Citations:

*References with an asterisk represent articles or reports that I do not actually have, but I do have an abstract or an article that cites the papers specifically. For all others, I have the article.

Peer Reviewed (74)

Birds

* Boelman, NT, L Gough, J Wingfield, S Goetz, A Asmus, HE Chmura, JS Krause, JH Perez, SK Sweet, KC Guay. 2014. Greater shrub dominance alters breeding habitat and food resources for migratory songbirds in Alaskan arctic tundra. *Global Change Biology* 21 (4): 1508-1520

> Climate warming is affecting the Arctic in multiple ways, including via increased dominance of deciduous shrubs. To understand how increasing deciduous shrub dominance may alter breeding songbird habitat, we quantified vegetation and arthropod community characteristics in both graminoid and shrub dominated tundra. Shrub canopies had higher canopy-dwelling arthropod availability (i.e. small flies and spiders) but lower ground-dwelling arthropod availability (i.e. large spiders and beetles). Acknowledging the coarse resolution of existing tundra vegetation models, we predict that by 2050 there will be a northward shift in current White-crowned sparrow habitat range and a 20-60% increase in their preferred habitat extent, while Lapland longspur habitat extent will be equivalently reduced.

* Gilg, O, L Istomina, G Heygster, H Strøm, MV Gavrilo, ML Mallory, G Gilchrist, A Aebischer, B Sabard, M Huntemann, A Mosbech, G Yannic. 2016. Living on the edge of a shrinking habitat: the ivory gull, *Pagophila eburnea*, an endangered sea-ice specialist. *Biology Lett* 12 (11)

> The ongoing decline of sea ice threatens many Arctic taxa, including the ivory gull. From 2007 to 2013, we used satellite transmitters to monitor the movements of 104 ivory gulls originating from Canada, Greenland, Svalbard-Norway and Russia. Given the strong links between ivory gull, ice-edge and ice concentration, sea-ice decline will cause ivory gulls to continue to decline.

Langham, GM, JG Schuetz, T Distler, CU Soykan, C Wilsey. 2015. Conservation status of North American birds in the face of future climate change. *PLoS One* 10 (9): e0135350.

> Human-induced climate change is increasingly recognized as a fundamental driver of biological processes. Using two of the most comprehensive datasets of bird counts in the world, and correlative distribution modeling, we assessed geographic range shifts for 588 North American bird species during both the breeding and non-breeding seasons under future emission scenarios. During breeding season, areas such as central Alaska's boreal forests could gain as many as 80 species and lose as many as 69 species. In the non-breeding season, fewer species will be gained, and perhaps none in the northeast Arctic, but none will be lost, except in the Aleutians/Bering Sea. However, habitats, especially during breeding season, will change.

National Audubon Society. 2015. Audubon's birds and climate change report: a primer for practitioners. National Audubon Society, New York. Contributors: Gary Langham, Justin Schuetz, Candan Soykan, Chad Wilsey, Tom Auer, Geoff LeBaron, Connie Sanchez, Trish Distler. Version 1.3.

This document reflects research published in peer-reviewed articles. One of the data products is a set of maps of modeled climate suitability across three time periods and different climate scenarios. These are available online. For Alaska: http://climate.audubon.org/geographical-search/alaska. At this site is a list of the percent of summer and winter habitat range expected to be lost. The hardest impacts will be on the northern hawk owl, bohemian waxwing, American three-toed woodpecker, merlin, Barrow's goldeneye duck, and red-necked grebe, which will lose 90-100% of their summer habitat and over half their winter habitat. The Boreal Owl will lose 100% of winter habitat. Of 50 birds analyzed for Alaska, all but 3 will lose more than half of their summer habitat and half will lose more than half of their winter habitat. This includes common and iconic species such as the bald eagle, loons, and red crossbills.

*van Gils, JA, S Lisovski, T Lok, W Meissner, A Ozarowska, J de Fouw, E Rakhimberdiev, M Soloviev, T Piersma, M Klaassen. 2016. Body shrinkage due to Arctic warming reduces red knot fitness in tropical wintering range. *Science* 352: (6287): 819-821

Reductions in body size are increasingly being identified as a response to climate warming. Here we present evidence for a case of such body shrinkage, potentially due to malnutrition in early life. We show that an avian long-distance migrant (red knot, *Calidris canutus canutus*), which is experiencing globally unrivaled warming rates at its high-Arctic breeding grounds, produces smaller offspring with shorter bills during summers with early snowmelt. This has consequences half a world away at their tropical wintering grounds, where shorter-billed individuals have reduced survival rates. This is associated with these molluscivores eating fewer deeply buried bivalve prey and more shallowly buried seagrass rhizomes.

*Wauchope, HS, JD Shaw, Ø Varpe, EG Lappo, D Boertmann, RB Lanctot, RA Fuller. 2016. Rapid climate-driven loss of breeding habitat for Arctic migratory birds. *Global Change Biology* 23 (3):1085-1094.

Breeding conditions for Arctic shorebirds could shift, contract, and collapse by 2070 due to climate change. Of 24 shorebird species studied, 66%-83% could lose most of their breeding area. Declines will be fastest in western Alaska and eastern Russia, where Arctic birds are already becoming vulnerable as shrubs expand into the tundra and with them, red foxes.

Contaminants

Calder, RSD, AT Schartup, M Li, AP Valberg, PH Balcom, EM Sunderland. 2016. Future impacts of hydroelectric power development on methylmercury exposures of Canadian indigenous communities. *Environ Sci Technol* 50 (23): 13115-13122

Investigations of the potential environmental impact of a hydroelectric project in Labrador, Canada determined that creating the reservoir would increase methylmercury in the Churchill River 10-fold and more than double the methylmercury in a large fjord (Lake Melville) 40 km downstream, increasing the mercury in fish, birds, and seals harvested by local Inuit. This is expected to increase the mercury exposure of people living near the project.

Commented [K1]: The article does not directly discuss global warming, but this is the impact I would expect as permafrost melts and causes flooding

(also Fish) Carrie, J, F Wang, H Sanei, RW Macdonald, PM Outridge, GA Stern. 2010. Increasing contaminant burdents in an Arctic fish, burbot (*Lota lota*) in a warming climate. *Environ Sci Technol* 44: 316-322

Commented [K2]: Also called lush in Alaska. Important subsistence fish in the Y-K

The concentrations of mercury in burbot in the Mackenzie River, Canada, have increased significantly over the last 25 years, despite stable or falling global atmospheric concentrations, because warmer conditions and greater organic material from thaw stimulate methylating bacteria, and organic material is binding mercury and moving it to sediments where bacteria live. Both the accumulation of total mercury in lake sediment and the conversion of total mercury to methylmercury are likely increasing, resulting in the greater mercury observed in burbot.

Chetelat, J and M Amyot. 2009. Elevated methylmercury in High Arctic *Daphnia* and the role of productivity in controlling their distribution. *Global Change Biology* 15: 706-718

In lakes and ponds of the Canadian high Arctic, zooplankton containing *Daphnia* were mostly found in water bodies with high concentrations of dissolved carbon (ponds, eutrophied lakes). With climate warming, this type of productivity is expected to increase. *Daphnia* strongly bioaccumulates mercury, and had five times more mercury than water bodies dominated by copepod-zooplankton. Warmer water, more carbon, more *Daphnia*, more methylmercury could be route through which climate can influence methylmercury in lake biota.

(also Marine Mammals) Gaden, A, SH Ferguson, L Harwood, H Melling, GA Stern. 2009. Mercury trends in ringed seals (*Phoca hispida)* from the Western Canadian Arctic since 1973: associations with length of ice-free seasons. *Environ Sci Technol* 43: 3646-3988

The length of ice-free seasons influences the amount of mercury in the prey of ringed seals in the western Canadian Arctic. Both long (more than 5 months) and short (2 months) ice – free seasons caused an increase in mercury in ringed seals the subsequent year. Adult ringed seals establish territory in late fall, and the changes in muscle mercury reflect the mercury content of Arctic cod, the primary seal food source in late fall and winter. In heavy ice years, it may be the older (more contaminated) cod that survive and become food for seals. In years with short ice-seasons, there may simply be more Arctic cod to eat, since more light leads to greater phytoplankton growth and more zooplankton; that is, each cod is less contaminated, but more are eaten resulting in high total mercury in seals. Global warming is causing longer ice-free seasons, and may lead to higher mercury levels in circumpolar seal populations.

Hammerschmidt, CR, WF Fitzgerald, CH Lamborg, PH Balcolm, and C Mao Tseng. 2006. Biogeochemical cycling of methylmercury in lakes and tundra watersheds of Arctic Alaska. *Environ Sci Technol* 40: 1204-1211

Changes associated with a warming Arctic (increased weathering, temperature, productivity, organic loadings) may stimulate mercury methylation and inhibit photodecompositions, resulting in an increase in methylmercury available to aquatic life. This conclusion is the result of a study of four northern Alaska lakes near Toolik Lake. Mercury primarily enters from the atmosphere; the amount that enters lakes from tundra is currently minimal but expected to increase with warming. Photodecomposition currently removes 66-88% of the deposited mercury, reducing the amount that is bioaccumulated. However, with warming, the amount of organic carbon in lakes will increase. Organic carbon can "scavenge" (bind) deposited mercury and settles into the sediment. This simultaneously removes it from a form in which it can be degraded by photodecomposition and places it in sediment where it can be methylated.

Schuster, PF, RG Striegl, GR Aiken, DP Krabbenhoft, KF Dewild, K Butler, B Kamark, M Dornblaser. 2011. Mercury export from the Yukon River Basin and potential response to a changing climate. *Env Sci Technol* 45 (21): 9262-9267, https://pubs.er.usgs.gov/publication/70006305

Permafrost contains a substantial reservoir of mercury. Researchers determined that on average the Yukon exports 4400 kg of mercury per year. High mercury concentrations relative to other large Northern rivers suggest the source of mercury is rocks and soil, not the atmosphere. About 75% of the Yukon River Basin is permafrost, one of the most permafrost rich basins in the north. Climate warming will accelerate mercury mobilization from permafrost, as well as increasing organic carbon; the release of both together potentially increases methylation so that not only will more mercury be released, but more is likely to be bioavailable.

St. Pierre, KA, J Chetelat, E Yumvihoze, S Poulain. 2014. Temperature and the sulfur cycle control monomethylmercury cycling in high Arctic coastal marine sediments from Allen Bay, Nunavut, Canada. *Environ Sci Technol* 48: 2680-2687, (2014)

Warming may increase mercury methylation in marine sediments without an increase in demethylation. Sediment is not an important source of methylmercury in Allen Bay, Nunavut, where the sediment has little organic matter. However, raising the temperature increased the activity of sulfate-reducing bacteria, the microbes that methylate mercury. Therefore warmer sediments may cause more mercury to be bioavailable.

(also Fire) Wiedinmyer, C and H Friedli. 2007. Mercury emission estimates from fires: an initial inventory for the United States. *Environ Sci Technol* 41: 8092-9098

Commented [K3]: Not a direct study of climate impacts

Mercury is emitted during wildfires; Alaska had the highest averaged monthly emissions of all the states. The annual average of Alaska and the Lower 48 is 44 tons of mercury per year, about the same amount that is emitted from coal boilers (46 tons Hg per year). Alaska is expected to experience more and larger fires with global warming.

Fire

*Fauria, MM and EA Johnson. 2006. Large-scale climatic patterns control large lightning fire occurrence in Canada and Alaska forest regions. *J Geophys Res*: *Biogeosciences* 111: G040008

Large lightning wildfires in Canada and Alaska account for most of the area burnt and are main determiners of the age mosaic of the landscape. Active fire weather showed strong relations with Pacific Decadal Oscillation (PDO) at interdecadal timescales and with El Niño Southern Oscillation (ENSO) and Arctic Oscillation (AO) mostly at interannual (2 to 6 years) timescales. PDO-ENSO-AO interactions with active fire weather provide an explanation for changes in large fire occurrence frequency during the last centuries in the area.

