ESSAS Annual Science Meeting

Bridging the past and present to manage the future of northern fisheries and ecosystems

June 20-23, 2022

Fisheries Sciences Building

University of Washington, Seattle

Ecosystem Studies of Subarctic and Arctic Seas

ESSAS

Welcome!

On behalf of the symposium conveners, organizers, and the ESSAS Scientific Steering Committee, we welcome you to the 2022 Ecosystem Studies of Subarctic and Arctic Seas (ESSAS) Annual Science Meeting, whether you are traveling to Seattle to participate in person or joining us virtually on the Zoom platform with enhanced conference camera and microphone. In-person participants will meet at the Fisheries Sciences Building on the beautiful University of Washington Campus.

We are excited to meet in conjunction with the Oceans Past Initiative (OPI) and have developed a joint session that is meant to foster interactions and possible future collaborations between ESSAS and OPI. Under the ESSAS umbrella, we are excited to welcome scientists representing at least 7 countries with a range of expertise about sub-arctic and arctic marine ecosystems. We look forward to an excellent mix of both oral and poster presentations and encourage all participants to take advantage of this unique opportunity to exchange information, experiences and ideas with fellow marine scientists from around the Arctic. We hope that you will also use the occasion of this ASM as an opportunity to explore the University of Washington campus and the broader Seattle region.

We thank the Oceans Past Initiative for their enthusiastic support of a joint session and our sponsors for their generous support. In particular, we thank the Integrated Marine Biosphere Research (IMBeR) project, the Quaternary Research Center (University of Washington) and the School of Aquatic and Fisheries Sciences (University of Washington).

Here is to a productive, stimulating and enjoyable meeting!

Franz Mueter, Naomi Harada, Benjamin Planque
ESSAS Co-Chairs and Convenors

Ben Fitzhugh, Alan Haynie, Ben Laurel, Franz Mueter
Local Organizing Committee & program committee

DRAFT

IMBeR
Integrated Marine Biosphere Research

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SCHOOL OF AQUATIC and FISHERY SCIENCES

ESSAS Annual Science Meeting, June 19-23, 2022

For registration, information on housing and other details, please visit the ESSAS website

Tentative schedule

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Sunday, June 19, 2022

13:00 – 16:00	**ESSAS SSC meeting**
16:30 – 18:30	**Ice-Breaker Reception**

Monday, June 20, 2022.

Session 1: Learning from the Past to inform the Future
(Keynotes: 30 min, all others: 15 min, *(r)* denotes remote presentation, click on titles to see full abstract)

9:00 – 10:30	**Welcome and Conference Opening**	
	Jason Addison (Keynote)	**Paleoproductivity records in the Subarctic North Pacific Ocean: Baseline marine ecological data for the Holocene**
	Alan Haynie	Socioeconomic Scenarios in the Alaska Climate Integrated Modeling (ACLIM) Project
	Sturla Kvamsdal *(r)*	An exploratory analysis of warming effects on wealth in the Barents Sea fisheries
	Tannaz Alizadeh Ashrafi *(r)*	System dynamics modelling of CO_2 emissions in a trawl fishery
	Discussion	
10:30 – 11:00	**Coffee/Tea Break**	
11:00 – 12:30	Alberto Rovellllini	Development and calibration of an Atlantis ecosystem model for the Gulf of Alaska
	Ina Nilsen	How will climate changes affect the future Northeast Atlantic cod stock in the Nordic and Barents Seas?
	Lucie Buttay	Combining social and ecological time series to describe long-term dynamics of the Norwegian Sea ecoregion.

	Al Hermann	Coupled modes of projected regional change in the Bering Sea from a dynamically downscaling model under CMIP6 forcing
	Björn Birnir	The timing of Global Change
	Discussion	
12:30 – 14:00	**LUNCH**	
14:00 – 15:30	Cheryl Barnes	Model complexity has contrasting benefits for hindcasting and forecasting species responses to climate change
	Beatriz Dias	Prince William Sound marine ecosystem under different heatwave scenarios.
	Szymon Surma	Investigating food web structure and dynamics in the eastern Gulf of Alaska
	Carey R. McGilliard	Exploring future fishery-related climate impacts to Bering Sea-Aleutian Islands groundfish fishery using a mixed-species management strategy evaluation framework
	Cecilie Hansen	Effects of snow crab in the Barents Sea – Perhaps not only negative?
	Discussion	
15:30 – 16:00	**Coffee/Tea Break**	
16:00 – 17:15	Louise Copeman	Temperature-dependent survival and growth of early juvenile Bering Sea snow crab (*Chionoecetes opilio*) and Tanner crab (*Chionoecetes bairdi*): implications for optimal crab thermal habitat in a rapidly warming Alaska Arctic
	Mary Beth Decker	Cyclic variability of eastern Bering Sea jellyfish relates to regional physical conditions
	Sei-Ichi Saitoh *(r)*	Sustainable use of salmon resource under changing climate using multiple satellite datasets
	Joji Oida *(r)*	Detection of biologically productive water mass from ocean color satellite using chromophoric dissolved organic matter (CDOM)
	Discussion	

Tuesday, June 21, 2022

7:30 – 9:00	***Working Group Meetings / Business meetings (hybrid, as needed)***	
9:30 – 10:30	**Session 1 (continued): Learning from the Past to inform the Future**	
	Mats Huserbråten *(r)*	Arctic ecosystem impact assessment of oil in ice under climate change
	Irene Alabia	Pan-Arctic marine biodiversity patterns under recent climate
	Elizabeth Logerwell	Winners and Losers in a Warming Arctic: Potential Habitat Gain and Loss for Epibenthic Invertebrates of the Chukchi and Bering Seas
	Discussion	
10:30 – 11:00	**Coffee/Tea Break**	
11:00 – 12:30	**Session 2: Arctic Gadids - Past, present, and future**	
	Maxime Geoffroy (Keynote, r)	**Arctic cod (*Boreogadus saida*) in Arctic ecosystems: recent state, ecological role, and impact of climate change**
	Olga Maznikova *(r)*	Polar cod (*Boreogadus saida*) of the Siberian Arctic: distribution, stocks and biology
	Pavel Emelin *(r)*	Walleye pollock (*Gadus chalcogrammus*) in the western Chukchi Sea: distribution, biology, stocks and fishing
	Evgeniya Chikurova *(r)*	Phylogeographic and phylogenetic histories of two Eleginus species (Gadidae) based on Cyt b mtDNA gene
	Discussion	
12:30 – 14:00	**LUNCH**	
14:00 – 15:30	Nicolas Dupont	Change in the Barents Sea Arctic food-web dynamic based on biotic and abiotic environmental factors
	Robert Levine	Climate-driven shifts in abundance, distribution, and composition of the age-0 gadid community in the eastern Chukchi Sea
	Carmen David	The interactive effects of early life traits and changing environmental conditions on Arctic cod (*Boreogadus saida*) growth and recruitment in present and future scenarios
	Franz Mueter	Arctic Cod (*Boreogadus saida*) under newly formed sea ice
	Lightning talks (poster):	Genoa Sullaway, Carlissa Salant (Poster session Wednesday night)

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15:30 – 16:00	**Coffee/Tea Break**
16:00 – 18:00	***Working Group Meetings / Business meetings (hybrid, as needed)***

Wednesday, June 22, 2022

Joint ESSAS/OPI sessions

(Keynotes: 30 min, all others: 15 min, *(r)* denotes remote presentation, click on titles to see full abstract)

9:00 -10.30	**Ben Fitzhugh**	**Joint Welcome and Conference opening**
	Konstantina Agiadi (Keynote)	***Mesopelagic fish size response to Pleistocene climatic variability***
	Session I – World whaling 1	
	Youri van den Hurk *(r)*	The demise of the Atlantic grey whale
	Jason Colby	Devilfish coast: mapping the history of grey whales and people in the North Pacific
	Ruairidh Macleod *(r)*	Trapped in ambergris: can preservation of digestive tract metagenomes shed light on sperm whale health and symbionts?
10:30 – 11:00	**Coffee/Tea Break**	
11:00 – 13:00	**Session II – Integrating marine historical ecology and natural resource management**	
	Catherine West (Keynote, r)	Taking the Long View: Integrating Marine Historical Ecology and Natural Resource Management in the Gulf of Alaska
	Torstein Pedersen *(r)*	Fish otoliths from medieval archaeological excavations provide exploitation effect baselines
	Megan Victor *(r)*	Time Trawlers: An Archaeological Examination of the Fishing Station at Smuttynose Island and its Implications for the Ecosystem of the Isles of Shoals and the Gulf of Maine
	Ben Fitzhugh	Was there a Pleistocene North Pacific fishery? The evidence for boat use, maritime subsistence, and subarctic settlement around the North Pacific Rim.
	Guðbjörg Ásta Ólafsdóttir	Historical and contemporary concerns about the consistency of Atlantic cod ecotypes around Iceland.
	Iain McKechnie	Estimating ocean temperature trajectories from ancient Indigenous fishery catch records: an archaeological case study from the northeast Pacific
	Lane Atmore	Using ancient DNA to uncover the history of Atlantic herring exploitation and its impact on herring evolution and demography

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13:00-14:30	**LUNCH - EARLY CAREER RESEARCHER BREAKOUT**	
14:30 – 16:00	**Session III – World whaling 2**	
	John Nicholls	Global Leviathan Database - extractions through the modern and early modern periods
	Nina Veira	Portuguese whaling history: a digital data management journey
	Matthew Ayre	A high-resolution historical faunal archive from British Arctic whaling logbooks
	Sophia Nicolov	Whales at the ends of the worlds
	Laura Courto	Scrimshaw: unlocking the cultural and biological archive of sea mammal art
16:00 – 16:30	**Coffee/Tea Break**	
16:30 – 17:30	**Session IV – Multiple Stressors**	
	Benjamin Planque	Stakeholder perspectives on the response of the Barents Sea to multiple pressures
	Jessica Cross	The next decade of ocean acidification research in the Bering Sea: what we've learned and what's coming next
	Trond Kristiansen	Climate change impacts on marine light in Arctic ecosystems
	Discussion	
EVENING 18:00 – 19:30	**JOINT ESSAS AND OPI POSTER SESSION/RECEPTION (see OPI programme for additional posters)**	
	Hisatomo Waga (poster)	Satellite-based monitoring of phytoplankton phenology using a parametric modeling approach in the Northern Gulf of Alaska
	Junghyun Park (poster)	Increasing Arctic River Discharge and Its Role for the Phytoplankton Responses in the Present and Future Climate Simulations
	Hikaru Hikichi (poster)	Responses of mesozooplankton biomass to climate change in the southeastern Bering Sea shelf during the summers of 1955–2013 (summary of T/S Oshoro-Maru cruises) with special references to the taxonomic composition and normalised biomass size spectrum for several consecutive years at each climate regime
	Austin Flanigan (poster)	Understanding Pacific Halibut spatial dynamics in the northern Bering Sea
	Genoa Sullaway (poster)	Data integration to model lower trophic levels in the Eastern Bering Sea
	Michele Ottmar (poster)	Effects of ocean acidification and warming on fertilization, egg survival and size at hatch of early life stages Polar cod (*Boreogadus saida*)
	Andrew Majewski (poster)	Interannual abundance and habitat associations of demersal Arctic Cod (*Boreogadus saida*) in Amundsen Gulf
	Kali Stone (poster)	Growth, condition, and movement of juvenile Arctic cod (*Boreogadus saida*) in a warming Alaska Arctic

	Amalis Riera (poster)	Sounds of walleye pollock: a quantitative description
	Hillary Thalmann (poster)	Juvenile Pacific Cod foraging and growth in response to anomalous warming in Gulf of Alaska nursery habitats
	Carlissa Salant (poster)	Covarying lipid and fatty acid profiles among phytoplankton and Arctic cod (Boreogadus saida) in the Eastern Canadian Arctic

Thursday, June 22, 2022

Session 3 / Workshop: Subarctic Gadids - Past, present, and future

9:00 – 10:30	***Jessica Miller (Keynote)***	Thermal effects on early life stages of Gulf of Alaska Pacific Cod: shifts in phenology
	David Cote	Forecasted Shifts in Thermal Habitat for Cod Species in the Northwest Atlantic and Eastern Canadian Arctic
	Sofia Ferreira *(r)*	Spatio-termporal overlap of cod, haddock and capelin in the Norwegian-Barents Sea system
	Emily Geissinger	Condition, size, and winter duration affect winter survival probability in juvenile Atlantic cod (*Gadus morhua*) in a coastal ecosystem
	Ben Laurel	Pacific cod in the Anthropocene: an early life history perspective under changing thermal habitats
10:30 – 11:00	**Coffee/Tea Break**	
11:00 – 12:30	Giancarlo Correa	Modeling the multiple action pathways of projected climate change on the Pacific cod (*Gadus macrocephalus*) early life stages
	Jennifer Bigman	Predicting Pacific cod spawning habitat in a changing climate
	Lauren Rogers	Changes in spawn timing of walleye pollock and impacts on assessment surveys in the Gulf of Alaska
	Benjamin Planque	Forecasting Northeast Arctic cod stock biomass from climate signal – an appraisal of model skills
	Steven Barbeaux	Using an Environmentally Linked Assessment for Strategic Fisheries Management Planning
	Zoe Almeida	Warmer, earlier, faster: Cumulative effects of Gulf of Alaska heatwaves on the early life history of Pacific Cod

ABSTRACTS

Model complexity has contrasting benefits for hindcasting and forecasting species responses to climate change

Cheryl L. Barnes [1], Timothy E. Essington [1], Jodi L. Pirtle [2], Christopher N. Rooper [3], Edward A. Laman [4], Kirstin K. Holsman [4], Kerim Y. Aydin [4], James T. Thorson [4]

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Identifying and predicting species responses to climate change is a high priority in ecology. Species distribution models (SDMs) are commonly used to quantify environmental drivers of distributions and densities; however, we lack information about how well these models predict fine-scale population metrics under novel conditions. We compared the performance of a suite of SDMs when hindcasting species-habitat associations and forecasting responses to changing climates. We present two case studies from the Bering Sea, a system that has recently undergone considerable warming. Conventional statistics (R^2, % Deviance Explained, UBRE or GCV) were used to assess the performance of in-sample predictions (*i.e.,* hindcasts) for Arrowtooth Flounder (*Atheresthes stomias*) and Walleye Pollock (*Gadus chalcogrammus*).

