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Effect of environmental factors, especially hypoxia and typhoons, on recruitment of the gazami crab *Portunus trituberculatus* in Osaka Bay, Japan

Hiroyuki Ariyama · David H. Secor

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Abstract Important crustacean fisheries occur in semi-enclosed seas. These fisheries can be strongly affected by intense exploitation and episodic anthropogenic and climatic events, but the effects of such events remain largely uninvestigated. To assess the influence of such factors, we examined dredge catch data on the gazami crab *Portunus trituberculatus* in Osaka Bay, Japan from 1984 to 2008 and investigated various associated environmental factors. There were five peak monthly catches during the study period, which typically occurred in August or November. Relative abundance (measured as catch per unit effort) in August was positively associated with previous recruitments to the fishery, typhoon frequency, and dissolved oxygen saturation during the juvenile period. In comparison, relative abundance in November was strongly correlated with the number of typhoons and was also positively associated with dissolved oxygen levels in the bottom water. The results of our multi-decadal study suggest that hypoxia is a principal agent of mortality for juvenile crabs and that normoxia in the nursery habitats is a necessary condition for the successful recruitment of individuals into the adult population. The positive influence of typhoons on recruitment is probably due increased mixing in stratified coastal waters, which disrupts the persistent hypoxia in bottom waters, but other unknown processes may also contribute to favorable recruitments.

Keywords CPUE · Effect · Environmental factors · Gazami crab · Hypoxia · *Portunus trituberculatus* · Recruitment · Typhoon

Introduction

Semi-enclosed seas that receive large river drainages are frequently eutrophicated and support productive fisheries. However, beyond a certain threshold, excess nutrients accompanied with human impacts can yield unsuitable habitats, particularly due to persistent hypoxia [1, 2]. Osaka Bay (Fig. 1) is located in the eastern part of the Seto Inland Sea, western Japan. The Bay comprises the coastal perimeter of Japan's second largest urban–industrial center (Osaka-Kobe), and coastal industry and residential use have degraded nearshore habitats. By the 1960s and 1970s, Osaka Bay had been so seriously eutrophicated that hypoxia and anoxia persisted from May to September, leading to the collapse of benthic communities in adjacent environments [3, 4]. Although the frequency of hypoxia has lessened in recent years [5]—probably due to sewage treatment and other pollution controls—red tides still occur frequently, and hypoxia is often a persistent feature in the most urbanized portions of the Bay around the summer months. Despite degraded water quality and habitats, diverse and productive fisheries (e.g., trawl net, boat seine, purse seine) are active in Osaka Bay [6], resulting in total yearly landings between 25 and 45 thousand metric tons from 1996 to 2005 [7].

The gazami crab (swimming crab) *Portunus trituberculatus* is distributed throughout Japan, Korea, China, and

H. Ariyama (✉)
Marine Fisheries Research Center, Research Institute of Environment, Agriculture and Fisheries, Osaka Prefectural Government, Tanagawa, Misaki, Osaka 599-0311, Japan
e-mail: AriyamaH@mbox.epcc.pref.osaka.jp

D. H. Secor
Chesapeake Biological Laboratory, Center for Environmental Science, University of Maryland, 1 William St., Solomons, MD 20688, USA

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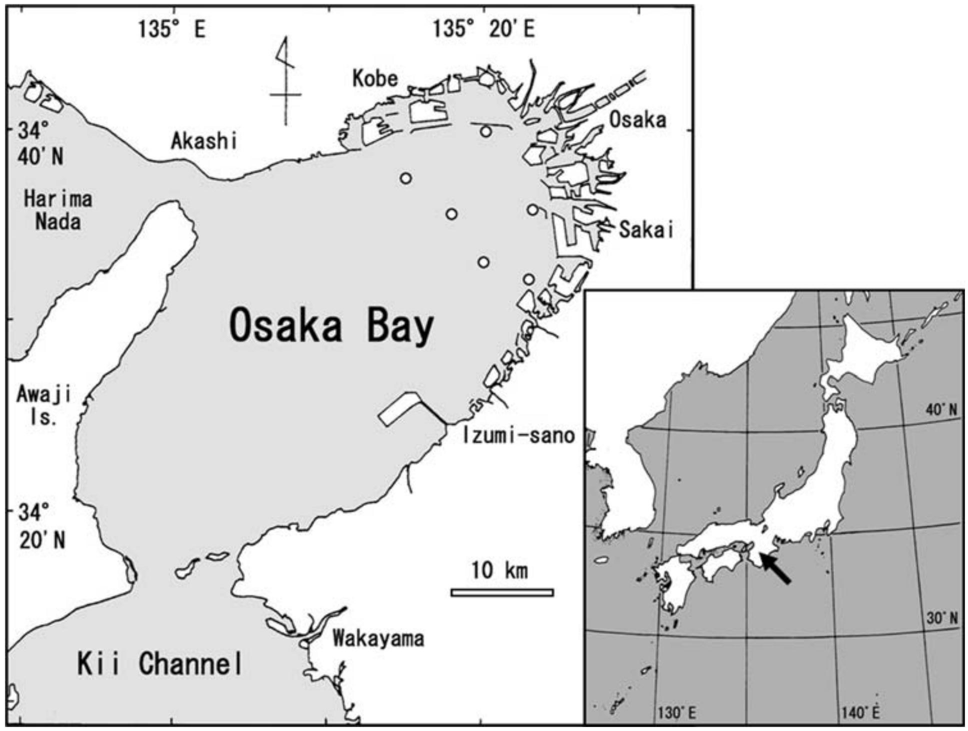

