# Background

The Gulf of Alaska (GOA) is a complex oceanic system that is predominately a downwelling system and is dominated by storms that vary both on monthly and decadal timescales. Within the GOA, there are several major oceanographic features that drive the underlying circulation of the system. Here, major large-scale circulation patterns are generally cyclonic, operating in a counterclockwise fashion. ***The Alaska Coastal Current (ACC)*** is a major feature that occurs along the inner shelf and continental slope of the GOA, which is mediated by wind driven processes, precipitation, and freshwater discharge (either from rivers or glacial melt). As such, the dynamics of the ACC are highly seasonal. The ACC starts approximately from the shelf of British Columbia and bifurcates around the Kennedy Stevenson Entrance, where a majority of the ACC (about 70%) traverses down ***Shelikof Strait and into Unimak and Samalga Pass, eventually entering into the Bering Sea***. Additionally, a smaller portion of the ACC joins up with the ***Alaska Stream*** (AS; discussed further below) as it bifurcates. Generally, the ACC is a nutrient poor current due to its reliance on freshwater discharge. The ACC is generally bounded from offshore currents due to the salinity gradient created by freshwater discharge (i.e., confined along the inner shelf and continental shelf), and the velocity of the current varies seasonally, given its reliance on freshwater discharge and wind dynamics. Another dominant oceanographic feature within the GOA system is the ***Alaska Current*** (AC), which is generally regulated by wind stress curl. The AC results from the North Pacific Current (from West Wind Drift), which bifurcates into two components (a northern component – the AC, and a southern component – the California Current). Additionally, the AC tends to follow the isobaths of the GOA via the bathymetric steering. The AC is characterized as a wide and slow moving current and is located in the eastern GOA, which has a relatively narrow continental shelf. At around the western GOA, which is characterized by a relatively wider continental shelf, the AC turns into a narrow swift moving current along the continental shelf, known as the AS. The AS traverses down the continental slope of the western GOA and down through the Aleutian Islands (AI) before it rejoins the North Pacific Current. Some drivers of how these currents interact and behave are often hypothesized to result from atmospheric variability. In particular, within the AC, eddies and meanders with the current have been hypothesized to develop through strong Aleutian Low events (i.e., low sea-level pressure) and resultant strong winds.

Seasonal variability in the GOA is typically characterized by reduced runoff in the winter, coupled with strong downwelling dominant winds, which generally results in reduced salinity at depth (i.e., given the downwelling of freshwater). Peak precipitation and runoff tend to occur from September through November, while the periods of June to July are relatively dry. With increased precipitation during the months of September to November, the ACC tends to exhibit an exemplified baroclinic structure. When coupled with strong storms and winds during the winter, transport mechanisms from the ACC lead to greater current velocity and transport. Storms tend to peak around October to March in the GOA, which subsequently deepens the mixed layer of the ocean as well, reducing stratification and entraining phytoplankton/productivity to the bottom. By contrast, downwelling favorable winds occur at a reduced frequency during the summer, and winds are generally more variable during this period. Thus, during the spring to summer period (i.e. May to September), there tends to be potential for a relaxation of downwelling favorable winds, facilitating upwelling along the coast. Such relaxation of downwelling winds during this period can weaken the mixed-layer depth, and when coupled with increased solar radiance during the summer months, can result in stratification processes occurring, promoting a spring phytoplankton bloom.

Considering that the GOA is a downwelling dominant system, it is paradoxical that the GOA is considered one of the most productive systems in the world. As such, the productivity from the GOA is likely impacted by a combination of factors, which can include topographic features and interannual variability that alter oceanographic features. Species that reside in the GOA likely exploit such features to aid in the success of recruitment, growth, and survival. With respect to Alaska sablefish, these species likely depend on various mechanisms within the GOA to ensure their success and proliferation. A key challenge for sablefish, who spawn along the continental slope is transport onto the shelf. Several mechanisms can aid in such transport mechanisms the GOA, which can include the formation and utilization of large-scale basin and mesoscale eddies. The utilization and prevalence of eddies has been thought to be beneficial for the success and survival of young sablefish given that eddies have been observed to have higher species richness and carry anomalous heat, salinity, nitrate, and nutrients from their formation region and can facilitate cross-shelf transport of both nutrients and resources, as well as larval transport onto the shelf. Furthermore, eddies can transport long filaments of chlorophyll from the shelf into the gulf, which can provide for rich foraging areas for many fish species (Ladd et al. 2007; Atwood et al. 2010). Here, the formation and prevalence of eddies and meanders has often been hypothesized to potentially result from events associated with a strong Aleutian Low, a positive Pacific Decadal Oscillation (PDO; leading mode of North Pacific sea surface temperature variability) phase, and El Nino events (associated with higher temperatures along the Alaska coast and increased runoff and precipitation) associated with the El Nino Southern Oscillation (ENSO), (Melsom et al. 1999; Gibson et al. 2019, 2023). In particular, during these events (i.e., positive PDO events), baroclinic instability in the AC and ACC as a result of increased precipitation can manifest, which aids in the development of eddies and meanders.