Retrospective skill testing was used to compare out-of-sample predictions (*i.e.,* forecasts) with observed distributions or densities. The most complex models, which accounted for spatial, temporal, and spatiotemporal variation in addition to static and dynamic habitat covariates, outperformed all other models when hindcasting population metrics. Static models that relied on long-term mean environmental conditions, however, exhibited greater forecast skill. Decreased forecast skill for dynamic models likely resulted from predicting species responses to temperatures outside the range of those used in model fitting. Thus, dynamic SDMs better reflect the amount of spatiotemporal variation in natural systems, but static SDMs may prove more skillful when forecasting responses to novel environmental conditions. We also found that model performance and forecast skill were dependent upon the species and population metric of interest, suggesting a negative relationship with niche breadth. Expanding environment-only SDMs to include spatiotemporal variation in fishing pressure, trophic interactions, and other important context-specific drivers would likely improve forecast skill. Nonetheless, our results demonstrate support for the use of retrospective skill testing in model selection rather than identifying forecast models *a priori* based on their ability to quantify species-habitat associations from the past.

Predicting Pacific cod spawning habitat in a changing climate

Jennifer Bigman[1], Lauren Rogers[1], Ben Laurel[1], Kelly Kearney[1,2], Kirstin Holsman[1], Al Hermann[2,4]

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Warming temperatures elicit shifts in habitat use and distributions of fishes, with uneven effects across life stages. Spawners and eggs are more sensitive to environmental conditions compared to other life stages and, thus, spawning location and egg development are often constrained spatially and temporally. Additionally, spawning dynamics are closely tied to population dynamics and fisheries management. To understand how temperature affects the spatiotemporal variability of spawning habitat, we predict the availability of thermally-suitable spawning habitat for Pacific cod in the eastern Bering Sea to the end of this century.

Specifically, we use bottom temperature hindcasts and projections from regionally downscaled global climate models, coupled with an experimentally-derived relationship between hatch success and temperature to examine how the extent, mean latitude, and consistency of spawning habitat changes over time. We also test whether year-class strength relates to the availability of suitable spawning habitat to understand how changes in habitat use may be linked to changes in fisheries productivity. We find that the extent and mean latitude of spawning habitat increase over time, particularly if no climate mitigation occurs in the future. Hotspots of spawning habitat are consistent within decades but do expand from the outer towards the middle and inner shelf by the end of the century. We find no correlation between the availability of suitable spawning habitat and year class abundance. Collectively, our results suggest that spawning habitat availability for Pacific cod increases and expands spatially across the southeastern Bering Sea shelf over time, and as such, is unlikely to affect fisheries productivity, at least in the near-term. This work highlights the use of coupling experimental data with climate models to identify complex dynamics among temperature, life histories, and ecology, and offers a pathway for examining life stage-specific changes in habitat use and distribution with climate change.

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Arctic cod (*Boreogadus saida*) in Arctic ecosystems: recent state, ecological role, and impact of climate change

Maxime Geoffroy[1], Caroline Bouchard, Hauke Flores, Dominique Robert, Harald Gjøsæter, Carie Hoover, Haakon Hop, Nigel Hussey, Jasmine Nahrgang, Nadja Steiner, Morgan Bender, Jørgen Berge, Giulia Castellani, Natalia Chernova, Louise Copeman, Carmen L. David, Alison Deary, George Divoky, Andrey Dolgov, Janet Duffy-Anderson, Nicolas Dupont, Joël M. Durant, Kyle Elliott, Stéphane Gauthier, Esther Goldstein, Rolf Gradinger, Kevin Hedges, Jennifer Herbig, Ben Laurel, Lisa Loseto, Sarah Maes, Felix Mark, Anders Mosbech, Sara Pedro, Harri Pettitt-Wade, Irina Prokopchuk, Paul E. Renaud, Fokje Schaafsma, Sarah Schembri, Cathleen Vestfals, Wojciech Walkusz

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We present a comprehensive overview of Arctic cod (*Boreogadus saida*) physiology, ecology, distribution, and habitats to assess how climate change affects the most abundant pelagic fish in the Arctic Ocean. This presentation identifies vulnerabilities to climate change for different life stages across the whole distribution range of Arctic cod. We explore the impact of environmental (abiotic and biotic) and anthropogenic stressors on Arctic cod with a regional perspective in a scenario up to the year 2050, and identify knowledge gaps constraining predictions. We conclude that the epipelagic eggs and larvae are more vulnerable to climate change than adults. Sea ice decline, ocean warming, change in freshwater input, changing prey field, increased competition, new predators, as well as pollution are the main stressors that present a high or very high risk of impacting Arctic cod population dynamics. The risk from fisheries is moderate and mainly limited to bycatch. Detrimental effects are stronger in regions with advection of Atlantic and Pacific waters. In contrast, Arctic cod may benefit from ocean warming in colder areas of the high Arctic. Overall, a decrease in total Arctic cod biomass and in the abundance of ice-associated individuals is predicted. In most Arctic seas, the relative abundance of Arctic cod within the fish community will likely fluctuate between cold and warm periods. A reduced abundance of Arctic cod, to the advantage of boreal fish species, can negatively impact the abundance, distribution, and condition of certain predators, whereas other species can successfully adapt to a more boreal diet. Management and stewardship measures adapted to specific regions of the Arctic that recognize the critical role of Arctic cod are required to ensure that increased anthropogenic activities do not exacerbate the impacts of climate change on northern marine ecosystems.

Phylogeographic and phylogenetic histories of two Eleginus species (Gadidae) based on Cyt b mtDNA gene

Evgeniya A. Chikurova[1,2], Alexei M. Orlov[1,2,3,4,5,6], Dmitry M. Shcepetov[7,8,9], Svetlana Yu. Orlova[1,3]

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The fishes of the genus *Eleginus* (Gadidae) are typical representatives of the cold water ichthyofauna of the northern hemisphere adapted to habitat under low temperatures. They play an important trophic role in the ecosystems of the Arctic and adjacent Pacific Ocean and serve as targets of commercial and artisanal coastal fisheries in many regions of the Russian North and Far East as well as in some coastal areas of Alaska and Japan. Their intra-species organization that is necessary for the rational exploitation of the stocks remains poorly understood, while their inter-species relationships were previously analyzed based on very limited samples. In the present report, the results of the study of inter-species relationships and population structure of the Navaga *Eleginus nawaga* and saffron cod *E. gracilis* are presented for the first time based on large-scale samples (986 individuals in 29 samples from the majority of the species' ranges) using the analysis of mtDNA *Cyt b* gene polymorphism. These results showed that both representatives of the *Eleginus* genus were independent species well differentiated from each other. Genetic analysis of *Eleginus* and *Microgadus* species showed that both representatives of the former genus may originate from the common ancestor closely related to *M. proximus*, while the divergence in the latter genus occurred considerably earlier. The data on haplotype diversity of the saffron cod samples within the area from Peter the Great Bay (Sea of Japan) to Alaskan waters and of the Navaga from the White Sea to Obskaya Guba in the Kara Sea are presented that allow for judging of phylogeographic histories of both *Eleginus* species and their intra-species structures within the studied areas.

DRAFT

Polar cod (*Boreogadus saida*) of the Siberian Arctic: distribution, stocks and biology

Olga A. Maznikova[1*], Pavel O. Emelin[1], Alexei M. Orlov[1,2,3,4,5,6]

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Polar cod (*Boreogadus saida*) is a widespread Arctic fish species. Due to its relatively high abundance, polar cod is occupying a central position in the Arctic food web, which makes it a reliable indicator of changes in high latitudes marine ecosystems. Polar cod biology and spatial distribution are described on the results of trawl surveys conducted in the Siberian Arctic (Laptev Sea, Chukchi Sea and East Siberian Sea) in August-September of 2003-2018. Spatial distribution and size composition of its individuals within the study area were characterized by similar patterns. Retreat of the polar front and a reduction in the area of ice cover leads to a northward shift in the boundaries of polar cod distribution and, as a consequence, to decreasing of its abundance within the study area and to restructuring of Siberian Arctic marine ecosystems. In all surveyed seas, polar cod aggregations consisted of individuals 3 to 29 cm long aged 0+ to 6+ years. The schoolings were represented by larger individuals near the bottom and by smaller fish in the water column. Due to the harsh climate conditions and low productivity, the smallest polar cod individuals were found in the East Siberian Sea. In the Chukchi and East Siberian seas, its main concentrations were observed within the near-bottom layer, while in the Laptev Sea they were recorded in the water column. The abundance and biomass of polar cod in the Chukchi Sea in different years ranged from 514 million inds. and 0.830 thousand tons (2008) to 8256 million inds. and 117.5 thousand tones (2003). Respective indices for the Laptev Sea amounted to 12753 million individuals and 233 thousand tones. The abundance and biomass of the East Siberian Sea polar cod were at a relatively low level compared to other seas (about 20 million inds. and 0.150 thousand tons).

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Walleye pollock (*Gadus chalcogrammus*) in the western Chukchi Sea: distribution, biology, stocks and fishing

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Walleye pollock is the most abundant and widely distributed species of the North Pacific.
In the Chukchi Sea, walleye pollock juveniles were first found in small quantities in its southern part in the late 1970s. However, until recently, there was no information on the occurrence of adult fish in the Chukchi Sea. Based on research of 7 trawl surveys conducted onboard Russian research vessels in 2003-2020 the data on the biology, spatial and vertical distributions of walleye pollock in the western Chukchi Sea are provided. Spatial distribution of walleye pollock does not fundamentally differ from that in other parts of its range. Schoolings in the water column during all the years of research were mainly represented by juveniles (FL 5-12 cm), which proportion varied from 93 to 100%, while medium-sized and large individuals in catches were rare. In bottom trawl catches, walleye pollock was represented mainly by both juveniles (FL 7-14 cm) and large-sized fish (FL 50-62 cm), and the proportion of medium-sized individuals was insignificant. Vertical distribution was characterized by an increase in the number of large and older fish with a decrease in depth as well as the predominance of adult fish and juveniles at shallow depths. The age structure of walleye pollock was significantly different from that of both the western and eastern Bering Sea. Age groups representing recruitment of commercial stock (aged 3-5 years) were not observed in the catches. This may testify that the walleye pollock population of the western Chukchi Sea depends on the migration activity of individuals from the Bering Sea. Bottom trawl surveys in 2019-2020 period allowed to set for the former area a total allowable catch as 37,200 t for 2021 and 2022 fishing seasons and to start walleye pollock fishery there in 2021 when over 4,000 t were caught.

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System dynamics modelling of CO_2 emissions in a trawl fishery

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Bottom trawling is heavily dependent upon the combustion of fossil fuel due to towing heavy nets across the ocean floor and long distanced steaming, and as such contributes to increased atmospheric concentrations of greenhouse gases and global warming. The amount of released CO_2 emissions is a function of fishers' harvest behavior, driven by bioeconomic conditions of the fishery such as the fish availability at different fishing locations, the distance to the home port, market condition, fishing quota, and regulatory scheme. In the light of increasing concerns over climate change, regulators have put forward the idea of fuel taxation. In response to the rise in tax and fishing cost, trawlers are likely to adopt a new fishing strategy to sustain maximum expected profit from holding fishing quota. Considering the interacting feedbacks between the regulatory system and fishing behavior, a system dynamics approach is developed to examine whether the introduction of fuel taxation influences the profit-maximizing harvest pattern of the Norwegian cod trawl fleet in terms of decisions underlying when and where to fish cod and how much to fish per trip within quota management constraints. To this aim recordings of fishing data on a haul-to-haul basis of 32 Norwegian cod trawlers over the period from 2011 to 2019 are used. I also assess the efficiency of the fuel taxation policy in reducing CO_2 emissions from the trawl fleet. Relevant policy implications are discussed in detail.

