Spatial and Monthly Changes of Sea Surface Temperature, Sea Surface Salinity, Chlorophyll *a*, and Zooplankton Biomass in Southeastern Alaska: Implications for Suitable Conditions for Survival and Growth of Dungeness Crab Zoeae

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To investigate conditions for the survival and growth of Dungeness crab zoeae in situ, spatial and monthly changes of sea surface temperature (SST), sea surface salinity (SSS), Chlorophyll *a* (Chl *a*), and zooplankton biomass were measured in four transects: upper Chatham, Icy Strait, Cross Sound, and Icy Point in southeastern Alaska from May to September, 1997-2004. Monthly mean SST was coldest in May, increased throughout the summer months, and decreased in September. SST was coldest in the Cross Sound transect, intermediate in the upper Chatham and Icy Strait transects, and warmest in the Icy Point transect. SSS of northern stations in the upper Chatham and Icy Strait transects decreased throughout the summer months and increased in September, while that of other transects did not vary. Monthly mean Chl *a* was highest in May and decreased thereafter. Chl *a* in the upper Chatham and Icy Strait transects were relatively higher from May through September than those in the Cross Sound and Icy Point transects. Mean zooplankton biomass was highest in the Icy Strait transect in May and lowest in the Icy Point transect in September. This research suggests that oceanographic conditions during the season of Dungeness crab zoeae in southeastern Alaska may not constrain the survival and growth of Dungeness crab zoeae.

Key words: Dungeness crab zoeae, Survival, SST, SSS, Biomass, Chl *a*

Introduction

The planktonic larval stage of benthic marine invertebrates may be a bottleneck in their life history. Oceanographic changes such as salinity, temperature, and chlorophyll concentration have been related to the interannual variation of invertebrate larval recruitment that ultimately may affect the population (Chelton et al., 1982; Navarrete et al., 2002). Natural larval mortality may result from a combination of planktonic larval cycle and hydrographic variations in the sea (Lough, 1976; Armstrong, 1983).

A major hydrographic variable in the environment that affects crab larvae may be water temperature. Water temperature affects reproductive biology of invertebrates, including the time before and after molt (Ebert et al., 1983; Hartnoll, 1982; Reed, 1969). Although larval survival and stage duration are in-

dependent of the previous and subsequent stages, intermolt period varies inversely with temperature at all stages (Shirley et al., 1987; Sulkin and McKeen, 1989; 1996; Moloney et al., 1994). In particular, at temperatures lower than 6°C Dungeness crab larvae may not be able to grow (Jamieson and Phillips, 1988). A long period of larval development causes larvae to experience seasonal changes in water temperature as development proceeds (Lough, 1976; Reilly, 1983; Booth et al., 1985; Jamieson and Phillips, 1988). Also, temperature directly influences larval activity and swimming behavior (Sulkin, 1984; Shirley and Shirley, 1988; 1989).

Alternately, salinity may have synergistic effects with temperature in larval survival of Dungeness crabs. Compared with the effects of temperature, the influence of salinity on the duration of development through individual stages is relatively weak or nonexistent (Kinne, 1971). However, metabolic rate

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increases under suboptimal salinity conditions, while it decreases in supraoptimal salinity in the larvae of euryhaline species (Kinne, 1971). Dungeness crab larvae are hatched as prezoeae and molt to zoeae within about an hour (MacKay, 1942; Buchanan and Milleman, 1969). In general, the prezoeal period of Dungeness crabs increases with increasing salinity up to 32 while temperature ranged from 10.5°C to 17.5°C has no effect on the duration of the prezoeal stage (Buchanan and Milleman, 1969).

Different populations of the same species may vary in duration and frequency of reproductive cycles in different areas of their distribution range, particularly for their northern conspecifics (Sastry, 1983). Water temperature, diet, photoperiod and other environmental conditions have been connected to variations in reproductive cycles in many crustaceans. Alaska is the northern boundary of the range of Dungeness crab populations (Hart, 1982), and Dungeness crabs in Alaska have different reproductive and life cycles from southern populations. Females in southeastern Alaska do not reproduce annually while females in southern latitudes do (Swiney et al., 2003). Dungeness crab zoeae in southeastern Alaska hatch from April through July, with most hatching occurring in late May and June (Shirley et al., 1987; Stone and O'Clair, 2001; Swiney and Shirley, 2001) while those in California, Oregon, and Washington hatch during winter and spring (Reed, 1969; Lough, 1976; Reilly, 1983). The Alaskan winter is not suitable for the survival and growth of Dungeness crab larvae because of low temperatures and poor food conditions (Ziemann et al., 1991; Etherington et al., 2004).

