



Expansion of the Southeast Alaska Network Vital Signs Monitoring Program to the Outer Coasts of Wrangell-St. Elias National Park and Preserve and Glacier Bay National Park and Preserve



Mount St. Elias (18,009 feet)—also known as *Was'eitushaa*, the Tlingit name that means “mountain at the head of Icy Bay” or “mountain inland of *Was'ei*”—in Wrangell-St. Elias National Park and Preserve.

NPS / JAMIE WOMBLE

Expansion of the Southeast Alaska Network Vital Signs Monitoring Program to the Outer Coasts of Wrangell-St. Elias National Park and Preserve and Glacier Bay National Park and Preserve

Science Report NPS/SR—2025/349

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Abstract

Despite its extensive scale and global significance, the Outer Coast region of Wrangell-St. Elias and Glacier Bay national parks and preserves was not included in the National Park Service Inventory & Monitoring Program until 2019. The relatively pristine Outer Coast is undergoing rapid change. Multiple stressors, including projected increases in air and ocean temperatures, increased rates of ocean acidification, changes in glacier mass balance and volume, isostatic rebound, and growth in vessel traffic and visitation have the potential to impact local ecosystems and landscape dynamics through both direct and indirect pathways. Given expected future changes to the region, establishment of an integrated multidisciplinary long-term monitoring program to better understand ecosystem processes and inform park management is essential.

Here, sampling is proposed to establish baseline conditions and inform the design of a long-term, interdisciplinary monitoring program focused on key environmental drivers and their influences on fjord and nearshore biological communities. The plan is based on conceptual ecological models identified during the Southeast Alaska Network (SEAN) scoping process as well as recent publications and frameworks that are focused on integrated marine and coastal ecosystem science.

This document outlines a research and monitoring plan, leveraging methods based on published protocols for a subset of existing SEAN vital signs in combination with sampling to inform future protocol development. The vital signs included are: (1) weather and climate; (2) glacial dynamics; (3) landform and landcover; (4) oceanography; (5) marine predators, including marine birds and marine mammals; and (6) environmental contaminants. Data and associated metadata will be deposited to the National Park Service's DataStore and public data repositories. Quantitative analyses and systems-level models will be used to integrate physical, chemical, and biological components of park ecosystems, to identify ecosystem linkages, document status and trend of key resources, and identify information gaps and future monitoring needs. Results will be synthesized in peer-reviewed publications and recommendations will be presented for long-term monitoring along the Outer Coast region of Wrangell-St. Elias and Glacier Bay national parks and preserves.

Introduction

The remote outer coastal region of Wrangell-St. Elias National Park and Preserve (WRST) and Glacier Bay National Park and Preserve (GLBA), extending from Cross Sound northward along the outer coast of Glacier Bay to the Copper River Delta, includes over 310 miles (500 km) of shoreline, 4,672 square miles (12,100 km²) of coastal lands, and 234 square miles (607 km²) of marine jurisdiction (Figure 1). This places the Outer Coast among the most significant coastal areas under National Park Service (NPS) stewardship. Part of a UNESCO Biosphere Reserve and World Heritage Site, the region contains an impressive array of globally significant resources, including North America's largest tidewater and piedmont glaciers, a major transboundary wilderness river, recently deglaciaded tidewater fjords, and large aggregations of fish, seabirds, and marine mammals (Womble et al. 2005 and 2009; Barclay et al. 2006; Jansen et al. 2015; Kissling et al. 2007a; Loso et al. 2014; Witteveen et al. 2011). The expansive Outer Coast region supports a broad range of ecosystem services, including traditional hunting and subsistence activities (De Laguna 1972; Deur et al. 2015; Crowell 2016), commercial fisheries (Caldwell 1986), and tourism, contributing directly to local, regional, and state economies (Danby et al. 2003; Cullinane and Koontz 2020).

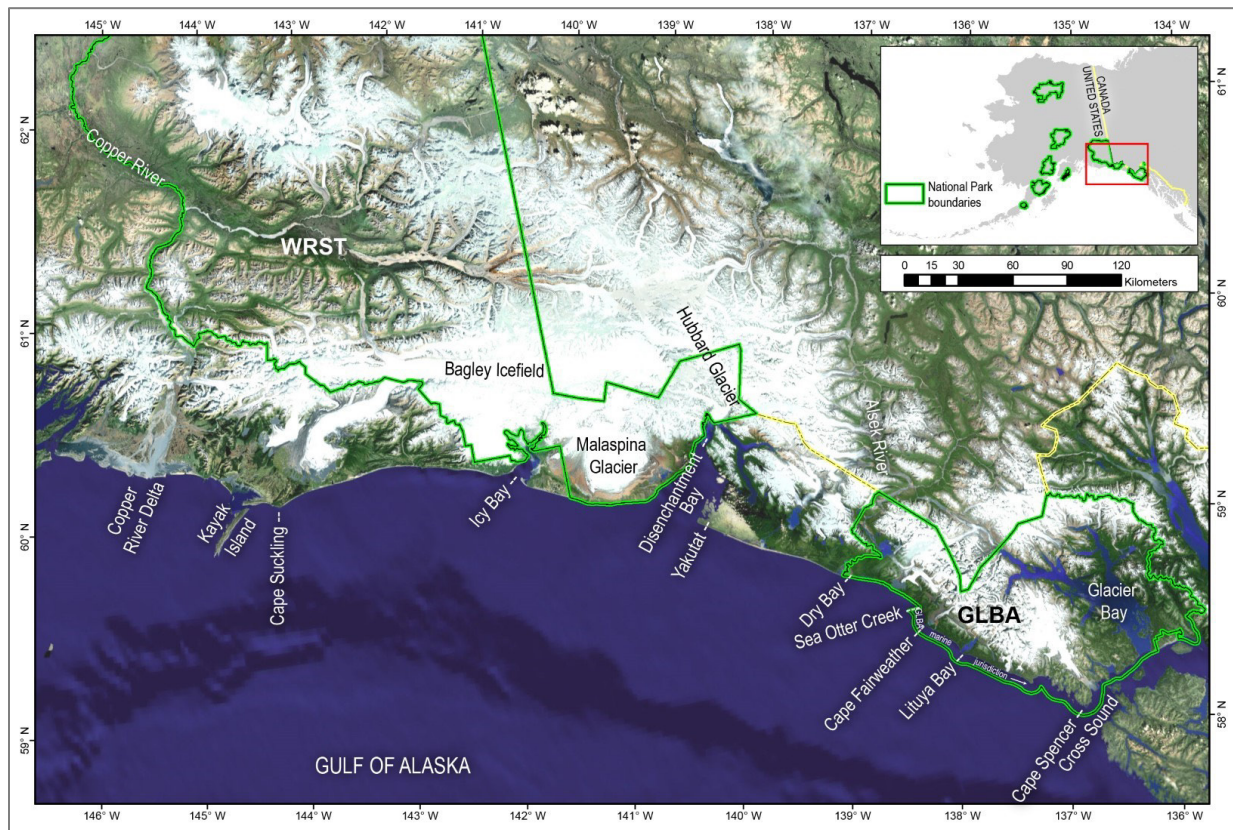


Figure 1. Outer Coast of WRST and GLBA, extending from Cross Sound to the Copper River Delta and including Lituya Bay, Disenchantment Bay, Malaspina Glacier, and Icy Bay.

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The relatively pristine Outer Coast is undergoing rapid change. Multiple stressors, including projected increases in air and ocean temperatures, increased rates of ocean acidification, changes in glacier mass balance and volume, isostatic rebound, and growth in vessel traffic and visitation have the potential to impact local ecosystems and landscape dynamics through both direct and indirect pathways. Given expected future changes to the region, establishment of an integrated multidisciplinary long-term monitoring program to better understand ecosystem processes and inform park management is essential.

Despite its extensive scale, global significance, and persistent environmental threats, funding to support monitoring efforts along the Outer Coast of GLBA and WRST was not available until 2019. Terrestrial and cryosphere monitoring and research in WRST have been conducted by the Central Alaska Network (CAKN) and the park, but marine resources along the inner continental shelf and fjords are more closely aligned with the existing Southeast Alaska Network (SEAN) monitoring program. Thus, during CAKN program development, coastal resources in WRST were intentionally set aside to be incorporated into the SEAN program later. Although the SEAN experienced considerable resource constraints during its early phases of development, recent funding dedicated to broadening the network's efforts has now enabled the expansion of monitoring efforts to the Outer Coast of WRST and GLBA. The following plan describes a conceptual framework and methods for a 4-year study to inform the design of an integrated ecosystem monitoring program for the Outer Coast. To the extent practical, sampling priorities as well as field and analytical methods are aligned with the current SEAN Vital Signs Monitoring Plan (Moynahan et al. 2008) but with increased spatial scope. In several cases where important ecosystem components were not included in the original SEAN program, preliminary sampling to evaluate future additions is incorporated. Methods for these additional components have been aligned with ongoing research efforts in GLBA, WRST, and the Northern Gulf of Alaska (NGA) and to support broader regional inference.

Results of sampling will be published to the NPS IRMA DataStore and public repositories along with formal metadata to ensure long-term security and discoverability. Findings will be synthesized in a study report and/or peer-reviewed publications, including refined or new conceptual and quantitative ecosystem models that capture the current state of knowledge and recommendations for long-term monitoring program design. Strong engagement of park managers during program design and implementation is key for relevance and sustainability (Fancy and Bennetts 2012). A formal SEAN program review, currently scheduled for 2027, will be the primary opportunity to present study findings and associated recommendations for program expansion to park managers and the SEAN Board of Directors.

Outer Coast Expansion Area Description

In the following plan, the SEAN Outer Coast monitoring program expansion area (hereafter “Outer Coast”) is defined as inner continental shelf marine waters to 12 miles (19 km; 10 NM) offshore plus associated coastal lands from the Copper River Delta to Point Carolus at the mouth of Glacier Bay in the eastern Gulf of Alaska (Figure 1). It encompasses nearshore coastal areas of GLBA and WRST, including the fjords and glaciers in and adjacent to Lituya, Yakutat, Disenchantment, and Icy Bays. The expansion area's terrestrial scope is not strictly defined but focuses on landscape components

like rivers and glaciers that interact directly with coastal waters. Along the Outer Coast, many of the larger rivers (e.g., the Copper and Alsek Rivers) and glaciers (e.g., the Bering, Yahtse, Malaspina, Hubbard, and Grand Plateau Glaciers) reach far inland and are only partially within NPS (or even United States) jurisdictional boundaries. These features and the lands that surround them are therefore pertinent to the monitoring program in a manner comparable to the importance of oceanographic conditions outside NPS boundaries, as described below.

Land and marine jurisdiction along the Outer Coasts of WRST and GLBA are mixed. Public lands include portions of two NPS units (WRST and GLBA), the Tongass National Forest Yakutat Ranger District, State lands administered by the Alaska Mental Health Trust, Bureau of Land Management lands, and municipal lands administered by the City and Borough of Yakutat. Private ownership is primarily near Yakutat and Icy Bay. GLBA also holds jurisdiction over marine waters out to about 3.5 miles (6 km; 3 NM) from Point Carolus to just north of Cape Fairweather at Sea Otter Creek. The State of Alaska holds marine jurisdiction out to about 3.5 miles (6 km; 3 NM) from Sea Otter Creek, northward of Cape Fairweather, adjacent to the northernmost portion of GLBA (both national park and the preserve portion) and including waters adjacent to WRST. Beyond GLBA and State waters, the National Oceanic and Atmospheric Administration (NOAA) maintains jurisdiction to the Exclusive Economic Zone boundary at 230 miles (370 km; 200 NM) offshore. Given this diversity of land and marine ownership, collaboration will be crucial to planned ecosystem-scale science and resource stewardship efforts. Within the NPS, cooperative conservation continues to be promoted as a best practice by NPS Management Policies (NPS 2006).

Environmental Setting

The Outer Coast expansion area occupies vast and dynamic land and seascapes. The Chugach and St. Elias Mountains, including GLBA's Fairweather Range, are one of the world's highest coastal ranges (elevation maxima >5,000 m). As moisture-laden air flows off the Gulf of Alaska and abruptly encounters this vertical relief, it rises and cools rapidly. The resulting abundant precipitation sustains the region's icefields, rivers, and coastal temperate rainforest ecosystem. A series of prominent fjords bisect the Outer Coast. These deep, narrow estuaries were, or are presently being, excavated by terrestrial glaciers (Syvitski et al. 1987) and link landscape and ecosystem-level processes along the ice-ocean boundary (O'Neel et al. 2015; Straneo et al. 2016; Bianchi et al. 2020). The coastal Northern Gulf of Alaska, encompassing both nearshore environments and the continental shelf, is a productive subarctic marine ecosystem that connects deep offshore waters with a range of terrestrial influences.

Weather and Climate

Weather conditions throughout the expansion area are cool, wet, and strongly influenced by the Pacific Ocean. Low elevation weather stations provide multi-decadal records geographically bracketing the Outer Coast (Figure 2). Mean annual temperatures from 1981–2010 decrease from Sitka (7.4°C) to Cordova (4.2°C) as annual temperature range increases (Sitka 5.2°C, Cordova 8.4°C; NOAA 2021). Yakutat typically receives the most precipitation (3.9 m), with Sitka (2.2 m), Cordova (2.3 m), and Juneau (1.6 m) receiving less. September and October are the wettest months at all stations. Data from high elevations are intermittent yet corroborate models showing persistently cold montane temperatures and precipitation far greater than at sea level (Lader et al. 2020).

Alaska's climate has been rapidly changing in parallel with global shifts. Annual mean air temperatures have risen over the last 70 years (Figure 2; NOAA 2021), with Cordova, Yakutat, and Juneau warming at about equal rates (0.27–0.29°C/decade) and Sitka slightly slower (0.17°C/decade). Precipitation exhibited high interannual variability and no significant change at most sites, though Juneau showed an increasing trend of 0.07 m/decade. Annual totals likely mask changes in seasonality. Climate models predict continued warming at roughly the same rates noted above, including fewer frost days per year and increased total precipitation with more intense extreme events, and lower snowfall totals (Lader et al. 2020). Such changes in daily and seasonal weather will significantly impact physical and biological systems along the Outer Coast.

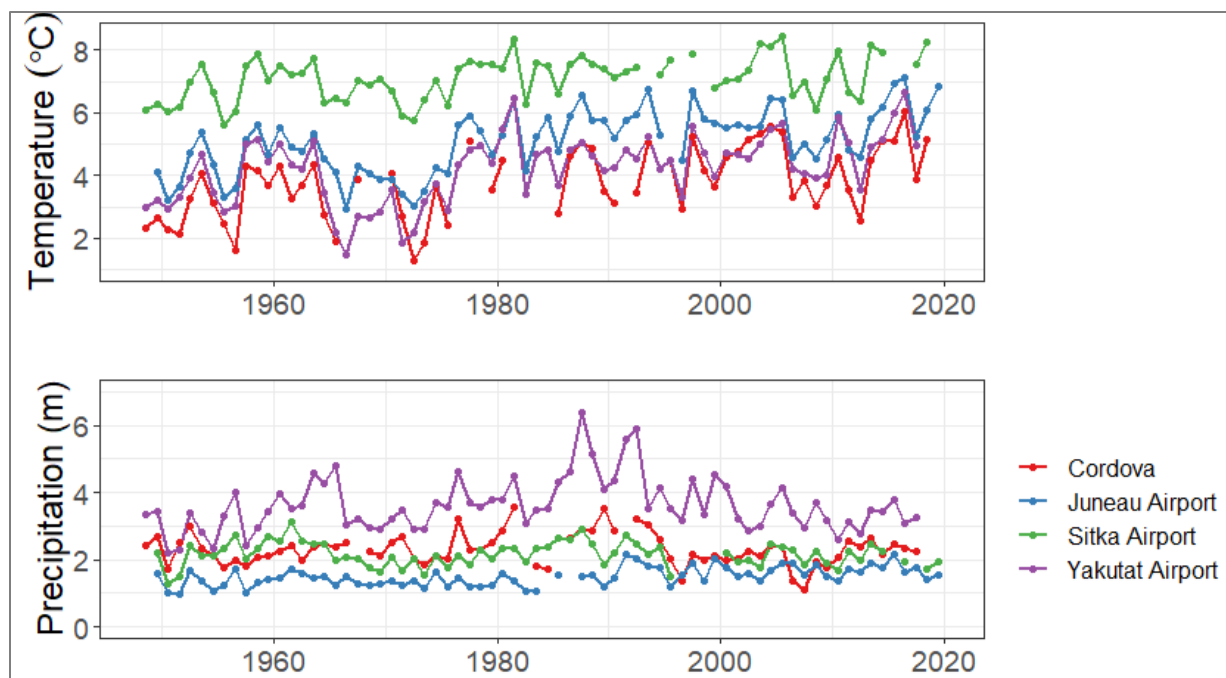


Figure 2. Annual mean temperatures (top) have been rising while annual total precipitation (bottom) has held steady over the last few decades at four stations in southeast Alaska. Data from NOAA (2021).

