Effects of the Sitka Eddy on juvenile pink salmon in the eastern Gulf of Alaska

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Abstract

A fisheries oceanographic survey has collected physical and biological data from the eastern Gulf of Alaska during the month of July since 2010. The Sitka Eddy is a mesoscale feature that can impact physical and biological characteristics of the eastern Gulf of Alaska, and it can occur during July. Herein, the historical presence of a Sitka Eddy during July in this region was examined between 1993 and 2015 using satellite-derived altimetry, and interannual distributions of juvenile pink salmon (*Oncorhynchus gorbuscha*) were compared between 2010 and 2015. Biological characteristics of juvenile pink salmon and oceanographic conditions were compared between 2010 (strong eddy) and 2012 (weak eddy), and a further analysis across the Sitka Eddy was conducted for 2010. The Sitka Eddy occurs regularly in the eastern Gulf of Alaska, but strong events that occurred during July and likely to impact migrating salmon were only evident in 13% of the 23 years examined. Juvenile pink salmon catch distribution appeared to be deflected offshore by the Sitka Eddy in July of 2010, compared to nearshore distributions in 2011 through 2015. In 2010, temperatures were warmer, chlorophyll-a had a greater range, and juvenile pink salmon were distributed farther offshore as compared to 2012. Juvenile pink salmon diets were dominated by euphausiids in 2010 and large copepods in 2012. Additionally, Fulton's condition factor (K), insulin-like growth factor I (IGF-I), and whole body energy content (WBEC) were all lower in 2010. In 2010, temperatures reached a station maximum of 12.60 °C on the southeastern edge of the Sitka Eddy, and chlorophyll-a concentrations reached a local minimum of 0.077 µg/l in the center of the eddy. Juvenile pink salmon from the eastern edge of the Sitka Eddy had significantly elevated values of K and IGF-I ($p < 0.05$), but WBEC did not vary significantly across the Sitka Eddy. Fish north of Cross Sound, which was outside of the Sitka Eddy, exhibited significantly lower K-values ($p < 0.05$) and relatively lower values of

IGF-I and WBEC as compared to conspecifics south of Cross Sound. While the Sitka Eddy may act as an oasis offshore, when it impinges onto the shelf, it can squelch normal coastal production. By recognizing interannual variation in eddy magnitude, location, and impact to physical and biological characteristics, we can better understand and interpret interannual differences in the Gulf of Alaska ecosystem.

Key words: Pink salmon; Gulf of Alaska, anticyclonic eddy; Sitka Eddy; juvenile salmon; Insulin-like growth factor.

1. Introduction

Mesoscale eddies can restructure water masses and influence the physical and chemical properties therein (e.g., Lévy et al., 2001), and biophysical interactions resulting from eddy formation can lead to increases in primary and secondary production (Brickley and Thomas, 2004), shifts in larval fish assemblages (Atwood et al., 2010), and promotion of energy transfer to higher trophic levels (Ream et al., 2005; Godø et al., 2012). Anticyclonic mesoscale eddies are common oceanographic features that form on the eastern boundary of the Gulf of Alaska (GOA) interacting with water masses as they propagate westward (Okkonen et al., 2001). The naming convention of these eddies follows their successive discovery by Tabata (1982) of Sitka eddies off Southeast Alaska, by Crawford and Whitney (1999) of Haida eddies off Haida Gwaii of northern British Columbia, and by Gower (1989) of Yakutat eddies off the northern-most part of the GOA (Figure 1). However, evidence of higher trophic levels being impacted by eddies in the GOA is limited, and the potential that the Haida, Sitka, and Yakutat eddies may influence early life stages of commercially important groundfish and salmon remains unknown.

In the GOA, mesoscale anticyclonic eddies propagate westward from their formation regions along the eastern and northern continental margins (Crawford and Whitney, 1999; Okkonen et al., 2001). Most GOA eddies form in late winter and early spring; almost all rotate anticyclonically with typical diameters of 100 to 300 km (Crawford, 2002). Interannual variability in surface winds, which are related to the Pacific Decadal Oscillation and El Niño, can influence the formation and magnitude of eddies in the eastern GOA (Combes and Di Lorenzo, 2007). In addition, strong gap winds that blow episodically through breaks in the surrounding mountain ranges can result in the formation of eddies in the region (Ladd and Cheng, 2016). In years when the gyre circulation is strong, eddy propagation is more likely along the slope, whereas when gyre circulation is weak, eddy propagation is predominantly into the basin (Ladd et al., 2007). The Sitka Eddy travels at approximately 1.3 cm/s (Grower, 1989; Matthews et al., 1992), though the clockwise currents within eddies of the region can be in the range of 20–55 cm/s (Okkonen et al., 2003; Ladd et al., 2005a).

The GOA is a predominantly downwelling system, yet the ecosystem is productive (e.g., Stabeno et al., 2004). The central surface waters of the gulf are high-nutrient, low-chlorophyll due to iron limitation (Boyd et al., 1995; Ladd et al., 2005b). High iron levels typical of coastal waters have been observed in eddy core waters (Johnson et al., 2005; Ladd et al., 2009) and likely contributed to high chlorophyll levels during spring and summer in and near eddies that were formed along the eastern margin of the GOA (Crawford et al., 2005). When eddies are near the continental margin they can entrain coastal surface waters rich in nutrients and chlorophyll and sweep these waters far offshore (Crawford et al., 2005; Crawford et al., 2007). Often accompanying this offshore eddy flow is an onshore sweep of chlorophyll-poor basin water towards the continental margin, and sometimes onto the shelf (Crawford et al., 2005; Weingartner, 2005). An alignment of sea surface height anomaly and satellite-measured chlorophyll reveals that almost half the ocean-surface chlorophyll in basin waters of the northern GOA is associated with anticyclonic eddies, yet these eddies normally fill only ten percent of the surface area (Crawford et al., 2007). There is great interannual variability in the occurrence, size, and duration of these eddies (Ladd et al., 2007; Henson and Thomas, 2008), and thus, the resulting influence of these features on the GOA ecosystem may vary widely geographically and interannually.

All five species of Pacific salmon (Chinook *Oncorhynchus tshawytscha*, chum *O. keta*, coho *O. kisutch*, pink *O. gorbuscha*, and sockeye *O. nerka*) from a variety of stocks originating in Washington, British Columbia, and southeast Alaska are found in the eastern GOA during the summer months and migrate primarily in a northwest direction along the continental shelf (Hartt and Dell, 1986; Fisher et al., 2007; Tucker et al., 2009; Beacham et al., 2014a). River systems with large runs tend to dominate the catches in some regions, as is the case with the majority of juvenile sockeye salmon captured off the coast of southeast Alaska coming from the Fraser River, British Columbia (Beacham et al., 2014b). Because northern stocks exit rivers later in the year, they typically exhibit a smaller body size relative to conspecifics from stocks originating farther south which have spent more time feeding in the ocean (Beacham et al., 2014b; Hertz et al., 2016). As the more southern originating fish move north, they have a tendency towards an increased body size and energy density (Tucker et al., 2009).

Salmon grow and develop from juveniles to mature fish in the GOA, where the quality and quantity of their prey may be influenced by bottom-up forces. Juvenile salmon growth has been linked to environmental variability in the northern California current system, providing a direct stock-specific indicator of recruitment (Fisher and Pearcy, 1995; Fisher et al., 2014). Insulin-like growth factor I (IGF-I) studies have documented variation in regional growth rates in juvenile coho, sockeye, and chum salmon along the coast of British Columbia (Ferriss et al., 2014), and local-scale variation in IGF-I has been related to local-scale oceanographic features (Journey et al., *in press*). It has been noted that cross-shelf exchange resulting from eddies may be important to pink salmon marine survival rates in the GOA, based on information from carbon isotope values (Kline, 2010). Therefore, the likely result of a juvenile salmon encountering an eddy is an effect to its health and condition.

Ocean currents influence the distribution and growth of a fish through deflection and associated energy expenditure during a migration. For example, tagged adult sockeye salmon were deflected south while returning to British Columbia in 1958 when a Sitka Eddy was present but not in 1957 when no eddy was present (Hamilton and Mysak, 1986). This counterintuitive result can be explained using computer simulations that showed a Sitka Eddy itself does not alter adult salmon migration routes or metabolic expenditures, but it could deflect migrating salmon southward via interruption of the northward flowing Alaska Current (Healey et al., 2000). Swimming speed is often proportional to body length (BL), and a reasonable assumed fixed speed for juvenile salmon of one BL/s increases their vulnerability to strong ocean currents compared to adults; for example, juvenile sockeye salmon that were 13 to 25 cm in length had a swimming speed of 0.95 BL/s, or 12.4 to 23.8 cm/s (Welch et al., 2011), which is much less than an adult speed closer to 50 cm/s (Hamilton and Mysak, 1986). Even an unsustainable critical swimming speed for a control group of juvenile pink salmon (4–12g) was 44.1 ± 1.7 cm/s (Incardona et al., 2015). With the eastern edge of the Sitka Eddy flowing southward with current velocities on the order of 20–40 cm/s (Okkonen et al., 2003; Ladd et al., 2005a), there is great potential for this eddy to impede or displace juvenile salmon traveling northwestward along the eastern boundary of the GOA. The movement of the entire feature can also deflect or entrain larval fish (Atwood et al., 2010). Even at slow propagation speeds of 1.5 cm/s, a hypothetical juvenile salmon travelling 20 cm/s swimming across an eddy with a diameter of 200 km will spend 12 days within an eddy, during which time it will have propagated 16 km offshore. The above examples illustrate how the swift currents and slower eddy propagation can both impact fish movements.

Eddies regularly form in the eastern GOA, creating the potential for biophysical interactions that may cascade through the food web (Weingartner et al., 2009). To consider the potential for interactions between larval or juvenile fish and an eddy in the eastern GOA, we focused on juvenile pink salmon captured in a surface trawl (upper 30 m) of a fisheries oceanographic survey that occurs during the month of July. First, the variability of Sitka eddies over 23 years was examined to provide a historical context of eddies in the region. Next, juvenile pink salmon distributions relative to the presence of the Sitka Eddy were compared for a period of six years. Additionally, physical and biological survey data were contrasted between 2010, a year when a Sitka Eddy was present during the survey, and 2012, a year without a well-developed eddy during the survey. Finally, an analysis of biological characteristics of juvenile pink salmon was conducted across the Sitka Eddy that was present in 2010. Possible mechanisms to explain interactions between a Sitka Eddy and juvenile pink salmon in the eastern GOA were considered.