It is also important to consider their tolerance for different temperatures, particularly at young ages. Studies have generally found that juvenile sablefish are fairly intolerant to cold water (lethal temperatures < 2C; (Sogard and Olla 2001) and thus, recruitment success, survival and growth can be impaired during cooler interdecadal events (i.e., a negative PDO or La Nina). It has also been shown that the survival of larvae is highly correlated with an abundance of food, where large year classes have been associated with increases in food availability. Primary food items for juvenile sablefish include: 1) euphausiids, 2) copepods, 3) pelagic tunicates, 4) amphipods (Sigler et al. 2001). As noted, the presence and prevalence of eddies and meanders can bring anomalous sources of nutrients to surface waters, which can potentially enhance primary and secondary productivity within the GOA system. Recent studies have shown that doliolids (tunicata; Pinchuk et al. 2021) exploited such features (i.e., mesoscale eddies) during an anomalous marine heatwave from 2014 – 2016, which are prey items of juvenile sablefish as noted above, and likely help enhance survival rates of juvenile sablefish if encountered. However, the production of both primary and secondary productivity is highly dependent on the presence and availability of nutrients, which can potentially be inhibited by the fact that the GOA exhibits downwelling favorable winds. Given that, other aspects of nutrient transport (aside from eddies discussed above) are needed. From an interdecadal variability perspective, it is likely that the strengthening of the Aleutian Low pattern increases winter cool air from the Arctic, which has the potential to enhance productivity in the central North Pacific basin by decreasing surface temperatures, increasing storms and turbulence, while increasing upwelling and mixing of cold-nutrient rich waters (Shotwell et al. 2014). The increased nutrient productivity within the central North Pacific basin could potentially be advected onto the GOA shelf through the North Pacific Gyre and AC, increasing productivity along the Alaska coast along the shelf. Simultaneously, increased winds as a result of lower sea level pressures (i.e., intense Aleutian Low) could facilitate wind-driven transport of nutrients from offshore regions to the nearshore (i.e., onshore Ekman transport; the convergence of nitrate rich basin water and iron rich freshwater from the coast). Such coupling between interdecadal events and resultant transport of nutrients from the central North Pacific, the formation of eddies and meanders, the ability for zooplankton species to take advantage of these conditions, and the generalist diet of Alaska sablefish likely all play a role in governing the recruitment, growth, and survival success.

In addition to the different interannual factors that impact the success of Alaska sablefish, various aspects of their life-history have likely adapted to exploit the various oceanographic features available. Starting with their initial life-stages, eggs are spawned on the slope at about 300 – 800m (around January - March) and are generally retained at depths of about 400m and deeper, remaining somewhat buoyant. It is generally assumed that a majority of spawning occurs along the eastern and central GOA, which has a narrower continental shelf (relative to the western GOA) and may facilitate for easier cross-shelf mechanisms to transport larvae onto the shelf, through tidal amplifications, local patterns of upwelling, and interactions with the complex topography of the GOA (i.e., interactions with troughs, submarine canyons, and banks can result in tidally generated internal waves, shelf-slope eddies, and current meanders that can also bring oceanic water up to the shelf). However, some spawning likely also occurs around the western GOA region. Simulation studies have suggested that spawning along the western GOA continental slope does not result in egg and/or larval retention within the GOA, given the westward influence of the ACC, AS, and AC, and instead, likely results in eggs and larvae being transported in the Bering Sea and Aleutian Islands (assuming that no directed movement occurs). The transition from eggs to larvae is thought to occur after several weeks (12 – 30 days), where larvae are relatively large in size (~6mm), which may help improve survival rates. Furthermore, larvae are thought to only exhibit movements after about a month, during which they ascend to the neuston (around May) and are able to control their vertical movements, through the development of fairly large pectoral fins during this life-stage. As such, if eddies or meanders were to be encountered, larvae and juveniles are likely to be able to maintain their vertical positions within eddies, while exhibiting directed horizontal movements towards inshore regions when encountered. Directed horizontal movements are not unlikely for sablefish, particularly given their large pectoral fins, and because simulation studies have found that in the absence of horizontal movements, larvae rarely get advected into known regions of high juvenile sablefish abundance (Gibson et al. 2019).