NPS / NOAA

Glacial Dynamics

Both GLBA and WRST are glacier-dominated landscapes (Loso et al. 2014). WRST has 3,121 glaciers occupying 7,156 square miles (18,534 km²; 34.8%) of the park area and is the most extensively glaciated unit in the NPS system. GLBA has 1,045 glaciers covering 1,570 square miles (4,068 km²; 30.6%) within its boundaries. Considering the entire Outer Coast, 218 distinct “coastal glaciers” reaching within 1.2 miles (2 km) of the shoreline are at least partly in GLBA and WRST, while 1,233 are within 6.2 miles (10 km) of the coast, including some of the largest individual glaciers in Alaska. The total area covered by the 1,233 coastal glaciers is 8,223 square miles (21,297 km²), a figure that includes the entire coverage of each glacier beyond NPS units to private or state lands, other conservation units, and Canada.

Across Alaska, the atmosphere and ocean are warming, and glaciers are retreating. From 1948 to 2010, GLBA’s glaciers lost ~15% of their area and WRST’s 5% (Figure 3; Loso et al. 2014). Even with complexities of tidewater glacier dynamics (discussed below), the current and expected future regional pattern is one of sustained and accelerating ice loss and terminus retreat (Larsen et al. 2015). The few exceptions, including Hubbard (Stearns et al. 2015) and Yahtse Glaciers (Durkin et al. 2017), are presently advancing tidewater glaciers out of phase with the modern climate.

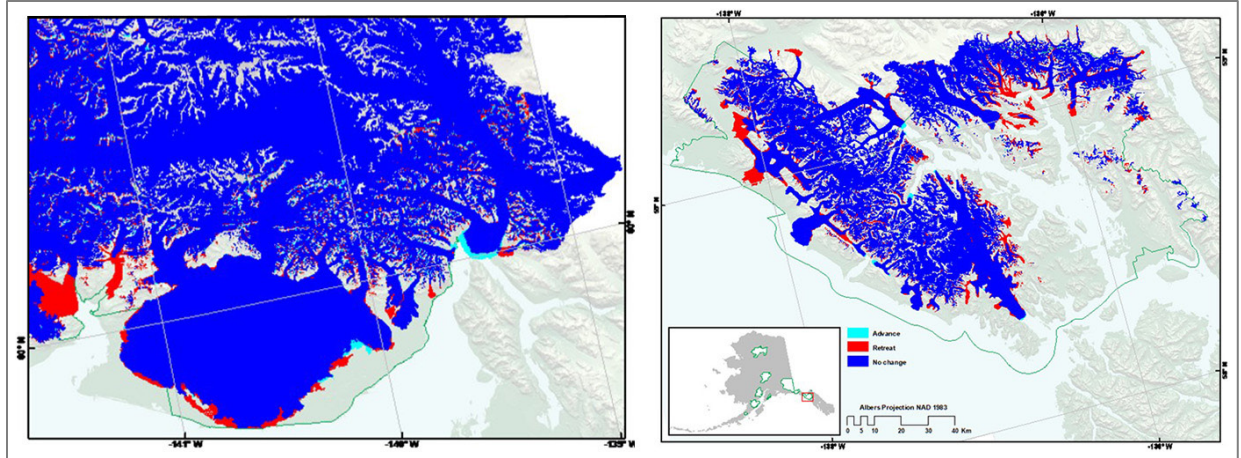


Figure 3. Glacier outlines in GLBA (left) and the coastal portion of WRST (right). Red represents glacier retreat—area covered by glaciers at the map date (1948 or 1962) but not at the modern date (2010). Light blue represents glacier advance—area covered only at the modern date. Dark blue represents area covered at both times (Loso et al. 2014).

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Historically, many Outer Coast glaciers reached the Pacific Ocean (Figure 4 white line shows glacial maximum ~15,000 years ago), and a small but significant number still do. Tidewater glaciers have complex relationships with ocean conditions, fjord shape, and terminus sediment dynamics (Post et al. 2011; Brinkerhoff et al. 2017); their behavior is cyclical (Post 1975). In favorable conditions, a glacier may advance, pushing a wedge of sediment that protects it from relatively warm fjord water. Once retreat begins, or if the glacier enters a wider/deeper area, seawater contact increases leading to greater iceberg calving and submarine melt (Motyka et al. 2003; Bartholomaus et al. 2013, McNabb et al. 2015). Rapid retreat often occurs until the terminus is grounded; with reduced area available for melt, the glacier's mass balance then becomes positive, and a new advance restarts the cycle. Periods (years to decades) of stability during the retreat phase are possible if the terminus is in a constricted area of the fjord (McNabb and Hock 2014). For these reasons, tidewater glaciers may change more rapidly than, and out of phase with, nearby land-terminating glaciers (Hock et al. 2019).

Most glacial fieldwork during the SEAN Outer Coast study will focus in the Disenchantment Bay/Hubbard Glacier area, largely for logistical reasons. Characteristics of several major glaciated areas representative of the broader region are summarized in Table 1, spanning a range of tidewater glacier cycle stages and physical features. Each of these areas will be assessed primarily through remote sensing (and perhaps some limited, opportunistic fieldwork).

Beginning along the western portion of the Outer Coast expansion area, Icy Bay (WRST) was formed by the rapid retreat of Guyot, Yahtse, and Tyndall Glaciers (Winkler 2000; Figure 4). Yahtse Glacier (393 square miles [1,019 km²] in 2010; Loso et al. 2014) dominates Icy Bay, along with other glaciers, and was retreating in the mid-20th century but has slowly advanced in recent years (Durkin et al. 2017; USGS 2021). Neighboring Icy Bay glaciers are retreating.

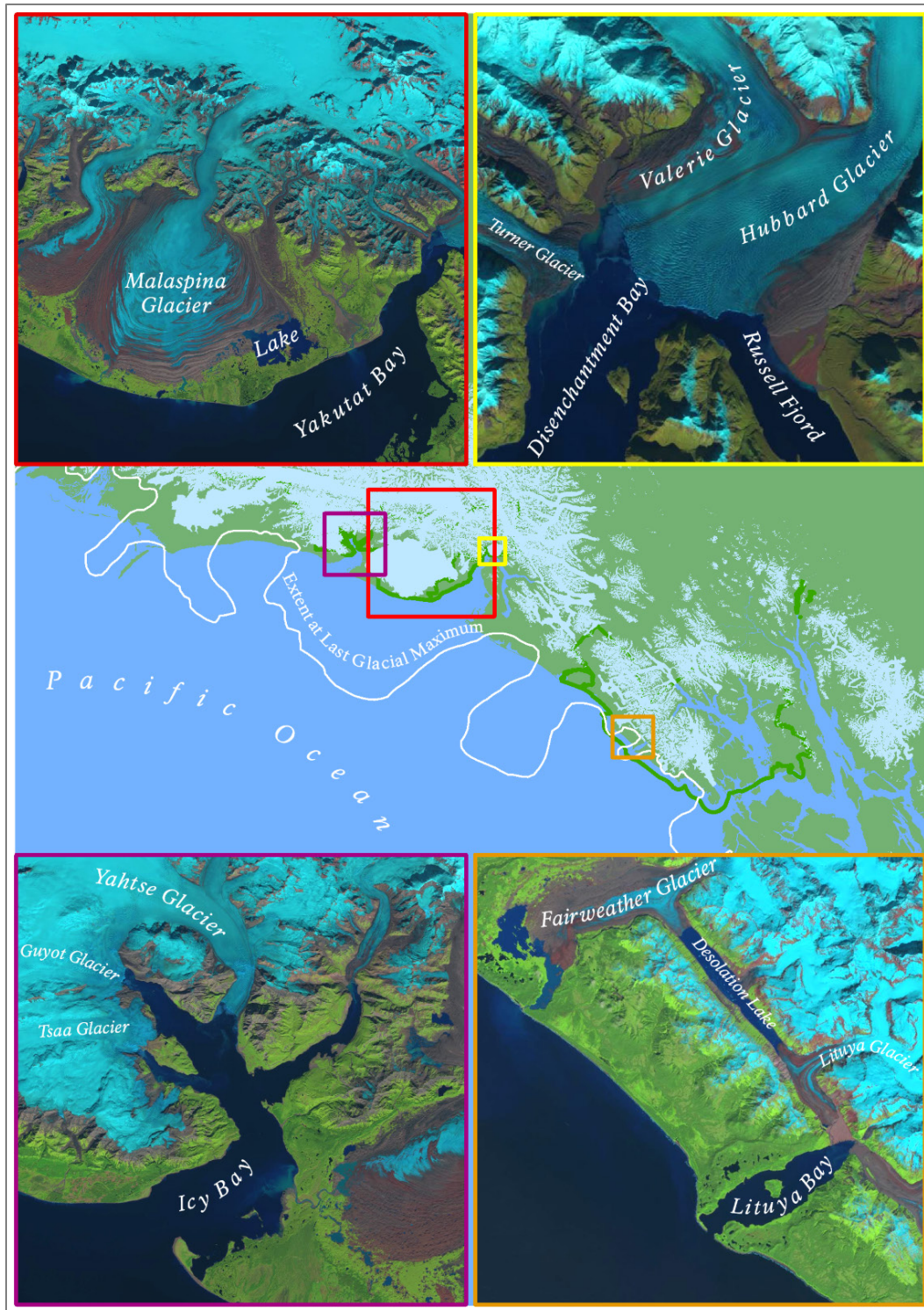


Figure 4. False color Landsat 8 images of Outer Coast study areas: Malaspina Glacier coastal zone and Yakutat Bay (upper left, image date 2019-9-6), Disenchantment Bay (upper right, 2020-10-10), Icy Bay (lower left, 2019-9-6), and Lituya Bay (lower right, 2020-7-1). Images from USGS (2021).

NPS / USGS

Table 1. Physical characteristics of fjords and glaciated areas along the Outer Coast.

Physical Characteristic	Icy Bay	Malaspina Glacier ^A	Disenchantment & Yakutat Bays	Lituya Bay
Watershed area (km ²)	2,145	5,763	6,641	285
Glacier area (km ²)	1,733	4,551	4,486	157
Glacier cover (%)	80.8	78.9	67.5	55.1
Number of active tidewater glaciers	4	1	3	0
Glacier status as of 2022	3 stable, 1 retreat	1 stable	2 advancing, 1 surging	2 stable (grounded)
Distance (km) glacier to Gulf of Alaska	35	2	52	12
Distance (km) glacier to shelf break	109	100	164	85
Water area of fjord (km ²)	266	2.5	842	28
Max depth (m)	180	15	260	140
Number of sills in fjord	2	1	2	1
Sill depth (m)	15, 34	1	25, 70	9

^A The incipient fjord in front of Malaspina Glacier, Sitkagi Lagoon, is changing rapidly; these numbers are for 2021.

Malaspina Glacier (WRST) is a large piedmont glacier (1,792 square miles [4,640 km²] for all 3 lobes in 2010; Larsen 2010) that presently remains extended near the continental shelf rather than retracted within a fjord. Malaspina is undergoing dramatic landscape transformations due to recent thinning and ice loss, though the central lobe began a surge in late 2020 (Figure 4). Several proglacial lakes have formed in front of the glacier, one of which is now connected to the ocean (Thompson et al. 2021). As climate change, glacier retreat, and sea level rise continue, this small estuarine lake may erode further to form a new bay, potentially accelerating Malaspina's retreat due to enhanced ocean influence.

North America's largest tidewater glacier, Hubbard Glacier (WRST; 1,228 square miles [3,180 km²] in 2010, including the Valerie Glacier lobe; Larsen 2010) has a high-elevation source area that originates primarily in Canada (Figure 4). Hubbard sits at the head of Disenchantment Bay and the terminus is presently stable.

Relative to Malaspina and Hubbard, glaciers further southeast along the Outer Coast are smaller. Arguably, the most important glaciers feed into Lituya Bay (GLBA), dominated by Lituya Glacier (30 square miles [77 km²] in 2010) and North Crillon Glacier (22 square miles [56 km²] in 2010; Larsen 2010). Both are presently grounded, but Lituya was tidewater as recently as the mid-1990s (USGS 2021; Figure 4). High sediment output from the associated rivers has built outwash plains that currently separate the glaciers from the marine waters of Lituya Bay.

Landform and Landcover

The Outer Coast's high degree of ice cover combined with rapid historic and ongoing glacier change has far-reaching, powerful landscape impacts. For example, river systems are significantly influenced

by upstream glacier extent (O’Neel et al. 2014; Loso et al. 2021) with regards to streamflow rate, timing of peak flows, channel configuration, water temperature, sediment load, and suitability as aquatic habitat (Pitman et al. 2020). As glaciers transition from marine- to land-terminating, physical changes in the surrounding landscape co-occur, such as decreased slope stability, increased frequency of landslides, and chemical characteristics of freshwater runoff (Higman et al. 2018; Moon et al. 2018; Hopwood et al. 2019; Amundson et al. 2020; Coe 2020). Lakes may form as grounded glaciers retreat from their terminal moraines, and periodic catastrophic drainage events release vast amounts of water in only a few days with mostly unstudied implications for downstream sedimentation and biota (Shugar et al. 2020). Extensive and long-lived glacier retreat leads to isostatic rebound (uplift of the unloaded earth surface; Larsen et al. 2004, 2005) with consequences for shoreline positions, beach profiles, and river gradients. Areas exposed by glacier retreat are colonized by new soil organisms and vegetation, and existing vegetation may be exposed to changing microclimates and propagule dispersal (Fastie 1995). Surficial sediments like glacial till, outwash gravel, and other materials can be rapidly deposited or eroded, with the two processes commonly occurring in close temporal and spatial proximity (Williams 2018; Curran et al. 2017). Snowfall melts more quickly from bare and vegetated ground than from the glacier surface, and meltwater routing can change dramatically as ice mass is reduced (Young et al. 2021).

Changes such as those listed above fundamentally alter the landscape structure upon which physical and ecosystem processes function. The composition, quantity, patch configuration, and juxtaposition of these and other terrestrial landscape components control energy and material flow, inputs to marine systems, habitat availability, and wildlife movement patterns. These components can be divided into two broad types: landforms, which refer to the abiotic structures of the landscape (mountains, river channels, moraines, beaches, etc.), and landcover, which describes the materials that blanket the landforms (in most landscapes primarily vegetation, but in this landscape glaciers and lakes are equally important). Many landscape components can be observed, quantified, and mapped using remote sensing tools, the primary monitoring strategy of this vital sign. Where remote sensing detects rapid changes in landform and landcover patterns, as is often the case along the glaciated Outer Coast, targeted field-based investigations may occur to characterize their nature in more detail.

Oceanography

The eastern Gulf of Alaska continental shelf is bathymetrically complex and ranges from 19–50 miles (30–80 km) wide. Glacial and tectonic processes have created submerged canyons and moraines (Carlson et al. 1982). The continental slope is dominated by the Alaska Current, a 62–124 mile (100–200 km) wide counterclockwise flow bringing warm water from lower latitudes in the North Pacific (Weingartner et al. 2009). The region is highly productive; however, it favors wind-driven coastal downwelling and trophic links are not completely understood (Stabeno et al. 2004; Weingartner et al. 2009). Over the inner continental shelf (within about 22 miles [35 km] of shore) the Alaska Coastal Current dominates, a wind-forced flow fed by glacier melt, snow melt and precipitation as well as runoff from the nearby coastal mountains (Weingartner et al. 2005; Stabeno et al. 2016). Numerous fjords cut through the shoreline, linking land and sea in unique and highly dynamic settings. Fjord ecosystem composition and function are controlled by exchange of heat, salt,

freshwater, nutrients, and biota with the adjacent coastal ocean, the presence of terrestrial versus tidewater glaciers (Figure 5; Meire et al. 2017), and other features (e.g., fjord depth, sill depth/location, degree of tidal mixing).