2. Methods

2.1 Study Region

This study occurred in the eastern GOA, along the outer coast of southeast Alaska, between 55.5 and 58.5 °N and 134.5 and 139.5 °W. Offshore, the continental shelf is approximately 5–10 km wide, with depths less than 300 m, and inside protected waters are heavily influence by coastal run-off and glacial melt (Weingartner et al., 2009). In our study area, inside protected waters and offshore waters are connected by Cross Sound (Figure 1), which continues offshore as a submerged canyon and has the potential for increased mixing and primary production (Weingartner et al., 2009; Stabeno et al., 2016). Cross Sound is also the primary point where northern southeast Alaska salmon enter the open ocean, with the majority migrating in the northwestward direction (Orsi et al., 2000). Salmon originating from southern Southeast Alaska, British Columbia, and the Pacific Northwest can be found in the nearshore and offshore waters as they continue their migration in the GOA (Beacham et al., 2014b; Hertz et al., 2016).

2.2 Data Acquisition

2.2.1 The eastern GOA surface trawl survey

Fisheries oceanographic surveys have been conducted annually in the eastern GOA during the month of July, beginning with the initial survey (pilot survey) in 2010. For this analysis, survey data from 2010 to 2015 were utilized. Physical and biological attributes of the eastern GOA pelagic ecosystem were assessed, including oceanography and relative juvenile fish abundance.

Surface trawls were conducted on stations that were equally spaced on a grid from the coast to approximately 100 nautical miles offshore. The Nordic 264 rope trawl used during the pilot year was 184 m long with mouth dimensions averaging 19 m wide by 20 m deep; the headrope was buoyed so that fishing occurred right below the surface, and net meshes decreased from 162.6 cm near the mouth to a 0.8-cm knotless liner. Subsequent surveys utilized a larger Cantrawl model #400, a 198-m midwater rope trawl with mouth dimensions averaging 44 m wide by 38 m deep, modified for use in the epipelagic zone, with mesh sizes ranging from 162 cm to a 1.2-cm cod end mesh liner. Each haul was 30 minutes and was towed at approximately 2.5–4.5 knots across a station, with the haul direction determined by current, wind, and swell conditions. For more details on this survey, see Strasburger et al. (2018).

For comparisons between 2010 and 2012, conductivity-temperature-depth (CTD) profiles and water samples allowed the tracking of temperatures and chlorophyll-a concentrations (chl-a). A Seabird model 19+ was utilized in 2010 with two Niskin bottles collecting water (0 and 10 m), while a Seabird 16+ was utilized in 2012 with six Niskin bottles sampled from a rosette (0, 10, 20, 30, 40, and 50 m). Note that a fluorometer was included in 2012 but not in 2010; therefore, only discrete chl-a samples from 0 and 10 m were collected during both years. Because values from these depths were linearly related ($R^2 = 0.93$ in 2010; $R^2 = 0.91$ in 2012), only 10-m samples were included in this analysis. Following the retrieval of Niskin bottles, 300-ml water samples were filtered through Whatman GF/F filters (pore size 0.7µm) and immediately frozen at -40 °C aboard the ship.

After each trawl was retrieved at a sampling station, the catch was emptied onto a sorting table where fish were separated according to species and age class. The first two juvenile salmon of each species captured were bagged individually for calorimetry analysis and the next ten were bagged in bulk for diet analysis. Blood samples from juvenile salmon were collected via heparinized syringe; blood was immediately centrifuged, and the plasma was removed from the red blood cells and stored in a -40 °C freezer aboard the ship. Fish samples were frozen whole in a -20 °C freezer on board the ship. Fork length (FL, mm) and wet weight (g) of up to 50 individuals per species were measured at each station. Any additional fish were weighed in bulk for calculation of total station catch. We focused on pink salmon because they were the most abundant and widely distributed among the juvenile salmon and because of their commercial importance to the southeast Alaska region. Additionally, there are inherent differences between returning pink salmon during odd and even years, so comparisons between 2010 and 2012 included fish harvested during odd years, 2011 and 2013. Relative abundances of juvenile pink salmon were compared by using catch per unit effort (CPUE), which was calculated by dividing total catch number by the volume of water (km^3) sampled at a given station.

2.2.2 Altimetry in the eastern GOA

The presence of mesoscale eddies within the survey grid was not identified before or during sampling, but anticyclonic eddies in the northern hemisphere can be identified by positive sea-level anomalies (SLA) measured via satellite. Gridded (0.25° latitude by 0.25° longitude) daily mean SLA along with geostrophic current anomalies (u, v) were downloaded from the Global Ocean product, a multimission delayed-time altimeter satellite dataset provided by E.U.

Copernicus Marine Environment Monitoring Services (CMEMS, 2017). The anomalies were computed with respect to a twenty-year mean and include data from all altimeter missions.

2.3 Post survey processing

All CTD data and frozen samples were processed following the conclusion of the survey. Chl-a samples were stored in a -80 °C freezer until processing, and within 6 months, filters were analyzed for total chl-a (µg/l) using a Turner Designs (TD-700) bench top fluorometer following standard acidification methods (Parsons et al., 1984). Chl-a data were natural-log transformed prior to analysis. Temperature recorded from the CTDs was averaged over the top 20 m of the water column for each station.

Plasma samples used for IGF-I determination were transported frozen and stored in a -80 °C freezer until processing. Concentration of plasma IGF-I for individual fish was measured using the time-resolved fluorescence immunoassay developed by Small and Peterson (2005) as modified by Ferriss et al. (2014). Across individual assays, all samples were standardized using inter-assay pools of juvenile coho salmon plasma at three known IGF-I concentrations (low, medium, and high), corresponding to approximately 75, 50, and 25 % binding in the immunoassay. Data standardization and complete laboratory techniques are detailed in Ferriss et al. (2014).

Juvenile pink salmon diets were determined from stomach contents which were frozen in a -20 °C freezer after the survey. At the laboratory, frozen fish were thawed, stomachs were removed, and the food bolus was preserved in 10% formalin. Stomach contents were then microscopically examined and prey items were identified to the lowest taxonomic level possible. Each of the taxonomic groups was blotted and weighed to the nearest 0.1 mg, and prey were summarized by major prey categories: euphausiid, copepod, fish, gastropod, amphipod, and other (e.g. barnacle larvae, chaetognath, and decapods). Prey composition was examined as percent weight by prey category and summarized by year and across sampled eddies.

We used metrics for condition, growth, and energy density to assess the relative health of juvenile pink salmon. Fulton's condition factor (K) assumes fish weight scales to the cube of its length (Fulton, 1904). All juvenile salmon with lengths and weights measured were used to calculate K ($K = 10^6 * W/L^3$), where W was wet weight (g) and L was FL (mm). IGF-I provided a metric for immediate health; laboratory studies have demonstrated that IGF-I levels are stimulated by feeding and reduced by fasting within a time-scale of hours to days and are directly related to growth rate over periods of approximately one week (Beckman et al., 2004; Beckman, 2011; Shimizu et al., 2009). Whole fish were stored in a -20 °C freezer after the survey and before processing to determine whole body energy content (WBEC). Fish were dried until reaching a constant weight and ground to a uniform powder before pressing approximately 0.15 g into a pellet. Samples from two juvenile pink salmon per station were processed using a 1425 Parr micro-bomb calorimeter to determine calories per gram of dry weight. We converted this to kilojoules per gram of wet weight (kJ/g) prior to analysis.

2.4 Data Analysis

Our primary method for this analysis was comparing summary statistics (means, standard errors, and ranges) and mapping of (1) SLA and speeds of geostrophic current anomalies from 1993 to

2015, (2) juvenile pink salmon distribution from 2010 to 2015, (3) survey data from strong eddy year 2010 and weak eddy year 2012, and (4) survey data by eddy defined groups in 2010. All maps were created utilizing the R-based (R Core Team, 2016) packages "PBSmapping" (Schnute et al., 2015) and "raster" (Hijmans, 2016). Additional statistical analysis was conducted across eddy defined groups in 2010.

2.4.1 Altimetry in the eastern GOA, 1993 to 2015

Maps were created to illustrate the interannual differences in location, size, and intensity of eddies across the eastern GOA survey area during July (Figure 2). Each year was represented by averaging the daily SLA and speeds of geostrophic current anomalies ($\sqrt{u^2 + v^2}$) for the month of July.

2.4.2 Juvenile pink salmon distribution from 2010 to 2015

Catches of juvenile pink salmon in surface trawls were mapped from 2010 to 2015. This survey has been slightly modified every year in terms of stations occupied and timing to accommodate available ship time and survey priorities. As such, only samples from the month of July were included from stations between 55.5 and 58.5 °N and 134.5 and 139.5 °W. Natural-log transformed catch numbers, deemphasizing large catches, were mapped to illustrate relative distribution of juvenile pink salmon captured during July of each year.

2.4.3 Comparison of eastern GOA survey between 2010 and 2012

Direct comparisons were made between a year when a strong Sitka Eddy was present on the survey (2010) and one when only a weak eddy was observed (2012). Temperature, chl-a, and juvenile pink salmon data (CPUE, K, IGF-I, and WBEC) were mapped. Mean values and standard errors of these characteristics were calculated for each year, and CPUE data were natural-log transformed before mapping to make differences more visually recognizable. Average July geostrophic current anomalies were overlain on maps as references to the magnitude and direction of eddy circulation. The minimum and maximum SLA and speed of current anomaly from July were determined for the region between 55.5 and 58.5 °N and 134.5 and 139.5 °W. Juvenile pink salmon diet data were summarized by year.