The general pattern of larvae ascending to the neuston during the months of May also generally coincides with stratification processes and an offshore spring bloom, which has been found to be correlated with recruitment success (Gibson et al. 2019). As larvae develop into juveniles, it is thought that the transition from offshore to inshore regions tends to occur during the months of June to August, which corresponds with warmer water temperatures, and the highest metabolic potential for growth during this period. As noted above, sablefish tend to prefer inshore habitats as juveniles. However, it is commonly observed during high recruitment events, that juveniles will also inhabit the shelf regions, suggesting that individuals can utilize and are adapted to a variety of habitats. The ability to utilize a wide array of habitats as juveniles is likely attributed to their generalist diet, where they are able to consume a variety of prey items, minimizing the impacts of inter or intra-specific competition as juveniles. While these adaptations are not necessarily related to the physical aspects of oceanography, it does suggest that individuals that are transported into Bering Sea and Aleutian Island through the ACC, AC, and AS are likely able to be successful, despite the differences in species assemblages among these regions. Consequently, sablefish life-history is likely adapted to the oceanographic features of Alaska through 1) spawning locations (i.e., most spawning occurring along the narrow continental slope of the eastern GOA), 2) spawn and hatch timing coinciding with periods of peak productivity, 3) development of large pectoral fins to aid in transport, and 4) the ability to utilize a variety of habitats and prey items.

# Proposal

## Title:

Towards ecosystem-based linkages in stock assessment: A case-study of Alaska sablefish

## Summary

Alaska sablefish (*Anoplopoma fimbria*) are a groundfish whose annual success is episodic and is hypothesized to be governed by environmental transitions. However, specific environmental linkages to population processes that determine the success and health of the resource still remain unknown. Various hypotheses have previously linked the success of sablefish to interannual climate variability, with subsequent downstream effects on larval transport, food availability, and habitat suitability. Here, I propose to investigate the value and impact of incorporating environmental information for explaining sablefish recruitment. Our approach seeks to incorporate environmental information through the use of a state-space age-structured integrated stock assessment, which are well-suited for incorporating information with missing data and has previously been shown to be successful in utilizing environmental information. Outcomes from this project will not only improve our understanding of environmental drivers on the recruitment success of Alaska sablefish but will further facilitate the operational use of ecosystem information within single-species stock assessment models.

## Rationale

Recent variability in climate conditions in Alaska has resulted in major alterations in the dynamics of many fish stocks (Suryan et al. 2021), with subsequent impacts on associated fisheries. While species such as Pacific cod (*Gadus macrocephalus*) have experienced drastic declines in abundance (Barbeaux et al. 2020), species such as Alaska sablefish (*Anoplopoma fimbria*) have thrived during this period, where unprecedented high recruitment events have been observed (Goethel et al. 2023). In general, sablefish recruitment dynamics have been thought to be a combination of maintaining a base level of spawning biomass necessary to allow for reproduction, and prevailing environmental conditions that mediate the survival of juvenile sablefish. Although various hypotheses exist regarding environment drivers mediating the recruitment success of sablefish, these factors have rarely been tested within the context of a stock assessment model (notable exception; Shotwell et al. 2014), and thus, fail to utilize all existing information (e.g., age-composition, removals) for estimating population dynamics. Furthermore, previous studies were limited in the length of existing time-series for environmental variables and were only limited to utilizing a coarse set of environmental variables. In this study, I propose to expand existing work by: 1) incorporating a prolonged time-series, coupled with a broader suite of environmental variable within a state-space age-structured integrated stock assessment, and 2) evaluate the implications of incorporating environmental covariates to explain recruitment processes.

