as the PMH, may impact distinct trophic pathways in the marine system differently (Robinson et al. in press).

Impacts from the Heatwave are Persistent Across Marine Ecosystems

Many biological shifts attributed to the heatwave, from changes to offshore primary production to shifts in nearshore rocky intertidal communities, persisted for at least five years after the onset of the Pacific Marine Heatwave. In many cases, the perturbation was strong enough to override typical local-scale drivers of the system (Suryan et al. 2021). Marine heatwaves are expected to become more common and widespread because of climate change. Our studies offer insight into the varying extent of responses to this broad-scale perturbation.

The studies highlighted here are the result of coupling long-term monitoring data with focused research studies to assess changes over time in marine ecosystems in and adjacent to national parks in Alaska. In the absence of long-term monitoring data, documenting responses to such a large-scale perturbation as the Pacific Marine Heatwave would not be possible. Our oceans are experiencing myriad changes, both direct and indirect, and subsequent consequences from climate change such as (but not limited to): ocean acidification, deoxygenation, changes in stratification, and decreased productivity. Documenting how species respond to these changes will allow us to anticipate potential outcomes of future perturbations and monitor how and when recovery may occur.

REFERENCES

Arimitsu, M. L., J. F. Piatt, S. Hatch, R. M. Suryan, S. Batten, M. A. Bishop, R. W. Campbell, H. Coletti, D. Cushing, K. Gorman, R. R. Hopcroft, K. J. Kuletz, C. Marsteller, C. McKinstry, D. McGowan, J. Moran, S. Pegau, A. Schaefer, S. Schoen, J. Straley, and V. R. von Biela. 2021. Heatwave-induced synchrony within forage fish portfolio disrupts energy flow to top pelagic predators. Global Change Biology 27(9): 1859-1878.

Bond, N. A., M. F. Cronin, H. Freeland, and N. Mantua. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophysical Research Letters 42(9): 3414–3420.

Dean, T. A., J. L. Bodkin, and H. A. Coletti. 2014. Protocol Narrative for Nearshore Marine Ecosystem Monitoring in the Gulf of Alaska: Version 1.1. Natural Resource Report NPS/SWAN/NRR - 2014/756. Fort Collins, Colorado.

Eisenlord, M. E., M. L. Groner, R. M. Yoshioka, J. Elliott, J. Maynard, S. Fradkin, M. Turner, K. Pyne, N. Rivlin, R. van Hooidonk, and C. D. Harvell. 2016. Ochre star mortality during the 2014 wasting disease epizootic: Role of population size structure and temperature. Philosophical Transactions of the Royal Society B: Biological Sciences 371(1689): 20150212.

Frölicher, T. L., E. M. Fischer, and N. Gruber. 2018. Marine heatwaves under global warming. Nature 560: 360-364.

Hastings, K. K., T. S. Gelatt, J. M. Maniscalco, L. A. Jemison, R. Towell, G. W. Pendleton, and D. S. Johnson. 2023.
Reduced survival of Steller sea lions in the Gulf of Alaska following marine heatwave. Frontiers in Marine Science 10: 1127013.

Gabriele, C. M., C. L. Amundson, J. L. Neilson, J. M. Straley, C. S. Baker, and S. L. Danielson. 2022.
Sharp decline in humpback whale (*Megaptera novaeangliae*) survival and reproductive success in southeastern Alaska during and after the 2014–2016 Northeast Pacific marine heatwave. Mamm Biol 102: 1113-1131.

Gruber, N., P. W. Boyd, T. L. Frölicher, and M. Vogt. 2021.
Biogeochemical extremes and compound events in the ocean. Nature 600: 395-407.

Konar, B., T. J. Mitchell, K. Iken, H. Coletti, T. Dean, D. Esler, M. Lindeberg, B. Pister, and B. Weitzman. 2019.
Wasting disease and static environmental variables drive sea star assemblages in the northern Gulf of Alaska. Journal of Experimental Marine Biology and Ecology 520: 151209.

Maniscalco, J. M. 2023.
Changes in the overwintering diet of Steller sea lions (*Eumetopias jubatus*) in relation to the 2014–2016 northeast Pacific marine heatwave. Global Ecology and Conservation 43: e02427.

Piatt, J. F., J. K. Parrish, H. M. Renner, S. K. Schoen, T. T. Jones, M. L. Arimitsu, K. J. Kuletz, B. Bodenstein, M. Garcia-Reyes, R. S. Duerr, R. M. Corcoran, R. S. A. Kaler, G. J. McChesney, R. T. Golightly, H. A. Coletti, R. M. Suryan, H. K. Burgess, J. Lindsey, K. Lindquist, P. M. Warzybok, J. Jahncke, J. Roletto, and W. J. Sydeman. 2020.
Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014-2016. PLOS ONE 15(1): e0226087.

Sweeney, K. L., B. Birkemeier, K. Luxa, and T. Gelatt. 2022.
Results of Steller Sea Lion Surveys in Alaska, June-July 2021. Memorandum to The Record. Results of Steller Sea Lion Surveys in Alaska, June-July 2021 (noaa.gov)

Robinson, B., H. A. Coletti, B. Ballachey, J. L. Bodkin, K. Kloecker, S. B. Traiger and D. Esler. In press.
Lack of strong responses to the Pacific marine heatwave by benthivorous marine birds indicates importance of trophic drivers. Marine Ecology Progress Series.

Suryan, R. M., M. L. Arimitsu, H. A. Coletti, R. R. Hopcroft, M. R. Lindeberg, S. J. Barbeaux, S. D. Batten, W. J. Burt, M. A. Bishop, J. L. Bodkin, R. Brenner, R. W. Campbell, D. A. Cushing, S. L. Danielson, M. W. Dorn, B. Drummond, D. Esler, T. Gelatt, D. H. Hanselman, S. H. Hatch, S. Haught, K. Holderied, K. Iken, D. B. Irons, A. B. Kettle, D. G. Kimmel, B. Konar, K. J. Kuletz, B. J. Laurel, J. M. Maniscalco, C. Matkin, C. A. E. McKinstry, D. H. Monson, J. R. Moran, D. Olsen, W. A. Palsson, W. S. Pegau, J. F. Piatt, L. A. Rogers, N. A. Rojek, A. Schaefer, I. B. Spies, J. M. Straley, S. L. Strom, K. L. Sweeney, M. Szymkowiak, B. P. Weitzman, E. M. Yasumiishi, and S. G. Zador. 2021.
Ecosystem response persists after a prolonged marine heatwave. Scientific Reports 11:6235.

Traiger, S. B., J. L. Bodkin, H. A. Coletti, B. Ballachey, T. Dean, D. Esler, K. Iken, B. Konar, M. R. Lindberg, D. Monson, B. Robinson, R. M. Suryan, and B. P. Weitzman. 2022.
Evidence of increased mussel abundance related to the Pacific marine heatwave and sea star wasting. Marine Ecology : e12715

Weitzman, B., B. Konar, K. Iken, H. Coletti, D. Monson, R. Suryan, T. Dean, D. Hondolero, and M. Lindeberg. 2021.
Changes in rocky intertidal community structure during a marine heatwave in the northern Gulf of Alaska. Frontiers in Marine Science 8: 1-18.

Whitlock, S. L., J. N. Womble, and J. T. Peterson. 2020.
Modelling pinniped abundance and distribution by combining counts at terrestrial sites and in-water sightings. Ecological Modelling 420: 108965.

Womble, J. N., J. M. Ver Hoef, S. M. Gende, and E. A. Mathews. 2020.
Calibrating and adjusting counts of harbor seals in a tidewater glacier fjord to estimate abundance and trends 1992 to 2017. Ecosphere 11(4): e03111.

Womble, J. N., P. J. Williams, R. W. McNabb, A. Prakash, R. Gens, B. S. Sedinger, and C. R. Acevedo. 2021.
Harbor seals as sentinels of ice dynamics in tidewater glacier fjords. Frontiers in Marine Science 8: e634541.

RESEARCH REVIEW

How Wildlife are Responding to a Warming Climate

Nina Chambers, Maggie MacCluskie, Krista Bartz, Bridget Borg, Matthew Cameron, Will Deacy, Grant Hilderbrand, Kyle Joly, Amy Larsen, Tania Lewis, Buck Mangipane, Carol McIntyre, Jeremy Mizel, Pat Owen, David Payer, Joshua Schmidt, and Mathew Sorum; National Park Service

Alaska spans vast range of latitude and elevations, encompassing a broad array of habitat types from temperate coastal rain forests to alpine and Arctic tundra. Therefore, the corresponding impacts of climate change, including implications to wildlife, also vary greatly. Research and long-term monitoring provide insights into how wildlife are responding.

Citation:
Chambers, N., M. MacCluskie, K. Bartz, B. Borg, M. Cameron, W. Deacy, G. Hilderbrand, K. Joly, A. Larsen, T. Lewis, B. Mangipane, C. McIntyre, J. Mizel, P. Owen, D. Payer, J. Schmidt, and M. Sorum. 2023. Research Review: How Wildlife are Responding to a Warming Climate. *Alaska Park Science* 22(1): 56-69.

Alaska spans wide latitudinal and elevational ranges, leading to a diverse array of habitat types from temperate coastal rain forests to alpine and Arctic tundra. Therefore, the corresponding impacts of climate change and their implications to wildlife also vary greatly. In addition to warming temperatures and changes in precipitation, climate-driven extremes and events like heavy snowfall, rain-on-snow, and even drought have affected many parks in recent years. Below we describe our observations from research and monitoring studies conducted in Alaska parks and provide context for those observations where possible.

Some species adapt to environmental conditions quickly.

Insects and wood frogs are species that respond quickly to environmental conditions and cues. Some shorebird species and caribou have adapted their timing for migration to take advantage of changing conditions, while other species like wolves are having pups earlier.

- *Some shorebirds have adapted to earlier spring insect emergence*. Shorebirds migrate to Alaska in the spring to nest and raise young when they can take advantage of a plentiful food source: insects. Insect populations respond quickly to environmental conditions; they emerge based on snow melt and warming air temperatures. Across Arctic North America, insects are emerging an average of 1-2.5 days earlier per decade. In response, some shorebird species have adapted to match this timing by arriving to their breeding grounds earlier. Other shorebird species have adapted by adjusting their egg-laying to be within a shorter time period after they arrive (Shaftel et al. 2021). In some cases, populations of insects that shorebird adults and chicks eat peaked before the chicks hatched, resulting in a “trophic mismatch” through reduced food availability when energy demands are greatest for offspring. The degree of mismatch between insect availability and demand for insects by nestlings varied by location and species (Kwon et al. 2019).

- *Frogs are nimble in adapting to environmental conditions*. Wood frogs have one of the most widespread ranges of frogs in North America—from the southeastern U.S. to the Canadian subarctic and as far north as the Brooks Range in Arctic Alaska. It is the only amphibian found this far north and has a surprising adaptation to the cold—it freezes in the winter and thaws out to carry on with life in the spring. Like many species of wildlife, amphibians time their breeding season to correspond to optimal conditions for success. Warmer air temperatures and less snow cover have changed the amount of spring runoff and reduced the amount

Mountain goats in Glacier Bay National Park and Preserve are already genetically isolated. Will they survive shifts in climate?
NPS/TANIA LEWIS

Some wolves are denning earlier to take advantage of earlier springs, while other wolves show consistent denning dates.
NPS/REMOTE CAMERA

of aquatic breeding habitat. Using acoustic monitoring from 2011-2017, we found a strong relationship between frog-calling activity and temperature and snowpack. Monitoring is ongoing, but our findings so far suggest that wood frogs will rapidly adjust the timing of their breeding (Larsen et al. 2021).

- *Some wolves may be denning earlier; if they don't, they could be missing out.* Wolves use den sites for giving birth and to provide a protected area for young pups and nursing females. A study that looked at wolf denning patterns over 25 years determined that wolves in east-central Alaska may be denning earlier in the spring in response to warmer weather and food availability for the new pups (Joly et al. 2018). Another study that looked at eight populations of wolves across North America between 2000 and 2017 found that the onset of spring shifted a full two weeks earlier, but the average denning date did not change, which highlights the complexity inherent with localized adaptations to changing climate conditions (Mahoney et al. 2020).

Some species benefit in the short term from warmer temperatures, earlier growing seasons. Some species benefit from warmer weather and an earlier, longer growing season. What we don't know yet is how warm it can get and still be beneficial.

- *Insects thrive in a warming climate and increased insect harassment stresses caribou.* As the climate warms, some insects thrive. When caribou are harassed by insects, they tend to move more and eat less (Joly et al. 2020, Ehlers et al. 2021). Warm, windless summers that favor insects lead to poorer maternal health and delayed arrival at the calving grounds the following spring (Gurarie et al. 2019). During cooler, windier summers, caribou remain healthier because they spend less time avoiding insects and more time eating. Unfortunately, herds that arrive late continue to be at a disadvantage because their calves have less time on the summer feeding range before migrating back to the winter range in the fall (Gurarie et al. 2019). In light of predictions for increasingly warm summers, greater insect harassment could offset any potential gains from increased forage availability or conditions, but the degree to which one outweighs the other remains unclear.

- *Lake trout appear to benefit from warming conditions in Southwest Alaska.* Warmer air temperatures mean earlier ice break-up, longer ice-free seasons, and increased zooplankton production in high-latitude lakes. Together, these conditions help lake trout, at the top of the food chain, grow larger, based on a study of seven deep, low-nutrient lakes in southwest Alaska (von Biela et al. 2020). What we don't know yet is whether this benefit continues once lakes warm past the range of natural variation, particularly in the deeper waters normally used as thermal refugia by cold-loving species like lake trout.
- *A longer growing season could mean more food for bears.* With a warmer climate and longer growing season, there may be more food available for bears, especially in resource-limited places like the Arctic. A study that looked at brown bear body size and condition, and number of cubs produced between 1977 and 2016, found that food availability is important to bear health and survival, but that the effects are variable by year and location (Hilderbrand et al. 2019). As the climate warms, increased primary productivity increases populations of small mammals, like ground squirrels, which are an important food for bears (Wheeler et al. 2015). Generalizations and extrapolations over longer periods of time or geographic area are less helpful to wildlife managers than understanding local conditions and local food sources (Hilderbrand et al. 2019). But bears are omnivores and are very flexible in their food sources and their behaviors, which will likely allow them to adapt to a changing climate.

Some species benefit, at least in the short term, from a warming climate. Lake trout (above) benefit from a longer ice-free season.
NPS/EVAN BOOHER

Bears (right) are very adaptable, using a wide variety of food sources, and may benefit from a longer growing season.
NPS

Salmon are cold-water adapted and have optimal temperature envelopes that are important at each life stage. Some warming could lead to changes in timing of life-stage transitions, and those changes could be beneficial at early life stages. But if water temperatures exceed optimal thermal envelopes, they can lead to fish die-offs at later life stages, unless cold-water refugia are accessible. NPS/DAN YOUNG

Many species are navigating complex interactions of climate-driven habitat changes. Changes from a warming climate are variable. A number of species experience positive and negative impacts from a changing climate and we are still teasing out these effects based on our science and long-term monitoring.

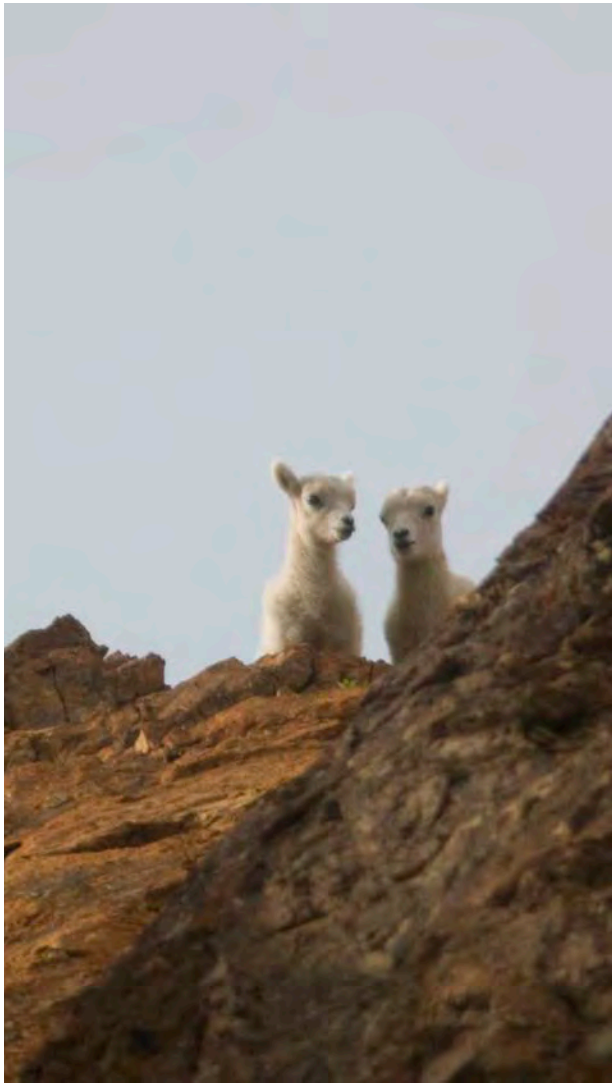
- *Salmon may adapt to warming climate, if they have cold-water refugia.* For Pacific salmon species, key life stage transitions depend on variables that are affected by climate warming. For example, hatching from eggs and emergence from gravel, depend on water temperature and the timing of reproduction (Beacham and Murray 1990). In a study of 25 sockeye salmon populations from the Bristol Bay region, hatching and emergence estimates spanned broad time periods: from September of the year of spawning to June of the following year for hatching, and from December of the year of spawning to August of the following year for emergence (Sparks et al. 2018). These broad time periods indicate that both hatch and emergence timing vary more widely than spawning timing, even for populations sharing the same nursery lake. The wide variation in hatching and emergence timing among populations may serve to buffer Bristol Bay sockeye salmon, as a whole, from climate change (Sparks et al. 2018). Furthermore, projections of future water temperatures through 2099 suggest that hatch timing could shift earlier by 16 to 60 days. Less known is whether spawn timing and food availability will shift in response to climate change, too.

- *Shrub-adapted and forest-adapted songbirds respond to weather and climate changes differently.* Weather varies from year to year and climate is the long-term trend of weather patterns. Songbirds, like many species, are impacted by both short-term weather and long-term climate. Weather and climate can have complex and sometimes conflicting effects on songbirds and all songbird species don't respond in the same way. For example, songbirds that use shrub habitats increased their numbers in the year following a warm nesting season, but over a long-term warming climate trend, decreased in number and shifted upslope as trees and shrubs also shifted to higher elevations (Mizel et al. 2016). Overall, the temperature during the previous year's nesting period had the greatest short-term impact on the number of songbirds observed (1995-2019). The amount of rain and snow, and the timing of snowmelt, affected different songbird species in different ways, but generally, drier conditions and earlier snowmelt led to a greater abundance of songbirds (Mizel et al. 2021).

- *Bald eagles produce more young when salmon run earlier.* Bald eagles often rely on salmon that return to fresh waters during the breeding season, but reproductive success can be affected by climate through both direct and indirect pathways (Schmidt et al. 2020). A study in Southwest Alaska found that warmer April temperatures were associated with increased nestling production in bald eagles (Wilson et al. 2018). In contrast, along the upper Copper River in southcentral Alaska, bald eagle nest success was positively related to early season salmon runs, although warmer springs appeared to moderate the effect of salmon abundance. This perhaps counter-intuitive result is thought to be related to increased glacial melt runoff (the Copper River has large glacial inputs) which makes it more difficult for eagles to detect salmon in the silty river (Schmidt et al. 2020). This means that although warmer temperatures may be beneficial during the early part of the nestling phase, increased glacial melt in some areas may have a countervailing impact by reducing availability of salmon as food for nestlings.

- *Dall's sheep benefit from warmer winters, unless it causes a thaw.* A study of sheep survival across Alaska found that adult sheep had higher survival during warmer winters, likely because they spent less of their energy reserves to stay warm (Van de Kerk et al. 2020). Springs with delayed snowmelt led to fewer lambs and overall population declines (Rattenbury et al. 2018). Lambs thrive when summers are warm and plants are abundant. This allows rapid weight gain, which prepares lambs for winter and appears to make them less vulnerable to predators like coyotes and golden eagles (Van De Kerk et al. 2020). Although both lambs and adults benefit from warmer conditions, a warming climate may negatively impact sheep. If winter temperatures increase enough to melt snow or cause freezing rain, a thick crust of ice can form, which can make it difficult or impossible for sheep to reach the plants below. Thus, sheep survival is the lowest in winters that have many thaws. So, warm winters are good for sheep, as long as it isn't warm enough to melt snow or create ice. Recently, sheep populations in Alaska have been in decline, which suggests that the negative effects of warming during winter may be overriding the benefits of warmer weather for sheep. Sheep are also losing habitat as warmer temperatures allow shrubs to move up in elevation. This is expected to harm sheep as shrubs replace the tender plants that they prefer and provide ambush cover for predators.

- *Some caribou are calving earlier to take advantage of early spring growth.* Adult females tend to choose sites to deliver their calves with abundant, high-quality food and rely on the predictability of those sites year after year (Cameron et al. 2018, 2020). Studies that looked at the timing of caribou calving in Arctic Canada found that some populations of barren-ground migratory caribou and northern mountain woodland caribou were calving earlier as the climate warmed to take advantage of new growth in the spring (Davidson et al. 2020), but this trend wasn't evident for all Arctic herds when analyzed together (Couriot et al 2023). Another study (Gurarie et al. 2019) found that the start of spring migration for caribou herds across North America is triggered at roughly the same time by large-scale, ocean-driven climate cycles. Despite a synchronized start, arrival at their respective calving grounds depends on the previous summer's weather conditions. When the researchers compared arrival times with climate and weather data, they consistently found that caribou herds arrived at the calving grounds earlier when they experienced cool, windy conditions the previous summer: conditions with less insect harassment.



Dall's sheep lambs thrive in warm summers with abundant food. They grow more quickly and are less vulnerable to predation. But winter rain makes it difficult to impossible for them to access plants under the ice, leading to mortality. Poor winter survival has been a recent contributor to sheep population declines.
NPS

Extensive monitoring and research have been done on caribou in Alaska. We've learned that they respond to both weather and climate with short-term actions and long-term trends in behavior. From the timing of calving and migration to insect harassment, they are constantly responding to changing conditions. And how their movements and populations change impacts many people in Alaska.
NPS/PAMELA SOUSANES

Timing of fall is later and winters have more snow.

Fall and winter weather conditions impact migration and over-winter survival of some wildlife species.

- *Caribou migrate later.* Colder temperatures and the first snowfalls of the winter are the main signals caribou use to initiate their fall migration (Cameron et al. 2021). Interestingly, caribou update their decisions based on local conditions. For example, if they move into a warm valley with little or no snow, they may slow down their migration and stay in that area longer before moving on. This reliance on local weather cues makes the fall migration more variable, even within a herd, because some of the herd may be in different locations and experiencing different conditions. Even with the variation in timing, the trend is that fall migration has become later for the Western Arctic Herd over the last three decades, a trend that will likely continue as temperatures warm (Cameron et al. 2021). This has disrupted local subsistence practices, some of which have been in the same place for tens of thousands of years and promises to remain a major concern for local communities that rely on caribou (Baltensperger and Joly 2019).

- *Winter conditions can be important drivers for wolf populations and their prey.* Because wolves are sensitive to seasonal weather conditions, they may be able to adapt to shifts in climate (Mahoney et al. 2020). Wolf survival, natality (the number of wolves added to the pack in a year), and population size increased following years with deeper snow (Borg and Schirokauer 2022). Sometimes, long-legged prey like moose and caribou can move through deep snow easier than wolves. But at some point, and especially with icing events, even they have a hard time moving in deep snow and have limited access to food resources, such as lichen for caribou. A weakened and vulnerable prey can be a boon for wolves and other predators and scavengers. However, trends toward heavier snowfall may reduce ungulate densities, thus limiting prey availability for wolves, and ultimately wolf abundance.

It can take 1-2 years for wolf populations to respond to changes in primary or secondary prey (i.e., caribou and snowshoe hare, respectively). This suggests that wolves are limited by prey availability. A warming climate may mean more favorable conditions for wolves with more warm, moist winter air and greater snow depth. Conversely, conditions like warmer summers may favor ungulate population increases and ungulate body condition. Increasing numbers of caribou in good condition could mean that ungulates are less vulnerable to predation. This in turn increases search area and territory sizes for wolf packs, leading to fewer wolf packs in the same area.

How hot is too hot?

When will species hit the limits of their ability to adapt? Extreme heat and drought can cause river water to exceed temperatures that fish can stand and result in massive die-offs. Large-scale fires can result in habitat loss that can impact many species. Freeze-thaw or icing events can create food shortages and physical hardships for many species, such as caribou, moose, and small mammals. As these events become more common and widespread, wildlife will face hardships and we have yet to fully understand how they will be impacted.

- *Moose show signs of heat avoidance*. Moose are another cold-adapted species that has been moving farther north as the climate warms and shrubs move into higher latitudes (Tape et al. 2016). Increased shrub abundance may lead to even more moose in the far north (Joly et al. 2012). Moose population declines have been noted in the lower-48 states connected to increasing temperatures causing heat stress (Lenarz et al. 2009, McCann et al. 2013). We were surprised to see some early signs of heat-avoidance behaviors in Alaska among

In a warming climate, moose may become more vulnerable to stresses. With heavier snowfall and icing events, they may become more vulnerable to predation by wolves as they struggle through deep snow and ice. Moose are also sensitive to heat and are already showing behaviors of heat avoidance.
NPS/MATT CAMERON

moose in Gates of the Arctic National Park and Preserve—above the Arctic Circle. Moose sought out increased forest canopy cover to reduce heat stress (Jennewein et al. 2020). As fires become more extreme and burn larger areas of the Arctic, moose may have a harder time finding forest cover to get out of the heat.

- *Caribou may avoid burned areas for decades after a wildfire*. As wildfires increase with climate change, we found that burned areas were primarily avoided in the winter, and if caribou did wander through a burned area, they spent time where the fire was less severe and where lichens were in greater abundance relative to the rest of the burn. This pattern was due to lichens, the primary forage of wintering caribou, taking decades to recover after a burn (Joly and Cameron 2018, Joly et al. 2011). While grasses recover quickly after a fire and are a source of nutrition, caribou still mostly avoided burned areas even in the summer (Palm et al. 2022).

- *Climate change will likely reduce habitat, movement corridors, and gene flow for mountain goats*. Mountain goats are found in coastal mountain ranges extending from Kodiak Island to Southeast Alaska. They are dependent on alpine habitats with steep terrain nearby to escape predators. A recent study of mountain goats in Glacier Bay National Park and Preserve characterized the fine-scale genetic population structure and examined how future climate change could impact their population density (Young et al. 2022). Climate change predictions call for increased summer temperatures throughout Southeast Alaska which has been found to decrease goat survivorship (White et al. 2011). Further, warming temperatures facilitate increased tree growth at high elevations, effectively replacing alpine habitat with forest where food resources are lower and predation risk higher (White et al. 2018). Mountain goats must either adapt to this changing environment by adjusting daily activity budgets or move to more suitable habitat, which would likely mean moving higher in elevation for as far as the height of the mountain will allow. Mountain goats are able to disperse across glaciers, but due to predators, are not as successful dispersing across the low-elevation valleys that remain after glaciers retreat. At least one small sub-population of mountain goats in Glacier Bay National Park is already genetically isolated due to recent glacier retreat. Small populations are more strongly influenced by climate change due to their limited genetic diversity, and reductions in travel corridors.

Fire is another consequence of a warming climate that impacts wildlife habitat.
NPS/FLEUR NICKLEN

Shrubs are moving north.

Shrubification, the movement of shrubland farther north, is occurring in part due to warmer soil temperatures and is bringing along moose, beavers, and songbirds. Shrubs benefit these species and potentially other species, like caribou, but as shrub habitat moves north and upward in elevation, it crowds out habitats and the species that rely on them that were already there, such as lichen-rich tundra, providing more fuel for wildland fires. Species that depend on habitats above shrub- and treeline (such as sheep and goats) will feel the pinch as vegetation changes move upward in elevation as well.

- *Shrubification may benefit caribou, but benefits are offset by a loss of lichen.* Across much of the caribou's range in Alaska and Canada, expansion of deciduous shrubs is occurring northward and upward in elevation as a result of increased temperature linked to climate change. Caribou browse the preferred protein-rich leaves from shrubs that help them and their calves grow and gain weight during the summer months. But insect harassment, especially when the days are warm and the winds are calm, keeps caribou from spending more time in the shrubs and pushes them into tundra and on snow patches to avoid insects. There may be a beneficial effect of shrubs moving into higher latitudes, as this could mean more nutritious browse will be available in summer, but there is a trade-off in space for lichens that caribou depend on during the winter months (Ehlers et al. 2021, Joly et al. 2020). Another downside of shrub expansion for caribou is that it may allow for more moose, and their main predator, wolves, to move into their habitat as well as

Shrubification has provided expanded habitat for moose and beaver into the Arctic. Beaver dams and the lakes they form are contributing to climate change by thawing permafrost faster and releasing methane and carbon dioxide.
NPS

provide hiding places for caribou predators to ambush them (Joly et al. 2012).

- *Beavers are moving north and contributing to climate change*. Beavers, like moose, are moving north into the Arctic as shrubs move farther north. Beavers are ecosystem engineers, creating their own habitats, which can be beneficial to many species of fish, birds, and insects. But, beaver ponds have greatly increased in Arctic Alaska (Tape et al. 2022). When beaver dams create ponds and lakes, they thaw the underlying permafrost faster, which releases carbon from the soil and through the water creating methane and carbon dioxide—powerful greenhouse gases. In this way, beavers are not only responding to the warming climate, but also accelerating the effects of climate change locally (by thawing permafrost) and globally (by releasing more greenhouse gases; Tape et al. 2018).

As research shows, species are impacted by a changing climate differently depending on their sensitivities and flexibility to adapt. Warming temperatures, longer growing seasons, wetter springs, drier summers, heavier snowfalls, and other consequences of a warming climate all stimulate changes in the environment (e.g., water availability and plant communities) that ripple through the food web. Long-term monitoring, research, and modeling have given us some insights into changes that are occurring now as well as what we might see in the future.