DRAFT

Stakeholder perspectives on the response of the Barents Sea to multiple pressures

Benjamin Planque[1], Nina Mikkelsen[1,2]

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Human activities, climate variability and change, and other drivers affect the structure and dynamics of the Barents Sea, as well as the ecosystem services it provides. Anticipating the combined effects of these multiple drivers is required to support management decisions, but stakeholder groups, managers and scientists may hold different points-of-view on the functioning of the Barents Sea and may therefore have distinct anticipations.

This contribution explores how stakeholders can anticipate the consequences of changes in multiple drivers on the Barents Sea ecosystem and its associated services. The approach is based on a scoping exercise followed by qualitative modelling. The scoping exercise was conducted with six stakeholder groups representing different sectors (fishing, shipping, tourism, oil and gas) and interest (environmental protection), during a 2-day workshop and subsequent dialogues. From this, several hierarchical conceptual models of the Barents Sea were constructed. The conceptual models were then used to develop qualitative models that predict how different components of the Barents Sea may respond to changes in one or several driving forces. We applied selected scenarios of changes in human activities and changes in the biomass of animal groups to assess the effects of cumulative impacts. These modelling experiments were conducted on a *synthesis model* common to the stakeholder groups and on *stakeholder-specific models*. The model results indicate that cumulative impacts are mostly additive. The comparison of results across models reveals that the conclusions derived from the *synthesis model* are robust and reflect well the perspectives of the various stakeholders. This suggests that there exists a common understanding of the Barents Sea functioning across stakeholder groups and that, at least in some instances, a common representation of the system may be used to support ecosystem-based management.

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Forecasting Northeast Arctic cod stock biomass from climate signal: an appraisal of model skills.

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Recent publications have argued for the possibility of making robust forecasts of cod stocks biomass in the Barents Sea several years in advance. The core idea in these contributions is that the dynamic of cod biomass is partly controlled by the sea temperature regime and that sea temperature can be predicted several years in advance. A central point to these studies is the measure of the "skill" of the model predictions. High skill is interpreted as the opportunity to make robust predictions about the future biomass of cod stocks, several years in advance, and then use these predictions to support management. In this presentation, I distinguish prediction skills from forecast skills and discuss the differences between the two when these are used to assess the performance of a model. I explore the possibility that the reported prediction skills could have emerged by chance. I also discuss which type of skills may be appropriate if predictions are to be used to support management. A re-analysis of the data indicates a high risk that the originally reported prediction skills could have arisen by chance. The newly estimated forecasting skills are generally lower than the prediction skills originally reported. Finally, forecasts from a control model based on persistence-only are often as good or better than the forecasts from temperature-base models. These results highlight the challenges in producing climate-based cod stock forecasts that are sufficiently robust to support ecosystem-based management.

DRAFT

Satellite-based monitoring of phytoplankton phenology using a parametric modeling approach in the Northern Gulf of Alaska

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The fundamental food source for higher trophic level animals in marine systems is the carbon produced by the phytoplankton community. Observations and modelling studies suggest that the ocean is becoming increasingly stratified in response to a warming climate, limiting nutrient exchange to the upper sunlit ocean and favoring small cells able to grow in warmer, nutrient poor conditions. Phytoplankton assemblages dominated by smaller cells are associated with longer food chains and decreased energy transfer to higher trophic levels such as zooplankton, and ultimately, fish. In the Northern Gulf of Alaska (NGA) threats of increased water column stratification are amplified by accelerated glacial melt, a sea surface warming trend roughly twice the global average, and more recently, recurring 'heatwave' events. These changes also threaten to alter the NGA's phytoplankton blooms, upon which numerous species rely on for survival. Given that the NGA contains one of the largest and most valuable fisheries in the nation, investigating these climate-driven threats and linking them to fisheries is of immense social and economic importance. To further accurate monitoring of seasonal phytoplankton dynamics in the NGA, this study examines the performance of a parametric modeling approach to capture phytoplankton phenology in the NGA over the time period 2003–2021. To this end, time-series of satellite-retrieved phytoplankton biomass were modeled using a parametric Gaussian function, as an effective approach to capture the development and decay of seasonal phytoplankton blooms. In general, the timing, duration, and amplitude of phytoplankton blooms are known to be essential features that define phytoplankton phenology. The present study will demonstrate the robustness/uncertainties of the parametric modeling approach for satellite-based monitoring of phytoplankton phenology in the NGA.

DRAFT

Effects of ocean acidification and warming on fertilization, egg survival and size at hatch of early life stages Polar cod (*Boreogadus saida*)

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Warming temperatures and rising pCO_2 levels are co-occurring and present the need for a greater understanding of multistressor effects on marine species. Recent studies on growth and survival under elevated pCO_2 suggests a species-specific response with physiological complexity not necessarily linked to species habitat. Polar cod (*Boreogadus saida*), a pelagic, keystone species, serves as a high energy food source for marine mammals and seabirds. Early life stages of Polar cod are sensitive to temperatures above 3.5°C but vulnerability to synergistic effects of elevated pCO2 levels and temperature are unknown. We examined fertilization, hatching success and size at hatch of Polar cod in two experiments. In one experiment, Polar cod eggs obtained from a captive broodstock were fertilized at pH 7.6 and 8.0 with fertilization success in 3 replicates scored after 24 hours of incubation at 1°C. Fertilization success varied across egg batches (obtained from different females), but was higher at pH 8.1 than 7.6 in 12 of the 15 batches. In a separate experiment, replication with 2 independent, mixed parentage groups of Polar cod eggs were incubated from 5 and 8 days post fertilization (dpf) to hatch under a factorial design of 3 pH (7.5, 7.7, 8.0) and 2 temperature (1°C, 3.5°C) treatments. The higher temperature reduced the time to hatch and survival to hatch and resulted in higher rates of malformations. Higher temperatures also resulted in larvae hatching at a smaller size (length) but with increased yolk area. Elevated pCO_2 appeared to have no effect on hatching success, size at hatch or yolk area. These observations of elevated pCO_2 levels affecting fertilization success, but not egg development, demonstrate stage-specific effects and the need to consider climate variation at all life stages of marine fishes.

DRAFT

Juvenile Pacific Cod foraging and growth in response to anomalous warming in Gulf of Alaska nursery habitats

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Pacific Cod *(Gadus macrocephalus)*, an ecologically and commercially important fish species in the Gulf of Alaska, is highly susceptible to warming ocean temperatures. Following two marine heatwaves in 2014-2016 and 2019, the population declined by ~75%, leading to the closure of the federal fishery in 2020. Early life stages of Pacific Cod may be particularly susceptible to arming, including age-0 juveniles during periods of rapid summer growth in coastal nursery habitats. To evaluate potential consequences of extreme thermal variability on juvenile Pacific Cod, we assessed the size, diet composition, and recent growth of post-settled age-0 juveniles collected from Kodiak Island in July and August, 2006 - 2019. Juvenile Pacific Cod were ~40% larger during warmer years, with more extreme size discrepancies by August. Non-metric Multidimensional Scaling (NMS) ordinations of diet composition explained 86% of overall variability in July and 76% of variability in August. Body size was correlated with axis 1 of the NMS ordination in both July and August ($r > 0.50$), and temperature was correlated with axis 1 by August ($r = -0.71$). In both July and August, smaller prey items (e.g. copepods and cladocerans) were more common in years prior to the heatwaves, and larger prey items (e.g. mysids, polychaetes, and shrimps) were more common during the heatwaves. The final three weeks of nursery growth in both July and August were strongly influenced by fish size, ocean temperature, and year (Mixed Effects Model; $p < 0.001$), but NMS axis scores did not significantly contribute to daily otolith increment width in either month. Together, patterns in size, diet composition, and recent nursery growth suggest that larger, faster-growing age-0 Pacific Cod may have a survival advantage during heatwave conditions, which likely drives their foraging patterns in the nursery, leading to consumption of larger and more diverse prey during heatwave conditions.

Modeling the multiple action pathways of projected climate change on the Pacific cod (*Gadus macrocephalus*) early life stages

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Understanding how future ocean conditions will impact fish early life stages and the effects on population recruitment is critical for the adaptation of fisheries communities to climate change. In this study, we used an oceanographic (Bering10K) and a mechanistic individual-based model (IBM) for larval and juvenile fish to analyze how climate change (warming and ocean acidification) may impact the hatch success, growth, survival, and spatial distribution of Pacific cod (*Gadus macrocephalus*) in the eastern Bering Sea during 2010-2100. We evaluated two emission scenarios: RCP8.5 (high emissions, low mitigation efforts) and RCP4.5 (medium emissions and mitigation efforts). Under the high emission scenario, the Bering10K projected an increase in temperature, pCO_2 concentration, and large-bodied copepod in the cod larval habitat, while a decrease in euphausiids and small-bodied copepods are expected. We observed that warmer years produced faster growth rates but decrease survival probability by increasing starvation, which agreed with the current knowledge of the ecology of this species. Projected environmental changes produced an increase in hatch success and growth by the end of the century; however, they also triggered a reduction in the probability of survival and dying from starvation. Ocean warming was the main driver of these changes, whereas ocean acidification had negligible impacts. We also identified a larval retention area in the southeastern Bering Sea, which also had a higher survival probability and smaller larval sizes. Based on these results, recruitment is expected to decrease in the future, which may have ecological and socio-economic impacts in the Alaska region. Our results support the hypothesis that starvation might be a crucial driver of recruitment in the eastern Bering Sea as observed for other gadids.
Keywords: climate change, Pacific cod, fish, recruitment, individual-based modeling, mechanistic modeling

DRAFT

Increasing Arctic river discharge and its impacts on the phytoplankton response under present and future climate simulations

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Arctic amplification is known to accelerate the hydrological cycle in high-latitude landmasses, which eventually leads to increased river discharge into the Arctic Ocean. However, the majority of climate models in the Coupled Model Intercomparison Project 5 (CMIP5) tend to underestimate Arctic river discharge. This study elucidates the role of additional Arctic river discharge for the phytoplankton responses under present and future climate simulations. In the present climate simulation, the additional freshwater input showed a decrease in the phytoplankton in spring due to the increasing sea ice, and in summer, it showed an increase in phytoplankton due to the surplus nitrate left over from spring and induced vertical mixing. Similar processes occurred in future climate simulations. However, in those simulations, the major response region of phytoplankton to additional freshwater input was altered from the Eurasian Basin to the Canadian Basin and the East-Siberian Sea. This is because the current marginal ice zone in the Barents-Kara Sea, where phytoplankton mainly responds, moves toward the East-Siberian-Chukchi Sea. We suggest that Arctic river discharge is potentially an important contributing factor for Arctic ecosystems in both present and future climate that controls sea ice and nutrient distribution.

DRAFT

Spatio-termporal overlap of cod, haddock and capelin in the Norwegian-Barents Sea system

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The Norwegian-Barents Sea (NBS) system is very productive. However, the extent to which this productivity is challenged remains uncertain for many species. Cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), and capelin (*Mallotus villosus*) are three key species in the NBS ecosystem. In this study, we investigate the interaction of these three species and assess the impact their spatio-temporal overlap at their pelagic larval stages has on their survival. In this study, we ask: what is the effect of the spatio-temporal overlap between the three species (cod, haddock, and capelin) on their survival at later stages? Thus, our objectives are to quantify the overlap in both space and time, and to assess whether the overlap affects the survival of the three species. Data on larval abundances were collected during the ichthyoplankton surveys run by the Knipovich Polar Research Institute of Marine Fisheries and Oceanography in both spring (April−May) and summer (June−July) by using an egg net and ring trawl. Data on survival indices were collected from the Arctic Fisheries Working Group from the International Council for the Exploration of the Sea. We then calculated the spatio-temporal overlap of the three species and test it against the survival indices of each. We observed a negative effect of the overlap between cod and the species it competes with (haddock and capelin) explaining 12 % of cod recruitment at age 0, whereas the negative effect of overlap between haddock and the species it competes with (cod and capelin) explain 11 % of haddock recruitment at age 0. The overlap between capelin and the other species does not show a significant result. These results improve the understanding of how these species use their critical habitats to face emerging environmental stressors such as habitat loss, oil spills, and climate change.

DRAFT

Historical and contemporary concerns about the consistency of Atlantic cod ecotypes around Iceland.

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Atlantic cod is a keystone species that remains among the most economically important demersal fish in the North Atlantic despite severe stock depletion resulting from overexploitation. Throughout its distributional range Atlantic cod is composed of populations or ecotypes that vary across environmental gradients, such as temperature or salinity, across geographical regions and in phenotypic traits, importantly, in migratory propensity. This variation has repeatedly been linked to genetic divergence on several genomic inversions or “supergenes”. The origin of these supergenes is ancient and variation in cod migratory behavior has been noted throughout historical times. This life-history variation is likely to have contributed to the relative resilience of Atlantic cod to environmental change and exploitation. In the sub-arctic North Atlantic cod ecotypes exhibiting longer foraging migration and preferentially seeking cooler temperatures, or migratory cod, are present both around Iceland and Norway. Icelandic migratory cod seek cooler arctic waters for feeding but they are currently dependent on warmer nearshore waters for spawning, transport of eggs and larvae and, critically, growth at nursery grounds. Here, data on the consistency, growth, foraging ecology and movement of Atlantic cod ecotypes in Icelandic waters in historical times will be presented and discussed in the context of how current anthropogenic stressors may differently affect the ecotypes, specifically at early life-stages.