*Hu, FS, PE Higuera, JE Walsh, PA Duffy, LB Brubaker, ML Chipman. 2010. Tundra burning in Alaska: Linkages to climatic change and sea ice retreat. *J Geophys Res: Biogeosciences* 115: G04002

Recent climatic warming has resulted in pronounced environmental changes in the Arctic, including shrub cover expansion and sea ice shrinkage. Here we report paleoecological evidence showing that recent tundra burning is unprecedented in the central Alaskan Arctic within the last 5000 years. Analysis of lake sediment cores reveals peak values of charcoal accumulation corresponding to the Anaktuvuk River Fire in 2007, with no evidence of other fire events throughout the past five millennia in that area. Atmospheric reanalysis suggests that the fire was

favored by exceptionally warm and dry weather conditions in summer and early autumn. The Anaktuvuk River Fire coincides with extreme sea ice retreat, and tundra area burned in Alaska is moderately correlated with sea ice extent from 1979 to 2009 (r = _0.43, p = 0.02). These results contribute to an emerging body of evidence suggesting that tundra ecosystems can burn more frequently under suitable climatic and fuel conditions.

(also Vegetation) Jafarov, EE, VE Romanovsky, H Genet, AD McGuire. SS Marchenko. 2013. The effects of fire on the thermal stability of permafrost in lowland and upland black spruce forests of interior Alaska in a changing climate. *Environ Res Lett* 8: 035030, 11 p

Fire is an important factor controlling the composition and thickness of the organic layer in the black spruce forest ecosystems of interior Alaska. Fire that burns the organic layer can trigger dramatic changes in the underlying permafrost, leading to accelerated ground thawing within a relatively short time. In this study, we addressed the following questions. (1) Which factors determine post-fire ground temperature dynamics in lowland and upland black spruce forests? (2) What levels of burn severity will cause irreversible permafrost degradation in these ecosystems? The results indicate that climate warming accompanied by fire disturbance could significantly accelerate permafrost degradation. In upland black spruce forest, permafrost could completely degrade in an 18 m soil column within 120 years of a severe fire in an unchanging climate. In contrast, in a lowland black spruce forest, permafrost is more resilient to disturbance and can persist under a combination of moderate burn severity and climate warming.

Kendall, NW, HB Rich, LR Jensen, TP Quinn. 2010. Climate effects on inter-annual variation in growth of the freshwater mussel (*Anodonta beringiana*) in an Alaskan lake. *Freshwater Biology* 55: 2339-2346.

Iliamna Lake is warming, with the result that freshwater mussels are growing larger. Longer ice-free seasons, possibly driven by warmer air temperatures in October, January, and February, provide increased light and warmth and are also tied to the increase in mussel growth.

Rocha, AV, MM Loranty, PE Higuera, MC Mack, FS Hu, BM Jones, AL Breen, EB Rastetter, SJ Goetz, GR Shaver. 2012. The footprint of Alaskan tundra fires during the past half-century: implications for surface properties and radiative forcing. *Environ Res Lett* 7

Recent large and frequent fires above the Alaskan arctic circle have forced a reassessment of the ecological and climatological importance of fire in arctic tundra ecosystems. Remote sensing data and a literature review of thaw depths indicate that tundra fires have both positive and negative implications for climatic feedbacks including a decadal increase in albedo radiative forcing immediately after a fire, a stimulation of surface greenness and a persistent long-term (>10 year) increase in thaw depth.

Fish and shellfish

Abdul-Aziz, OI, NJ Manta, KW Myers. 2011. Potential climate change impacts on thermal habitats of Pacific salmon (*Onchorhynchus* spp.) in the North Pacific Ocean and adjacent seas. *Can J Fish Aquat Sci* 68: 1660-1680

Salmon are sensitive to temperatures, with temperatures of 7-13 ˚C or higher causing negative impacts, depending on life stage and season. Based on spatially explicit representations of thermal habitats in the North Pacific and part of the Arctic ocean, projected summer habitat for

Chinook decreased by 86%, for sockeye 45%, for steelhead 36%, and coho, pink and chum habitat decreased 30%; winter habitat for sockeye decreased 38%. The open ocean Gulf of Alaska habitat for Chinook (in summer) and sockeye (summer and winter) could be completely lost by 2100. However, salmon are expected to expand northward. Because sockeye diets overlap with pink and chum in the ocean, pink and chum could outcompete sockeye. The study only looked at the impact of temperatures and did not bring in potential additional impacts of ocean acidification or other factors.

Bryant, MD. 2009. Global climate change and potential effects on Pacific salmonids in freshwater ecosystems of Southeast Alaska. *Climatic Change* published online Jan 14, 2009 DOI 10.1007/s10584-008-9530-x

Mapping of future sea rise and literature review inform potential impacts to each salmon species under climate change scenarios for Southeast Alaska. Pinks and chum expected to have higher mortality due to higher water temperatures and lower stream flows; there will be loss of habitat with seawater rise into spawning areas. For sockeye and coho, expect changes in growth and survival related to changes in run timing and zooplankton availability. Pools that provided cool refuge during spawning and rearing will warm, causing increased stress and mortality on Chinook. Landslides, due to more rain, will introduce sediment and affect habitat for all species.

Greene, CM, JE Hall, KR Guilbault, TP Quinn. 2010. Improved viability of populations with diverse life-history portfolios. *Biol Lett* 6: 382-386

Commented [K4]: Not an impact of climate change, but failing to maintain habitat will cause climate to have greater impact

Life history diversity of Bristol Bay sockeye improves productivity over long time scales and buffers population fluctuations, although diversity has a negative impact on short term time scales. This means different life-history types are favored in one year or another, due to processes like changes in precipitation, ice, and lake levels. The findings suggest that reducing the diversity of stocks by artificial propagation, habitat alteration, and size- or age-selective harvest will harm long term population abundance. Habitat protection and restoration will help, and may be critical in maintaining populations under climate change and habitat disturbance.

Griffiths, JR and DE Schindler. 2012. Consequences of changing climate and geomorphology for bioenergetics of juvenile sockeye salmon in a shallow Alaska lake. *Ecol Freshwater Fish* 21 (3): 349-362

Warming from climate change has and will continue to alter lake thermal conditions and affect the growth and ecology of fishes. Black Lake is a large, shallow, turbid lake in the Chignik watershed that is a highly productive sockeye lake. The region has had a 1.4 ˚C from 1960-2005, causing earlier ice out, and fry that emigrate earlier are faced with metabolic stress from warm water. Researchers determined that if fish can maintain feeding rates, it will offset the metabolic costs of activity in warm water. Maintaining connections between the lake and tributaries was crucial to reducing salmon metabolic costs with climate warming, particularly as the lake level drops.

Griffiths, JR, DE Schindler, LS Balistieri, GT Ruggerone. 2011. Effects of simultaneous climate change and geomorphic evolution on thermal characteristics of a shallow Alaskan lake. *Limnol Oceanogr* 56 (1): 191-205

At Black Lake, a large shallow lake in the Chignik system, warmer air temperatures have driven lake thermal conditions and is causing the lake to reach temperatures (above 15 ˚C) that negatively impact salmon. Warmer conditions may have driven juvenile salmon to outmigrate a month early in 2005. Additionally, geomorphic conditions unrelated to climate may cause tributaries to disconnect from the lake. If this happens, the lake would lose cool water inputs and warm faster. The study shows the importance of tying climate trends, such as the change in lake tributary temperatures, tributary flow, lake stratification, and lake evaporation, to natural processes like erosion unrelated to climate to determine cumulative effects that drive biological responses.

Healey, M. 2011. The cumulative impacts of climate change on Fraser River sockeye salmon (*Onchorhynchus nerka*) and implications for management. *Can J Fish Aquat Sci* 68: 718-737

The effects of climate change most relevant to Fraser River sockeye are warming of freshwater and marine habitat, altered hydrology in spawning rivers, reduced productivity in nursery habitats, and changed distribution of predator and prey species. For example, at the egg stage, increased temperatures will cause higher metabolic rates resulting in smaller fry, which result in lower survival rates when fry move to lakes or problems emerging to the lakes; early emergence to lakes can mean fish arrive before spring bloom, which results in lower survival. The weight of evidence indicates that these will negatively affect growth and survival of Fraser River sockeye at all life stages, and effects of one life stage will carry forward to next life stages and subsequent generations for a cumulative impact. Salmon can adapt to climate change, but probably not enough to sustain productivity. Management in the Arctic should protect potentially productive habitats and facilitate their colonization by Pacific salmon.

Commented [K5]: Although this is on BC salmon, it is relevant to AK. Same mechanisms. And a plug for keeping AK habitat as fish from Canada move north. There is an excellent table that shows the effects of global warming at each stage of salmon life cycle.

Commented [K6]: I have several more journal articles on Canadian salmon but did not put them in the bibliography

Hovel, RA, SM Carlson, TP Quinn. 2016. Climate change alters the reproductive phenology and investment of a lacustrine fish, the three-spine stickleback. *Global Change Biology* doi: 10.1111/gcb.13531

In Lake Aleknagik, part of the Wood River system in Alaska, lake temperatures are warmer and ice breaks up earlier than in the 1960s; in response, the three-spine stickleback is breeding earlier and some have two broods a year instead of one. The three-spine stickleback and juvenile sockeye salmon share the same habitat; whether increased numbers of stickleback compete with salmon or provide salmon with more food remains to be seen. It may be that stickleback will live shorter lives, due to the physiological cost of having additional broods. The study was done from 1962-2015.

Commented [K7]: This is the first to have actual observations of changes in breeding frequency in a vertebrate directly related to climate.

Commented [K8]: Related news article is in the Alaska Dispatch at https://www.adn.com/alaska-news/science/2017/01/29/as-water-temperatures-warm-some-fish-are-breeding-earlier-and-more-often/

Ishida, Y, T Azumaya, M Fukuwaka, N Davis. 2002. Interannual variability in stock abundance and body size of Pacific salmon in the central Bering Sea. *Prog Oceanog* 55: 223-234

Climate change affects sea temperatures, which in turn affect chum and sockeye distribution and density, which in turn effects salmon growth through competition. Chum and sockeye were relatively abundant in the northern Gulf of Alaska when sea surface temperatures were low (1985-1990) but were abundant in the Bering Sea when temperatures were high in the Gulf (1977-1984, 1991-2000). Sockeye near the southern limit of their distribution decreased in abundance when sea surface temperatures increased. With density, diets changed, possibly to

provide a way for different salmon species occupying the central Bering Sea to decrease competition for food.

Johnson, SP and DE Schindler. 2009. Trophic ecology of Pacific salmon (*Onchorhynchus* spp.) in the ocean: a synthesis of stable isotope research. *Ecol Res* 24: 855

Pacific salmon will need to respond to marine climate variation, which shifts the abundance of prey. Sockeye, chum, and pink salmon move offshore into the deep ocean after their first year at sea and have considerable overlap in the open ocean, while many populations of Chinook and coho tend to remain in coastal waters. Stable isotopes show that sockeye, pink, and chum salmon compete for prey or at least feed on prey that occupy the same trophic level, such as jellyfish and gelatinous zooplankton, and verify the dependence of Chinook and coho on coastal resources. Future climate may impact coastal and pelagic resources differently, with implications for salmon abundance.