How the National Park Service Contributes to Global Knowledge of Wildlife

Research and monitoring conducted in Alaska parks by the National Park Service and partners has resulted in numerous datasets that are highly valuable to understanding environmental changes resulting from a warming climate in Alaska and beyond. This is because high-latitude regions are seeing changes much faster, and Alaska's parks are large and relatively naturally functioning. Large, long-term datasets contribute to greater scientific understanding, and the collaboration of NPS scientists in international forums help inform global scientific questions and conservation. Below are some examples of how NPS scientists and datasets have contributed to global knowledge.

Shorebird data in Alaska contributes to pan-Arctic understanding of how shorebird populations may be impacted by climate change.

Kwon, E., E. L. Weiser, R. B. Lanctot, S. C. Brown, H. R. Gates, G. Gilchrist, S. J. Kendall, D. B. Lank, J. R. Leibezeit, L. McKinnon, E. Nol, D.C. Payer, J. Rausch, D. J. Rinella, S. T. Saalfeld, N. R. Senner, P. A. Smith, D. Ward, R. W. Wisseman, and B. K. Sandercock. 2019. Geographic variation in the intensity of warming and phenological mismatch between Arctic shorebirds and invertebrates. Ecological Monographs 89(4): e01383.

Shaftel, R., D. J. Rinella, E. Kwon, S. C. Brown, H. R. Gates, S. Kendall, D. B. Lank, J. R. Liebezeit, D. C. Payer, J. Rausch, S. T. Saalfeld, B. K. Sandercock, P. A. Smith, D. H. Ward, and R. B. Lanctot. 2021. Predictors of invertebrate biomass and rate of advancement of invertebrate phenology across eight sites in the North American Arctic. Polar Biology 44: 237-257.

Weiser, E. L., R. B. Lanctot, S. C. Brown, H. R. Gates, ... D. Payer, et al. 2020. Annual adult survival drives trends in Arctic-breeding shorebirds, but knowledge gaps in other vital rates remain. The Condor: Ornithological Applications 122: 1-14.

A pan-Arctic status and trends of understudied bird species.

Franke, A., K. Hawkshaw, S. Ambrose, ... C. L. McIntyre, et al. 2020. Status and trends of circumpolar peregrine falcon and gyrfalcon populations. Ambio 49(3): 762-783.

Fuglei, E., J. A. Henden, C. T. Callahan, O. Gilg, J. Hansen, R. A. Ims, A. P. Isaev, J. Lang, C. L. McIntyre, R. A. Merizon, O. Y. Mineev, Y. N. Mineev, D. Mossop, O. K. Nielsen, E. B. Nilsen, A. O. Pedersen, N. M. Schmidt, B. Sittler, M. H. Willebrand, and K. Martin. 2018. Circumpolar status of Arctic ptarmigan: Population dynamics and trends. Ambio 49: 749-761.

Alaska's extensive wildlife movement database contribute to global understanding of migration.

Global Initiative on Ungulate Migration

Kauffman, M. J., F. Cagnacci, S. Chamaillé-Jammes, M. Hebblewhite, J. G. C. Hopcraft, J. A. Merkle, T. Mueller, A. Mysterud, W. Peters, …, K. Joly, et al. 2021. Mapping out a future for ungulate migrations. Science 372 (6542): 566-569.

Arctic Animal Movement Archive

Davidson, S. C., G. Bohrer, E. Gurarie, S. LaPoint, P. J. Mahoney, ... K. Joly, ... J. P. Lawler, ...B. Mangipane, ... C. L. McIntyre, ... P. A. Owen, ... M. S. Sorum, ... et al. 2020. Ecological insights from three decades of animal movement tracking across a changing Arctic. Science 370(6517): 712-715.

REFERENCES

Baltensperger, A. P. and K. Joly. 2019. Using seasonal landscape models to predict space use and migratory patterns of an Arctic ungulate. Movement Ecology 7 (18).

Beacham, T. D. and C. B. Murray. 1990. Temperature, egg size, and development of embryos and alevins of five species of Pacific salmon: A comparative analysis. Trans. Am. Fish. Soc. 119(6): 927-945.

Borg, B. L. and D. W. Schirokauer. 2022. The role of weather and long-term prey dynamics as drivers of wolf population dynamics in a multi-prey system. Frontiers in Ecological Evolution 10: 791161.

Cameron, M. D., J. M. Eisaguirre, G. A. Breed, K. Joly, and K. Kielland. 2021. Mechanistic movement models identify continuously updated autumn migration cues in Arctic caribou. Movement Ecology 9(54): 12 pp.

Cameron, M. D., K. Joly, G. A. Breed, C. P. H. Mulder, and K. Kielland. 2020. Pronounced fidelity and selection for average conditions of calving area suggestive of spatial memory in a highly migratory ungulate. Frontiers in Ecology and Evolution 8: e564567.

Cameron, M. D., K. Joly, G. A. Breed, L. S. Parrett, and K. Kielland. 2018. Movement-based methods to infer parturition events in migratory ungulates. Canadian Journal of Zoology 96: 1187-1195.

Couriot, O. H., M. D. Cameron, K. Joly, J. Adamczewski, M. W. Campbell, T. Davidson, A. Gunn, A. P. Kelly, M. Leblond, J. Williams, W. F. Fagan, A. Brose, and E. Gurarie. 2023. Continental synchrony and local responses: Climatic effects on spatiotemporal patterns of calving in a social ungulate. Ecosphere 14(1) e.4399.

Davidson, S. C., G. Bohrer, E. Gurarie, S. LaPoint, P. J. Mahoney, ... K. Joly, ... J. P. Lawler, ...B. Mangipane, ... C. L. McIntyre, ... P. A. Owen, ... M. S. Sorum, ... et al. 2020. Ecological insights from three decades of animal movement tracking across a changing Arctic. Science 370(6517): 712-715.

Ehlers, L., G. Coulombe, J. Herriges, T. Bentzen, M. Suitor, K. Joly, and M. Hebblewhite. 2021. Critical summer foraging tradeoffs in a subarctic ungulate. Ecology and Evolution 11(24): 17835-17872.

Gurarie, E., M. Hebblewhite, K. Joly, A. P. Kelly, J. Adamczewski, S. C. Davidson, T. Davison, A. Gunn, M. J. Suitor, W. F. Fagan, and N. Boelman. 2019. Tactical departures and strategic arrivals: Divergent effects of climate and weather on caribou spring migrations. Ecosphere 10(12): e02971.

Hilderbrand, G. V., K. Joly, M. S. Sorum, M. D. Cameron, and D. D. Gustine. 2019. Brown bear (*Ursus arctos*) body size, condition, and productivity in the Arctic, 1977-2016. Polar Biology 42: 1-6.

Jennewein, J. S., M. Hebblewhite, P. Mahoney, S. Gilbert, A. J. H. Meddens, N. T. Boelman, K. Joly, K. Jones, K. A. Kellie, S. Brainerd, L. A. Vierling, and J. U. H. Eitel. 2020. Behavioral modifications by a large, northern herbivore to mitigate warming conditions. Movement Ecology 8(39): 14 pp.

Joly, K., O. Couriot, M. D. Cameron, and E. Gurarie, E. 2020. Behavioral, physiological, demographic, and ecological impacts of hematophagous and endoparasitic insects on an Arctic ungulate. Toxins 12: 334.

Joly, K., M. S. Sorum, and M. D. Cameron. 2018. Denning ecology of wolves in east-central Alaska, 1993-2017. Arctic Institute of North America 71(4): 444.

Joly, K. and M. D. Cameron. 2018. Early fall and late winter diets of migratory caribou in northwest Alaska. Rangifer 38(1):27-38.

Joly, K., P. A. Duffy, and T. S. Rupp. 2012. Simulating the effects of climate change on fire regimes in Arctic biomes: Implications for caribou and moose habitat. Ecosphere 3(5): 1-18.

Joly, K., K., D. R. Klein, D. L. Verbyla, T. S. Rupp, and F. S. Chapin. 2011. Linkages between large-scale climate patterns and the dynamics of Alaska caribou populations. Ecography. 34:345-52.

Kwon, E., E. L. Weiser, R. B. Lanctot, S. C. Brown, H. R. Gates, G. Gilchrist, S. J. Kendall, D. B. Lank, J. R. Leibezeit, L. McKinnon, E. Nol, D.C. Payer, J. Rausch, D. J. Rinella, S. T. Saalfeld, N. R. Senner, P. A. Smith, D. Ward, R. W. Wisseman, and B. K. Sandercock. 2019. Geographic variation in the intensity of warming and phenological mismatch between Arctic shorebirds and invertebrates. Ecological Monographs 89(4): e01383.

Larsen, A. S., J. H. Schmidt, H. Stapleton, H. Kristenson, D. Betchkal, and M. F. McKenna. 2021.
Monitoring the phenology of the wood frog breeding season using bioacoustic methods. Ecological Indicators 131: 108142.

Lenarz, M. S., M. E. Nelson, M. W. Schrage, and A. J. Edwards. 2009.
Temperature mediated moose survival in northeastern Minnesota. The Journal of Wildlife Management 73(4): 503-510.

Mahoney, P. J. K. Joly, B. L. Borg, M. S. Sorum, T. A. Rinaldi, D. Saalfeld, H. Golden, A. D. M. Latham, A. P. Kelly, B. Mangipane, C. Lambert Koizumi, L. Neufeld, M. Hebblewhite, N. T. Boelman, and L. R. Prugh. 2020.
Denning phenology and reproductive success of wolves in response to climate signals. Environmental Research Letters 15(12): 125001.

McCann, N. P. R. A. Moen, and T. R. Harris. 2013.
Warm-season heat stress in moose (*Alces alces*). Canadian Journal of Zoology 91(12): 893-898.

Mizel, J.D., J. H. Schmidt, and C. L. McIntyre. 2021.
Climate and weather have differential effects in a high-latitude passerine community. Oecologia 195: 355-365.

Mizel, J. D., J. H. Schmidt, C. L. Mcintyre, and C. A. Roland. 2016.
Rapidly shifting elevational distributions of passerine species parallel vegetation change in the subarctic. Ecosphere 7(3): 1-15.

Palm, E. C., M. J. Suitor, K. Joly, J. D. Herriges, A. P. Kelly, D. Hervieux, K. L. M. Russell, T. W. Bentzen, N. C. Larter, and M. Hebblewhite. 2022.
Increasing fire frequency and severity will increase habitat loss for a boreal forest indicator species. Ecological Applications 32(3): e2549.

Rattenbury, K. L., J. H. Schmidt, D. K. Swanson, B. L. Borg, B. A. Mangipane, and P. J. Sousanes. 2018.
Delayed spring onset drives declines in abundance and recruitment in a mountain ungulate. Ecosphere 9(11): e02513.

Schmidt, J. H., J. Putera, and T. L. Wilson. 2020.
Direct and indirect effects of temperature and prey abundance on bald eagle reproductive dynamics. Oecologia 192: 391-401.

Shaftel, R., D. J. Rinella, E. Kwon, S. C. Brown, H. R. Gates, S. Kendall, D. B. Lank, J. R. Liebezeit, D. C. Payer, J. Rausch, S. T. Saalfeld, B. K. Sandercock, P. A. Smith, D. H. Ward, and R. B. Lanctot. 2021.
Predictors of invertebrate biomass and rate of advancement of invertebrate phenology across eight sites in the North American Arctic. Polar Biology 44: 237-257.

Sparks, M. M., J. A. Falke, T. P. Quinn, M. D. Adkison, D. E. Schindler, K. Bartz, D. Young, and P. A.H. Westley. 2018.
Influences of spawning timing, water temperature, and climatic warming on early life history phenology in western Alaska sockeye salmon. Canadian Journal of Fisheries and Aquatic Sciences 76: 123-135.

Tape, K. D. J. A. Clark, B. M. Jones, S. Kantner, B. V. Gaglioti, G. Grosse, and I. Nitze. 2022.
Expanding beaver pond distribution in Arctic Alaska, 1949 to 2019. Scientific Reports 12: 7123.

Tape, K. D., B. M. Jones, C. D. Arp, I. Nitze, and G. Grosse. 2018.
Tundra be dammed: Beaver colonization of the Arctic. Global Change Biology 24: 4478-4488.

Tape, K. D., D. D. Gustine, R. W. Ruess, L. G. Adams, and J. A. Clark. 2016.
Range expansion of moose in Arctic Alaska linked to warming and increased shrub habitat. PLOS ONE 11(7): e0160049.

Van de Kerk, M., S. Arthur, M. Bertram, B. Borg, J. Herriges, J. Lawler, B. Mangipane, C. Lambert Koizumi, B. Wendling, and L. Prugh. 2020.
Environmental influences on Dall's sheep survival. Journal of Wildlife Management 84: 1127-1138.

von Biela, V. R., B. A. Black, D. B. Young, P. van der Sleen, K. K. Bartz, and C. E. Zimmerman. 2020.
Lake trout growth is sensitive to spring temperature in southwest Alaska lakes. Ecology of Freshwater Fish 30(1): 88-99.

Wheeler, H.C., J. D. Chipperfield, C. Roland, and J. C. Svenning. 2015.
How will the greening of the Arctic affect a common ecosystem engineer? Vegetation effects on burrowing networks and activity of arctic ground squirrels. Oecologia 178(3): 915-929.

White, K. S., G. W. Pendleton, D. Crowley, H. J. Griese, K. J. Hundertmark, T. McDonough, L. 534 Nichols, M. Robus, C. A. Smith, and J. W. Schoen. 2011.
Mountain goat survival in coastal 535 Alaska: Effects of age, sex, and climate. Journal of Wildlife Management 75: 1731-1744.

White, K. S., D. P. Gregovich, and T. Levi. 2018.
Projecting the future of an alpine ungulate under climate change scenarios. Global Change Biology 24: 1136–1149.

Wilson, T., J. Schmidt, B. Mangipane, R. Kolstrom, and K. Bartz. 2018.
Nest use dynamics of an undisturbed population of bald eagles in Lake Clark National Park and Preserve, Alaska. Ecology and Evolution 8(15): 7346-7354.

Young, K. B., T. M. Lewis, K. S. White, and A. B. A. Shafer. 2022.
Quantifying the effects of recent glacial history and future climate change on a unique population of mountain goats. Biological Conservation 272(109631): 1-8.

NPS biologist Carol McIntyre conducts field work on golden eagles in the winter, travelling by dog sled.
NPS

Responding to the Effects of Climate Change on Subsistence in Alaska

Rachel Mason and Amy Craver, National Park Service

Climate change threatens dire consequences for many Alaska Native villages in remote areas, where subsistence hunting, fishing, and gathering are critical to livelihoods. Although Northern communities have a deep cultural history of adapting to change, they are highly vulnerable to current rapid changes and intensifying impacts.

Citation:
Mason, R. and A. Craver. 2023. Responding to the effects of climate change on subsistence in Alaska. *Alaska Park Science* 22(1): 70-79.

A typhoon, smoke from wildfires, and increasing rain are not what most people imagine when thinking of the Arctic, yet these are some of the climate-driven events included in the National Ocean Atmospheric Administration's *2022 Arctic Report Card*. The Report Card, an annual update on the state of the Arctic, shows in detail how climate change is transforming the icy, snowy Arctic into a warmer, wetter environment. It describes how warming air temperatures, shrinking sea ice, shorter periods of snow cover, increased wildfires, rising levels of precipitation, and changes in animal abundance and migration patterns profoundly affect the safety, food security, health, economic wellbeing and cultural traditions of Alaska Natives and other Arctic residents (Druckenmiller et al. 2022).

Although Northern communities have a deep cultural history of adapting to change, they are highly vulnerable to the impact of rapid climate change. In the Alaskan Arctic, the Bering, Chukchi, and Beaufort seas have undergone changes in ocean circulation, currents, water temperatures, and nutrient availability, with serious impacts on fisheries. On land, thawing permafrost impacts roads, which have to be continually rebuilt. With warming temperatures, early breakup and late freeze-up create poor ice conditions, making access to hunting areas for important subsistence species more dangerous (Brown et al. 2018). In some northern communities, ice cellars are melting, making long-term storage of traditional foods more difficult. Winter storm surges, also linked to climate change, erode coastlines, make travel difficult by land or sea, and destroy cabins and camps used for subsistence activities (USDA Northwest Climate Hub 2023).

In Alaska, the word "subsistence" is not just about getting food for nutrition but represents a way of life and a relationship with wild resources. Subsistence foods connect people to their culture and their environment. Harvesting, processing, and eating wild foods contributes to the physical, mental, and spiritual well-being of individuals and communities. For rural Alaskans, including Alaska Natives with cultural and spiritual ties to the land going back millennia, and non-Natives who choose to live a self-sufficient lifestyle far from stores, cash-paying jobs, and the state's few roads, subsistence is part of what defines them.

Some of the most damaging effects of climate change in Alaska have been the social and cultural impacts for subsistence users. When individuals and families are unable to procure subsistence foods, traditional sharing becomes more difficult. Hunters esteemed for their abilities and willingness to share food

Aerial view of the Arctic coast after Typhoon Merbok, leaving behind destroyed structures, debris, and eroded coastline. Storms like these are becoming more frequent and impact people's access to and storage of traditional subsistence foods.
NPS/TAHZAY JONES

Alaska is the only state where the federal government manages public lands and waters for subsistence, prioritizing and preserving this way of life. The Alaska National Interest Lands Conservation Act (ANILCA), passed in 1980, ensures that qualified rural residents, Alaska Native and non-Native, will have the opportunity to pursue subsistence uses. Federal lands represent about 230 million acres, or 60% of the land in the state. In ANILCA Section 803, subsistence uses are defined as "the customary and traditional uses by rural Alaska residents of wild, renewable resources for direct personal or family consumption as food, shelter, fuel, clothing, tools or transportation…"

may find their roles changing as the landscape changes. Older generations may no longer be able to teach young people about subsistence harvesting and processing. Additionally, as subsistence opportunities decline, it may become cost prohibitive to stay in the village, encouraging residents to relocate to hub villages and Anchorage (Pete 2010). Relocation to urban areas makes it even harder to maintain subsistence activities and networks. Ultimately, relocation to a new village site or to an existing village or regional hub may be the only options as villages disappear or become uninhabitable due to climate change-related erosion or flooding.

This article describes the challenges climate change poses to subsistence harvests, tells some of the ways subsistence users have adapted to change, and suggests how the NPS can support continued subsistence opportunities in Alaska. We focus on parklands from two regions of Alaska: the Northwest, represented by the Western Arctic Parklands and Bering Land Bridge National Preserve; and Interior Alaska, with examples from Denali National Park and Preserve and Wrangell-St. Elias National Park and Preserve.

Northwest Alaska

Subsistence users in Northwest Alaska, many of whom live along the coast and depend on ocean resources, are experiencing many of the accelerated effects of climate change seen throughout the Arctic. A team led by Kristen Green and Anne Beaudreau interviewed subsistence users in the primarily Iñupiat communities of Kotzebue and Kivalina to discover what factors related to climate change were causing stress to subsistence users. The stressors most frequently cited were changes in sea ice, weather, coastal erosion, raised water levels and flooding, changes in snow cover, and degradation of permafrost. These stressors have unique effects on mammal populations, fishing practices, and community infrastructure.

Marine mammals, particularly those whose primary habitat is sea ice, have been among the species most affected by climate change. Ringed seals, for example, depend on stable ice for mothers to nurse their pups. Polar bears now have to swim much further to reach the ice, which is their most productive hunting habitat (Jones 2011). The shrinking sea ice also means a decline in opportunities for subsistence hunters because of lack of habitat and unsafe hunting conditions. Local residents mentioned shifts in harvest seasons for bearded seal and beluga (Green et al. 2021).

Processing a seal.
NPS/EMILY MESNER

Climate change has also affected marine mammal processing. In Kotzebue, for example, where bearded seal is a top subsistence priority, it has been harder to process this species, because the meat rots before it can dry (Green et al. 2021). In whaling communities, brittle shore ice conditions make it difficult to set up base camps or process whales onshore. Whale hunters and biologists on the North Slope of Alaska say that in recent years whales arrive earlier, whales are further offshore, and waters are rougher (Herz 2019).

The behavior of terrestrial mammals has also been affected by climate change. Caribou, a prime subsistence species for many Alaskans, live through the winter on lichens they eat through the snow. Increased precipitation may create icy crusts on the snow, making it harder for caribou to access their food, increasing the chances of winter starvation. On the other hand, warmer temperatures may also lead to earlier plant growth on calving grounds, providing increased nutrition for cows and calves.

Other land mammals have been impacted as well. When it gets too warm in the summer, moose typically seek shelter rather than foraging for nutritious foods needed to keep them healthy. Bears have been noticed coming out of hibernation early or even never hibernating. Beaver are moving north in areas where they were not previously located. A recent study found that from 2002 to 2019, the number of beaver dams grew from two to 98 in an area of less than 40 square miles near Kotzebue (Jones et al. 2020).

The effect of climate change on fish is complicated. Changes in water temperature can be consequential for fish survival (Moerlein et al. 2013). Changing water levels and shallower rivers directly impact fishing; locations that have been reliable in the past are no longer a sure bet and sometimes force people to find new spots to fish. Fishing nets or fish wheels snag on the river bottom or fill more quickly with debris, often sustaining damage in the process. Decreases in salmon runs particularly threaten a key subsistence resource for many Alaska Native communities.

In Northwest Alaska, subsistence harvesters in Noatak, Shungnak, and Selawik have noted that environmental changes are impacting their subsistence fishing practices. Lower water levels are impeding boat access to favorite fishing locations. Unpredictable weather conditions challenge traditional fish drying practices. In all three communities, residents are noticing increasing numbers of beaver moving into fishing areas resulting in dams that block boats from accessing fishing locations and creating lower water levels (Moerlein et al. 2013).

Climate change has also exacerbated the problems of erosion and flooding in rural Alaskan communities. Melting permafrost makes coastlines more prone to erosion, and barrier sea ice is coming later in the year. In Northwest Alaska, storm surges exacerbate normal erosion. Coastal villages, such as Shishmaref and Kivalina, are vulnerable to increasingly violent fall storms. These villages depend heavily on subsistence hunting, especially marine mammals. As a result of severe storms, families in Shishmaref and other coastal communities have lost their winter supplies of walrus, fish, seal, and seal oil.

Melting permafrost and erosion have increased flooding risks and caused the land around homes to erode. Several buildings in Shishmaref have crumbled into the ocean. There has been ongoing discussion of relocation of the whole village, with costs estimated at up to $1 million per household. Subsistence harvests may cost more if the community is moved. Subsistence hunters use more fuel, and their mode of transportation (e.g., boats, snowmachines) wears out faster, when they have to travel further to harvest resources. In addition to the monetary cost, relocation would cause considerable disruption to community life. If residents of a coastal community are moved further inland, they may lack knowledge of or traditional access to hunting areas near their

Kids learn how to process a caribou.
NPS/MARCY OKADA

new village. Sharing networks that households and families enjoyed in their home communities may be stressed or cease to function altogether. Relocating village residents to hub communities or urban areas would make it even harder and costlier to maintain subsistence activities and social networks. Many residents of threatened communities are aware of the possible consequences of moving and seek to avoid them in advance in the selection of relocation sites.

Interior Alaska

Communities in Interior Alaska face many of the same climate change-related problems as those on the coast. However, because of the need to travel long distances in the Interior, transportation is a special priority. People traveling across Interior Alaska are encountering climate-related changes in the environment that are challenging their traditional access to important local resources, which makes subsistence hunting costlier and riskier. New challenges include increased uncertainty about how to best prepare for seasonal changes, dangerous physical trail conditions, and unprecedented negative impacts on community life.

Rivers in Interior Alaska have always provided critical travel corridors for residents in this mostly-roadless region. Travel is usually by boat and four-wheelers in summer, and by snowmachines or dogteam in winter (Brown et al. 2018). For Interior Alaska residents, the Yukon, Tanana, Kuskokwim, and Chandalar rivers are equivalent to major highways around urban areas.

Historically, rivers and lakes have been efficient winter travel routes for snowmachine and dogteam travel (Schneider et al. 2013). Thick, stable, and predictable ice meant safe and reliable winter travel. Increasingly, subsistence users are reporting that rivers and lakes freeze later and thaw earlier than in the past. Thin ice and open water are becoming more common in midwinter, restricting access to usual travel routes and creating extremely dangerous conditions. More frequent occurrences of shelf ice forming along riverbanks can pose obstacles to snowmachine routes all winter long.

During the summer, residents of the Interior traverse large water bodies by boat or, on land, use all-terrain vehicles on limited trails. Increased erosion can make boat travel on rivers more dangerous due to the increased amounts of debris in the water, with river channels becoming shallower and wider. More sediment deposition in rivers can also quickly change well established river channels, increase the size of sandbars, and make some rivers shallower and harder to navigate. Communities located along rivers also face increased risk from flooding.

Some effects of climate change make subsistence resources more accessible. For example, unseasonably high or low water in September—an important time for moose hunting—can either help or hinder hunting. High water on main rivers covers riverbanks where moose might otherwise be found but can also fill small tributaries that improve hunting access. Abnormally low water prevents access to lakes and sloughs near river channels.

In the past two decades, Interior Alaska residents have observed changes in river ice that create significant hindrances to travel and subsistence practices. The Wrangell-St. Elias National Park and Preserve Subsistence Resource Commission recently completed a study by the Ahtna Intertribal Research Commission to gather first-hand knowledge from local subsistence users about changing ice and snow conditions in the Copper River Basin. These users reported changes in river ice, snowpack, and wind conditions over time, including later freezeups and earlier breakeups. Some of these users had observed increased difficulty in accessing key subsistence areas since as early as the 1970s (Miller 2023).

Near Denali National Park and Preserve, lifelong Alaskans Miki and Julie Collins from Lake Minchumina acknowledge that subsistence life in the bush always requires flexibility in response to severe weather conditions; however, with climate-related changes, they no longer know what to expect. During a big rainstorm in November of 2010, they were confused and alarmed by conditions that were far outside the normal range for that time of year. When there are early spring breakups they must rush to sled in supplies and fill their woodsheds before the snow melts. They have also observed that due to hot summers they are catching fewer fish.

One of their biggest challenges in responding to environmental change is planning for an unpredictable future. Miki and Julie struggle with questions: Should they rush to finish a new dog sled for trapping even though it has been years since they needed a sled by mid-October? Should they pull their fish net at the first sign of freezing even though in recent years the first ice is generally followed by weeks of warm weather (Collins 2016)?

Trails used for subsistence activities are also impacted by climate change. Trails and roads located close to riverbanks and lakes are increasingly being damaged or completely

A dog sled gets stuck in the soft winter ground.
PHOTO COURTESY OF MIKI AND JULIE COLLINS

Uncertain travel conditions make it difficult to access cabins and other places used for subsistence activities.
PHOTO COURTESY OF MIKI AND JULIE COLLINS

A family uses ATVs to go hunting. Environmental conditions, such as thin ice and open water make it dangerous to travel and machines more likely to break down.
NPS/AMY CRAVER

destroyed by bank erosion. Banks are steeper, making it more difficult to get to portages. Although trails are always important corridors for accessing resources, trail access across lakes and wetlands is limited in summer by the increased presence of water. On land, unseasonably wet conditions quickly deteriorate trails and sometimes make them impassible.

Subsistence users from Cantwell who hunt in the Traditional Use Area of Denali National Park and Preserve reported seeing more sinkholes on their way to their moose hunting camp, which are likely related to thawing permafrost (Mayo, personal communication, 2020). During the fall hunting season, these holes fill with water and sometimes cut off trail access. ATVs and snowmachines get stuck in the sinkholes.

Recently, delayed and more variable seasonal snow accumulation, as well as rain precipitation during winter, are making winter travel harder and unpredictable (Cold et al. 2020). Rain-on-snow icing events (such as one during the winter of 2021/2022 at Denali) are more common and leave the snowpack crusty, thin, and hard. Trails are much rougher and are hard on sled suspensions and dogs' feet. It is much easier to get stuck on brush and overheat snowmachines that need a deep, soft snowpack to cool engines. With these changing conditions, there is more use of four-wheelers during the winter season.

Environmental changes also impact people as they traverse the landscape. Travel is more dangerous in conditions such as open water during winter, or debris-filled rivers during summer. The changes in the landscape are hard on equipment, causing boat motors to clog more often or ATVs to break down. In some cases, access can improve; for example, high water levels in fall have allowed travel up small streams that may have previously been unnavigable (Green et al. 2021).

Some hunting, fishing, trapping, and gathering opportunities are reduced or even missed, with increased variability in seasonal weather and physical events such as the timing of fall freeze-up and spring break-up. River ice deteriorates faster in the spring, increasing the length of the period when river travel by snowmachine is unsafe yet boating is still impossible (Brown et al. 2018). Higher precipitation levels and warm temperatures during a time of year that was previously dry and cool affects fall hunting opportunities. All these environmental changes have made for more uncertain travel conditions throughout the year.

In addition to its effect on travel and subsistence harvests, climate change has many other impacts on community life. Researchers led by the Tanana Chiefs Conference conducted a study to document Traditional Ecological Knowledge (TEK) on climate change observations from the Koyukon Athabascan people of Allakaket and the Iñupiaq people of Alatna. Both communities reside near the Gates of the Arctic National Park and Preserve. The study included observations of species and habitat change as well as traditional stories associated with climate change.

Like many Native peoples across Alaska and the Arctic, the residents of Alatna and Allakaket are noticing changes in temperatures while the seasonal patterns are far less predictable than in the past. Community members consistently mentioned that freeze-up is getting later. They also noted that springtime is arriving earlier and it is getting warmer faster. This change is not just significant to subsistence activities but also to the social life of both communities. Alatna, located across the Koyukuk River from Allakaket, does not have a school, store, health clinic, gas station or airport, so it impacts the entire community when the river is not suitable for travel during freeze up and break up. When the Koyukuk River freezes up two weeks later than usual, the children from Alatna cannot attend the school located in Allakaket. The ice instability has a direct impact on school attendance (Watson 2018).