DRAFT

Change in the Barents Sea Arctic food-web dynamic based on biotic and abiotic environmental factors

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The Arctic part of the Barents Sea is currently facing a range of environmental changes identified as "borealization". The phenomenon includes a decreasing sea-ice cover, increasing sea temperatures and the increasing presence of boreal piscivorous species such as the Atlantic cod (*Gadus morhua*). As Atlantic cod expands in the Northern Barents Sea, the predation level on forage fish species, otherwise preyed on by sea-ice adapted marine mammals such harp seal (*Pagophilus groenlandicus*), may increase. In this context, we focused on a key Arctic fish species and common prey for both Atlantic cod and harp seal: the polar cod (*Boreogadus saida*). Varying abundance and distribution of the capelin (*Mallotus villosus*) stock, which is also a common prey for both Atlantic cod and harp seal, has been previously suggested to affect the predation of both predators on polar cod. In the light of current environmental changes, we quantified the effects of both predators on the abundance-at-age of polar cod depending on both summer sea-ice cover and capelin stock using a threshold multilinear regression in a Bayesian framework. Using a 31-year times series (1986-2017) of polar cod abundance, we showed that predation effects on adult polar cod vary depending on summer sea-ice cover and capelin stock conditions. Significant predation effects of both predators were associated with years of low capelin stock values. However, significant effects of Atlantic cod and harp seal varied between years of low and high summer sea-ice cover. Our results suggest that the "borealization" of the Barents Sea Arctic may lead to a shift in food web dynamics. Effects of expanding subarctic predators may alter predation pressure on lower trophic levels of the Arctic food web with unclear ecosystem consequences.

DRAFT

The interactive effects of early life traits and changing environmental conditions on Arctic cod (Boreogadus saida) growth and recruitment in present and future scenarios

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Fish larval growth and consequently recruitment success are mediated by the interaction of early life history traits (e.g., hatching timing, size at hatch) and environmental conditions (e.g., temperature, sea-ice cover, food availability). Optimal growth enhances recruitment success, i.e., reaching a length threshold corresponding to complete metamorphosis to juvenile stage. Early hatching and larger size at hatch offer an advantage to those larvae, while optimal temperatures and sufficient food availablility enhance their growth. We used a bioenergetic model (BEM) as an integrative tool to simulate the growth of larval Arctic cod (*Boreogadus saida*) and to test the sensitivity of modeled growth to temperature and food conditions. To simulate realistic environmental conditions, BEM was coupled to an ocean sea-ice and transport model. We tested different monthly hatching cohorts (March – June; 2005 – 2014) and size at hatch (4 – 7 mm). Present conditions related to food quantity and quality were simulated based on stomach content observations of wild larvae. Scenarios of change in food conditions were simulated by decreasing the food consumption in the model and/or switching to other type of prey, for example from Arctic to boreal copepods which have a lower energetic content. Larval length at the end of summer was compared among scenarios in two different Arctic regions and among warm and cold years. As a future Arctic warming scenario, we tested how the lengthening of the growth season and an increase in water temperature by 1.5 ºC will affect larval growth. Finally, we evaluated optimum growth and recruitment success between present and future scenarios.

DRAFT

Development and calibration of an Atlantis ecosystem model for the Gulf of Alaska

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The Gulf of Alaska (GOA) is a large ecosystem with complex bathymetry and oceanography that supports high fishery revenues. In the past, the GOA has been exposed to climate events, such as marine heat waves, that have had complex effects on multiple ecosystem components, resulting in productivity fluctuations and trophodynamic shifts. While it is unclear how the GOA ecosystem and the fisheries it supports will respond to future climate change, ecological models can help anticipate future change scenarios and evaluate management measures that address changes in stock and ecosystem status. We present the development of an end-to-end, spatially explicit, deterministic, dynamic simulation ecosystem model for the GOA using the Atlantis framework, and describe the current state of model calibration and skill evaluation. The model area extends along the GOA continental shelf, from Vancouver Island (Canada) to 170º W along the Aleutian Islands (Alaska), and from the tideline to 1000 m depth. The model captures the GOA food web using 78 functional groups, including single-species groups for some ecologically and commercially important species, and encompasses all size classes from nutrient pools and plankton to megafauna. Atlantis GOA features a geophysical sub-model forced with outputs from oceanographic models (ROMS-NPZ) for the Northeast Pacific, and as such can be used as a simulation tool to explore ecological and fisheries responses to climate events. We present how Atlantis GOA will be used in hindcast mode to explore the ecosystem-level effects of the 2013- 2016 marine heat wave, and in forecast mode to simulate the effects of future climate change on ecosystem productivity, allowing us to evaluate the effectiveness of various management strategies under a changing climate. Atlantis GOA, together with other ecological models for the GOA, can help better predict and strategically manage outcomes for the GOA ecosystem under climate change.

DRAFT

Thermal effects on early life stages of Gulf of Alaska Pacific Cod: shifts in phenology

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Understanding the effects of environmental variability and climate change on recruitment in marine populations is critical for conservation and management. Variation in the abundance of Pacific Cod in the Gulf of Alaska has been related to water temperature with greater production during cooler periods; however, the mechanisms underlying this pattern remain unclear. Furthermore, a dramatic reduction in Pacific Cod abundance was observed after a prolonged marine heatwave from late 2014-2016. Thus, a better understanding of thermal effects on Pacific Cod is a research priority. We combined structural analysis of otoliths with field and laboratory data to estimate spawn timing, determine size and timing of hatch, and reconstruct growth for fish collected during the pelagic larval and juvenile stages. We used larvae collected in mid-late May (7 years) and settled juveniles collected in July (11 years). Hatch dates for both larvae and juveniles were notably earlier in the years during and after the prolonged marine heatwave (2015-2019): mean hatch dates were 14 d earlier for larvae and 23 d earlier for juveniles. Given that warmer temperatures increase development rates, we determined mean water temperature (at 100-250 m) during embryonic development for larval and juvenile collections. Mean water temperature averaged 0.89 °C warmer during development for larvae and 1.6 °C warmer for juveniles in the years after 2014 than before. Based on laboratory-derived development rates, these temperature differences could account for ~25% of the shift in hatch dates for the larvae and up to 50% of the shift for juveniles. Therefore, other factors, such as changes in the timing of spawning or selective mortality, also contributed to the observed shifts in hatch timing. Understanding how Pacific Cod respond to thermal variation will be integral for disentangling processes regulating survival to recruitment and predicting population-level responses to climate variation.

DRAFT

Combining social and ecological time series to describe long-term dynamics of the Norwegian Sea ecoregion.

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One challenge for Integrated Ecosystem Assessments (IEAs) is to synthesize historical changes that have occurred in multiple components of the social-ecological system, from climate to the ecosystem and to humans. One output of the current IEA for the Norwegian Sea is a summary of decadal changes that is easily accessible to non-scientists. This summary primarily focuses on the physical and ecological dimensions of the ecosystem. In the present work, we extend the current IEA with time-series that describe the most important sectors and activities in the ecoregion (fishing, oil and gas production, shipping and aquaculture) and some related pressures (species extractions, bycatch, contaminants, noise, etc). We use TRend Estimation and Classification (TREC) to reveal common trends among time-series and summarise the main changes that have occurred in the Norwegian Sea ecoregion during the last three decades. In addition, we use an extension of the TREC method to identify extreme observations in recent years that could warrant special attention. Most of the time series of human activities presented a positive trend over the period considered with the exception of Oil production that increased until 1996 and then decreased. Primary production increased, zooplankton biomass decreased and while no trend was observed for most of fish stock biomass, herring biomass decreased over the period considered. Herring catches decreased until 2016 and then increased in recent years but the total catch value increased steadily. Our results provide the first integrated description of changes in the Norwegian Sea from physics to humans and highlight the potential of the TREC method to be used in IEAs to properly synthetize the information in many different time series and provide warning for recent extremes events.

DRAFT

Interannual abundance and habitat associations of demersal Arctic Cod (*Boreogadus saida*) in Amundsen Gulf

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The demersal fish community structure of Amundsen Gulf was assessed through a multi-year trawl survey as part of the Canadian Beaufort Sea – Marine Ecosystem Assessment (CBS-MEA) between 2013 and 2019. Arctic Cod (*Boreogadus saida*) was an influential species in structuring the marine fish community, numerically dominating catches across habitats and years and showing a strong association with deeper and warmer waters of Atlantic origin. Despite its ubiquitous presence, Arctic Cod abundance was highly variable both interannually and spatially, potentially in response to shifting environmental and prey-based drivers. Arctic Cod are important prey for a variety of marine mammals, fish, and birds, making them integral to ecosystem health and stability. Variability in the distribution and abundance of Arctic Cod may therefore impact the distribution and health of its predators which, in turn, affects subsistence hunting and fishing in the coastal communities of the Inuvialuit Settlement Region. Understanding the variability in Arctic Cod distribution and abundance is key to predicting future recruitment and assessing change in the Amundsen Gulf ecosystem. We present the first comprehensive community structure analysis of demersal marine fishes in the Amundsen Gulf, with specific focus on Arctic Cod as a keystone species of regional importance.

DRAFT

Changes in spawn timing of walleye pollock and impacts on assessment surveys in the Gulf of Alaska

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Changes in phenology, or the seasonal timing of events, are a widely-documented response to changes in climate. Spawn timing, in particular, has been shown to be sensitive to temperature in many fishes. Beyond implications for recruitment and survival of offspring, climate-driven changes in the timing of spawning can affect the availability of fish to surveys designed to monitor their abundance, complicating efforts to assess stock status and sustainably manage fisheries through a changing climate. We analyzed changes in the spawn timing of walleye pollock (*Gadus chalcogrammus*) using ichthyoplankton time-series from the Western Gulf of Alaska (1979 – 2019). We found that warmer temperatures led to earlier spawning and larval first feeding, consistent with expectations of advanced spring phenology under warming. However, spawner age also played a role, with an older stock spawning earlier on average. We then investigated whether changes in spawn timing could be affecting the availability of pollock to one of the main assessment surveys for the species: the winter Shelikof Strait acoustic survey. In recent years, biomass estimates from the four surveys that monitor Gulf of Alaska pollock have diverged, giving conflicting estimates of stock biomass and temporal trends, which have in turn increased uncertainty in the stock assessment. We found that changes in spawn timing relative to survey timing explain a significant portion of recent and historical discrepancies in survey biomass estimates. Based on this, we developed a time series of covariates for survey catchability for the stock assessment model to account for changing availability of pollock to the winter Shelikof survey. As climate change accelerates, changes in phenology will bring new challenges for the monitoring and assessment of fish stocks. We show that knowledge of underlying ecological processes can guide approaches to account for these changes in assessment frameworks, expanding our toolkit for climate-ready fisheries management.

DRAFT

Winners and losers in a warming Arctic: Potential habitat gain and loss for epibenthic invertebrates of the Chukchi and Bering seas

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We examined how the epibenthic invertebrate community in the Pacific Arctic might be affected by increased ocean temperatures. We used catch and bottom temperature data from surveys from 2009-2018 in the Bering and Chukchi seas and grouped taxa into 5 clusters according to median temperature and temperature range. We then used an ensemble of 8 climate models to forecast bottom temperature to 2050 and 2100 and to show how the amount and distribution of temperature habitat, the area that falls within the observed temperature range of each of the 5 clusters, might change with ocean warming. We found that by 2050 there were 50% decreases in temperature habitat for all clusters except for the cluster with the broadest temperature range, and that temperature habitat contracted to the north. By 2100 there was very little temperature habitat for all clusters, except the broadest range cluster, and habitat further contracted to the north. The cluster with a cold median temperature and the narrowest range had virtually no temperature habitat by 2100. These "losers" were primarily gastropods and mussels which are prey for endangered Pacific walrus, a food resource in native Alaskan communities, and for commercial groundfishe. The cluster with the broadest temperature range had suitable temperature habitat throughout most of the Bering and Chukchi Seas, except in the areas closest to shore. The most abundant species of these "winners" was the basketstar *Gorgonocephalus cf. arcticus*. The loss of habitat for all but the "winners" could impact species diversity of the Bering and Chukchi Seas because the "winner" cluster accounted for only 8% of all taxa. Our results provide the first indications that the epibenthic invertebrate community in the Bering and Chukchi seas, which supports marine mammals, seabirds and human communities, may be seriously impacted by future ocean warming.