Fig. 1 Study area. *Open circles* observation sites of environmental factors in the innermost portion of Osaka Bay

Formosa [8] and is one of the important edible crabs in Japan. In Osaka Bay, the crab is caught mainly by trawl net (Ishigeta-style dredge and Itabiki-style trawl), but landings can fluctuate wildly over two orders of magnitude [9]. The hatching season of gazami larvae is from June to September, and the duration of the pelagic period of larvae varies from 13 to 37 days according to water temperature [10]. Three cohorts of the crab are present in Osaka Bay: (1) an early cohort of juveniles settles in demersal habitats in July, and young crabs migrate to the fishing ground in September; (2) a middle cohort settles in August and migrates to the fishing ground in October–November; (3) a late cohort settles in September and migrates the following June–August after an extended period in the nursery ground [9]. The nursery ground in Osaka Bay includes a shallow sandy substrate, similar to other nursery areas in Japan, but in years of high abundances (large harvests), it also comprises muddy bottom substrate (approx. 10 m in depth) in the innermost portion of Osaka Bay [9, 11, 12].

Few studies have investigated the cause of these fluctuating yields in gazami harvests. Shiota [13] examined the relationship between adult harvests, new recruits to the fishery, and numbers of megalopal larvae in Hiuchi Nada (Seto Inland Sea, Japan). He concluded that year-to-year variability was associated with megalopa numbers but that a longer term decline in yield was due to overfishing. In Ariake Sound (Kyushu, Japan), Shimano et al. [14] detected significant (positive and negative) correlations between annual catches and water color, bottom water temperature, phosphate, nitrite, dissolved inorganic nitrogen, chemical oxygen demand, and catch in the previous year, but they were unable to provide a framework for how these factors specifically affected landings. In Osaka Bay, Ariyama [12] suggested a strong positive association between summer landings and incidence of hypoxia during the previous autumn. The aim of the study reported here was to more broadly address how hypoxia has affected recruitment in the context of multiple environmental and meteorological factors in Osaka Bay over a 25-year period. An important factor is typhoons, which are a pervasive feature in Osaka Bay and coastal Japan during the summer and autumn and likely to influence crab recruitments.

Materials and methods

To understand the abundance and distribution of the gazami crab in Osaka Bay, we examined landings data from 1984 to 2008. These data were obtained from a single representative fisherman who uses an Ishigeta-style dredge and fishes as part of the Izumi-sano Fishing Cooperative in middle Osaka Prefecture. This Cooperative engages in most of the trawl effort within Osaka Bay, with the fishing location in the Osaka Bay at any one time being dependent upon season and fish availability. Most fishermen within the Cooperative deploy dredges and trawls in groups with other vessels. The yearly income of the representative fisherman was strongly correlated with the average income of dredge fishermen of the Cooperative during the study period (t test: $P < 0.001$). Consequently, we assumed that the catch of the fisherman was also representative of that of the Cooperative. This fisherman provided daily records of the fished area and the number of caught crabs (ovigerous and non-ovigerous). Based on these records, we estimated monthly catch per unit effort (CPUE). In our study, CPUE corresponds to crabs/boat/day.

To evaluate environmental factors affecting the CPUE of the crab, we performed a principal component analysis (PCA) and a stepwise multiple regression analysis (MRA) using an add-in software for Excel. The following data were used in the calculation: (1) CPUE during peak harvest months was used as an index of recruitment (newly recruited crabs usually comprise most of catch during the peak harvest months [9]); (2) CPUE 2 months before the peak harvest was used to index of background abundance (partial recruitments appeared at $\leq$1 month prior to peak harvest months); (3) CPUE of ovigerous females in the hatch month was used as an index of spawner stock abundance; (4) temperature- and salinity-indexed environments experienced by pelagic larvae (the average of conditions at the surface and at a depth of 5 m was used because most larvae inhabit the surface at night and the 5-m-deep layer during the daytime [15]); (5) dissolved oxygen saturation on the bottom represented conditions experienced by benthic juvenile crabs (on the settlement and 2 weeks after the settlement); (6) number of typhoons approaching the Kinki district (Osaka, Hyogo, Kyoto, Shiga, Nara, and Wakayama Prefectures) as an index of potentially catastrophic events that affect pelagic larvae and/or benthic juvenile crabs (Japan Meteorological Agency: http://www.data.jma.go.jp/fcd/yoho/typhoon/statistics/accession/kinki.html; accessed 29 Oct 2009). The months of hatch and pelagic and benthic stages were estimated from Hamasaki [10] and Ariyama [9]. Environmental factors were averaged from six sites (routine observation stations nos. 13–18 at a depth of 13–18 m; Fig. 1) representing biweekly measures in the innermost portion of Osaka Bay [16]. Although it would have been desirable to include indices on predator and prey abundances, insufficient data supported such measures.