Subsistence users observe climate change first-hand. Bob and Carrie Uhl lived in rural camps at Cape Krusenstern for 54 years. They spent their summers in a tent or tiny cabin on the beach at Sisualik, where they were able to fish and hunt marine mammals. In the winter, they moved inland to a more sheltered cabin where trees provided wood for heat, a stream running under the ice provided water, and moose and caribou provided food. They were the last full-time residents of the Monument. Bob kept a daily journal of resource observations of the Cape Krusenstern area from 1990 to 2004. He generously gave permission for the National Park Service to publish and use his journals **in order to share this valuable insight into a vanishing way of life.**

Community Strategies for Resilience

Traditionally, communities and families respond to ordinary fluctuations in subsistence foods through harvesting flexibility and increased sharing. Alaska Natives and rural residents share subsistence resources, labor, equipment, and cash within and between extended families. Sharing resources through extensive social networks limits vulnerability to food shortages. It is traditional to share labor in harvesting and processing as well. Also, when one resource becomes unavailable or inaccessible, harvesting more of another resource makes up the shortfall. One traditional strategy to combat fluctuating resources is to harvest multiple species and trade any excess harvest to other communities. Coastal communities have often traded marine mammal products in exchange for land mammal products from inland. Climate change can especially impact cooperation if several preferred subsistence resources are at risk at the same time. Sharing, trading, and cooperation may pose new challenges if people need to move to new subsistence areas or need to disperse farther to harvest foods. In the face of individual and community relocation, and of increased difficulty in procuring traditional foods, these networks will need to become more complex and stretch over wider distances (Callaway 2013).

Subsistence users from Kotzebue and Kivalina identified some of the strategies they might employ if harvesting animals became more challenging due to environmental changes and unpredictable conditions. One strategy was to use different or multiple means of transportation (boat, ATV, or snowmachines) to hunt on land or sea ice, or to travel to subsistence camps (Green et al. 2021). When hunters have to travel further, they need bigger and more expensive boats and motors, and they need to pay more for fuel. Wealthier families are thus able to gain greater access (Godduhn et al. 2014). In Kotzebue, some subsistence users reported using the internet and social media to find locations and abundance of animals. They also mentioned the need to shift to hunting new species, which would necessitate time to acquire knowledge about how to harvest new plants and animals. Increased sharing and cooperation, however, could mediate climate change-caused stress on subsistence activities (Green et. al. 2021).

Subsistence users from the Denali region suggested changes in Park management to account for environmental changes by shifting hunting regulations based on current seasonal weather conditions, reestablishment of traditional practices such as sheep hunts and changes to regulations to allow younger family members to hunt for elders (Knapp et al. 2014). In addition, to promote traditional mentorship, the NPS can support culture camps and school programs to ensure that opportunities

Nunamiut travelers assess a snowmachine as they return to Anaktuvuk Pass.
NPS

continue for intergenerational transmission of knowledge, and so that people of all ages can learn about changes to the environment.

In other parks, staff are working with Subsistence Resource Commissions to develop wildlife regulatory proposals to respond to impacts of climate change on resource populations, habitat, and harvest seasons. In the Alaska region, the NPS Subsistence Advisory Committee has been systematically funding subsistence harvest projects where there are information gaps or urgent concerns. The data gathered in these projects may be compared to past or future years to document changes in harvest levels, use areas, and sharing.

Corrie Knapp's dissertation research at Denali National Park and Preserve explored how climate change challenges conservation strategies of protected areas. Knapp interviewed long term Denali National Park and Preserve staff, scientists, subsistence community users, bus drivers, and business owners to assess what types of observations can contribute to adaptation planning for climate change that will positively impact both ecological resources and local subsistence users. The study demonstrates that observations of users on the ground can provide important information to understanding climate change and should be included with other stakeholders' engagement and adaption planning for conservation areas. With increased participation by stakeholders in climate adaptation planning, managers can make better informed decisions (Knapp et al. 2014).

Future NPS projects are needed in order to mitigate the impacts of climate change on subsistence uses and develop climate change adaptation strategies. The agency can collaborate with tribes and local communities to develop awareness, education, and knowledge about climate change. For example, establishing a central online database of local subsistence topics, such as where berries grow, when and where ice develops, and the thickness of seal blubber and caribou fat could help develop the bigger picture of regional and systemic change. The NPS can work with schools and other agencies to increase education about climate change, highlighting concrete examples of climate change that could motivate subsistence users and others to change their behaviors toward the environment. As part of the Federal Subsistence Management program, the NPS should support changes to regulations that mitigate the impacts of climate change, such as establishing proxy hunts, reestablishing traditional practices that promote wider distribution of harvests, and integrating local observations and knowledge more effectively in decision making.

The effects of climate change have already greatly impacted the lives of subsistence users in Alaska. Documenting environmental changes, and identifying the directions of change, can help rural subsistence users, as well as federal and state managers, prepare for the challenges of the future.

REFERENCES

Brown, D., T. Brinkman, D. Verbyla, C. Brown, H. Cold, and T. Hollingsworth. 2018.
Changing river ice seasonality and impacts on Interior Alaskan communities. Weather, Climate, and Society 10(4): 625-640.

Callaway, D. S. 2013.
The long-term threats from climate change to rural Alaskan communities. Alaska Park Science 12(2): 86-91.

Collins, J. 2016.
When Snow Becomes Rain and Other Impacts of Warming Weather on Subsistence Life in Alaska. Available at: https://www.nps.gov/dena/getinvolved/dca_collins.htm (accessed July 20, 2023)

Cold, H. S. T. J. Brinkman, C. L. Brown, T. N. Hollingsworth, D. R. N. Brown, and K. M. Heeringa. 2020.
Assessing vulnerability of subsistence travel to effects of environmental change in Interior Alaska. Ecology and Society 25(1): 20.

Druckenmiller, M. L., R. Thoman, and T. A. Moon. 2022.
Arctic Report Card 2022: Executive Summary 2022. NOAA Technical Report OAR ARC 22-01. 2022.

Godduhn, A. R., N. M. Braem, and M. L. Kostick. 2014.
Subsistence Wildlife Harvests in Kotzebue, Alaska, 2012-2013. Alaska Department of Fish and Game, Division of Subsistence, Juneau, Alaska, USA.

Green, K. M., A. H. Beaudreau, M. K. Lukin, and L. B. Crowder. 2021.
Climate change stressors and social-ecological factors mediating access to subsistence resources in Arctic Alaska. Ecology and Society 26(4): 15.

Green, K. M., S. S. Fletcher, A. H. Beaudreau, and S. M. Whiting. 2020.
Iñupiaq values in subsistence harvesting: Applying the community voice method in Northwest Alaska. Society & Natural Resources 33: 122-137.

Herz, N. October 29, 2019.
No Bowhead Sightings Yet For Alaskan Whalers. Some Blame Climate Change. Alaska Public Radio. Available at: https://www.npr.org/2019/10/29/774177054/no-bowhead-sightings-yet-for-alaskan-whalers-some-blame-climate-change (accessed July 20, 2023)

Jones, B. M., K. D. Tape, J. A. Clark, I. Nitze, G. Grosse, and J. Disbrow. 2020.
Increase in beaver dams controls surface water and thermokarst dynamics in an Arctic tundra region, Baldwin Peninsula, northwest Alaska. Environmental Research Letters 15(7): 075005.

Jones, N. 2011.
The polar bear struggle. Nature Climate Change 1: 433.

Knapp, C. N., F. S. Chapin III, G. P. Kofinas, N. Fresco, C. Carothers, and A. Craver. 2014.
Parks, people, and change: The importance of multistakeholder engagement in adaptation planning for conserved areas. Ecology and Society 19(4): 15pp.

Miller, O. 2023.
Winter travel, access, and changing snow and ice conditions in Alaska's Copper River Basin. Natural Resource Report. NPS/WRST/NRR—2023/2508. National Park Service. Fort Collins, Colorado.

Moerlein, K., C. Carothers, and J. A. Lopez. 2013.
Observations of Changing Conditions in Northwest Alaska and Impacts on Subsistence Practices. Alaska Park Science 12(2): 58-63.

Pete, M. 2010.
Written testimony for field hearing on "The Changing Arctic: Implications for Federal Resources and Local Communities" before the Senate committee on commerce, science, and transportation. Available at: Senate Hearing, 111TH Congress - The Changing Arctic: Implications For Federal Resources and Local Communities | PDF | Exclusive Economic Zone | Northwest Passage (scribd.com) (accessed July 20, 2023)

Schneider, D. P., C. Deser, J. Fasullo, and K. E. Trenberth. 2013.
Climate data guide spurs discovery and understanding. Eos 94(13): 121-130.

U.S. Department of Agriculture Northwest Climate Hub. 2023.
A storm is brewing: Climate change and coastal storms in western Alaska. Available at: https://www.climatehubs.usda.gov/hubs/northwest/topic/storm-brewing-climate-change-and-coastal-storms-western-alaska (accessed July 20, 2023)

Watson, A. 2018.
Ethnographic Overview and Assessment of Gates of the Arctic National Park and Preserve: Subsistence Land Use of the Kobuk Preserve. National Park Service, Alaska Region.

Hanging salmon in a smokehouse to cure.
NPS/CAROL ANN WOODY

Using Satellite Imagery to Detect the Changing Seasonality of River Ice

Dana R.N. Brown, Christopher D. Arp, Todd J. Brinkman, Melanie Engram, and Katie V. Spellman
University of Alaska Fairbanks

Barbara A. Cellarius and Mark E. Miller,
National Park Service

River ice navigability has changed, making conditions unreliable and unsafe for many traditional activities. Using satellite remote sensing, researchers have documented the historical changes in local river ice seasonality and characterized the patterns and drivers of open water hazards along rivers.

Citation:
Brown, D. R. N., C. D. Arp, T. J. Brinkman, B. A. Cellarius, M. Engram, M. E. Miller, K. V. Spellman. 2023. Using satellite imagery to detect the changing seasonality of river ice. *Alaska Park Science* 22(1): 80-89.

For many Alaskans, rivers are important travel corridors, both in the open-water season and over the ice cover in winter. Rivers provide access to the broader landscape, including hunting, fishing, trapping, and gathering areas that support the traditional harvest of local wild resources (Brown et al. 2022, Wolfe 2004). In areas throughout the state, climate change has negatively impacted river ice conditions for travel, with later and less predictable freeze-up, thinner ice, more open-water leads, and earlier break-up (Brown et al. 2018, Carothers et al. 2014, Cold et al. 2020, Herman-Mercer et al. 2011). These conditions can limit the window of wintertime river ice travel and access to resources, and present serious safety risks to travelers.

The Copper River Basin of Southcentral Alaska is one such area where residents have expressed concern about major changes in river ice conditions and the impacts on their lives. This is a rural area with small communities located along a road network primarily to the west of the Copper River (Figure 1). With only one bridge, local residents must cross the river to access land to the east of their communities. This land is within the traditional territory of the Ahtna people and currently comprises Wrangell-St. Elias National Park and Preserve, with inholdings owned by Ahtna, Incorporated, a regional Alaska Native Corporation, and Chitina Native Corporation, a village Alaska Native Corporation , as well as Native allotments owned by individuals (Figure 1). Several other rivers cross the park, further creating barriers to access when ice conditions are unsafe. Residents recall a time decades ago when they were able to easily and predictably cross ice-covered rivers in winter; however, this has become more difficult with rivers freezing later (or not at all), with unpredictable and unstable ice, and earlier break-up (Miller 2023).

These concerns prompted studies of wintertime access to subsistence resources in the national park and preserve. This study focuses on the use of satellite remote sensing to achieve two main objectives: (1) to document the historical changes in local river ice phenology (i.e., seasonality) and (2) to characterize the geospatial patterns and drivers of open water hazards along rivers. Our goals were to understand how river ice navigability has changed and to foster safe access to traditional lands and resources.

Open water on the Copper River, February 14, 2023, Wrangell-St. Elias National Park and Preserve.
NPS/BARBARA CELLARIUS

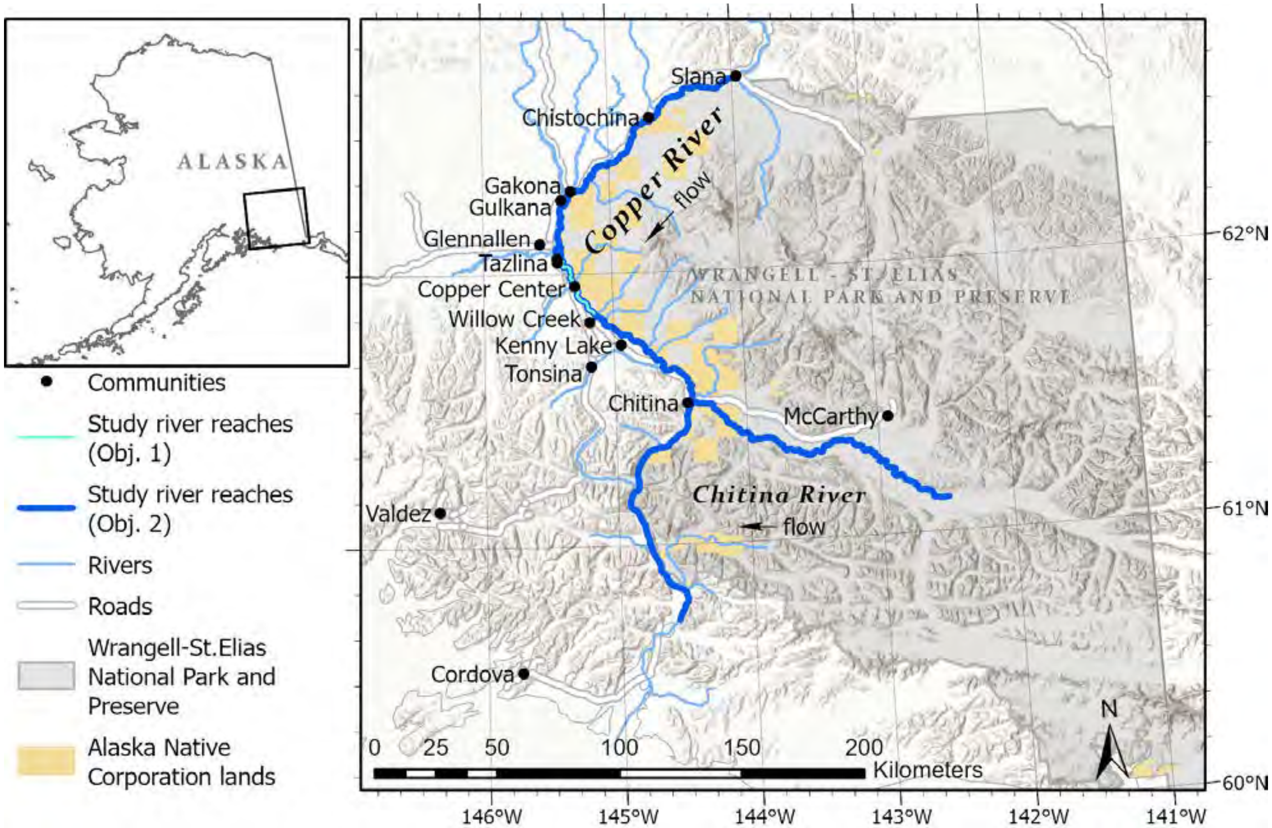


Figure 1. Study area map within the Copper River Basin of southcentral Alaska showing Copper River and tributaries, nearby communities, roads, boundaries of Wrangell-St. Elias National Park and Preserve, and Alaska Native Corporation lands within those boundaries. Study river reaches are depicted in cyan for Objective 1 (changes in river ice phenology) and royal blue for Objective 2 (geospatial patterns of ice cover).
LAND STATUS FROM BUREAU OF LAND MANAGEMENT AND ALASKA DEPARTMENT OF NATURAL RESOURCES, AND TOPOGRAPHY FROM ESRI, FAO, NOAA, USGS.

Long-term Change and Variability in River Ice Cover and Accessibility

We investigated changes in river ice cover and navigability using a ~50-year archive of satellite imagery from the Landsat Program. This analysis was focused on a 30-km portion of the Copper River near the community of Copper Center during water years (WY) 1973 to 2021. The water year is defined as October 1 – September 30, and named after the calendar year in which it begins. We chose this reach because it lies within the swath overlap of different satellite passes, which allowed us to maximize the frequency of Landsat observations. We examined variation in weekly ice extents, which we defined into categorical classes to represent the potential for widespread river ice travel (high ice extent) versus relative inaccessibility (low-moderate ice extent; Figure 2). These classifications were based on our visual interpretation of satellite imagery. The high ice extent class was defined as < 25 % of the river reach length affected by open water. Photos submitted by citizen scientists and from time-lapse cameras helped inform and validate our interpretations of the satellite imagery (Figure 2; Bondurant et al. 2022, FEI 2022, GLOBE 2022). Large open-water leads were easily detectable in the satellite imagery, but not all subpixel (<60-m) water features or other ice-related hazards could be identified.

From year-to-year, we observed substantial variation in the timing, duration, and presence of high ice extents that would enable widespread river travel (Figure 3). Winters with incomplete freeze-up, or with only one week of high ice extent, were very common in recent years: WY 2013, 2014, 2015, 2018, 2019, and 2020. Though less common, winters with incomplete freeze-up were documented even in the early years of the Landsat record, including WY 1976 and 1983. However, there were numerous years for which we could not determine the occurrence of incomplete freeze-up, due to historic and seasonal gaps in suitable Landsat imagery.

Comparing weekly ice extent between the approximately equal time periods of WY 1973-1997 with WY 1998-2021, we found that the more recent time period had a consistently lower proportion of high ice extent observations for the full freeze-up through break-up cycle (Figure 4). For the WY 1973-1997 time period, there was an eight-week period (first week of February through last week of March) where the majority of weekly observations (>50%) were of

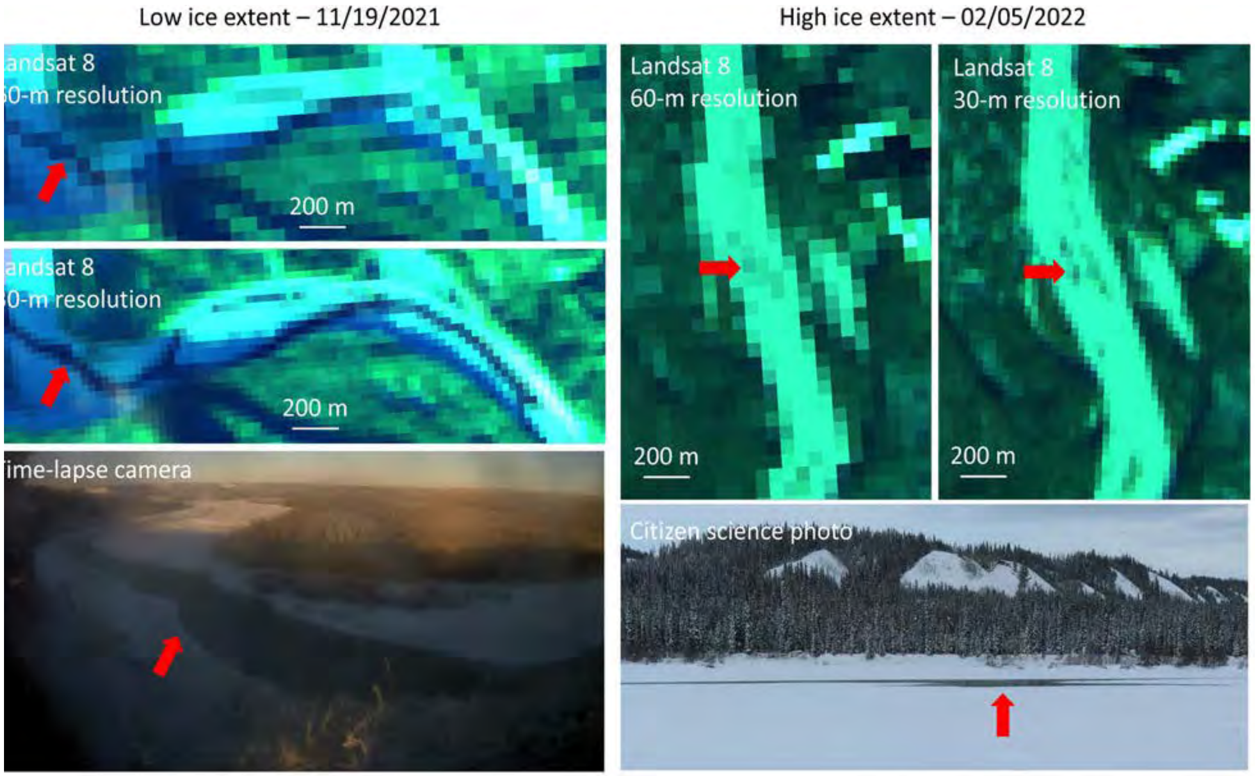


Figure 2. Example of low (left panel) and high (right panel) ice extent classes shown for segments of the Copper River study reach north of Copper Center. Classes were assigned by interpreting Landsat images at 60-m resolution to be consistent across sensors. Landsat 8 images are shown in the resampled 60-m resolution and original 30-m resolution, and are displayed with shortwave infrared, near infrared, and green bands. Below are photographs taken from a fixed time-lapse camera (left) and citizen science observer (right) on the same dates as the satellite image acquisitions. Open water is present in both low and high ice extents. Red arrows indicate the location of open water pictured in the photographs on the Landsat images.

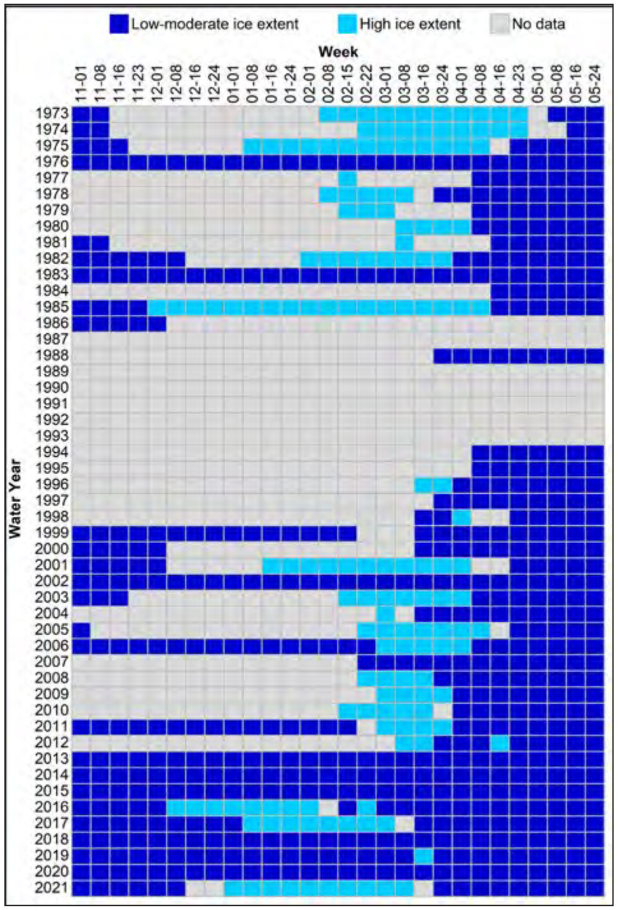


Figure 3. Matrix of gap-filled ice extent observations of 30-km reach of Copper River near Copper Center derived from Landsat imagery, summarized by week and water year, showing the historic and seasonal structure of data gaps and the interannual variation in weekly ice extents.

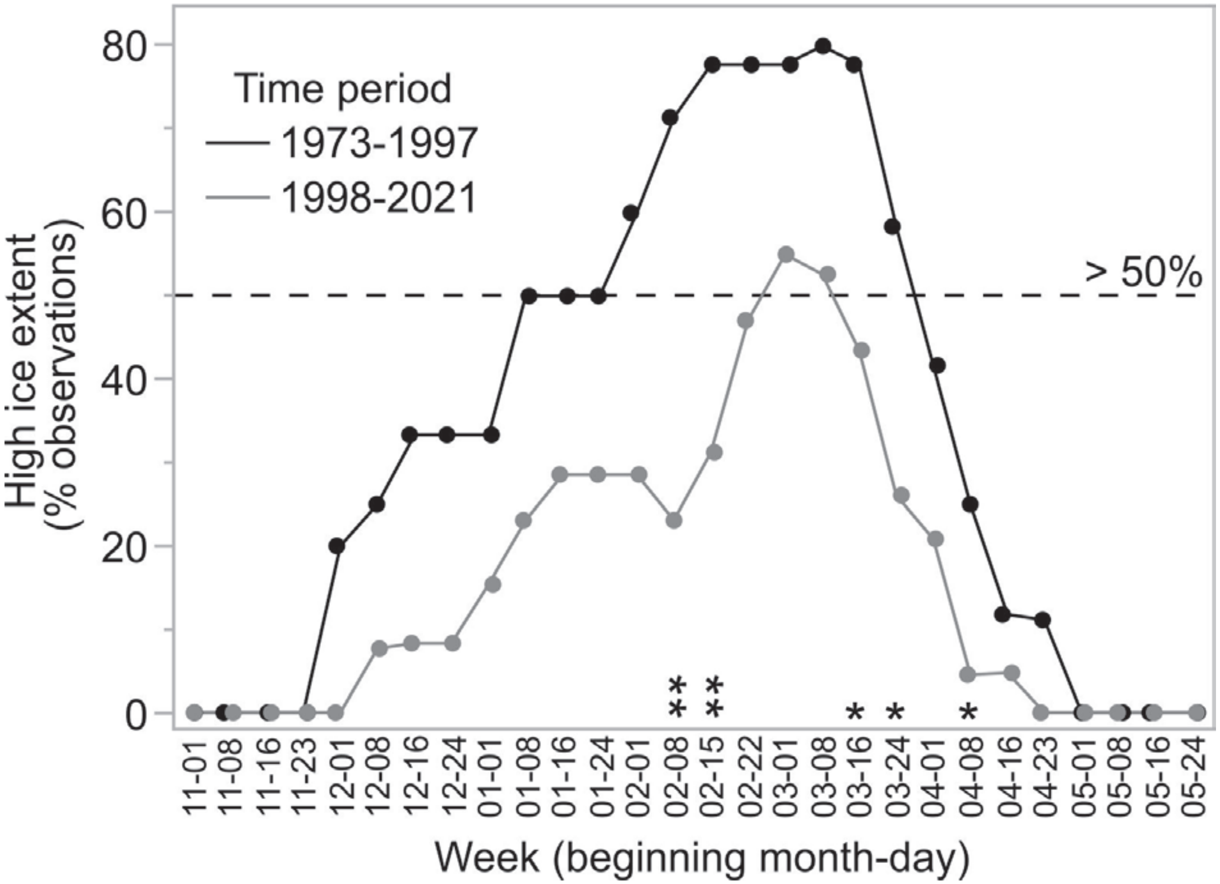


Figure 4. Weekly occurrence of high ice extent expressed as percentage of total Landsat observations by time period (Water Year (WY) 1973-1997 and 1998-2021) for 30-km reach of Copper River near Copper Center, showing the reduced occurrence of high ice extents in the recent time period. The majority of weekly observations by time period were of high ice extents for the points above the dashed reference line (>50%). Statistical significance of weekly contingency analyses conducted from 02-08 through 04-08 is denoted as **P < 0.05 and *P < 0.1.

high ice extents. By contrast, the WY 1998-2021 time period only had a two-week period (first and second weeks of March) where the majority of observations were of high ice extents.

To examine trends in weekly ice extent throughout the time series (WY 1973-2021), we used logistic regression to relate the proportion of observed ice extent categories to year on a weekly basis. The seasonal scope of this analysis was limited to late winter through spring (second week of February through second week of April), as only these weeks had a sufficient number of data points in each category. We found significant declines in the probability of high ice extents for each week tested (Figure 5a). Between WY 1973 and 2021, the probability of weekly high ice extent occurrence declined by an average of 53.3 (± 6.6) percentage points (difference in percentages, not the percent change; Figure 5b). For example, the probability of high ice extent between WY 1973 and 2021 declined from 74% to 17% for the second week of February, from 89% to 37% for the second week of March, and from 48% to 1% for the second week of April. For WY 1973, ice extent was most likely high (ranging from 68% to 89% probability) for eight of the nine weeks tested, whereas for WY 2021, high ice extent was unlikely (ranging from 7% to 40% probability) for this same time span.

To infer longer-term changes (WY 1943-2021) in ice extent for our study reach beyond the years of the Landsat record, we first examined relationships between our observations and metrics of local air temperature. Daily freezing degree days (FDD) were calculated by subtracting the daily mean air temperature from 0°C. Daily FDD is therefore positive when mean air temperature is below freezing, and negative when above freezing. Accumulated freezing degree days (AFDD) is the sum of daily FDD from the beginning of the water year. We found that AFDD was strongly related to ice extent for eight of the nine weeks tested with logistic regression (early February - early April, P = 0.0003 - 0.02). We therefore used seasonal $AFDD_{Oct\text{-}Apr}$ for the full potential ice season to represent climatic conditions relevant to the river ice cover. Despite high variability among years, we found that seasonal $AFDD_{Oct\text{-}Apr}$ decreased by 15% from WY 1943 to 2021 (linear regression, $r^2 = 0.07$, $P = 0.02$; Figure 6). This

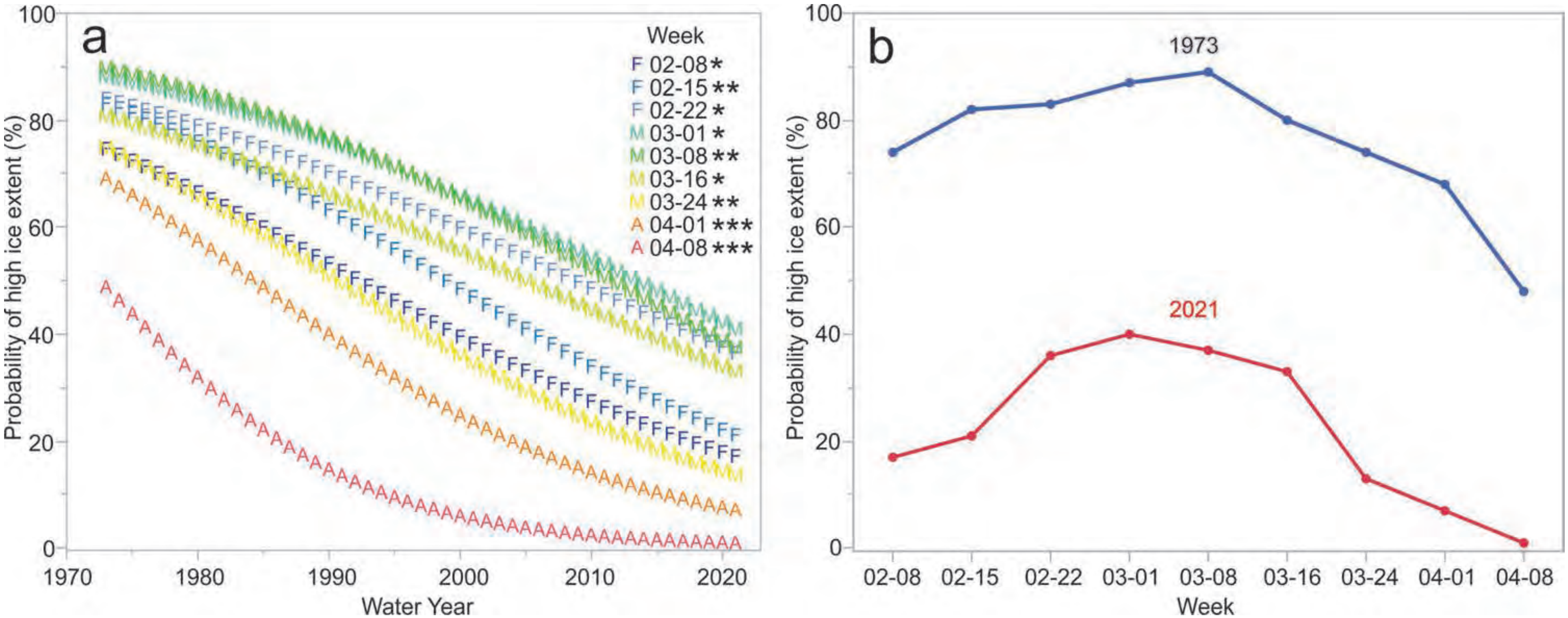


Figure 5. Change over time in the probability of high ice extents on Copper River study reach from logistic regression analyses of Landsat-derived observations.