The next decade of ocean acidification research in the Bering Sea: what we've learned and what's coming next

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Over the last decade, ocean acidification (OA) has emerged as one of the most prominent issues in Alaskan marine research, and a possible threat to culturally and commercially important marine resources. Multiple communities around the state are now engaged in their own OA studies and monitoring, and are asking a common question: what risks does my region face? These are especially salient questions for Alaskans because the intensity, duration and extent of OA events have been greater here than other ocean basins. Given the pace of the observed changes due to OA around Alaska, the area is commonly referred to as a bellwether and the proverbial "canary in the coal mine" for the rest of the global ocean. Here, we will take a look back at the last ten years of OA research in the Bering Sea, and highlight new, cutting-edge synthesis and biogeochemical modeling, forecasting, and projection efforts that have dramatically increased our capacity to understand Alaskan OA from a large-scale perspective. For example, multi-decadal projections provide spatio-temporal information for how OA conditions may evolve throughout the Bering Sea shelf and highlight key differences between climate emissions scenarios, providing a regional perspective for the impact of climate mitigation strategies. Meanwhile, near-term products provide fisheries stakeholders with updated environmental information for stock assessment and the fisheries management process. This effort recently culminated with the development of an indicator for the Eastern Bering Sea Ecosystem Status Report (ESR) and input into the Ecosystem and Socioeconomic Profiles (ESPs) for two crab stocks. Our vision is to continue developing and refining this approach and to expand available products to identify new risks and emerging resilience of Alaskan ecosystems. Ultimately, we hope these products guide sound, evidence-based decisions that support sustainable marine resource management for the largest U.S. fishery.

DRAFT

Climate-driven shifts in abundance, distribution, and composition of the age-0 gadid community in the eastern Chukchi Sea

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Age-0 Arctic cod (*Boreogadus saida*) have historically dominated the pelagic fish community in the Chukchi Sea in summer, with few adults present in the region. Recently, reductions in sea ice and increases in warming and transport have led to an increase in Pacific-origin waters on the Chukchi shelf in summer. To examine the potential effects of these environmental changes on the pelagic community, we conducted autonomous and ship-based surveys in summer 2017, 2018, and 2019. Throughout this period, bottom-moored echosounders continuously measured fish abundance and movement at several locations. Together, these observations indicate that the abundance and composition of the pelagic community on the Chukchi Sea shelf are highly variable over seasonal and annual time scales. Summer surveys found that age-0 Arctic cod were the most abundant pelagic fish in all four survey years. Age-0 walleye pollock (*Gadus chalcogrammus*), which were scarce and confined to the southern Chukchi Sea in previous years, were present in high abundance throughout the Chukchi Sea shelf in 2017 and 2019. We hypothesize that the changes in abundance and species composition are tightly coupled to recent changes in temperature and the transport of Bering Sea waters onto the Chukchi shelf. The substantial increase in age-0 pollock in recent years suggests that environmental conditions now allow this species to extend its northern range into the central and southern Chukchi Sea, at least on a seasonal basis. Seasonally, fish abundance was very low in winter, increased in May, and reached peak abundance in late summer. Age-0 gadids were displaced to the northeast, consistent with the dominant advection on the shelf. Fish speeds and headings were strongly correlated with local currents, providing evidence that behavior plays a limited role in the displacements of these populations.

DRAFT

Taking the long view: Integrating marine historical ecology and natural resource management in the Gulf of Alaska

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Natural resources across the Gulf of Alaska are under threat from climate change, invasive species introductions, coastal erosion, and other hazards. In the face of such change, resource managers in this region are increasingly looking to Indigenous knowledge, historical archives, and archaeological and paleoenvironmental data to understand long-term variability in ecosystems and human-animal interactions. Drawing on examples from migratory bird rehabilitation, invasive species eradication, and fisheries management in a marine historical ecology framework, this paper addresses how such interdisciplinary, collaborative work might inform management by: a) constructing a common vocabulary; b) integrating across time scales; and c) establishing common goals based in management concerns.

DRAFT

Using an environmentally linked assessment for strategic fisheries management planning

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Modern fisheries are largely managed based on assumptions of stationarity in the productivity of stocks consistent with a baseline time-period. As productivity depends on environmental conditions, the assumption of stationarity in productivity is dependent on future environmental conditions varying within the bounds of the assumed baseline conditions. The climate of the earth is changing due to anthropogenic forcing and although there are long-term objectives of minimizing these impacts, these impacts appear to be largely unavoidable and irreversible over the next century. Therefore, it is essential that climate change is considered in developing fisheries management plans and harvest control rules to assure long-term sustainable fisheries.

Here we consider an ecosystem-linked single species assessment model for Gulf of Alaska Pacific cod (*Gadus macrocephalus*) in which environmental conditions drive key biological elements of productivity and projecting these models forward using forecasts generated from International Panel for Climate Change (IPCC) Representative Concentration Pathway (RCP) scenarios. Ecosystem-linked model projections assume stationarity in the relationship between environmental conditions and biological elements contributing to productivity instead of assuming stationarity in productivity itself. In this model sea surface and bottom temperatures, and the occurrence of marine heatwaves are used to drive growth, natural mortality, and recruitment. This model is used to obtain estimates of stock productivity under three IPCC RCP scenarios using five climate models under each scenario to the end of the century. We observe significant variability in productivity among climate model projections, however under all of the IPCC scenarios productivity is reduced in comparison to status quo, more so under higher carbon concentration scenarios. There is much uncertainty in the management advice that is provided from the method presented, however the greatest source of variability in study results is among RCPs, determined by how we act, or fail to act, on controlling global greenhouse gas emissions.

DRAFT

Cyclic variability of eastern Bering Sea jellyfish relates to regional physical conditions

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A substantial increase in jellyfish biomass, primarily *Chrysaora melanaster*, was documented over the eastern Bering Sea shelf throughout the 1990s. Their biomass peaked in summer 2000 and then declined precipitously, stabilizing at a moderate level during 2001-2008. Surveys since 2009 indicated that jellyfish biomass had increased once again to late-1990s levels, but then declined dramatically in 2016 and 2017. The onsets of the biomass increases and declines coincided with transitions between climatic regimes. Our previous investigations of a 27-year time series examined relationships between jellyfish biomass and temperature, ice cover, atmospheric variables, current patterns, zooplankton biomass, and associated fish biomass in two regions using Generalized Additive Models (GAMs). These analyses indicated that jellyfish outbreaks during 1982-2004 were influenced regionally by interacting biophysical variables such as sea ice cover, sea surface temperature, currents, wind mixing and food availability. Using updated environmental data from 1982-2017, we reran our GAM analyses to determine if models using solely physical variables and lag of jellyfish biomass could describe accurately the more recent increases of Bering Sea jellyfish. GAMs hindcasting jellyfish biomass for the period 1982-2017 explained a large fraction of the variance, 92.3% and 86.4%, for the southeast and northwest portions of the survey area, respectively. We developed more parsimonious models by calculating the variance inflation factor for each term and dropping highly correlated terms. The resulting GAMs continued to explain a significant portion of the variance in jellyfish biomass, i.e., 78.2% and 73.5%, in the southeast and northwest survey areas, respectively. Jellyfish, which are both predators and competitors of fish, appear to be responding to changes in physical conditions and are important for understanding ecosystem changes in the eastern Bering Sea. Development of models that use more readily available physical parameters is key to predicting jellyfish abundance and their impacts on commercially important species.

Paleoproductivity records in the Subarctic North Pacific Ocean: Baseline marine ecological data for the Holocene

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The coastal regions of the Subarctic North Pacific Ocean (SNPO) experience some of the highest levels of primary productivity in the global ocean. However, this area is susceptible to impacts from climate-related ecological perturbations, such as "The Blob" marine heat wave event of CE 2015-2017. The unprecedented impacts from this event, such as the crash of modern Pacific cod stocks and the occurrence of the largest toxic diatom bloom ever observed, were not anticipated. Therefore, geologic records offer an opportunity to examine past time intervals for analogues of future change to better predict and understand potential trends and ecological impacts.

A Holocene compilation of biogenic silica (opal) data for the last 10,000 years was generated using a combination of new laboratory measurements and literature review as an estimate of past diatom-based phytoplankton productivity from the Gulf of Alaska (GoAK; n = 4), Bering Sea (BS; n = 5), Sea of Okhotsk (n = 10) and the Northwest Pacific (n = 5) margins of the SNPO. These data suggest contemporaneous shifts in all of these areas towards higher diatom productivity during the late-middle Holocene, particularly after ~4000 cal yrs BP. A second regional increase is also seen in both the GoAK and BS regions at ~1000 cal yrs BP.

This presentation will explore the intricacies of the SNPO Holocene opal data synthesis in conjunction with published studies that describe: (1) paleo-environmental records of SNPO atmospheric and oceanic processes; and (2) paleo-ecological reconstructions of finfish abundance (Pacific salmon, Pacific cod, herring, and anchovy). As the opal-based phytoplankton data represents an important link between physical forcing and higher trophic level dynamics, a key output from this study will be a better understanding of how these elements have interacted in the past, which will provide new insights for the future of the SNPO ecosystem under projected future climate change.

Investigating food web structure and dynamics in the eastern Gulf of Alaska

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DRAFT

The Gulf of Alaska (GOA) hosts numerous federally protected species and valuable fisheries, both of which were adversely impacted by a severe marine heatwave in 2014-15. The eastern Gulf of Alaska (EGOA) is distinguished from waters to the west (WGOA) by many features of its oceanography, ecology, and fisheries. However, the EGOA has received comparatively less scientific attention than the WGOA. We attempted to remedy this situation by developing mass-balance models of the EGOA food web in 1990-1993 (when reliable time series began) and 2014-15 (during the heatwave). The study area includes federal and state waters overlying the continental shelf and upper slope (0-1000 m) from 54°40'N northwest to 147°W, excluding Prince William Sound and the Inside Passage. The EGOA models represent ecosystem structure as a network of biomass pools and fluxes informed by fisheries-independent surveys, fisheries catches, and oceanographic (ROMS-NPZ) models. These models contain 72 functional groups (i.e., species or groups thereof sharing basic ecological traits) spanning all trophic levels and size classes. They also include 19 fishing fleets defined mainly by gear and target species. Functional group and fleet structure focuses on protected species and commercial fisheries. These models, developed in collaboration with the GOA Climate Integrated Modeling, GOA Integrated Ecosystem Assessment (IEA), and Sitka IEA projects at the Alaska Fisheries Science Center, revealed the directions and strengths of trophic interactions in the EGOA before and during the heatwave. Furthermore, the 1990-1993 model was fitted to time series to provide hindcasts of ecosystem dynamics. The EGOA models are also expected to support projections of ecosystem states, as well as closed-loop simulation testing of fisheries management strategy performance, under various scenarios of climate change. Finally, these models present an opportunity for multi-model inference together with a mass-balanced WGOA model, a GOA end-to-end model, and a GOA multi-species model.

Pan-Arctic marine biodiversity patterns under recent climate

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The Arctic region is experiencing drastic climatic changes over the past decades bringing about potential ecological surprises. Here, we explored changes in marine biodiversity and potential species co-occurrences across eight Arctic marine areas defined by the Circumpolar Biodiversity Monitoring Program from 2000-2019. We compiled occurrence data for 55 marine taxa belonging to four different species guilds and environmental information to simulate and predict species-specific spatial distributions. From multi-ensemble species distribution model outputs, we examined the spatial and temporal biodiversity patterns and potential species co-occurrences over time and between contrasting periods of region-specific summer sea ice conditions during the last two decades. Our preliminary analyses revealed region-based differences in species richness and potential species co-occurrences between high and low summer sea ice years. In particular, we observed declines in the species richness and frequency of pair-wise species co-occurrence between high and low sea ice periods in contiguous regions of the Davis-Baffin Bay and Hudson Complex. In contrast, adjacent regions of the Pacific Arctic and Beaufort Sea as well as the Atlantic Arctic and Kara-Laptev Sea highlighted increases in species richness and pair-wise co-occurrences. These spatial patterns emerged in response to modeled northward habitat range expansions of marine species under low summer sea ice conditions. Our initial results show contrasting regional impacts of warming and sea ice loss across the different Arctic marine areas and could provide relevant insights on potential vulnerability of the regions to recent climate changes.

DRAFT

Prince William Sound marine ecosystem under different heatwave scenarios.

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As marine heatwave frequencies rise, understanding ecosystem responses is necessary to create management strategies. These extreme events can have long-term impacts on ecosystems; therefore, it is important to understand how heatwaves persistence will affect declined small pelagic populations such as Prince William Sound herring. Here we review past marine heatwaves in Prince William Sound to create future scenarios. We explore how these events affect herring and consequently Prince William Sound marine food web, and if the persistence of these events (duration and occurrence) results in biological regime changes. To achieve the goal, we: 1) used a mass balanced food web-based ecosystem model (Ecopath with Ecosim) to represent Prince William Sound marine ecosystem; 2) fit times series of biomass, fishing effort and landings for the fished functional groups in Ecosim, the dynamic portion of the ecosystem model; 3) generated a trend using dynamic factor analysis (DFA) of past biological time series;
4) developed three marine heatwave scenarios from the DFA trend result (the first uses the 2015 marine heatwave, the second simulates two consecutive marine heatwaves, the third the persistence of three consecutive marine heatwaves); 5) evaluated herring response to the scenarios; and 6) used network analysis to calculate how the marine food web is affected. This preliminary simulation work shows the vulnerability of herring to the increase of North Pacific marine heatwaves and the consequences to Prince William Sound marine food web. Moving forward, we hope to extend the analysis to understand the links between environmental and biological regime shifts.