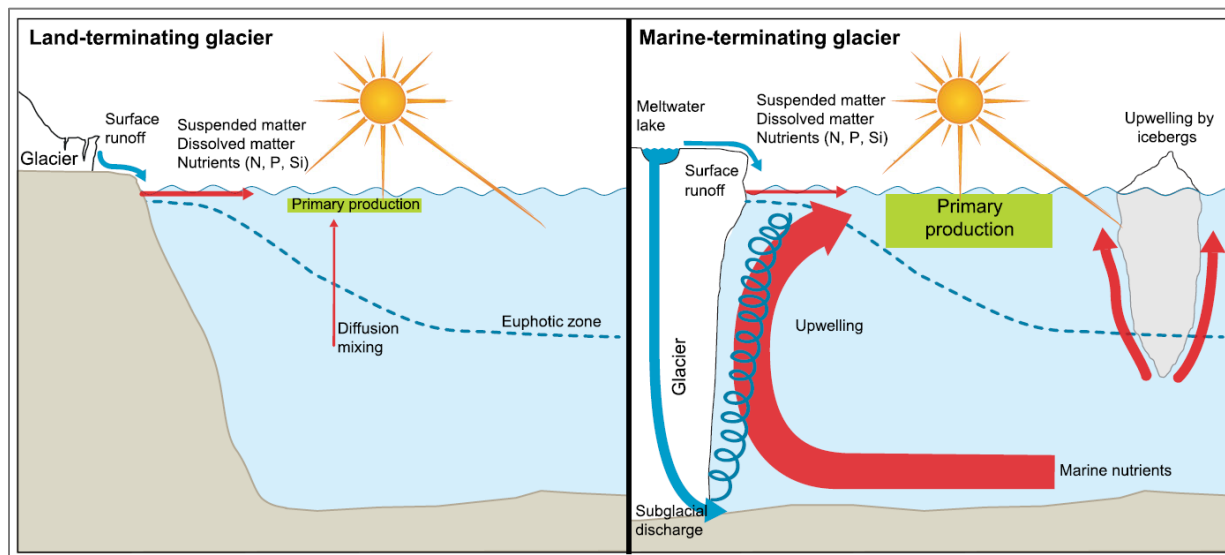


Figure 5. Key differences in physical, chemical, and biological processes in fjords with land-terminating (left) and marine-terminating glaciers (from Meire et al. 2017).

GLOBAL CHANGE BIOLOGY

Marine waters in the Gulf of Alaska were anomalously warm in 2014–2016 (Bond et al. 2015) and human-induced climate change has greatly increased the risk and frequency of such events (Walsh et al. 2018). Measurements in Glacier Bay and at the mouth of Resurrection Bay near Seward showed similar ($r^2 = 0.54$) manifestations of this heatwave and the 2008–2013 cool interval (Figure 6). Near-surface (0–50 m) waters outside Resurrection Bay exhibited a 50-year warming trend of $0.24^\circ\text{C}/\text{decade}$ (Danielson et al. 2021), while across the entire water column 1993–2019 GLBA temperature data detected warming of $0.10^\circ\text{C}/\text{decade}$ (Danielson et al. 2022; Gabriele et al. 2022). Multi-disciplinary investigations note that heatwave effects persist years beyond the initial most acute period (Suryan et al. 2021) though the full extent of impacts is not well understood. Influence on tidewater glacier mass balance is likely of utmost importance as ocean temperature accounts for 50% of terminus ablation in Svalbard, Norway (Holmes et al. 2019) and Yahtse Glacier in Alaska's Icy Bay (Bartholomaeus et al. 2013).

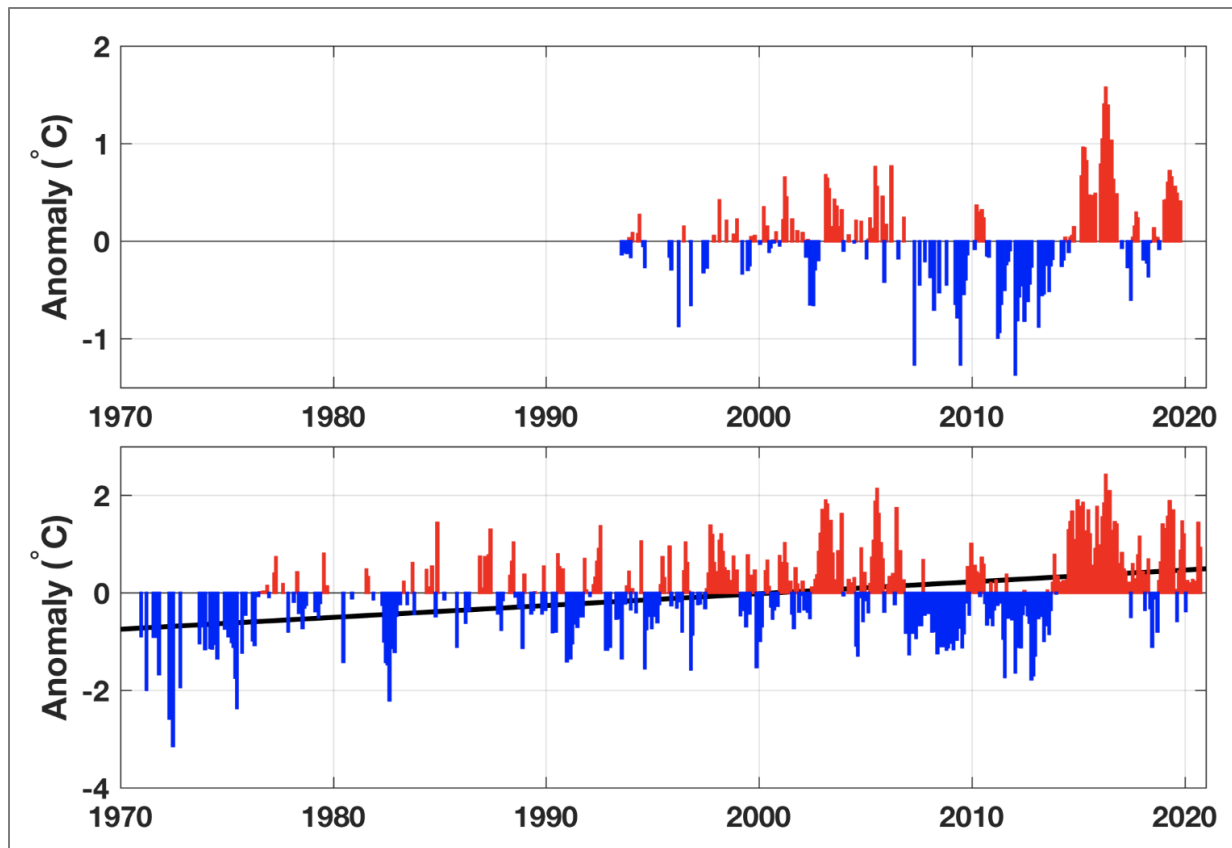


Figure 6. Monthly temperature anomalies averaged across the upper 50 m of the water column from all SEAN GLBA oceanographic monitoring stations (top) and at station GAK-1 (bottom) at the mouth of Resurrection Bay in northern Gulf of Alaska. The GAK-1 period of record best fit trend (black line) shows a 1.2°C warming over 50 years. Note difference in vertical scales.

NPS / UAF

A large proportion of anthropogenic atmospheric CO₂ is absorbed by ocean surface waters (Feely et al. 2004); this process lowers seawater pH and creates corrosive conditions known as ocean acidification (OA). In turn, OA decreases availability of the calcium carbonate minerals (aragonite and calcite) used by many marine organisms for the formation of shells and skeletons (Feely et al. 2004 and 2009). Fjord and nearshore ecosystems can be sensitive to OA as the low buffering capacity of glacier melt plumes enhances CO₂ uptake (Evans et al. 2014; Reisdorph and Mathis 2014; Cai et al. 2020; Hauri et al. 2020; Hopwood et al. 2020). Throughout the Gulf of Alaska, fjords episodically experience reduced aragonite and calcite levels, particularly when glacier discharge is highest. Given the current rate of Outer Coast deglaciation, OA will likely become a major ecological stressor in fjords and marine waters along the Outer Coast.

Apart from the SEAN's GLBA work (Danielson 2012) and Seward Line Program (<http://research.cfos.uaf.edu/sewardline/>) sampling in Prince William Sound and along the Kenai Peninsula, ongoing monitoring in the northeastern Gulf of Alaska focuses primarily on the open ocean. Autonomous profiling (ARGO) floats measure only deep offshore waters (>1,500 m). Remote sensing provides a rich suite of sea surface observations, but most satellites are limited to cloud-free

conditions, don't well-resolve the nearshore, and lack the ability to resolve most chemical and biological parameters of interest. The Outer Coast expansion area represents an along-shore gap of over 500 km between any consistent in situ oceanographic monitoring efforts. Pilot study marine sampling will focus in Disenchantment/Yakutat Bays, Lituya Bay, and along the GLBA continental shelf, with other areas added as weather/ice conditions, vessel time, and logistics allow.

Marine Food Web

Gulf of Alaska continental shelf and nearshore ecosystems are highly productive, supporting a biologically diverse food web. Productivity is largely controlled by light and nutrient availability. Water column structure and dynamic physical processes (i.e., strong wind events, tidal exchange, and eddies; Stabeno et al. 2004) supply nutrients to surface waters where they are utilized by primary producers. A broad suite of mid-trophic species (large zooplankton and small fishes) transfer energy produced by phytoplankton to economically and culturally important top-level predators.

Mid-Trophic Communities

Zooplankton community structure and population dynamics are influenced more by instantaneous environmental conditions than individual survival from year to year (Taylor et al. 2002; Hays et al. 2005; Richardson 2008). Initiatives to understand zooplankton variability have been ongoing for multiple decades with the Northern Gulf of Alaska Long-term Ecological Research (NGA LTER) program presently sampling along the Seward Line, in Prince William Sound, off Kodiak Island, and near the Copper River Delta. Fjord studies focusing on biological oceanography in the Gulf of Alaska are limited (Coyle and Pinchuk 2003; Robards et al. 2003; Arimitsu et al. 2016; McKinstry and Campbell 2018; Stemmler 2019). Zooplankton sampling along the outer coast is complementary with other ongoing studies in the Gulf of Alaska.

Small schooling (forage) fish in the region include juvenile sockeye and pink salmon, pollock, herring, sandlance, eulachon, capelin, and lanternfish. Large winter/spring aggregations of spawning eulachon provide a critical pulse of high-energy prey for seabirds and marine mammals prior to the reproductive season (Womble et al. 2005). Herring spawn in Yakutat Bay during late spring, while capelin favor cooler, more turbid fjord waters (Arimitsu et al. 2008; Bishop and Green 2009).

Nearshore and deep-sea benthic invertebrates from mollusks to sea stars are important prey for groundfish, marine birds, and sea otters. Climate change and extreme events have led to disease outbreaks (e.g., sea star wasting disease; Harvell et al. 2019) and species assemblage alterations. While Feder et al. (1981) characterized benthic assemblages in portions of the expansion area, little is known about fjord benthos or spatiotemporal community structure trends. Neither forage fish nor benthic species are part of the SEAN Outer Coast marine monitoring program due to financial, personnel, and logistical limitations.

Marine Fish

The Outer Coast supports populations of many economically or culturally important fishes (see Human Uses), among them five species of Pacific salmon with complex yet relatively brief anadromous lifecycles. Short- and long-term environmental changes have profound impacts, from

drought-driven low water levels that restrict spawning access, to rising stream temperatures that alter development rates in early life stages, to shifting melt timing that threatens emerging juveniles (Schoen et al. 2017). Retreating glaciers will open new spawning areas (O’Neel et al. 2015; Pitman et al. 2020). Offshore, ocean temperature and zooplankton food resources strongly influence the distribution, growth, and success of maturing salmon. A suboptimal environment, such as during marine heatwaves, has negative repercussions for rate/timing of spawning, fecundity, nutrient transport to riparian ecosystems, commercial value, and population resilience (Oke et al. 2020). Alaskan landscape transformation and climate change effects are mixed, benefiting some salmon populations while being detrimental to others (Schoen et al. 2017).

Marine Birds and Marine Mammals

Seabirds, sea ducks, shorebirds, and gulls utilize Outer Coast fjord ecosystems and nearshore stopover areas in Yakutat Bay, the Alsek River, and the Yakutat Forelands (Kissling et al. 2007a and 2007b; Schoen et al. 2013). Physical processes associated with ice calving and shallow fjord sills create localized upwelling that transports nutrients and prey to the surface, creating productive foraging areas for marine birds (Stempniewicz et al. 2017; Urbanski et al. 2017). The Kittlitz’s murrelet, a small endemic seabird of conservation concern, nests and forages in fjords and nearshore coastal areas along the Outer Coast (Kissling et al. 2007b).

Numerous marine mammals occur along the Outer Coast, including both resident and migratory species. Harbor seals and Steller sea lions are typically residents in the region with seasonal shifts associated with foraging and reproduction (e.g., Womble et al. 2005 and 2009; Womble and Gende 2013; Jansen et al. 2014; Rehberg et al. 2018). Sea otters occur along the Outer Coast region and are increasing after near extinction (Eisaguirre et al. 2021). A small population of beluga whales that has been isolated geographically and genetically occurs in Disenchantment and Yakutat Bays (Lucey et al. 2015; O’Corry-Crowe et al. 2015). Harbor porpoise, Dall’s porpoise, and orcas also occur in the nearshore coastal waters along the Outer Coast. Humpback, minke, and grey whales make annual migrations to the Outer Coast region from breeding areas thousands of kilometers away.

Tidewater glaciers calve icebergs into the marine environment which serve as pupping, molting, and resting habitat for some of the largest seasonal aggregations of harbor seals in Alaska and the world (Jansen et al. 2015) in fjords in coastal WRST and GLBA. Ice habitat provides a stable platform for nursing pups during the brief lactation period, reduces pup predation risk, and likely limits disease transmission (Fay 1974; Calambokidis et al. 1987; Blundell et al. 2011). Harbor seals that pup and rest in fjords in coastal WRST and GLBA also use marine waters in the fjords and along the Outer Coast region of the eastern Gulf of Alaska for foraging and travel (Womble and Gende 2013; Womble et al. 2014; NOAA 2018) (Figure 7). The reliance of harbor seals on iceberg habitat for critical life-history events provides a direct link between changes in tidewater glaciers and harbor seals.

Harbor seals are an important cultural and subsistence species for the Yakutat Tlingit (Crowell et al. 2024; Crowell 2024). Harbor seals are also a highly sought after viewing opportunity for visitors to Disenchantment and Icy Bays, many of which arrive on cruise ships. Research by NOAA and NPS

has focused on understanding seal-vessel interactions in Disenchantment Bay, where the number of cruise ships has increased in recent years (Jansen et al. 2010 and 2015; NOAA 2018).

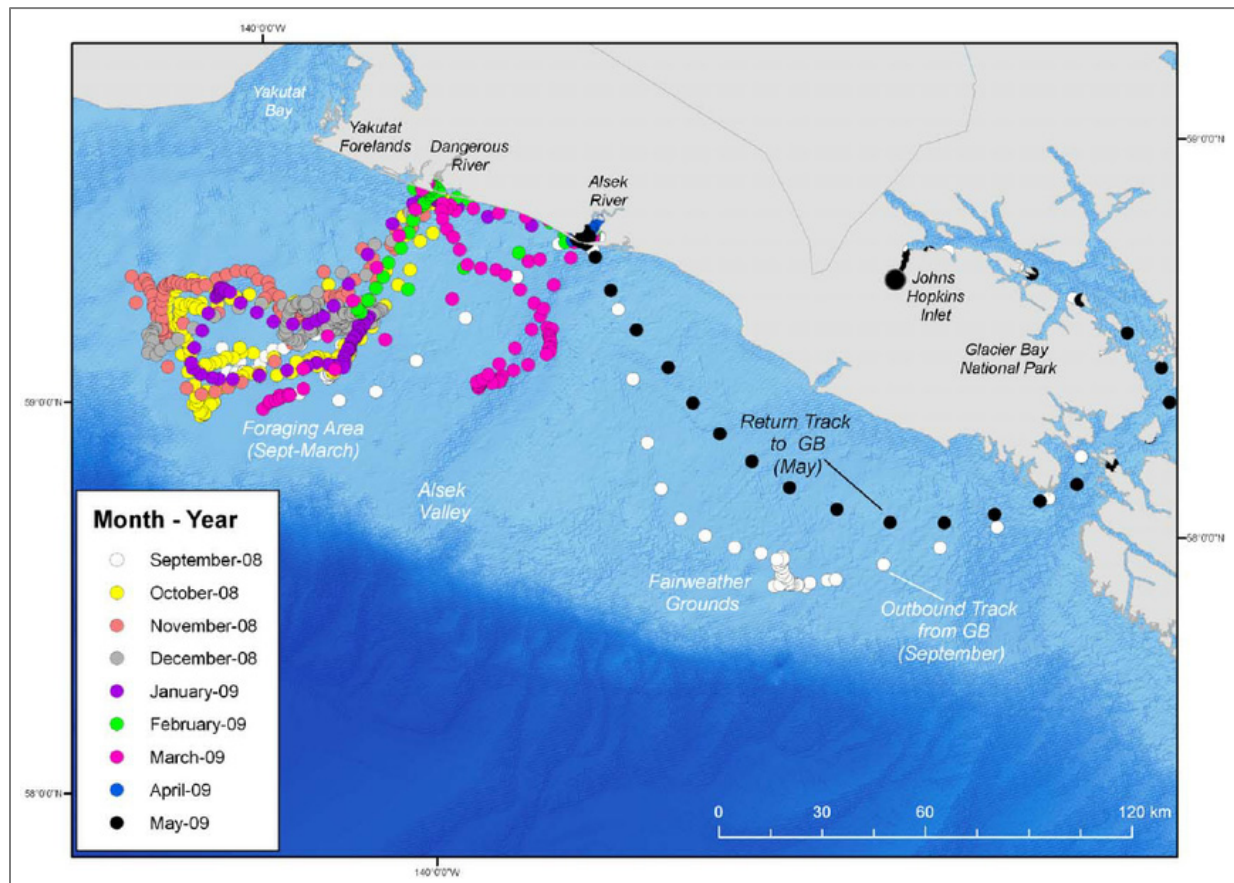


Figure 7. State-space modeled track of an adult female harbor seal tagged in Johns Hopkins Inlet, Glacier Bay National Park in September 2007. PV08GB21 spent greater than 200 days in the eastern Gulf of Alaska and exhibited a high degree of fidelity to a region ~95 km from shore from September 2008 to February 2009. In late February, the adult female seal transitioned to the mouth of the Alsek River where eulachon were aggregated for spawning in late winter and spring (from Womble and Gende 2013).