Kaeriyama, M, M Nakamura, R Edpalina, JR Bower, H Yamaguchi, RV Walker, KW Myers. 2004. Change in feeding ecology and trophic dynamics of Pacific salmon in the central Gulf of Alaska in relation to climate events. *Fish Oceanog* 13 (3): 197-207

The effects of climate events on the feeding ecology and trophic dynamics of Pacific salmon (*Oncorhynchus* spp.) in offshore waters of the central Gulf of Alaska were investigated during early summers (1994–2000), based on analyses of stomach contents, and carbon and nitrogen stable isotopes (d13C and d15N). Gonatid squids were the dominant prey of all salmon species except for chum salmon. During the 1997 El Nino event and the 1999 La Nina event, squids decreased sharply in the diets of all Pacific salmon except coho salmon in the Subarctic Current, and chum salmon diets changed from gelatinous zooplankton (1995–97) to a more diverse array of zooplankton species. A δ13C and δ15N analysis indicated that all salmon species occupied the same branch of the food web in 1999– 2000. We hypothesize that high-seas salmon adapt to climate-induced changes in their prey resources by switching their diets either within or between trophic levels.

Kortsch, S, R Primicerio, M Fossheim, AV Dolgov, M Aschan. 2016. Climate change alters the structure of arctic marine food webs due to poleward shifts of boreal generalists. *Proc R Soc B* 282: 20151546

Changes in species composition and abundance have been documented in Arctic ocean species. In the Barents Sea, “generalist” fish such as Atlantic cod (*Gadus morhua)* and haddock (*Melanogrammus aeglefinus*) and some seabirds have been moving poleward, taking advantage of increasing seawater temperatures, reduced sea ice coverage, and longer ice-free periods. They are altering the structure of arctic marine food webs, increasing the connection between pelagic and benthic habitat.

Lehodey, P, AM Barange, T Baumgarter, G Beaugrand, K Drinkwater, J-M Fromentin, SR Hare, G Ottersen, RI Perry, C Roy, CD van der Lingen, F Werner. 2006. Climate variability, fish, and fisheries. *J Climate* 19: 5009-5032.

Fish populations fluctuate on time scales of decades to centuries. This review presents examples and describes known mechanisms linking climate variability and fish populations. Relevant to Alaska, during the positive phase of the Pacific Decadal Oscillation (PDO), there is more precipitation in the northeastern North Pacific leading to more food for salmon. However, the positive effect of increased food supply on the growth of salmon in the Gulf of Alaska was offset by increased abundance of salmon, therefore more competition and smaller body size. The mechanisms that affect fish populations include atmospheric conditions that create changes in sea ice cover, and heat flux that affects sea surface temperatures, which effects wind-driven circulation and the availability of nutrients.

*Luizza, MW, PH Evangelista, CS Jarnevich. 2016. Integrating subsistence practices and species distribution modeling: assessing invasive elodea's potential impact on Native Alaskan subsistence of Chinook salmon and whitefish. *Env Mgmt* 58: 144

Alaska's first freshwater aquatic invasive plant *Elodea* is spreading in part due to rapid climate change in the state. Using habitat data and subsistence knowledge, models of future climate (2040-2059) indicate moderate to strong predictability that can be used by state management. Interaction of fish subsistence patterns, known spawning and rearing sites, and elodea habitat highlight areas that will need to be monitored.

Martinson, EC, HH Stokes, DL Scarnecchia. 2012. Use of juvenile salmon growth and temperature change indices to predict groundfish post age-0 year class strengths in the Gulf of Alaska and Bering Sea. *Fish Oceanog* 21 (4): 307-219.

The ocean growth of juvenile salmon is a proxy for ocean productivity. Along with temperature, it was tested to see if it could predict groundfish productivity. However, recruitment of groundfish was more closely tied to climate variables during a specific life stage. More age-2 pollock were linked to warmer than average air temperatures near the Pribilofs and less ice in the Bering Sea. However warm summers during the age-0 stage of life resulted in high mortality due to lack of lipid-rich pretty. Cool weather in late summer during the age-0 stage followed by a warm spring optimized overwinter survival.

Martinson, EC, JH Helle, DL Scarnecchia, HH Stokes. 2008. Density-dependent growth of Alaska sockeye salmon in relation to climate-oceanic regimes, population abundance, and body size, 1925-1998. *Mar Ecol Progress Series* 370: 1-18

Analysis of 74 year time series of growth and abundance indicates that sockeye growth varied with climate, population abundance, and body size. During cool years, growth was negatively related to abundance; during warm years, growth was positively related to abundance. This suggests that a shift to cool years or very warm years when there are high population levels may reduce salmon growth and increase competition for resources.

*Ou, M, TJ Hamilton, J Eom, EM Lyall, J Gallup, A Jiang, J Lee, DA Close, S-S Yun, CJ Brauner. 2015. Responses of pink salmon to CO2-induced aquatic acidification. *Nature Climate Change* doi: 10.1038/nclimate2694

Pink salmon that begin life in freshwater with high concentrations of carbon dioxide, at levels expected 100 years in the future, are smaller and there sense of smell is reduced, which reduces their chances of survival and reproduction. Once old enough to outmigrate, they were less able to use oxygen to exercise, affecting the ability to find food, evade predators, and migrate.

Rich, HB Jr, TP Quinn, MD Scheurell, DE Schindler. 2009. Climate and intraspecific competition control the growth and life history of juvenile sockeye salmon (*Onchorynchus Nerka*) in Iliamna Lake, Alaska. *Can J Fish Aquat Sci* 66: 238-246

Recent climate change causes longer ice-free seasons and thermal conditions in high latitude lakes, leading to more phytoplankton and zooplankton. Spring air temperatures at Iliamna Lake have warmed 3.3 ˚C since 1962, leading to earlier ice breakup and warmer lake waters. This has led to larger salmon fry in Iliamna Lake, a cold lake with low density of juvenile salmon. In Lake Alekangik, temperature did not have this effect. The size of fish at the end of the first growing season affects smolt size and age at outmigration, and therefore survival at sea.

*Schindler, DE, DE Rogers, MD Scheuerell, CA Abrey. 2005. Effects of changing climate on zooplankton and juvenile sockeye salmon growth in Southwestern Alaska. *Ecology* 86 (1): 198-209

We explored the effects of density-dependence and changing climate on growth of juvenile sockeye salmon and the densities of their zooplankton prey in the Wood River system of southwestern Alaska between 1962 and 2002. The timing of spring breakup has moved about seven days earlier now than it was in the early 1960s, mostly in response to the warm phase of the Pacific Decadal Oscillation that persisted from the mid-1970s to the late 1990s. This progression toward earlier spring breakup dates was associated with warmer summer water temperatures and increased zooplankton (especially Daphnia) densities, which translated into increased sockeye growth during their first year of life. The number of spawning adults that produced each year class of sockeye had a strong negative effect on juvenile sockeye growth rates, so that the size of the density-dependent effect was, on average, twice as large as the effect of spring breakup date. These results highlight the complexity of ecological responses to changing climate and suggest that climate warming may enhance growing conditions for juvenile salmonids in large lakes of Alaska.

*Sergeant, CJ, JB Armstrong, EJ Ward. 2014. Predatory-prey migration phenologies remain synchronized in a warming catchment. *Freshwater Biology* 60 (4): 724-732

An analysis shows that Dolly Varden, a type of char, adjusts their migrations so they can continue to feed on salmon eggs, even as shifts in climate alter the timing of salmon spawning. In Auke Creek, pink, sockeye, and coho now migrate to spawning grounds 7-10 days earlier.

Shanley, CS and DM Albert. 2014. Climate change sensitivity index for Pacific salmon habitat in Southeast Alaska. *PLoS One* 9 (8)

Egg-to-fry survival may be one of the most important impacts as increased stream discharge and flooding occurs as a result of warming in watersheds with steep mountains transitioning from snow to rain-fed hydrology. From September to March, when salmon eggs are in streambed gravel, discharge is expected to increase 1- to 3-fold, increasing the risk that eggs will be washed out. Steelhead, which spawn in headwaters, will be at lower risk. Coho, sockeye, and Chinook spawning in mid-portions of watersheds will be more exposed unless they bury eggs deep, a trait related to body size. Overall, there will be shifting productivity between streams; the great variety of streams will help salmon be able to survive.

Glaciers

Crusius, J, AW Schroth, S Gasso, CM Moy, RC Levy, M Gatica. 2011. Glacial flour dust storms in the Gulf of Alaska: hydrologic and meteorological controls and their importance as a source of bioavailable iron. *Geophys Res Letters* 38 (6)

> Glacial melt carries "rock flour", the remains of bedrock ground up by the glacier. This material is rich in minerals like iron, which, when deposited in the Gulf of Alaska, promotes phytoplankton growth. Dust also carries iron to ocean waters; visible plumes of dust from the Kenai Peninsula to Yakutat have been captured by NOAA satellites.

Fortner, SK, BG Mark, JM McKenzie, J Bury, A Trierweiler, M Baraer, PJ Burns, LA Munk. 2011. Elevated stream trace and minor element concentrations in the foreland of receding tropical glaciers. *App Geochem* 26:1792-1801

> As glaciers recede, sulfide-bearing rock is exposed. In the Rio Quilcay watershed in the Peruvian Andes, 20 of 22 stream samples had pH values below 4, significantly lower than glacial fed streams globally. The pH and trace metals concentrations were comparable to acid mine drainage.

Commented [K9]: Although the work was done in the Andes, this would be expected in Alaska as well in locations where glaciers overly sulfide outcroppings and bedrock. I have not matched glaciers to known geology, but might be a good idea to have that done.

O'Neel, S, E Hood, AL Bidlack, SW Fleming, ML Arimitsu, A Arendt, E Burgess, CJ Sergeant, AH Beaudreau, K Timm, GD Hayward, JH Reynolds, S Pyare. 2015. Icefield-to-ocean linkages across the northern Pacific coastal temperate rainforest ecosystem. *BioScience* 65 (5): 499-512

> Glacial melt affects biological communities downstream, including Pacific salmon and herring. It changes freshwater inputs to streams. Impacts on salmon are site specific and complex; habitat is better as stream temperatures are raised above freezing and there is less turbidity but worse where stream temperatures rise too much and where streamflow becomes flashier. Warmer streams may shift salmon fry migration earlier, when food is not available, resulting in lower survival and growth. Glacial melt also drives the Alaska Coastal Current that moves heat, nutrients, and organisms northward, providing the basis for Alaska fisheries. Glacial melt carries organic material and metals, such as iron, that boost phytoplankton in rivers and coastal environments, but also releases mercury and other contaminants once deposited from the atmosphere onto glaciers. The biophysical linkages will affect salmon growth, stream and lake contamination, hydropower, and tourism (glacier viewshed; fish, birds, seals dependent on glacial calving).

Insects

Bowden, JJ, A Eskildsen, RR Hansen, K Olsen, CM Kurle, TT Høye. 2015. High-Arctic butterflies become smaller with rising temperatures. *Biology Lett* 11 (10)

> The metabolic cost of increased temperature could reduce body size but long growing seasons could also increase body size as was recently shown in an Arctic spider species. Here, we present the longest known time series on body size variation in two High-Arctic butterfly species: *Boloria chariclea* and *Colias hecla*. We measured wing length of nearly 4500 individuals collected annually between 1996 and 2013 from Zackenberg, Greenland and found that wing length significantly decreased at a similar rate in both species in response to warmer summers. Body size is strongly related to dispersal capacity and fecundity and our results suggest that these Arctic species could face severe challenges in response to ongoing rapid climate change.