Arctic Cod (*Boreogadus saida*) under newly-formed sea ice in the Pacific Arctic

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Arctic cod (*Boreogadus saida*), a key forage fish in the Arctic, may be particularly susceptible to changing sea ice conditions, although their dependence on sea ice is poorly understood. Therefore, we examined the under-ice distribution, abundance and condition of Arctic cod during the fall and early winter to assess whether newly-formed sea ice provides suitable habitat for growth and survival. Ice-associated Arctic cod and macro-zooplankton were sampled along the outer shelf and slope of the Chukchi and Beaufort seas using a Surface and Under-Ice Trawl. Chlorophyll, zooplankton and fish in the underlying water column were assessed using discrete water samples, vertical plankton tows and acoustic backscatter recorded by an EK80 echosounder, respectively. Chlorophyll concentrations were low at the bottom of the ice and throughout the upper 50 m. Moderate abundances of zooplankton were observed in the upper 100 m of the water column. Small *Pseudocalanus, Oithona similis* and *Microcalanus* sp. were numerically dominant, while biomass was dominated by larger calanoid copepods and chaetognaths. Stomachs of juvenile Arctic cod contained pelagic zooplankton, several fish species and ice-associated amphipods, suggesting that juvenile Arctic cod captured under the ice were actively feeding on both pelagic and ice-associated prey. The mean wet weight of juvenile Arctic cod at a given length was higher in November than that of the same cohort caught during late summer; however, their lipid content was considerably lower. Observed lipid densities under the ice in November were at or near the level at which laboratory-reared juveniles experience high mortality, suggesting that their survival likely depends on continued prey availability. Acoustic backscatter suggests that small fish, most likely Arctic cod, were present throughout the study region and were found in multiple layers in the water column. We found some evidence that smaller fish ascended into a warmer subsurface layer at solar noon, presumably to feed, while the strongest backscatter indicative of fish was typically associated with cool intermediate waters that separate the surface layer from warmer Atlantic waters below. The use of ice-associated habitat by juvenile Arctic cod may be one strategy to access available prey resources while minimizing metabolic requirements and predation.

DRAFT

Coupled modes of projected regional change in the Bering Sea from a dynamically downscaling model under CMIP6 forcing

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Three different global earth system models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) were used to explore anticipated changes in the Bering Sea under high (SSP126) and low (SSP585) carbon mitigation scenarios (i.e. low and high emission scenarios), via dynamical downscaling. A multivariate pattern analysis, based on Empirical Orthogonal Functions applied to monthly time series reveals strong coupling of changes across several biophysical variables and the global forcing itself, on both yearly and multidecadal time scales. Rising air and ocean temperatures from the global models are strongly coupled with rising regional temperatures and reduced ice cover/thickness, as well as strong changes to the phenology of the plankton food chain, including reduced biomass of large zooplankton in the fall. This method ultimately provides a compact way to estimate the changes to many regional attributes under a variety of global change scenarios. Application of this method to a broad ensemble of the CMIP6 global model air temperatures suggests that compared to present conditions, the Bering Sea shelf bottom temperatures in July will warm by an average of ~4 °C by the end of the 21st century under SSP585, as compared with ~1 °C under SSP126, with greatest warming focused on the outer northern shelf. An extension of the method, based on Machine Learning, is also described.

DRAFT

Responses of mesozooplankton biomass to climate change in the southeastern Bering Sea shelf during the summers of 1955–2013 (summary of T/S Oshoro-Maru cruises) with special references to the taxonomic composition and normalized biomass size spectrum for several consecutive years at each climate regime

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DRAFT

The T/S Oshoro-Maru visited the southeastern Bering Sea shelf during the summers of 1955-2013. During these visits, mesozooplankton samples were collected using the same methods: vertical tows of a NORPAC net from 150 m depths or near-bottom to the surface. Wet weight biomass was measured for each sample. Using these data, we studied yearly changes of mesozooplankton biomass and analyzed the effects of environmental parameters: temperature, salinity, stratification index, pycnocline depths, and interactions with large-scale climate indices. The mesozooplankton biomass showed common yearly changing patterns related to climate regime shifts. Thus, as climate regime shifts during the study period, the four changing timings have been reported: 1976/77, 1988/89, 1998/99, and 2005/06. The mesozooplankton biomasses were the lowest for the warmest period (2000-2005). The highest biomasses were observed for the cold period (2007-2013). The supplemental taxonomic and normalized biovolume size spectra (NBSS) data were also obtained by ZooScan for two consecutive years in four different climate regimes. Zooplankton biomass exhibited annual changes, with high and low values varying at each climate regime shift. ZooScan analysis revealed anomalous zooplankton abundance during 2003/2004 dominated by Cnidaria and the lowest abundance of whole-sized copepoda. Because of this anomalous community, the NBSS in 2003/2004 was characterized by the most moderate slope and lowest intercept which varied greatly from the other climate regimes. The effects of climate index and environmental variables on zooplankton were evaluated using structural equation modeling. Throughout the region, the significant interactions between climate indices and zooplankton were in the following pathway: North Pacific index → ice retreat timing → temperature above thermocline → zooplankton biomass. Through the five climate regimes, zooplankton biomass was high in the cold regimes and low in the warm regimes. These negative interactions between zooplankton biomass and temperature at the surface layer suggest that the concept of the Oscillating Control Hypothesis holds true for long-term observations.

Understanding Pacific Halibut spatial dynamics in the northern Bering Sea

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DRAFT

In recent years, the fish assemblage has been changing in the Northern Bering Sea (NBS), where rising water temperature has correlated with increases in abundance of sub-arctic fish species. One such species is the Pacific halibut (*Hippoglossus stenolepis*), a commercially important flatfish that is a potentially valuable resource in the NBS. To optimize harvest opportunities of this increasingly available fish, informed management is important, which in part requires understanding halibut movements and spatial dynamics in the region. Currently, this information is scarce, and as such, the current management paradigm makes a number of assumptions generalizing Pacific halibut movements within NBS management areas. To obtain spatial dynamic information for Pacific halibut in this region to better inform management decisions, pop-up satellite telemetry tags were attached to large, mature female Pacific halibut in two locations in the NBS. Data recovered from these tags was used to assess movement and habitat occupancy within the region. Preliminary findings indicate that tagged individuals remained within the NBS and Central Bering Sea, with Pacific halibut crossing multiple management boundaries, including the Russian maritime border. During the winter spawning season, Pacific halibut made long migrations to the shelf edge, ranging as far south as the Pribilof Islands. Additionally, some individuals returned to their tagging location the following year, an indication of inter-annual site fidelity to summer foraging areas. These findings are important to both local stakeholders and managers when making management decisions about this increasingly available resource.

An exploratory analysis of warming effects on wealth in the Barents Sea fisheries

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The Barents Sea and Arctic regions in general are facing significant impacts from climate change. A major concern is increasing temperatures. I explore four different scenarios of temperature impacts on the Barents Sea cod, its fishery, and the level of natural capital – wealth – that the fish stock represents. My framework incorporates interaction with the main prey, capelin, under uncertainty in the population dynamics equations and under two relevant management regimes. One regime is based on maximum sustainable yield (MSY) and one is based on ecosystem-based management (EBM). Because of uncertainty over how warming will impact the Barents Sea cod, the investigated scenarios include both positive and negative impacts on parameters in the population dynamics. Wealth under MSY is surprisingly robust to temperature impacts, and only under one scenario with negative impacts is there a significant wealth effect and then only in the long run. The EBM regime would increase wealth in all scenarios, but outcomes are more sensitive to the type and significance of the temperature impact.

DRAFT

Data integration to model lower trophic levels in the Eastern Bering Sea

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Ecosystem based fisheries management (EBFM) necessitates inclusion of environmental data and trophic links into fisheries modeling efforts. Recognizing these links is important as bottom-up processes can significantly impact fish population dynamics. In the Eastern Bering Sea (EBS), changes to zooplankton community dynamics can significantly shift fisheries productivity and changes in regional climate patterns are likely affecting zooplankton production. Currently the Regional Ocean Modeling System for nutrients, phytoplankton and zooplankton (ROMS-NPZ) estimates temporal and spatial variability in zooplankton biomass in the Eastern Bering Sea. The output of the ROMS-NPZ has yet to be compared with observational data. Model refinement can allow expanded use of ROMS-NPZ output in management decisions. We compare biomass predictions from the ROMS-NPZ Bering 10k model for an abundant copepod, *Calanus* spp., with a thirty-year time series of zooplankton field data collected by the NOAA Alaska Fisheries Science Center. We use *Calanus* spp. for this initial comparison as calanoid copepods underpin the EBS food web as an important prey item for fish, marine mammals, and birds. Using a GAM framework, we quantify the level of agreement between survey observations and ROMS-NPZ model predictions and include covariates to identify locations in space and time where discrepancies between the datasets may exist. Preliminary results indicate that the ROMS-NPZ and empirical data have higher agreement than expected and discrepancies were predictable when a spatial smoother was incorporated into the model.
These comparisons are a first step in a data integration process to further bolster zooplankton data availability for use in EBFM efforts. Future work will expand the species included in this comparison to include other copepod species and euphausiids.

DRAFT

Condition, size, and winter duration affect winter survival probability in juvenile Atlantic cod (*Gadus morhua*) in a coastal ecosystem

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Juvenile Atlantic cod (*Gadus morhua*) in coastal Newfoundland settle in nearshore habitats in 3-6 pulsed events each year. These pulses create a broad size-structured year-class during the first year of life. The combination of multiple pulses and variable winter harshness creates conditions of metabolic stress resulting in size-structured survival. Juveniles that settle early in the growing season potentially grow larger and produce more fat reserves prior to winter compared to individuals settling later in the season. We hypothesized that early settling juveniles would be in better condition prior to winter facilitating their survival through long, harsh winters. We use a generalized linear model with a binomial distribution (logistic ANCOVA) to evaluate changes in relative winter survival over a 20-year period, combining juvenile cod survey data and archived juvenile cod samples with winter temperature records to determine the impact of winter duration, body condition, and settlement time on overwinter survival. Our analyses demonstrate the importance of condition entering winter, combined with size and settlement timing, for overwinter survival. Effects of winter duration on survival were less than expected. Body condition and settlement time play important roles in subsequent survival. Our findings advance the importance of settlement time for overwinter survival in sub-arctic marine ecosystems in a changing climate.

The Timing of Global Change

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Because of its responsiveness to changes in the marine environment, it has been suggested by Rose in 2005 that the capelin, a small pelagic fish that is key to the ecology and fisheries of the North Atlantic, could be seen as a "canary in the coalmine" to detect signals of changes in the Arctic Ocean. We will describe the historical data that make possible a quantitative assessment of the geographical shift capelin migration-paths and spawning grounds undergo with increasing temperature, and the time it takes to make these shifts long-lasting. Then we introduce recent data that make these quantitative measurements more accurate and predictive. The Copernicus database of the European Union is used to examine the evolution of the returning Atlantic water (from Svalbard) that is forming a warmer and saltier boundary current under the colder and fresher East Greenland polar current. The returning Atlantic water has a temperature range (-1 to 3 degrees Centigrade) suitable for feeding migrations of the capelin. This current is reaching further north along the coast of North East Greenland and we use Copernicus to simulate this evolution. We then validate the Copernicus data with measurements made in the fall expeditions of the Marine and Freshwater Research Institute, in Iceland, along the East Coast of Greenland. We identify trends in Copernicus data showing that the returning Atlantic water boundary current may reach the major glacier streams draining a large portion of the Greenland Glacier, in the relatively near future, and use the capelin data to predict when this may happen.

Effects of snowcrab in the Barents Sea – Perhaps not only negative?

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The invasion and continuing expansion of snow crab in the Barents Sea has provided the area with a new, valuable, harvestable resource. On the negative side, this invasion may lead to changes in the ecosystem, including structural changes and shifts in energy pathways due to predator-prey effects. However, not all expanding species have detrimental effects on their new environment. To explore ecosystem effects of the snow crab in the Barents Sea ecosystem, we've applied an end-to-end ecosystem model; the Nordic and Barents Seas Atlantis model (NoBa). NoBa includes 53 species and functional groups, and is forced by physical forcing from a regional ocean modellling system (ROMS). The snow crab has been added as an age-resolved component. Its simulated population development from 1995 and forward captures the slow growth in the beginning, with a steeper increase in the 2020s, thereafter reaching a stable population level of around 1.2 million tons. With a new ecosystem component, there are many unknowns, including predator-prey effects and impacts of different harvest regimes. To explore the footprint of snow crab in the Barents Sea we explored a set of different scenarios, including harvest levels on snow crab, options for larvae dispersal and predator-prey effects. The current size restrictions in the management regime are taken into account. Based on our simulations, snow crab might have found a niche where the benthic community is able to sustain the predation, thereby causing fewer ecosystem effects. The simulations include the potential development of the snow crab population in the future (1995-2068).