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As sentinels of ecosystem variability and change, marine birds and mammals serve as indicators of shifts in climate, oceanographic conditions, prey availability, and habitat (Moore 2008; Moore and Kuletz 2019). For example, the 2014–2016 marine heatwave resulted in rapid changes among nearshore and pelagic fauna across the Gulf of Alaska, including mass mortality events for seabirds (Suryan et al. 2021) and lower survival and reproduction in marine mammals (humpbacks; Gabriele et al. 2022). Likewise, number and nutritional quality of forage fish were reduced, negatively impacting the health of higher trophic levels (Piatt et al. 2020; Arimitsu et al. 2021). The rocky intertidal zone shifted from a rockweed-based system to one dominated by mussels and barnacles, with corresponding changes in ecological function and as-yet unknown implications for the wider food web (Weitzman et al. 2021). Given current global trends in ocean warming (Danielson et al.

2021 and 2022), recent heatwave events offer example concerns for a future Gulf of Alaska marine ecosystem.

Goals and Objectives

Long-term natural resource monitoring in NPS units is fundamental to science-based resource stewardship (NPS 1992; Fancy et al. 2009). To meet this objective, parks were divided into 32 networks based on ecoregions and natural resource information needs. At each network, including the SEAN, a standard process—conceptual model development, resource inventories, target subject selection—was completed to develop a formal monitoring plan (NPS 1992; Moynahan et al. 2008).

This Outer Coast study plan builds off the SEAN Vital Sign Monitoring Plan (Moynahan et al. 2008), supplementing aspects of the program’s prior design process to facilitate monitoring choices for the expansion area. The study plan relies on conceptual models to identify priority information needs, sampling to assess feasibility and baseline variability, and analyses and quantitative models to evaluate the performance of candidate parameters for long-term ecosystem monitoring utility.

The overarching goal of the Outer Coast expansion is to establish an integrated, interdisciplinary, long-term, marine and coastal terrestrial ecosystem monitoring program. Coordinated observations of key environmental parameters will improve understanding of how ecosystem drivers influence the status and trends of physical and biological resources. This information will provide baseline data and inform GLBA and WRST management decision-making processes. The following specific objectives guide planning, implementation, and subsequent interpretation of findings.

1. **Document ecological linkages to focus sampling.** As a key first step, a series of conceptual frameworks linking drivers of change and possible ecological responses are presented to guide sampling efforts.
2. **Evaluate candidate monitoring parameters and sampling locations.** Prior research, inventory, and monitoring activities along the Outer Coast are limited in scope. This study will inform long-term program design by testing field logistics and ensuring feasibility within cost and time constraints. Site-specific preliminary observations also quantify baseline conditions and verify efforts will meet information needs. Exploratory and preliminary analyses will evaluate performance of candidate monitoring parameters.
3. **Develop preliminary ecosystem model to synthesize findings.** A Bayesian Network model will be created to examine potential responses of different physical processes or biological dynamics to ecosystem change through time. Importantly, this model will serve to communicate the state of knowledge, including recognized data limitations and information gaps, helping to facilitate discussions about potential future monitoring program adaptations to improve efficiency, performance, and relevance.
4. **Engage and collaborate with park staff and managers and facilitate long-term monitoring design adaptations.** Given that the Outer Coast of GLBA and WRST was not incorporated into the CAKN or SEAN Vital Sign Monitoring Plans, adaptations to existing programs should be considered to incorporate additional resources and management information needs. To ensure a rigorous and unambiguous process for any such changes and

strong engagement by park stakeholders, a formal program review will be completed in 2027 to facilitate the exchange of information and evaluation of monitoring design choices.

Conceptual Ecosystem Framework

A conceptual framework outlines relationships and feedback between key ecosystem components. As a foundation for monitoring, it (1) formalizes current understanding of physical, biological, and ecological processes, (2) links abiotic and biotic data and processes, and (3) facilitates communication among scientists, parks, and stakeholders from multiple backgrounds (Fancy and Bennetts 2012; Reynolds et al. 2016). The SEAN's Vital Signs Monitoring Plan development process created conceptual models summarizing key drivers of regional environmental change to aid parameter selection for long-term study (Fastie and Derr 2007). These models captured terrestrial, freshwater, and marine ecosystem components, landscape-scale processes, and SEAN park resource management concerns (Moynahan et al. 2008). The Outer Coast study extends many current SEAN vital signs, including Weather and Climate, Glacier Dynamics, Landform and Landcover, Oceanography, Marine Predators, and Environmental Contaminants.

While the Outer Coast study's primary purpose is to guide future monitoring program design, the conceptual framework below also identifies conterminous opportunities for both short- and long-term research to better understand park ecosystems and inform management. Recent reviews promoting multidisciplinary environmental science in heavily glaciated regions shaped the Outer Coast plan, with recommendations for integrated ice-ocean observing systems, collaborations across physical and biological disciplines, stakeholder engagement, and synergy with complementary ongoing efforts (Lydersen et al. 2014; O'Neel et al. 2015; Straneo et al. 2019; Bianchi et al. 2020). O'Neel et al. (2015) provide a particularly relevant synthesis of Alaska's icefields and downstream rivers, rainforests, and estuaries through physical, chemical, and biological linkages in a concept they term the "icefields-to-oceans continuum." The authors advocate for coordinated, holistic, systems-level research emphasizing dynamics in glacierized versus ice-free fjords, neighboring shelf waters, and surrounding landscapes. Expansion area glacially influenced terrestrial and marine ecosystems are biologically vibrant though the interwoven processes sustaining such productivity are complex and poorly resolved.

In alignment with the icefields-to-oceans continuum (O'Neel et al. 2015), the Outer Coast study's overarching framework is that **climate** influences ocean **heat content**, **seawater chemistry**, **glacial dynamics**, **iceberg production**, and **freshwater input**. In turn, these processes impact terrestrial **landforms and landcover** and exert control over **marine primary production**, which influences the **marine food web** including mid-trophic levels (zooplankton and small-schooling fish) and **marine birds and marine mammals** (Figure 8). Long-term monitoring programs that are process-oriented and management-applicable ensure focus and relevance (Nichols and Williams 2006). Conceptual models encompassing each planned vital sign are described below.

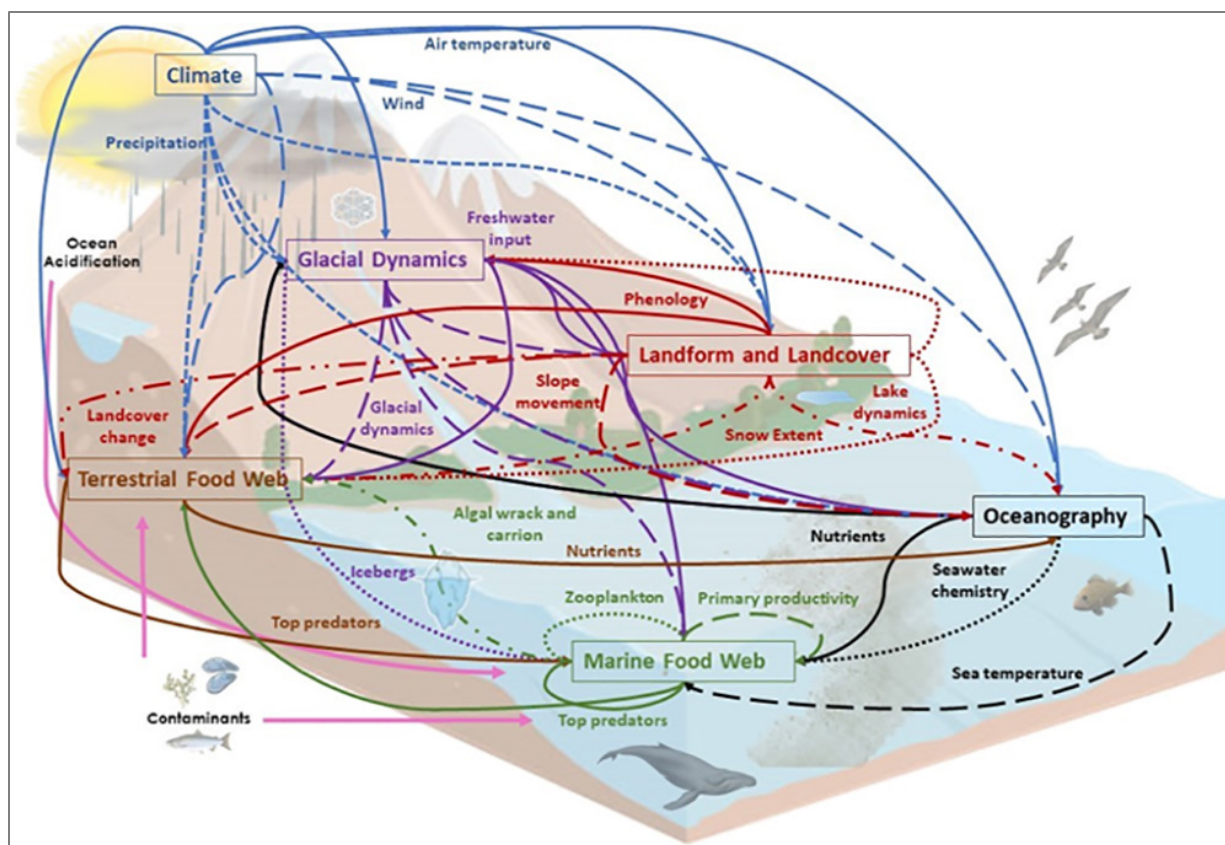


Figure 8. Conceptual framework for the Outer Coast study. Boxes represent ecosystem submodels, and lines denote conditional relationships between components originating from a specific submodel to be monitored during efforts. Pink arrows represent stressors affecting submodels.

NPS

Climate Submodel

A fundamental driver of ecosystem processes, climate is a critical component of the study. Observed air temperature, atmospheric moisture content, precipitation, and wind are shaped by local factors (e.g., orography and land cover) and global-scale climate patterns and teleconnections. The local climate directly impacts glaciers when warm temperatures melt ice or snowfall adds mass.

Atmospheric conditions control marine conditions and hydrographic structure via surface wind stress as well as ocean-atmosphere heat and moisture fluxes. On land and in the ocean, climate influences the speed of chemical, physical, and biological activity. Thus, climate characteristics will be used as dependent variables, (i.e., covariates) in all other submodels. This study will assess air temperature and precipitation (rainfall + snowfall) as the two most influential weather variables for glacier dynamics and surface oceanographic conditions.

Glacial Dynamics Submodel

Continuation and probable acceleration of observed glacier mass loss is predicted globally, including most tidewater systems. One submodel component will examine whether continued warming will lead to continued mass loss in Alaska, where land-terminating glacier loss as a steady function of

climatic trends is expected but tidewater glacier dynamics reflect a more complex suite of processes. All glacier changes have direct and indirect impacts on regional hydrology, geomorphology, biogeochemical fluxes and cycling, biodiversity, aquatic and marine food webs, ecosystem services, and natural hazards. Among these many effects, glacier monitoring in the expansion area will focus on delivery of freshwater, icebergs, and nutrients to the marine environment.

This study will assess glacier surface area, surface elevation, velocity, and mass balance through a combination of satellite image analysis, field observations, and calculations which are core metrics for evaluating current glacier status and predicting future trends. Climate and Ocean data (described above and below, respectively) will be linked to rates of glacier change. At tidewater glaciers, terminus position plus iceberg size and distribution will be quantified, informing glacier location and patterns in advance/retreat rate, calving, and iceberg habitat for harbor seals.

Landform and Landcover Submodel

Climate-driven changes in temperature and precipitation affect landscape dynamics such as seasonal phenology, lake size, and slope movements (e.g., landslides). All are important drivers of small-to-regional scale terrestrial shifts and influence the ocean ecosystem through sediment and freshwater input. Large outburst flood events can drastically change lake conditions with implications for glaciers and nearby marine environments.

This study will assess timing and extent of snowpack, timing and intensity of the growing season, patterns and trends in lake number and size, and the location, size, type, and potential impacts of slope movement events within the Outer Coast Expansion area.

In response to climate and landscape processes, Alaska's landcover is ever-shifting (Jin et al. 2017; Potter and Alexander 2020). This study will map current landcover types across the Outer Coast Expansion area using recent (approximately 2016) satellite imagery to support detection and quantification of future changes. Changing landcover has implications for the terrestrial ecosystem including wildlife and freshwater storage and runoff into the marine ecosystem.

Ocean Submodel

Oceanography addresses physical, geological, chemical, and biological aspects of marine ecosystems. Ocean physics dictates key processes that drive the character and function of fjord-ocean systems, including regulation of biota via bottom-up forcing. Controlling both nutrient delivery and light levels, physical processes determine the extent of primary productivity, its timing, potential for dispersal, and seasonal and interannual variation in abundance, biomass, and spatial distribution of organisms. Oceanographic conditions, including current patterns and mixing, structure of salinity, temperature and stratification, sedimentation rates, and light penetration exhibit spatial and temporal structure and can mask or obscure causes of top-down and/or anthropogenic change in populations and community structure. Ocean acidification occurs when absorbed atmospheric CO₂ lowers seawater pH. Saturation states of calcium carbonate minerals decrease, driving dissolution of the shells and skeletons of calcifying marine organisms and destruction of marine habitat (e.g., coral) and important benthic prey (e.g., crabs, mussels).

This program component will assess linkages in the glacial-marine food web to estimate how oceanographic gradients in fjords and coastal regions influence biological communities across trophic levels. Physical and chemical hydrographic structure (temperature, salinity, light, nutrients, dissolved oxygen) will be assessed vertically and horizontally via summer season vessel-based water column profiles. These data inform understanding of the influence of local fjord geomorphology and oceanic currents, heat content, freshwater content, nutrient standing stocks, stratification and oceanographic fronts, which all help regulate glacier calving and mass loss, food web structure and productivity. Time series measurements from oceanographic moorings will assess many of these same parameters year-round, resolving their time evolution relative to oceanic interactions with Climate and Glacier parameters. Samples will be collected to characterize the magnitude and spatial variability of ocean acidification and evaluate how this environmental stressor impacts the health and biomass of zooplankton.

Pelagic Food Web Submodel

Nearshore Gulf of Alaska pelagic communities are comprised of phytoplankton, zooplankton, small forage fish, larger predatory fish, and a diverse array of marine birds and mammals. Diatoms and dinoflagellates make up the majority of phytoplankton biomass, serving as the food web base; nutrient and light availability control primary production timing and magnitude. Zooplankton production is tightly coupled to environmental parameters such as seawater chemistry and water column structure. These pelagic organisms are sensitive indicators of ecosystem change due to their ability to amplify environmental signals through rapid non-linear responses. Forage fish, benthic invertebrates, and larger predatory fish are also recognized as important to the regional marine food web, though little is known about their community structure, nutritional value, or spatially explicit abundance in the expansion area. With limited resources, the effort will only sample zooplankton as a mid-trophic linkage. Spatiotemporal gradients in fjord and coastal conditions and prey availability influence seabird and marine mammal distribution, abundance, and foraging behavior. Fjords with tidewater glaciers have higher productivity than those with land-terminating glaciers due to enhanced nutrient upwelling along the ice face. Furthermore, harbor seals rely upon ice habitat in tidewater glacier fjords during the energetically demanding pupping and molting seasons.