Panel (a, above left) shows weekly probability curves over the full time series (WY 1973-2021) and panel (b, above right) compares probability between the first and last years of the time series (WY 1973 and 2021).

Decreasing trends in probability of high ice extents were found for all weeks tested. Statistical significance is denoted as ***P < 0.01, **P < 0.05, *P < 0.1.

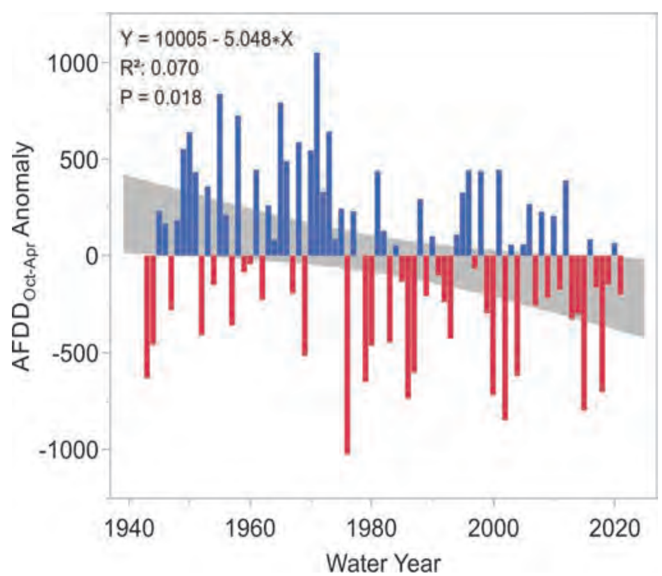


Figure 6 (left). Trend and variation in accumulated freezing degree day $(AFDD)_{Oct\text{-}Apr}$ anomaly from WY 1943-2021, derived from local daily mean air temperatures. Positive anomalies (colder than average) are shown with blue bars, negative anomalies (warmer than average) are shown in red. Statistics for simple linear regression are reported, and the 95% confidence interval for the mean response is shown in gray, showing a 15% decline in $AFDD_{Oct\text{-}Apr}$ and long-term warming trend.

trend indicates a long-term change over the last ~80 years towards warmer conditions and reduced ice cover through the freeze-up to break-up cycle.

Together, these analyses suggest that the formation of an ice cover conducive to travel (high ice extent) has shifted to later in the winter, that incomplete freeze-up has become more common, and that break-up has advanced to earlier in the springtime. The reduced and sometimes nonexistent periods of widespread ice cover can seriously limit the ability of residents to cross the river near their communities to access traditional lands and subsistence resources. However, we expected the patterns of open water occurrence to vary along the length of the river, which was the second focus of our study.

Geospatial Patterns in River Ice Cover and Open Water Occurrence

To assess geospatial variation in accessibility, we mapped open water area by river reach using Sentinel-2 optical imagery from late-winter for three recent years (WY 2018, 2020, and 2021). This analysis included approximately 217 miles (350 km) of the Copper River from Slana to south of Chitina. We compared open water area with hydrologic and geomorphic characteristics of the river reaches (Figure 7). We also examined Sentinel-1 Synthetic Aperture Radar (SAR) imagery and mapped water occurrence throughout the winters of WY 2018-2020 to visualize the progression of freeze-up (Figure 8). SAR remote sensing works by sending radar signals from the satellite sensor to Earth and measuring the strength of the signal that is reflected back to the sensor ("backscatter intensity"), which is influenced by the physical properties of the target.

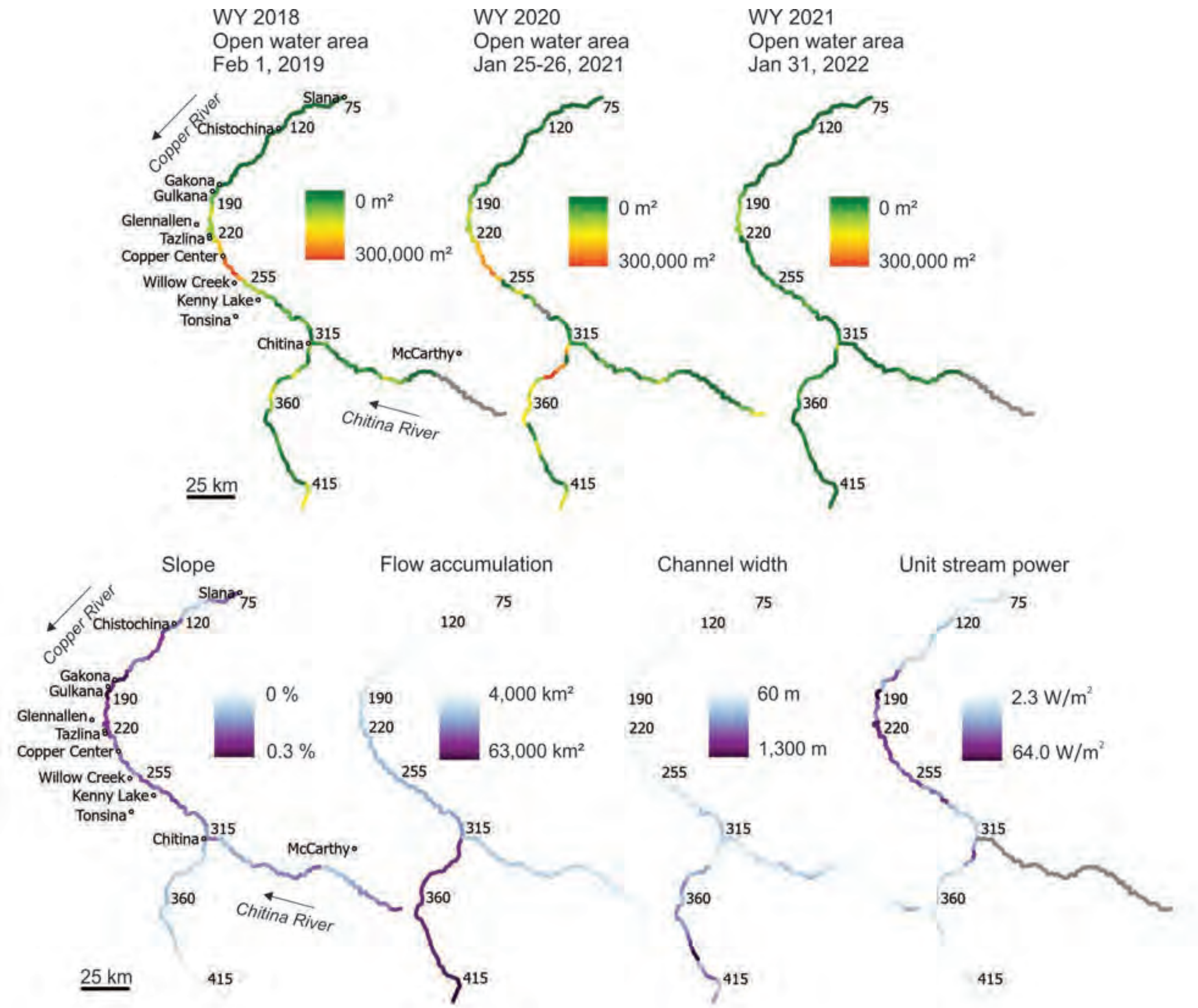


Figure 7. Geospatial patterns of late-winter open water area (top panel) and hydrologic characteristics (bottom panel) of Copper and Chitina Rivers by 5-km reach. Numbers along Copper River indicate river-km at tributaries that demarcate reaches with distinct hydrologic characteristics. Total areas of open water in late winter were calculated from Sentinel-2 multispectral images acquired in the water year (WY) on dates indicated. Hydrologic characteristics include river slope, flow accumulation, cumulative channel width, and unit stream power. Arrows indicate flow direction and nearby communities are indicated. Study reaches with no data are depicted in gray.

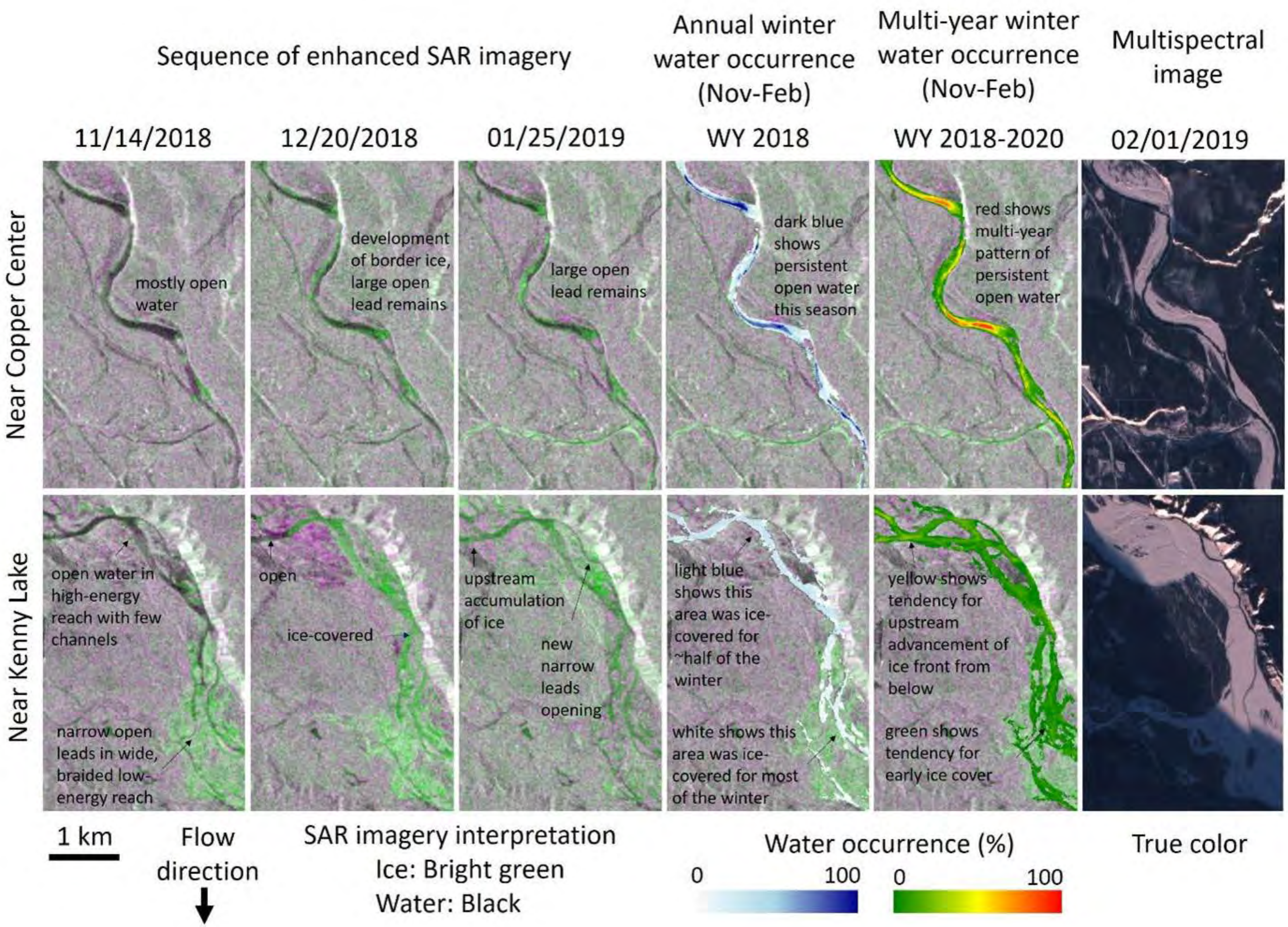


Figure 8. Sentinel-1 SAR imagery was enhanced by combining autumn and winter scenes and water occurrence was mapped throughout winter (by compositing threshold-based water classifications) to examine the progression of freeze-up and averaged over multiple winters to identify patterns. Multispectral images (Sentinel-2) were used for validation. Above are examples from a high-energy reach of the river near Copper Center that tends to remain open through much of winter, and near Kenny Lake, where ice develops in low-energy braided reaches and then accumulates upstream. Distance from downstream jamming points influences the timing of freeze-up.

While the extent of open water varied among years, some clear geospatial patterns emerged that can help guide decisions related to local river ice travel and access (Figures 7 and 8). For example, we found that a segment of the upper Copper River between Slana and Gakona had consistently low areas of open water in late winter and may currently provide the most reliable opportunities for community-accessible ice travel and crossings. The area between Kenny Lake and Chitina had low to moderate extents of open water. By contrast, extensive areas of open water and large contiguous leads tended to persist late into winter in the area between Gulkana and Willow Creek, including by Tazlina and Copper Center.

Much of this geographic variation in persistent open water we attribute to patterns of stream flow energy, river morphology, and distance from ice jamming points affecting the development of the ice cover. We quantified flow energy as unit stream power. High river discharge, high channel slope, and narrow channel width can each contribute to high flow energy of a river reach. In general, we found that areas with high flow energy stayed open the longest, and areas with low energy and braided reaches tended to develop an ice cover earlier. Freeze-up typically begins with the development of border ice along banks. This ice cover expands laterally over time as skim ice forms or surface ice floes accumulate. High flow velocity can limit both of these processes (Shen 2010). The physical structure of narrower, sinuous, or braided reaches can accelerate the development of a complete ice cover since the border ice has a shorter distance to span and river bends provide jamming points that fill with flowing ice (Chu and Lindenschmidt 2019, Shen 2010). Once an ice front forms, ice floes can then accumulate and fill the open areas upriver. Multiple ice fronts can co-occur along the length of the river.

Interestingly, we found that ice often bridges a narrow high-energy reach below Chitina at Wood Canyon in early winter. The ice front may then advance rapidly upriver through relatively low energy and braided reaches between Chitina and Kenny Lake, and eventually into the higher energy reaches above as the winter progresses. In warmer winters, however, the advance of this ice front is inhibited and some reaches above Willow Creek (including near Copper Center) remain partially open all season.

Conclusions

This research suggests a severely diminishing season of river ice travel on the Copper River due to increasing air temperatures, including delayed or incomplete freeze-up and early break-up. This finding echoes the experiences of local residents who can no longer predictably and safely access hunting and gathering areas, private land, and public land located across the river from their communities (Miller 2023). With projected increases in air temperature, precipitation, and river discharge in this basin over the next century (Valentin et al. 2018), we can expect the duration and the contiguity of the river ice cover to continue to decline, and the activities that depend on the ice cover to be further challenged.

This study also shows geospatial variation in freeze-up and open water occurrence along the river, patterns that appear to be driven by flow energy, channel form, and the bidirectional effects of ice flow and accumulation. By mapping these patterns, we identified potential winter river ice crossing areas and areas prone to open water, which may help improve the accessibility of the landscape and preparedness for inaccessibility and hazardous conditions. In addition, these river characteristics, in conjunction with climate projections, may provide the information needed to anticipate future river ice conditions to help communities plan for and adapt to a changing climate.

Acknowledgements

A technical version of this manuscript was published in *Arctic, Antarctic, and Alpine Research* (Brown et al. 2023a). Data, map products, and code for this project are freely available (Brown et al. 2023b). This project was supported by the U.S. Department of Interior, National Park Service (P20AC00031), the National Science Foundation Arctic Observing Network and Navigating the New Arctic programs (1836523), NASA Citizen Science for Earth Systems Program (80NSSC21K0858 and 80NSSC22K1915), and the Interdisciplinary Research for Arctic Coastal Environments (InteRFACE) project through the Department of Energy, Office of Science, Biological and Environmental Research Earth and Environment Systems Sciences Division's Regional and Global Model Analysis (RGMA) program, awarded under contract grant: #89233218CNA000001 to Triad National Security, LLC (Triad).

We thank Allen Bondurant, Caroline Ketron, and Paul Atkinson for maintaining cameras, all the citizen science ice observers, the Fresh Eyes on Ice team, and the NASA GLOBE Observer program. We appreciate the constructive feedback from David Thoma and anonymous reviewers.

REFERENCES

Bondurant, A., C. Arp, D. Brown, and K. Spellman. 2022.
Alaska river ice phenology camera network, 2019-2022. Arctic Data Center.

Brown, D. R. N., C. D. Arp, T.J. Brinkman, B. A. Cellarius, M. Engram, M. E. Miller, and K. V. Spellman. 2023a.
Long-term change and geospatial patterns of river ice cover and navigability in Southcentral Alaska detected with remote sensing. Arctic, Antarctic, and Alpine Research 55(1): 2241279.

Brown, D., C. Arp, T. Brinkman, B. Cellarius, M. Engram, M. Miller, and K. Spellman. 2023b.
River ice and open water extent from satellite imagery, Copper River Basin, Alaska (1973-2022). Arctic Data Center.

Brown, D. R. N., T. J. Brinkman, G. P. Neufeld, L. S. Navarro, C. L. Brown, H. S. Cold, B. L. Woods, and B. L. Ervin. 2022.
Geospatial patterns and models of subsistence land use in rural Interior Alaska. Ecology and Society 27(2): 23.

Brown, D. R. N., T. J. Brinkman, D. L. Verbyla, C. L. Brown, H. S. Cold, and T. N. Hollingsworth. 2018.
Changing river ice seasonality and impacts on interior Alaskan communities. Weather, Climate, and Society 10(4): 625-640.

Carothers, C., C. Brown, K. J. Moerlein, J. Andrés López, D. B. Andersen, and B. Retherford. 2014.
Measuring perceptions of climate change in Northern Alaska: Pairing ethnography with cultural consensus analysis. Ecology and Society 19(4).

Chu, T. and K. E. Lindenschmidt. 2019.
Effects of river geomorphology on river ice freeze-up and break-up rates using MODIS imagery. Canadian Journal of Remote Sensing 45(2): 176-191.

Cold, H. S., T. J. Brinkman, C. L. Brown, T. N. Hollingsworth, D. R. N. Brown, and K. M. Heeringa. 2020.
Assessing vulnerability of subsistence travel to effects of environmental change in interior Alaska. Ecology and Society 25(1).

Fresh Eyes on Ice (FEI). 2022.
Ice observer, Fresh Eyes on Ice, University of Alaska Fairbanks. Available at: https://obs.feoi.axds.co/observations/ (accessed July 1, 2022)

Global Learning and Observations to Benefit the Environment Program (GLOBE). 2022.
GLOBE Observer, Global Learning and Observations to Benefit the Environment Program, NASA. Available at: https://observer.globe.gov (accessed May 30, 2022)

Herman-Mercer, N., P. Schuster, and K. Maracle. 2011.
Indigenous observations of climate change in the Lower Yukon River Basin, Alaska. Human Organization 70(3): 244-252.

Miller, O. 2023.
Winter travel, access, and changing snow and ice conditions in Alaska's Copper River basin. Natural Resources Report NPS/WRST/NRR-2023/2508. Fort Collins, Colorado.

Also see: Traditional knowledge of changes in winter conditions in Alaska's Copper River basin, this issue.

Shen, H. T. 2010.
Mathematical modeling of river ice processes. Cold Regions Science and Technology 62(1): 3-13.

Valentin, M. M., T. S. Hogue, and L. E. Hay. 2018.
Hydrologic regime changes in a high-latitude glacierized watershed under future climate conditions. Water (Switzerland) 10(2).

Wolfe, R. J. 2004.
Local traditions and subsistence: A synopsis from twenty-five years of research by the State of Alaska, Technical Paper 284. Alaska Department of Fish and Game.

Traditional Knowledge of Changes in Winter Conditions in Alaska's Copper River Basin

Odin Miller, Ahtna Intertribal Resource Commission

In Alaska's Copper River Basin, less reliable snow and ice have presented challenges for traditional winter activities such as trapping, hunting, and gathering firewood. Some of these challenges have been persistent since the 1970s. Elders, culture-bearers, and expert trappers shared their extensive knowledge and experience of change on the Copper River through interviews.

Citation:
Miller, O. 2023. Traditional knowledge of changes in winter conditions in Alaska's Copper River Basin. *Alaska Park Science* 22(1): 90-101.

Winter conditions play an important role in social-ecological systems in the rural Far North. Snow facilitates access to much of the landscape during the winter months, while frozen rivers and other waterbodies are highways on which people travel. Access to subsistence foods and other resources depends on the presence of snow and ice. Similar to elsewhere in Alaska and the Circumpolar North, the Copper River Basin's changing snow and ice conditions have presented a variety of challenges related to winter travel and activities such as trapping, hunting, fishing, and gathering firewood.

Traditional Use of the Copper River Basin and Socioeconomic Changes

The Ahtna (Atnahwt'aene), a Northern Dene Athabaskan group, have a traditional territory that includes virtually the entire Copper River Basin, as well as parts of the Upper Susitna and Tanana River basins (Figure 1). Until the early 20th century, virtually all Ahtna lived a semi-nomadic lifestyle, relocating several times each year in order to make a living from the sparse landscape. Typical winter activities on the land included hunting for moose and caribou, trapping for furbearing animals, fishing on frozen rivers and lakes, and gathering firewood. Although the Ahtna traveled extensively throughout the year, travel was easiest during the winter months, when snow smoothed out the landscape and allowed sleds to be pulled, and when frozen rivers could be easily crossed. Largest among these rivers was the Copper, both banks of which were inhabited by the Ahtna.

The 20th century brought a huge influx of outsiders into the region and dramatic consequent changes to Ahtna culture. Newly constructed highways provided year-round access to much of the region, while increasing numbers of Ahtna settled in permanent villages, all of which were located on the west side of the Copper River. Wage employment, heavy-handed government agents, shortages of wild food (Ahtna now had to compete with hordes of outsiders for fish and game), and the availability of groceries and other services in villages all contributed toward this trend of sedentarization (Simeone 2018). By 1950, nearly all Ahtna had settled in permanent villages or towns. Some still followed more limited patterns of seasonal migration, camping out for weeks at a time for subsistence activities, although this gradually disappeared over the following decades.

Close connection to the land and dependence on wild foods and other resources have persisted as part of Ahtna culture, however. Many nonnatives in the region also consider hunting, fishing, gathering, and trapping to be important to their lifestyles. In modern times, many of these activities take place during the summer and fall

Copper River downstream of the confluence with the Tazlina River, March 2022. Changing ice and snow conditions create unexpected patches of open water and dangerous crossing conditions.
NPS/BARBARA CELLARIUS

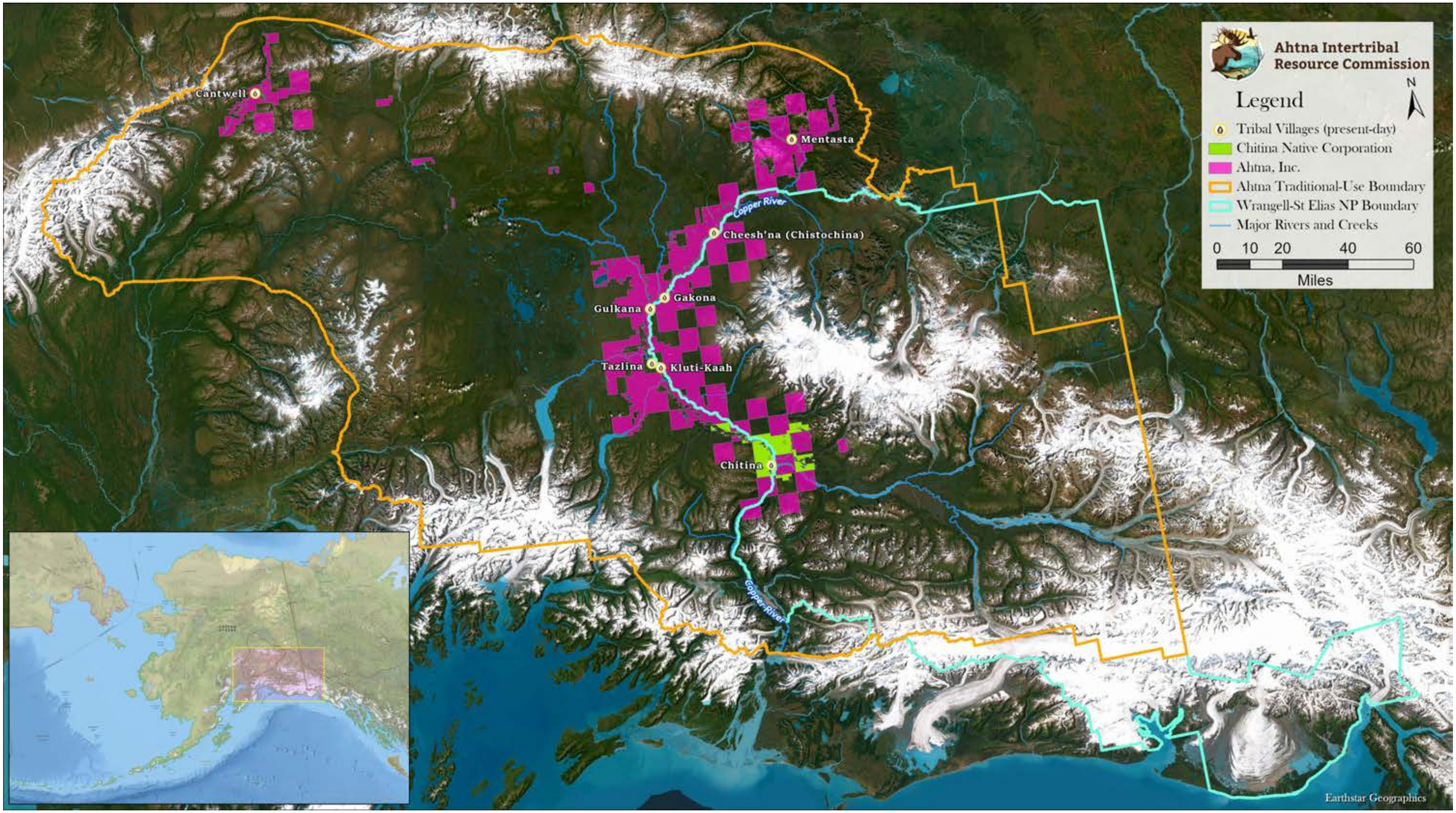


Figure 1. Map showing Ahtna Traditional Use Territory, contemporary Ahtna villages, Wrangell-St. Elias National Park boundary, and Alaska Native Corporation lands.
MAP PRODUCED BY THE AHTNA INTERTRIBAL RESOURCE COMMISSION/CASEY CUSICK

months, although winter hunting, fishing, and firewood gathering continue. Of particular significance is trapping, since it is an activity that is practiced exclusively during the winter. From the late 1800s through the mid-1900s, trapping was one of the main sources of income for many people and families in the region. As wage employment became increasingly prominent during the latter half of the 20th century, trapping gradually declined as a primary source of income. Volatile fur prices also played a role in fluctuating trapping participation during the 20th century. Nevertheless, trapping has continued as either a main seasonal occupation or as a non-professional activity for some residents of the region. As practitioners of an exclusively winter activity, trappers depend on predictable snow and ice conditions.

How Climate, Snow, and Ice Conditions are Changing

The Copper River Basin has a subarctic continental climate, where winter conditions have historically prevailed between October and April or May. However, the region is undergoing rapid climatic changes. The Arctic and subarctic regions are warming faster than virtually anywhere else on earth (Hinzman et al. 2005), while winter conditions in Alaska are warming faster than those of any other season (Wendler and Shulski 2009). The past few decades have seen a surge of research on climate change impacts on subsistence activities in the Far North, including Alaska, much of it focused on changing resource abundance, quality, or both.

Other research has explored how climate change is affecting winter travel. Dangerous Ice, a set of oral interviews conducted for Project Jukebox, an online collection of the University of Alaska Fairbanks Oral History Program (n.d.), focuses on climate-related impacts to winter travel and access on rivers and lakes in Interior Alaska. Interview respondents include subsistence hunters and trappers, scientists who study ice conditions, mushers, and recreational snowmachiners. In another study, Brown and others (2018) used a combination of geospatial data and local observations to analyze freeze-up and breakup timing (also see Brown et al., this issue). They found that while breakup was occurring significantly earlier in all communities for which they analyzed data, later freeze-up dates were occurring in only some communities.

There is little published information that specifically discusses snow and ice conditions in the Copper River Basin. There are a few scattered references to snow and ice conditions in the accounts of early Euro-American explorations of the Copper Basin. Most significantly, Lieutenant Henry Allen and his party traveled up the lower Copper River in early April 1885, as ice conditions were first beginning to degrade for the season. The party then ascended and descended the Chitina and Chitistone rivers during the latter half of April and the beginning of May, as the ice was actively breaking up (Allen 1887). Allen's report contains frequent observations of the ice conditions as he encountered them. At the end of April, for instance, the party encountered ice as it descended the Chitina River:

> After having waited a few hours for the ice to go out, and realizing no advantage by our delay, we carried our boat and baggage to the north bank of the Chittyná, at its junction with the Chittystone, and went into camp. […] An investigation showed that the ice in the Chittyná would not allow the use of a boat, and a considerable delay seemed inevitable. […] In the afternoon, at 3 p. m., we started out with the boat well loaded, carrying, besides our own party, two men, two women, five children, twelve dogs, and the worldly possessions of all (Allen 1887: 56).