Time trawlers: An archaeological examination of the fishing station at Smuttynose Island and its implications for the ecosystem of the Isles of Shoals and the Gulf of Maine

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Humans have indeed engaged with marine ecosystems for subsistence, transportation, and profit. During the seventh century and eighteenth centuries, when 'cod was king,' the codfish trade in the North Atlantic interwove skilled knowledge of the local marine ecosystem, international trade with its promises of sustenance and luxury, and the particular pressures of the frontier to produce a unique tableau of information. Through community-based, collaborative archaeology, these intricate threads of data can be teased apart, as was done at the site featured in this paper: the former fishing settlement on Smuttynose Island in the Isles of Shoals, off of the Maine /New Hampshire border (1623-1780). The team conducted the excavations through the Shoals Marine Laboratory in partnership with the community-based Smuttynose Island Stewardship Program. During the course of the project, which ran from 2009 to 2012, the team examined climate change at Shoals, with a careful eye toward current conditions, while also noting changes in the codfish populations and the larger ecosystem, including invasive species. Although rather isolated, the project found ways to record, excavate, and preserve this archaeological site *with* input from the community whose heritage was most tied to it. The historical and ecological impact of the fishermen at the Isles are inextricably entwined; by including the local and descendant communities in the examination and preservation of the site, they are actively connected to its future – and the larger future of the Gulf of Maine.

Growth, condition, and movement of juvenile Arctic cod (*Boreogadus saida*) in a warming Alaska Arctic

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Arctic cod (*Boreogadus saida*) is a highly abundant fish species in Arctic and sub-Arctic ecosystems and is an integral component of northern latitude food webs. Warming conditions and corresponding shifts in sea-ice extent and timing, prey quality and availability, and predator/competitor interactions have greatly complicated established life history patterns for this species. In the face of these biotic and abiotic stressors, it has become increasingly important to expand what is known of Arctic cod ecology in the context of climate change. Simultaneous assessments of multiple response metrics and the underlying mechanisms are inherently challenging and relatively limited for wild Arctic cod specimens. This study simultaneously compares the ontogenetic growth, movement, and condition of wild-caught juvenile Arctic cod between recent cool and warm thermal conditions in the US Arctic. In addition to providing basic age and growth information of the juvenile life stage, otoliths were also sampled for trace elements and stable oxygen isotopes to characterize the chemical and thermal histories experienced by juvenile Arctic cod. We also explored whether otolith trace element and isotopic signatures allow for comparisons of juvenile movement patterns and aid in understanding the population structure during these early life stages. This work will contribute to a larger study that combines growth outcomes with lipid data to explore whether the growth and condition of wild Arctic cod respond to temperature in a manner consistent with laboratory findings. Results from field and laboratory approaches may help to clarify the impacts of warming on growth and lipid storage, both of which impact overwinter survival and thus recruitment dynamics.

Fish otoliths from medieval archaeological excavations provide exploitation effect baselines

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We compared stock origin, size, age and growth rates from archaeological excavation at two sites in northern Norway to those of cod catches from the early and late part of the 20th century. Samples of well-preserved cod otoliths were available from excavations at Storvågan in Lofoten (68° 12'N) (A.D. 1156-1285) close to the present major spawning grounds of Northeast Arctic and another sample from ca. AD 1450-1680 from Værbukta (70° 57' N). For comparison, modern otoliths were sampled from areas situated close to Storvågan and Værbukta. Zone numbers and increments (mm) were calculated from images of the cut otoliths and stock origin Northeast arctic cod (NAC) or coastal cod (CC) were determined. Fish lengths-at-age from pre-20th century samples were back-calculated from zone increments and nonlinear relationships between fish length and otolith size from modern cod.

The pre-20th century cod from Storvågan was dominated by NAC (mean age = 12.0 years, mean length = 82.9 cm) of age 9-16 years and were much older and larger than the early cod from Værbukta which were dominated by CC of age 2-6 years (mean age = 4.4 years, mean length = 53.4 cm). Pre-20th century cod from Storvågan had shorter back-calculated length-at-age than modern cod from Lofoten, indicating slower individual growth than in modern NAC. In contrast, cod from Værbukta had similar length at age as in modern samples. Age-distributions from pre-20th century from Storvågan cod and from the 1930s from Lofoten, suggests that both age at maturity and mortality rates were similar for these time periods, but strongly contrast the truncated and young age-distributions of spawning NAC after 1980 that reflect the high fishing mortality rate after 1950 and decrease in median maturation age to approximately 7 years.

Climate change impacts on marine light in Arctic ecosystems

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Climate change will affect light across Arctic ecosystems, impacting productivity, phenology, and recruitment. We quantify seasonal variation in light in the water column in response to changes in sea ice and snow, storm-driven waves, cloud cover, ozone, and chlorophyll content, which change both absorption and reflection. Using CMIP6 inputs and a simplified radiative transfer model, we find that increased open water and ocean warming will lead to increases in both visible light (PAR) and UV light by 2100. These increases in PAR and UV light result in greater irradiance in the water column, and changes in productivity depending on species and life stage. These changes vary spatially and temporally across ecosystems, with greater light in the spring and summer for the Barents Sea and in the fall for the Chukchi Sea. Changes in the light regime in the Arctic will have major impacts on the survival and distribution of species like polar cod by affecting sea ice, temperature, and food availability. For example, a decrease in sea ice will result in less protection and lower survival rates for eggs. Larval growth will be affected both by greater growth rates due to temperature, but potentially less available food due to changes in productivity. Together, these impacts will likely result in major changes to Arctic species and overall food-web structure.

Covarying lipid and fatty acid profiles among phytoplankton and Arctic cod (*Boreogadus saida*) in the Eastern Canadian Arctic

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Arctic cod (*Boreogadus saida*) inhabit a central space in the Arctic marine food web, linking lower trophic levels (phytoplankton and zooplankton) to higher order consumers such as fish, mammals, and birds. Research into the biochemistry of trophic transfer remains an important component of ecosystem health management, especially in the wake of food web reorganization due to climate change. In 2019, lipid metrics of Arctic cod and phytoplankton were measured within the Canadian Arctic. Specifically, lipid class and fatty acid profiles were analyzed in order to 1) identify possible regional differences, 2) compare the profiles and assess if biomarkers could be traced from phytoplankton to Arctic cod within specific regions, and 3) relate lipids to spatial patterns in condition and diet of Arctic cod.

An Analysis of Similarity (ANOSIM, $p > 0.05$) was conducted between fatty acids (presence above 1%) in phytoplankton and Arctic cod as a function of Canadian Arctic regions surrounding Baffin Bay. Significant regional differences in fatty acid compositions were found between both surface phytoplankton (Clarke's R = 0.470, $p = 0.001$) and Arctic cod livers ($R = 0.19$, $p = 0.007$). More detailed analysis using non-metric multidimensional scaling (nMDS) revealed a northern and southern regional separation. For surface phytoplankton, this north/south separation was driven by fatty acids indicative of diatoms, 20:5ω3 and 16:1ω7, in the northern stations, and 18 carbon monounsaturated fatty acids (MUFAS) in the south. Multivariate analyses of Arctic cod livers mirrored the patterns in phytoplankton with the north/south separation also driven by higher diatoms in the north. Unlike phytoplankton however, 20 and 22 carbon MUFAS dominated Arctic cod livers. These co-varying profiles of Canadian Arctic phytoplankton and Arctic cod storage tissues give crucial insight into the transfer of lipids within Arctic food webs, and further highlight the need for more regional specific assessments.

Sustainable use of salmon resource under changing climate using multiple satellite datasets

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Chum salmon is one of the important fishery resources in the North Pacific. Recently, under a changing climate, the return of chum salmon to Hokkaido has tended to decrease. In particular, more precise juvenile release operation is required to adapt for warming sea temperature during its sea entry. It is necessary for this precise operation to predict the coastal marine environment during the release period and monitor short-term changes in coastal residency. Here, we developed a supporting information system for the optimization of salmon release operations in the Okhotsk coast. This system was designed as a web-based visualization consisting of two site-based services, for monitoring the marine environment (marine site) and supporting salmon release operation (release site). The coastal residence period for chum salmon is a critical phase in the early stage of its life history. However, recent increases in water temperatures and marine heat waves in the Bering Sea and the Gulf of Alaska posed serious concerns for the survival of migrating salmon during its second and third year. Thus, becoming increasingly important for the sustainable harvest of salmon under a rapidly changing climate. We utilized multiple satellite datasets and re-analysis data from a numerical forecast model to monitor the feeding and wintering environments of chum salmon at sea. This project is supported from 2022-2024 by the Japan Aerospace Exploration Agency (JAXA) /Earth Observation Research Center (EORC) under its third Research Announcement on the Earth Observations (EORA3) for promoting research, utilization, and social implementation of data from JAXA Earth observation satellites.

Forecasted shifts in thermal habitat for cod species in the northwest Atlantic and eastern Canadian Arctic

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Climate change will alter ecosystems and impose hardships on marine resource users as fish assemblages redistribute to habitats that meet their physiological requirements. Marine gadids represent some of the most ecologically and socio-economically important species in the North Atlantic, but face an uncertain future in the wake of rising ocean temperatures. We applied CMIP5 ocean temperature projections to egg survival and juvenile growth models of three northwest Atlantic coastal species of gadids (Atlantic cod, Polar cod, and Greenland cod), each with different thermal affinities and life histories. We illustrate how physiologically based species distribution models (SDMs) can be used to predict habitat distribution shifts and compare vulnerabilities of species and life stages with changing ocean conditions. We also derived an integrated habitat suitability index from the combined surfaces of each metric to predict areas and periods where thermal conditions were suitable for both life stages. Suitable thermal habitat shifted poleward for the juvenile life stages of all three species, but the area remaining differed across species and life stages through time. Arctic specialists like Polar cod are predicted to experience reductions in suitable juvenile habitat based on metrics of egg survival and growth potential. In contrast, habitat loss in boreal and subarctic species like Atlantic cod and Greenland cod may be dampened due to increases in suitable egg survival habitats as suitable juvenile growth potential habitats decrease. These results emphasize the need for mechanistic SDMs that can account for the combined effects of changing seasonal thermal requirements under varying climate change scenarios.

Estimating ocean temperature trajectories from ancient Indigenous fishery catch records: an archaeological case study from the northeast Pacific

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Climate change is altering the distribution and composition of marine fish populations globally but comparatively little is known about preindustrial fisheries with respect to climatic variability. Here, we develop and extend the Mean Temperature of the Catch approach (Cheung et al. 2013) to ancient Indigenous fisheries catch records at two coastal archaeological sites on western Vancouver Island, Canada. We devised an analytical process that calculates 'ancient Mean Temperature of the Catch' (aMTC) from zooarchaeological data, temperature preferences, and proportional biomass estimates. We observe an increase in aMTC over a 5,000-year period at two contemporaneously occupied archaeological sites with comparatively cooler catches from 5,000-3,000 cal yr BP and warmer catches during 1,800-250 cal yr BP. These are consistent with palaeoceanographic sea surface temperature reconstructions from sediment cores off British Columbia and in the Gulf of Alaska. Because this method requires converting measures of fish bones into estimates of fish size structure, abundance, biomass, and finally aMTC, opportunities exist to account for both variation and uncertainty at every step. Nevertheless, given that preindustrial fisheries data are ubiquitous in coastal archaeological sites, this method has the potential to be applied globally to broaden the temporal and geographic scale of ocean temperature baselines.

Temperature-dependent survival and growth of early juvenile Bering Sea snow crab (*Chionoecetes opilio*) and Tanner crab (*Chionoecetes bairdi*): implications for optimal crab thermal habitat in a rapidly warming Alaska Arctic.

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Long-term laboratory studies on temperature-dependent (-1.5 to 16 °C) growth and survival in early juvenile Alaska snow crab (*Chionoecetes opilio*) and Tanner crab (*Chionoecetes bairdi*) were conducted. *A priori* we assumed that snow crab would have a stenothermal response adapted to cold conditions (< 3 °C) whereas Tanner crab would have a more eurythermal response. However, survival was generally similar between the two species and decreased at temperatures above 7 °C and below 0 °C. Intervals between molting events (inter-molt period) and the proportional change in size at each molt (molt increment) were temperature and species dependent. Tanner crab had both shorter inter-molt durations and larger molt increments at temperature > 2 °C, compared to snow crab. Largest molt increments for both species were measured at temperatures between 0 °C and 5 °C, indicating efficient growth at lower temperatures. Above 2 °C, absolute growth rates (mm day^{-1}) were higher in Tanner crabs compared to snow crabs. Temperature-dependent survival and growth functions were coupled to an ensemble of CMIP6 Earth System Models statistically downscaled bottom temperature data (1/12th degree resolution) to examine historical and future projections of thermal habitat for *Chionoecetes* crab in the Eastern Bering and Chukchi Seas (1993-2100). By the end of the century, average summer bottom temperatures are projected to approach 7.5 °C across much of the eastern Bering Sea shelf, a level beyond the optimal thermal limit for long-term survival of *Chionoecetes* spp (<80% survival over 200 days). Optimal summer thermal habitat (< 5 °C) will move offshore and northward and be limited to the northwest Bering Sea shelf and the central Chukchi Sea by 2100. Different temperature - growth responses may result in juvenile Tanner crab having a future growth advantage over snow crab across the full latitudinal extend of the Bering and Central Chukchi seas.