Rich, ME, L Gough, NT Boelman. 2013. Arctic arthropod assemblages in habitats of differing shrub dominance. *Ecography* 36 (9): 994-1003

Recent climate warming in the Arctic has caused advancement in the timing of snowmelt and expansion of shrubs into open tundra. Such an altered climate may directly and indirectly affect arctic arthropod abundance, diversity and assemblage taxonomic composition. Patterns of abundance within the five most abundant arthropod orders differed, with spiders (Order: Araneae) more abundant in open tundra habitats and true bugs (Order: Hemiptera), flies (Order: Diptera), and wasps and bees (Order: Hymenoptera) more abundant in shrub-dominated habitats. Some arthropod orders showed significant relationships with other vegetation variables, including maximum shrub height (Coleoptera) and foliar canopy cover (Diptera). As climate warming continues over the coming decades, and with further shrub expansion likely to occur, changes in arthropod abundance, richness, and diversity associated with shrub-dominated habitat may have important ecological effects on arctic food webs since arthropods play important ecological roles in the tundra, including in decomposition and trophic interactions.

Mammals and marine mammals

*Breed, GA, CJD Matthews, M Marcoux, JW Higdon, B LeBlan, SD Petersen, J Orr, NR Reinhart, SH Ferguson. 2017. Sustained disruption of narwhal habitat use and behavior in the presence of Arctic killer whales. *PNAS* 114 (10): 2628-2633

We tracked predator (killer whales) and prey (narwhal) in the Eastern Canadian Arctic. When killer whales were present (within about 100 km), narwhal moved closer to shore, where they were presumably less vulnerable. Effects extended beyond discrete predatory events and persisted steadily for 10 d. Our findings have two key consequences. First, given current reductions in sea ice and increases in Arctic killer whale sightings, killer whales have the potential to reshape Arctic marine mammal distributions and behavior. Second and of more general importance, predators have the potential to strongly affect movement behavior of tracked marine animals.

Huntington, HP, LT Quakenbush, M Nelson. 2016. Effects of changing sea ice on marine mammals and subsistence hunters in northern Alaska from traditional knowledge interviews. *Biology Lett* 12: 20160198

Marine mammals are important sources of food for indigenous residents of northern Alaska. Changing sea ice patterns affect the animals themselves as well as access to them by hunters. We interviewed hunters in 11 coastal villages from the northern Bering Sea to the Beaufort Sea. Hunters reported extensive changes in sea ice and weather that have affected the timing of marine mammal migrations, their distribution and behaviour and the efficacy of certain hunting methods. Amidst these changes, however, hunters cited offsetting technological benefits, such as more powerful and fuel-efficient outboard engines. Other concerns included potential impacts to subsistence hunting from industrial activity such as shipping and oil and gas development.

*Jenkins, DA, N Lecomte, JA Schaefer, SM Olsen, D Swingedouw, SD Côté, LPellissier, G Yannic. 2016. Loss of connectivity among island-dwelling Peary caribou following sea ice decline. *Biology Lett* 12: 20160235

Global warming threatens to reduce population connectivity for terrestrial wildlife through significant and rapid changes to sea ice. Using genetic fingerprinting, we contrasted extant connectivity in island-dwelling Peary caribou in northern Canada with continental-migratory caribou. We next examined if sea-ice contractions in the last decades modulated population connectivity and explored the possible impact of future climate change on long-term connectivity among island caribou. We found a strong correlation between genetic and geodesic distances for both continental and Peary caribou, even after accounting for the possible effect of sea surface. Under the persistent increase in greenhouse gas concentrations, reduced connectivity may isolate island-dwelling caribou with potentially significant consequences for population viability.

(also Fire) Joly, K, PA Duffy, TS Rupp. 2012. Simulating the effects of climate change on fire regimes in Arctic biomes: implications for caribou and moose habitat. *Ecosphere* 3 (5): 1-18

Migratory barren-ground caribou (*Rangifer tarandus granti*) rely heavily on terricolous lichens to sustain them through the winter months. Lichens preferred by caribou can take 50 or more years to recover after being consumed by wildfires. We forecast that the total area burned (AB) in the near term (2008-2053) will be 0-30% greater than during our historic reference period (1950-2007) depending on the climate model (CGCM3.1 or ECHAM5) considered. Further into the future (i.e., 2054-2099), we forecast AB to increase 25-53% more than during our reference period. The simulated declines in the quantity of core winter range in the future due to larger and more frequent fires could impact caribou abundance through decreased nutritional performance and/or apparent competition with moose. These impacts would likely be detrimental to the subsistence users that rely on this resource. Additionally, changes in the fire regime and decreases in caribou abundance could amplify feedback mechanisms, such as decreasing albedo, by facilitating shrub growth that may hasten climate-driven changes to the composition and structure of vegetation communities in the low Arctic.

*Laidre, KL, I Stirling, LF Lowry, O Wiig, MP Heide-Jørgensen, SH Ferguson. 2008. Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecol Appl* 18 (2 Suppl): S97-125.

We review seven Arctic and four subarctic marine mammal species, their habitat requirements, and evidence for biological and demographic responses to climate change. The hooded seal, the polar bear, and the narwhal appear to be the three most sensitive Arctic marine mammal species, primarily due to reliance on sea ice and specialized feeding. The least sensitive species were the ringed seal and bearded seal, primarily due to large circumpolar distributions, large population sizes, and flexible habitat requirements. We provide a framework for determining sensitivity, distinguish between highly sensitive species and good indicator species, and discuss regional variation regarding the effects of climate change.

*Moore, SE and HP Huntington. 2008. Arctic marine mammals and climate change: impact and resilience. *Ecol Appl* 18 (2 Suppl): 157-165

Evolutionary selection has refined the life histories of seven species (three cetacean [narwhal, beluga, and bowhead whales], three pinniped [walrus, ringed, and bearded seals], and the polar bear) to spatial and temporal domains influenced by the seasonal extremes and variability of sea ice, temperature, and day length that define the Arctic. Recent changes in Arctic climate may challenge the adaptive capability of these species. Nine other species (five cetacean [fin, humpback, minke, gray, and killer whales] and four pinniped [harp, hooded, ribbon, and spotted seals]) seasonally occupy Arctic and subarctic habitats and may be poised to encroach into more northern latitudes and to remain there longer, thereby competing with extant Arctic species. A synthesis of the impacts of climate change on all these species hinges on sea ice. Resilience scenarios suggest that: (1) some populations of ice-obligate marine mammals will survive in two regions with sea ice refugia, while other stocks may adapt to ice-free coastal habitats, (2) ice-associated species may find suitable feeding opportunities within the two regions with sea ice refugia and, if capable of shifting among available prey, may benefit from extended foraging periods in formerly ice-covered seas, but (3) they may face increasing competition from seasonally migrant species, which will likely infiltrate Arctic habitats. The means to track and assess Arctic ecosystem change using sentinel marine mammal species are suggested to offer a framework for scientific investigation and responsible resource management.

(also Vegetation) *Tape, KD, K Christie, G Carroll, JA O'Donnell. 2016. Novel wildlife in the Arctic: the influence of changing riparian ecosystems and shrub habitat expansion on snowshoe hares. *Global Change Biology* 22 (1): 208-219

Warming during the 20th century has changed the arctic landscape, including aspects of the hydrology, vegetation, permafrost, and glaciers, but effects on wildlife have been difficult to detect. This study examines the habitat and range of snowshoe hares (*Lepus americanus*) in northern Alaska. We explore linkages including stream flow, air temperature, floodplain shrub habitat, and snowshoe hare distributions. Our analyses show that the peak discharge during spring snowmelt has occurred on average 3.4 days per decade earlier over the last 30 years and has contributed to a longer growing season in floodplain ecosystems. The effects of longer and warmer growing seasons are estimated to have stimulated a 78% increase in the height of riparian shrubs. Earlier spring discharge and the estimated increase in riparian shrub height are consistent with observed riparian shrub expansion in the region. Our browsing measurements show that snowshoe hares require a mean riparian shrub height of at least 1.24–1.36 m, a threshold which our hindcasting indicates was met between 1964 and 1989. This generally coincides with observational evidence we present suggesting that snowshoe hares became established in 1977 or 1978. Warming and expanded shrub habitat is the most plausible reason for recent snowshoe hare establishment in Arctic Alaska. The establishment of snowshoe hares and other shrub herbivores in the Arctic in response to increasing shrub habitat is a contrasting terrestrial counterpart to the decline in marine mammals reliant on decreasing sea ice.

Vowles, T, C Lovehav, U Molau, RG Björk. 2017. Contrasting impacts of reindeer grazing in two tundra grasslands. *Environ Res Letters* 12 (3)

Plant communities in Arctic and alpine areas are changing due to higher temperatures and longer vegetation periods and it is uncertain how this will affect plant-herbivore dynamics. For instance, relatively fast-growing, deciduous shrub species that are the most responsive to warming may also be the most targeted by herbivores such as reindeer, giving less palatable evergreen shrubs the chance to expand. At the grass heath, evergreen low shrub abundance had more than doubled, regardless of grazer treatment, whereas at the low herb meadow, evergreen shrubs had increased only outside exclosures while deciduous tall shrubs and forbs were significantly more abundant inside exclosures. Consequently, as the balance in these competitive interactions is shifting due to climate warming, we conclude that the potential of herbivory to influence this balance is considerable yet highly site dependent.

Ocean acidification

*Bednar, N, RA Freely, JCP Reum, B Peterson, J Menkel, SR Alin, B Hales. 2014. *Limacina helicina* shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. *Proc Roy Soc B: Biolog Sci* 281 (1785): 20140123

> NOAA research determines that acidity off the West Coast continental shelf waters during upwelling (April – September) is dissolving the shells of pteropods, zooplankton that provide food for salmon and herring. Although this was predicted, it is occurring several decades faster than expected.

Permafrost

Brown, DRN, MT Jorgenson, TA Douglas, VE Romanovsky, K Kielland, C Hiemstra, ES Euskirchen, RW Ruess. 2015. Interactive effects of wildfire and climate on permafrost degradation in Alaskan lowland forests. *J Geophys Res Biogeosci* 120: 1619-1637

> Wildfires from 1930-2010 in the Tanana Flats cause permafrost to thaw and settle; up to 0.5 m of thaw settlement was documented after recent fires. Settlement caused flooding and further thawing along forest margins. Results and models indicate permafrost is increasingly vulnerable to substantial thaw and collapse after moderate- to high-severity fires and there is less ability of permafrost to recover after fires.

Hope, C and K Schaefer. 2016 Economic impacts of carbon dioxide and methane released from thawing permafrost. *Nature Climate Change* 6: 56-59

> The Arctic is warming roughly twice as fast as the global average. If greenhouse gas emissions continue to increase at current rates, this warming will lead to the widespread thawing of permafrost and the release of hundreds of billions of tonnes of CO_2 and billions of tonnes of CH_4into the atmosphere. Under the A1B scenario, CO_2 and CH_4 released from permafrost increases the mean net present value of the impacts of climate change by US$43 trillion, or about 13% (5-95% range: US$3-166 trillion), proportional to the increase in total emissions due to thawing permafrost. The extra impacts of the permafrost CO_2 and CH_4 are sufficiently high to justify urgent action to minimize the scale of the release.

Koch, JC, CP Kikuchi, KP Wickland, P Schuster. 2014. Runoff sources and flow paths in a partially burned, upland boreal catchment underlain by permafrost. *Water Resources Res* 50 (10): 8141-8158

> Boreal soils in permafrost regions contain vast quantities of frozen organic material that is released to terrestrial and aquatic environments via subsurface flow paths as permafrost thaws. By coupling measurements of permeability, infiltration potential, and water chemistry with a stream chemistry end-member mixing model, we determined that burned soils are the dominant source of water and solutes reaching streams in summer, whereas unburned soils may provide longer term storage and residence times necessary for production of anaerobic compounds.

