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# Stable isotope variations in otoliths of Pacific halibut (*Hippoglossus stenolepis*) and indications of the possible 1990 regime shift

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## Abstract

Stable oxygen and carbon isotope ratios ( $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ) from archived otoliths of Pacific halibut, *Hippoglossus stenolepis*, were measured to examine the most recent regime shifts in British Columbia and the Gulf of Alaska.  $\delta^{18}\text{O}$  values of these otoliths ranged from  $-1.5$  to  $+2.8\text{‰}$  VPDB, and were consistent with the life stages and migration behavior of halibut.  $\delta^{13}\text{C}$  varied from  $-3.3$  to  $+0.9\text{‰}$  VPDB, but did not show a transition from the juvenile to the adult stage as does  $\delta^{18}\text{O}$ . Evaluation of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values of mature halibut (ages 8–12) indicated that the 1977 regime shift might have a warming impact on the northeast Pacific fish stocks. In contrast, a possible regime shift around 1990 with a bottom seawater temperature decrease of about  $2\text{ °C}$  might have occurred in both the areas. The connection between stable isotope variations in otoliths and the climate regime shifts is thus potentially useful in studying the population dynamics of Pacific halibut, and decadal scale (e.g., the last 20–30 years) ocean environmental changes.

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**Keywords:** Otolith; Halibut; Regime shift;  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ; North Pacific

## 1. Introduction

Pacific halibut, *Hippoglossus stenolepis*, are bottom dwellers that have longer life spans than most other groundfishes with a maximum estimated age of 55 years (Munk, 2001). Since 1923, the stock has been managed by the International Pacific Halibut Commission (IPHC) that has systematically collected otoliths for more than 60 years. The distribution, biology, and management of Pacific halibut have been extensively

documented, particularly in the IPHC internal publications (e.g., annual reports, scientific reports, and technical reports). Female halibut grow faster but mature more slowly than males. Spawning occurs annually from November to March along the edge of the continental shelf at depths between 100 and 550 m (St-Pierre, 1984). After about 6 months of westerly and northwesterly drifting, larvae gradually settle to the ocean floor and adapt to the bottom life (IPHC, 1987). Over the course of several years, juvenile halibut move offshore and undertake a migration to the east and south that counters the larval drift (Trumble et al., 1993). The counter-migration ends at about the time of sexual maturity, and adult halibut (ages > 8)

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migration is minimal except for seasonal movement from winter spawning grounds to summer feeding grounds, and vice versa (Skud, 1977).

The long time series of halibut catch, age, and growth data provides a unique opportunity to evaluate the biological response of Pacific halibut to environmental changes. The relatively new hypothesis of regime shifts has presented the scientific community with a new framework in which to investigate ecosystem changes in the North Pacific. A “regime shift” is a synchronous change in variables defined as “a multi-year period of linked recruitment patterns in fish populations or as stable means in physical data series” (Beamish et al., 1999), and is related to ocean climate. Several studies have demonstrated that decadal scale (last 20–30 years) regime shifts may

have effects on fish productivity comparable to or greater than fishing activities (Beamish and Bouillon, 1993; Francis and Hare, 1994; Steele, 1996; Mantua et al., 1997). Changes in growth, recruitment, and production of Pacific halibut also vary at a decadal scale (Clark et al., 1999). Recent regime shifts occurred during the winter of 1976–1977, and possibly in the late 1980s (Beamish et al., 1999). These investigations, however, are based primarily on catch data and relevant oceanographic and meteorological conditions. Stable oxygen and carbon isotope ratio analyses ( $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ) from otoliths of Pacific halibut have the potential to obtain independent chemical records to test the regime shift hypothesis, and will provide evidence that regime changes directly affect bottom fish.