Zooplankton, including meroplankton such as Dungeness crab larvae, is consumed by many Alaskan fish species (Sturdevant et al., 1999), including salmon juveniles. Also, Dungeness crab larvae are omnivorous and can consume phytoplankton and zooplankton (Lough, 1976; Hartman and Letterman, 1978) although little is known about their diets in situ.

The research area is an area with high abundances of adult populations of Dungeness crabs, which provide the basis for a lucrative commercial fishery (Taggart et al., 2004a, b). An understanding of how variations in oceanographic conditions might affect larval survival and recruitment could be important to fisheries management and harvest forecasting.

The densities of Dungeness crab zoeae in zooplankton tows in this area (Park, 2007) were as high as those reported from collections along the California, Oregon, Washington, and British Columbian

coasts (Lough, 1976; Reilly, 1983). Although some allocthonous Dungeness crab zoeae may have been advected into the study area (Park et al., 2007), most zoeae may be indigenous to the study area (Park, 2007).

The SouthEast Coastal Monitoring (SECM) survey has been conducted by Auke Bay Laboratory (ABL), National Fisheries Marine Service (NMFS) since 1997 to study the ecology of the early oceanic phase of Pacific salmon (*Oncorhynchus* spp.). The SECM survey investigates relationships between Pacific salmon production and climate changes, and attempts to assess marine growth, survival, distribution, migration, and ocean carrying capacity for salmon in southeastern Alaska. Zooplankton and hydrographic data for the present study were collected during the SECM survey.

This research investigated the spatial and monthly changes of SST, SSS, Chl *a*, and zooplankton biomass within the SECM survey area of 16 stations along four transects in southeastern Alaska. Geographic Information System (GIS) software was used to explore spatial and monthly patterns of SST, SSS, Chl *a*, and zooplankton biomass. Finally this research estimated oceanographic conditions that may affect the survival and growth of Dungeness crab zoeae.

Materials and methods

Larval data

Zooplankton and hydrographic data were collected monthly at 16 stations arrayed along four transects in upper Chatham Strait, Icy Strait, Cross Sound, and Icy Point in southeastern Alaska (Fig. 1) by the NOAA vessel, *RV John N. Cobb*, during the last 10 days of each month from May to September, 1997–2004. The sampling stations were in depths of 60 to 1,300 m and for the transects located within inland waters were approximately 3.2 km apart (Table 1). Tides in the area are semidiurnal with a maximum range of approximately 7 m and an average range of 4 m (Hooe and Hooe, 2002; Park et al., 2004). All samples were collected during daylight, between 0700 and 2000 h, Alaska Standard Time. SST and SSS were measured to the precision of 0.1 at 1 m depth with an onboard thermosalinograph (Sea-Bird SBE 21); salinity is reported as practical salinity unit (PSU).

At each station, a 60-cm diameter Bongo net with 505 and 333 μ m mesh was deployed once to a depth of 200 m, or to within 10 m of the bottom, with a double oblique tow. Here, I report on samples collec-

Fig. 1. Zooplankton sampling stations in southeastern Alaska, May-September 1997-2004.

Table 1. Localities and coordinates of monthly zooplankton sampling stations in southeastern Alaska. Zooplankton were collected at 16 stations in four transects in marine waters of the northern region in southeastern Alaska, May-September 1997-2004

Locality	Station	Latitude	Longitude	Offshore distance (km)	Bottom depth (m)
Upper Chatham Strait	UCA	58°04'57N	135°00'08W	3.2	400
	UCB	58°06'22N	135°00'91W	6.4	100
	UCC	58°07'95N	135°04'00W	6.4	100
	UCD	58°09'64N	135°02'52W	3.2	200
Icy Strait	ISA	58°13'25N	135°31'76W	3.2	128
	ISB	58°14'22N	135°29'26W	6.4	200
	ISC	58°15'28N	135°26'25W	6.4	200
	ISD	58°16'38N	135°23'98W	3.2	234
Cross Sound	CSA	58°09'53N	135°26'96W	3.2	300
	CSB	58°10'91N	135°28'68W	6.4	60
	CSC	58°12'39N	135°30'46W	6.4	200
	CSD	58°13'84N	135°32'23W	3.2	200
Icy Point	IPA	58°20'12N	135°07'16W	6.9	160
	IPB	58°12'71N	135°16'96W	23.4	130
	IPC	58°05'28N	135°26'75W	40.2	150
	IPD	58°53'50N	135°42'60W	65.0	1,300

ted with the 333 μm mesh. A General Oceanics model 2031 or Rigosha flow meter was placed inside the nets for measurement of filtered water volumes. Zooplankton samples were preserved in 5% buffered formalin aboard the vessel and transported to the laboratory. Zooplankton biomass (DV, displacement volume in mL/m^{-3}) was used as a proxy for standing stock of zooplankton. Displacement volume and Chl *a* were obtained from the Auke Bay Laboratory (Unpubl. data, Auke Bay Lab, NMFS).