(also Vegetation) Lara, MJ, H Genet, AD McGuire, ES Euskirchen, Y Zhang, DRN Brown, MT Jorgenson, V Romanovsky, A breen, and WR Bolton. 2015. Thermokarst rates intensify due to climate change and forest fragmentation in an Alaskan boreal forest lowland. *Global Change Biology* 22 (2): 816-829

Thermokarst has affected the wetlands-rich lowlands of the Tanana Flats in central Alaska for centuries, but the region has warmed significantly in the last half-century and many soils are within 0.5 ˚C of thawing. From 1949-2009, permafrost thaw and thermokarst resulted in the loss of birch forests. Although birch was lost due to thermokarst, spruce was not. Birch forests have soils with higher ice content. The loss of birch may be evidence that permafrost temperatures in ice-rich birch forests have destabilized, which is consistent with the observation that permafrost is near the thaw point.

Melvin, AM, P Larsen, B Boehlert, JE Nuemann, P Chinowsky, X Espinet, J Martinich, MS Baumann, L Rennels, A Bothner, DJ Nicolsky, SS Marchenko. 2017. Climate change damages to Alaska public infrastructure and economics of proactive adaptation. *PNAS* 114 (12): E122-E131 (www.pnas.org/cgi/doi/10.1073/pnas.1611056113)

Commented [K10]: Related news story is Yereth Rosen, Feb 10 2017, Study: climate change will be costly to Alaska's public infrastructure. https://www.adn.com/alaska-news/environment/2017/02/09/climate-change-to-be-costly-to-alaskas-public-infrastructure-study-says/

The potential economic damage to Alaska infrastructure from climate-driven flooding, precipitation, permafrost thaw, and freeze-thaw cycles were analyzed, along with estimated coastal erosion losses for villages. The largest climate damages will result from road flooding and damage to buildings from permafrost thaw, with smaller damage to airports, railroads, and pipelines. The largest damage will occur in Interior and Southcentral Alaska. Without adaptation, expenses from 2015-2099 are estimated at $5.5 billion. Adaptation could save $2.3-$2.9 billion and prevent road flooding entirely in four study areas.

* O'Donnell, JA, GR Aiken, DK Swanson, S Panda, KD Butler, AP Baltensperger. 2016. Dissolved organic matter composition of Arctic rivers: Linking permafrost and parent material to riverine carbon. *Global Biogeochem Cycles* 30 (12): 1811-1826

Recent climate change in the Arctic is driving permafrost thaw, which has important implications for regional hydrology and global carbon dynamics. Here we examined watershed controls on dissolved organic material composition in 69 streams and rivers draining a broad region of Arctic Alaska. Parent material and ground ice content significantly affected the amount and composition of dissolved organic material; concentrations were higher in watersheds underlain by fine-grained loess compared to watersheds underlain by coarse-grained sand or shallow bedrock and higher in rivers draining ice-rich landscapes.

*Petrone, KC, LD Hinzman, H Shibata, JB Jones, RD Boone. 2007. The influence of fire and permafrost on sub-arctic stream chemistry during storms. *Hydolog Processes* 21 (4): 423-434.

We examined the influence of permafrost and a prescribed burn on concentrations of dissolved organic carbon and other solutes in streams of an experimentally burned watershed and two reference watersheds in the Caribou–Poker Creeks Research Watershed in interior Alaska. Stormflow in the low-permafrost watershed was dominated by precipitation, whereas the high-permafrost watershed was dominated by flow through the active permafrost. Groundwater flow paths controlled stream chemistry. Thawing of the active layer increased soil water storage in the high-permafrost watershed from July to September, and attenuated the hydrologic response and solute flux to the stream.

Raynolds, MK, DA Walker, KJ Ambrosius, J Brown, KR Everett, M Kanevskiy, GP Kofinas, VE Romanvsky, Y Shur, PJ Webber. 2014. Cumulative geoecological effects of 62 years of infrastructure and climate change in ice-rich permafrost landscapes, Prudhoe Bay Oilfield, Alaska. *Global Change Biology* 20 (4): 1211-1224

> Thermokarst has affected broad areas of the Prudhoe Bay Oilfield, and a sudden increase in the area affected began shortly after 1990 corresponding to a rapid rise in summer air temperatures and permafrost temperatures. Between 1990-2001, 19% of the natural area was showing signs of themokarst expansion, such as more small ponds, more lakeshore erosion, and greater microrelief. Road dust and roadside flooding are causing more extensive thermokarst near roads and gravel pads. Thermokarst also occurred far from facilities, causing study lakeshore erosion 1949-1983 and a more than fourfold increase recently 1983-2010. Changes in hydrology and vegetation undoubtedly affect the distribution of insects, shorebirds, waterfowl and small mammals, and possibly on fish.

Toohey, RC, NM Herman-Mercer, PF Schuster, EA Mutter, and JC Koch. 2016. Multidecadal increases in the Yukon River Basin of chemical fluxes as indicators of changing flowpaths, groundwater, and permafrost. *Geophys Res Lett* 43: 1-11

> The Yukon River Basin is expected to be a hotspot of warming in Alaska. Analysis of the water chemistry database 1982-2014 showed significant increases in calcium, magnesium, sodium, sulfate, and phosphorous for the Yukon and Tanana Rivers. The trends suggest permafrost degradation has increased the weathering of mineral soils, and deeper groundwater flow paths are occurring. The changing hydrology and water chemistry may have implications for aquatic life.

*Walter-Anthony, KM, P Anthony, G Grosse, J Chanton. 2012. Geologic methane seeps along boundaries of Arctic permafrost thaw and melting glaciers. *Nature Geoscience* 5: 419-426

> Methane accumulates in subsurface hydrocarbon reservoirs; an estimated 1,200 Pg is stored in the Arctic subsurface, compared to around 5 Pg in the global atmosphere. In the Arctic, permafrost and glaciers form a "cryosphere cap" that traps the gas, preventing it from leaking from the reservoirs. The disintegration of permafrost and glacial retreat is facilitating the release of methane. The researchers mapped over 150,000 methane seeps in lakes.

Commented [K11]: Impact: potential for explosions and formation of craters, as seen in the massive craters in Siberia, some of which are next to gas fields

Commented [K12]: Related news article, Rosen Aug 2016

*Walter-Anthony, K, R Daanen, PAnthony, T Schneider von Deimling, C-L Ping, JP Chanton, and G Grosse. 2016. Methane emissions proportional to permafrost carbon thawed in Arctic lakes since the 1950s. *Nature Geoscience* 9: 679-682

> Permafrost thaw exposes previously frozen soil organic matter to microbial decomposition. This process generates methane and carbon dioxide, and thereby fuels a positive feedback process that leads to further warming and thaw. The authors combine radiocarbon dating of lake bubble methane and soil organic carbon for lakes in Alaska, Canada, Sweden and Siberia and estimate that 0.2 to 2.5_Pg permafrost carbon was released as methane and carbon dioxide in thermokarst expansion zones of pan-Arctic lakes during the past 60 years.

Weather

*Bintanja, R and FM Selton. 2014. Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat. *Nature* 509: 479-482

> Arctic precipitation is expected to increase by 50% or more. This is due to increases in surface evaporation, which in turn are due to retreating winter sea ice caused by global warming.

Francis, JA and SJ Vavrus. 2012. Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geo Res Letters* 39 (6)

> Arctic amplification (AA) - the observed enhanced warming in high northern latitudes relative to the northern hemisphere - is evident in lower-tropospheric temperatures and in 1000-to-500 hPa thicknesses. Two effects are identified that each contribute to a slower eastward progression of Rossby waves in the upper-level flow: 1) weakened zonal winds, and 2) increased wave amplitude. Slower progression of upper-level waves would cause associated weather patterns in mid-latitudes to be more persistent, which may lead to an increased probability of extreme weather events that result from prolonged conditions, such as drought, flooding, cold spells, and heat waves.

Francis, JA and JE Overland. 2014. Implications of rapid Arctic change for weather patterns in northern mid-latitudes. *US Clivar Variations* 12 (3)

> There has been a substantial increase in the occurrence of high amplitude jet stream patterns during autumn over all regions and over North America and the Atlantic in winter and summer. These jet stream patterns are linked to extreme weather in Northern Hemisphere mid-latitudes, such as flooding in the UK in 2014 and "Snowmageddon" in North America in February 2010. Increases in summer may be due to decline in late spring snow cover at high latitudes.

Vegetation

* Beck, PSA, GP Juday, C Alix, VA Barber, SE Winslow, EE Sousa, P Heiser, JD Herriges, SJ Goetz. 2011. Changes in forest productivity across Alaska consistent with biome shift. *Ecology Letters* 14: 373-379

> Global vegetation models predict that boreal forests will shift first at the biome's margins, with evergreen forest expanding into current tundra while being replaced by grasslands or temperate forest at the biome's southern edge. We evaluated changes in forest productivity since 1982 across boreal Alaska by linking satellite estimates of primary productivity and a large tree-ring data set. Trends in both records show consistent growth increases at the boreal-tundra margins that contrast with drought-induced declines throughout interior Alaska. Ultimately, tree dispersal rates, habitat availability and the rate of future climate change, and how it changes disturbance regimes, are expected to determine where the boreal biome will undergo a gradual geographic range shift, and where a more rapid decline

Buma, B, PE Hennon, CA Harrington, JP Popkin, J Krapek, MS Lamb, LE Oakes, S Saunders, S Zeglan. 2016. Emerging climate-driven disturbance processes: widespread mortality associated with snow-to-rain transitions across 10˚ of latitude and half the range of a climate-threatened conifer. *Global Change Biology* doi: 10.1111/gcb.13555

> Substantial mortality of western hemlock, Sitka spruce, and yellow-cedar is linked to the transition from snowy winters to ones dominated by rain; the roots freeze when the soil does not have the insulating snow layer. This has been observed in Alaska and British Columbia. Approximately 7% of the range of yellow cedar has had significant mortality; up to 50% of the remaining range is expected to transition to rainy winters by the end of the century.

Danby, RK and DS Hik. 2007. Variability, contingency and rapid change in recent subarctic alpine tree line dynamics. *J Ecology* 95 (2): 352-363

> Boundaries between forest and tundra ecosystems, tree lines, are expected to advance in altitude and latitude in response to climate warming. We examined recent tree line dynamics at six topographically different, but climatically similar, sites in south-west Yukon, Canada. Dendroecological techniques were used to reconstruct changes in density of the dominant tree species, white spruce (*Picea glauca*), and to construct static age distributions of willow (*Salix spp.)*, one of two dominant shrub genera. Spruce advanced rapidly on south-facing slopes and tree line rose 65 - 85 m in elevation. Tree line did not advance on north-facing slopes, but stand density increased 40-65%. Differences observed between aspects were due primarily to the differential presence of permafrost. The changes observed at several sites are suggestive of a threshold response and challenge the notion that tree lines respond gradually to climate warming.

*Tape, KD, D Verbyla, JM Welker. 2011. Twentieth century erosion in Arctic Alaska foothills: the influence of shrubs, runoff, and permafrost. *J Geophys Res – Biogeosciences* 116: G4

> Recent changes in the climate of Arctic Alaska, including warmer summers and a lengthened growing season, have increased vegetation productivity and permafrost temperatures. We found that tall shrubs occupied floodplains and streams in 1986 and have been expanding their coverage along these corridors. We postulate that the increase in shrubs since 1980 in landscape positions prone to erosion has contributed to the decline in erosion. A decrease in the magnitude and frequency of runoff events has likely also contributed to the decline in erosion. Our results indicate a general decline in erosion since 1980 that is contemporaneous with shrub expansion and peak runoff decline, punctuated by episodic erosion events in one of four catchments.