2.4.4 Eddy-based analysis in 2010

To examine the effect of the Sitka Eddy on local oceanography and biology we divided stations from July 2010 into areas inside and outside of the eddy as well as latitudinally across the survey grid. Eddy groups were based on SLA and geography, and these were used for analysis of variance (ANOVA) testing. Because the survey occurred over several weeks, we utilized daily SLA data from CMEMS to interpolate values for stations on the day which they were sampled. The eddy in 2010 had a maximum SLA of 31.6 cm, and spanned approximately 185 km longitudinally and 165 km latitudinally. Stations with an interpolated SLA greater than 20 cm were considered to be wholly in the eddy and placed in the “In.Eddy” group. Stations with an interpolated SLA between -2.5 and 20 cm in close radial proximity to the center (i.e., continuously decreasing SLA from the maximum) of the eddy were considered to be on its edge. The edge of the eddy was then split into two equal groups, one along the northern edge or “N.Eddy” group, and the other along the eastern edge or “E.Eddy”. No stations were sampled along the southern or western boundary of the eddy. The remainder of the stations were considered outside of the eddy and divided along survey grid lines that run perpendicular to the coast, separating stations north of Cross Sound, south of Sitka Sound, and those in between as follows: stations north of the "K-line" classified as northern outside or the "N.Out" group, stations on and south of the "D-line" classified as southern outside or the "S.Out" group, and those in between as middle outside or the "M.Out" group (Figure 1). The resulting number of stations by eddy group is as follows: 18-N.Out, 8-M.Out, 10-S.Out, 9-N.Eddy, 9-In.Eddy, and 9-E.Eddy.

A multifaceted approach was taken to describe spatial characteristics of juvenile pink salmon distribution and growth as they relate to the presence of a Sitka Eddy in 2010. First, the mean and standard error of temperature, chl-a, and juvenile pink salmon CPUE, K, IGF-I, and WBEC were calculated by eddy group. To test whether temperature, chl-a, K, IGF-I, or WBEC varied among eddy group, we utilized an ANOVA test with a subsequent TukeyHSD *post hoc* test. Residual plots were used to assess assumptions of normality and independence, and these assumptions were met unless stated otherwise. When the assumption of equal variance was not met, as indicated by Levene's test ($p < 0.05$), then Welch's ANOVA assuming unequal variance with a subsequent Games-Howell *post hoc* test was conducted. Statistical analyses were conducted using the R base package (R Core Team, 2016) in addition to the packages "car" (Fox and Weisberg, 2011) and "userfriendlyscience" (Peters, 2016). Juvenile salmon diet data were also summarized by eddy group.

3. Results

3.1 Characterization of a Sitka Eddy using altimetry, 1993 to 2015

Visual inspection of maps showing SLA and geostrophic current anomalies averaged for the month of July show the presence or absence of a Sitka Eddy in the eastern GOA. There is evidence for eddy circulation in most years, but the intensity of current velocities and range in SLA vary greatly (Figure 2). Weak eddy formation was visible in 1994, 1997, 1999, 2000, 2001, 2006, 2007, 2009, and 2012, with somewhat stronger anticyclonic currents present in 1996, 1998, 2002, 2003, 2008, 2011, 2013, and 2014. Strong eddy circulation is evident in 1993, 1995, 2004, 2005, 2010, and 2015 (Figure 2). Anomalous southward flow in the nearshore corridor, where juvenile salmon are most likely to be migrating northward, was only evident in about half of examined years, making these eddy currents a common feature that can influence juvenile salmon. However, of the 23 years examined, only 1993, 1996, and 2010 (~13%) showed southward anomalies greater than 30 cm/s near the coast.

3.2 Juvenile pink salmon distribution from 2010 to 2015

Juvenile pink salmon were captured just outside of Cross Sound during all six years; however, the distribution of catches varied south of Cross Sound and offshore (Figure 3). There were always juvenile pink salmon captured from at least one nearshore station, and between 2012 and 2015, the distribution appears to be limited to this nearshore region (Figure 3). Differences in the location of stations sampled during July make direct comparison challenging, as offshore stations in 2011 were sampled later in August such that a western boundary is uncertain using only July catches. Additionally, an abbreviated survey in 2015 only surveyed north of Sitka Sound and offshore in the northern half. Considering the years with broad coverage (2010, 2012, 2013, and 2014), it is clear that 2010 is the only year in which juvenile pink salmon were broadly dispersed offshore, even at latitudes where there were none captured at the nearshore stations (Figure 3).

3.3 Comparison of eastern GOA survey between 2010 and 2012

Sampling during July of 2010 and 2012 was similar but included some differences, with 63 stations examined from 2010 and 68 from 2012. The majority of stations overlie each other geographically, though in 2010, some stations stretched farther north and south, while the 2012 survey sampled more stations in the southwest portion of the grid (Figure 4). Average latitude and longitude of stations from 2010 and 2012 were (57.3 °N, 137.2 °W) and (57.1 °N, 136.9 °W), respectively.

3.3.1 Altimetry over eastern GOA survey, 2010 and 2012

Despite both years having anticyclonic eddies in nearly the same location, the ranges of SLA and speeds of current anomaly in 2010 were greater than in 2012, indicating a stronger eddy was present in 2010 (Figure 2). In 2010, SLA spanned between -10.9 and 31.6 cm, and speed of current anomaly spanned from 0.7 to 57.2 cm/s. In 2012, SLA only spanned between -9.5 and 13.3 cm, and speed of current anomaly spanned from 0.1 to 29.2 cm/s.

3.3.2 Temperature and chlorophyll

On average, surface waters were warmer and chl-a (at 10 m) was slightly higher in 2010 compared with 2012, though geographical variation occurred (Figure 4). Though the means differed, the range of surface water temperatures was similar in both years, with a mean of 11.52 °C and a range of 8.73 to 12.60 °C in 2010, and a mean of 10.87 °C and range of 8.91 to 12.00 °C in 2012. Stations near Cross Sound had the coolest surface temperatures in both years. Though the annual means were only slightly different, the maximum value of chl-a was higher in

2010, with a mean of 0.99 µg/l and range of 0.08 to 5.74 µg/l compared to a mean of 0.95 µg/l and range of 0.10 to 3.05 µg/l in 2012. There was a north to south warming trend in 2010, while the reverse was apparent in 2012. Temperatures along the coast were cooler than adjacent offshore waters and exhibited the highest chl-a concentrations in both years. Although chl-a concentration was low in the southwestern portion of the grid for both years, this region was the warmest section in 2010 and relatively cool in 2012 (Figure 4).

3.3.3 Juvenile pink salmon CPUE

Overall, CPUE was higher in 2010, occurring over a broad region compared to 2012 when catches were lower and narrowly distributed at the nearshore stations (Figure 4 and Table 1). At stations which captured juvenile pink salmon, CPUE ranged between 950 and 320,344 fish per km^3 in 2010 and between 715 to 79,347 fish per km^3 in 2012. CPUE was relatively high for both years near Cross Sound, and in 2010 CPUE was also relatively high at southern and southwestern stations (Figure 4).

3.3.4 Juvenile pink salmon diets

Diets were examined from 267 juvenile pink salmon in 2010 and 70 in 2012, and overall, diets were dominated by euphausiids in 2010 and copepods (mostly > 2.5 mm) in 2012 (Figure 5). Diets in 2012 were more varied, with amphipods (hyperiids) and gastropods common and even dominant at some stations. In 2010, gastropods were a smaller component of diets across the survey grid (Figure 5).

3.3.5 Juvenile pink salmon condition, growth, and energy density

Juvenile pink salmon examined in 2010 were smaller (mean FL of 129.5 mm with a range between 81 and 246 mm, and mean weight of 22.0 g with a range between 3 and 188 g) compared to 2012 (mean FL of 145.2 mm with a range between 83 and 195 mm, and mean weight of 33.0 g with a range between 4 and 82 g). Values of K, IGF-I, and WBEC were all higher in 2012 compared to conspecifics in 2010 (Table 1). Individual juvenile pink salmon had K values between 0.33 and 1.39 in 2010 and between 0.53 and 1.51 in 2012. Both years exhibited relatively lower values of K north of Cross Sound and along the coast, with a relative maxima at the farthest south transect in 2012 and offshore of Sitka Sound in 2010 (Figure 6). Values of IGF-I ranged from 32.4 to 88.1 in 2010, with a local maxima coinciding with K, while these values ranged from 46.2 to 117.4 in 2012, increasing from south to north (Figure 6). The range of WBEC was between 4.2 and 5.7 kJ/g in 2010, with low overall variation across the survey grid and local maxima in the northern and southern portions; WBEC was between 4.6 and 6.2 kJ/g in 2012, with the highest value occurring southwest of Cross Sound (Figure 6).

3.4.1 Temperature and chlorophyll

Mean temperatures in 2010 were warmer within the eddy compared to stations outside (Figure 4): E.Eddy (12.09 °C), In.Eddy (11.92 °C), N.Eddy (11.71°C), S.Out (11.51 °C), M.Out (11.46 °C), and N.Out (10.93 °C). We were unable to assume homogeneous variance (Levene's test, $p < 0.001$), but we still detected a significant difference in temperatures among eddy groups (Welch's ANOVA, $p < 0.001$). The N.Out group exhibited significantly lower temps than the N.Eddy (Games-Howell, $p < 0.05$), In.Eddy (Games-Howell, $p < 0.01$), and E.Eddy (Games-Howell, $p = 0.001$) groups. Additionally, the E.Eddy group was significantly warmer than the M.Out group (Games-Howell, $p < 0.05$).

All non-eddy groups exhibited higher mean chl-a than all eddy groups, with an increasing gradient from the north to the south: N.Out (0.81 μg/l), M.Out (1.07 μg/l), and S.Out (2.40 μg/l). Within the eddy groups, the center of the eddy was chl-a depleted relative to the edges: N.Eddy (0.62 μg/l), In.Eddy (0.33 μg/l), and E.Eddy (0.73 μg/l). At the station level, chl-a was highest along the coast, decreasing towards the eddy center and increasing on the offshore edge (Figure 4). After taking the natural-log of chl-a values to meet our normality assumption, we were able to detect a significant difference in chl-a among eddy groups (ANOVA, $p < 0.001$). The S.Out group exhibited significantly higher levels of chl-a than the N.Eddy (TukeyHSD, $p < 0.01$), In.Eddy (TukeyHSD, $p < 0.001$), and N.Out (TukeyHSD, $p < 0.05$) groups.