Results

Monthly CPUEs from 1984 to 2008 showed large fluctuations, with a range from 0 to 319 crabs/boat/day (Fig. 2). There were five seasonal sampling periods, with over 100 crabs/boat/day during the 25-year study: August 1988, August–November 1996, October–December 1997, October–March 2004/2005, and May–Aug 2005. The distributions of CPUEs from June to December for the harvests during these years are shown in Fig. 3. In 1988 and 1996, strong peaks in harvests occurred during the summer—August 1988 and July 1996—with CPUEs subsequently decreasing after October. Peak harvests occurred in the northeast and middle sections of Osaka Bay. In contrast, large catches occurred in 1997 and 2004 starting in October

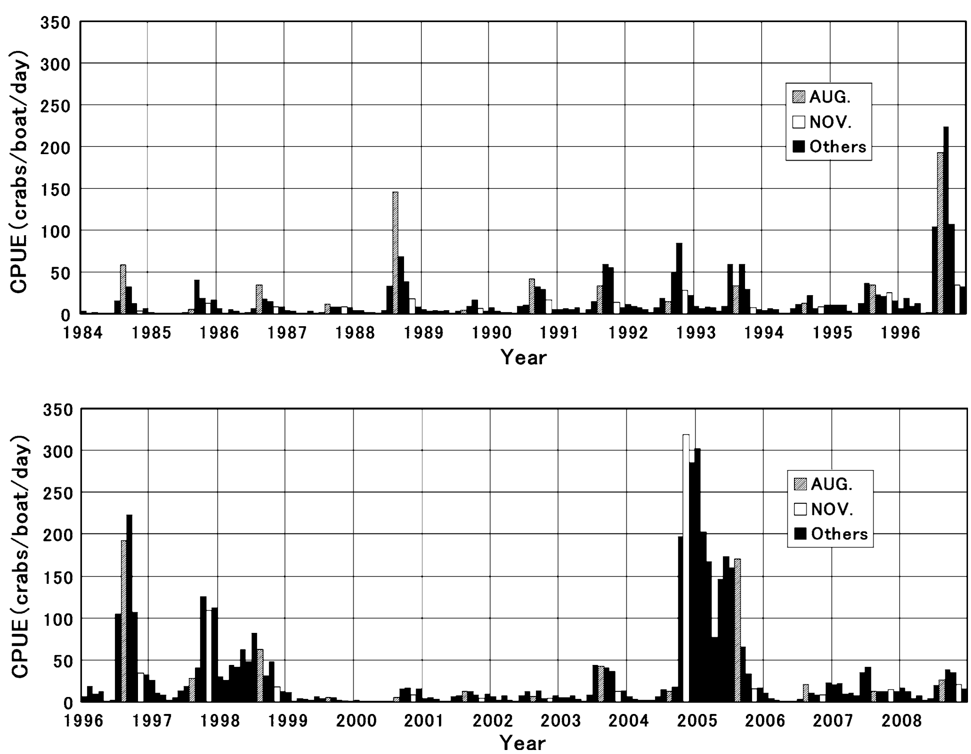

Fig. 2 Monthly fluctuation of catch per unit effort (*CPUE*) of the gazami crab *Portunus trituberculatus* in the representative fisherman's record at Izumi-sano from 1984 to 2008