This study will assess phytoplankton biomass and zooplankton abundance, biomass, and community composition to quantify and describe the magnitude of primary and secondary production available to fuel the region's marine food web. Sampling will be co-located with ocean measurements to evaluate spatiotemporal influence of nutrients, seawater temperature, icebergs, and other environmental characteristics in relation to zooplankton dynamics.

Top marine predator community structure, distribution, and abundance will be assessed through surveys along a glacier-to-ocean gradient and will be linked with oceanographic and zooplankton sampling. As a sentinel of ice dynamics in tidewater glacier fjords, harbor seals will be monitored in Disenchantment and Icy Bays to link abundance and distribution with availability and persistence of icebergs from tidewater glaciers.

Environmental Contaminants

Organic and inorganic pollutants pose ecological and human-health risks, potentially driving loss of habitat quality and biodiversity, biomagnification, and illness from consumption of contaminated subsistence resources. Southeast Alaska's coastal ecosystems are continually exposed to long-distance non-point source threats, including airborne pollutants and drifting marine debris. River runoff may transport metals from natural terrestrial weathering sources and melting glaciers release legacy contaminants. Most critically, marine shorelines are susceptible to local emissions of combustion products that affect air quality, and catastrophic pollution events such as oil spills, given the volume of regional vessel traffic. Cruise ships frequently transit Cross Sound and the Outer Coast during the summer season, visiting Disenchantment and Icy Bays, while personal and commercial vessels travel the region year-round. To date, marine mussel tissue analyses from GLBA, including sites along the Outer Coast assessed in 2007, found contaminant concentrations were very low or below detection limits (Tallmon 2012; Rider et al. 2020). Lichen or freshwater fish tissue samples have not been collected from the expansion area. Baseline airborne, freshwater, and marine contaminants results are expected to geographically align with patterns of human use.

Methods

The following section overviews data collection methods and analytical approaches targeting abiotic and biotic ecosystem drivers and associated marine biological communities (Table 2 and Appendix A). For logistical reasons, initial sampling will focus in Disenchantment and Yakutat Bays but with the explicit intention to sample more broadly to the extent that time and resources permit, including within Icy and Lituya Bays and along the inner continental shelf from WRST to GLBA (Figure 9). These outlying areas permit data and process exploration along a gradient of glacial influence (Table 1).

Data collection methods include fixed-site instrumentation to monitor weather and climate, oceanography, and glaciers. Vessel-based surveys will collect physical, chemical, and biological oceanographic data in conjunction with seabird and marine mammal observations. Aerial surveys and/or unmanned aerial systems (UASs) will be used for reconnaissance of proposed sampling sites and to assess the spatial distribution of harbor seals and ice in fjords. Remotely sensed imagery will be used to quantify aspects of glacial dynamics and landform/landcover metrics.

A single research cruise is planned each year, with the first slated for 2022. However, in future years supplemental sampling from a combination of smaller vessels and/or aircraft may also occur to better understand patterns of temporal and spatial variability. Large vessel operations will be scheduled upon availability and cost of suitable platforms. Sampling designs for individual vital signs will be refined annually based on findings and feasibility determinations. The SEAN program review planned for 2027 provides an opportunity to evaluate additions and adaptations to the network's existing vital sign suite to effectively and efficiently incorporate the Outer Coast region, as well as improve program performance and relevance in other ways. Monitoring protocols will be created or revised, as appropriate, following the program review.

Planning and compliance logistics for annual research efforts will be completed each winter in advance of the upcoming field season. A vessel contract will be procured based on cruise duration and number of scientists needed to complete the scope of work. Financial constraints imposed by the annual budget allocation may scale cruise duration. Research permits will be obtained from GLBA and WRST in coordination with SEAN Technical Committee representatives. Permits from various entities will also be required for marine mammal aerial surveys, camera installations, oceanographic moorings, and biological collections for contaminants.

Table 2. Sampling priorities for the Outer Coast expansion study.

Vital Sign	Variables Monitored	Sites	Methods
Environmental Contaminants	Common marine pollutants in bay mussels; nitrogen and sulfur pollutants in arboreal lichens; mercury in Dolly Varden	15 distributed marine sites; 3 lichen sites; 3 freshwater sites	SEAN protocol: Sergeant et al. (2018)
Glacial Dynamics	Tidewater glacier terminus positions, glacier surface elevations, iceberg production	Hubbard (priority), Yahtse, Lituya, and Malaspina Glaciers	SEAN protocol in development
Landform and Landcover	Summaries of snow dynamics (max extent, snow off dates); phenology (start of season date, time of peak greenness, end of growing season, duration of growing season); area, distribution and number of lakes; location, size, type, and potential impacts of slope movement events	Within 20 miles (30 km) of park boundaries for all metrics except slope movements, which will be restricted to areas with highest potential risk and impact	SWAN, ARCN, CAKN, and IMD national protocols (Reed et al. 2006; Wieczorek and Snyder 2009; Larsen et al. 2011; Swanson et al. 2017; DeVivo et al. 2018)
Marine Predators: Harbor Seals and Ice	Abundance, index of productivity, distribution relative to % icebergs/brash ice/open water	Disenchantment (priority) and Icy Bays	Jansen et al. (2006), Ver Hoef and Jansen (2015), Womble et al. (2020 and 2021)
Marine Predators: Marine Birds and Mammals	Index of use, density, distribution relative to oceanographic conditions and zooplankton dynamics	Disenchantment (priority), Icy, and Lituya Bays	SEAN protocol in development
Oceanography: Physical	Salinity, temperature, density, pressure, turbidity, irradiance (PAR); underway sea surface salinity, sea surface temperature, ocean current profiles, underwater sound	100 distributed stations; underway data between stations; one stationary mooring site in Disenchantment Bay	Water column CTD casts: SEAN protocol: Johnson and Sharman (2014); Mooring operation: Danielson et al. (2021)
Oceanography: Chemical	Macronutrients (nitrate, nitrite, phosphate, silicic acid, ammonium); total alkalinity, dissolved inorganic carbon, pH, calcite and aragonite saturation states	50 distributed stations	NGA LTER; Reisdorph and Mathis (2014)
Oceanography: Biological	Chlorophyll-a concentration and fluorescence; zooplankton abundance, biomass, and community composition	50 distributed stations	NGA LTER; Questel et al. (2013)
Weather and Climate	Air temperature, humidity, wind speed, wind direction, rainfall, snow depth, soil temperature	2 or 3 new mid-elevation stations	SEAN protocol implementation plan: Bower et al. (2017)

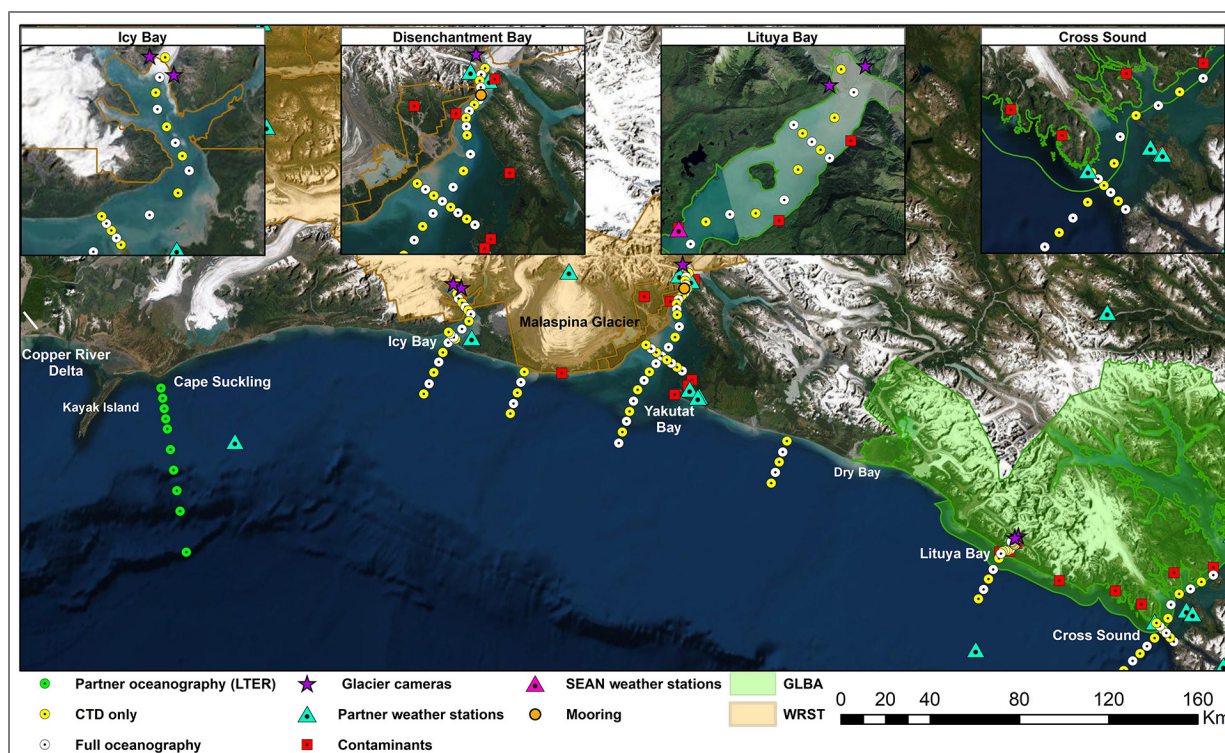


Figure 9. Proposed Outer Coast study sampling locations and existing SEAN and partner weather stations. Map represents the expansion area's full geographic scope and best-case sampling scenario; primary focus will be in Disenchantment/Yakutat Bay with data collection in other areas as logistically and financially feasible. White circles denote Full Oceanography stations where vertical profiles, chemistry, and biological samples will be collected whereas yellow circles represent CTD-only locations.

NPS

Weather and Climate

The existing network of climate stations operated by NPS, NOAA, the Cold Regions Research and Engineering Laboratory (CRREL), and the National Weather Service (NWS; Figure 9) will be utilized to understand weather patterns affecting the expansion area and evaluate available downscaled reanalysis products. These stations provide hourly real-time observations for much of southeast Alaska, capturing air temperature, rainfall, snow depth, wind speed and wind direction, among other parameters. Temperature and precipitation trend analyses will be completed with long-term data (>30 years) from stations in Sitka, Juneau, Yakutat, and Cordova. Less extensive data (<30 years) will add to understanding of spatial patterns and short-term variations. Extreme weather events will be documented for their potential as episodic ecosystem disturbances.

The SEAN operates eight weather stations in GLBA including three along the Outer Coast (Dry Bay, Desolation Hills, and Lituya Bay); these sites help fill a gap in observations that would otherwise span nearly 200 miles (320 km) between Juneau and Yakutat. Across Alaska, data from high elevations (>1,640 feet [500 m]) are sparse and inconsistent. High-elevation observations are key to understanding glacier behavior and forecasting future freshwater runoff volumes (Arendt et al. 2009).

Continued collection of weather data across spatial and elevation gradients is essential to validate projections of future climate and track deviations from expected patterns.

University and government partners plan to install weather stations in coastal WRST to support glacier research. CRREL operates a station on Haenke Island (59.973°N, 139.537°W). The University of Idaho and Boise State installed a station near Turner Glacier in 2020 (roughly 60.005°N, 139.619°W). The University of Alaska Fairbanks intends to establish one or two stations on Malaspina Glacier in 2021 (roughly 60.111°N, 140.484°W). At the end of the university projects in 2023 or 2024, SEAN will replace 2 or 3 of the university stations with NPS stations. Reconnaissance fieldwork in 2022, discussions with partners, and review of initial data will inform our decisions about site suitability for long-term monitoring.

Gridded climate data, such as reanalysis output and climate projections, will be necessary to run the glacier runoff models described below. For southeast Alaska, reanalysis data is available from Daymet, among others (Thornton et al. 2020). Historical and projected climate information is available from Alaska Climate Adaptation Science Center (Lader et al. 2020).

Glacial Dynamics

Given the geographic extent of the Outer Coast expansion area and its vast number of glaciers, field-based monitoring will focus on a single fjord/glacier system with options for expanding to three additional glaciers. Sites were chosen along a gradient of the tidewater glacier cycle and present-day ocean-glacier connectivity to examine the ecological consequences of ice retreat. Since the glaciers are large, have rough surfaces, and are logistically difficult to access, remote sensing will be a key tool to understand glacier change in the present day. Numerical models will be employed for hindcasts and future projections.

A nested approach will be used to organize glacier study efforts; the two spatial scales are described separately below. Four smaller focal areas are proposed, and a separate suite of measurements are planned for a larger regional subset (many to all) of the glaciers along the Outer Coast.

Focal Scale

Focal scale detailed measurements will occur primarily in Disenchantment Bay; to the extent possible, additional observations in Icy Bay, Lituya Bay, and Malaspina Glacier will be incorporated. A single glacier was chosen as the program emphasis because logistical challenges risk impairing a more broadly ambitious field program. In Disenchantment Bay, Hubbard Glacier will be the priority as it is well-studied (Stearns et al. 2015) and currently advancing slowly. In Icy Bay, well-studied Yahtse Glacier (Bartholomaeus et al. 2013), a tidewater system that is presently stable or advancing slightly, is of greatest interest. In Lituya Bay, the focus will be on land-terminating Lituya Glacier as it impounds Desolation Lake. The Malaspina Glacier will be examined due to its rapid rate of change and profound landscape impacts; if the narrow strip of land between the glacier and ocean erodes, a new fjord may open. Information gained from publicly available data sources enables estimates of glacier mass balance, advance and retreat rates, properties of icebergs utilized by wildlife, freshwater inputs to the fjord and their impact on fjord circulation, and sediment delivery for each focal glacier.

Photogrammetry

Geo-tagged photos of focal glacier terminus fronts will be taken from the research vessel during annual cruises. Using photogrammetry software, these photos will yield 3D models of terminus positions and characteristics such as ice-front height and surface roughness. Resulting images and 3D models give perspective on the glacier face that cannot be achieved from satellite remote sensing.

Aerial Photographs

Aerial photographs from harbor seal surveys will be used to quantify fjord ice characteristics including percent open water, brash ice, icebergs, and iceberg size (e.g., McNabb et al. 2016; Womble et al. 2021). Ice covariate data described here relate directly to the harbor seal monitoring effort (see Harbor Seals and Ice Aerial Photographic Surveys for more detail) and provide input to calving relationships developed for the studied tidewater glaciers. The same workflow may be trialed for high-resolution commercial satellite imagery (Neuhaus et al. 2019).

Time Lapse Cameras

Time lapse cameras aimed at the focal glacier front and/or near-terminus fjord and resulting imagery will enable calculation of front positions at a much finer time resolution (1 image per minute or hour) than is possible from satellite imagery (1 image per week or 2 weeks). Furthermore, time lapse cameras are advantageous as they are often beneath the clouds. Depending on the available camera sites, iceberg tracking and fjord surface circulation calculation may be possible, as has been demonstrated for Johns Hopkins Inlet in GLBA and LeConte Bay (Kienholz et al. 2019). In the first year (2022), one site will be installed overlooking Hubbard Glacier (60.045°N, 139.573°W) with a Cyclapse Pro consisting of a 1.5 m tripod, camera housing, and 20-Watt solar panel. Reconnaissance of sites near Lituya Glacier (58.6718°N, 137.4867°W or 58.6679°N, 137.5173°W) and Yahtse Glacier (60.1315°N, 141.3655°W or 60.1532°N, 141.4219°W) will also be completed.

Glacier-Related Oceanography

Outer Coast oceanographic sampling will also inform glacier analyses. From ship-based CTD profiles and continuous fixed-site mooring measurements, freshwater fluxes into each fjord will be calculated following methods outlined in Bartholomaus et al. (2013). Seasonal patterns in surface freshwater plume transport, depth, and fjord stratification and vertical mixing can be discerned.

Regional Scale

The tasks outlined below will be completed for all or as many coastal glaciers as possible. Because the focal areas described above are included within the broader group of coastal glaciers, the following tasks are therefore applicable to focal glaciers as well. The best available regional runoff model will integrate focal- and regional-scale glacier data, aiding extrapolation of parameters of interest from measured glaciers to unmeasured glaciers and regional totals. The model will also utilize climate projections to assess future changes in regional runoff, iceberg production, and other physical characteristics of the coastal environment.