3.4.2 Juvenile pink salmon catch

The proportion of stations at which juvenile pink salmon occurred varied among the different eddy groups: 50%-N.Out, 37.5%-M.Out, 90%-S.Out, 56%-N.Eddy, 67%-In.Eddy, and 89%-E.Eddy. An apparent gap in distribution appears for the N.Eddy and M.Out groups, which exhibited much lower CPUE (Table 1), despite the high levels of chl-a observed (Figure 4). These eddy groups coincide with eastward flowing geostrophic current anomalies, advecting offshore waters towards the coast during 2010. CPUE was highest in the S.Out group, with high values in the In.Eddy, E.Eddy, and N.Out groups as well (Figure 4 and Table 1).

3.4.3 Juvenile pink salmon diets

There was some variation in diets across eddy groups, though euphausiids were the dominant taxa in stomachs at all stations. An increased contribution of copepods to diets was evident for stations in the N.Out group, and fish were relatively more prevalent in diets of the N.Eddy and N.Out groups (Figure 5). Only one empty stomach was observed in 2010, from a fish caught in the S.Out group.

3.4.4 Juvenile pink salmon condition

Among eddy groups in 2010, K values for juvenile pink salmon was highest for the E.Eddy group and lowest for the N.Out group. An increasing gradient in K values from north to south existed both inside and outside of the eddy (Table 1 and Figure 6). We were unable to assume homogeneous variance (Levene's test, $p < 0.001$), but we still detected a significant difference in K values among eddy groups (Welch's ANOVA, $p < 0.001$). The N.Out and M.Out groups both had significantly lower K values than In.Eddy, E.Eddy, and S.Out (Games-Howell, $p < 0.05$ for all). The E.Eddy was also significantly higher than the In.Eddy group (Games-Howell, $p < 0.05$).

3.4.5 Juvenile pink salmon growth

Values of IGF-I for juvenile pink salmon were highest for the E.Eddy group and relatively lower for all others (Table 1 and Figure 6). Outside of the eddy, IGF-I values were nearly identical, while a gradient existed within the eddy, declining from the E.Eddy to In.Eddy group, and reaching a low at the N.Eddy group. We were unable to assume homogeneous variance (Levene's test, $p = 0.026$), but we still detected a significant difference among eddy groups (Welch's ANOVA, $p < 0.01$). The E.Eddy group exhibited IGF-I values significantly higher than the N.Eddy group (Games-Howell, $p < 0.01$).

3.4.6 Juvenile pink salmon energy density

The highest WBEC was observed for the N.Out and S.Out groups, and the lowest for the N.Eddy group (Table 1 and Figure 6). No significant difference in WBEC among eddy groups was detected (ANOVA, p = 0.09), but there was a gradient within the eddy, where WEBC was highest for the E.Eddy group, similar for In.Eddy group, and lowest for the N.Eddy group (Table 1).

4. Discussion

The Sitka Eddy may be a mechanism that can deflect juvenile salmon into more or less favorable environmental conditions as they travel northward in the eastern GOA. During July of 2010 when an anticyclonic Sitka Eddy was present near the eastern GOA shelf, juvenile pink salmon were observed offshore in the middle regions of the survey grid and infrequently in the nearshore environment just south of Cross Sound. In July of 2011 through 2015, when only weak eddy circulation was evident, juvenile pink salmon were more limited to the nearshore stations. The Alaska Current flows towards the northwest along the eastern GOA continental shelf (Weingartner, 2005), and when an eddy is not present, juvenile salmon swim with these flows on their northward alongshore migration. However, when a strong Sitka Eddy is present in this region, as was the case in 2010, the nearshore salmon migration corridor is interrupted as the northern edge of the eddy advects offshore waters from west to east and nearshore waters are advected alongshore to the south and offshore to the west and southwest. We believe that the presence of a strong Sitka Eddy is likely to have an effect on salmon stocks from southern Southeast Alaska, British Columbia, and the Pacific Northwest that contend with anomalous head currents, while stocks from northern Southeast Alaska only rarely have the potential for negative interactions with this feature as they exit Cross Sound and move northward.

The formation and propagation of eddies in the eastern GOA can be related to the general climate patterns in the North Pacific Ocean, and eddies may be one mechanism through which climate can impact salmon. A positive Pacific Decadal Oscillation, negatively related to the North Pacific Index (NPI), results in strong southeasterly winds that lead to an increase in coastal downwelling, increase in SLA, and intensification in the GOA gyre circulation (Combes and Di Lorenzo, 2007; Hermann et al., 2016). While these conditions can lead to the formation of eddies, warm El Niño conditions can also destabilize the Alaska Current and further contribute to the formation of an eddy field (Melsom et al., 1999), thus resulting in some of the strongest eddy events recorded (Combes and Di Lorenzo, 2007). The NPI experienced during the entry of pink salmon into the ocean is positively correlated with pink salmon harvests the following year (Wertheimer et al. 2016). Because large mesoscale eddies form during winters with a low NPI, this could be a mechanism to explain why juvenile pink salmon entering the ocean during a lower NPI result in poorer returns the following year. The 2010 Sitka Eddy formed during the winter of 2009–2010, which was characterized by a negative NPI anomaly of -2.41 (Hurrell and National, 2017) and warm El Niño conditions (Kim et al., 2011). Climatic shifts can cause variable eddy formation in the eastern GOA, and in conjunction with other climate-mediated processes such changes to zooplankton community composition (see the observed differences in zooplankton found in diets between 2010 and 2012, Fig. 5), a strong eddy likely negatively influences juvenile salmon. The ability to test this hypothesis is limited because southeast Alaska returns include northern and southern stocks, while our juvenile salmon data are not stock specific. However, the presence of a strong eddy in the eastern GOA (Yakutat, Sitka, or Haida) may be a good indicator for basin-scale climate variation, such as general shifts in the prey community, and this merits further investigation.

4.1 Altimetry

When present, the Sitka Eddy is a possible mechanism for climatic variability to influence biophysical interactions. Because the Sitka Eddy is generally centered at the edge of the sampling grid, 57 °N 138 °W (Tabata, 1982), we would only expect to occasionally sample over this feature, but recognition of this feature prior to sampling will allow for adaptive sampling in the future. There has been a lot of variation in the location and magnitude of the Sitka Eddy along the eastern GOA, and this retrospective analysis of July altimetry data in the eastern GOA from the years 1993 to 2015, found only three years (1993, 1996, and 2010) during which an eddy was likely to greatly impede juvenile salmon migrations with speeds of current anomalies greater than 30 cm/s in the nearshore corridor. It is also possible to utilize satellite derived data, such as sea surface temperature (SST) and chl-a when discrete data is not available (Figure A.1 and A.2).

4.2 Juvenile pink salmon distribution

When there are strong southward current anomalies along the coast of southeast Alaska, they are likely to deflect the juvenile salmon migrating northwards. Juvenile salmon were clearly more widely distributed in 2010, when an anticyclonic Sitka Eddy was present, compared to all other years surveyed when no strong eddy was present. Because northward migrating juvenile salmon are encountering anticyclonic current speed anomalies that are faster than regular swimming speeds, the current likely deflects fish westward. As the fish progresses towards the center of the eddy, the anticyclonic currents relax, which allows further northward progression into the center of the eddy and eventually into the west to east currents along the northern edge. In 2010, there were relatively few juvenile pink salmon found in the northern edge of the eddy and middle nearshore region where current anomalies were advecting offshore waters eastward and southward, respectively. In years when no strong current anomalies were deflecting juvenile pink salmon, they were primarily found in the nearshore corridor where chl-a appears to be greatest.

4.3 Differences between 2010 with an eddy and 2012 without an eddy

Values of SLA and speed of current anomaly from the region immediately sampled by the survey in 2010 and 2012 provided a good indication of the difference in eddy intensity experienced during these years. The greater minima and maxima of these variables was indicative of a stronger eddy in 2010, providing quantitative differences in addition to the already observed qualitative differences in the maps. In the future, a near-real-time analysis of SLA and speed of current anomaly values mapped over the survey region can be conducted before the start of the survey, allowing for adaptive sampling across this feature if desired. This information can further be used to aid the *post-hoc* interpretation of physical and biological characteristics such as temperature, chl-a, species distribution, and fish growth when surveys coincide with a Sitka Eddy, providing a better understanding of the impact of environmental drivers on juvenile fishes in the eastern GOA.

In general, the surface waters exhibited similar temperature structure in 2010 and 2012 (Figure A.1), though when averaged over the top 20 m, waters were slightly warmer in 2010 compared to 2012. This difference may be linked to the same climatic differences that led to the formation of a strong Sitka Eddy that year. For example, the moderate El Niño conditions that occurred in 2009/2010 likely played a role in the formation of the 2010 Sitka Eddy (Combes and Di Lorenzo, 2007), and these conditions also produce warmer air temperatures and SST in eastern Alaska (Papineau, 2001). Values of chl-a differed less, and as expected, chl-a was highest along the coast and more varied offshore for both years due to the higher availability of terrigenous derived iron nearshore that becomes a limiting factor offshore in the GOA (Wu et al., 2009). Satellite derived variables can give more insight into this region, and average July sea surface temperatures were similar between 2010 and 2012, though the Sitka Eddy appears to be pulling warmer water farther offshore on its southern edge and drawing cooler water shoreward in 2010 (Figure A.1). The average chl-a concentration for July appears greater in 2012, especially along the coast, though extensive cloud cover in 2010 resulted in limited ocean color observations over the Sitka Eddy (Figure A.2).

Euphausiids were the dominant prey of juvenile pink salmon in 2010, while copepods were dominant in 2012. Zooplankton information was not available for 2010, making a direct comparison of the available zooplankton communities experienced during both surveys untenable; however, the Southeast Coastal Monitoring project has examined zooplankton in nearby Icy Strait between May and August from 1997 through 2015. For 2010, euphausiids were anomalously high while large calanoid copepods were anomalously low, while 2012 exhibited average copepod abundance, less than average euphausiid abundance, and the highest abundance of gastropods recorded (Fergusson and Orsi, 2016). It remains unclear if the eddy had any influence on observed diets, as euphausiids were the dominant prey item across the entire survey region in 2010, and this highlights the complexity of the bio-physical relationships in the GOA.