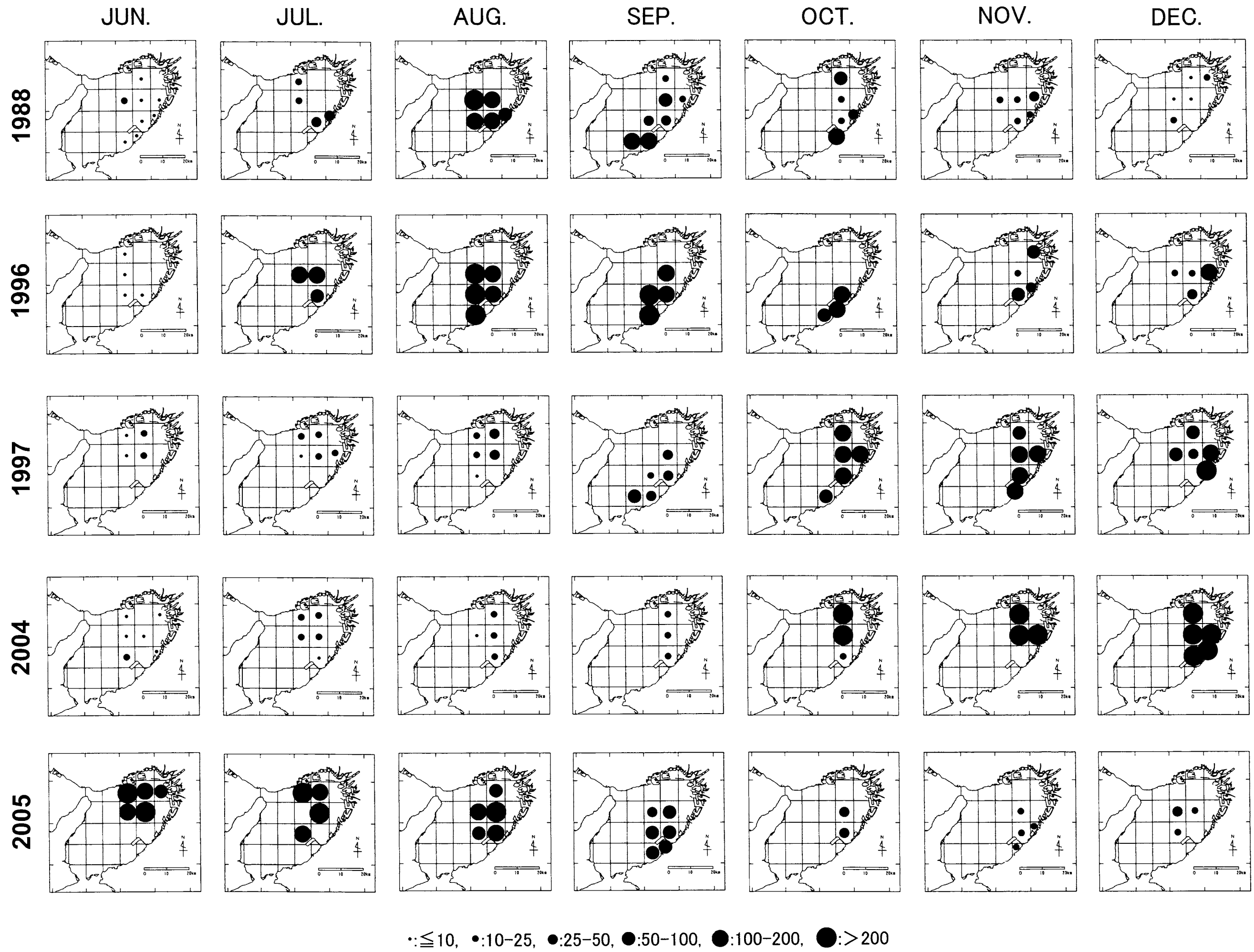

Fig. 3 Distributions of CPUEs of the gazami crab *P. trituberculatus* in the representative fisherman's record at Izumi-sano from June to December in 1988, 1996, 1997, 2004, and 2005

over a wide area of Osaka Bay (1997) or in the northern area (2004) of the eastern part of the Bay. The large catch in this latter region continued from 2004 up to September 2005.

Because large catches in July–August were derived from the late cohort and those in October–November from the middle cohort [9], an index of recruitment of each of these cohorts was compiled for the months of August and November, respectively (Tables 1, 2).

Based on the results of the PCA performed on the CPUE in August (CA), we selected three principal components, which explained 29.2, 24.8 and 14.5% of the modeled variance, respectively (Table 3). CA loadings (0.550 onto PC1 and 0.384 on PC2) and other loadings on PC1 and PC2 indicated that the CPUE in June (CJ) and number of typhoons (NT) were strongly correlated with the CA (Fig. 4). In contrast, the first four principal components of the PCA conducted on the CPUE in November (CN) together explained 75.4% of the modeled variance (Table 4). Component loadings of CN were 0.795, −0.039, −0.256, and 0.393 for PC1 through PC4, respectively; therefore, we investigated loadings onto PC1 and PC4 (Fig. 5). These loadings indicated a strong relationship among CN, NT, and dissolved oxygen (DO) in August (DOA), and a weak relationship between CN and DO in September (DOS).

The results of the MRA gave the following equation on CA showed positive correlation between CA and CJ:

$$\mathrm{CA} = 0.7435\mathrm{CJ} + 1.301\mathrm{DOS} - 35.05\,(P < 0.05) \qquad (1)$$

For CN, the following equation provided the best fit:

$$\mathrm{CN} = 25.82\mathrm{NT} + 2.304\mathrm{DOS} - 8.572\mathrm{SA} + 102.0\,(P < 0.001) \qquad (2)$$

where SA is the salinity in August. However, multicollinearity was detected in SA because the partial correlation coefficient had an opposite sign to the simple

