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Size, diet, and condition of age-0 Pacific cod (*Gadus macrocephalus*) during warm and cool climate states in the eastern Bering sea

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ABSTRACT

The revised Oscillating Control Hypothesis for the Bering Sea suggests that recruitment of groundfish is linked to climatic processes affecting seasonal sea ice that, in turn, drives the quality and quantity of prey available to young fish for growth and energy storage during their critical life history stages. We test this notion for age-0 (juvenile) Pacific cod (*Gadus macrocephalus*) by examining the variability in size, diet, and energetic condition during warm (2003–2005), average (2006), and cool (2007–2011) climate states in the eastern Bering Sea. Juvenile cod stomachs contained high proportions of age-0 walleye pollock (by wet weight) during years with warm sea temperatures with a shift to euphausiids and large copepods during years with cool sea temperatures. Juvenile cod were largest during years with warm sea temperatures and smallest during years with cool sea temperatures. However, energetic status (condition) of juvenile cod was highest during years with cool sea temperatures. This result is likely linked to the shift to high quality, lipid-rich prey found in greater abundance on the shelf and in the stomach contents of juvenile cod during cool years. Our examination of juvenile cod size, diet, and energetic status provided results that are similar to those from studies on juvenile pollock, suggesting that the common mechanisms regulating gadid recruitment on the eastern Bering Sea shelf are climate state, prey quality and quantity, and caloric density of gadids prior to winter.

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1. Introduction

The continental shelf of the eastern Bering Sea supports important fisheries for walleye pollock (*Gadus chalcogrammus*), Pacific cod (*Gadus macrocephalus*), flatfish and crab. These populations have undergone large fluctuations due to natural climate variability. The potential for climate warming in the Bering Sea has heightened the need for data to better understand impacts of climate variability on ecologically and commercially important fish stocks. Probably the greatest effect of climate variability on the southeastern Bering Sea ecosystem will be the annual difference in the extent and duration of winter and spring sea ice (Stabeno et al., 2012). These characteristics are believed to affect the quality and quantity of prey resources that, in turn, impact growth, fitness, and survival of young fish (e.g. walleye pollock; Hunt et al., 2011).

Understanding how fish allocate energy for growth and lipid storage during critical life history stages is important for assessing climate impact on fish recruitment. For young fish, differential mortality occurs during two critical periods (e.g. first feeding and winter) that are related to energy allocation strategies in larval and juvenile fish (Post and Parkinson, 2001). For larval fish, somatic growth is important because smaller fish may be more susceptible to size-selective predation (Post and Prankevicius 1987). For juvenile fish, large size and high energy reserves (e.g. lipid) are important because they can face severe energy deficits prior to, and during winter (Sogard and Olla, 2000; Heintz and Vollenweider, 2010; Farley et al., 2011). For instance, the energetic status of age-0 Bering Sea walleye pollock in late summer is increasingly recognized as a predictor of age-1 abundance the following summer (Heintz et al., 2013). For these age-0 pollock, the consumption of high quality prey improved their growth and nutritional condition, reducing energy deficits over-winter, leading to increased survival.

The oscillating control hypothesis (OCH) that links climate variability to Bering Sea groundfish (e.g. walleye pollock) recruitment (Hunt et al., 2002) was revised (Hunt et al., 2011) based in part on new findings from survey data (Bering Aleutian Salmon International Survey; Farley et al.,2005) regarding the importance of energetic status to fish survival (Heintz et al., 2013). Originally, the OCH predicted that warm temperatures and early ice retreat

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on the eastern Bering Sea shelf would lead to increased productivity in the pelagic ecosystem that, in turn, would improve the chances of successful recruitments for groundfish. However, recent data indicate that changes in prey composition and abundance during periods of warm temperatures and early ice retreat may have been detrimental to age-0 groundfish survival. Specifically, larger zooplankton taxa, such as lipid-rich *Calanus* spp., were less abundant during years with warm temperatures (Coyle et al., 2011). Consequently, age-0 pollock that fed on lower quality prey during warm years had reduced lipid reserves at the end of summer and increased over-winter mortality (Heintz et al., 2013). Thus the OCH was revised to state that reduced winter mortality for age-0 pollock occurs during years with cool temperatures because increased numbers of lipid-rich prey, combined with lower metabolic demand, allow age-0 walleye pollock to acquire greater lipid reserves by late summer (Hunt et al., 2011).

Pacific cod is a widespread marine species found on the continental shelves throughout the North Pacific and Bering Sea. Pacific cod spawn demersal eggs with larvae rising to the surface waters immediately after hatch (Doyle et al., 2009; Hurst et al., 2009). By July, age-0 cod are known to settle to the bottom and inhabit the demersal, shallow waters of coastal Alaska (Abookire et al., 2007; Laurel et al., 2007); however, in the Bering Sea, age-0 cod do not appear to be restricted to shallow nearshore habitats, but instead are commonly captured across the broad shelf in both demersal and pelagic trawl surveys (Hurst et al., 2012). Observational data for age-0 Pacific cod and walleye pollock during late summer suggest that their distributions overlap on the eastern Bering Sea shelf; however, pollock distribution tends to be more widespread and variable than that of Pacific cod (Hurst et al., 2012). While there may be some differences in distribution between age-0 walleye pollock and Pacific cod on the eastern Bering Sea shelf, their recruitment dynamics appear to be synchronous (Mueter et al., 2007), suggesting that the primary ecological drivers (e.g. OCH) of recruitment in these two species are similar in the Bering Sea.