After a descent of about 4 miles, the ice forbade further progress. But by the following day ice was no longer impeding progress, and Allen notes that "nearly all the snow and ice in the river-bed had disappeared" (Allen 1887: 56). Similarly, Allen's account contains descriptions of weather and snow conditions during the same timeframe: "On May 4 we left camp, contrary to the wishes of our native friends, in quite a snowstorm, which turned to rain towards the middle of the day" (Allen 1887: 57).

Unfortunately, Allen's account is unable to provide broader temporal context for his observations, as it was limited to the one season of his journey. Many subsequent expeditions, such as those of Abercrombie (1900) and Powell (1909), took place during the summer months and did not attempt to ascend the Copper River. (Abercrombie and Powell both accessed the Copper River valley by traveling over the Valdez and Klutina glaciers).

Despite the wealth of oral history interviews conducted in the Ahtna region, it is difficult to find source material that specifically discusses the topic of winter snow and ice conditions. The fieldnotes of anthropologists Frederica de Laguna and Catherine McClellan contain a 1960 interview with Kluti-Kaah Elder Elizabeth Pete that includes a brief discussion of winter ice conditions and breakup timing on the Copper River:

> **[Elizabeth Pete]:** From November to April we can walk across the Copper River.
>
> **[Interviewer]:** How long does it take the ice to go down the river?
>
> **[Elizabeth Pete]:** Oh, about 10 days […] just jam up. Then big break up comes the last. Sometimes the 5th of May; when we have an early spring, the last of April (de Laguna and McClellan 1960: Box 7.1; 7.10.60).

Although unfortunately very limited in detail, Pete's statement generally aligns with what today's Elders have said about the months when the Copper River was crossable during the mid-20th century.

Interviews Conducted

Nine oral interviews were conducted with local residents who had extensive knowledge and experience with winter activities in the Copper River Basin (see Figure 2). Respondents were selected based on their experience, using a purposive sampling strategy (Bernard 2018).

Of particular interest was trapping, because it is primarily done in the winter and is thus particularly sensitive to changing conditions. As well, there has historically been a significant amount of trapping activity on the east side of the Copper River, which cannot be accessed in the winter if the river is not frozen. Eight of the nine interview respondents had either current or former trapping experience. Of these, six had trapping experience in the region dating back to the 1970s or earlier. Four interview respondents had trapping experience within the past two decades.

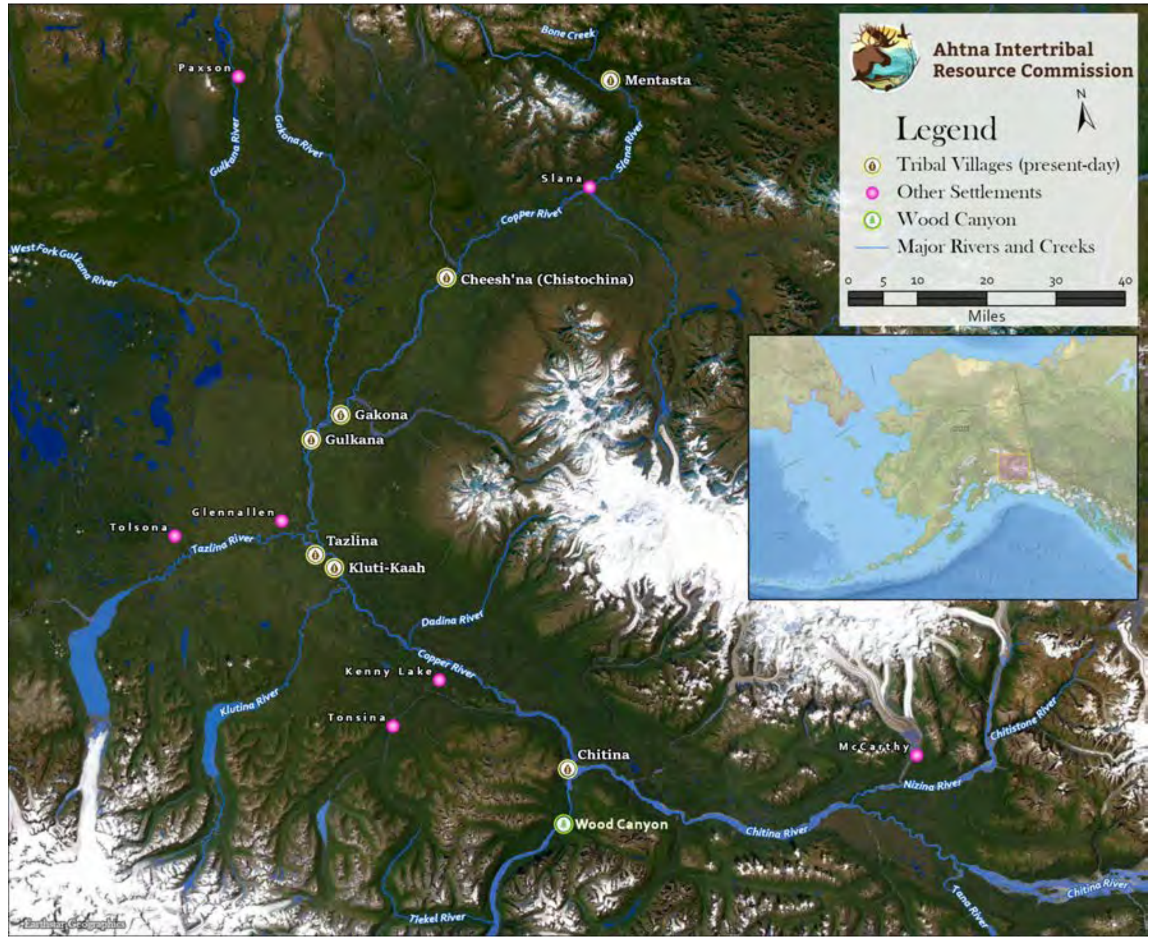


Figure 2. The Copper River drainage, showing major tributaries and communities mentioned in this report.
MAP PRODUCED BY THE AHTNA INTERTRIBAL RESOURCE COMMISSION/ CASEY CUSICK

People Interviewed	Approximate timeframe covered in interview	Locations described in interview	Tribal affiliation (if applicable)
Wayne Bell	1970s – 1990s	Tazlina – Chitina	Ahtna
Joe Bovee	1990s – present	Copper Center – Gakona	
David Bruss	1970s – present	Copper Center – Chitina, Chitina River drainage, Copper River below Chitina River confluence	
Charlie David	1970s – 2010s	Mentasta Lake area	Upper Tanana
Nick Jackson	1950s – 1970s	Copper Center – Dadina	Ahtna
Mike McCann	1970s – present	Chitina River drainage	
Philip Sabon	1950s – 1980s	Copper Center area	Ahtna
Dave Sarafin	2000s – present	Tazlina/Klutina river drainages	
Ray Stickwan	1970s	Copper Center area	Ahtna

Ice Conditions, Travel, and Access

A majority of respondents indicated that ice conditions were more favorable for travel in past decades compared to recent years. In the past, crossing rivers was less treacherous and could be done earlier in the fall and later in the spring. Even in midwinter, travel across or along rivers and streams tended to be more predictable, with some exceptions. But in more recent years, ice has been slower to form and quicker to break up, presumably as a result of warmer temperatures during the winter and shoulder seasons (i.e., late fall and early spring). Even during midwinter, a number of respondents have described more variable, and treacherous, ice conditions (for example, areas of open water or jumbled ice blocks on rivers). However, a few said they had not noticed a clear pattern of change in ice conditions over the years they had spent trapping, perhaps coinciding with the noisy fluctuations inherent in these climatic trends.

In the 1970s and earlier, respondents characterized crossing the Copper River as a very unremarkable feat. The river could be crossed in many places throughout its length. Wayne Bell and Nick Jackson described crossing the Copper, and traveling along its length, in the Copper Center area. In those days, people used to cross the river frequently for a variety of activities, including woodcutting and visiting family cabins on the east side. While there were still dangerous spots and areas of open water, these were easy to see and avoid, as Wayne Bell described:

> **Odin Miller [OM]:** Yeah. You never had to worry about […] ice?
>
> **Wayne Bell [WB]:** Nope. You just kind of pick your way—maybe a hole here and there but, those days, you could see [inaudible] because it was so cold. If there was open water you'd see steam coming through, you don't walk that way. And the ice was always three feet thick. I mean four feet thick, so you don't have to check the ice or nothing like that. You just don't walk where the steam coming out.
>
> **OM:** You didn't have to wait for certain conditions or—
>
> **WB:** No-no.

Jackson similarly noted that the ice "used to freeze solid," apart from open areas where streams flowed into the main river. He said that during his childhood in the 1940s and 1950s, his father had a trapline in the Dadina River valley, approximately 12 miles below Copper Center. He and his father would walk from Copper Center down the length of the river to access the Dadina.

Over the course of several decades, respondents have observed large-scale changes in ice conditions. Philip Sabon, an Ahtna Elder and a longtime trapper, who grew up across from Copper Center on the east side of the river, said that he and his family members had noted warming trends in the region for many decades, eventually leading to the river no longer freezing:

> **Karen Linnell [KL]:** When did that river quit freezing up in winter?
>
> **Philip Sabon [PS]:** Oh, geez, a long time—about 20 years now.
>
> **KL:** About 20 years now?
>
> **PS:** It freeze once in a while. Usually freeze October month, I think. No more it. My grandpa used to say Alaska warming up back in the '30s. I don't believe him. When I find out, it's 1950. Alaska warming up. Yeah it's. I see that. Not too cold. Yeah.

In the 1970s, later freeze-ups and earlier breakups began to shorten the trapping season (Brown et al., this issue). Nick Jackson said he had noticed the changing ice conditions on the Copper River by 1970, the last year he trapped on its east side. When asked, he affirmed that this change had an influence on his decision to stop trapping there, noting that he had to pull his traps early due to degrading ice.

Ray Stickwan, who trapped with Sabon as a young adult on the east side of the river across from Copper Center, similarly said the two began to observe changing ice conditions in the late 1970s. This shortened the trapping season by making it impossible to cross until later in the winter (Figure 3):

> **[Ray Stickwan]:** Um, yeah you couldn't even go across, like later on in the '70s right there, I remember we were having trouble. And these places he's about, the river was—like I said this was like January or so and we didn't want to—we couldn't wait till spring, you know, 'cause, by the time spring comes around, trapping's over with. So we had to go over and do our trapping when we can, you know, within a couple months.

Even when solid ice eventually does form, the later freeze-up season dates shorten the trapping season, as David remarked:

Figure 3. Approximate locations of crossing places on the Copper River during recent years, as described by interview respondent Joe Bovee.
MAP PRODUCED BY THE AHTNA INTERTRIBAL RESOURCE COMMISSION/CASEY CUSICK

Charlie David [CD]: Even, during October, used to cross that river down there. Nowadays you go down there in October to go fishing. Spear fishing.

Odin Miller [OM]: Wow. Used to be you could walk on it and now, no ice at all.

CD: Nothing. Maybe later in December when—you know. You only got one month of trapping left to do and, what's the use?

Changing Snow Conditions and Travel

As with river-ice conditions, respondents described significant changes in winter snow conditions occurring since the mid-20th century. Decreasing snowpacks—especially during the early season—have hindered winter access along the snowmachine trails used by trappers and others. However, changes in snow conditions have been more inconsistent and irregular than corresponding changes in river ice conditions. For instance, the winter of 2021-2022 began with very little snow, but ultimately saw record levels of snowfall (USDA NRCS 2022) in the Copper River Basin.

In past decades, snowfall and seasonal conditions were generally more regular, and snow could be quite deep by early November. Bell recalled that "it snowed a lot here them days," referring to conditions in the 1970s, while McCann reported that in past decades, low snowpacks early in the season did not present problems for traveling. This suggests that conditions were more predictable, in the sense that there was rarely or never too little snow for snowmachine travel. According to Bruss:

[David Bruss]: I can remember some years, before the 10th of November, where I would

> have to make special snowmachine trips to break trails open 'cause the snow was already three feet deep and trying to haul a sled full of traps to start with I needed a trail through that much snow to even begin so. We've had years when I've had to break trails open before the season just to have an established trail to work on but, it seems like, you know the trend has been less snow and later snow than what it was 40-50 years ago.

Bruss also mentioned a year during the 1980s during which there was barely enough snow in the Chitina valley to ride a snowmachine and there were areas of bare ground even at the end of February, when he was pulling his traps. But he said that this is an "exception to the rule." Bruss, who began trapping in the 1970s, did not characterize this as a change from prior conditions he had experienced. Bruss, who began trapping in the 1970s, does not characterize this as a change from prior conditions he had experienced.

As with ice conditions, the change in snow conditions was a gradual one that has taken place over the past several decades—although fewer respondents have described observing changing snow conditions as far back into the past. Stickwan described how he began to notice the consistency of the snow changing during his later years of trapping with Sabon:

> **[Ray Stickwan]:** Um, the snow was different […] I mean we call it rotten snow. Because you know where you had the hard crust snow and stuff you're able to go across. You know and ice and stuff like that, cross those creeks and stuff like that. All over there, when it colder, right there it was easy to, uh, make trails over there but you know when you got rotten snow it's like a—there's like slushy stuff right there and you—even, that affected the snowmachines, […] We used to have to bring a hatchet and clean out the ice in there, you know chipping the ice and stuff away there. Because the wetness, the wet snow. It was not like the dry snow on top of there before we used to have.
>
> But it changed, that changed, I remember that, too right there we were trying to get over. And we had to constantly clean. Not just that the skis even. [Snow] would stick to the skis we had to bring our own wax. You know, just use wax […] put some wax on it ['cause it] help it slide through snow better. […] I just remember that snow changed,

Open water on the Copper River north of Copper Center, January 2022.
NPS/BARBARA CELLARIUS

Open water on the Copper River north of Copper Center, March 2022.
NPS/BARBARA CELLARIUS

> right there, too, [actually] the warmer it got. I mean, but like those trails, there was a lot of places turned rotten fast.

In more recent years, some respondents have described a lack of snow, particularly in the early season, as a major problem. David even cited it as a major reason why he stopped trapping:

> **Odin Miller [OM]:** Like let's say if all of a sudden, the fur prices went up really high and it got to be worth it again. But if the weather conditions kept getting worse and worse, would there be certain changes you'd make to the trail to adapt?
>
> **Charlie David [CD]:** No, I wouldn't—like I say, with the weather, you know, you depend on snow for trapping. And maybe it snows two-three times a year here, that's it. And then when it snow it snow. Like October-month. You go out, try and set your trap, and there's no snow out there. And you try to use 4-wheeler and doesn't work. [Well it's] snowmachine. I mean it, [I'd say it] really affects how you trap. The weather.
>
> And, maybe end of October, around November, started raining. […] Going away, tradition. And it's all depends on the weather. And you can't—even you change your tactic you're still be dealing with rain, no snow. You just give up.

A related problem that has interacted with the more variable snow conditions is shrubification, or the proliferation of shrubs in areas of the forest and tundra that were previously clear. As a process that is occurring throughout the Arctic and subarctic, shrubification is closely associated with changing climatic conditions (Myers-Smith and Hik 2017). Several respondents discussed the issue, saying that increased growth of plants and shrubs has made travel through the forest more difficult during the winter months. This is potentially compounded during years with low snow cover. Stickwan said that in the past "you could see a long ways," but that in recent decades, "And all of a sudden all of these alders like this were coming that you had to cut through." Bruss said he sometimes has to carry a chainsaw with him trapping, which had never previously been necessary. Heavy snows can cause trees and brush to fall into the trail—a bigger problem now that the vegetation is thicker.

Related Socioeconomic Changes

A number of socioeconomic changes occurred concurrently with the changing snow and ice conditions. The earliest and most significant of these was the abandonment of settlements on the east side of the Copper River. This took place gradually during the first half of the 20th century (Simeone and Miller in preparation)—by the early 1950s, nobody permanently lived on the river's east side. It is likely that access issues, in general, contributed to the abandonment of these settlements, since modern villages and their amenities (schools, post offices, etc.) were located on the west side of the river. Even before climate-change impacts became an issue, people living on the east bank could not travel across the river during the shoulder seasons in the spring and fall.

The increasing prevalence of year-round employment has similarly affected use of the landscape—and in particular, the east bank of the Copper—during the winter months. During the early 20th century, opportunities for wage employment were limited in rural Alaska (Reckord 1983), and trapping was one of the main sources of monetary income for many families. By the 1970s, however, year-round employment was becoming increasingly common, precluding full-time trapping for a growing number of Copper Basin residents, as Stickwan noted: "Nobody was doing—in fact, like I said, there was so much money, from the pipeline and everybody working unions and everything else right there that it wasn't […] financially responsible to even try to think about—if anybody, um, trapped, it was just more because they wanted to."

Several respondents described the transition from dog team to snowmachine, which largely took place in the late 1960s and 1970s, around the time respondents first took note of changing ice conditions. One advantage of dogs is that they could sense where it was safe to cross the rivers, as Sabon explained: "You know you gonna come back. Even nighttime. The river—they know where solid ice. I let 'em go. I trust them. Next day I see their tracks—where it's solid ice they go."

McCann, who did not begin using a snowmachine until the 1990s, because he did not trust the technology, similarly said that dogs would stop as soon as they encountered overflow water:

> **[Mike McCann]:** Well, with a snowmachine you can run right into overflow, and then if it's cold or if you don't get it out it'll freeze up or this and that and everything but dogs won't. Soon as the lead dog gets his feet wet, he stops. […] Yeah, they won't go into overflow unless you make 'em. You know. Yeah. If there's overflow under the snow, they'll stop. So there's a lot of advantages to dogs in a way, you know.

However, the power of modern snow-machines enables them to speed across areas of unstable ice or even open water. Bruss noted, "[…] there's a lot of places you can cross a snowmachine that I would never try to do on foot." For instance, Bell described having to "skip," or hydroplane, across the overflow waters of the Copper River on a snowmachine, a crossing that would not have been possible on foot or dog team. McCann also noted that switching to a snowmachine enabled him to cover more territory. He described the process of breaking trail as being significantly easier on a snowmachine than with a dog team.

Northern lights dance above the Copper River.
NPS/BARBARA CELLARIUS

Conclusion

Traditional knowledge suggests that climate change has had a demonstrable impact on winter access to the landscape. Elders have noted a clear pattern of decline in ice conditions during the past several decades, with obvious impacts to trappers and others who depend on frozen rivers and lakes for travel. While snow conditions have been variable, people have experienced snow as less reliable than in the past, particularly during the early part of the season. Combined, these changing conditions have made winter access to the landscape significantly more difficult.

At the same time, climate change should be regarded as part of a suite of social-environmental factors driving changing relationships between people and the landscape.

Both changing ice conditions and non-climate factors, such as technological change and the rise of wage employment, have contributed to changes in patterns of winter activities. This, in turn, has brought about further change in how local people understand and relate to the landscape.

Acknowledgements

This article is an abridged version of a technical report (Miller 2023). The study was conducted as part of a cooperative agreement between the National Park Service and Ahtna Intertribal Resource Commission (AITRC), a nonprofit organization based in Glennallen that seeks to manage fish and wildlife resources on traditional Ahtna Athabaskan lands. Thank you to Casey Cusick, AITRC's Geographic Information Systems Specialist, for creating the maps for this article.

First and foremost, the author thanks the interview participants who generously shared the time and knowledge that made this report possible: Wayne Bell, Joe Bovee, David Bruss, Charlie David, Nick Jackson, Mike McCann, Philip Sabon, Dave Sarafin, and Roy Stickwan. Thank you to the National Park Service (NPS) Wrangell-St. Elias National Park and Preserve for providing funding for this project through a cooperative agreement with AITRC. In particular, thanks to Barbara Cellarius, the NPS Agreement Technical Representative for this project, for providing administrative support, technical assistance, and guidance on this project, as well as reviewing and providing comments on drafts of the report. Thank you to Karen Linnell, AITRC's Executive Director, who participated in one of the interviews.

REFERENCES

Abercrombie, W. R. 1900.
A Military Reconnaissance of the Copper River Valley, 1898. In Compilation of Narratives of the Exploration of Alaska, 563-590. Washington: U.S. Government Printing Office.

Allen, H. T. 1887.
Report of an Expedition to the Copper, Tanana, and Koyukuk Rivers in the Territory of Alaska in the Year 1885. Washington: U.S. Government Printing Office.

Bernard, H. R. l. 2018.
Research Methods in Anthropology: Qualitative and Quantitative Approaches. 6th Ed. Walnut Creek: Altamira Press.

Brown, D. R. N., T. J. Brinkman, D. L. Verbyla, C. L. Brown, H. S. Cold, and T. N. Hollingsworth. 2018.
Changing river ice seasonality and impacts on interior Alaskan communities. Weather, Climate and Society 10: 625-640.

Also see: Brown, D. R. N., C. D. Arp, T. J. Brinkman, B. A. Cellarius, M. Engram, M. E. Miller, and K. V. Spellman. 2023. Long-term change and geospatial patterns of river ice cover and navigability in Southcentral Alaska detected with remote sensing. Arctic, Antarctic, and Alpine Research 55(1): 2241279.

Brown and others, this issue.

De Laguna, F. and C. McClellan. 1960.
Unpublished fieldnotes, MS 299. On file at Alaska State Library Archives, Juneau, AK, and Ahtna Intertribal Resource Commission, Glennallen, AK.

Hinzman, L. D., N. D. Bettez, W. R. Bolton, F. S. Chapin, et al. 2005.
Evidence and implications of recent climate change in northern Alaska and other Arctic regions. Climatic Change 72(3): 251-298.

Miller, O. 2023.
Winter travel, access, and changing snow and ice conditions in Alaska's Copper River Basin. Natural Resource Report. NPS/WRST/NRR—2023/2508. National Park Service. Fort Collins, Colorado.

Myers-Smith, I. H. and D. S. Hik. 2017.
Climate warming as a driver of tundra shrubline advance. Ecology 106(2): 547-60.

Powell, A. J. 1909.
Trailing and Camping in Alaska. New York: A. Wessels.

Reckord, H. 1983.
That's the Way We Live: Subsistence in the Wrangell-St. Elias National Park and Preserve. Anthropology and Historic Preservation, Cooperative Park Studies Unit, Occasional Papers no. 35. Fairbanks: University of Alaska Fairbanks.

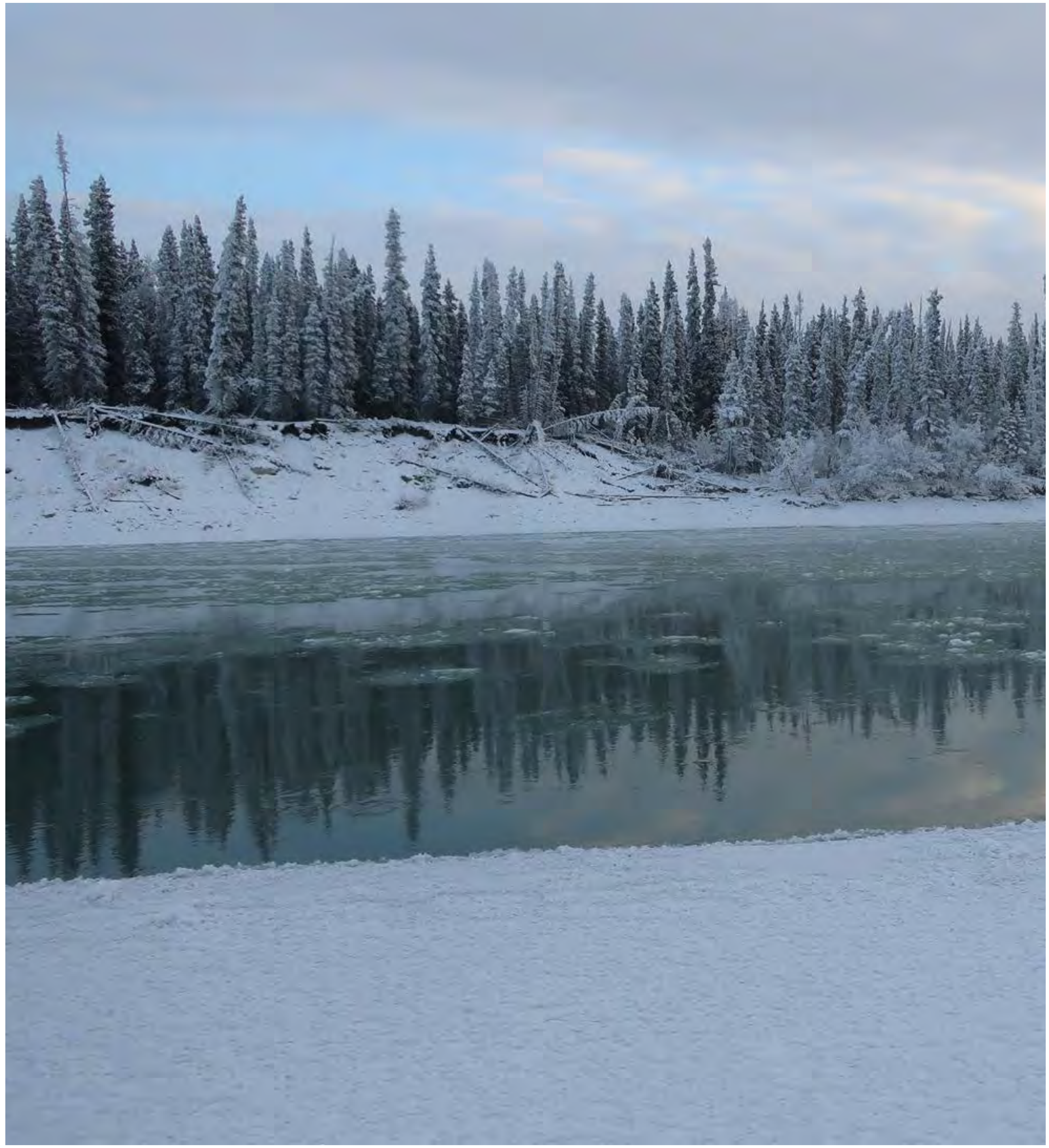
Simeone, W. E. 2018.
Ahtna: *Netseh Dae' Tkughit'e'* "Before Us, It Was Like This." Glennallen, Alaska: Ahtna, Inc.

Simeone, W. E. and O. T. W. Miller. In preparation.
Ahtna and Wrangell-St. Elias National Park and Preserve: An Ethnographic Overview and Assessment. Technical report. Copper Center, Alaska: Wrangell-St. Elias National Park and Preserve.

University of Alaska Fairbanks Oral History Program. n.d.
Dangerous Ice. Project Jukebox.
Available at: http://jukebox.uaf.edu/site7/dangerice (accessed 15 March 2022)

USDA NRCS [United States Department of Agriculture Natural Resource Conservation Service]. 2022.
Alaska Snow Survey Report. Available at: https://www.nrcs.usda.gov/wps/cmis_proxy/https/ecm.nrcs.usda.gov%3a443/fncmis/resources/WEBP/ContentStream/idd_607E9680-0000-CD11-913BC9FBB57CAB56/0/Alaska+Snow+Survey+Report+May+2022.pdf. (accessed 8 August 2022)

Wendler, G. and M. Shulski. 2009.
A Century of Climate Change for Fairbanks, Alaska. Arctic 62(3): 295-300.



Open water on the Copper River north of Copper Center, January 2022.
NPS/BARBARA CELLARIUS


2005

Communicating Science and Inspiring Hope

John Morris, Retired, National Park Service

Laura Buchheit, U.S. Forest Service

Jamie Hart, Laurie Lamm, and Paul Ollig, National Park Service

Climate change is a task society must address sooner rather than later. Park interpreters know it's important to explain the science, the changes happening on the landscape, and the reasons why, but that's only half their task. They aspire to inspire; to provoke their audiences to care. Societal action is the ultimate measure of success for effective communication.

Citation:
Morris, J., L. Buchheit, J. Hart, L. Lamm, and P. Ollig 2023. Communicating science and inspiring hope. *Alaska Park Science* 22(1): 102-109.

Effective communication about the changing climate is more than informing people about facts, it's inspiring them to appreciate and care about what the facts represent. Successful park interpreters provoke their audiences to take action and support efforts to respond effectively to the climate changes taking place in parks (Tilden 2008, Beck and Cable 1998). That's not always an easy task.

A recent study from the Yale Program on Climate Change Communication (Leiserowitz et al. 2022) found that 64% of Americans are somewhat or very worried about climate change, yet 67% of these same individuals admit they "rarely" or "never" discuss it with their friends or family. This points to the important role interpreters, educators, and science communicators have to encourage discourse and inspire people to take action. Interpreting climate change begins by understanding the science, identifying relevant culturally appropriate connections to each audience, and using the best available techniques for people to engage with the science in memorable ways.

Since 2004, the National Park Service has collaborated with National Aeronautics and Space Administration (NASA), and other federal agencies including the U.S. Fish and Wildlife Service and the U.S. Forest Service, in the Earth to Sky Partnership. In this partnership, interpreters, educators, and scientists form a community of practice to learn, share science findings and communication techniques, and develop science-rich interpretive products and programs for use in parks, refuges, and other place-based education sites. Example communication products, archives, and other valuable resources for effective science communication are available on the Earth to Sky website.

At their best, interpretive products are simple and straight-forward. The goal is to let observation and experience inspire appropriate action in response. Earth to Sky helps both communicators and scientists understand when the audience experience is sufficient, and when additional methods of discovery are needed. This article highlights examples that illustrate the process of telling stories of a changing climate while inspiring action and hope in response.

When the story to tell is complex or not obvious, interpreters can use a clear and intentional process to guide their communication efforts (NPS 2016a). The steps to do this include defining the key messages to convey, figuring out who the audiences are to receive them, and customizing the best methods to use so each message is successfully delivered.

Interpretation, like this sign in Kenai Fjords National Park marking where Exit Glacier ended in 2005, helps people tangibly visualize climate change impacts.
NPS/JESSICA WEINBERG MCCLOSKEY

A special emphasis upon audience-centered experiences and grounding the products in both science and Indigenous knowledge is also important. Most Alaska parks are subsistence parks with communities that have lived experience of climate change effects on the environment, fish and wildlife, and way of life. Reflection of the communities and culture that are part of the parks and might serve to engage public with direct and tangible understanding of impacts of climate change, inspire them to take action, and instill hope.