Table 1 Data used for calculating the CPUE in August

Year	(1) CPUE in August (crabs/boat/day)	(2) CPUE in June (crabs/boat/day)	(3) CPUE of ovigerous females in the previous August (crabs/boat/day)	(4)-1 Surface temperature in early September of the previous year (°C)	(4)-2 Surface salinity in early September of the previous year (psu)	(5)-1 Dissolved oxygen saturation on the bottom in middle-late September of the previous year (%)	(5)-2 Dissolved oxygen saturation on the bottom in early October of the previous year (%)	(6) Number of typhoons approaching the Kinki district in the previous year
1984	58.25	0.06	–	28.58	28.41	43.05	37.33	3
1985	5.18	1.20	0.30	27.63	30.15	58.42	51.00	1
1986	34.64	2.30	0.09	28.15	29.78	53.80	58.17	3
1987	10.94	1.47	0.53	27.24	30.33	57.32	65.02	3
1988	146.06	4.55	0.11	26.58	30.43	54.05	70.00	2
1989	3.69	1.47	0.33	24.40	29.50	33.03	29.35	3
1990	41.94	9.45	0.46	25.72	23.34	40.23	73.33	2
1991	33.12	5.29	0.50	27.42	31.02	54.60	–	6
1992	14.86	6.81	1.65	26.18	29.73	65.03	–	4
1993	32.82	9.00	0.57	26.89	29.85	58.73	71.70	4
1994	12.53	6.00	0.71	26.02	27.52	34.25	62.87	6
1995	34.64	13.00	0.94	29.10	30.95	45.97	64.20	2
1996	192.33	2.42	1.86	27.09	29.65	70.95	59.25	1
1997	27.77	13.17	5.11	26.55	29.42	46.98	73.82	2
1998	62.73	47.85	1.31	27.66	30.14	61.05	64.88	4
1999	4.69	6.18	5.07	26.55	31.10	48.90	58.40	4
2000	5.00	0.85	1.00	27.94	28.37	52.42	63.38	2
2001	12.00	5.77	0.13	27.03	30.16	29.50	53.50	0
2002	6.29	7.00	0.77	24.82	30.79	27.70	58.00	3
2003	42.92	7.93	0.57	27.67	30.87	65.94	68.36	4
2004	12.77	6.75	0.77	28.03	24.28	67.98	72.24	4
2005	170.13	173.80	0.15	26.00	28.61	45.92	64.30	9
2006	20.50	1.08	15.56	25.89	29.48	25.67	48.47	3
2007	12.23	35.31	0.13	27.37	29.39	59.65	74.23	2
2008	25.58	4.07	0.08	27.78	29.18	52.92	55.17	4

CPUE Catch per unit effort

– No data, and the data sets including no data were not used for calculations in 1984, 1991, and 1992

Table 2 Data used for calculating the CPUE in November

Year	(1) CPUE in November (crabs/boat/day)	(2) CPUE in September (crabs/boat/day)	(3) CPUE of ovigerous females in July (crabs/boat/day)	(4)-1 Surface temperature in early August (°C)	(4)-2 Surface salinity in early August (psu)	(5)-1 Dissolved oxygen saturation on the bottom in middle-late August (%)	(5)-2 Dissolved oxygen saturation on the bottom in early September (%)	(6) Number of typhoons approaching the Kinki district
1984	3.56	32.00	0.05	25.85	28.43	9.55	33.18	1
1985	12.18	40.64	0.25	27.25	27.29	8.82	14.67	3
1986	7.86	17.47	0.73	23.33	29.43	48.67	41.52	3
1987	8.47	8.28	0.40	26.53	27.86	33.33	49.17	2
1988	17.75	69.00	0.43	23.68	29.19	17.88	44.22	3
1989	5.86	9.42	1.29	24.20	30.19	38.75	66.83	2
1990	16.36	31.83	0.29	26.40	30.16	35.67	–	6
1991	13.75	59.77	0.85	25.42	27.92	40.82	42.57	4
1992	28.58	48.93	3.47	23.75	31.41	53.87	41.13	4
1993	7.54	59.43	4.42	24.62	27.92	33.25	15.33	6
1994	8.00	22.00	1.07	27.91	31.41	29.15	45.80	2
1995	25.50	22.88	2.08	27.19	26.30	27.10	38.55	1
1996	34.38	223.67	3.21	29.06	28.85	51.15	44.28	2
1997	109.50	40.50	3.17	27.16	24.79	41.33	33.50	4
1998	18.00	31.54	3.64	28.16	29.49	33.55	55.45	4
1999	0.62	5.00	0.93	27.64	29.49	13.10	51.63	2
2000	8.08	16.00	0.14	27.84	29.85	29.35	50.50	0
2001	4.29	12.20	1.29	27.15	30.10	64.17	30.20	3
2002	3.77	14.00	0.50	29.39	29.54	73.69	37.19	4
2003	12.09	40.57	2.92	26.59	28.83	29.82	24.78	4
2004	318.73	17.63	0.60	25.66	30.66	53.59	68.28	9
2005	15.88	64.93	15.67	25.82	29.66	42.50	32.03	3
2006	8.15	10.29	0.27	26.27	23.64	30.35	33.03	2
2007	14.86	12.45	2.00	25.72	29.51	33.44	46.53	4
2008	21.27	38.31	1.21	28.18	29.55	38.35	47.53	2

– No data, and the data set including no data was not used for calculations in 1990