Glacier Outlines and Terminus Positions

Surface area of glaciers will be measured from satellite images. Loso et al. (2014) created a high-resolution set of modern-day glacier outlines for comparison with map date (1948 or 1962) outlines. McNabb and Hock (2014) generated a time series of glacier front positions for tidewater glaciers flowing into the Gulf of Alaska. Terminus position maps for study glaciers of interest will be updated using all available clear Landsat and Sentinel-2 imagery, aiming for two outlines per glacier per month, using the GEEDiT manual digitization tool (Lea 2018). This work will be supplemented by additional glacier outlines from the Glacier Status and Trends 2.0 effort.

Glacier Surface Elevations

A series of glacier surface elevations provides a useful gauge of change over time, and if made at comparable times of year (e.g., in the late melt season), these data also provide a direct measure of glacier-wide geodetic mass balance. Many techniques exist for these measurements, and all rely on remotely sensed data captured from aircraft or satellites; airborne lidar and structure from motion, as well as photogrammetric processing of paired stereo optical satellite imagery are among current options. During this study, an existing program of lidar-based surface elevation measurements collected by NASA's Operation IceBridge will be used via an extension of an existing collaborative agreement funded jointly by SEAN and the Glacier Status and Trends 2.0 project. The resulting time series of surface elevations for most large Outer Coast glaciers will inform development of subsequent strategies for longer-term elevation records.

Glacier-Related River Runoff

Surface-water hydrology is a recognized critical component of the icefield-to-ocean system, however the SEAN's inability to routinely (i.e., monthly) visit Outer Coast sites precludes establishment of new water quality monitoring and stream discharge gaging stations. The USGS's Alsek River station has recorded discharge since 2011 (https://waterdata.usgs.gov/ak/nwis/uv?site_no=15129120). Station upgrades in 2020 added specific conductance, dissolved oxygen, dissolved organic matter fluorescence, and turbidity measurements. Though a significant portion of Alsek runoff comes from Canada, these data increase understanding of glacier runoff properties in northern southeast Alaska.

Runoff Modeling

In the final year of the study, landscape-scale glacier and hydrology models of water runoff (Hock 1999; Hill et al. 2015; Beamer et al. 2016; Mosier et al. 2016; Crumley et al. 2019) will be tested. Many components of interest are included in Mosier et al.'s (2016) Conceptual Cryosphere Hydrology Framework model. Processes not included but important for the Outer Coast expansion area include frontal ablation of glaciers (combined effects of calving and frontal melt from the ocean; McNabb et al. 2015) and erosion and transport of sediment and nutrients under the glacier (Love et al. 2016). The preceding field measurements, remote sensing work, and climate analyses aim to satisfy the inputs needed to run these models.

Landform and Landcover

Currently, the Southwest Alaska Network (SWAN) provides statewide snow extent and Normalized Difference Vegetation Index (NDVI) data derived through their Landscape Processes Vital Sign

(Reed et al. 2006), greatly facilitating protocol adaptation to the Outer Coast expansion area. Available spatial files include maximum snow extent (500×500 m resolution every 8 days across an annual snow season) and phenology metrics (250×250 m resolution every 16 days; start of season (SOS), end of season (EOS), duration of the season, time of maximum NDVI, value at maximum NDVI, and total growing season). Start and end of seasons are identified using a backward-looking moving average approach to identify when a departure from an established trend in NDVI values occurs, suggesting the onset or conclusion of the growing season (Reed et al. 2006). The annual onset, conclusion, and duration of growing season and snow-covered days will be summarized and mapped across the Outer Coast expansion area using methods outlined in Reed et al. (2006) and Lindsay et al. (2015). Snow gauges and time-lapse cameras will be attached to SEAN weather stations in the study area as feasible to ground-truth results from imagery.

Patterns in lake density, type (e.g., proglacial), and size will be identified by adapting the Arctic Network/Central Alaska Network (ARCN/CAKN) Shallow Lake and Pond Limnology Monitoring Protocol (Objective 1; Larsen et al. 2011). Satellite imagery will be acquired during minimum snow extent (late summer or early fall) for areas within 20 miles (30 km) of WRST and GLBA boundaries (per DeVivo et al. 2018) using best available sources (e.g., Landsat, SAR). Images will be rectified (adapting Larsen et al. 2011 for areas with an elevation gradient) and lakes delineated using the National Hydrography Dataset as an initial template, then manually creating polygon boundaries within GIS or using deep learning algorithms to identify areas in each image containing water (Wu et al. 2020). Once lakes are initially delineated, future monitoring can track either abrupt (i.e., outburst flood events) or gradual changes (e.g., subsurface drainage) to lake presence, type, and size. Using the compiled lake GIS layer, summaries and visualizations will be made of baseline conditions across the study area.

Slope movements will be tracked using an adaptation of ARCN's Permafrost Monitoring Protocol—specifically the portion that identifies active-layer detachments and thaw slumps (Swanson 2017). ARCN methods rely on high-resolution imagery to detect areas of bare soil adjacent to vegetation. Relatively recent (2005 and later) high resolution imagery for the Outer Coast expansion area exists at 0.5- and 2.5-m resolution and will be used to map current features. Availability and cost of future imagery is unknown and may require resampling to focus on areas at high risk for slope movement or with greater implications of movement (e.g., near human development). NDVI will be derived from high resolution imagery to identify vegetated and unvegetated areas. Unvegetated areas will be overlaid with points in a GIS and landslide events will be identified either through systematic manual searching of unvegetated areas, or through deep learning algorithms that automate the search process (Bera et al. 2021). Rockslides can also be identified by comparing the contrast between bare soil and snow/ice and identifying lobate forms typical of rockslide deposits (Bessette-Kirton and Coe 2016). Identified features will be compared to recent work identifying rockslides in GLBA (Bessette-Kirton and Coe 2016) and coastal WRST (Bessette-Kirton and Coe 2020) to serve as a foundation for periodic resampling (e.g., in 5–10 years).

Maps and descriptions of current landcover (National Landcover Dataset, NLCD; Dewitz 2019) and landform types (e.g., surficial deposits; Becker et al. 2012; Brock et al. 1996; Kautz and Taber 2004)

will be summarized and compiled for the study area. Imagery used for the NLCD are from approximately 2016 (within 10 years) and thus likely representative of the Outer Coast's current vegetative state and will serve as a baseline for periodic (e.g., every 10 years) analyses of landcover change. Landforms are less dynamic, but the current state of knowledge has not been compiled for this region and landform characteristics are strongly linked to glacial dynamics, lake change and freshwater input into the marine ecosystem.

Oceanography

Collection and analytical methods for physical, chemical, and biological parameters are in accordance with ongoing oceanographic work in northern Gulf of Alaska by the NSF-funded NGA LTER (Northern Gulf of Alaska Long Term Ecological Research; <https://nga.lternet.edu/>) and NOAA's Eco-Foci (<https://www.ecofoci.noaa.gov/>) programs. Thus, the datasets collected in this monitoring effort will be easily integrated with and directly comparable to other regional time series, including the SEAN's long-running oceanography vital sign project in GLBA proper (Danielson 2012). The NGA LTER program will share data and samples from offshore of the Copper River Delta (Figure 9) to cost-effectively extend the along-shore extent of the Outer Coast expansion area. A University of Alaska Fairbanks (UAF) graduate student, working under the direction of Seth Danielson and partially funded by the SEAN, will begin quantifying and visualizing spatiotemporal oceanographic connectivity from Prince William Sound to Glacier Bay.

Physical

Oceanographic surveys will be conducted along systematic transects in fjords and along the continental shelf (Figure 9). Vertical profiles using a conductivity, temperature, and depth (CTD) data logger with a suite of ancillary instruments (Etherington et al. 2007; Johnson and Sharman 2014) will resolve hydrographic structure vertically through the water column and horizontally along transects. Measurement parameters will include seawater temperature, salinity, photosynthetically active radiation (PAR), chlorophyll-a fluorescence (which provides an index of in situ chlorophyll-a concentration and thus phytoplankton standing stock), turbidity or optical backscatter, and dissolved oxygen. Data will be collected at all oceanographic stations (Figure 9) and processed into 1-db averages following the SEAN oceanography protocol (Johnson and Sharman 2014).

Vessel-based underway oceanographic sampling provides additional contextual data that help interpretation and analysis of the hydrographic profiles. These include surface thermosalinograph (continuous temperature and salinity) observations and continuous measurements of ocean currents below the survey vessel using a hull-mounted or towed Acoustic Doppler Current Profiler (ADCP). Underway data are recorded every 1–10 seconds to provide very high-resolution depictions of the spatial distributions of temperature, salinity, and ocean currents.

Stationary oceanographic moorings will be deployed in Disenchantment Bay to provide year-round measures of fjord conditions. The moorings will record at relatively high temporal resolution (e.g., hourly intervals) and thus be capable of resolving many of the important processes contributing to the overall character of the fjord environment: tides, synoptic meteorological forcing (e.g., storm wind events), runoff freshets, and bottom water overturn and replenishment events. Furthermore, the

moorings will document seasonal transitions and, with multiple years of data, provide measures of interannual changes in fjord heat and freshwater content. Moorings will be outfitted with CTD dataloggers, an ADCP for current velocity measurements, optical sensors that record PAR and chlorophyll-a fluorescence, and an acoustic datalogger to record underwater sounds.

Nutrients and Chlorophyll-a

In conjunction with vertical profiles, seawater samples for nutrients and chlorophyll-a will be collected at the Full Oceanography stations (Figure 9) using Niskin bottles during the upcast of the CTD rosette at discrete depths (0, 10, 20, 30, 40, and 50 m) and within the chlorophyll-a maximum if outside these predetermined depths. Additional nutrient samples at 100, 150, 200, 250 and 500 m will be collected where water depths permit. Seawater for nutrient samples will be filtered through a 0.45 μm cellulose membrane filter and immediately frozen at -20°C . Thawed samples will be analyzed for concentrations of nitrate, nitrite, phosphate, ammonium, and silicic acid using a Technicon AutoAnalyzer II following methods that conform to World Ocean Circulation Experiment – Joint Global Ocean Flux Study standardization and analysis procedures (Gordon et al. 1993).

Seawater for chlorophyll-a will be filtered under low pressure through two sequential filters: 20 μm pore-size polycarbonate and 0.7 μm pore-size glass fiber filters. If time permits, chlorophyll-a extractions will be carried out at sea immediately after filtration (Graff and Rynearson 2011). Otherwise, filters will be immediately frozen at -20°C until analysis. The chlorophyll-a pigment will be extracted from filters using acetone for 24 hours at -20°C and analyzed on a Turner Trilogy fluorometer (Parsons et al. 1984). Size-fractionated chlorophyll-a concentrations provide insights to the dominant types of phytoplankton, where data from the 20 μm filter will represent the micro-phytoplankton (e.g., diatoms) and data from the 0.7 μm filter will represent the nano- and pico-phytoplankton (e.g., dinoflagellates and cyanobacteria, respectively) size classes. Total chlorophyll-a concentrations will be used to calibrate the CTD fluorometer measurements.

Carbonate Parameters

Seawater samples for dissolved inorganic carbon (DIC) and total alkalinity (TA) will be collected from Niskin bottles on the CTD rosette, focusing on three depths over the water column (surface, middle, and bottom) at Full Oceanography stations (Figure 9). DIC/TA samples will be drawn from each Niskin bottle into 200 mL borosilicate bottles, fixed with 200 μL of a 10% mercuric chloride (HgCl_2) solution, and sealed until analysis.

Seawater samples will be sent to the UAF's Ocean Acidification Research Center (OARC) to determine DIC and TA using an Automated Infra-Red Inorganic Carbon Analyzer (AIRICA) and a Versatile Instrument for the Detection of Total Alkalinity (VINDTA), respectively. Analytical uncertainty is 2 mmol/kg for each sample. Saturation state (Ω), pCO_2 , and pH will be calculated from DIC, TA, temperature, salinity, phosphate, and silicic acid data using CO_2SYS (Mathis and Questel 2013; Reisdorph and Mathis 2014). Aragonite saturation states (Ω_{Ar}) will be correlated to zooplankton community composition (including holo- and meroplankton), biomass, and health to determine the degree to which ocean acidification is impacting lower trophic organisms. For example, waters where $\Omega_{\text{Ar}} < 3$ indicate that zooplankton are in a stressed environment; when waters

are undersaturated ($\Omega_{Ar} < 1$), zooplankton communities are expected to decrease in biodiversity and decline in biomass in addition to physical signs of shell dissolution in organisms such as pteropods and meroplanktonic larvae.

Zooplankton

The zooplankton community will be characterized in conjunction with oceanographic parameters using samples from Full Oceanography stations (Figure 9) collected with two net systems. To sample small-bodied zooplankton (e.g., copepods, larvaceans, early life stages of benthic organisms), a pair of 150 μ m-mesh ring nets will be hauled vertically while the ship remains stationary. To target larger-bodied and more mobile zooplankton (e.g., euphausiids, chaetognaths, amphipods, pteropods), a 505 μ m-mesh bongo net will be utilized in a double oblique tow while the ship maintains an average speed of 2 kts. Nets will be towed to a maximum of 200 m or within 3 m of the sea floor for shallow stations. Volume of water filtered will be measured using General Oceanic flowmeters mounted in the mouth of each net. From each system, one net sample will be preserved in 10% buffered formalin for community analysis and the second will serve as a backup in case the primary is compromised or be preserved in 95% ethanol for potential DNA barcoding for species identification. Any captured large scyphozoan jellyfish will be identified, photographed, weighed, and measured before being returned to the ocean. Formalin-preserved samples will be analyzed at UAF under a Leica MZ16 microscope where individual organisms will be counted, measured, life stage recorded, and classified to the most specific taxonomic level possible using the ZoopBiom software (Roff and Hopcroft 1986). Weights will be calculated using species-specific length-weight relationships, and abundance and biomass of organisms will be calculated per unit volume using ZoopBiom (Questel et al. 2013; Ershova et al. 2015; Smoot and Hopcroft 2017).

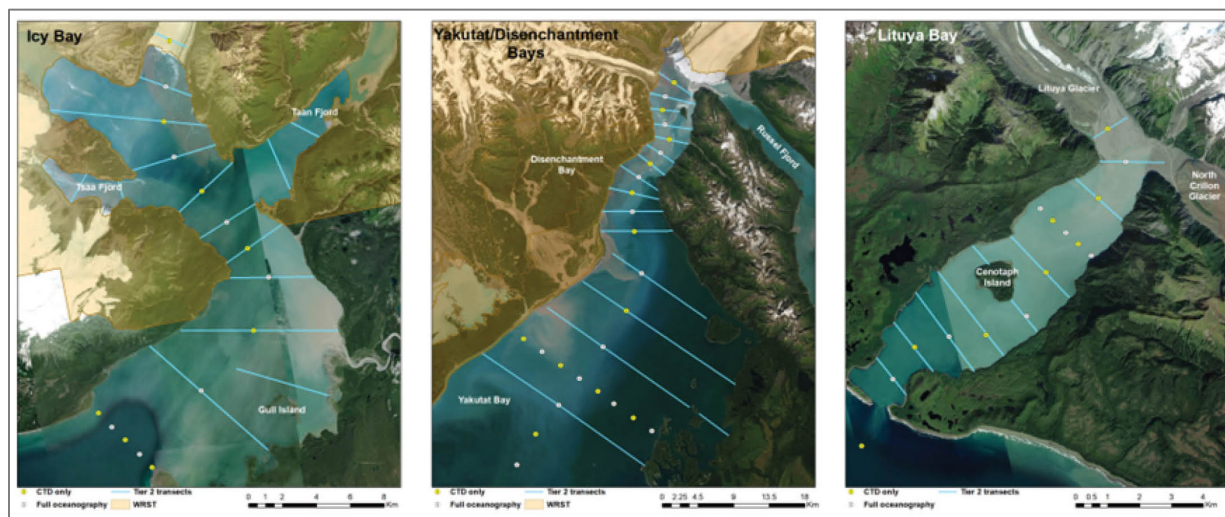


Figure 10. Oceanographic sampling locations and marine predator Tier 2 transects in (left to right) Icy, Yakutat/Disenchantment, and Lituya Bays.

NPS

Marine Predator Surveys

Surveys will be conducted to estimate density, indices of use, and at-sea distribution of marine birds, including diving and surface piscivores and planktivores (Suryan et al. 2016), and mammals in relation to oceanographic and zooplankton parameters. Surveys will be conducted from the bow of a vessel by observers using binoculars. Observers identify, enumerate, and estimate distance to the identified subject using a distance sampling approach (Buckland et al. 2001) within 150 m of either side of the vessel. Survey methods build upon previous multi-species surveys conducted in tidewater glacier fjords and nearshore regions along the Outer Coast (e.g., Kissling et al. 2007a and 2007b; Schoen et al. 2013; Arimitsu et al. 2016).