For oceanographic data, the mean value for each month during the sampling period was selected to

represent the monthly oceanographic features of the area. Oceanographic data were averaged and contoured with a Radius Base Function in ArcGIS 9.1 (ArcGIS9.1, 2001). Although there were insufficient data points to evaluate spatial autocorrelations for geostatistical interpolation, Radius Base Function was used because oceanographic data were assumed to be continuous over the study areas and the function was deterministic. In addition, because the contours of the areas between transects did not indicate real oceanographic features of the area, the contours of the images between transects were not presented.

Fig. 2. Seasonal change of sea surface temperature (SST) during 1997-2004. Sea surface temperatures were measured at 1 m depth using CTD (conductivity, temperature and depth). SST were averaged by month and imaged by Radius Base Functions in the geostatistical analyst extension of ArcGIS 9.1.

Results

Monthly mean SST was coldest in May, increased throughout the summer, and decreased in September (Fig. 2). SST were coldest in the Cross Sound transect, intermediate in the upper Chatham and Icy Strait transects, and warmest in the Icy Point transect. Monthly variation of SST in the Cross Sound transect had relatively narrow ranges from 6.7 to 9.3°C while those in the Icy Point transect ranged widely from 7.1

to 15.0°C.

Monthly mean SSS varied seasonally in the upper Chatham and Icy Strait transects, while SSS was relatively stable in the Cross Sound and Icy Point transects (Fig. 3). The SSS of northern stations in the upper Chatham and Icy Strait transects decreased throughout the summer months and increased in September.

Monthly mean Chl *a* was highest in May and de-

Fig. 3. Seasonal change of sea surface salinity (SSS) during 1997-2004. Sea surface salinities were measured at 1 m depth using CTD (conductivity, temperature and depth). SSS were averaged by month and imaged by Radius Base Functions in the geostatistical analysis extension of ArcGIS9.1.

creased thereafter (Fig. 4). Chl *a* in the upper Chatham and Icy Strait transects were relatively higher in May through September than those in the Cross Sound and Icy Point transects. In May, mean Chl *a* ($3.1\text{--}6.6\text{ mg/m}^3$) was highest at the northernmost stations in the upper Chatham and Icy Strait transects. In the Icy Strait transect, mean Chl *a* concentrations were lower, and ranged from 1.3 to 2.3 mg/m^3 . From July to September, mean Chl *a* concentrations at all stations were below 2.0 mg/m^3 .

Mean zooplankton biomass was highest in the Icy Strait transect and lowest in the Icy Point transect throughout the sampling period (Fig. 5). In May, mean zooplankton biomass ranged from 0.6 to 0.9 mL/m^3 except at CSC, CSD and in the Icy Point transect. In particular, in the Icy Point transect, zooplankton biomass was relatively low, ranging from $0.2\text{--}3.0\text{ mL/m}^3$. Mean zooplankton biomass was highest in the Icy Strait transect in all months.

Fig. 4. Seasonal change of Chl *a* during 1999-2004. Chl *a* were averaged by month and imaged by Radius Base Functions in the geostatistical analyst extension of ArcGIS 9.1.

Discussion

The research sites except the Icy Point transect were located within the Alexander Archipelago in southeastern Alaska and surrounded by snowfields, glaciers, numerous estuaries, and densely forested mountains. In particular, Glacier Bay, located in the middle of the study area between the Cross Sound and Icy Strait transects, discharges a large volume of freshwater from glacial meltwater and precipitation during the summer (Hooe and Hooe, 2002). The

decrease in SSS in the Icy Strait and upper Chatham transects throughout the summer likely resulted from increased freshwater discharge from Glacier Bay and small rivers near the study areas owing to seasonal melt of ice and snow and rainfall. In the Cross Sound transect, the narrow mouth (Fig. 1) and shallow depth (Table 1) may have resulted in upwelling of deep water of high salinity being brought to the surface with turbulence associated with tidal movements, as suggested by Cokelet et al. (2007).