Primary factors influencing efficiency of fish growth are temperature, prey quality/quantity, and activity rates (e.g., Kerr, 1971; Handeland et al., 2008; and Leeseberg and Keeley, 2014). All three metrics of growth/condition that we observed were lower in 2010 compared to 2012. While temperature is positively related to early marine growth of salmon (e.g. Orsi et al., 2000), temperature does not have a great effect on juvenile salmon metabolism when the thermal range is optimal, between 8–19 °C for the maximum feeding rate and 5–16 °C for a 50% of the maximum feeding rate (Beauchamp et al., 2007). Since temperature ranges during 2010 were considered within this optimal range, prey quality and quantity, or possibly a temperature effect on prey, are more likely responsible for the observed difference. The quality of dominant prey types by year were comparable: euphausiids in 2010, 3.11 kJ/g, and large copepods in 2012, 2.63 kJ/g (Davis et al., 1998; Boldt and Haldorson, 2002), suggesting prey quantity as the more likely cause for the differences in juvenile pink salmon growth between 2010 and 2012. Low prey quantities occur when there are too many predators relative to the number of prey or when productivity is low. High numbers of pink salmon in 2010 compared to 2012 is a potential reason for the difference in IGF-I observed, and despite having high quality prey available, there was not a sufficient quantity of it that would translate into increased higher growth relative to 2012. Alternatively, lower chl-a in 2010 suggests that primary productivity was lower than 2012, and this may result in a more limited density of prey in 2010 compared to 2012.

4.4 Differences across a Sitka Eddy in 2010

By examining survey data associated with different eddy based groups defined with altimetry, we were able to better understand how a Sitka Eddy may help explain the unexpected distribution of juvenile pink salmon and associated biological characteristics observed in 2010. The greatest overall differences were observed between the N.Out group and the others. These are largely attributed to differing water characteristics associated with and differing stocks of pink salmon exiting from Cross Sound (Orsi et al., 2000). Surface waters at stations in the N.Out group differed from the remainder of the survey grid in 2010, with cooler temperatures and moderate chl-a concentrations which were likely a result of the cooler, turbid, freshwater associated with the glacial fed waters exiting Cross Sound (Weingartner et al., 2009). Catches of pink salmon exiting Cross Sound and heading north were relatively high, and these fish were predominantly out migrating from northern Southeast Alaska origins (Orsi et al., 2000), while those conspecifics captured south of Cross Sound were likely originating from southern Southeast Alaska, British Columbia, and the Pacific Northwest (Beacham et al., 2014b; Hertz et al. 2016). Similarly, the smaller size of juvenile pink salmon in the N.Out and M.Out group is likely a function of these originating in northern Southeast Alaska, which means they exited their natal streams later in the year and had spent less time feeding in the ocean compared to conspecifics originating from farther south stocks. The diets of juvenile pink salmon in the N.Out group exhibited a greater portion of copepods, more similar to diets taken in 2012 than the other eddy groups in 2010.

Focusing on just those groups south of Cross Sound, the Sitka Eddy appears to play a more significant role, and various patterns emerge in juvenile pink salmon growth and condition across eddy groups. As pink salmon from southern Southeast Alaska, British Columbia, and the Pacific Northwest travel northwards, they appear to be deflected offshore by the eddy. Juvenile pink salmon found in the E.Eddy group had the highest values for K, indicating positive conditions to that point in their migration, and the highest values of IGF-I, indicating recent positive conditions. However, as they progress northward and are deflected offshore, juvenile salmon health, as reflected by K, IGF-I, and WBEC, declines in the center of the eddy and gets progressively worse on the northern edge of the eddy. Because all three indicators for health decline across the eddy, juvenile salmon are probably being retained in the Sitka Eddy for extended periods of time. Using an eddy circulation speed of 30 cm/s and an offshore-northward deflection of approximately 220 km, fish going with the flow would be entrained for about eight and half days. If any time is spent swimming against the current, a likely scenario for a northwest migrating fish encountering a south flowing current, the length of time in the eddy will be much greater.

4.5 A conceptual model for the size and distribution of juvenile pink salmon in the eastern GOA

Mesoscale eddies are one potential oceanographic feature that, when present, may impact larval and juvenile fish distributions. When only weak anticyclonic circulation was observed in 2012, juvenile pink salmon were only captured along the nearshore corridor, which coincided with relatively higher chl-a (Figures 4, A.2). The geostrophic currents associated with anticyclonic circulation in 2012, did not appear strong enough to deflect juvenile pink salmon away from the coast. We hypothesize that the presence of a Sitka Eddy in the eastern GOA can impede the northward migration of juvenile salmon by displacing southern origin stocks offshore where chl-a levels decline and conditions are less favorable to survival.

The historical assessment of a Sitka Eddy on the survey grid during the month of July indicated that juvenile salmon exiting Cross Sound and migrating northward are much less likely to encounter an eddy at this time and place (Figure 2). Therefore, in the rare year when a Sitka Eddy induces westward or southward currents near Cross Sound, which was only 2011 in this analysis (Figure 2), this feature may have an effect on juvenile salmon originating in northern Southeast Alaska. There is also the possibility that a Yakutat Eddy could impact these stocks as they progress farther north and west. Owing to the more recent time of entry into the marine environment and localized entry into the open ocean at Cross Sound, this region was expected to always have relatively smaller fish in greater abundance relative to regions farther south, and this is what was observed in both 2010 and 2012.

It is possible that the presence of the Sitka Eddy actually reduces pink salmon production. Although a Sitka Eddy can be considered an oasis when offshore and surrounding waters have low productivity, in this study, an eddy impinged onto the shelf is advecting offshore water to the coast, which may squelch normal coastal production. During years in which no strong eddy is present, as was observed in 2012, juvenile salmon originating farther south should increase in size as they progress northward; thus, due to more time in the ocean to feed, they would be expected to be larger than conspecifics exiting Cross Sound (Figure 7). Conversely, when a Sitka Eddy was present in 2010, the northern edge advected chl-a depleted waters from offshore onto the coast, while chl-a rich nearshore waters were advected to the southeast corner of the eddy – the E.Eddy group. Therefore, we propose that juvenile salmon encountering a front in the southeast corner of the eddy may find adequate primary and secondary production, leading to normal levels of juvenile salmon growth and condition, but as these fish are deflected off-shelf, they will encounter chl-a depleted waters with fewer prey resources leading to poorer condition (Figure 7).

5. Conclusions

This study emphasizes the possible influence of a mesoscale eddy in the eastern GOA to disrupt the northward migration of juvenile salmon with repercussions that influence growth. Juvenile salmon progressing northwards along the coast of southeast Alaska are feeding to build up energy reserves that will improve their ability to overwinter. Physical features that hinder this movement, or alter the primary and secondary production in the ecosystem, may impact the rate of survival. It is possible that the presence of an eddy can have a match-mismatch type effect on juvenile fish unable to swim through the currents associated with the eddy. While a larger fish in an area with little or poor quality prey can swim faster than the eddy current to an area with improved prey options, smaller juvenile fish are more likely to be deflected or entrained by an eddy and unable to improve a poor situation. For juvenile salmon originating in southern Southeast Alaska and south, their initial encounter with the southeastern corner of the eddy may match the fish in a region with normal to high primary and secondary production associated with nearshore waters being advected offshore and mixed. However, as these same fish are deflected towards the eddy core and northern eddy edge, the juvenile salmon are mismatched into a region with much lower primary and secondary production associated with offshore waters being advected shoreward. For fish originating in northern Southeast Alaska and exiting Cross Sound, the Sitka Eddy appears less likely to have a significant effect.

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8. Figure Captions

Figure 1. Map of the Gulf of Alaska, where lines with arrows indicate ocean currents, nominal locations of anticyclonic eddies and significant geographic features in survey region are labeled, and the Southeast Alaska study region is shown in the bold black rectangle. Inset shows stations sampled during the 2010 survey including the dotted “K” and “D” survey grid lines used to separate stations into eddy groups for statistical comparisons; the open triangle is N.Eddy, open circle is In.Eddy, open square is E.Eddy, closed triangle is N.Out, closed circle is M.Out, and closed square is S.Out. Light gray arrows shown on inset indicate average geostrophic current anomaly speed from altimetry data with a reference scale in the upper right.

Figure 2. Average July sea surface level anomalies (colors represent cm) and geostrophic current anomaly speed (arrows represent cm/s) averaged for the month of July with reference scales in the top right of the upper left panel. Two isobaths indicate the offshore edge of the continental

shelf (300 m) and the continental slope (2000 m). Data downloaded from Copernicus Marine Environment Monitoring Services.

Figure 3. Distributions of juvenile pink salmon from surface trawl surveys in July for years 2010–2015. Solid black circles reflect relative catch abundance as natural-log (n), and “X” denotes a zero catch. Two isobaths indicate the offshore edge of the continental shelf (300 m) and the continental slope (2000 m).

Figure 4. Temperature (°C) averaged over the top 20 m (top), natural-log transformed chlorophyll-a concentration (µg/l) at 10-m depth (middle), and natural-log transformed CPUE (number/km^3) for juvenile pink salmon (bottom), with 2010 on the left and 2012 on the right. An “X” indicates a catch of zero, and arrows indicate mean geostrophic current anomaly speed (cm/s) from altimetry data. Two isobaths indicate the offshore edge of the continental shelf (300 m) and the continental slope (2000 m).

Figure 5. Percent of stomach contents by the six prey categories listed, averaged by years (2010 and 2012; top) and broken into eddy groups (2010; bottom). Sample size is shown in parentheses.

Figure 6. Juvenile pink salmon health metrics: Fulton’s condition factor (K where N=5+; top), insulin-like growth factor-I (IGF-I where N=2+; middle), and whole body energy content (WBEC where N=2; bottom) averaged by station for 2010 on the left and 2012 on the right. An “X” indicates a catch of zero, and arrows indicate average geostrophic current anomaly speed

(cm/s) from altimetry data. Two isobaths indicate the offshore edge of the continental shelf (300 m) and the continental slope (2000 m).

Figure 7. Schematic of hypothesized influence of an eddy on juvenile pink salmon distribution and growth in the eastern Gulf of Alaska. Arrows indicate average geostrophic current direction associated with a Sitka Eddy, size of fish reflects relative growth and condition, and location reflects distribution.

9. Tables

Table 1.