Table 3 Variances explained and component loadings of first three principal components conducted on the CPUE in August

Variances	PC1	PC2	PC3
Variance explained (%)	29.2	24.8	14.5
Component loadings			
(1) CPUE in August (CA)	0.550	0.384	0.396
(2) CPUE in June (CJ)	0.489	0.766	0.148
(3) CPUE of ovigerous females (COF)	−0.512	0.150	0.063
(4)-1 Temperature in September (TS)	0.533	−0.645	0.146
(4)-2 Salinity in September (SS)	−0.191	−0.140	0.894
(5)-1 Dissolved oxygen (DO) in September (DOS)	0.774	−0.431	0.147
(5)-2 DO in October (DOO)	0.709	−0.158	−0.364
(6) Number of typhoons (NT)	0.333	0.763	−0.064

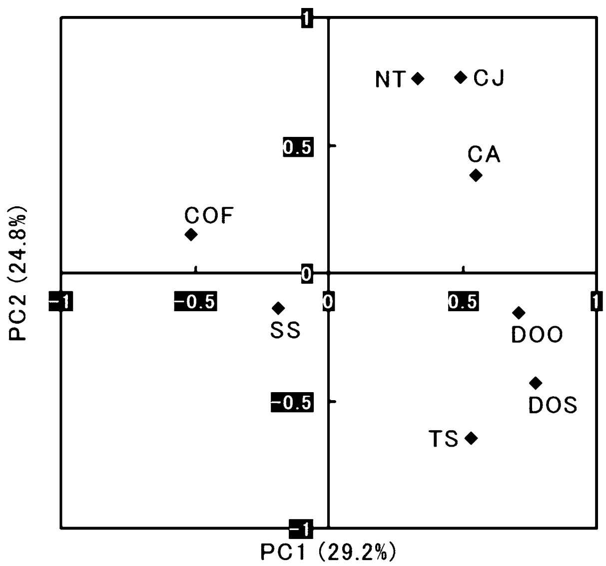

Fig. 4 Distribution of principal component (PC) loadings for parameters associated with CPUE in November (see Table 1). See Table 3 for definitions of abbreviations

correlation coefficient. The exclusion of SA yielded the following equation, which showed positive correlations between CN, NT, and DOS:

$$\mathrm{CN} = 24.65\mathrm{NT} + 1.786\mathrm{DOS} - 120.0\,(P < 0.001) \qquad (3)$$

Discussion

Multivariate analyses indicated that the crab abundance in August depended mainly upon the background abundance in June (PCA and MRA), the number of typhoons (PCA), and the dissolved oxygen saturation in middle-late September (MRA) of the previous year. The analyses also supported the suggestion that new recruits in November were strongly influenced by the number of typhoons (PCA and MRA) and correlated with the dissolved oxygen saturations in middle-late August (PCA) and early September (PCA and MRA).

Because both of the CPUEs in August and November were positively associated with bottom dissolved oxygen during the juvenile period, we investigated changes in the level of dissolved oxygen during years with large landings (Fig. 6) [17–20]. The first step was to examine the juvenile oxygen condition for the peak August catches (1988, 1996, and 2005). In 1987 (conditions prior to peak landings in 1988), hypoxia was pervasive in middle July in the eastern coastal area of Osaka Bay but had disappeared by the middle of September. In 1995 (conditions prior to peak landings in 1996), conditions of severe hypoxia had developed by the middle July and remained until early September, vanishing by mid-September. Oxygen saturations in both years were relatively high in the middle of September and early October. These facts suggest some tendency for large recruitments when the oxygen condition during the benthic juvenile stage is good. In comparison, in 2004 (conditions prior to peak landings in 2005), strong hypoxia had developed in the innermost portion of the Bay in late September. Because the size of the harvested crabs in July and August, 2005 (the average carapace width was approx. 150 mm in August [21]) was larger than the standard size of the late cohort (approx. 110–120 mm [9]), we can estimate that the former were derived from the middle cohort and that the large landing by the middle cohort continued from October in 2004 to August in 2005.

We then examined the case of large catches in November (1997 and 2004). In 1997, weak hypoxia occurred from early August to early September in the innermost portion of the Bay; this condition had disappeared by late September, although there was strong hypoxia along the middle of the eastern coast in early September. Relatively high oxygen saturation persisted in 2004, with the exception of late September. These observations support the association between relatively high oxygen levels from middle–late August to early September and high landings in November.