## Proposed Mechanisms (Hypotheses)

Existing studies have provided mechanisms and linkages for environmental drivers related to sablefish recruitment success. In particular, it is hypothesized that a strengthening of the Aleutian Low, which is generally associated with positive Pacific Decadal Oscillation (PDO) events (leading mode of North Pacific sea surface temperature variability), increases winter cool air from the Arctic that enhances productivity in the central North Pacific basin. Here, the cool air decreases surface temperatures and increases turbulence in the region, resulting in upwelling and vertical mixing of cold nutrient rich waters that are transported into the Gulf of Alaska (GOA), thereby increasing primary productivity and food availability for juvenile sablefish (Shotwell et al. 2014). Concomitantly, an intense Aleutian Low and positive PDO has been hypothesized to enhance the activity and development of anticyclonic eddies, which has not only been shown to be a hotspot for biological productivity (Atwood et al. 2010), but may also serve as a transport mechanism onto the shelf and other regions (e.g., egg transport from the WGOA into the Bering Sea or Aleutian Islands), thereby increasing system connectivity and promoting successful settlement and recruitment of sablefish (Ladd et al. 2007; Gibson et al. 2019, 2023). In addition to the successful onshore transport of sablefish through the presence of eddies, survival at young ages is also generally thought to be governed by factors related to food availability. In fact, studies have found that the offshore spring primary productivity (i.e., chlorophyll) and onshore summer primary productivity are related to the recruitment success of sablefish (Gibson et al. 2019). Furthermore, increased upwelling during the months of July in the eastern GOA (where a majority of juvenile sablefish tend to be found) has also been found to be related to recruitment, presumably due to increased production from nutrients (Coffin and Mueter 2016). Thus, the combination of eddies, increased convergence of nutrient rich offshore waters into onshore regions, and onshore and offshore primary productivity likely all play a role in governing the successful settlement and recruitment of sablefish in the population.

## Proposed Environmental Variables

Alaska sablefish are a single genetic population, exhibit extremely high movement rates, and are assessed as a coast-wide stock. Furthermore, while spawning and recruitment processes are hypothesized to occur heterogeneously across the GOA, with most individuals spawning around the EGOA and CGOA regions, it is likely that environmental conditions are favorable across Alaska, as opposed to being focused on a particular region. Thus, environmental variables utilized to investigate the proposed hypotheses will be on an Alaska wide scale, but will vary based on timing, generally coinciding with sablefish life-history events. The following environmental variables will be investigated in the current study:

1. An index of the Aleutian Low, which will be summarized using the North Pacific Index (NPI) representing different sea-level pressures. Here, negative values of the NPI represent low sea-level pressures, and hence an intense Aleutian Low, which is hypothesized to be beneficial for sablefish recruitment,
2. An index of the PDO, derived as the leading mode of North Pacific sea surface temperature variability. Here, positive values of the PDO are indicative of warmer temperatures, which are thought to be favorable for sablefish growth, but also favorable for increasing system connectivity,
3. An index for eddy kinetic energy anomalies average across the months of April to June derived using gridded altimetry data. Periods of April to June are chosen given that these periods generally encapsulate the critical period in which juveniles need to be advected onto the shelf and into onshore regions. Positive anomalies here will represent strong eddy activity, and hence increased productivity and improved recruitment conditions,
4. An index of July upwelling favorable winds across Alaska will be incorporated. While studies have found that regional indices of upwelling in the EGOA correspond to favorable recruitment events, I believe that it would be more appropriate to utilize an Alaska wide index of upwelling (given reasons discussed above).
5. An index of May offshore primary production, where positive values indicate increased chlorophyll levels, and will be used as a proxy for primary and secondary production, reflecting food availability for sablefish immediately after ascending to the neuston, where most juveniles are likely still offshore. Thus, positive values are hypothesized to result in favorable recruitment conditions,
6. Lastly, an index of July onshore primary production, where positive values similarly indicate increased chlorophyll levels, and will be used as a proxy for primary and secondary production. Here, this index reflects potential food availability for sablefish once they have entered onshore regions, and positive values are similarly hypothesized to be favorable for recruitment.

For a summary of the proposed mechanisms, hypothesized relationships, and rationale for the incorporation of the proposed environmental variables, refer to Table 1 and Figure 1.

Table 1. A summary of proposed environmental variables to be incorporated in this study.

|  |  |  |  |
| --- | --- | --- | --- |
| Environmental Variable | Time Scale of Variable | Rationale | Hypothesized Direction |
| North Pacific Index | Annual | Reflects the sea level pressure of the Aleutian Low. Negative values indicate strong Aleutian Lows that may advect nutrient rich water into the Gulf of Alaska and result in improved offshore spring primary production. | Negative values correspond to favorable recruitment. |
| PDO Index | Annual | Sablefish are sensitive to cold temperatures. A positive PDO may reflects warmer sea surface temperature conditions. The index is also hypothesized to increase eddy formation and improves cross-shelf connectivity. | Positive values correspond to favorable recruitment. |
| Eddy Kinetic Energy Index | April - June | Increased eddy kinetic energy improves cross-shelf transport of sablefish into onshore regions. | Positive values correspond to favorable recruitment. |
| Upwelling Winds | July | Increased upwelling winds in July across Alaska likely facilitates primary and secondary production and corresponds to when juveniles have likely entered their nursery grounds (i.e., onshore) | Positive values correspond to favorable recruitment. |
| Offshore Primary Production | May | Increased offshore primary production during May across Alaska improves the probability of sablefish encountering favorable feeding conditions, while they are residing in offshore areas as larvae (i.e., prior to onshore transport). | Positive values correspond to favorable recruitment. |
| Onshore Primary Production | July | Increased onshore primary production during July across Alaska improves the probability of sablefish encountering favorable feeding conditions, while they are residing in onshore areas as juveniles (i.e., following onshore transport). | Positive values correspond to favorable recruitment. |