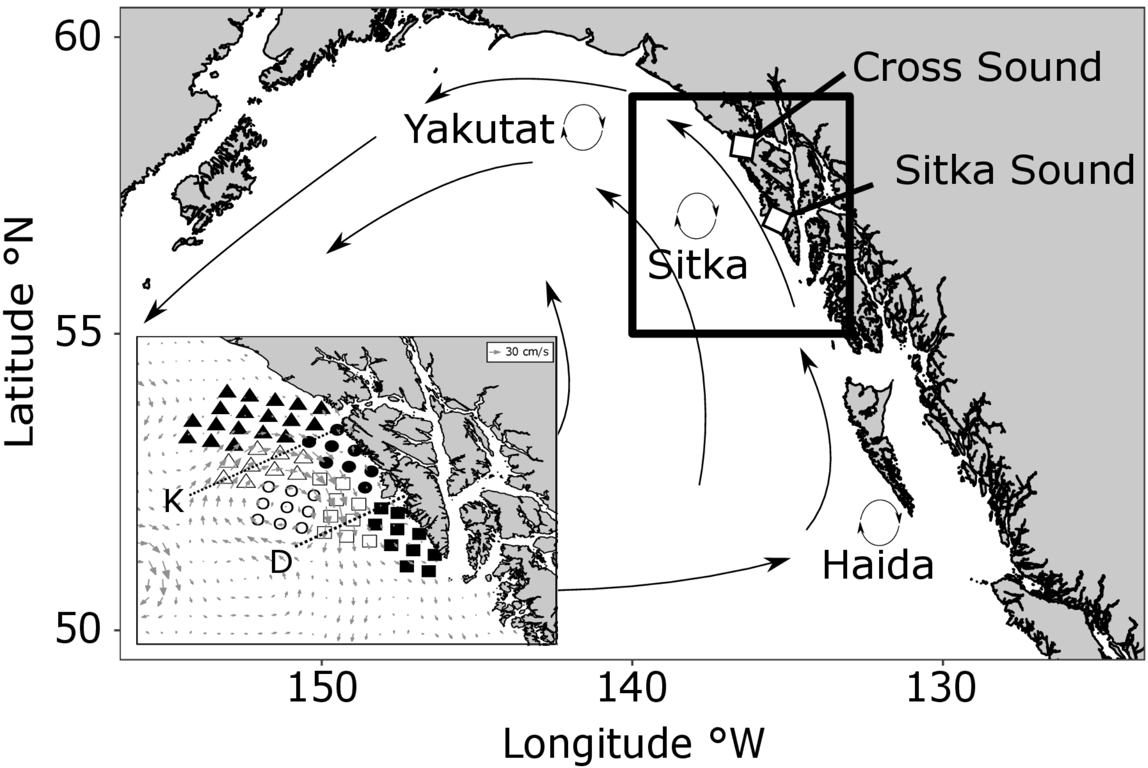
	CPUE	N_{LWK}	FL	Weight	K	N_{IGF}	IGF-I	N_{EC}	WBEC
2010	3.7 ± 0.85	1002	129.5 ± 0.69	22.0 ± 0.54	0.94 ± 0.004	300	56.5 ± 0.54	72	4.9 ± 0.03
2012	0.4 ± 0.15	471	145.2 ± 1.11	33.0 ± 0.77	0.97 ± 0.005	101	66.1 ± 1.13	34	5.3 ± 0.08
N.Eddy	0.4 ± 0.15	34	126.7 ± 2.39	19.7 ± 1.18	0.94 ± 0.019	21	51.3 ± 1.45	10	4.7 ± 0.06
In.Eddy	5.3 ± 1.76	209	129.3 ± 0.86	21.3 ± 0.50	0.95 ± 0.005	64	55.3 ± 1.05	12	4.8 ± 0.04
E.Eddy	3.9 ± 1.28	181	143.0 ± 1.31	30.5 ± 1.01	0.98 ± 0.006	68	60.1 ± 1.14	12	4.8 ± 0.08
N.Out	3.9 ± 0.92	217	115.0 ± 0.78	13.6 ± 0.31	0.87 ± 0.008	45	56.8 ± 1.11	16	5.0 ± 0.09
M.Out	0.8 ± 0.27	64	108.8 ± 3.04	14.0 ± 2.04	0.88 ± 0.018	6	56.8 ± 2.73	6	4.8 ± 0.11
S.Out	7.1 ± 2.26	297	136.8 ± 1.48	28.8 ± 1.41	0.97 ± 0.006	96	55.8 ± 1.10	16	5.0 ± 0.09

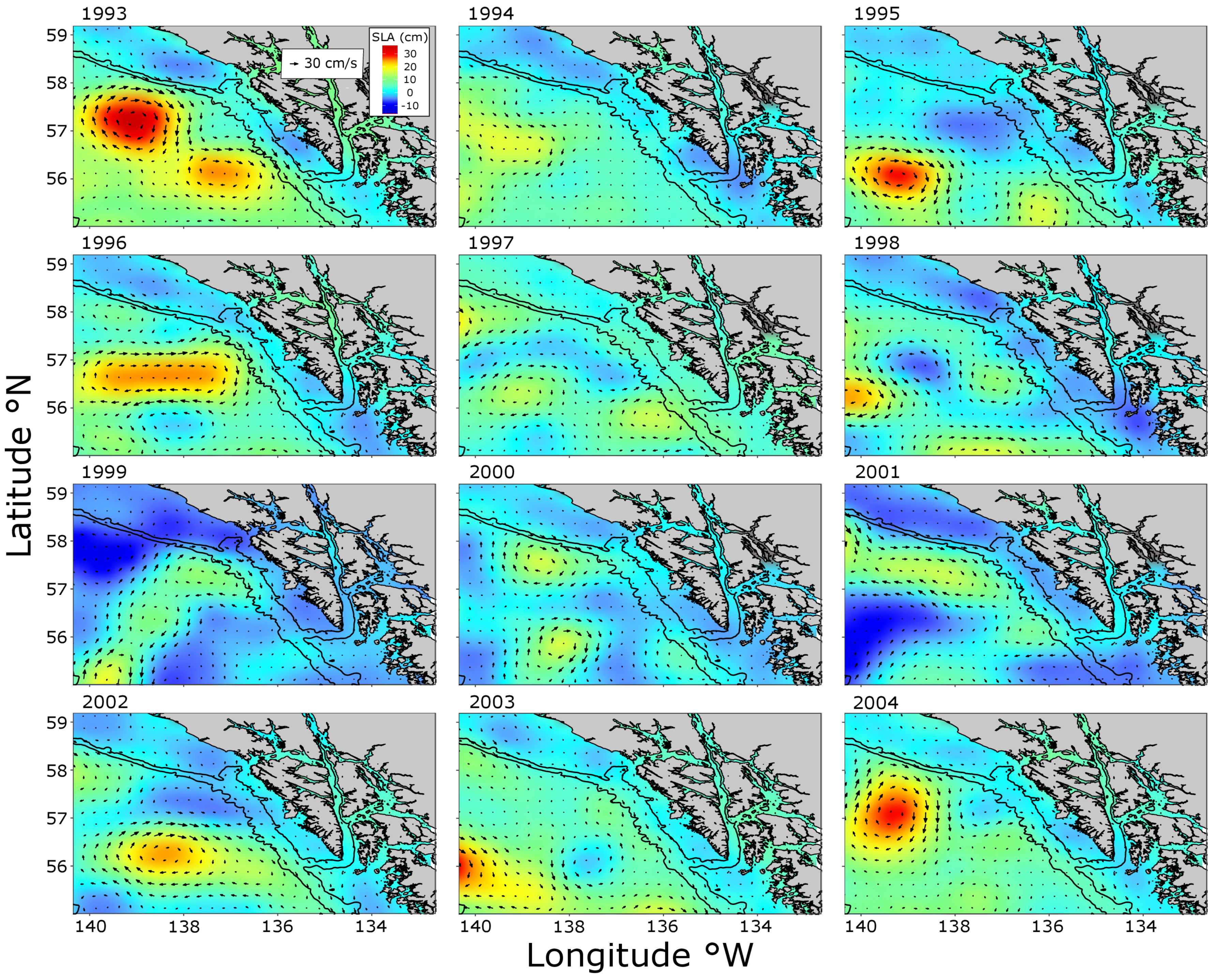
Table 1. Summary table of juvenile pink salmon data by year (2010 and 2012) and across eddy groups (2010 only) showing mean ± standard error of catch per unit effort (CPUE, 10^4 number/km^3), fork length (FL, mm), weight (g), Fulton's condition factor (K), insulin-like growth factor I (IGF-I), and whole body energy content (WBEC, kJ/g). The number of fish that were measured for FL, weight, and K (N_{LWK}), IGF-I (N_{IGF}), and WBEC (N_{EC}) are included.