In the laboratory, juvenile gazami crab (carapace width 47–68 mm) showed 100% survival for 24 h at 25°C and

Table 4 Variances explained and component loadings of first four principal components conducted on the CPUE in November

Variances	PC1	PC2	PC3	PC4
Variance explained (%)	27.6	18.7	15.7	13.5
Component loadings				
(1) CPUE in November (CN)	0.795	−0.039	−0.256	0.393
(2) CPUE in September (CS)	−0.030	0.677	0.318	0.151
(3) CPUE of ovigerous females (COF)	0.077	0.746	0.043	−0.391
(4)-1 Temperature in August (TA)	−0.217	0.076	0.583	0.670
(4)-2 Salinity in August (SA)	0.498	−0.134	0.538	−0.525
(5)-1 DO in August (DOA)	0.602	0.312	0.317	0.097
(5)-2 DO in September (DOS)	0.534	−0.552	0.410	−0.044
(6) Number of typhoons (NT)	0.790	0.234	−0.432	0.119

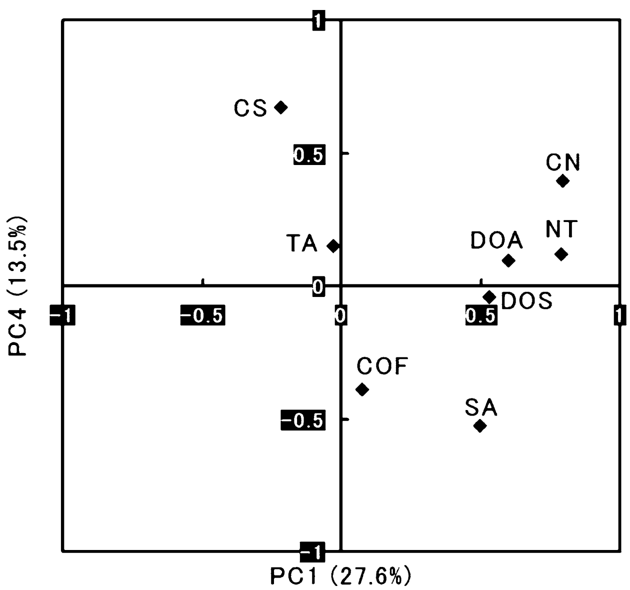

Fig. 5 Distribution of PC loadings for parameters associated with CPUE in November (see Table 2). See Table 4 for definitions of abbreviations

27% dissolved oxygen saturation (1.93 mgO_2/l), while 17 and 83% of the crabs died at 16% (1.14 mgO_2/l) and 12% (0.86 mgO_2/l) dissolved oxygen saturation, respectively [22]. These results indicate that the tolerance of this crab for hypoxia is relatively high but that severe hypoxia (<27% DO saturation) is lethal. Although Ariyama et al. [11] inferred that large gazami crabs can escape hypoxic water, most juvenile crabs probably die under severe hypoxic conditions owing to their low swimming ability. In fact, Ariyama [12] observed many dead juvenile crabs after an attack of blue tide (upwelling of hypoxic water to the surface) within the innermost coastal waters of Osaka Bay. Consequently, normoxia in the nursery habitats is a necessary condition promoting subsequent recruitment. Hypoxic conditions have also been shown to be associated with a decline in the harvest of the blue crab *Callinectes sapidus* [23]. The blue crab has a similar swimming ability to the gazami crab, and adult crabs are able to move quickly from hypoxic water depending on the level of the dissolved oxygen [24, 25]. However, juvenile blue crabs were unable to avoid hypoxic or anoxic water to any significant extent in the laboratory [26]; therefore, many juvenile crabs may be killed by severe hypoxia, similar to the gazami crab. Failure of juvenile recruitment owing to hypoxia was also observed in Japan for the portunid crab *Charybdis bimaculata* in Ise Bay [27] and the mantis shrimp *Oratosquilla oratoria* in Tokyo Bay [28].

The number of typhoons approaching Osaka Bay showed a strong effect on November recruitments and a weak effect on August recruitments. A noteworthy year was 2004 when a remarkable harvest occurred from October and an extreme number of typhoons hit Osaka Bay: nine versus the average number of 3.0 (mean from 1984 to 2008, excluding 2004). These typhoons likely promoted the survival of juveniles. Interestingly, this association is in contrast to results reported on the blue crab in Albemarle Sound, where hurricanes were associated with recruitment failure [29]. Typhoons and hurricanes bring heavy rainfall and strong winds, and the rainfall lowers the salinity of seawater. Moreover, strong winds disrupt the stratification of sea water [30] and raise bottom sediments [31]. In both analyses conducted on the CPUE in November, the effect of typhoons was greater than that of dissolved oxygen, which suggests that typhoons have positive effects beyond increased water column mixing and reduced hypoxia. Hurricanes (and typhoons) actually have a number of various environmental effects on coastal ecosystems [32]. One of these may be a decrease in predation by the dragonet *Repomucenus* spp., a principal predator of juvenile crabs [9] that dwells in the innermost portion of the Bay [11]. Another effect is inferred to be an increase in the available prey for juvenile crabs. High abundances (503–7430 ind/m^2) of the polychaete worm *Paraprionospio patiens*, potential prey of juvenile crabs, inhabit the shoal areas of Osaka Bay [33, 34]. It is believed that typhoons disproportionately affect such shoal areas,