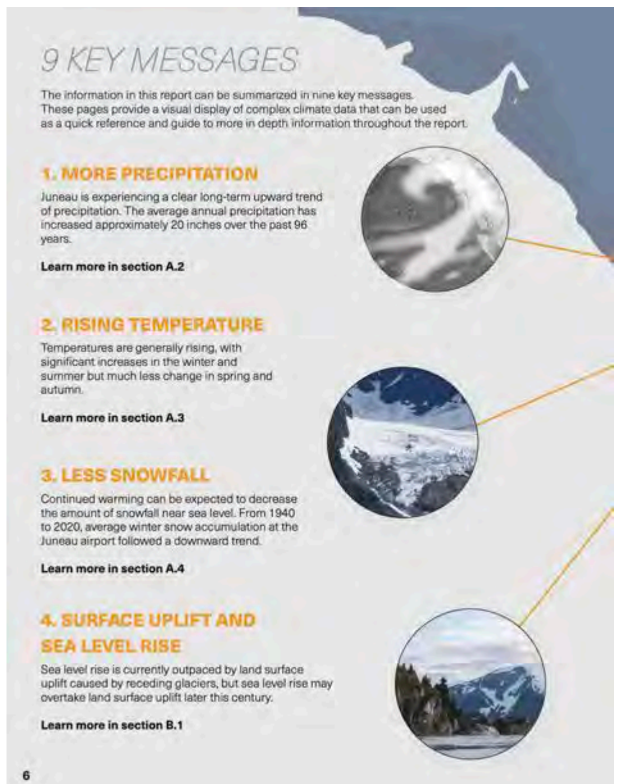
Recent models of human cognition and behavior recognize that conclusions audiences draw from their own discussion and shared experiences are much more powerful than those they are told to draw by someone else (Toomey 2023). As with science, interpretation is peer reviewed and evaluated to make sure it can be replicated or improved, as needed. In some cases, when multiple messages and audiences are involved, a formal plan is developed to outline a full communication campaign.

Defining Key Messages

What are the main concerns park managers need to address? What do they want constituents to care about and do in response? In developing interpretive products, interpreters use science to define the key messages and provide an understanding of the questions being studied. Steeping the audience in science helps reinforce any key messages or questions that need to be remembered. Most of all, grounding the products in science helps communicators explain what success would look like and why the issue is relevant to people.

Juneau's Changing Climate and Community Response

The community of Juneau designed and published *Juneau's Changing Climate and Community Response* as a unique way to inform and engage members of the community, decision makers, academics, and non-profits alike (Alaska Coastal Rainforest Center 2022). Using contributions from a variety of scientists and community members, the authors sought to develop key messages and recommended actions that could serve the whole community. The nine key messages are intended for use as a quick reference. Unique for this type of report, these key messages highlight actions by Juneau's civil society, including local non-profit organizations.



Clearly defining key messages engages the reader and provides context for recommended actions.
ALASKA COASTAL RAINFOREST CENTER

Identifying the Audience and Relevance

Once a key message or theme is defined, the next step in the interpreter's process is to determine how those messages and themes are most relevant and to whom. For each message, it works best to identify as many groups of potentially interested parties as possible. Although each person may have unique interests and values to consider, there are often groups of people who share similar concerns. To communicate best, it's important to know what is relevant to each group. This step may address community groups, tour guides and vendors, managers, visitors, students and teachers of various grades, social organizations, commercial organizations, and even scientists themselves. For some groups a written publication may be most effective, while for others, an in-person meeting or event might be best.

Interpreting Climate Change to Cruise Ship Passengers

At Glacier Bay National Park and Preserve, interpreters meet the majority of park visitors on cruise ships. Park programs and products need to be portable and engaging to supplement the experience visitors have while cruising through the park. These products also serve as catalysts for conversation about the park's significant meanings and issues, including climate change. Rangers use short presentations, a traveling visitor center, and informal roving activities to connect with thousands of diverse passengers. Social science research concluded that a majority of Glacier Bay visitors want to experience wilderness landscapes and often develop a strong sense of connection to Glacier Bay, even after just one visit (Furr et al. 2021). Yet, even though cruise ship passengers are surrounded by wilderness, their elevated shipboard viewpoint keeps them at a distance from the primary features.

In-person interaction and ranger displays help cruiseship passengers engage with climate change and the park.
NPS

Rangers and displays become a vital catalyst for passengers to have a more personal engagement with the resource. The informal setting puts passengers in control of the conversation by letting them choose what to talk about with the rangers. Passengers choose from an array of possible scientific, historical, and indigenous topics, and rangers encourage them to share from their own expertise and experience in a true dialogue of interest. Visitors often acknowledge these personal contacts with rangers as a highlight of their trip, while the desk displays and handouts provide the catalysts for that engagement and connection.

Based on social science and Earth to Sky connections, Glacier Bay interpreters recently revised the traveling desk displays onboard cruise ships to focus on the science of how climate is influencing the park. These new displays facilitate curiosity and encourage visitors to start talking about glaciers and climate change. The enthusiasm coming from their conversations create long-lasting memories.

Determining Appropriate Technique(s)

Once the audience has been identified, the next step is determining an appropriate method or communication technique to use to best reach that audience. Is a publication or exhibit going to be most accessible? Will a personal science presentation be possible? For a small community or village, is there an existing communication medium being used, like a TV or radio station, or local newspaper or bulletin? Are mailing addresses available, emails, or phone contacts? Taking the time to figure out what will work best for each group will make any outreach much more effective. Often, there may be a combination of several strategies that could work in tandem.

Listening to the Ice

In Kenai Fjords National Park, the science of global warming and climate change is delivered to elementary and middle-school classrooms across the United States, Canada, Australia and elsewhere, through a distance learning program, *Listening to the Ice*. A park ranger engages students with questions, video content, and other techniques designed to broaden their local and global understanding of climate change and leave them with a hopeful attitude about the future of the natural environment. Park rangers engage with audiences ranging from 4th graders in their classrooms, to potential visitors, and virtual travelers in retirement communities.

Interpretive Planning

For large projects, communicators will create a comprehensive interpretive plan that organizes and describes all these elements in a long-term strategy. Plans like this can be developed for all levels and regions of an organization or community. It has been done already at a national level for the National Park Service (NPS 2016b) as well as by the Department of the Interior within its climate change strategy (DOI 2021).

These plans, called Interpretive Concept Plans, help to define and develop key messages and communication strategies for telling a park's significant stories and engaging the various audiences with ways they can learn about, experience, and enjoy those stories before, during, and after their visits to the park. The development of the plan itself is a communication exercise that benefits all parts of a park's community and is revised periodically over time.

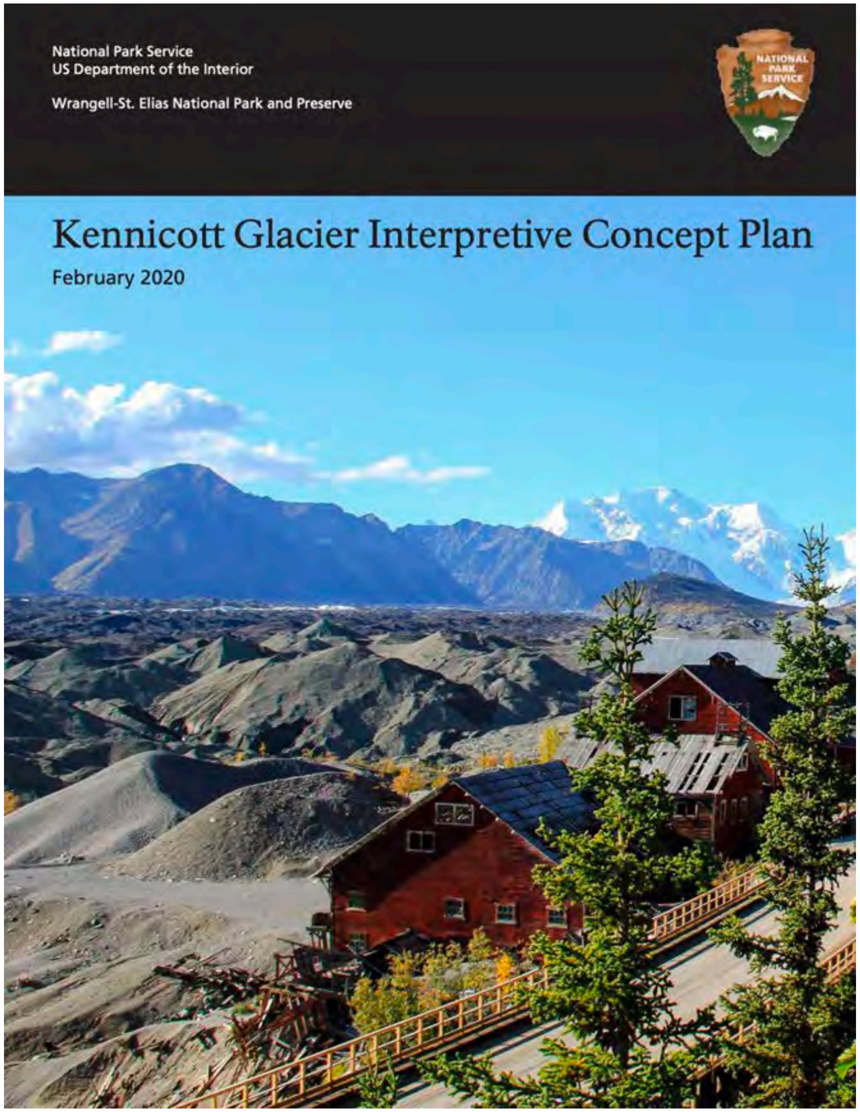
Kennicott Glacier Interpretive Concept Plan

Of the thousands of glaciers in Alaska, the Kennicott Glacier in Wrangell-St. Elias National Park and Preserve is one of the most easily accessible to visitors. It is dynamic and shrinking rapidly, which presents an opportunity, if not an imperative, to interpret these changes and their drivers (e.g., climate change). Because Kennicott Glacier is so accessible, and the changes it is undergoing are generally typical of other non-tidewater glaciers in the state, it can also be a springboard to talk about what we are learning about glaciers in Alaska generally.

One of the most common questions asked of interpretive staff in Kennecott (pointing to the debris-covered toe of the glacier) is: "Are those mining tailings?" The persistence of the question demonstrates that visitors to the park are drawing vitally important, but incorrect, conclusions about the roles of both mining and glacier change in the evolution of the natural environment in the Kennicott Valley. Until recently, there was no systematic effort to collect and present to staff, or directly to the visitors themselves, a coherent, accessible, and accurate depiction of the central role that the Kennicott Glacier plays, and has played, in the cultural and ecological history of the Kennicott Valley. The valley provides an exceptional opportunity to interpret the role that climate change is playing in the evolution of the nation's largest national park.

For these reasons, in 2020, an interpretive plan was developed to help the park provide visitors with an understanding of the extent, nature, and consequences of glacier change in Alaska, and the Kennicott Glacier specifically. Part One describes the purpose and significance of the plan, identifies the intended audiences, and introduces interpretive themes. Part Two describes the interpretive opportunities that are geographically based within the existing (or planned) infrastructure of the valley. It includes both on-site interpretive opportunities as well as virtual, web-based outreach, personally delivered and self-directed.

The park has committed to actions in this plan and is starting implementation in 2023. One new product will help answer the previously mentioned question of "Are those mine tailings?" in the form of an interpretive wayside. Park staff take the visitors' most commonly asked questions and answer them on an interpretive sign. The sign addresses the dramatic changes that have been observed,



Overarching Theme

Rapid changes in and around the Kennicott Glacier affect the entire landscape and reflect similar changes occurring at thousands of other Alaskan glaciers.

Primary Themes

- Kennicott Glacier has changed over short and long timescales in response to both natural and anthropogenic climate change.
- Ongoing glacier retreat is made conspicuous by the fact that the entire mining-era infrastructure of the Kennicott Valley was built at what was then the edge of the now-retreating glacier, and by the ongoing relationship between local residents, repeat visitors, and the changing glacier margin.
- The glacier's response to climate change is largely predictable and can be described in terms of variables like glacier size (extent and volume), ice velocity, and terminus position.
- Indirect consequences of glacier change are less predictable and include surprising effects on diverse processes.
- Rivers that enter and emerge from the glacier are highly dynamic and have profoundly impacted human development in the valley.
- Development of new ecological communities has occurred, and continues to occur, on the land adjacent to the glacier margin.
- Changes in the Kennicott Valley are representative of changes in other places and environments within Alaska, and in other glaciated regions of the planet.

Interpretive planning puts all the pieces together—key messages/themes, identified audiences, relevance, and appropriate techniques employed in appropriate places. In this case, the science (about glaciers) presented here not only pertains to the glaciers experienced at this park, but as an example of glaciers throughout Alaska.
NPS

using historical context and stories from those that lived in the area from the mining days to the modern era. Another technique for audience engagement being considered, is a citizen science product that allows visitors to play a part in capturing change, firsthand. Chronolog is a product that allows visitors to snap a photo, upload it, and then the photo becomes a part of a timelapse of the scenery that can be viewed online. In this case, the photo-taking platform would be placed within view of the Kennicott Glacier and visitors would play a part in capturing glacier change.

A Direct Link to Science

The theme and messages used in communication products about science issues depend on close collaboration between interpreters and scientists. A specific benefit of the Earth to Sky partnership is the enhanced relationship it enables with a wide diversity of world-class climate scientists. Since 2015, NASA's Arctic Boreal Vulnerability Experiment (ABoVE), has involved hundreds of scientists in a large-scale study to examine environmental change across the Arctic. They seek to gain a better understanding of the vulnerability and resilience of ecosystems and society to this changing environment. Through the partnership with Earth to Sky, interpreters and educators have learned how ABoVE field-based and process-level studies by scientists help provide a foundation to better understand and predict future changes and their implications across the Arctic. As the research campaign enters its third and final phase, new communication products will be developed to share these results with many audiences.

Pretty Rocks: A Denali Challenge

Geologists have documented the Pretty Rocks landslide in Denali National Park and Preserve which has been active since at least the 1960s. In recent years, it has evolved from a minor maintenance issue to a substantial visitor safety concern. Based on climate data from 1950 to 2010, the park has experienced a temperature increase of 7.7°F, one of the largest increases among all national parks (Gonzales et al. 2018). This increase in mean annual temperatures combined with heavy precipitation events is causing permafrost to thaw, resulting in the recent acceleration of many landslides in the area (Swanson et al. 2021).

The Pretty Rocks landslide in 2019 after a heavy rain.
NPS/WEEBEE ASCHENBRENNER

Prior to 2014, the Pretty Rocks landslide only caused small cracks that required moderate maintenance every 2-3 years. In recent years, the rate accelerated from inches *per year* prior to 2014, to inches *per month* in 2017, inches *per day* in 2019, and up to 0.65 inches *per hour* in 2021 (see more on the Denali National Park and Preserve website). Due to climate change, a problem previously solved by minor road repairs has become difficult to overcome with short-term solutions. Since 2021, interpreters have been posted at the road closure to communicate the issue to park visitors.

One of the most effective communication approaches about Pretty Rocks has resulted from those roving interpreter contacts with visitors at the point of the road closure in the park. Visitors are informed and encouraged to make the 2.5 mile hike up to an overlook on the park road where they can experience for themselves the site of the landslide. Their amazed reactions and personal accounting of the experience, have been universally moving and supportive of the park. Time-lapse videos showing the movement of the slope have also been very effective communication products. No doubt, personal engagement with this and other evidence of climate change will continue to be important tools for park staff.

Instilling Hope

Global temperatures are warming and many ecosystem changes are occurring rapidly, especially at higher latitudes. One message coming from scientists and northern communities is that changing climate is a task society must address sooner rather than later.

Interpreters know it's important to explain the science, the changes happening on the landscape, and the reasons why, but that's only half their task. They aspire to inspire; to provoke audiences to care for the resources at risk. Societal action is the ultimate measure of success for effective communication.

David Orr, longtime poetry critic for the *New York Times*, said: "Hope is a verb with its shirtsleeves rolled up" (Good News Network 2022). When interpreters create products with the above principles effectively addressed, the results will inspire people to action. And those actions will give us all hope for the future.

REFERENCES

Alaska Coastal Rainforest Center. 2022.
Juneau's Changing Climate and Community Response. Supported by the U.S. Geological Survey Alaska Climate Adaptation Science Center, U.S. Department of the Interior. 53 pp.

Beck, L. and T. T. Cable. 1998.
Interpretation for the 21st Century: Fifteen guiding principles for interpreting nature and culture. Sagamore Publishing. 242 pp.

Department of the Interior (DOI). 2021.
Climate Action Plan. Department of the Interior, Policy Statement for Climate Adaptation and Resilience. 30 pp.

Furr, G., C. Lamborn, A. Sisneros-Kidd, C. Monz, and S. Wesstrom. 2021.
Backcountry visitor experience and social science indicators for Glacier Bay National Park. Natural Resource Report NPS/GLBA/NRR—2021/2301. National Park Service, Fort Collins, Colorado.

Gonzalez, P., F. Wang, M. Notaro, D. J. Vimont, and J. W. Williams. 2018.
Disproportionate magnitude of climate change in United States national parks. Environmental Research Letters 13(10): 104001.

Good News Network. 2022.
Quote of the Day, October 15. Available at: https://www.goodnewsnetwork.org/david-orr-quote-about-hope/# (accessed December 21, 2022)

Leiserowitz, A., E. Maibach, S. Rosenthal, J. Kotcher, J. Carman, L. Neyens, T. Myers, M. Goldberg, E. Campbell, K. Lacroix, and J. Marlon. 2022.
Climate Change in the American Mind, April 2022. Yale University and George Mason University. New Haven, CT: Yale Program on Climate Change Communication.

National Park Service (NPS). 2016a.
Interpreting Climate Change Self-Study Modules, National Park Service Interpretive Development Program and Climate Change Response Program.

National Park Service (NPS). 2016b.
National Climate Change Interpretation and Education Strategy. Washington, DC.

Swanson, D. K., P. J. Sousanes, and K. Hill. 2021.
Increased mean annual temperatures in 2014-2019 indicate permafrost thaw in Alaskan national parks. Arctic, Antarctic, and Alpine Research 53: 19.

Tilden, F. 2008.
Interpreting Our Heritage, 4th revised edition. The University of North Carolina Pres. 224 pp.

Toomey, A. H. 2023.
Why facts don't change minds: Insights from cognitive science for the improved communication of conservation research. Biological Conservation 278: 109886.

Planning for Future Climates at Wrangell-St. Elias: Mainstreaming Park-Based Actions

Joel H. Reynolds, Mark E. Miller, Amber Runyon, Gregor W. Schuurman, National Park Service

Jeremy Littell, U.S. Geological Survey

Pamela J. Sousanes, Tom Olliff, Larry Perez, Wylie Carr, David Lawrence, and Jeneva Wright, National Park Service

Deciding how to act in the face of climate change can be overwhelming. Yet any park can act to begin integrating climate change considerations into their operations. Read how Wrangell-St. Elias National Park and Preserve, the National Park Service Climate Change Response Program, and their partners advanced the park's efforts to understand, adapt to, mitigate, and communicate with the public about climate change.

Citation:
Reynolds, J., M. E. Miller, A. Runyon, G. W. Schuurman, J. Littell, P. J. Sousanes, T. Olliff, L. Perez, W. Carr, D. Lawrence, and J. Wright. 2023. Planning for future climates at Wrangell-St. Elias: Mainstreaming park-based actions. *Alaska Park Science* 22(1): 110-127.

Warming temperatures are creating management challenges in Alaska parks. Thawing permafrost is a major concern because it leads to many ecological, physical, and chemical changes across the landscape (see Sousanes et al., this issue). The loss of sea ice exposes shorelines to winter storms, resulting in rapid erosion and loss of cultural sites and artifacts. Archaeologists must prioritize sites for excavation and conservation based on their vulnerability to erosion and other climate-related risks (see duVall, this issue). The warming climate impacts wildlife species, both terrestrial and marine (see Chambers et al. and Coletti et al., this issue). Climate-driven glacial retreat has cascading effects on river flow regimes, aquatic ecosystems, and subsistence salmon resources, as well as geophysical hazards in mountain and coastal regions (Higman et al. 2018, Jacquemart et al. 2022). These ecological and physical changes impact people—especially those who live near parks and depend on natural resources for subsistence (see Mason and Craver, this issue) and those who manage parks and seek to adapt operations to climate-driven changes, like loss of access due to landslides along road corridors (Lader et al. 2023).

Climate change is the largest and most persistent threat to our parks and requires a focus on managing for continuous change. How can park staff not only respond to the immediate impacts of climate change on park resources and operations, but also prepare for impacts in the foreseeable future? The National Park Service (NPS) Climate Change Response Strategy Update (NPS in press) provides a framework centered around four cornerstones of action: understand, adapt, mitigate, and communicate. These cornerstones underlie the NPS Alaska Leadership Council's main themes for climate change communication (ALC 2023-25 workplan): Indigenous knowledge, science, how NPS is addressing the challenge, and what the Alaska parks are doing.

Every park can take several basic steps under these cornerstones. These fundamental "mainstreaming actions" help parks address climate change in daily operations and decisions and may be augmented or tailored to park-specific situations. They are part of the next phase of evolution in how the agency works to meet its mission in its second century.

Examples largely drawn from the recent Wrangell-St. Elias National Park and Preserve (Wrangell-St. Elias) Resource Stewardship Strategy (RSS) planning process illustrate the mainstreaming actions. Early in this planning process, park staff identified climate change as a foremost concern with pervasive implications for park resources and values. The

Merging of two glaciers in Wrangell-St. Elias National Park and Preserve.
NPS/NEAL HERBERT

RSS provided an opportunity to take a deep dive into those implications; the NPS Climate Change Response Program (CCRP) and the U.S. Geological Survey (USGS) Alaska Climate Adaptation Science Center (AK CASC), and the USGS North Central Climate Adaptation Science Center (NC CASC) provided support.

The deep-dive RSS included both a multi-resource climate change vulnerability assessment using subject-matter expertise (Runyon et al. in press) followed by scenario-based adaptation planning (Schuurman et al. in press).* While the effort's scope and complexity are unique, many concerns and considerations at Wrangell-St. Elias equally apply to other parks in Alaska. We hope these examples and insights will help other parks advance their own efforts to manage for change.

The actions described below appear in a sequence, with some clear dependencies, but parks should act on whichever step(s) are timely. Understanding deepens through action and learning; invariably, parks will revisit these steps as conditions and context further evolve. Each section highlights key resources, and a summary of useful links appears at the end.

*The Wrangell-St. Elias reports use the term *implications* in a manner synonymous with *vulnerabilities*. As the adaptation planning report notes, *implications* is sometimes preferred because of its (1) consistency with terminology used by NPS planners to characterize potential resource response to anthropogenic threats, and (2) neutrality, which helps workshop participants readily imagine both negative and positive climate change-driven resource condition change (e.g., expansion of salmon habitat due to glacial retreat).

Definitions

adaptive capacity
The ability of … organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences of climate change. (Adaptive capacity is sometimes used to refer to the capacity of human communities and organizations to adapt to climate change. It is important to clarify the definition in any given usage: the first, narrower definition focuses on adaptive capacity as a factor in understanding climate-driven vulnerabilities; the second, broader definition focuses on an institution's ability to respond intentionally to those vulnerabilities; see Step 5: Build Climate Change Information into your Plans and Operations).

climate
Climate is generally defined as the average weather patterns or trends for a region over decadal or longer time spans; components usually include seasonal patterns of temperature, precipitation, wind, and relative humidity.

climate change adaptation
An intentional management response to observed climate changes or plausible future changes that involves identifying, preparing for (e.g., developing strategy and specific actions), and responding to (e.g., implementing actions) those changes. The desired outcome from the management response is to retain current conditions, recover from climate variations (perhaps to an altered state), or adjust to changing conditions that may include major transformation in practices or state. Adaptation may seek to "moderate harm or exploit beneficial opportunities" (IPCC 2014).

All definitions except RSS are from NPS (2021a).

exposure
A measure of the character, magnitude, and rate of changes a target may experience. In the climate change context, this includes changes in climate drivers (e.g., temperature, precipitation, solar radiation) as well as changes in related factors (e.g. sea-level, water temperatures, drought intensity, lightning frequency, ocean acidification).

sensitivity
The degree to which climate change affects a resource, facility, or other target either adversely or beneficially. The effect may be direct (e.g., increased stress or mortality of cold-water fish due to increased water temperatures on exceptionally hot days) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise).

resource stewardship strategy
A dynamic planning tool used to set goals for natural and cultural resource stewardship and track progress in achieving and maintaining desired conditions.

target
The specific aspect of a system that decisions or actions aim to affect. The target could be a resource, an asset, a process, a subsystem, etc. Often used to define not only the feature of interest (e.g., a species or a historic structure), but also a specific characteristic of that feature (e.g., species distribution or condition of the historic structure).

vulnerability
The degree to which a physical, biological, or socioeconomic system is susceptible to and unable to cope with adverse impacts of climate change.

Understand

STEP 1. KNOW YOUR PARK'S CLIMATE STORY

Wrangell-St. Elias' climate story includes both how climate has changed in the (recent) past and how it may change in the future. Information on past and plausible future climates comes from different sources. While communities in Alaska have many resources to help answer these questions, we focus on resources for park-specific summaries. Given the spatial and temporal scale of *climate*, the websites listed at the end of this article provide a rich foundation for basic understanding of climate trends for Alaska and elsewhere.

Different data products serve different purposes. Each NPS inventory and monitoring (I&M) network in Alaska sustains weather stations and provides summaries of those station observations (hourly, daily, monthly; search by network in the NPS DataStore in IRMA, the Integrated Resource Management Applications portal). Those observations are available for investigating local weather trends and a resource's *climate sensitivities*. The NPS Climate of Alaska web site provides links and points of contact.

NPS station observations are integrated with those from stations across Alaska to create gridded historical climate products with statewide coverage. The integration incorporates factors such as topography and changing network configurations to create a temporally and spatially complete, error-checked product (e.g., no missing data). These products generally are available over longer time periods and provide broad spatial coverage with a uniform spatial resolution (usually of a few kilometers) and temporal resolution (usually daily or monthly). As an example, the National Oceanic and Atmospheric Administration's (NOAA) nClimGrid provides a 5-km gridded product from 1925 to the present. Gridded historical products covering Alaska are available from the USGS AK CASC (Littell 2023) and University of Alaska Fairbanks' Scenarios Network for Alaska + Arctic Planning (SNAP) as well as other sources. Spatiotemporal coverage and resolution vary widely, as do methods for development and resulting products, so which data products are "best" depends on your information needs. For the Wrangell-St. Elias RSS, CCRP climate scientists summarized historical climate trends (Figure 1) from a gridded historical product selected through discussion with climate scientists at the AK CASC. A forthcoming effort provides coarser-resolution, statewide trends for Alaska climate divisions (Ballinger et al. 2023) summarized from both NOAA nClimGrid and a reanalysis product (ERA5 - C3S 2017).

Wrangell-St. Elias has many plausible future climates due to the complexity of climate variability, the developing science of climate modeling, and uncertainty regarding future greenhouse gas emissions. While the number of climate projections and the large size and topography of Alaska parks pose some challenges for planning (Runyon et al. in press), there are strategies for developing a small but representative subset of these futures in order to identify the range of impacts and risks plausible in the foreseeable future (Lawrence et al. 2021).

Two to four plausible future climates appear to be both sufficient to characterize a range of risks due, ultimately, to changes in temperature and precipitation (Brekke et al. 2009, Snover et al. 2013, Miller et al. 2022), and useful for multi-resource scenario planning (where a small set of climate scenarios helps constrain the complexity; Lawrence et al. 2021). Scenario-based planning identifies impacts under each plausible climate scenario, including even potential high-impact events with low probability of occurrence (however plausible). Looking across all scenarios broadly constrains the consequences of uncertainty and identifies implications under a range of bracketing future conditions (Dessai et al. 2009), though it does not eliminate uncertainty.

Climate scenarios are most effective when selected through consideration of the climate sensitivities of the targeted resources (e.g., soil moisture or heat index may be more relevant to resource sensitivities than just temperature and precipitation; Lawrence and Runyon 2019). Other methods of model selection (e.g., weighting or selecting a subset of projections based on historical model skill, Littell et al. 2011, Terando et al. 2020) could produce somewhat different scenarios and thus adaptation ideas. Although most climate assessments do not develop probabilistic outcomes, such approaches are often employed when relative likelihoods of outcomes across many models are preferred over just the range of impacts. For example, in impacts modeling where complex interactions of future conditions require considering the combined risk and likelihood, decision makers may want more scenarios to better represent the distribution of possible futures (e.g., Pierce et al. 2018).