## Modelling Approach

To assess the importance of environmental covariates in helping explain recruitment processes, I will utilize a state-space integrated age-structured model that incorporates data from age-composition, abundance indices from a survey, and fishery removals. In general, the model structure will mimic the current assessment methods, except for the recruitment sub-model (Goethel et al. 2023). Given the lack of discernable stock recruitment relationship for Alaska sablefish, the proposed study will assume mean recruitment dynamics, following lognormal deviations, similar to the parameterization of the most recent stock assessment. Here, we seek to incorporate the environmental covariates described above in a unified fashion within the assessment model. However, it is apparent that many of these variables are related to each other, which could result in issues related to parameter confounding, when attempting to simultaneously incorporate all covariates (i.e., through the formulation of a multiple linear regression model). Thus, this study primarily proposes to incorporate the framework of a structural equation model as part of the recruitment sub-model. In particular, utilizing the hypothesized relationship depicted in Figure 1, we aim to formulate a mechanistic relationship between the environmental variables in Table 1 and recruitment deviations:

where *R* represents annual recruitment, represents the mean recruitment parameter estimated, is a function describing the structural equation model depicted in Figure 1, and describes the residual error, which is governed by , where represents the degree of variability allowed for recruitment deviations. Formulating this relationship utilizing a state-space approach is beneficial because it not only allows for the estimation of latent variables that are unobserved (i.e., missing environmental data; Thorson et al. 2024), but also allows for the objective estimation of the variance parameter governing recruitment deviations.

The evaluation of the value of incorporating environmental information in stock assessments is a developing field, and it remains unclear how model selection should be conducted (Rogers et al. 2024). Furthermore, to my knowledge, no studies have attempted to embed a structural equation model describing the effects of different environmental linkages on recruitment deviations. Thus, I propose to evaluate the value of incorporating such information by constructing three separate model configurations:

1. utilizing the full suite of time-series indicators (Table 1) collected via empirical data (model *Full*; i.e., using equation 1),
2. individual time-series collected via empirical data for each environmental variable (model(s) *Cov*, where *Cov* represents the specific variable tested). Here, a single covariate is used for each model, resulting in 6 separate models, and the structural equation model described in equation 1 collapses into a simple linear regression, and
3. no environmental time-series are included.

The three models described above will then be evaluated against each other by comparing if model fits to recruitment age-composition data and or abundance indices (in units of numbers) improve. Additionally, a retrospective analysis on recruitment estimates within the assessment framework (i.e., using Mohn’s rho) will be utilized to compare the retrospective performance of different model configurations, which can help elucidate the most appropriate predictors and model structures. Lastly, if the incorporation of these environmental variables explains additional variability in the recruitment function, the estimated value of would decrease, which could be used as another metric to evaluate the utility of these environmental indices (e.g., the percent change in process variance among models).

The outcomes derived from this framework will improve our mechanistic understanding of how various environmental variables influence the recruitment success of Alaska sablefish, enabling us to better capture ongoing changes within the environment. If substantive environmental relationships are detected utilizing this framework, it is expected that the uncertainty from recruitment estimates will be reduced. This reduction in recruitment uncertainty has the potential to improve the accuracy of biomass and recruitment estimates, with the potential for more realistic population projections, thereby providing invaluable support for more informed and effective management decisions. Ultimately, the proposed framework will contribute to the advancement of ecosystem-based fisheries management practices for Alaska sablefish, enabling both decision makers and stakeholders to adopt more adaptive management and harvesting approaches.

# Figures

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Figure 1: Hypothesized relationship (and associated signs) between environmental variables and their impact on recruitment. Arrows depicted in this figure relate exogenous variables to endogenous variables (i.e., relationship of explanatory variables to response variable) (note that the length of the arrows are not meant to indicate the strength of the expected relationship but were lengthened for illustration purposes).

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