10. Appendix Figure Captions

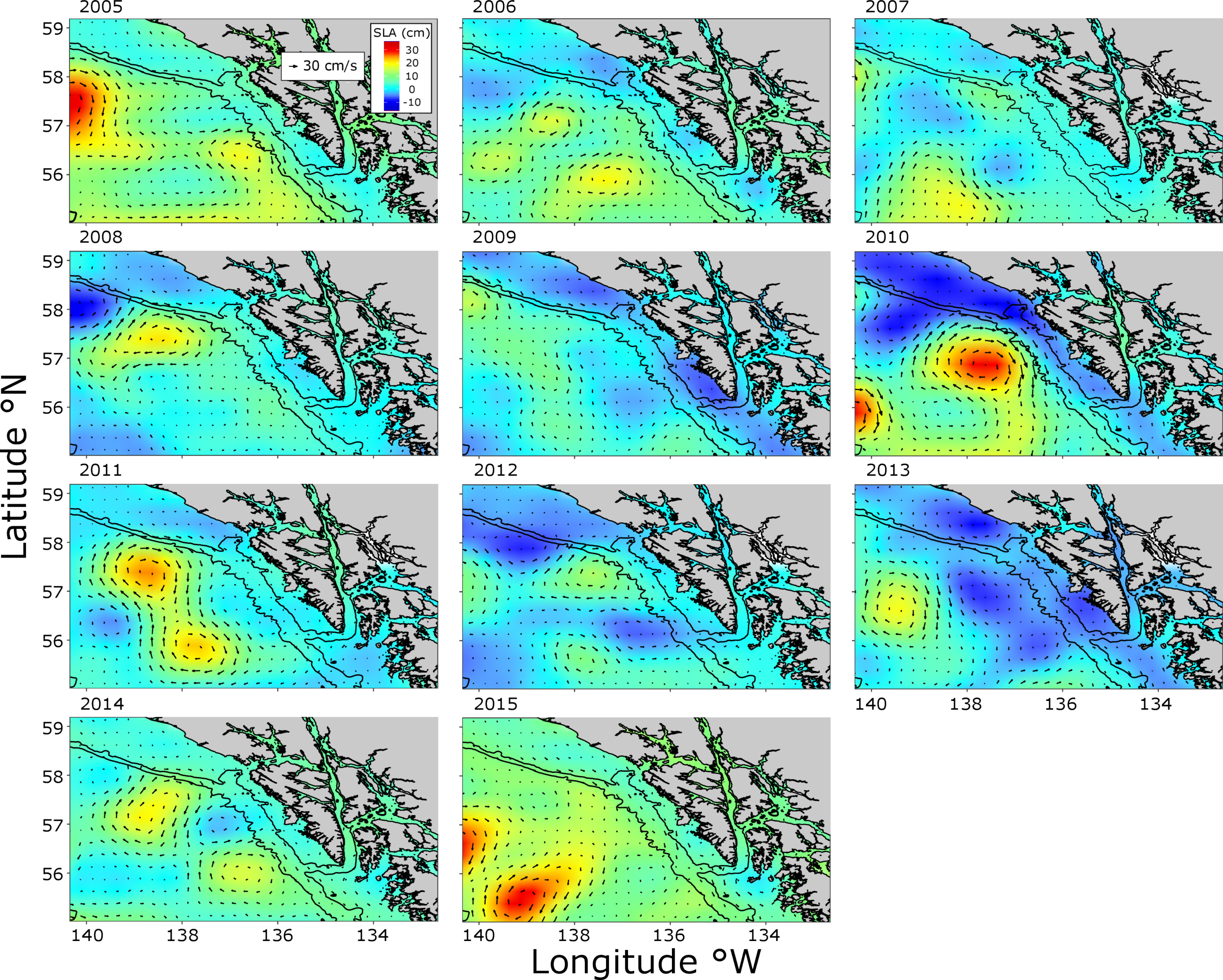
Figure A.1. Sea surface temperatures (SST) averaged for the month of July (color scale represents °C). Reference scale for SST varies by year, though 2010 and 2012 have been set to the same scale for comparison. Daily optimum interpolation SST was downloaded from https://www.ncei.noaa.gov/erddap/index.html and is described in Banzon et al. (2016). Sea level anomaly contours (contour interval: 5 cm) are overlaid.

Figure A.2. Chlorophyll-a concentration (µg/l) was natural-log transformed (log(chl); color reference scale is in the top right of the upper left panel) and averaged for the month of July. These data were downloaded from oceancolor.gsfc.nasa.gov (NASA, 2014). Sea level anomaly contours (contour interval: 5 cm) are overlaid.

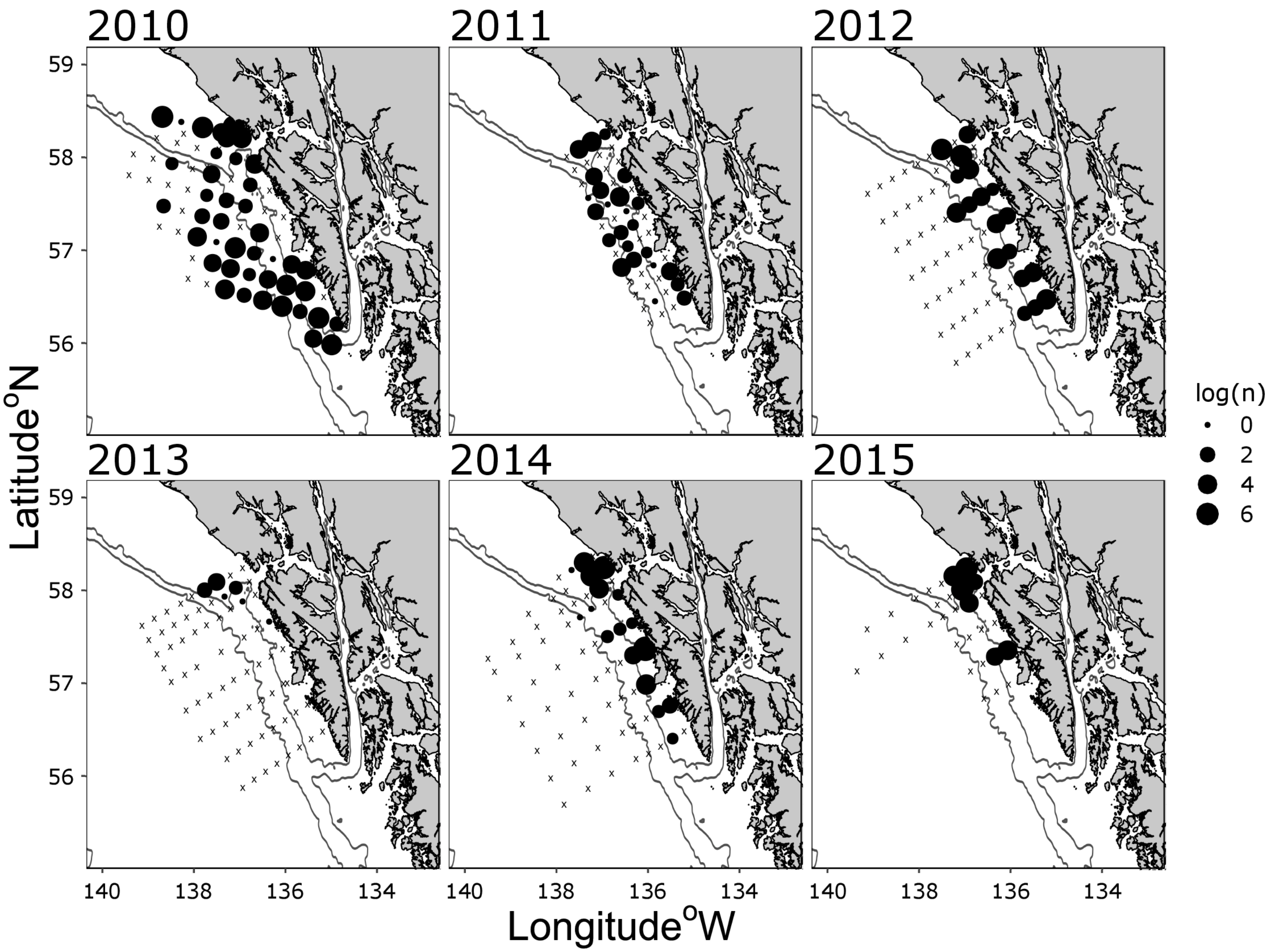

Cross Sound
Sitka Sound
Yakutat
Sitka
Haida
30 cm/s
K
D
60
55
50
150
140
130
Latitude °N
Longitude °W

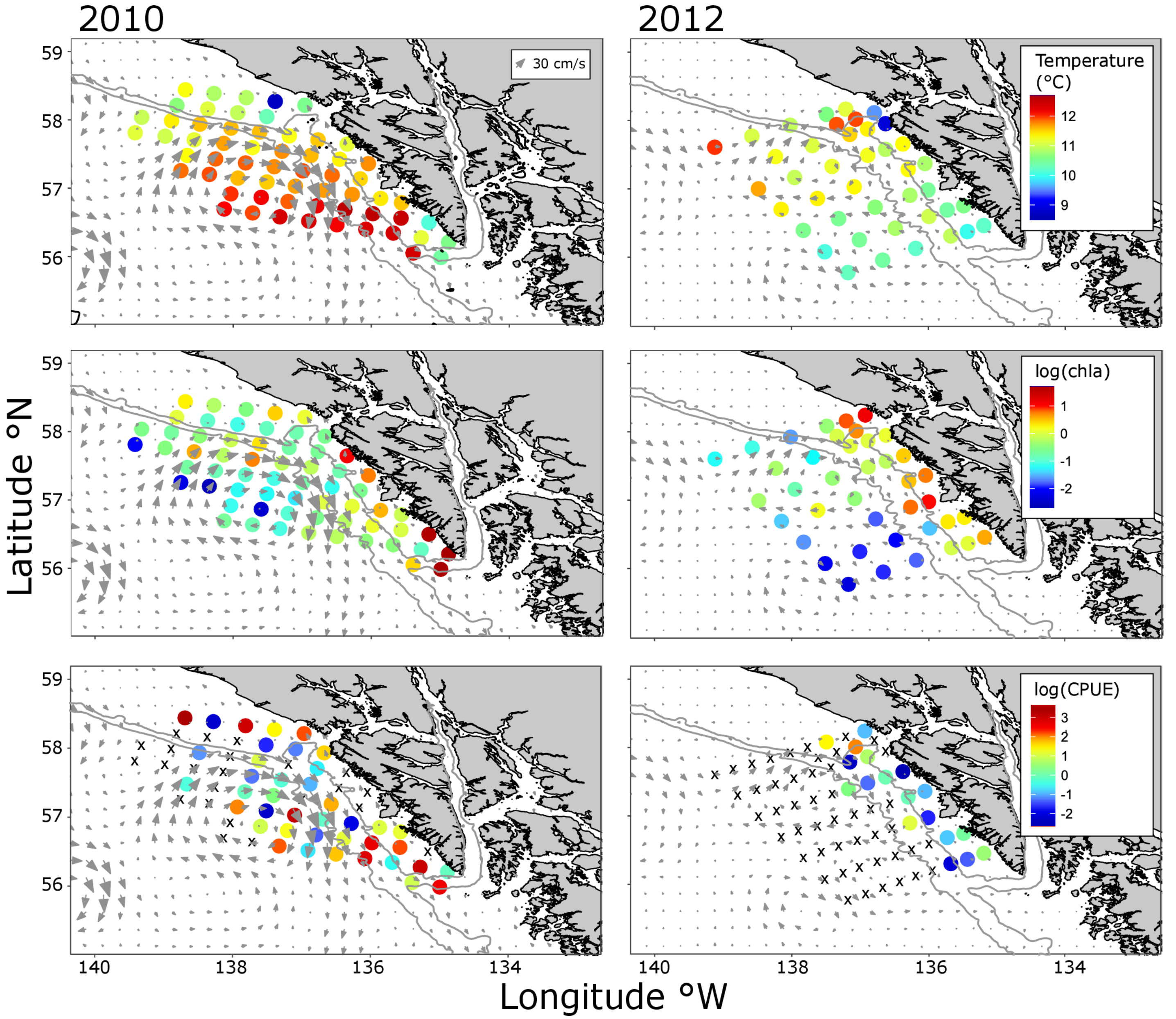


1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
SLA (cm)
30
20
10
0
-10
30 cm/s
59
58
57
56
140
138
136
134
Latitude °N
Longitude °W