Miscellaneous

Temme, AJAM. 2015. Using climber's guidebooks to assess rock fall patterns over large spatial and decadal temporal scales: an example from the Swiss Alps. *Geografiska Annaler: Series A, Phys Geog* 97:793-807

> Global warming is increasing landslides and rock falls. Documentation in guidebooks from 1864 to 2014 were analyzed to determine the frequency of rock falls in climbing areas. Although steady for nearly 100 years, there has been a remarkable increase in rock fall danger in the last 30 years. This is correlated with a slope aspect, and rock fall increased most on slopes with an eastern or western aspect where the freeze-thaw effect is strongest.

Gray lit & news (36)
Several of these, as from Audubon, UW, NPS have the quality of peer-reviewed material but are not in journals, so would be considered "gray literature".

Birds
Liebezet, J, E Rowland, M Cross, S Zack. 2012. Assessing climate change vulnerability of breeding birds in Arctic Alaska. A report prepared for the Arctic Landscape Conservation Cooperative. Wildlife Conservation Society, North America Program, Bozeman, MT. 167pp. (http://arcticlcc.org/assets/products/ARCT2011-11/reports/Vulnerability_Assessment_report_WCS_2012.pdf)

> Using temperature, moisture, sea-level rise, and other factors, in the context of two global emissions scenarios, 54 bird species were ranked by vulnerability. The results ranked two species as highly vulnerable (Gyrfalcon, Common Eider), seven as moderately vulnerable (Brant, Steller's Eider, Pomarine Jaeger, Yellow-billed Loon, Buff-breasted Sandpiper, Red Phalarope, Ruddy Turnstone), and five as likely to increase (Savannah Sparrow, Lapland Longspur, White-crowned Sparrow, American Tree Sparrow, Common Redpoll). The most important contributions to vulnerability include: specialization, having a strong coastal orientation, dependence on other species to meet habitat needs, dependence on wetlands.

National Audubon Society. 2013. Developing a management model of the effects of future climate change on species: a tool for the Landscape Conservation Cooperatives. Unpublished report prepared for the US Fish and Wildlife Service. 258p.

> Hunan-induced climate change is a fundamental driver of biological processes. A 7-year long study analyzing decades of bird observation data with climate (now and projected scenarios through 2080) was conducted to determine how bird species were likely to shift in summer and winter seasons. The model was verified by testing it against historical data, and determined to be a better predictor of winter species richness than summer. Species richness in winter is driven by cold temperatures; in summer richness increases with precipitation and declines in areas with the warmest temperature and greatest daily temperature fluctuations. The overall species richness of winter birds will increase, particularly in Western Alaska, but remain the same in the Arctic and eastern Alaska. Summer birds will increase across Interior Alaska but remain the same or decline in Northwest Alaska, Western Alaska, and the Aleutians/Bering Sea regions.

*Wildlife Conservation Society. 2013. Breeding birds vulnerable to climate change in Arctic Alaska: a story of winners and losers. *Science Daily* (www.sciencedaily.com/releases/2013/04/130403092537.htm)

> An assessment of 54 breeding bird species determined that two species, the gyrfalcon and common eider, are likely to be "highly vulnerable" by 2050. Seven other species would be "moderately vulnerable" while five species would likely benefit from a warming climate.

Commented [K13]: This is the short version of the paper listed as Liebezet et al 2012 above in peer review

Fire
Joly, K, TS Rupp, RR Jandt, ES Chapin III. 2009. Fire in the range of the Western Arctic caribou herd. Alaska Park Science 8 (20): 68-73.

> Fire consumes lichen, the winter forage of caribou. The study reviewed information on tundra fire (1950-2007) for managing caribou winter range and meteorological factors that explain

variability in fires. Climate warming may increase fire size and frequency, with impacts to wildlife and people.

Fish

Alaska Salmon Program. 2011. Alaska salmon research 2010. University of Washington, School of Aquatic and Fisheries Sciences, SAFS-UW-1001. Seattle. (https://digital.lib.washington.edu/researchworks/bitstream/handle/1773/17092/1101_lr.pdf?sequence=1)

Air temperatures have warmed over the last 50 years, leading to ice breaking up on average 10 days earlier. With earlier light penetration into the lake and warmer temperatures, there is higher density of zooplankton in summer. This is most pronounced in August-September when sockeye fry are feeding almost entirely on zooplankton. Specific zooplankton species are affected differently by warming trends. Interspersed with the general warming trend were cool spikes including July 2010 as the wettest on record with the 16th coldest spring air temperatures (1962-2010).

Church, WA and RL Burgner. 1960 (revised 2009). Studies on the effect of winter climate on survival of sockeye salmon embryos in the Wood River lakes, Alaska 1952-1959. University of Washington, School of Aquatic and Fisheries Sciences, SAFS-UW-0901. Seattle. (https://digital.lib.washington.edu/researchworks/bitstream/handle/1773/15541/0901.pdf?sequence=1&isAllowed=y)

Commented [K14]: This was done before scientists were aware of global warming. The significance of the study in the context of climate is that we are seeing low and no snow years in this area, which could kill salmon embryos by freezing them in lake beaches.

Winter climate conditions affect sockeye survival. An important source of egg mortality is freezing in spawning gravel, which is most severe in lake-beach spawning areas when the protection of lake water or snow cover is gone. As winter progresses, lake levels may drop and expose beaches, and protection needs to be through snow cover unless there is groundwater upwelling to moderate temperatures.

Cohn, BR. 2009. Recent paleoenvironmental changes recorded in three non-anadromous lakes in Southwest Alaska: effects of climatic and vegetation dynamics on lake productivity. Thesis. University of Alaska, Fairbanks.

Where no long term observational records of temperature exist, paleolimological samples can determine how changes in temperature and precipitation impacts lake chemistry and landscape vegetation. Warmer air temperatures (Pacific Decadal Oscillation overlaid on general climate warming) have led to increased biological productivity in some oligotrophic lakes in the Lake Clark watershed. Productivity may be additionally influenced by the expansion of alder, a nitrogen source, as glaciers recede. However, negative impacts occur when drought causes stress on vegetation.

E&E News. 2013. Climate change threatens Southeast Alaska's salmon habitat. Dec 9, 2013. http://www.eenews.net/climatewire/stories/1059991457/

Salmon productivity could shift in Southeast Alaska as temperatures rise and rainfall increases due to climate change. Annual temperatures are expected to rise to 44 ˚F in February by 2080, and rain could increase 20 inches while snowfall could drop 30%. Higher streamflow could scour salmon habitat, while glacial meltwater timing and stream temperatures could change.

Johnson, T. 2016. Climate change and Alaska fisheries. Alaska Sea Grant. University of Alaska Fairbanks. 36p. (http://doi.org/10.4027/ccaf.2016)

This report summarizes many studies, observations, and personal communications about impacts already being felt by Alaska fisheries and those reasonably predicted based on events along the West Coast and BC: "look down the coast and there is our future" (Bruce Wright, APIA). Progressive long-term warming of the North Pacific Ocean is occurring. Ice is thinning; ice-associated algae and phytoplankton sink to the seafloor out of reach of fish if ice melts too early. Predation, competition, and disease, which are just beginning, will increase. Pollock face multiple threats when waters warm, from an increase in jellyfish and other predators to fewer lipid-rich copepods that they feed on, decreasing pollock winter survival and causing a crash in stocks. Pollock in the Bering Sea are worth more than $1 billion in wholesale value, but are predicted to decline by up to 58% by 2050. Arrowtooth flounder, which prey on and compete with halibut, are increasing. Some species in the Bering Sea are shifting north (e.g. eulachon, halibut, snow crab) while others are staying deeper (e.g Pacific cod), and some may move off the continental shelf into Russian waters. Snow crab abundance is tied to winter sea ice extent, and are likely to decrease substantially with warm water, as they have done during warm phases of the PDO, and commercial fishing for them may come to an end by 2100. Harmful algae and diatoms that thrive in warm water and produce neurotoxins have been detected in 13 species of Alaska mammals along the entire Alaskan coast, and could be behind dramatic seabird die-offs. Warm ocean water also causes outbreaks of bacteria that cause severe GI infection in people that eat raw oysters, and have occurred recently in Alaska shellfish farms.

Commented [K15]: This had a lot of information and referenced a lot of peer reviewed material but I didn't have time to pull the peer review material up and reference it separately.

Mauger, S. 2013. Stream temperature monitoring network for Cook Inlet salmon streams 2008-2012, synthesis report. Cook Inletkeeper for Alaska Dept Env Conservation (ACWA 13-01) and US Fish and Wildlife Service (F12AC01078) . (https://dec.alaska.gov/water/wqsar/pdfs/Reports/Stream-Temperature-Monitoring-Network-Synthesis-2013-ADEC.pdf)

Over a five year period, temperatures were collected in 48 non-glacial streams around Cook Inlet. The vast majority of streams exceeded Alaska's water temperature criteria for the protection of fish, especially in 2009 when temperatures exceeded 13˚C at 47 sites, 15˚C at 39 sites, and 20˚C at 17 sites. Large watersheds with low slope and low elevation are inclined to have the warmest temperatures and be most sensitive to increasing air temperature. The analysis indicates average July water temperatures in 27% of the streams will increase by at least 2˚C and may result in greater incidences of disease, less egg and fry survival, lower juvenile growth rates, and more pre-spawning mortality for salmon by 2099.

Glaciers

Moore, C, D Young, J Shearer. 2012. Evaluating effects of atmospheric and terrestrial disturbance in a Southwest Alaska lake. National Park Service, Southwest Alaska Network. (https://acwi.gov/monitoring/conference/2012/M4/M4Moore20120504.pdf)

Glaciers cover 13% of the Lake Clark National Park and Preserve; between 1987-2007 about 20% of glacial mass was lost in general, with up to 40% loss in Merrill Pass.

Moore, C and J Shearer. 2011. Water quality and surface hydrology of freshwater flow systems in Southwest Alaska. 2010 annual summary report. Natural Resources Technical Report, NPS/SWAN/NRTR-2011/428. National Park Service, Southwest Alaska Network.

Late freeze-ups, warm winter water, and cool summer water temperatures at Lake Clark indicate weather is trending towards warmer and wetter. Warm and wet conditions on glaciers that surround the lake drive cold water into it. The summer of 2010 was cool and wet, providing both glacial melt and rain that caused cooler lake surface temperatures. However, increased glacial melt also increases the sediment that enters the upper end of the lake ("glacial flour").

Human Health/Alaska Native Communities

Alaska Native Tribal Health Consortium. 2016. Community observation on climate change: Arctic Village, Fort Yukon, and Venetie, Alaska. ANTHC Center for Climate and Health. (http://anthc.org/wp-content/uploads/2016/01/Upper-Yukon-River-Climate-Assessment-Final.pdf)

Along the Upper Yukon and Chandalor River, residents observe changes in seasons, greater frequency of unusual weather, less snow and ice, higher temperatures, more wildfire, lakes and creeks drying, river change and erosion. For example, low snow and dry conditions have killed trees, so there is more firewood, but make it hard to travel and access the wood. Low snow may also cause hibernating animals to freeze. Lakes and rivers freeze to the bottom so that water umps fail. Climate change is reducing the cost of heating, but now people are putting in air conditioners, and getting allergies they didn't have before. Climate change is also causing plants, fish, insects, and animals to emerge at times and in places where and when they have not been seen before, raising questions about how the food chain and subsistence will change. In Arctic Village, most of the houses had to be re-leveled as ground thaw caused them to tilt; utility poles also are tilting. At Fort Yukon, some fish camps have fallen into the river. Rivers are open later, and overflow, normally not seen until March, is seen in January, and there is much more bank erosion. In Venetie, river erosion has caused the loss of wells..