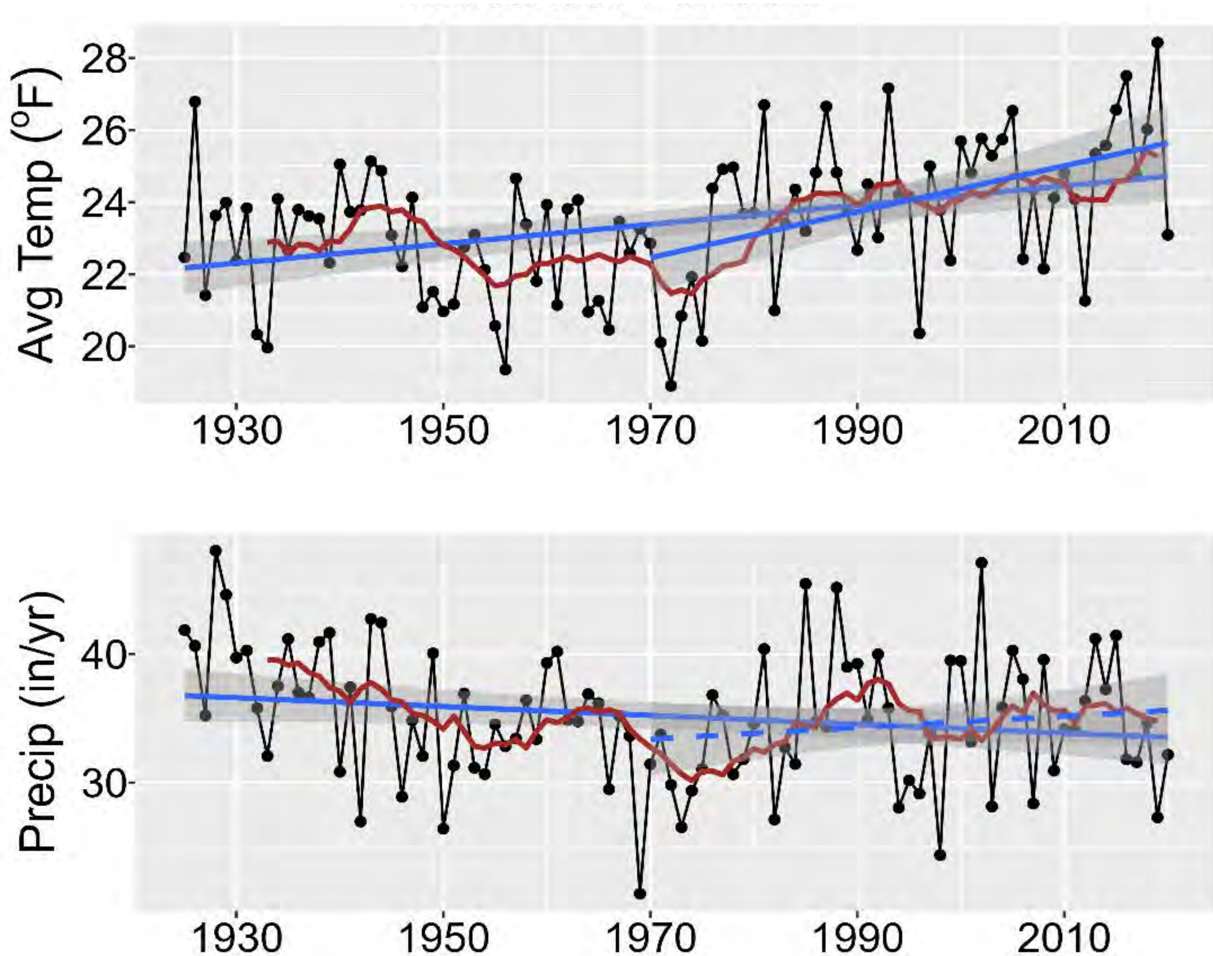


Figure 1. Historical Wrangell St-Elias National Park and Preserve annual mean temperature (top panel) and annual total precipitation (lower panel) from 1925-2020. Black points and lines show annual values, and red lines are 10-year running averages. Each graph includes two blue linear regression lines—one for the entire period and one for 1971-2019 (avoiding the period of global cooling due to industrial pollution, Wild et al. 2007). Statistically significant regression lines ($p<0.05$) are solid, and non-significant lines are dashed. Gray-shaded areas around the regression lines represent point-wise confidence intervals of y values. Data from the NClimGrid historical gridded dataset (Vose et al. 2014).

The Wrangell-St. Elias RSS considered twenty projections of future climate: two emission scenarios projected by each of ten global climate models (GCMs; Figure 2). Each was treated as equally likely; there was no explicit accounting for individual model skill (Runyon et al. in press). Three of those twenty projections were selected (called *climate futures*, Figure 2) as the climate scenarios for use in considering the range of plausible resource impacts or responses (called *climate-resource scenarios*; Runyon et al. in press). The selection considered aspects of the climate projections (per season average temperature and precipitation, measures of water deficit, and others) identified as most relevant to RSS priority resources (a subset of which are listed in Table 1). Technical details are in Runyon and others (in press).

The AK CASC has created summaries for every NPS unit in the Alaska region for a range of historical and projected climate metrics (Littell 2023); contact Pam Sousanes for further details or Jeremy Littell for questions regarding the data release. The AK CASC and SNAP are also finalizing the Northern Climate Reports website (in beta testing for release in FY24) that provides summary statistics, graphics, and geospatial displays for a wide range of projections and impacts, including ranges of projected changes in permafrost, wildfire flammability, and potential vegetation change. The site provides these summaries for each protected area, watershed subbasin (HU8 level), and community (and other jurisdictions) in Alaska and the Yukon. Planned updates of Northern Climate Reports include more climate futures and hydrologic metrics.

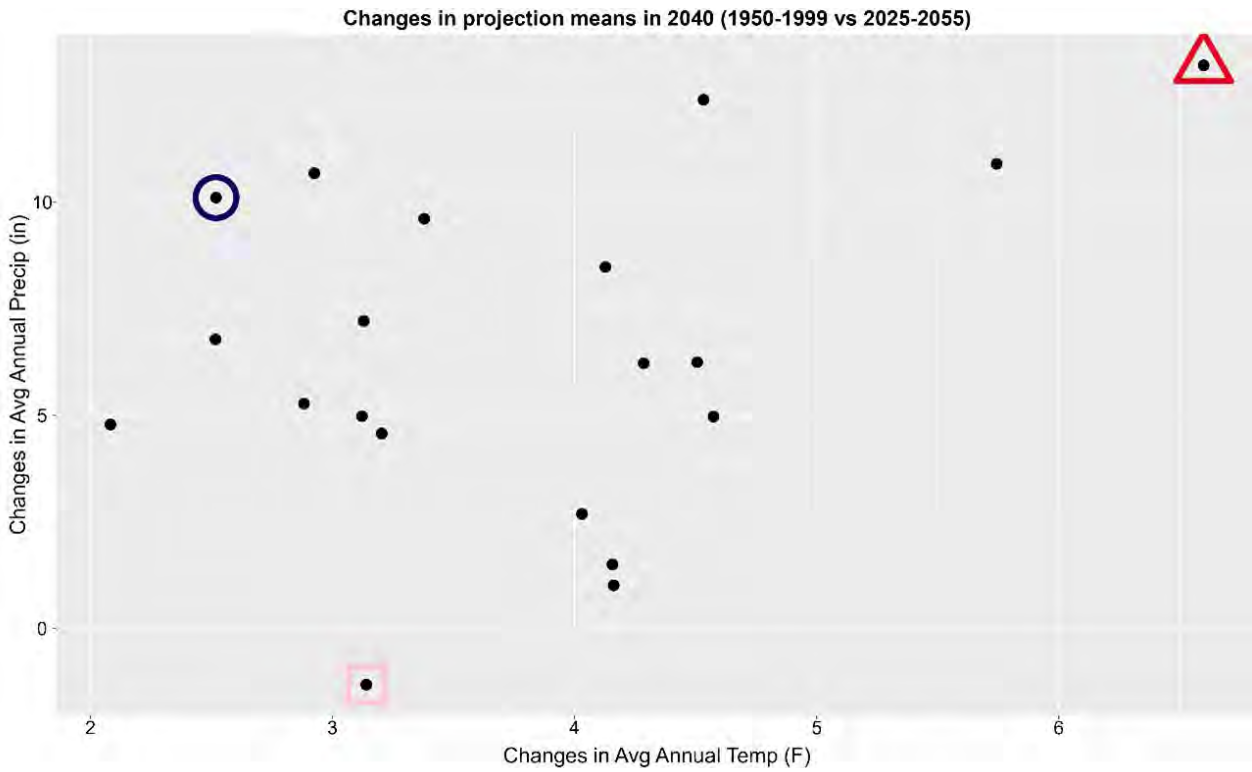


Figure 2. Projected changes in average annual temperature and precipitation for Wrangell-St. Elias National Park and Preserve. Points represent differences between average values for the three-decade period 2025-2055 versus 1950-1999 for each of the twenty projections. For example, average annual temperature is projected to increase by at least 2°F across all projections. Projections that were selected as divergent climate futures are identified as: blue circle – warm wet; pink square – warm dry; red triangle – hot wet (also see Table 2).

Table 1. A subset of priority resources and associated resource components considered as targets for the scenario-based climate change vulnerability assessment phase of the Wrangell-St. Elias RSS, listed, broadly, from physical to ecological to social-ecological systems. For the full set of priority resources and components, see Runyon et al. in press.

Resource Group	Resource Components
Hydrology	Glaciers
	Rivers
	Non-glacial streams
	Lakes
Vegetation	Boreal forests
	Subalpine shrub/woodlands
	Alpine tundra
Wildlife (biology)	Caribou
	Moose
	Dall's sheep
	Wolves
	Brown bears & black bears
Aquatics	Salmon
	Freshwater fishes
Cultural resources	Archaeological resources
	Cultural landscapes
	Historical / prehistoric structures
	Kennecott Mines NHL
	Museum collections
Human systems	Motorized recreation
	Aviation
	Backcountry use
Subsistence	Salmon
	Freshwater fishes
	Moose
	Wood & berries
Wilderness	Solitude
	Night skies
	Wilderness character

STEP 2. UNDERSTAND HOW CLIMATE CHANGE MIGHT AFFECT YOUR RESOURCES

Proactively managing Wrangell-St. Elias' resources requires understanding their climate-driven vulnerabilities. Climate change vulnerability assessments (CCVAs) identify both the *vulnerability* of the assessment *targets* (e.g., specific resources, facilities, or operations) to plausible future climates and, in the process, the vulnerability's cause. A CCVA typically evaluates three factors: (1) the target's climate *exposure*, (2) its *sensitivity* to that exposure, and (3) for targets that are living resources, their *adaptive capacity*. Combined, these factors describe vulnerability. The vulnerability's cause will inform possible adaptation actions, actions considered may differ for a vulnerability driven more by high sensitivity than by high exposure.

Resources mentioned in Step 1 help identify a park's climate exposure. Depending on the motivating management decision, more specific exposure information may be required (e.g., seasonality of precipitation dynamics rather than just annual mean temperature and total precipitation; see Lawrence et al. 2019). Understanding of sensitivities can come from park and regional staff, especially I&M network subject matter experts (SMEs), other partner SMEs, Indigenous partners, and the scientific literature.

Since sensitivities depend on the target, and exposure depends on the target's location, no single CCVA will answer all park questions and inform all park decisions. Different types of management decisions require different types of CCVAs. A CCVA for a major infrastructure investment concept may only require qualitative consideration of the major exposure concerns and the (broad) sensitivities of the proposed structure, while a CCVA to inform the final design and siting of that structure can require much more rigor. Some CCVAs produce ranked relative vulnerabilities, some produce numerical vulnerabilities, and some qualitatively characterize vulnerabilities and highlight critical ones. Which approach is appropriate depends on the level of detail required to inform the decision, resources available to conduct the CCVA, and the state of scientific understanding required to project target responses to future climates (also called *impact modelling*).

The uncertainty associated with projected climate impacts is usually much larger for impacts on individual species or ecological communities than it is for impacts on physical processes. Subsequently, CCVAs focused on biological or ecological targets are often more qualitative than quantitative due to data limitations.

Many CCVAs have been conducted in Alaska over the last decade, including broad-scale CCVAs focused on major ecotypes (e.g., in northwest Alaska, Jorgenson et al. 2015) or drivers of ecosystem change (e.g., changes in flammability), specific regions (e.g., Chugach National Forest and Kenai Peninsula, Hayward et al. 2017), or parks (exposure summaries and some major physical drivers of change; park-specific scenario planning reports in IRMA). Resource-specific CCVAs have targeted physical resources (e.g., snow, Littell et al. 2020), biological resources (e.g., breeding birds, Liebezeit et al. 2012), subsistence resources (e.g., on the Yukon-Kuskokwim Delta, Herman-Mercer et al. 2019), and even aspects of operations (e.g., moose monitoring methods, Kellie et al. 2019; landslide risks, Lader et al. 2023). Starting points for locating CCVAs include the latest National Climate Assessment, the projects and publications of the AK CASC, SNAP, and the Alaska Center for Climate Assessment & Policy, and IRMA for park-specific or park-funded products. Many human-community-focused CCVAs are available through Adapt Alaska and SNAP's Community Charts tool.

Despite the significant climate-change vulnerabilities facing parks, relatively few have site- or resource-specific CCVAs targeting their major management decisions (Peek et al. 2022, Michalak et al. 2021).

The Wrangell-St. Elias RSS considered a broad suite of priority resources and associated resource components—more than 50 in all—and conducted a (qualitative) CCVA for each. For each resource target, the SMEs drew on their knowledge and experience regarding the target's sensitivities to identify the potential implications for that resource under each climate future. For some targets, like glacial rivers, the implications were similar in nature and direction under each climate future, but differed in magnitude of impact (Table 2). For others, like sockeye salmon, the uncertainty regarding potential impacts on freshwater rearing populations was so great as to mask potential differences between scenarios. For example, under each scenario, while rearing conditions are expected to improve, population variability is expected to increase (Runyon et al. in press). The park is reviewing these critical uncertainties to identify priority research and monitoring needs.

The results provide an assessment of critical vulnerabilities for each resource target and help inform priorities for further scoping (Table 2, excerpts from Runyon et al. in press). While

Table 2. Highly abbreviated and simplified examples of relative vulnerabilities identified under each of the three climate futures (scenarios) for select natural and cultural resource targets considered by the Wrangell-St. Elias National Park and Preserve RSS. Magnitudes are for mid-century relative to historical period 1950-1999. The more extensive summaries in Runyon and others (in press) include summaries of critical uncertainties shared across scenarios for each target resource.

	Climate Scenario 1 (warm, wet summers, more snow)	**Climate Scenario 2** (dry summers and falls, early snow melt)	**Climate Scenario 3** (hot summer, mild winter, rainy)
Hydrology—glacial rivers	• more runoff (14%) • more Fall floods • less river ice (and ice-based access) • less bank stability	• more (6%) and earlier runoff • lower, earlier base flows • longer ice-free season • less bank stability	• more runoff (30%) • more Fall floods • earlier base flows • no river ice • more bank erosion
Riverine archeology	Sites degraded or destroyed due to more flooding causing direct erosion and flood-driven human land use changes.	Sites degraded or destroyed due to more landslides (post-wildfires), more erosion (from flooding), and wildfire-driven human land use changes.	Sites severely degraded or destroyed due to erosion from flooding and wildfires and flood-driven human land use changes.
Coastal archeology	Reduced site integrity due to possible saltwater intrusion and likely flooding. Site inundation due to more coastal change.	Reduced site integrity due to likely saltwater intrusion and flooding. Site inundation due to dramatic coastal change.	Reduced site integrity due to saltwater intrusion and flooding. Greatly increased site inundation due to dramatic coastal change.

finer details of exposure and, perhaps, resource sensitivity, may differ from park to park, the RSS provides a broad foundation for use in CCVAs at other parks.

STEP 3. IMPROVE WORKFORCE UNDERSTANDING OF CLIMATE CHANGE

A key tenet of the NPS Climate Change Response Strategy Update (NPS in press) is that all employees have a role in incorporating climate change into their realm of park operations and planning. This requires a basic level of climate change literacy, which the NPS CCRP supports through the development of training plans, content delivery, outcomes evaluation, and coordination across bureaus in the Department of the Interior. Training is also available through the National Conservation Training Center and other sources. The Department of the Interior is currently coordinating workforce literacy curricula across bureaus (contact CCRP for details).

The *2016 NPS Workforce Climate Change Literacy Needs Assessment and Training Strategy* provides a service-wide blueprint for cultivating a climate-capable workforce. The strategy informs training for specific occupational categories and investments in future curricula. The CCRP offers a blended portfolio of formal and informal learning opportunities targeting NPS employees across occupational series (NPS 2016a). Many of the formal training modules are free and available on demand for self-paced learning.

Training in Action

The Wrangell-St. Elias RSS involved Alaska NPS staff from more than 15 resource disciplines and five organizational units in addition to the park and partners. This broad engagement provided a common understanding of major climate trends, plausible climate futures, and potential impacts and adaptation actions at the park. It also ensured participating NPS staff from other parks and programs understand the basic steps of incorporating climate change into park plans and operations and thus are better able to help staff at their parks/programs in such efforts.

Adapt

STEP 4. MANAGE RESOURCES AND FACILITIES WITH CLIMATE IMPACTS IN MIND

After determining the most important climate change vulnerabilities associated with a management issue, the next step is to decide whether, when, and what adaptation actions may be beneficial to prevent or mitigate potential impacts. The report *Resist-Accept-Direct (RAD)—A Decision Framework for the 21st Century Natural Resource Manager* (Schuurman et al. 2020, see also Schuurman et al. 2022) frames the suite of management goals available when responding to ecosystems facing potential rapid, irreversible ecological change. The framework encourages natural resource managers to consider strategic, forward-looking goals rather than just maintain management goals based on past conditions. There are only three RAD options:

1. *Resist* the trajectory, by working to maintain or restore ecosystem composition, structure, processes, or function based on historical or acceptable current conditions.
2. *Accept* the trajectory, by allowing ecosystem composition, structure, processes, or function to change autonomously.
3. *Direct* the trajectory, by actively shaping ecosystem composition, structure, processes, or function toward preferred new conditions (Schuurman et al. 2022).

The options differ in *if* and *how* managers intentionally intervene to shape the trajectory of ecosystem change. *Where* and *when* they do decide to intervene, managers can choose preferred ecological outcomes that vary from return to a historical benchmark to persistence of existing (non-historical) conditions or emergence of conditions for which there may be no local precedent. Note that for most natural resources, maintaining either historical or current conditions will be increasingly costly and over time may become infeasible.

While developed with natural resources in mind, the RAD framework can also help identify feasible management approaches for cultural resources and facilities. Ongoing work (Wright and Hylton 2022) is helping to identify and categorize cultural resource adaptation strategies across the full RAD spectrum, including:

- Limiting climate exposures of cultural heritage resources *in situ*;
- Reducing the sensitivity of resources *in situ*;
- Reducing exposure by removing resources from their environmental context and accepting diminished integrity; or
- Acknowledging imminent destruction, mitigating data loss, and preserving the memory and stories that the resources represented.

For natural resource managers who have intentionally established an appropriate goal for a given resource (and thus determined whether to resist, accept, or direct), a useful aid for developing specific strategies or actions to achieve that goal may be found in the "adaptation menus" developed by the Northern Institute of Climate Applied Science. These menus are focused on a specific management domain (e.g., wildlife management, fire-adapted ecosystems, etc.) and identify management strategies and associated actions from extensive syntheses of the published literature (Swanston et al. 2016). Three of the thirteen wildlife adaptation strategies, for example, are (1) maintain and enhance genetic diversity, (2) facilitate shifts in the geographic range of the species in anticipation of future conditions, and (3) adjust harvest regulations to manipulate populations of harvested species. Although focused on the tribes and forests of Minnesota, Wisconsin, and Michigan, the *Dibaginjigaadeg Anishinaabe Ezhitwaad: A Tribal climate adaptation menu* (Tribal Adaptation Menu Team 2019) provides a menu of culturally appropriate adaptation strategies and actions. While not all of these menus of strategies and actions will be appropriate to protected areas in Alaska, like RAD, they provide a starting point for prompting broad and creative adaptation thinking.

The Wrangell-St. Elias RSS led to detailed step-by-step documentation of the workflows for both the CCVA and adaptation development phases. The draft guidance includes templated worksheets. Staff at Haleakalā National Park are testing the guidance in their self-facilitated scenario-based adaptation planning process, with technical support from CCRP. The guidance is expected to become available in late FY24.

Adaptation in Action

The Wrangell-St. Elias Facility Management Program is seeking to conduct a comprehensive structural risk assessment of historic structures in the Kennecott Mines National Historic Landmark regarding vulnerability to increasing snow loads, such as those that triggered major roof collapses in late winter 2021 and 2022. The park's Resource Stewardship and Science Program acquired funding to support research assessing implications of increasing discharge in the Copper River (projected to increase by 48% by end of this century, Valentin et al. 2018) on migratory success of genetically determined stocks of sockeye salmon, a vital park resource with a broad spectrum of associated natural, cultural, subsistence, and economic resource values. Both efforts are intended to lead to development of feasible and long-term adaptation actions. It is generally more straightforward to conduct CCVAs and develop adaptations for single assets or resources that are well delineated than for multiple, integrated resources such as communities or ecosystems.

STEP 5. BUILD CLIMATE CHANGE INFORMATION IN YOUR PLANS AND OPERATIONS

Policy Memo 12-02 (NPS 2012), Applying National Park Service Management Policies in the Context of Climate Change, reminds park managers of the comprehensive scope and flexibility of Management Policies (NPS 2006) and the need to ground decisions in the best available science using transparent decision making. Thus, park planning processes must account for novel environmental dynamics and trajectories of ecological transformation stemming from climate change. This accounting is achieved by incorporating climate change considerations into existing planning processes and tools, not by conducting a separate planning endeavor. As described in Step 2, the specific decision or planning focus dictates the framing of the vulnerability assessment and, thus, the framing of the adaptation process.

Planning for a Changing Climate (P4CC; NPS 2021b) guides NPS planners and managers in identifying climate adaptation options as a regular practice across comprehensive, strategic, and implementation plans. It advances and customizes Climate-Smart Conservation (Stein et al. 2014) to NPS planning purposes. Specifically, P4CC highlights that climate-informed planning processes must:

1. *Develop forward-looking goals that consider future climatic conditions.* Adaptation planning looks to the future, not the past, by using climate projections to adopt forward-looking goals; and
2. *Consider more than one scenario of the future when developing management strategies and actions.* Given the uncertainty in the speed and magnitude of future climate change, considering multiple scenarios is necessary to develop adaptation strategies that are robust, that is, can protect or mitigate against a range of impacts.

The P4CC cycle (Figure 3) follows the familiar stages of adaptive management because climate change adaptation is a continuing process rather than an endpoint. The other steps highlighted in this article all stem from the cycle. Implicit in the cycle is the need for increased attention to effectiveness monitoring of adaptation actions and documenting and sharing lessons learned.

P4CC training for planners is offered regularly. CCRP has worked with Park Planning and Special Studies and the Denver Service

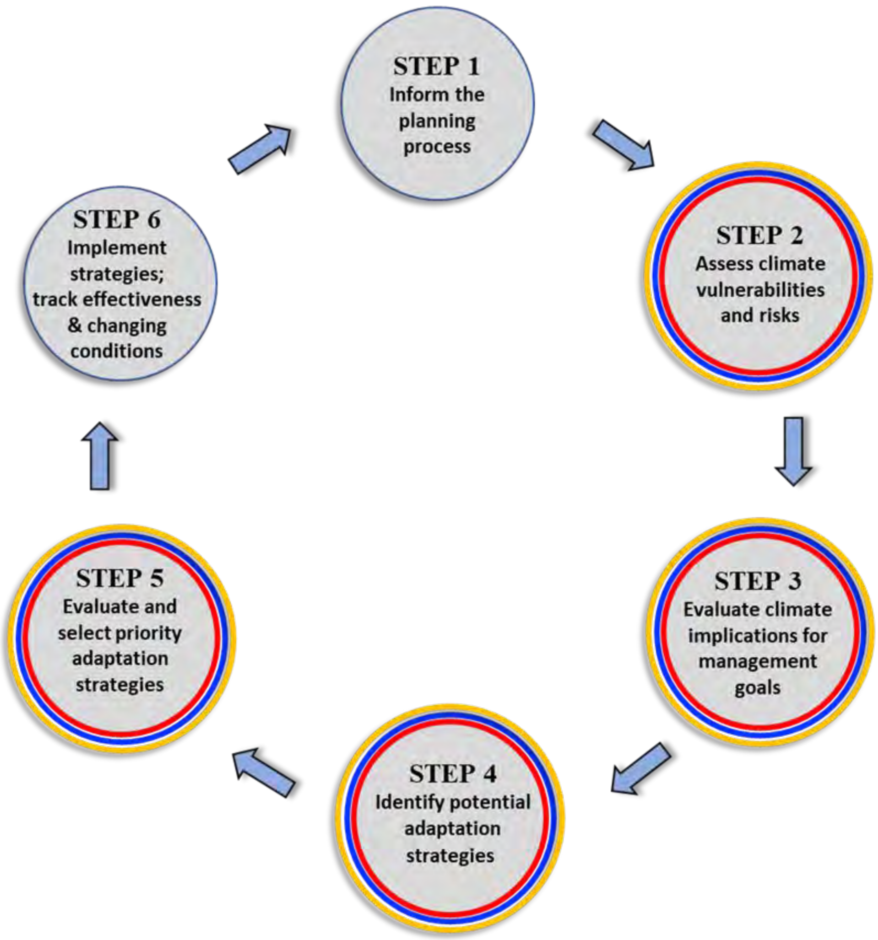


Figure 3: The NPS Planning for a Changing Climate (P4CC) process. Colored circles around steps 2-5 indicate where key principles of developing forward-looking goals and considering multiple scenarios play a critical role.

Center to standardize and streamline how to include climate change in the development of Resource Stewardship Strategies (NPS 2020). A P4CC handbook for any NPS planning process, further detailing the component tasks under each stage of the cycle, is under development.

Incorporating climate considerations into facility management is addressed in Policy Memo 15-01 (NPS 2015a) and its companion handbook (NPS 2015b, NPS 2023a). The handbook includes a Natural Hazard Checklist to screen the most likely hazards a project may confront; completing the checklist is required for any submission to the Bureau Investment Review Board. Incorporating climate considerations into cultural resource management is addressed in Policy Memo 14-02 (NPS 2014) and the companion Cultural Resources Climate Change Strategy (Rockman et al. 2016).

Scenario Planning

NPS has used scenario planning since 2007 to help parks make climate-informed decisions despite the uncertainty in future climate trajectories (Star et al. 2016). Scenario planning asks the simple question of *What might happen?* In doing so, it encourages planners and managers to (1) explore a variety of plausible future conditions; (2) evaluate the implications of those conditions; and (3) identify a portfolio of possible management strategies. This is why it is a fundamental component of implementing Planning for a Changing Climate (NPS 2021b).

Methods have evolved since the earliest NPS scenario-planning efforts, with modern scenario-based planning efforts focusing on management priorities using scenarios grounded in plausible climate projections (Miller et al. 2022). Unfortunately, this period has also provided enough time for many parks to find that a number of imagined, worst-case scenarios were scooped by reality in recent years, reinforcing the value of using scenarios to counter optimism bias and anticipate high-impact, low probability events.

For those interested in learning more, *Scenario Planning: An Introduction* provides a self-paced learning activity on the Common Learning Portal that highlights key principles and steps in the process. The Climate Change Scenario Planning Showcase provides examples of scenario planning in action at parks across the country.

Adaptation in Action

The Wrangell-St. Elias RSS addressed select natural and cultural resources and focused on climate change adaptation strategies framed in relation to plausible future climate scenarios, scenario-specific implications for priority resources, and goals that acknowledge climate change as an overarching management context (Schuurman et al. in press). For example, park staff expressed the park's goal for subsistence management as ensuring the continuation of subsistence uses adequate to meet users' needs in the context of changing environmental and societal conditions, while also ensuring the health and continued presence of harvested resources. Adaptation strategies for harvested resources were specified broadly as monitor, study, and manage resource (e.g., moose, salmon, and caribou) populations in a climate change-informed way—that is, to address the key uncertainties identified by the CCVA(s). Park staff then identified, for each broadly framed adaptation strategy, specific high-priority actions to address anticipated needs specific to one or more of the climate-resource scenarios.

Example: Maintain awareness of regional and park-level moose abundances and trends, including reviewing and updating monitoring methods, if necessary. For example, consider adopting Northwest Alaska parks' switch from fall to spring population surveys in response to declining fall snow (recognizing the loss of data on bull:cow ratios through this method) to ensure that methods are robust to projected changes in climatic conditions and sensitive to important potential climate change effects on the species.

Mitigate

STEP 6. CREATE A SUSTAINABILITY PROGRAM TO MITIGATE THE ROOT CAUSES OF CLIMATE CHANGE

Park managers are modifying operations to both reduce greenhouse gas (GHG) emissions and adapt decision making to novel, climate-driven challenges (NPS 2010). Both components, mitigation and adaptation, are essential. After all, the NPS manages the largest number of built assets of any civilian agency in the federal government (NPS 2016). NPS efforts to mitigate production of GHGs take many forms, as exemplified by the ten broad sustainability goals identified in the Green Parks Plan (NPS 2023b).

Sustainability in Action

Wrangell-St. Elias is reducing the carbon footprint of Kennecott operations. In 2022, the propane-fueled power generation system in Kennecott was replaced with a hybrid power system of solar photovoltaic array and back-up propane generator. This upgrade has the potential to reduce greenhouse emissions attributable to park operations in Kennecott by approximately 85%. The park is also replacing gasoline-powered utility vehicles, used in support of Kennecott operations, with electric ones.

Communicate

STEP 7. COMMUNICATE WITH THE PUBLIC ABOUT CLIMATE CHANGE IN YOUR PARK

National parks are living laboratories where the effects of climate change can be readily observed and interpreted. Given an annual reach of 800 million in-person and digital visitors—and our vast cadre of communication specialists—the NPS is uniquely positioned to advance public dialogue on the climate crisis and support future adaptation solutions. Studies have found that park visitors are interested in climate change discussions at parks (Davis et al. 2012), and each park has its own story to engage visitors in climate change at the local level (Roberts et al. 2021).

The CCRP provides guidance and inspiration for park-level communications. The National Climate Change Interpretation and Education Strategy (NPS 2015c) advances four broad goals for communicating about the science and impacts of climate change across the NPS. The NPS climate change website provides robust, public-facing information on NPS climate change response. Climate-related updates also are shared regularly through dedicated monthly newsletters and via social media platforms, such as Twitter and Facebook.

Several ongoing, targeted efforts further support park-level communication. Research on visitors' perceptions of climate change (Davis et al. 2012) and current methods for online climate-change interpretation (Roberts et al. 2021), both of which included Alaska parks, provide insight to guide the development of products and messaging. Annual offerings of the Interpreting Climate Change virtual course and the Earth to Sky Academy provide training to front-line communicators on best practices in

Wayside exhibits at parks, like this one at Wrangell-St. Elias National Park and Preserve, help visitors understand the effects of climate change.

climate communication. And curriculum-based K-12 education on climate-related topics is supported through various partnership efforts (Perez et al. 2020), including the Park for Every Classroom program.

Technical assistance requests, one-time project funding, and youth internship programs provide additional opportunities to advance discrete climate communication projects. In the past, such mechanisms have supported the development of park wayside exhibits, park-specific climate web pages, interpretive multi-media videos, and climate communication strategies.