Two scales of marine predator surveys are planned. The primary objective of Tier 1 surveys is to estimate the density and spatial distribution of marine predators relative to oceanographic and zooplankton covariates (e.g., Renner et al. 2012; Arimitsu et al. 2012 and 2016; Suryan et al. 2016). Tier 1 surveys will be conducted concurrently with oceanographic and zooplankton sampling along transects that are approximately mid-channel and perpendicular to the bathymetric gradient in Lituya, Disenchantment, and Icy Bays (Figure 9). During transits between fjords, marine predators will be opportunistically surveyed along the Outer Coast during daylight hours.

Tier 2 surveys provide more comprehensive and finer-scale coverage for estimates of fjord species distribution and abundance in Icy, Disenchantment, and Lituya Bays (e.g., Kissling et al. 2007b; Schoen et al. 2013). Surveys will be conducted from a small boat deployed from the larger research vessel along transects that are perpendicular to shore and bisect an oceanographic sampling location (Figure 10). Surveys will originate from points nearest or furthest from the ship depending on environmental conditions and will alternate shorelines for the starting point of each transect. Tier 2 surveys commence 500 m from the research vessel survey line to ensure birds are not double-counted and when possible, will be conducted prior to the ship reaching the sampling point to minimize vessel-induced movement of birds. Surveys will be conducted during daylight hours with Beaufort scale ≤ 2 . CTD casts will be conducted at 0.6 miles (1 km) intervals during Tier 2 surveys to collect oceanographic data coincident with marine predator data. Transect locations and length may change based on fjord ice conditions and logistical constraints. Tier 2 transects were added to Tsaa and Taan fjords and adjacent to Gull Island in Icy Bay to ensure data were < 3 miles (5 km) apart (Figure 10).

Hierarchical N-mixture models (Royle 2004) will be used to estimate abundance while accounting for imperfect detection in a single model using distance sampling and incorporation of covariates including oceanographic conditions, zooplankton diversity and abundance, and weather variables collected during monitoring efforts for marine seabirds and mammals (e.g., Goyert et al. 2016).

To estimate spatio-temporal trends, georeferenced count data from vessel surveys will be gridded over the study area at a resolution supported by the data to identify hotspots (i.e., areas of above average density) in occurrence, abundance, persistence and trends in abundance through time. The persistence of hotspots through time will be examined to identify important areas for a species or guild, and anomalies in counts will provide insight into patterns of variation in abundance (Santora and Sydeman 2015). Given that oceanographic physical-chemical structures and zooplankton

communities are dynamically evolving fields, statistical methods that permit modeling of top-level consumers and habitat conditions will be employed to better understand dynamics between physical gradients, mid-trophic species, and top-level consumers. Joint distribution models estimate the strength and direction of association among species or guilds within and among trophic levels and allow those associations to vary by environmental covariates (Pollock et al. 2014; Tikhonov et al. 2017). In addition to abundance, community metrics such as diversity, evenness, and indices of dissimilarity will be modeled to describe ecosystem structure variability in space and time (Ricotta 2017; Chao and Ricotta 2019; Schumm et al. 2019). Data from marine predator surveys will be incorporated into the North Pacific Seabird Database (Drew and Piatt 2015), a central repository for multi-agency seabird observations in the North Pacific Ocean.

Harbor Seal and Ice Aerial Photographic Surveys

Aerial photographic surveys will be conducted in Disenchantment and Icy Bays to quantify how changes in iceberg habitat influence harbor seal distribution and abundance during the June pupping period and August molting period. In collaboration with partners at NOAA's Marine Mammal Laboratory and Duke University Marine Robotics and Remote Sensing Laboratory, we will conduct systematic aerial photographic surveys, using fixed-wing aircraft and/or unoccupied aerial surveys (UAS), to quantify the spatial distribution and abundance of harbor seals and ice following methods developed by Jansen et al. (2006), Ver Hoef and Jansen (2015), and Womble et al. (2020). These efforts will also quantify the availability and characteristics of ice using aerial photographs and machine learning techniques (McNabb et al. 2016; Womble et al. 2021).

Fixed-wing aerial surveys will be flown at approximately 1,000 feet (305 m) at 90 to 95 kts along established transects spaced ~200 m apart and spanning the length of the fjord from the glacier terminus to the mouth following Jansen et al. (2006). Surveys will be conducted between 1200 and 1800 local time, as higher counts of seals typically occur one to four hours after solar noon (Mathews and Pendleton 2006). During surveys, non-overlapping digital photographic images (Figure 11) will be taken directly under the plane using a vertically aimed digital single-lens reflex (DSLR) camera (Nikon D2X, 12.4 megapixel) with a 60 mm focal length lens (Nikon AF Micro-NIKKOR, 2.8D). The camera will be attached to a tripod head and mounted to a plywood platform secured in the belly porthole of the aircraft. An image will be captured every 2 seconds, using a digital timer (Nikon MC36) operated by an observer. The firing rate and transect spacing allow for a gap between images of approximately 15 m end-to-end and 70 m side-to-side to ensure that images are sufficiently separate, and seals are only sampled once. Each digital photo will cover approximately 80×120 m at the surface of the water with ~3.7 cm pixel resolution (Figure 11).

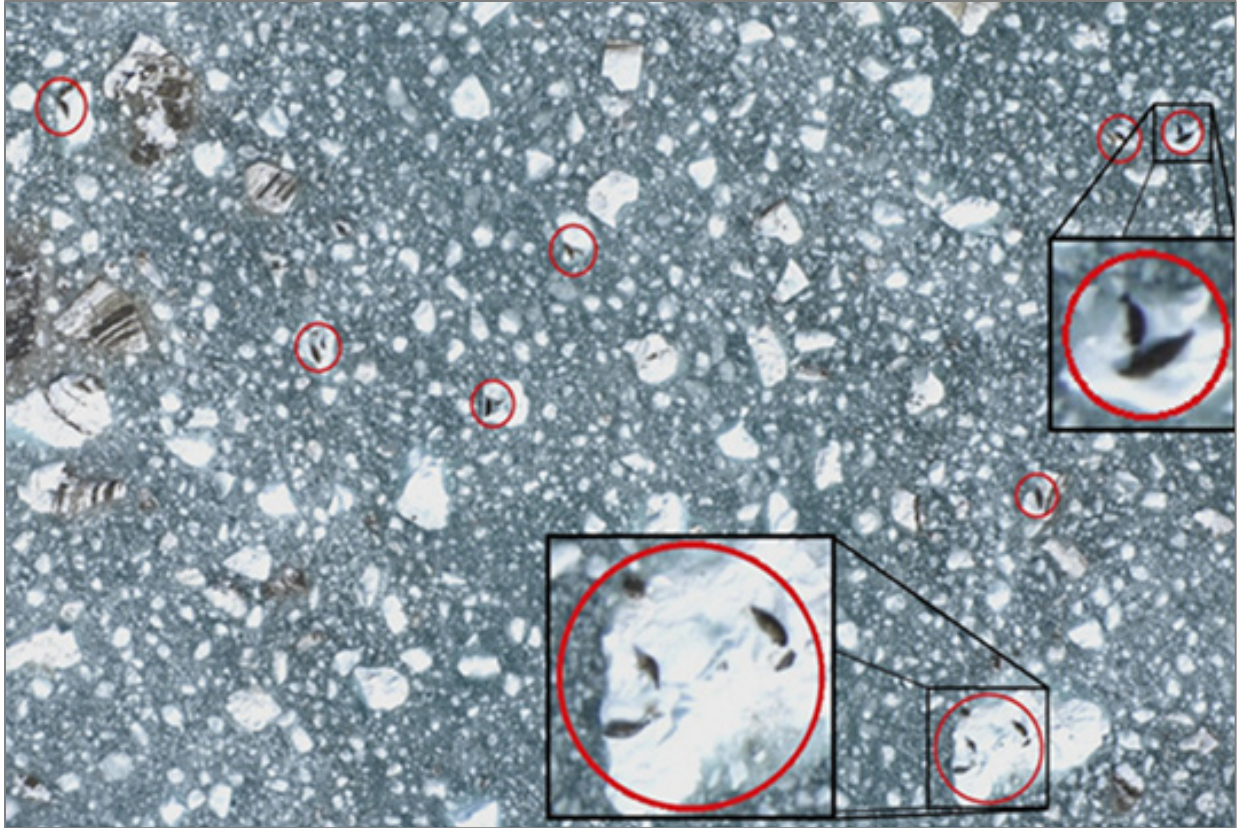


Figure 11. Aerial photographic image of harbor seals and ice during the June pupping season in Johns Hopkins Inlet, GLBA. Harbor seal adults and pups are shown in red circles (Womble et al. 2021).

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Images from each survey will be embedded as a raster layer in an ArcGIS project. Each photo will be examined by a trained observer using digital photo software and each seal marked as a point feature in an ArcGIS shapefile. After all images are reviewed and all seals marked, the point locations will be summed within each image, assigned to the photo centroid, and exported for statistical analysis (Womble et al. 2020). Object-based image analysis (Blaschke 2010; Blaschke et al. 2014; Figure 12) will quantify the amount and characteristics of ice habitat from survey images. Multiple ice habitat covariates will be extracted, including iceberg (%; defined as the percent of each scene that is icebergs greater [1.6 m^2]), brash ice (%; defined as the percent of each scene that is ice smaller than [1.6 m^2]), water (%; defined as the percent of each scene that is water), iceberg size (m^2 ; defined as average size of icebergs in each scene), and distance to the terminus of the glacier (km; defined as the distance from the glacier calving face to the center point of each image). Detailed methods and workflows for this process are described in McNabb et al. (2016) and Womble et al. (2021).

Unoccupied aerial survey methods and platforms are rapidly evolving for conducting surveys of marine mammals, including pinnipeds (Johnston et al. 2019). We will collaborate with partners at Duke University Marine Robotics and Remote Sensing Laboratory and NOAA's Marine Mammal Laboratory to use the most appropriate and efficient UAS platforms to conduct surveys of harbor seals and ice in WRST & GLBA.

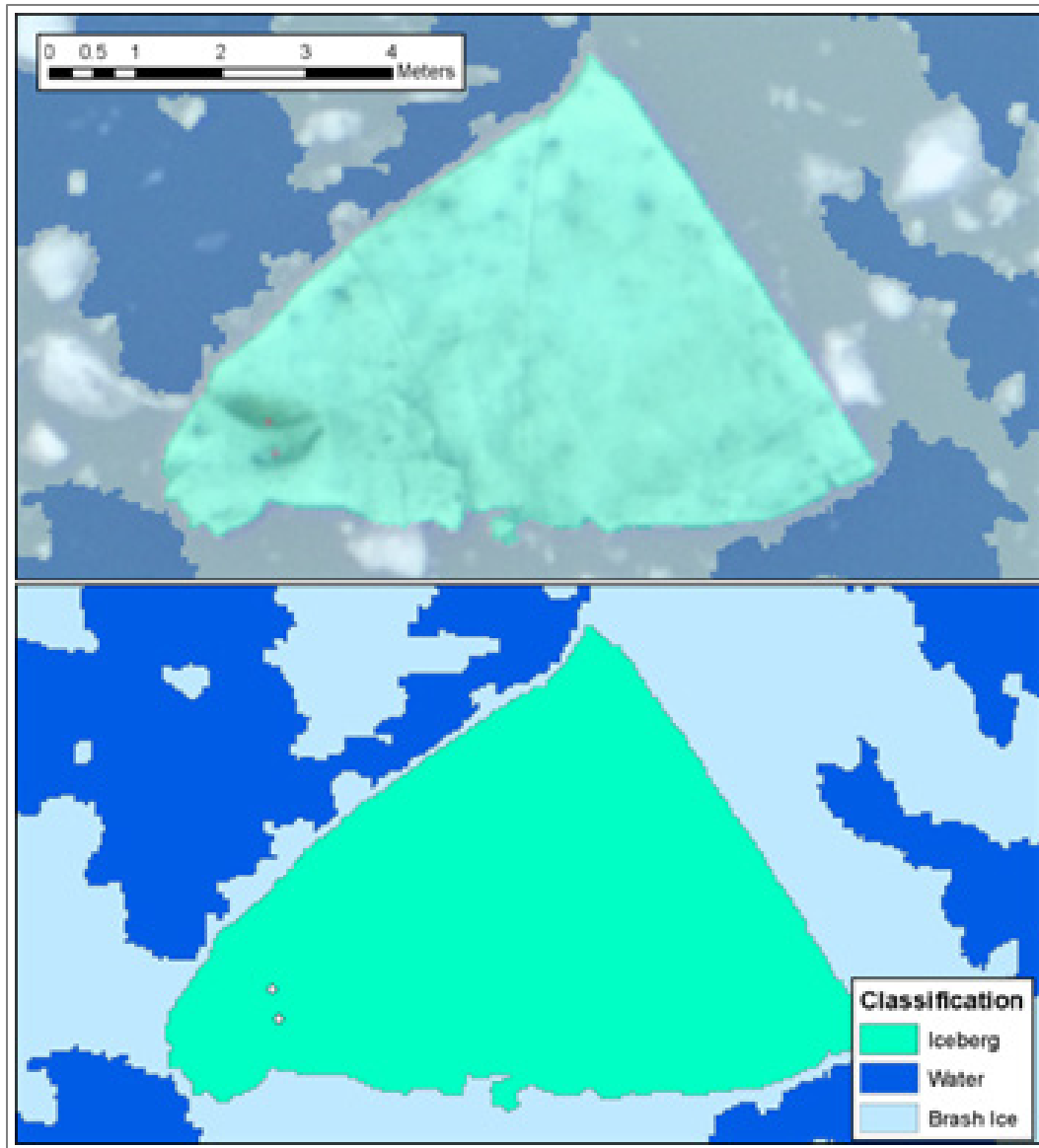


Figure 12. Example of iceberg, brash ice, and water classification with original aerial image from Johns Hopkins Inlet in GLBA, using object-based image analysis workflow (McNabb et al. 2016).

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Iceberg habitat for harbor seals is a dynamically evolving resource and can be influenced by tidewater glacier calving dynamics, fjord bathymetry, freshwater input, winds, and tides. Multivariate conditional autoregressive models and spatial point process models will be used to describe the spatio-temporal distribution of ice and harbor seals in fjords following methods developed in Womble et al. (2021).

Efforts to better understand the influence of ice on harbor seal distribution and abundance in Disenchantment and Icy Bays build upon monitoring and research conducted by NOAA Marine Mammal Laboratory (Jansen et al. 2006; Jansen et al. 2010; Jansen et al. 2015), recent collaborative

studies led by NPS and NOAA aimed at understanding the behavioral and bioenergetic consequences of vessel disturbance on harbor seal pups in Disenchantment Bay (NOAA 2018), and ongoing monitoring and research of harbor seals and ice in Johns Hopkins Inlet in GLBA (Womble et al. 2010, 2020 and 2021). The systematic methods described above are also implemented at approximately 30 tidewater glacier fjords in Alaska and data are used to estimate stock-specific ($n = 12$ genetically distinct harbor seal stocks in Alaska) and Alaska-wide abundance estimates of harbor seals by NOAA (e.g., Muto et al. 2019) as required under the Marine Mammal Protection Act.

Environmental Contaminants

Marine, freshwater, and airborne contaminants will be sampled using bay mussels, Dolly Varden, and arboreal lichens, respectively, as sentinel species following the methods of Sergeant et al. (2018). An inventory of marine contaminant concentrations in bay mussels will be completed to inform the selection of long-term monitoring sites. Three sites will be selected for monitoring priority airborne contaminants and air quality using arboreal lichens, based on known or suspected air quality gradients and distribution of forest types. Three sites will be chosen for monitoring mercury, the highest priority freshwater pollutant, in Dolly Varden based on logistical considerations and distribution of the species. For all contaminants, data interpretation will consider local human and vessel activity, potential glacial influences, and previous pollution monitoring efforts across the study region (e.g., Tallmon 2012; Schirokauer et al. 2014; Cyr et al. 2017; Rider et al. 2020).

Marine

Fifteen sites are proposed for intertidal bay mussel (*Mytilus trossulus*) collections along the Outer Coast (Figure 9). Proposed locations represent zones of high vessel activity and human use (hot controls in Elfin Cove and Yakutat Harbor) as well as remote bays, exposed coastlines, and areas under active glacial influence. Some GLBA/Cross Sound sites were previously sampled in 2007 (Tallmon 2012), providing a temporal comparison for this sector; no historic data exist for the remainder of the region. Sessile filter feeders living up to 20 years, mussels aggregate contaminants in their tissues and thus provide insight into localized environmental conditions and pollution events over the previous several years (Rider et al. 2020). Samples will be collected during August and September after multiple months of passing ship traffic, representing the greatest concern from local communities.