In this paper, we describe patterns of interannual variation in size, diet, and energetic status (biological characteristics) of age-0 Pacific cod in the eastern Bering Sea based on 8 years of fishery-independent survey data. The period examined (2003–2011) was characterized by significant variation in thermal regime in the Bering Sea, allowing us to consider the potential effects of climate variability on the biological characteristics of cod that may impact their winter survival. We discuss these biological characteristics for cod in relation to those found for age-0 walleye pollock (Coyle et al., 2011; Heintz et al., 2013) and examine their potential for increasing our understanding of recruitment processes in relation to climate variability.

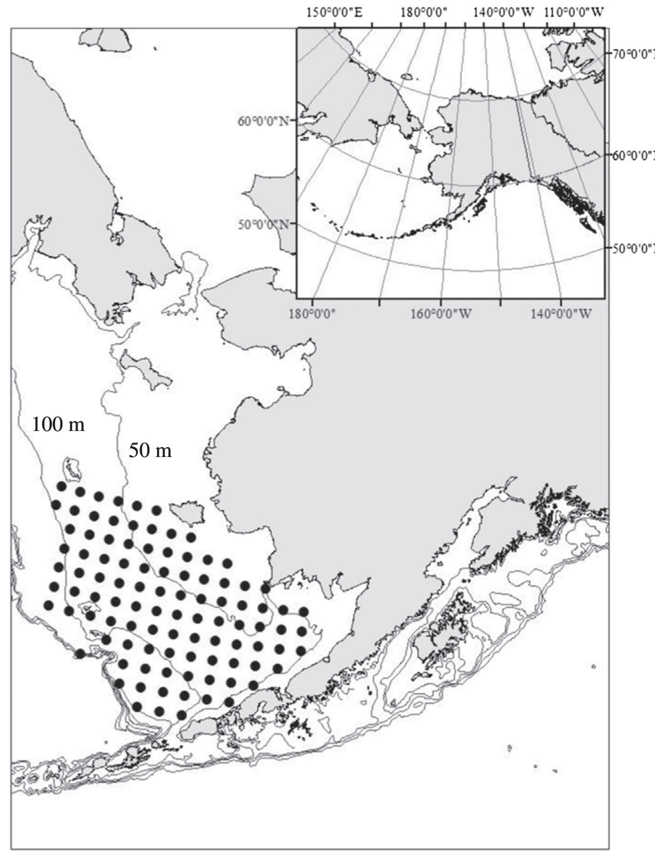

Fig. 1. Survey grid (core stations) for the 2003–2011 Bering-Aleutian Salmon International Survey. Contour lines are associated with the 50 m and 100 m bottom depths delineating the inner (< 50 m depth), middle (50–100 m depth), and outer (> 100 m depth) domains.

Table 1
Sampling summary.

Year	Vessel(s)	Start date	End date
2003	Sea Storm	31-August	28-September
2004	Sea Storm	14-August	28-September
2005	Sea Storm	14-August	06-October
2006	Sea Storm/Northwest Explorer	16-August	20-September
2007	Sea Storm	15-August	08-October
2008	Oscar Dyson	11-September	27-September
2010	Oscar Dyson	18-August	24-September
2011	Oscar Dyson	23-August	15-September

2. Methods

2.1. Field sampling

The biological characteristics (size, diet, energy content) of age-0 Pacific cod (hereafter “juvenile cod”) in the eastern Bering Sea were described for eight cohorts (2003–2011; 2009 was omitted due to lack of samples), based on catches from the Bering-Aleutian Salmon International Survey (BASIS). Surveys were conducted from chartered fishing vessels (38-m FV “Sea Storm” or the 49-m FV “Northwest Explorer”) or the 64-m NOAA ship “Oscar Dyson”. The surveys were conducted during similar time periods (mid-August through late September), with sampling effort beginning in eastern Bristol Bay and moving northwest through the eastern Bering Sea (Fig. 1). Slight changes in the survey locations, sampling dates, and the number of stations sampled in a given year were due to weather conditions and other factors. A summary of annual sampling is provided in Table 1. Fish were collected with a 198-m long midwater rope trawl composed of hexagonal mesh wings and a body fitted with a 1.2-cm mesh codend liner (Farley et al., 2005). Buoys were attached to the headrope to fish near-surface depths (mouth opening of 55-m horizontal by 20-m vertical). The net was towed at speeds from 3.5 to 5.0 knots (approx 6.5–9.3 km per hour) for 30 min during daylight hours.

Our use of surface trawl samples for understanding early marine ecology of juvenile cod was explained in Hurst et al. (2012). While the survey was not designed to sample age-0 Pacific cod, they were a regular component of the catch. In addition, catch rates of juvenile cod are correlated with those of age-1 fish captured in the Bering Sea bottom trawl survey. There is also little known on when juvenile cod settle to a fully benthic distribution, but during late summer, juvenile cod tend to be captured in greater numbers in the surface trawl than in the bottom trawl. Therefore, the assumption is that the catches in the surface trawl

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