Partner

STEP 8. COLLABORATE WITH YOUR PARTNERS

The scales of climate change impacts far exceed the ability of any one park, agency, or organization to effectively respond as a single entity, highlighting the value of partnerships in increasing our collective ability to respond to climate change. But this is nothing new for Alaska parks as the scales of these protected areas already have led to long-standing partnerships in wildlife monitoring and management, among others. Since 2010, the challenges of climate change have introduced some new partners, namely the USGS AK CASC and, through 2017, the five U.S. Fish and Wildlife Service-hosted landscape conservation cooperatives, three of which continue advancing community and landscape-scale collaboration under the Northern Latitudes Partnerships. All these entities have a strong record of helping parks respond to climate change.

Partnership in Action

For its RSS, the Wrangell-St. Elias park staff ensured that many key partners were engaged both to share the climate information products and broaden awareness of potential impacts as well as draw heavily on partner expertise and insights. More than 55 partners, ranging from the Ahtna Intertribal Resource Commission to Prince William Sound Science Center, participated in the scenario-based adaptation planning portions of the RSS (see full list of participants in Runyon et al. in press and Schuurman et al. in press).

Communication in Action

Wrangell-St. Elias is actively working to increase climate change content in interpretive messages oriented towards park visitors and the public more broadly, with current content development focusing primarily on glaciers. In 2020, park and regional office staff together produced the Kennicott Glacier Interpretive Concept Plan (Chambers et al. 2020), which "… focuses on providing park visitors with an understanding of the extent, nature, and consequences of glacier change in Alaska and the Kennicott Glacier, specifically." The overarching interpretive theme expressed in the plan is that "rapid changes in and around the Kennicott Glacier affect the entire landscape and reflect similar changes occurring at thousands of other Alaska glaciers." Plan implementation is ongoing via a phased process led by the park's Interpretation and Education Team in collaboration with Resources and Facilities Teams. While this plan focuses on the Kennicott valley, the park also is in the process of updating interpretive panels to be displayed in the exhibit hall at the Copper Center Visitor Center Complex, with climate change content also focusing on glaciers.

Evaluate and Learn

Climate change greatly increases the uncertainties managers must contend with. Future management decisions will be more successful to the degree we dedicate ourselves now to assessing the effectiveness of our climate adaptation actions and sharing the lessons learned. Assessments will be most effective when they are considered and designed soon after or in conjunction with the initial adaption action (Lynch et al. 2022). For example, if you implement a specific action as part of a goal to resist the ecological trajectory, also articulate what thresholds will trigger the need to revisit that decision, such as: the threshold of reasonable costs, outcomes that are unacceptable (e.g., no natural regeneration from restoration efforts), and other trigger points.

Embracing and implementing basic adaptive management in our climate adaptations will help future park managers better navigate how to meet the NPS's mission under these changing conditions. As an organization that manages parks for learning and by learning, NPS leaders have an outsized role in prioritizing *in situ* learning and adaptation, and in supporting the novel actions required by climate change.

Conclusion

Alaskans, and especially those directly engaged with protected areas in the state, are increasingly aware of the impacts of climate change on natural and cultural resources, subsistence lifeways, park facilities and operations, and visitor experiences. Such awareness can be overwhelming, both to individuals and the organizations managing those areas. The mainstreaming actions described in this report can be used to guide and advance resource stewardship in this era of uncertainty and novel change.

Alaska's expansive parks and preserves are an enviable foundation for learning about ecosystem responses and resilience to the many consequences of climate change, and for learning about effective adaptation actions in the face of those consequences. As the NPS Climate Change Response Strategy Update (in press) acknowledges, everyone has an important role in advancing climate change adaptation—especially NPS leaders who can prioritize climate topics, encourage action, and promote inclusivity. Together we can learn how to manage these changes across the next century.

Evaluation and Learning in Action

Wrangell-St. Elias is evaluating potential climate change implications for Copper River sockeye salmon stocks and rural communities' subsistence needs through projects with partners at the Prince William Sound Science Center, the University of Alaska Fairbanks College of Fisheries and Ocean Sciences, Alaska Department of Fish and Game, the Native Village of Eyak, and the Ahtna Intertribal Resource Commission. Two of these projects assess the potential effects of body condition and increasing river flows driven by climate warming and glacial melt on spawning migration success of sockeye salmon. These projects and three companion studies were motivated in part by Ahtna knowledge of long-term changes in sockeye and Chinook salmon runs in the upper Copper River drainage (Simeone and Valentine 2007) and recent (2018 and 2020) record-low runs of Copper River sockeye salmon that triggered concerns about food security for rural residents who rely on salmon as a vital subsistence resource. Results of these studies will inform an evaluation of potential future management strategies for Copper River salmon fisheries.

Acknowledgements

This article was only possible thanks to the sustained commitment and efforts by the staff of Wrangell-St. Elias and partners who collaborated with CCRP and Denver Service Center on the recent Resource Stewardship Strategy with scenario-based climate change adaptation planning. This article is based on Olliff and others (in press), which focuses on climate change adaptation at parks in the Intermountain Region. The first six authors greatly appreciate the foundation, largely preserved, provided by them and their co-authors.

If your park is engaged in a planning process or decision that requires more specialized climate summaries, reach out jointly to CCRP (via the System for Technical Assistance Requests) and the USGS AK CASC. These groups will collaborate to determine the information needed, available resources and capacities, and a path forward to address these needs.

Learn More

Interested in learning more? Here are some links that may be helpful.

- Climate change training from the NPS Climate Change Response Program (CCRP)
- Sign up for the CCRP newsletter.
- Climate Change and Your National Parks is an NPS website with informative links, including the Climate Change Scenario Planning Showcase.
- High-latitude Climate Change is an Alaska NPS website with relevant links and articles.
- How Monitoring Informs Park Conservation in a Changing Climate, a section on the Inventory & Monitoring website that shows examples of how monitoring data can be used to inform climate change action.
- The Alaska Center for Climate Assessment & Policy hosts monthly climate-focused webinars, including the popular National Weather Service AK Climate Outlook Briefing and has interactive climate data tools.
- The Alaska Climate Research Center provides a variety of products and services.
- NOAA's State Climate Summaries provides key messages and informative graphics that can be easily downloaded and used in presentations.
- The U.S. Global Change Research Program's National Climate Assessment summarizes the state of understanding for both the physical science of climate change and for the impacts, risks, and adaptation efforts in the United States.
- The USGS AK Climate Adaptation Science Center and the University of Alaska Fairbanks' Scenarios Network for Alaska + Arctic Planning provide a wide range of resources for diverse audiences (including interested public, researchers, and resource managers), on topics such as:
  - basic understanding of climate science and climate modeling,
  - common questions about climate modeling,
  - permafrost risks and hazards for communities, and
  - access to historical and projected downscaled data.
- U.S. Climate Resilience Toolkit is a clearinghouse of additional Alaska- or Arctic-focused resources.

REFERENCES

Ballinger, T. J., U. S. Bhatt, P. A. Bieniek, B. Brettschneider, R. T. Lader, J. S. Littell, R. L. Thoman, C. F. Waigl. J. E. Walsh, M. A. Webster. 2023.
Alaska terrestrial and marine climate trends, 1957-2021. Journal of Climate 36(13): 4375-4391.

Brekke, L. D., E. P. Maurer, J. D. Anderson, M. D.Dettinger, E. S. Townsley, A. Harrison, and T. Pruitt. 2009.
Assessing reservoir operations risk under climate change. Water Resources Research 45(4): W04411.

Chambers, N., J. Hart, M. Loso, R. Salazar, and M. Steigerwald. 2020.
Kennicott Glacier Interpretive Concept Plan. NPS Wrangell-St. Elias National Park and Preserve, Copper Center, AK. 32 pp.

Davis, S., S. Karg, and J. Thompson. 2012.
Climate Change Education Partnership Visitor Survey Summary Report. Place-based Climate Change Education Partnership. Fort Collins, CO.

Dessai, S., M. Hulme, R. Lempert, R. Pielke, Jr. 2009.
Do we need better predictions to adapt to a changing climate? EOS 90(13): 111-112.

Hayward, G. H., S. Colt, M. L. McTeague, T. N. Hollingsworth. 2017.
Climate change vulnerability assessment for the Chugach National Forest and the Kenai Peninsula. Gen. Tech. Report. PNW-GTR-950. Portland, OR; U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 340 p.

Herman-Mercer, N. M., M. Laituri, M. Massey, E. Matkin, R. C. Toohey, K. Elder, P. F. Schuster, and E. Mutter. 2019.
Vulnerability of subsistence systems due to social and environmental change: A case study in the Yukon-Kuskokwim Delta, Alaska. Arctic 72(3): 258-272.

Higman, B., D. H. Shugar, C. P. Stark, G. Ekström, M. N. Koppes, P. Lynett, A. Dufresne, P. J. Haeussler, M. Geertsema, S. Guilick, A. Mattox, J. G.Venditti, M. A. L. Walton, N. McCall, E. Mckittrick, B. MacInnes, E. L. Bilderback, H. Tang, M. J. Willis, B. Richmond, R. S. Reece, C. Larsen, B. Olson, J. Capra, A. Ayca, C. Bloom, H. Williams, D. Bonno, R. Weiss, A. Keen, V. Skanavis, and M. Loso. 2018.
The 2015 landslide and tsunami in Taan Fiord, Alaska. Nature Scientific Reports 8: 12993.

Intergovernmental Panel on Climate Change (IPCC). 2014.
Annex II: Glossary [Agard, J., E. L. F. Schipper, J. Birkmann, M. Campos, C. Dubeux, Y. Nojiri, L. Olsson, B. Osman-Elasha, M. Pelling, M. J. Prather, M. G. Rivera-Ferre, O. C. Ruppel, A. Sallenger, K. R. Smith, A. L. St Clair, K. J. Mach, M. D. Mastrandrea, and T. E. Bilir, editors]. In Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A.N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White, editors]. Cambridge University Press, New York, NY, USA.

Jacquemart, M., E. Welty, M. Leopold, M. Loso, L. Lajoie, and K. Tiampo. 2022.
Geomorphic and sedimentary signatures of catastrophic glacier detachments: A first assessment from Flat Creek, Alaska. Geomorphology 414: 108376.

Jorgenson, M. T., B. G. Marcot, D. K. Swanson, J. C. Jorgenson, and A. R. DeGange. 2015.
Projected changes in diverse ecosystems from climate warming and biophysical drivers in northwest Alaska. Climatic Change 130: 131-144.

Kellie, K. A., K. E. Colson, and J. H. Reynolds. 2019.
Challenges to monitoring moose in Alaska. Alaska Department of Fish and Game, Wildlife Management Report ADF&G/DWC/WMR-2019-1, Juneau.

Lader, R., P. Sousanes, U. S. Bhatt, J. E. Walsh, and P. A. Bieniek. 2023.
Climate indicators of landslide risks on Alaska national park road corridors. Atmosphere 14(1): 34.

Lawrence, D. J., A. N. Runyon, J. E. Gross, G. W. Schuurman, and B. W. Miller. 2021.
Divergent, plausible, and relevant climate futures for near- and long-term resource planning. Climatic Change 167: 38.

Lawrence, D. J. and A. N. Runyon. 2019.
Implications of climate change for the water supply of the Chisos Mountains developed area: Big Bend National Park technical assistance request 4945. Natural Resource Report. NPS/NRSS/CCRP/NRR—2019/2045. National Park Service. Fort Collins, Colorado.

Liebezeit, J., E. Rowland, M. Cross, and S. Zack. 2012.
Assessing Climate Change Vulnerability of Breeding Birds in Arctic Alaska. A report prepared for the Arctic Landscape Conservation Cooperative. Wildlife Conservation Society, North America Program, Bozeman, MT., 167pp.

Littell, J. S., D. McKenzie, B. K. Kerns, S. Cushman, and C. G. Shaw. 2011.
Managing uncertainty in climate-driven ecological models to inform adaptation to climate change. Ecosphere 2(9): 1-19.

Littell, J. S., J. H. Reynolds, K. K. Bartz, S. A. McAfee, and G. Hayward. 2020.
So goes the snow: Alaska snowpack changes and impacts on Pacific salmon in a warming climate. Alaska Park Science 19(1): 62-75.

Littell, J. S. 2023.
Alaska Climate Futures (mid and late 21st century) and Historical References (20th century). U.S. Geological Survey Data Release.

Lynch, A. J., L. M. Thompson, J. M. Morton, E. A. Beever, M. Clifford, D. Limpinsel, R. T. Magill, D. R. Magness, T. A. Melvin, R. A. Newman, M. T. Porath, F. J. Rahel, J. H. Reynolds, G. W. Schuurman, S. A. Sethi, and J. L. Wilkening. 2022.
RAD adaptive management for transforming ecosystems. Bioscience 72(1): 45-56.

Michalak, J. L., J. J. Lawler, J. E. Gross, and C. E. Littlefield. 2021.
A strategic analysis of climate vulnerability of national park resources and values. Natural Resource Report NPS/NRSS/CCRP/NRR—2021/2293. National Park Service, Fort Collins, CO.

Miller, B. W., G. W. Schuurman, A. J. Symstad, A. N. Runyon, and B. C. Robb. 2022.
Conservation under uncertainty: Innovations in participatory climate change scenario planning from U.S. national parks. Conservation Science and Practice 4(3): e12633.

National Park Service (NPS). 2006.
Management Policies. Washington, D.C.

NPS. 2010.
Climate Change Response Strategy. National Park Service, Washington, D.C.

NPS 2012.
Policy Memorandum 12-02. Applying National Park Services Management Policies in the Context of Climate Change.

NPS 2014.
Policy Memorandum 14-02. Climate Change and Stewardship of Cultural Resources.

NPS. 2015a.
Policy Memorandum 15-01, Addressing Climate Change and Natural Hazards for Facilities. U.S. Department of the Interior, Washington, D.C.

NPS. 2015b.
Addressing Climate Change and Natural Hazards. Facilities and Design Considerations. Level 3 Handbook. U.S. Department of the Interior, Washington, D.C.

NPS. 2015c.
The National Climate Change Interpretation and Education Strategy. National Park Service, Fort Collins, Colorado.

NPS. 2016.
Workforce Climate Change Literacy Needs Assessment and Strategy.

NPS. 2020.
Supplemental Guidance: Integration of Climate Change Scenario Planning into the Resource Stewardship Strategy Process. National Park Service.

NPS. 2021a.
Coming to terms with climate change: Working definitions. National Park Service, CCRP, Fort Collins, Colorado.

NPS. 2021b.
Planning for a Changing Climate: Climate-Smart Planning and Management in the National Park Service. National Park Service. Fort Collins, CO.

NPS. 2023a.
Addressing Climate Change and Natural Hazards Handbook: Checklist for Assessment of Environmental Change and Effects on National Park Service Facilities.

NPS. 2023b.
Green Parks Plan (3rd ed.). National Park Service, Sustainable Operations Branch. Green Parks Plan: Third Edition (nps.gov)

NPS. In press.
National Park Service Climate Change Response Strategy 2023 Update. National Park Service, Washington, DC.

Olliff, S. T., P. Benjamin, A. Erwin, J. Reynolds, W. Carr, L. Perez, G.W. Schuurman, D. Lawrence, J. Gross, A. Runyan, J. Wright, and M. Hylton. In press.
Responding to climate change-driven drought in the American Southwest: Using tools, frameworks, and strategies to build a park-based climate response. Intermountain Park Science, 202x. Lakewood, CO.

Peek, K. M., B. R. Tormey, H. L. Thompson, A. C. Ellsworth, and C. H. Hoffman (editors). 2022.
Climate change vulnerability assessments in the National Park Service: An integrated review for infrastructure, natural resources, and cultural resources. Natural Resource Report NPS/NRSS/CCRP/NRR—2022/2404. National Park Service, Fort Collins, Colorado.

Perez, L., A. Delorey, M. Nelson, R. Stubblebine, and M. Holly. 2020.
Every kid in a park climate change academies: Notes from the field. Park Stewardship Forum. 36(2): CCCA4-CEC-2018-006.

Pierce, D. W., J. F. Kalansky, and D. R. Cayan. 2018.
Climate, drought and sea level rise scenarios for California's fourth climate change assessment.

Roberts, R., M. Holly, and L. Perez. 2021.
Categorizing online climate change interpretation across the National Park System. Journal of Interpretation Research 26(1): 6-23.

Rockman, M., M. Morgan, S. Ziaja, G. Hambrecht, and A. Meadow. 2016.
Cultural Resources Climate Change Strategy. Washington, DC: Cultural Resources, Partnerships, and Science and Climate Change Response Program, National Park Service.

Runyon, A. N., G. W. Schuurman, B. C. Robb, J. Littell, M. E. Miller, and J. H. Reynolds. In press. Climate-resource scenarios to inform climate change adaptation in Wrangell-St. Elias National Park and Preserve. NPS Natural Resources Report NPS/WRST/NRR-2023/XXX. National Park Service, Fort Collins, Colorado.

Schuurman, G., D. N. Cole, A. E. Cravens, S. Covington, S. D. Crausbay, C. Hawkins Hoffman, D. J. Lawrence, D. R. Magness, J. M. Morton, E. A. Nelson, and R. O'Malley. 2022. Navigating ecological transformation: Resist–Accept–Direct as a path to a new resource management paradigm. BioScience 72(1): 16-29.

Schuurman, G. W., C. Hawkins-Hoffman, D. N. Cole, D. J. Lawrence, J. M. Morton, D. R. Magness, A. E. Cravens, S. Covington, R. O'Malley, and N. A. Fisichelli. 2020. Resist-accept-direct (RAD): A framework for the 21st-century natural resource manager. Natural Resource Report. NPS/NRSS/CCRP/NRR—2020/2213. National Park Service. Fort Collins, Colorado.

Schuurman, G. W., A. N. Runyon, B. C. Robb, M. Hylton III, and J. P. Wright. In press. Resource stewardship objectives and actions for climate change-sensitive cultural and natural resources in Wrangell-St. Elias National Park and Preserve: Outputs from January-February 2022 Climate Change Adaptation Strategy Development. NPS Natural Resources Report NPS/WRST/NRR-2023/XXX. National Park Service, Fort Collins, Colorado.

Simeone, W. E. and E. McC. Valentine. 2007. Ahtna knowledge of long-term changes in salmon runs in the upper Copper River drainage, Alaska. U. S. Fish and Wildlife Service, Office of Subsistence Management, Fisheries Resources Monitoring Program, Final Report (Study No. 04-553). Alaska Department of Fish and Game, Division of Subsistence, Juneau, Alaska. 136 pp.

Snover, A. K., N. J. Mantua, J. S. Littell, M. A. Alexander, M. M. McClure, and J. Nye. 2013. Choosing and using climate-change scenarios for ecological-impact assessments and conservation decisions. Conservation Biology 27(6): 1147-1157.

Star, J., E. L. Rowland, M. E. Black, C. A. F. Enquist, G. Garfin, C. H. Hoffman, H. Hartmann, K. L. Jacobs, R. H. Moss, and A. M. Waple. 2016. Supporting adaptation decisions through scenario planning: Enabling the effective use of multiple methods. Climate Risk Management 13: 88-94.

Stein, B. A., P. Glick, N. Edelson, and A. Staudt (eds). 2014. Climate-Smart Conservation: Putting Adaptation Principles into Practice. National Wildlife Federation, Washington, D.C.

Swanston, C. W., M. K. Janowiak, L. A. Brandt, P. R. Butler, S. D. Handler, P. D. Shannon, A. Derby Lewis, K. Hall, R. T. Fahey, L. Scott, A. Kerber, J. W. Miesbauer, L. Darling, L. Parker, and M. St. Pierre. 2016. Forest Adaptation Resources: climate change tools and approaches for land managers, 2nd ed. Gen. Tech. Rep. NRS-GTR-87-2. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 161 p. http://dx.doi.org/10.2737/NRS-GTR-87-2

Terando, A., D. Reidmiller, S. W. Hostetler, J. S. Littell, T. D. Beard Jr., S. R. Weiskopf, J. Belnap, and G. S. Plumlee. 2020. Using information from global climate models to inform policymaking—The role of the U.S. Geological Survey. U.S. Geological Survey Open-File Report 2020–1058, 25 pp.

Tribal Adaptation Menu Team. 2019. Dibaginjigaadeg Anishinaabe Ezhitwaad: A Tribal Climate Adaptation Menu. Great Lakes Indian Fish and Wildlife Commission, Odanah, Wisconsin. 54 pp.

Valentin, M. M., T. S. Hogue, and L. E. Hay. 2018. Hydrologic regime changes in a high-latitude glacierized watershed under future climate conditions. Water 10(2): 128.

Vose, R.S., S. Applequist, M. Squires, I. Durre, M. J. Menne, C. N. Williams Jr., C. Fenimore, K. Gleason, and D. Arndt. 2014. NOAA Monthly U.S. Climate Gridded Dataset (NClimGrid), Version 1. NOAA National Centers for Environmental Information.

Wild, M., A. Ohmura, and K. Makowski. 2007. Impact of global dimming and brightening on global warming. Geophysical Research Letters 34(4): 1-4.

Wright, J. P. and M. Hylton III. 2022. Plan the work, work the plan: An introduction to the National Park Service Climate, Science, and Disaster Response Program. Parks Stewardship Forum 38(3):389-411.

Contributors

Christopher D. Arp, Research Associate Professor, Water and Environmental Research Center, Institute of Northern Engineering, University of Alaska Fairbanks

Krista Bartz, Aquatic Ecologist, Southwest Alaska Network, National Park Service

Andrew Bliss, Physical Scientist, Southeast Alaska Network, National Park Service

Bridget Borg, Wildlife Biologist, Denali National Park and Preserve, National Park Service

Todd J. Brinkman, Associate Professor, Institute of Arctic Biology, University of Alaska Fairbanks

Dana R. N. Brown, Research Assistant Professor, International Arctic Research Center, University of Alaska Fairbanks

Laura Buchheit, Deputy District Ranger, Tongass National Forest, Juneau Ranger District, U.S. Forest Service

Matthew Cameron, Wildlife Biologist, Gates of the Arctic National Park and Preserve and Yukon-Charley Rivers National Preserve, National Park Service

Wylie Carr, Climate Change Planning Specialist, Climate Change Response Program, National Park Service

Barbara A. Cellarius, Anthropologist/Subsistence Coordinator, Wrangell-St. Elias National Park and Preserve, National Park Service

Nina Chambers, Science Communicator, Alaska Region and Inventory & Monitoring Division, National Park Service

Heather Coletti, Ecologist, Southwest Alaska Network, National Park Service

Amy Craver, Cultural Resource Historian, Denali National Park and Preserve, National Park Service

William Deacy, Wildlife Biologist, Arctic Network, National Park Service

Shina duVall, Regional Archeologist, Alaska Region, National Park Service

Melanie Engram, Research Assistant, Water and Environmental Research Center, Institute of Northern Engineering, University of Alaska Fairbanks

Christine Gabriele, Wildlife Biologist, Glacier Bay National Park and Preserve, National Park Service

Jamie Hart, Interpreter, Wrangell-St. Elias National Park and Preserve, National Park Service

Grant Hilderbrand, Associate Regional Director for Resources, Alaska Region, National Park Service

Ken Hill, Physical Scientist, Central Alaska Network and Arctic Network, National Park Service

Kyle Joly, Wildlife Biologist, Gates of the Arctic National Park and Preserve and Yukon-Charley Rivers National Preserve, Arctic Network, National Park Service

Peter Kirchner, Physical Scientist, Southwest Alaska Network, National Park Service

Deborah Kurtz, Natural Resource Program Manager, Kenai Fjords National Park, National Park Service

Laurie Lamm, Supervisory Park Ranger (Interpretation), Glacier Bay National Park and Preserve, National Park Service

Amy Larsen, Aquatic Ecologist, Gates of the Arctic National Park and Preserve and Yukon-Charley Rivers National Preserve, Arctic Network and Central Alaska Network, National Park Service

David Lawrence, Ecologist, Climate Change Response Program, National Park Service

Tania Lewis, Wildlife Biologist, Glacier Bay National Park and Preserve, National Park Service

Jeremy Littell, Research Scientist, Alaska Climate Science Center, U.S. Geological Survey

Denali, Alaska Range, Denali National Park and Preserve.
NPS/KEN HILL

Michael Loso, Physical Scientist, Wrangell-St. Elias National Park and Preserve, National Park Service

Buck Mangipane, Natural Resource Program Manager, Lake Clark National Park and Preserve, National Park Service

Maggie MacCluskie, Program Manager, Central Alaska Network, National Park Service

Rachel Mason, Senior Cultural Anthropologist, Alaska Region, National Park Service

Carol McIntyre, Wildlife Biologist, Denali National Park and Preserve, National Park Service

Mark E. Miller, Ecologist, Wrangell-St. Elias National Park and Preserve, National Park Service

Odin Miller, Anthropologist, Ahtna Intertribal Research Commission

Jeremy Mizel, Wildlife Biologist, Arctic Network and Central Alaska Network, National Park Service

John Morris, Alaska Coordinator, Earth to Sky Partnership, National Park Service (retired)

Jonathan O'Donnell, Ecologist, Arctic Network, National Park Service

Tom Olliff, Program Manager Landscape Conservation and Climate Change, Intermountain Region, National Park Service

Paul Ollig, Director of Interpretation and Education, Denali National Park and Preserve, National Park Service

Pat Owen, Wildlife Biologist, Denali National Park and Preserve, National Park Service

David Payer, Regional Wildlife Biologist, Alaska Region, National Park Service

Larry Perez, Communications Coordinator, Climate Change Response Program, National Park Service

Joel H. Reynolds, Climate Science and Adaptation Coordinator, Climate Change Response Program, National Park Service (retired)

Carl Roland, Plant Ecologist, Denali National Park and Preserve and Central Alaska Network, National Park Service

Amber Runyon, Ecologist, Climate Change Response Program, National Park Service

Joshua Schmidt, Biometrician, Central Alaska Network, National Park Service

Gregor W. Schuurman, Ecologist, Climate Change Response Program, National Park Service

Mathew Sorum, Wildlife Biologist, Gates of the Arctic National Park and Preserve and Yukon-Charley Rivers National Preserve, Arctic Network and Central Alaska Network, National Park Service

Pamela J. Sousanes, Physical Scientist, Central Alaska Network and Arctic Network, National Park Service

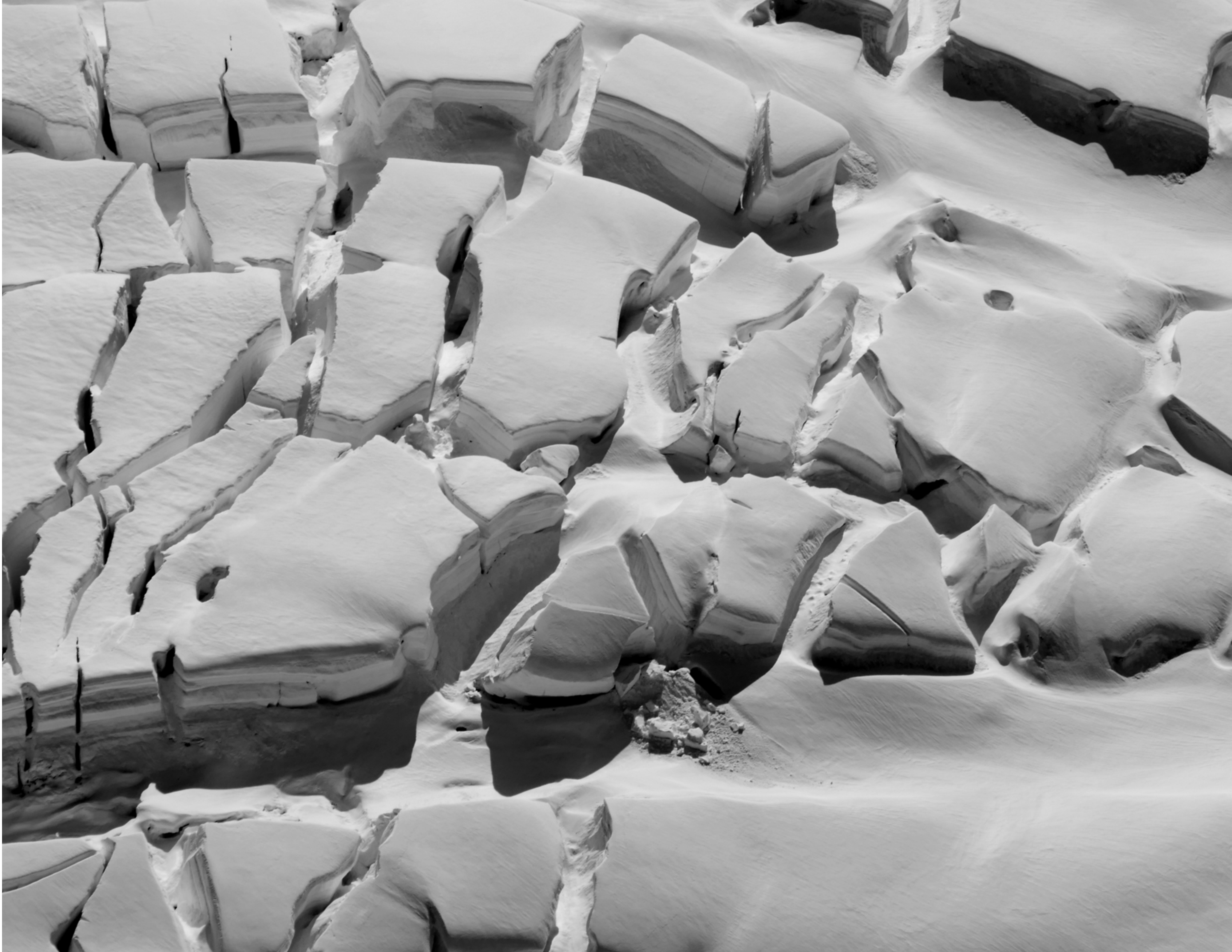
Katie V. Spellman, Research Associate Professor, International Arctic Research Center, University of Alaska Fairbanks

David Swanson, Terrestrial Ecologist, Arctic Network, National Park Service

Jamie Womble, Program Manager, Southeast Alaska Network, National Park Service

Jeneva Wright, Archeologist for Climate Change, Climate, Science, and Disaster Response Program, National Park Service

Crevasses in Kennicott Glacier, Wrangell-St. Elias National Park and Preserve.
NPS/KEN HILL



Alaska Park Science

ALASKA REGIONAL OFFICE
240 WEST 5TH AVENUE
ANCHORAGE, ALASKA 99501

www.nps.gov/subjects/alaskaparkscience/index.htm