How will climate changes affect the future Northeast Atlantic cod stock in the Nordic and Barents seas?

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The Barents Sea currently holds the largest cod stock (*Gadus morhua*) in the world. The cod plays an important role in the Norwegian economy, with the catches being worth over 7 billion NOK (Norwegian kroners). However, the future state of the stock and consequences for fisheries are uncertain, with studies on how climate changes will affect the cod stock showing disputing results. Warmer climate might increase suitable feeding area for cod, while at the same time causing potential negative effects on reproduction in cod or on its prey species. Changes in spatial distribution and/or spawning migration might influence the pattern and seasonality of the fisheries, with following impact on the economy along the coast. In this study we apply an Atlantis ecosystem model for the Nordic and Barents seas (NoBa) to study the impact of three different climate projections (SPP1-2.6, SSP2-4.5 and SSP5-8.5) on future fisheries with a focus on how this will affect the valuable NEA cod stock and potential consequences for fisheries. In all three scenarios, we have used two different spatial management scenarios for the cod fisheries, one where we restrict the fisheries to only harvest in the same areas where fishing occurs today, and one where harvesters can fish where the cod actually is. This will single out the spatial impact of climate change on the stock and the fisheries, and potential societal effects.

Arctic ecosystem impact assessment of oil in ice under climate change

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Warmer waters and retreating sea ice allow marine populations and human activities to expand northwards, introducing multiple pressures acting in synergy on Arctic coastal and oceanic ecosystems. It is imperative to develop risk assessments that take into account not only changes in the structure and function of marine ecosystems induced by climate change, but also existing and new initiatives to utilize Arctic marine ecosystem services, including living and non-living marine resources, shipping and tourism. Society benefits from knowledge supporting sustainable management of the marine environment and its resources by resource utilization at optimal levels with societal tolerable footprints. We address this by studying the polar cod (*Boerogadus saida*), a circumpolar species that plays an essential role in ice-associated food webs, such as in the Barents Sea, linking the lower (i.e. zooplankton) and higher (e.g. other fish, mammals, seabirds) trophic levels. We develop a data-driven mechanistic models for polar cod based on field and lab experiments to assess cumulative impacts of climate and oil spills on the key Arctic fish species relevant to stakeholders and policy development. The results presented here focus specifically on the survival success of early life stages of polar cod originating from different spawning grounds and times and the implications for population vulnerability to oil spills.

Detection of biologically productive water mass from ocean color satellite using chromophoric dissolved organic matter (CDOM)

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The northwestern Pacific and shelf region of the Bering Sea are one of the most biologically productive regions in the world. This feature is attributed to mixing of warm water with eutrophic cold water. Recent warming, freshening and sea ice decline, however, might change the distribution and properties of water masses that are important for ecosystems in these regions. Therefore, long-term and wide observation that capture recent changes in water masses are important for predicting future changes in marine resources and ecosystems. In this study, we have developed a method to derive water mass distribution from ocean color satellite using light absorption spectrum ($a_{\mathrm{CDOM}}(\lambda)$) of chromophoric dissolved organic matter (CDOM). We classified waters in the area into seven water masses (WMs) using in situ ultraviolet $a_{\mathrm{CDOM}}(\lambda)$ obtained during summers in 2006–2021. A classifier was created by machine learning using the WM number as the objective variable and temperature and the visible (VIS) $a_{\mathrm{CDOM}}(\lambda)$ as the explanatory variables. Distribution of the WMs were observed from MODIS-Aqua satellite by inputting sea surface temperature and VIS $a_{\mathrm{CDOM}}(\lambda)$ from the satellite to this classifier. The WMs distribution presented seasonal changes in surface water likely due to vertical mixing in winter and expansion of water with high CDOM concentration from spring to summer. This high CDOM water found only in April had a positive chlorophyll anomaly. It suggests that the method in this study could detect the water mass with a potential to induce high biological production in the study regions. In addition, it can be expected to extend the knowledge on the biogeochemical cycles and mechanism of primary production from local to regional or basin scale based on water mass. Therefore, it will be useful for verification of predictions from ecosystem models in the sub-Arctic seas.

Was there a Pleistocene North Pacific fishery? The evidence for boat use, maritime subsistence, and subarctic settlement around the North Pacific Rim.

Ben Fitzhugh

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This talk reviews the available evidence for maritime adaptations around the coasts of Northeast Asia from 40,000 years ago to the end of the last Ice Age. Drawing on the archaeological records of Northeast Asia and recent genetic and palaeoceanographic discoveries, I examine the probability of cryptic Maritime Beringian occupation in the Late Glacial Maximum (LGM) – whether it could have been a continuation of earlier more temperate and subtropical coastal adaptations or where it could have formed, if not. Recent evidence suggests the LGM North Pacific climate was milder in both winter and summer than the continental interiors of Beringia, making it plausible for maritime communities to form in areas of above average productivity such as the now submerged Pacific coasts of Hokkaido, Kamchatka and the north shore of the Alaska Peninsula/eastern Aleutians. With circumstantial evidence leaning heavily on the side of a coastal route for post-glacial settlement of the Americas, the question is no longer whether or not a Maritime Beringian population existed in the LGM but how people crossed the Bering Land Bridge, and – if by boat – how they manufactured their watercraft in a Beringian environment lacking abundant live trees. Future work - including by members of the PESAS WG - could focus on: improved physical models of the Northeast Asian/Beringian paleoshorelines and ocean dynamics to refine predictions on likely places to prospect for submerged evidence; marine coring of submerged but protected paleolakes, ponds and lagoons in those locations in search of evidence of human presence in the most likely productive “hotspots” for maritime settlement (e.g., sterols, sedDNA, etc.); and refinement of submarine archaeological techniques to survey those locations for positive archaeological evidence.

Sounds of walleye pollock: a quantitative description

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We present the first quantitative description of walleye pollock (*Gadus chalcogrammus*) sounds based on over 67 h of audio recordings of captive specimens at the Hatfield Marine Sciences Center (Oregon). Over 6000 sounds attributed to walleye pollock were recorded in April 2018. Preliminary measurements on 436 sounds revealed an average duration of 152 ms, a frequency range of 18 to 839 Hz, and an average peak frequency of 84 Hz. Quantification of the acoustic parameters of walleye pollock is an essential precursor to the implementation of passive acoustic monitoring (PAM) surveys for the species. The ability to include PAM surveys in studies of walleye pollock distribution would greatly enhance ongoing efforts to document how rapid changes in the species distribution due to climate change are affecting the Arctic and North Pacific ecosystems. In particular, there is concern about possible negative interactions with Arctic cod (*Boreogadus saida*) which has also recently been shown to be soniferous.

Pacific cod in the Anthropocene: an early life history perspective under changing thermal habitats

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The rapid decline in Pacific cod biomass following a recent Gulf of Alaska (GOA) marine heatwave (2014-16, 2019) may be one of the most dramatic documented changes in a sustainably managed marine fishery. As such, fisheries managers are exploring new recruitment paradigms for Pacific cod under novel environmental conditions. In this review, we address the challenges of managing and forecasting Pacific cod populations in the Eastern Pacific where thermal habitats for early life stages are undergoing varying rates of change across space and time. We use observational data and thermal habitat models to examine changes in distribution, abundance and demographics of the population from 1993 to 2020. Results indicate that reduced spawning habitat and early life stage abundance may be a precursor to regional population decline, but the apparent increases in size-at-age of larval and juvenile cohorts following warming represent potential climate resilience in the Gulf of Alaska. We contend that monitoring of thermal habitat and early life stages will need to consider how potential changes in phenology and growth impact later survival and potential recruitment into the adult population i.e., 'carry over effects.' These include complex size- and temperature-dependent energetics spanning seasonal habitats and through the first winter. Pacific cod management in the Anthropocene will therefore require new process investigations beyond those that can be conducted from single-season surveys focused on one life stage.

Socioeconomic Scenarios in the Alaska Climate Integrated Modeling (ACLIM) Project

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The Alaska Climate Integrated Modeling (ACLIM) project is an interdisciplinary effort to examine how predicted warming may impact the Bering Sea ecosystem – and to ensure that the management system is as prepared as possible for change (Hollowed et al., 2020). ACLIM integrates emissions scenarios with a suite of biological models – ranging from climate-enhanced single-species models to spatial ecosystem models. Each model includes different levels of ecosystem and fishing complexity and, which lets us examine the interaction of sources of climatic and biological variability, change, and uncertainty and how current and potential management measures influence the system. Central to projecting how future warming may affect the ecosystem and fisheries is having realistic catch projections. Realized catch is a result not just of the allowable biological catch (ABC) of each species, but the total allowable catch (TAC) allocated to each species under the ecosystem cap and to the harvest of each species given those TACs. For many species, catch is constrained not by the ABC or TAC, but by bycatch limitations or the lack of profitable targeting opportunities, given prices, costs, and management measures. Here we discuss the ATTACH model and socioeconomic scenarios that have been developed and new scenarios that are in development with stakeholder input. ATTACH retrospectively models how the North Pacific Fishery Management Council sets the TAC and how the fishery has been able harvest different species. ATTACH is then coupled with emissions scenarios and ecosystem models to project harvest. We show results of ATTACH coupled with an existing suite of socioeconomic scenarios and then the current process of developing expanded socioeconomic scenarios that will make the management system more resilient in the face of future change.

Exploring future fishery-related climate impacts to Bering Sea-Aleutian Islands groundfish fishery using a mixed-species manageme

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The multi-species groundfish fishery in the Bering Sea and Aleutian Islands (BSAI) is a large-scale fishery driven by trawl and longline catches, as well as several constraints. These constraints include a two million ton multi-species cap on total catches and bycatch limits for species such as Pacific halibut and Chinook salmon. As shifts in climate occur, the distribution of the component species and the targeting behavior of the fisheries is expected to change, leading to changes in the species composition of catches. Here we present new and expected developments in a management strategy evaluation (MSE) framework for the multi-species groundfish fishery in the BSAI where the constraints are modeled explicitly. We developed a model-based clustering method (R package clustTMB) to explore how species composition of catches may be changing over space and time, with plans to apply the method to BSAI groundfish data and to integrate modeling results into the MSE. Additionally, work is in progress to expand the number of species included in the current MSE model, along with relevant linkages between population dynamics and environmental variables such as temperature. With these new components, the MSE framework will be poised to simulate the dynamics of the multi-species groundfish fishery under a variety of future climate and fishery pathways, and to evaluate potential climate-ready harvest control rules.

Warmer, earlier, faster: Cumulative effects of Gulf of Alaska heatwaves on the early life history of Pacific Cod

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Global warming can alter fish early-life phenology and growth through individual, daily processes that scale up to populations. Recent marine heatwaves (MHWs) in the North Pacific Ocean dramatically reduced Pacific Cod (*Gadus macrocephalus*) populations in the Gulf of Alaska, with fewer but larger post-settlement juveniles observed during MHWs than before. Preliminary analyses indicated that these size shifts were due to changes in both hatch timing and growth during MHWs. To quantify the effect of temperature on hatch date and growth, we examined daily otolith increments of post-settlement age-0 juveniles collected during July near Kodiak Island, Alaska across 11 years before (2007, 2009-2010, 2012-2014), during (2015, 2016, 2019), and between (2017-2018) MHWs. Hatch dates differed due to heatwave status ($P < 0.001$). Mean hatch dates were 13 d earlier during and 23 d earlier after MHWs than before; however, significant differences in hatch dates only occurred between the periods before and between MHWs ($P = 0.02$). Individual growth estimated based on otolith increment widths and back-calculated growth showed similar trends; growth was positively correlated with temperature early in life with limited effects of temperature on growth later in life ($P < 0.001$). Hatch date also interacted with age to influence growth ($P < 0.001$), with later hatching individuals appearing faster growing than earlier hatching individuals between 1-2 months of life. Overall, we found that warming affected age-0 Pacific Cod through both earlier hatching and faster apparent growth, with the greatest effect of temperature on growth earlier in life. Interestingly, the only significant shift in hatch phenology from years before the recent MHWs occurred between MHWs (2017-2018), potentially indicating lingering effects of MHWs. Our results will advance understanding of how MHWs alter growth and performance of Pacific Cod, which helps explain and anticipate changes in size-structure and recruitment potential in near-future climates.