Alaska Native Tribal Health Consortium. 2015. Climate change in Bering Strait communities, Alaska. ANTHC Center for Climate and Health. (https://anthc.org/wp-content/uploads/2016/01/CCH_AR_032015_Climate-Change-Bering-Strait-Region.pdf)

The National Weather Service records show an increase in temperatures since 1940. Residents report warmer weather, winter rains, extreme rains, less snow. Warmer and wetter weather has spoiled food but created a longer season for collecting and treating community water and longer growing season for gardens. Permafrost, floods, erosion are impacting critical infrastructure; the Army Corps of Engineers expects 3+ feet of additional sea rise by 2100. Sewage lagoons, landfills, powerplants, air strips, water storage tanks, and clinics are in vulnerable areas.

Alaska Native Tribal Health Consortium. 2014. Climate change and health effects in the Bristol Bay region of Alaska. Project synthesis report. ANTHC Center for Climate and Health. (https://anthc.org/wp-content/uploads/2016/01/CCH_AR_042014_Climate-Change-Bristol-Bay-Region.pdf)

There are 28 communities in the region. Temperatures in Dillingham have increased 3.7 ˚F (1949-2009) and the region is becoming warmer and wetter. Positive benefits of changing climate include more berries, more swimming time, waterfowl staying longer, and flights make it through Lake Clark Pass more easily. Lake Aleknagik was open all winter in 2014, which had never

Commented [K16]: Many individual reports are very similar. Most of the effects have already been covered in the memo but these provide more references with first hand observations.

Commented [K17]: Most of the ANTHC reports reference UAF SNAP records as part of the report

occurred before, and people caught smelt in January. However, all but two communities indicated they were impacted by climate change, and most felt the impacts were negative. In a Climate Vulnerability Index, based on economic, sanitation, flood, and erosion information, the most vulnerable communities were Chignik Lagoon, Clarks Point, Dillingham, and Pilot Point; only three communities scored low on the index (King Salmon, Koliganek, Newhalen). Decreased berries; tundra fires; erosion risk at fish camps, roads and other infrastructure; warmer temperatures make it harder to dry fish are some of the negative impacts. Clinics have seen heat stroke in adults and febrile seizures in infants, along with more than double the people coming in for insect stings – in part due to wasps surviving warmer winters.

Alaska Native Tribal Health Consortium. 2014. Climate change in Atqasuk: strategies for community health. ANTHC Center for Climate and Health. (https://anthc.org/wp-content/uploads/2016/01/CCH_AR_072014_Climate-Change-in-Atqasuk.pdf)

Atqasuk is a river community on the North Slope that is getting warmer. Temperatures increased an average 5 ˚F (1949-2012), with 7.3 ˚F increase in winter. Between 1958-1997, only one day in August would exceed 39 ˚F, 1998-2013 there were 6 days, in 2003 there were 25 days.Many of the reported changes are unprecedented, such as funnel clouds and hail, raising concerns about food and water security, safety, and mental health related to the stress of adapting. Thousands of small lakes surround the community, providing the community water source and habitat for waterfowl, shorebirds, songbirds, and owls. Some lakes are going dry; others enlarging as permafrost thaws. Thawing soil is allowing shrubs with deep roots to outcompete shallow tundra plants. Early snowmelt, low river water levels, higher water temperatures, increased sediment from erosion pose challenges for fish and increasingly limit travel by boat. However rising seas have caused surges that allowed people to travel further upriver at some times. Pike, Chinook and silver salmon are new resources showing up. Other new species are red fox, which compete with Arctic fox and spread rabies, as well as lynx, coyote, ravens, and magpies. Lightning is occurring more often, damaging utility lines and bringing the risk of wildfire. Wildfire and freezing rain are reducing caribou habitat; coastal storm surges trap and drown entire herds. While low snow years are hard on ground mammals, new small trees bring in moose, porcupine, and beaver. Late river ice-up makes it harder to fish for burbot and other whitefish.

Alaska Native Tribal Health Consortium. 2014. Climate change in Nondalton: strategies for community health. ANTHC Center for Climate and Health.

The climate is warmer and wetter than in the past. Glaciers are melting, improving flight conditions through Lake Clark Pass but changing lake conditions; the water level of Lake Clark and Six Mile Lake is generally lower and the ice season is shorter. Warmer temperatures make it hard to dry fish, and some harvests have been lost. It has also caused heat stress in people and dogs; in 2013, temperatures were in the 70s and 80s for weeks and people had no air conditioning. There is increasingly less snowpack and more rain; excessive rain in 2012 led to the overflow of the sewage lagoon and flooded homes. There is more precipitation now for 9 months of the year.

Alaska Native Tribal Health Consortium. 2014. Climate change in Nuiqsut, Alaska: strategies for community health. ANTHC Center for Climate and Health. (https://anthc.org/wp-content/uploads/2016/01/CCH_AR_072014_Climate-Change-in-Nuiqsut.pdf)

The same temperature changes and any of the same observations (lakes drying up, early snowmelt, low water, high sediment, new species arriving, lightning, funnel clouds) as observed in Atquasuk, another North Slope community. In addition, musk ox herds have been trapped and drowned by coastal surges. The direction of the winds is changing. Willows have grown so tall caribou can't migrate through them. In 2007 the largest tundra fire on record occurred on the North Slope, burning over 240,000 acres. The boating season is longer on the Colville River, through October, but it is shallower, and also traveling in winter is harder due to unpredictable ice. Ice breakup (1949-2014) occurs earlier. Climate change is resulting in subsistence impacts including time of season, harvest success, ways to prepare and store food. Soft tundra in spring led to poor goose harvest. In fall, arctic cisco is running late, and freeze and thaw on the river make it hard to set nets. In one November, 10 people broke through river ice, including two elders – traditional knowledge is challenged. The mold *Saprolegnia* triggered by warm water has shown up in fall broad whitefish. Wet and warm conditions are preventing proper drying of fish, caribou and seal, while permafrost thaw and erosion is impacting ice cellars. Infrastructure is being damaged – water and sewer connection boxes need to be jacked up, houses are tilting, the school may erode into the river soon.

Alaska Native Tribal Health Consortium. 2014. Community observations on climate change: Nushagak River. ANTHC Center for Climate and Health.

Communities share observations of extreme weather, drought, changes in the river channel, bank erosion, lakes drying up, changes in vegetation. In Koliganek, there are fewer red salmon but many more chum. River ice was so thin, freezing and thawing, that no winter fishing was done. Bushes are as tall as trees. But heating costs are down. At New Stuyahok, the river has dropped by 4' since the 1960s. Dry weather followed by heavy rains damaged houses. Chinook and swallows arrive 2 weeks earlier. The heat makes it hard to dry whitefish and there are fewer salmon spawning areas. Allergies are worse and there are more wasps and insect stings. On the plus side, the season for fiddleheads is longer. At Ekwok, the ice only gets 3 feet thick; it was 8-12 feet in the 1970s. New birds and insects are arriving, like hummingbirds. Villages are part of the Local Environmental Observer network, and have put up cameras to document changes.

Alaska Native Tribal Health Consortium. 2012. Climate change in Selawik, Alaska: strategies for community health. ANTHC Center for Climate and Health (https://anthc.org/wp-content/uploads/2016/01/CCH_AR_052012_Climate-Change-in-Selawik.pdf)

Temperatures are increasing and causing permafrost to thaw, which has caused erosion, subsidence, and increased flood risk. Permafrost thaw has damaged water distribution lines, sewer lines, ATV trails, roads and bridges, houses and other infrastructure, increasing the cost of living.

Alaska Native Tribal Health Consortium. 2011. Climate change in Kiana, Alaska: strategies for community health. ANTHC Center for Climate and Health. (https://anthc.org/wp-content/uploads/2016/01/CCH_AR_102011_Climate-Change-in-Kiana.pdf)

Temperatures have been increasing. Infrastructure like utility poles and sewage lines are damaged by permafrost thaw and ice travel on the Kobuk River is becoming dangerous. Erosion is occurring on the river bank; houses and infrastructure on bluffs are vulnerable. Hot summers and lightning increase wildfire, dust, and allergies. Water sources are running dry.

Alaska Native Tribal Health Consortium. 2011. Climate change in Kivalina, Alaska: strategies for community health. ANTHC Center for Climate and Health. (https://anthc.org/wp-content/uploads/2016/01/CCH_AR_012011_Climate-Change-in-Kivalina.pdf).

Temperatures are increasing, especially in winter. Summers are drier. The Wulik River watershed is undergoing dramatic change with permafrost thaw and an increase in trees and shrubs. Beavers are increasing, and with them the risk of *Giardia*, however there are more moose and porcupine. Erosion has damaged infrastructure and increases in storm surges have caused contamination of the village with sewage, fuel, and solid waste.

Alaska Native Tribal Health Consortium. 2010. Climate change in Point Hope, Alaska: strategies for community health. ANTHC Center for Climate and Health. (https://anthc.org/wp-content/uploads/2016/01/CCH_AR_082010_Climate-Change-in-Point-Hope.pdf)

Temperatures are increasing; in 50 years it is projected that no winter months will average below 0 ˚F, but will range from 5 ˚F to 30 ˚F. There is less sea ice, and for a shorter time. Precipitation overall is increasing, but summers are drier, affecting community water supplies. Water supplies are also threatened by storm surge, saltwater intrusion, and melting permafrost. Food cellars, the air strip, and evacuation routes are vulnerable to erosion and flooding. Thawing permafrost is causing meat in food cellars to spoil. Malnutrition and anemia are increasing, possibly related to decreases in subsistence harvest of walrus and whales.

Enoch, C. 2016. Middle-Kuskokwim villages experience earliest breakup on record. KYUK. April 18, 2016. http://kyuk.org/middle-kuskokwim-villages-experience-earliest-breakup-on-record/

According to the National Weather Service breakup database, the earliest breakup for Kalskag was April 22, 1940; the records go back to 1938. Ice was moving around 4 pm Sunday around Aniak, Napaimute, Chuathbaluk and Kalskag, and is expected to be out within a few days.

Norton-Smith, K, K Lynn, K Chief, K Cozzetto, J Donatuto, M Hiza-Redsteer, LE Kruger, J Maldonado, C Viles, KP Whyte. 2016. Climate change and indigenous peoples: a synthesis of current impacts and experiences. Gen Tech Rep PNW-GTR-944 Portland, OR. US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Impacts are being felt on availability of traditional food, water resources, tribal economies and infrastructure, and more. However, they don't have access to funding through the Land and Water Conservation Fund and have to compete for resources in the Tribal Wildlife Grants Program. There is no government mechanism to assist in relocation, intensifying negative economic and health impacts.

Stern, G. 2015. The great Arctic experiment: climate change is affecting the region's estuaries, politics, and what it means to go home. *Science* 350 (6260): 520-521. AAAS News & Notes.

In Alaska's estuaries, climate change affects water temperature, water chemistry, and influences what species can survive in the ocean and further inland. Fish are particularly sensitive to chemical changes, which affects how they navigate. Humans are affected as well – people have fallen through the ice using traditional ice routes, whalers have lost their lives as the ocean becomes unpredictable, food traditionally stored in ice cellars has gone bad. Animals aren't migrating in the same patterns. Arctic communities are losing what it means to be home.

Insects

Barclay, E. 2008. Stinging wasps moving north due to global warming? National Geographic News. (http://news.nationalgeographic.com/news/2008/07/080716-wasps-stings.html)

Statewide more people are seeking care for insect stings. In 2006, two people in Fairbanks died from anaphylactic shock after yellow jacket stings, the first time such deaths had occurred. Milder winters and earlier springs are allowing insects like yellow jackets to survive; in 2006 Anchorage had ten times more than average according to Dr. Jeffrey Demain, director of the Allergy, Asthma, and Immunology Center of Alaska in Anchorage. In 2004, yellow jackets were found in Arctic Bay, Nunavut, where they had never been before.