Fig. 5. Seasonal change of zooplankton biomass during 1997-2004. Zooplankton biomasses were averaged by month and imaged by Radius Base Functions in the geostatistical analyst extension of ArcGIS 9.1.

The increase in SST throughout the summer months is related to the seasonal increase in surface heating. In the Cross Sound transect, mean currents are of an estuarine type, flowing out in the upper 100 m, and flowing in below the 100 m depth (P. Stabeno, Pacific Marine Environmental Laboratory, NOAA, pers. comm.). Vertical mixing of cold deeper waters associated with the narrow mouth (Fig. 1) and shallow depth of the Cross Sound transect (Table 1) may explain why the Cross Sound transect was generally cooler than other transects in the sampling

area.

Temperatures warmer than 15°C have been correlated with high mortality for late stage zoeae of Dungeness crab (Lough, 1976; Sulkin and McKeen, 1989) while megalopal distribution and abundance were not correlated with water temperature (Hobbs et al., 1992). Dungeness crab zoeae do not develop successfully in laboratory cultures at temperatures warmer than 20-21.5°C (Reed, 1969; Sulkin and McKeen, 1989). In my research, the warmest SST only once attained 15.6°C and ranged from 14 to

15°C very few times during 1997-2004. Cold temperature also influences zoeal survival; survival of zoeal stages in laboratory experiments was poor below 6.1°C (Reed, 1969). Temperatures below 6°C may result in cessation of larval development (Jamieson and Phillips, 1993). However, SST below 6°C were not observed in my study sites but were observed in deeper depths. In general, Dungeness crab larvae have diel vertical migration with a crepuscular pattern (Hobbs and Botsford, 1992; Park and Shirley, 2005). Thus, although the bathymetric distribution of Dungeness crab zoeae is imprecisely known, temperatures in my study site may not constrain the survival and growth of Dungeness crab zoeae.

The kinds of foods consumed by Dungeness crab larvae in situ are not known. However, laboratory experiments indicated that Dungeness crab zoeae which consumed nauplii of *Artemia salina* and *Balanus grandula* developed normally (Poole, 1966; Reed, 1969; Sulkin et al., 1998). Dungeness crab zoeae also feed on dinoflagellates (Hinz et al., 2001; Moore, 2003; Perez and Sulkin, 2005) and diatoms (Hartman and Letterman, 1978). In Auke Bay, a southeastern Alaskan fjord and embayment, large size diatoms such as *Thalassiosira* spp. and *Chaetoceros* spp. are predominant during the primary bloom in April; another large diatom *Skeletonema costatum*, a relevant food for Dungeness crab zoeae (Hartman and Letterman, 1978), is frequently the most abundant phytoplankton in June, but not every year (Ziemann et al., 1993). Under laboratory conditions, *Skeletonema costatum* or mixed foods with *Skeletonema costatum* allowed Dungeness crab zoeae to develop to ZIV or ZV stages (Hartman and Letterman, 1978). Nauplii of barnacles, including *Balanus grandula*, which is densely distributed in the intertidal areas of southeastern Alaska (O'Clair and O'Clair, 1998), hatch following the primary spring bloom in southeastern Alaska. The euphausiid, *Thysanoessa raschii*, and the bay copepods *Pseudocalanus* spp. also have similar hatching patterns (Coyle and Paul, 1990; Paul et al., 1990a, b). These nauplii of small crustaceans, along with phytoplankton species such as *Skeletonema costatum*, which occurs as a later successional phytoplankton, may be pertinent foods for Dungeness crab zoeae. Thus, many potential prey of Dungeness crab larvae occur in my study area. However, the sizes of these preys are small and they would have passed through the 333 µm mesh used in my sampling. Also, the amount of Chl *a* from each diatom species is unknown. Actual numbers of these potential prey items were likely underestimated with

the mesh sizes used in my sampling. A few incidentally caught nauplii were counted in the laboratory (pers. obs.). Accordingly, zooplankton biomass or Chl *a* may not represent food condition for Dungeness crab zoeae in situ because of the sampling biases of the large mesh net and lack of knowledge of Chl *a* contribution by different phytoplankton species.

Overall, this research does not demonstrate with certainty whether the survival and growth of Dungeness crab larvae were constrained by oceanographic conditions in the study area. However, in my research area, SSS, and SST were within published optimal ranges for the survival and growth of Dungeness crab zoeae and should not provide constraints to their survival.

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