Sampling locations were selected based on the Alaska ShoreZone dataset's mussel presence layer (Cook et al. 2017), with considerations for access logistics. As feasible, proposed Outer Coast collection sites will be evaluated from air or skiff during summer 2022 to confirm mussel presence/abundance, assess shore access and exposure, and identify viable alternate locations where needed. This preliminary reconnaissance will enable project refinement prior to actual sampling, improving both safety and likelihood of success.

Sites will be approached by small boat, foot, or aircraft where and as possible; nearby locations will be used if terrain, sea state, or safety preclude collections where proposed. Sampling will occur below mid-tide, with 100–180 (depending on size) individual mussels gathered from different clumps, rinsed of any sediment, and placed into new Ziploc bags (Sergeant et al. 2018). Site ID, time,

water temperature, approximate height of collection above water level, GPS location, height of the highest mussel distribution relative to water level, and total number of mussels taken will be noted. A vial of seawater for salinity measurement will also be collected. Mussels will be immediately placed on ice in a cooler following collection, then frozen upon returning from the field site and kept frozen until shipped to NOAA's Mussel Watch Program (Kimbrough et al. 2008) laboratory for analysis. Chemical contaminants (polycyclic aromatic hydrocarbons (PAHs; fuel sources), persistent organic pollutants (POPs; pesticides and industrial compounds), and a suite of heavy metals) in mussel tissues will be assessed following established methods of NOAA's National Status and Trend Program (Kimbrough and Lauenstein 2007; Kimbrough et al. 2007). Once baseline contaminant concentrations have been established, sites will be resampled approximately every five years.

Freshwater

Three locations for freshwater contaminants sampling are proposed; local knowledge of Dolly Varden distribution and stream access feasibility will be confirmed with GLBA and WRST Fisheries Biologists and contacts in Yakutat. In GLBA, a stream in the Dixon Harbor/Palma Bay or Lituya Bay region will be targeted, pending confirmation of Dolly Varden presence, with the site reached by Park research vessel or floatplane. Two rivers in coastal WRST that drain contrasting watersheds (tentatively Esker and Lucia Streams) are planned collection sites, accessed by small charter vessel from Yakutat and hiking. Fish will be collected in late July to mid-August. Note that in all cases the total number of fish euthanized at a given sampling location will depend on Alaska Department of Fish and Game and NPS Institutional Animal Care and Use Committee (IACUC) permit specifications.

Dolly Varden will be captured using Gees G-40 Minnow Traps (23 cm × 44.5 cm, 2.5 cm opening) baited with sterilized commercial salmon eggs or fresh salmon eggs in disinfected mesh bait bags. At each sampling site, a bait bag will be secured inside the minnow trap and the trap itself tied with a line to a nearby tree or rock. A range of suitable habitats will be sampled at each location (~five traps deployed per stream) to improve catch success—gently sloping gravel bars and small pools near large and small woody debris are optimal, while mid-channel or higher velocity areas should be avoided (Sergeant et al. 2018). All traps will soak for a minimum of six hours, ideally eight hours to overnight. Supporting information about the field site and stream conditions will also be noted.

After soaking, traps will be processed one at a time, so fish remain in the water until needed. For total mercury analysis, euthanized Dolly Varden should have a fork length between 80–150 mm and minimum 3–4 g wet mass (Cyr et al. 2017). From each site, at least 10 fish and up to 25 will be retained to ensure sufficient individuals reach the laboratory in good shape. Wearing nitrile gloves and mitigating contamination, one fish at a time will be examined for species, fork length, and mass; those not suitable for analysis will be returned to the stream. Euthanized Dolly Varden will be stored in certified clean aluminum foil and a labeled, sealed plastic bag. In the field, fish will be kept on ice; samples will be placed in a –20°C freezer within eight hours (Sergeant et al. 2018). For total tissue mercury concentration (ng/g wet weight) analysis following U.S. Environmental Protection Agency (EPA) Method 7473 (SW-846; EPA 1998), specimens will be sent to an approved laboratory.

Airborne

The three proposed lichen tissue chemistry sites represent a range of geographic features and bracket vessel activity in the Outer Coast focal region, Disenchantment/Yakutat Bay. This approach is similar to that utilized when the SEAN's six existing airborne contaminant sites were established (Sergeant et al. 2018). Graves Harbor (north of the entrance to Cross Sound) will be the GLBA index site, capturing Pacific Ocean influences without significant proximate vessel traffic; this area is accessible via day trip from Gustavus via Park research vessel or floatplane. In coastal WRST, lichens will be collected from mature low elevation forest inland from the Park's Esker Stream Cabin as well as on the west side of Gilbert Point near a proposed mussel site and potential new weather station/glacier camera. This pair of locations in Disenchantment Bay is intended to document conditions up- and downwind of the main glacier viewing area used by cruise ships as local emissions where airflow is topographically restricted are of particular interest. Samples will be collected in mid-August to late September, in alignment with other planned work for this vital sign, and every five years thereafter.

Three arboreal lichen species will be collected by hand at each site: *Hypogymnia enteromorpha*, *H. inactiva*, and *Platismatia glauca*. Advanced training is essential for proper lichen identification as other species have very similar characteristics; the GLBA Terrestrial Ecologist or U.S. Forest Service personnel will train SEAN staff. At designated monitoring plots, target species will be gathered from a minimum of eight different locations within one km of the site. Fresh lichens may be collected from tree branches or trunks, shrubs, fallen branches, or the forest floor while avoiding dirty, discolored, or decaying material. During sampling, staff will wear new, non-powdered vinyl or nitrile gloves to avoid contamination. Lichen specimens will be stored in clean, sealable plastic bags; each sample will consist of at least 14 grams of dry lichen. Supporting information about the field site will also be noted.

All collected lichens will be cleaned of insects, leaves and other such material, and air dried as soon as possible after fieldwork by spreading flat on blotter paper in a space free of air contaminants (e.g., dust, cooking particulates, smoke). Airborne contaminants samples will be sent to the University of Minnesota's Research Analytical Laboratory to be assessed for concentrations of nitrogen, sulfur, and 25 additional elements. Collection and analysis protocols conform with those developed for the Tongass National Forest and national Forest Inventory and Analysis program (Schirokauer et al. 2014; Sergeant et al. 2018).

Data Synthesis

In addition to basic exploratory analyses for individual monitoring parameters as described above, a Bayesian Network model will be created to catalogue the state of understanding and facilitate learning about ecosystem linkages. This model will examine potential responses of different physical processes or biological dynamics to ecosystem perturbations, such as increased air/sea temperature and glacier ablation through time.

Bayesian Networks are statistical models that describe relationships among ecosystem components. Each model component (node) is a random variable assigned probabilistic outcomes (e.g., temperature increasing, stable, decreasing) that are linked to outcomes in other nodes. Bayesian

Networks rely on machine learning algorithms to simultaneously optimize the probability of node outcomes using data and prior distributions (i.e., beliefs of what the system is doing derived from literature and expert opinion) based on the conditional relationships between the variables.

Perturbation of single or multiple model components (e.g., climate) propagate through the network, illustrating the effect of that change on the remaining nodes. The model structure facilitates asking “what if” questions, such as “how would a sustained increase in sea temperature affect the probability of top predator abundance increasing in the region?” More generally, one could look at the effect of increased sea temperature on all conditional nodes (e.g., glacier dynamics, icebergs, zooplankton).

Bayesian Networks can be expanded to be spatially and temporally explicit (Chee et al. 2016) and are commonly used to make predictions on future ecosystem states, detect structural changes in communities, and manage resources under uncertainty (Barton et al. 2012; Moe et al. 2016; Trifonova et al. 2017; Trifonova et al. 2019). They can also incorporate “hidden variables,” unmonitored ecosystem components (e.g., forage fish, benthic invertebrates) that could affect the uncertainty and outcomes of monitored nodes (Uusitalo et al. 2018; Trifonova et al. 2019). A conceptual framework for the Outer Coast ecosystem will guide model design; the Bayesian Network structure, linkages and prior distributions will be finalized after conducting a literature review and consulting with experts. These efforts will both facilitate understanding species and community interactions and their shifts relative to changing environmental conditions, as well as predicting changes in those interactions in response to future climate change.

Data Management

Best practices for data verification, validation, and publication will be followed to preserve the integrity, security, and accessibility of sampling information for posterity (Appendix B). Where vital sign monitoring efforts are directly expanded from published protocols, associated standard operating procedures (SOPs) for data management and publication will be followed to the extent practical (e.g., environmental contaminants sample collection, oceanographic profile collection and data processing, weather station operation). Data validation and verification procedures will be guided by the SEAN (Johnson and Moynahan 2008) and NPS Inventory and Monitoring Division (NPS 2008) data management plans. All projects will publish certified data products that have undergone basic QA/QC to the NPS IRMA DataStore and public data repositories. Formal metadata for all data streams will also be prepared following the Content Standards for Digital Geospatial Metadata (FGDC 1998, 1999, 2001, and 2002) to ensure proper description for later use. Compiled from relevant policies, guidelines, and best practices, Appendix B will guide data management procedures for all environmental parameters.

Reporting

Following data collection, exploratory analyses of data will be conducted with an emphasis on identifying data collection issues to be resolved, locations warranting additional focus, and opportunities for sampling optimization. Periodic web articles or research briefs will be prepared that provide overviews of recent fieldwork and data collection. Results will be shared with parks, local communities, and park visitors through presentations and meetings.

Results will be synthesized in peer-reviewed publications and recommendations will be presented for long-term monitoring along the Outer Coast, including key findings and visualizations from analyses for each candidate monitoring parameter. Specific analytical methods will vary by vital sign and data type (Appendix A) and interdisciplinary links between projects will be included. An ecosystem model will also be presented as a means of cataloguing the state of knowledge and identifying information gaps. Recommendations for long-term monitoring program along the Outer Coast will be included during the SEAN program review.

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Appendix A. Analytical Approaches

Data will be analyzed within and across submodels using a variety of techniques. Example visualization, summarization, and analysis methods and their application within each submodel are provided in Table 3 below. These are not comprehensive and will be amended as methods evolve.

Table 3. Description of analytical methods applied to each submodel.

Submodel	Analytical Approach	Examples
Climate	Mapping	Temperature through space
	Regression	Climate variables relative to regional climate data, elevation and land cover; wind stress, head and moisture fluxes relative to marine characteristics and hydrographic structure
	Time-series analysis	Temperature and precipitation from weather stations, river runoff from the USGS gauge on the Alsek River
Glacial Dynamics	Regression	Glacier extent relative to ocean and climate variables through time
	Remote sensing analysis	Establish glacier extents and variation through time; ice extent in fjords
	Time series analysis	Oceanographic mooring data relative to changes in ice conditions and glacial output
Landform and Landcover	Snow cover	Time series of maximum snow extent
	Phenology	Time series of start, peak, and end of growing season
	Lake extent	Establish lake extents and variation through time
	Slope movement	Geodatabase of slope movement occurrences
	Landcover mapping	Geodatabase of landform types, extents, and positions
Ocean	Mapping	Aragonite and calcite saturation states; zooplankton biomass
	Regression	Zooplankton biomass or diversity relative to ocean characteristics and climate variables; saturation relative to glacial characteristics and salinity; ocean structure relative to geomorphology, tidal exchanges and freshwater inputs; oceanic heat exchanges relative to haline and thermal conditions within fjords with and without tidewater glaciers
	Comparison tests (e.g., T-tests, ANOVA)	Oceanographic characteristics by fjord, time period
Food Web	Comparison tests (e.g., T-tests, ANOVA)	Contaminant concentrations by site; community structure by glacier or glacier type

Table 3. Description of analytical methods applied to each submodel.

Submodel	Analytical Approach	Examples
Food Web (continued)	Joint distribution models	Species richness, diversity, fjord effects and glacier and ocean characteristics
	Multivariate conditional autoregressive models	Spatio-temporal distribution of ice and seals
	Regression (including N-mixture models)	Abundance and occurrence of marine predators through space and time relative to environmental covariates

Appendix B. Data Management Best Practices

Data Collection

The following guidelines regarding data collection that affect data quality have been adopted by the IMD and should be adhered to within this study:

- Field crews will receive proper training.
- For any project using field equipment, calibration and maintenance should be conducted following procedures defined in the appropriate SEAN SOP. In the absence of an SOP, instrument manufacturer guidelines for calibration and maintenance should be followed.
- Wherever possible and appropriate, data loggers or field-based computers will be used to collect data. When this is not possible, data will be recorded on pre-formatted, project-specific data sheets that reflect the overall design of the project and minimize the amount of writing necessary to effectively record observations.
- When field data sheets are necessary, or more appropriate, their format will be reflected in the computer data entry interface to help ensure all relevant information is recorded and subsequent data entry errors are minimized.
- Completed field data sheets will be proofed for errors each day in the field. Data Entry

The following guidelines regarding data entry have been adopted by the IMD, and should be adhered to within this study:

- To the extent possible, data entry will be automated. This may simply entail downloading data from field-based computers but may include the application of new technology to allow for machine-driven data entry (e.g., voice- or optical character-recognition software).
- Data will be entered as soon as possible after collection.
- Data entry will be completed by someone familiar with data collection. The Project Leader (with assistance from the Data Manager if needed) will ensure that data entry staff is familiar with the database software, database structure, and any standard codes used by a network. At a minimum, data entry technicians should know how to open a data entry form, create a new record, edit an existing record, and exit the database properly. They must also learn how to correct mistakes made while typing.
- When possible, a two-person effort should be utilized, where an observer calls out readings to a recorder. The recorder should repeat the observation back to the observer to ensure accuracy and then enter the data.
- Data will be entered into pre-designed database forms that resemble field data sheets and maximize error control.
- For data collected on a device, data should be backed up onto an external drive or other mechanism at the end of each day of observations. This should include images, transcribed field data sheets, etc.

- Field data sheets should be scanned as PDFs as soon as possible. The Data Manager shall provide a location on the network to store these files.
- Be mindful of battery levels on any collection devices to ensure no loss of power and data occurs while in the middle of observations. Backup chargers and/or batteries are recommended.

Data Verification and Validation

It is imperative that data verification is conducted. The following methods are recommended to eliminate errors:

- Visual review at data entry: The data entry technician verifies each record after input into the computer software being utilized and immediately corrects any errors.
- Visual review after data entry: Upon completion of data entry, all records are reviewed, and errors are clearly marked and corrected. Ideally, the reviewer should be a different person than the data entry technician.
- Spatial data collected shall be viewed in a GIS and visually inspected for accuracy.
- A record of the data verification process for each data set shall be prepared by the Project Leader as part of formal metadata generation (further defined in the SEAN Metadata SOP).
- Data validation shall be performed per existing vital sign SOP, where available and appropriate. Some flexibility (exceptions) may be required due to unexpected conditions encountered during the initial survey. Such items may require later adjustments to existing SOPs.
- For environmental parameters not currently covered by an existing protocol, the Data Manager and Project Leaders shall refer to the National Data Management Plan (Ch. 7) to develop validations for these data sets.

Metadata Creation

Project Leaders and the Data Manager shall be responsible for the generation of metadata for all data collected as part of this study. Metadata content standards will adhere to those set by the Federal Geographic Data Committee (FGDC) and NPS policy.

- Fully compliant metadata is the goal (based on FGDC and NPS standards).
- Minimally compliant is the requirement in order to be able to publish to the NPS IRMA DataStore.
- In addition to the FGDC standards, which contain the complete list and details of both mandatory and optional metadata elements, the SEAN Metadata SOP should be the first reference to aid both Project Leaders and the Data Manager with the proper generation of metadata.
- Data Manager shall be responsible for the creation of XML metadata files based on the information provided by the Project Leaders.

Data Storage and Publication

Following data validation and verification, a final certified tabular data version, in .csv format, will be prepared by the Project Leader for each applicable vital sign. Certified data products accompanying XML metadata will be published to the NPS IRMA DataStore.

- Data Manager shall publish data packages (to include data sets, metadata files, manifest, and other relevant documentation) to the NPS IRMA DataStore at such time as these are deemed certified for public dissemination.
- Publishing of data shall be performed per existing vital sign SOP where available.
- Data Manager shall be responsible for the establishment of file/data set storage areas on the network server, along with ensuring backups are performed, per the SEAN SOP 204.
- Data Manager shall be responsible for the creation/maintenance/backup of any databases needed for the storage of collected data.

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