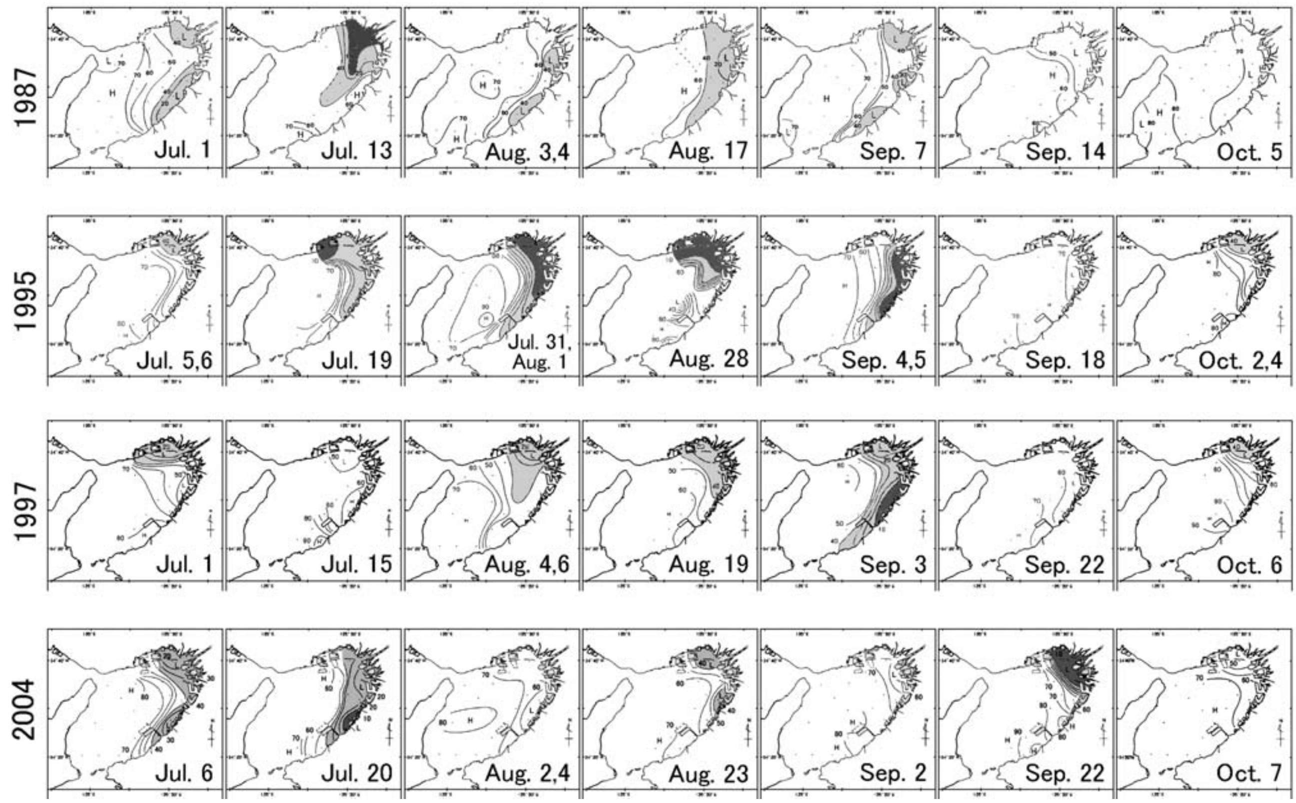

Fig. 6 Distributions of the dissolved oxygen saturations (%) on the bottom from early July to early October in 1987, 1995, 1997, and 2004. *Black* and *gray* parts show oxygen saturations of <10 and <40%, respectively

possibly increasing the production of this benthic prey. Interestingly, peak landings of the pink shrimp *Farfantepenaeus duorarum* following hurricanes have also been recorded, the cause of which may be the outwelling of detritus by defoliation associated with hurricanes [35]. The timing of typhoons is also important. In the case of the abalone *Haliotis diversicolor*, spawning is strongly associated with typhoon events, but the survival of post-larvae and juveniles is affected negatively when they directly experience typhoons [36]. In 2004, there were two, one, two, two, and two typhoons per month, respectively, from June to October. Thus, not only the frequency but the timing of typhoons may promote crab recruitment. Meteorologists have reported that the number of typhoons has been increasing in the western North Pacific in recent years [37]. Although human systems face increased catastrophic losses in the future, we speculate that the harvest of the gazami crab may increase as a response to increased storm events in Osaka Bay.

Abundances in August were apparently influenced by the background abundances in June. Because the carapace width of most crabs caught in June ranged from 100 to 150 mm [9], these crabs are estimated to be young crabs derived from the early and middle cohorts in the previous year. If previous cohort abundances are considerably larger than new recruitments, then the effect of this background abundance would be large. For example, the large catch in summer of 2005 was possibly the effect of the large middle cohort in the previous year, as stated above.

In conclusion, we have examined the effect of environmental factors on the recruitment of the gazami crab in Osaka Bay and found that hypoxia and typhoons strongly affect this recruitment. Future studies should also include trophic relationships upon which gazami depend, which were beyond the scope of our study.

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