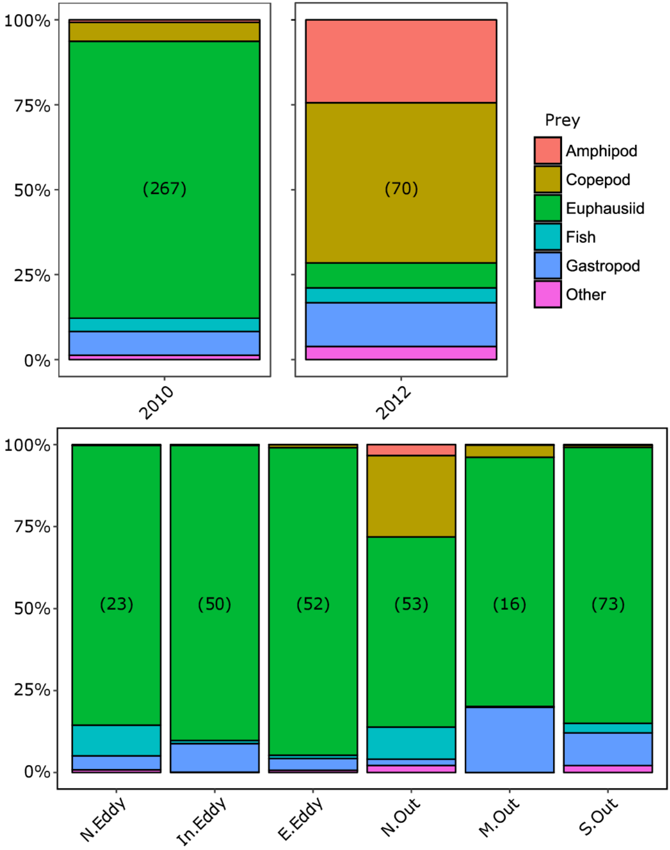


2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
SLA (cm)
30
20
10
0
-10
30 cm/s
59
58
57
56
140
138
136
134
Latitude °N
Longitude °W

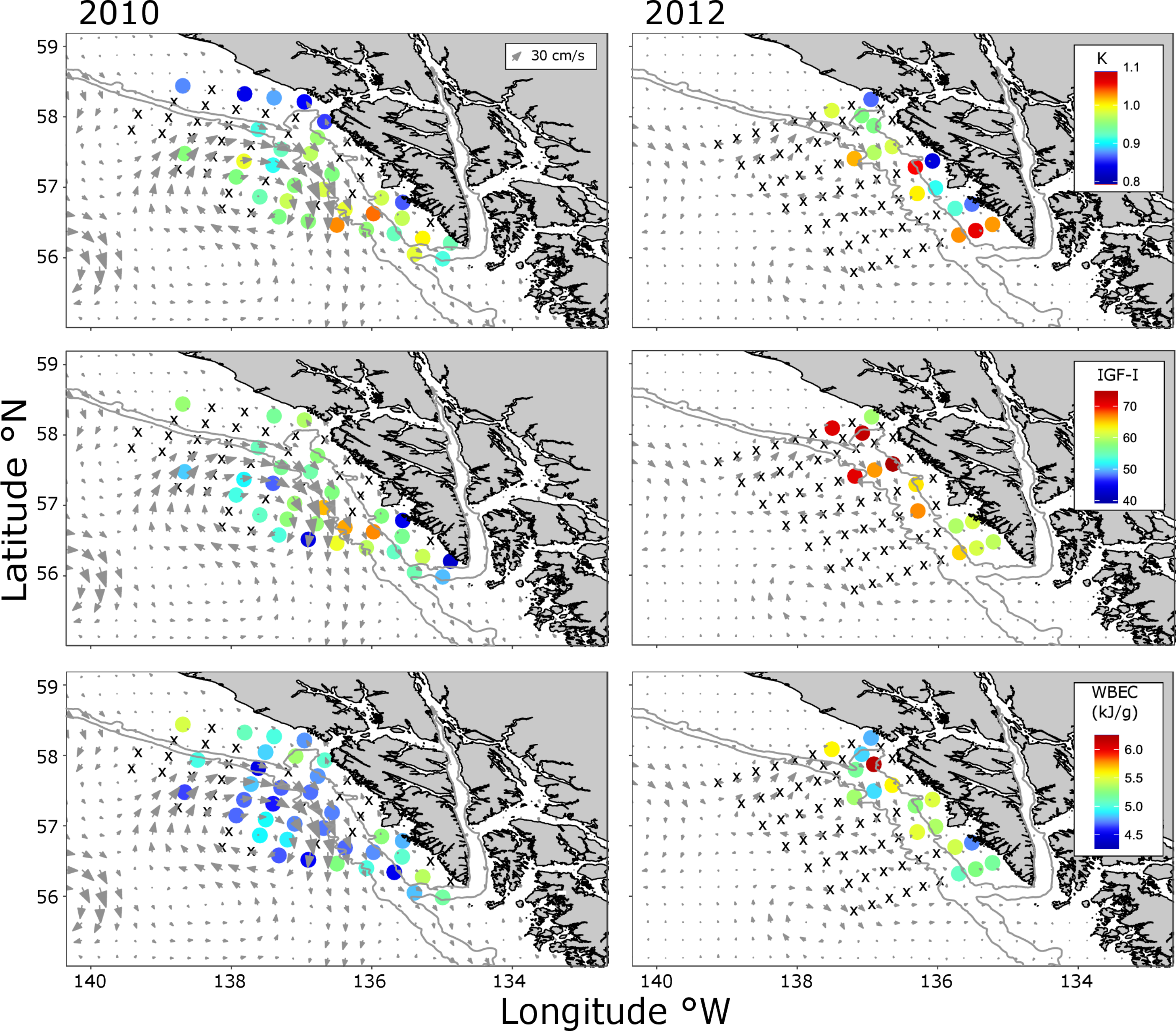

2010
2011
2012
2013
2014
2015
59
58
57
56
Latitude°N
140
138
136
134
Longitude°W
log(n)
0
2
4
6

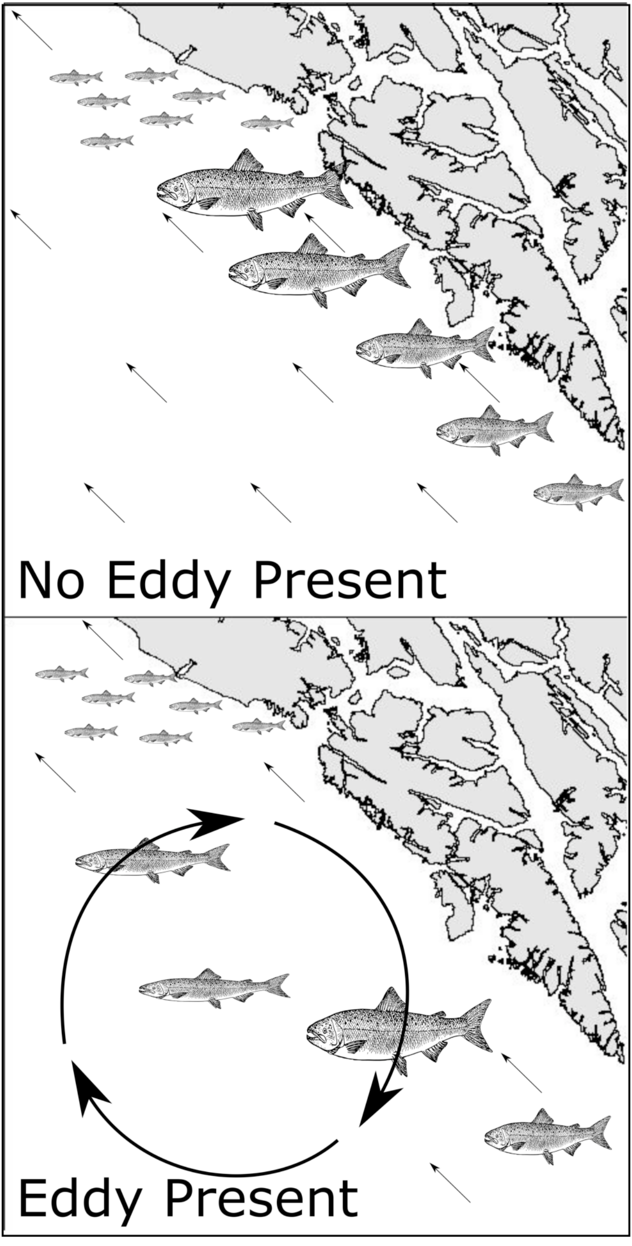


2010
2012
30 cm/s
Temperature (°C)
12
11
10
9
log(chla)
1
0
-1
-2
log(CPUE)
3
2
1
0
-1
-2
59
58
57
56
Latitude °N
140
138
136
134
Longitude °W



100%
75%
50%
25%
0%
(267)
(70)
2010
2012
Prey
Amphipod
Copepod
Euphausiid
Fish
Gastropod
Other
(23)
(50)
(52)
(53)
(16)
(73)
N.Eddy
In.Eddy
E.Eddy
N.Out
M.Out
S.Out


2010
2012
30 cm/s
K
1.1
1.0
0.9
0.8
IGF-I
70
60
50
40
WBEC
(kJ/g)
6.0
5.5
5.0
4.5
59
58
57
56
140
138
136
134
Latitude °N
Longitude °W


No Eddy Present
Eddy Present