State of Alaska, Epidemiology Bulletin. 2008. Increasing incidence of medical visits due to insect stings in Alaska. Alaska Department of Health and Social Services. (http://epibulletins.dhss.alaska.gov/Document/Display?DocumentId=242)

All regions except the Gulf Coast experienced a statistically significant increase in insect stings, with the greatest seen in Interior and Northern Alaska. Alaska has had a mean annual temperature increase of 3.4 ˚F over the past 50 years, with the greatest increases in the winter. Further work is warranted to determine if climate factors are changing patterns of insects.

Ocean

Rosen, Yereth. 2014. Gulf of Alaska warmest in 17 years of measurements. *Alaska Dispatch.* Nov 3, 2014. http://www.adn.com/article/20141103/gulf-alaska-waters-warmest-17-years-measurements

The top 300' of water in the Gulf of Alaska was up to 5 degrees above normal in the fall of 2014, according to the Alaska Ocean Observing System and other organization. It's the warmest in 17 years, and the warmth was outside the usual pattern of variation. More jellyfish than usual were observed, and fishermen caught a skipjack tuna and ocean sunfish, species not found in the Gulf of Alaska.

Permafrost

Rosen, Yereth. 2016. Scientists calculate methane loads bubbling up from Arctic lakebeds. *Alaska Dispatch.*August 28, 2016 (http://www.adn.com/arctic/2016/08/28/scientists-calculate-methane-loads-bubbling-up-from-arctic-lakebeds/)

Water bodies on permafrost are known as thermokarst lakes; they expand or contract as thaw causes the ground to cave in, then fill with water or drain. The lakes at the margins of these areas, where water has expanded and thawed previously dry land, are the areas with the most lake methane seeps. Over the past 60 years, 100 million to 300 million metric tons of methane have streamed up from the lakes in the Arctic. Currently Alaska's ecosystems absorb 3.7 million metric tons of atmospheric carbon as plants expand on thawing permafrost.

Weather

Edge, M. Southeast Alaska rainfall breaks records, prompts landslide, flood advisories. *Alaska Dispatch* Jan 21, 2015. https://www.adn.com/weather/article/rainfall-southeast-causes-landslide-flood-advisories-and-breaks-records/2015/01/21/

Record daily rainfall for January 20 show 10 broken records. The Juneau Airport broke the oldest record of 0.95 inches of rain (1948) with Tuesday's 1.23 inches. The most significant was at the Ketchikan Airport – the 2004 record of 3.14 inches was broken with 5.56 inches. Records in Snettisham, Petersburg, Haines, and Klawock were all broken by about an inch, as well as three Juneau locations. Several communities also set temperature records.

NOAA. 2015. Alaska sets new record for earliest day with temperatures in the 90s. http://www.climate.gov/news-features/event-tracker/alaska-sets-new-rec

On May 23, 2015 a new record was set for the earliest day in the year with a temperature over 90 degrees. A temperature of 91 ˚F was measured in Eagle, where measurements have been conducted since the 1890's.

Samenow, J. 2016. Temperature near North Pole jumped to 32 degrees this week. *Alaska Dispatch* Original article in the *Washington Post.* Dec 22, 2016. (https://www.adn.com/arctic/2016/12/22/weather-buoy-near-north-pole-hi)

The entire Arctic north of 80 degrees has witnessed a temperature spike of nearly 30 degrees, with weather near North Pole at 32 ˚F. A warm event of comparable intensity to what occurred in November would have been "extremely unlikely in a climate of a century ago". The loss of sea ice is making it easier for weather systems to transport heat to the poles.

Miscellaneous

Gould, AI, NEM Kinsman, MD Hendricks. 2015. Guide to projected shoreline positions in the Alaska Shoreline Change Tool. *Alaska Division of Geological and Geophysical Surveys* Misc Pub 158 (http://pubs.dggsalaskagov.us/webpubs/dggs/mp/text/mp158.pdf)

Coastlines that are experiencing a decline in landfast sea ice are increasingly exposed to high energy storm events in the fall. DGGS has developed a tool to measure shoreline loss.

Hanlon, T. 2016. Massive landslide crashes onto glacier in Southeast Alaska. *Alaska Dispatch.* July 2, 2016. www.adn.com/alaska-news/2016/07/02/massive-landslide-crashes-onto-glacier-in-southeast-alaska/

A 4,000 foot high mountainside collapsed southwest of Haines, sending over 100 million tons of rock and debris onto the Lamplugh Glacier below. The mountains are growing and shifting as ice melts away, causing them to rebound up as weight is unloaded. The extent to which this is exacerbated by climate change is not known.

Zamzow, K. 2014. Nondalton Integrated Resource Management Plan: water quality. Nondalton Tribal Council.

The climate is getting warmer and wetter. Residents have observed extreme changes, such as 50 degree weather in January 2014. Lake Clark is expected to rise in warm years (high glacial melt) and drop in cool years. High river levels and flooding occur with rapid thaw of deep snowpack, as was observed with the flooding of the Iliamna River in 2009; deep snow and rain in 2012 led to the highest lake levels and coldest lake temperatures on record. However record high temperatures and low rainfall in 2004 caused record low stream flows; low flows frequently mean warmer water. The Kijik and Little Kijik reached 17-19C, temperatures that negatively impact fish. Some glaciers will disappear; the Tazimina was formerly a glacial-fed river but the glacier has receded and does not provide water anymore. In the Tlikakila drainage, most of the glaciers present in 1957 have receded and thinned. The largest glacier in the basin, the Tanaina, lost 180 million cubic yards of ice per year between 1957-2006.

Some additional references (10)

This is material that was sent to me that does not pertain specifically to Section E of your memo, but I am including it in case it is useful. All are peer-reviewed.

Bintanja, R and F Krikken. 2016. Magnitude and pattern of Arctic warming governed by the seasonality of radiative forcing. *Scientific Reports*

Observed and projected climate warming is strongest in the Arctic regions, peaking in autumn/winter. Arctic warming (especially in winter) and sea ice decline are particularly sensitive to radiative forcing in spring, during which the energy is effectively 'absorbed' by the ocean (through sea ice melt and ocean warming, amplified by the ice-albedo feedback) and consequently released to the lower atmosphere in autumn and winter, mainly along the sea ice periphery.

*Fountain, AG, JL Campbell, EAG Schuur, SE Stammerjohn, MW Williams, HW Ducklow. 2012. The Disappearing Cryosphere: Impacts and Ecosystem Responses to Rapid Cryosphere Loss. *Bioscience*

The cryosphere-the portion of the Earth's surface where water is in solid form for at least one month of the year-has been shrinking in response to climate warming. In response, the ecosystems within the cryosphere and those that depend on the cryosphere have been changing. These changes affect biota in positive or negative ways, depending on how they interact with the cryosphere.

Ganguly, AE, K Steinhaeuser, DJ Erickson III, M Branstetter, ES Parish., N Singh, JB Drake, L Buja. 2009. Higher trends but larger uncertainty and geographic variability in 21st century temperature and heat waves. *PNAS*

Observed heat wave intensities in the current decade are larger than worst-case projections. Increased trends in temperature and heat waves, concurrent with larger uncertainty and variability, suggest greater urgency and complexity of adaptation or mitigation decisions.

*Kim, B-M, J-Y Hong, SY Jun, X Zhang, H Kwon, S-J Kim, JH Kim, SW Kim, and H-K Kim. 2017. Major cause of unprecedented Arctic warming in January 2016: Critical role of an Atlantic windstorm. *Scientific Reports*

In January 2016, the Arctic experienced an extremely anomalous warming event after an extraordinary increase in air temperature at the end of 2015. Observational analyses revealed that the abrupt warming was triggered by the entry of a strong Atlantic windstorm into the Arctic in late December 2015, which brought enormous moist and warm air masses to the Arctic. Although

the storm terminated at the eastern coast of Greenland in late December, it was followed by a prolonged blocking period in early 2016 that sustained the extreme Arctic warming.

*Koomey, J. 2013. Moving beyond benefit-cost analysis of climate change. *Environ Res Lett*

The conventional benefit-cost approach to understanding the climate problem has serious limitations. Fortunately, an alternative way of thinking about the problem has arisen in recent decades, based on analyzing the cost effectiveness of achieving a normatively defined warming target. This approach yields important insights, showing that delaying action is costly, required emissions reductions are rapid, and most proved reserves of fossil fuels will need to stay in the ground if we're to stabilize the climate. I call this method 'working forward toward a goal', and it is one that will see wide application in the years ahead.

Lewis, SC, AD King, SE Perkins-Kirkpatrick. 2016. Defining a new normal for extremes in a warming world. *Bulletin of the American Meteorological Society.*

The term 'new normal' has been used in scientific literature and public commentary to contextualise contemporary climate events as an indicator of a changing climate due to enhanced greenhouse warming. We provide a formal definition of a new climate normal relative to present based around record-breaking contemporary events and explore the timing of when such extremes become statistically normal in the future model simulations. Applying this method to the record-breaking global average 2015 temperatures as a reference event and a suite of model climate models, we determine that 2015 global annual average temperatures will be the new normal by 2040 in all emissions scenarios.

Meehl, GA and C Tebaldi. 2004. More Intense, More Frequent, and Longer Lasting Heat Waves in the 21st Century. *Science*

A global coupled climate model shows that there is a distinct geographic pattern to future changes in heat waves. Model results for areas of Europe and North America, show that future heat waves in these areas will become more intense, more frequent, and longer lasting in the second half of the 21st century. Observations and the model show that present-day heat waves over Europe and North America coincide with a specific atmospheric circulation pattern that is intensified by ongoing increases in greenhouse gases, indicating that it will produce more severe heat waves in those regions in the future.

*Notz, D and J Stroeve. 2016. Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission. *Science*

Arctic sea ice is retreating rapidly, raising prospects of a future ice-free Arctic Ocean during summer. Since climate-model simulations of the sea-ice loss differ substantially, we here use a robust linear relationship between monthly-mean September sea-ice area and cumulative CO_2 emissions to infer the future evolution of Arctic summer sea ice directly from the observational record. The observed linear relationship implies a sustained loss of 3 ± 0.3 m^2 of September sea-ice area per metric ton of CO_2 emission. Based on this sensitivity, Arctic sea-ice will be lost throughout September for an additional 1000 Gt of CO_2 emissions.

Overland, JE, K Dethloff, JA Francis, RJ Hall, E Hanna, S-J Kim, JA Screen, TG Shepherd, T Vihma. 2016. Nonlinear response of mid-latitude weather to the changing Arctic. *Nature Climate Change*

Are continuing changes in the Arctic influencing wind patterns and the occurrence of extreme weather events in northern mid-latitudes? The chaotic nature of atmospheric circulation precludes easy answers. The topic is a major science challenge, as continued Arctic temperature increases are an inevitable aspect of anthropogenic climate change. We propose a perspective that rejects simple cause-and-effect pathways and notes diagnostic challenges in interpreting atmospheric dynamics. We present a way forward based on understanding multiple processes that lead to uncertainties in Arctic and mid-latitude weather and climate linkages. We emphasize community coordination for both scientific progress and communication to a broader public.

Sewall, JO and LC Sloan. 2004. Disappearing Arctic sea ice reduces available water in the American west. *Geophys Res Lett* Vol 31

Recent decreases in Arctic sea ice cover and the probability of continued decreases have raised the question of how reduced Arctic sea ice cover will influence extrapolar climate. Using a fully coupled earth system model, we generate one possible future Arctic sea ice distribution. Our results indicate that future reductions in Arctic sea ice cover could significantly reduce available water in the American west.