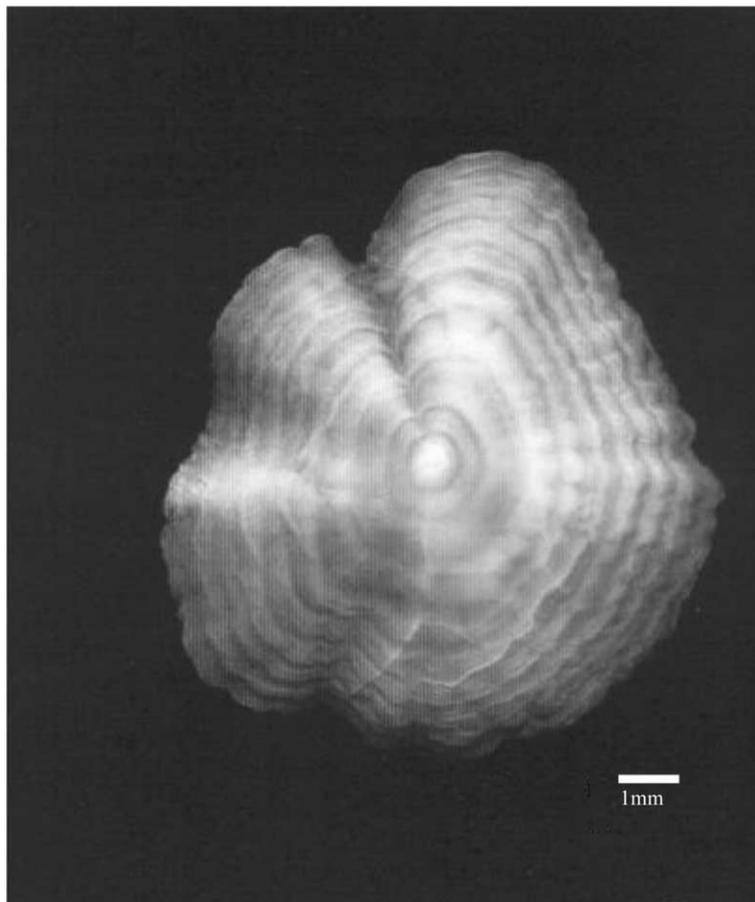


Fig. 1. Photograph of a sagittal otolith section of Pacific halibut, showing the size and the translucent (winter) and opaque (summer) otolith zones. Scale bar  $\approx 1$  mm.

Halibut otoliths are exceptionally large for extracting sequential isotopic records through an individual fish. In the surface of sagittal otoliths, there displays a regular series of translucent and opaque zones which alternate from the nucleus to the margin (Fig. 1). The opaque zones correspond to the rapid summer growth and the translucent zones to the slow winter growth (Quinn et al., 1983). The first attempt at stable isotope analysis of fish otoliths was by Devereux (1967), whose data suggested that the habitat of fish could be deduced from  $\delta^{18}\text{O}$  values of their otoliths. Otolith laminae grow continuously through the life of a fish, and faithfully record the environmental and climatic changes experienced by the fish. As a result,  $\delta^{18}\text{O}$  values of otolith aragonite can be used as a measure of temperature; with increasing temperature,  $\delta^{18}\text{O}$  decreases (Radtke et al., 1987; Kalish, 1991; Gao, 1997). In contrast to oxygen isotopes, carbon in otolith aragonite is deposited in isotopic disequilibrium with the ambient seawater, at least partially influenced by metabolic sources (Mulcahy et al., 1979; Schwarcz et al., 1998). Therefore, changes in  $\delta^{13}\text{C}$  values of otoliths can record changes in sexual maturity of the fish and dietary shifts, whereby higher trophic level foods result in higher  $\delta^{13}\text{C}$  values (Fry, 1988).

Although the potential of using stable isotope ratios of otoliths for environmental studies has been documented by many laboratory experiments, studies examining archived otoliths at annual or seasonal scales have rarely been reported (e.g., Patterson et al., 1993; Weidman and Millner, 2000; Gao et al., 2001a,b). To date, there have been no attempts to use stable isotopic tracers to address the impact of long-term climate-related ecosystem changes in the northeast Pacific. In this paper, we report the isotopic composition of individual Pacific halibut otoliths. It was expected that the lifetime isotopic variations of halibut would be consistent with their life stages from juveniles to adults as we observed in sockeye salmon (Gao and Beamish, 1999). The second goal of the research was to test if the isotopic records in halibut otoliths were consistent with other data sources for regime shifts in 1977 and possibly 1990. This was achieved by analyzing isotopic variations of the summer portion of mature halibut otoliths from two IPHC areas, because tagging data (Skud, 1977) show that little summer-to-summer movements occur for mature halibut.

## 2. Materials and methods

As an initial examination of how the environmental signal is tracked by stable isotope ratios, we carried out two tests in halibut otoliths. First, we selected two small sets of otoliths from tagged halibut to determine any differences in  $\delta^{18}\text{O}$  values. Five otoliths from halibut tagged from 1985 to 1992 and recovered in the eastern Aleutian islands (IPHC area 4A; Fig. 2). Another four otoliths from halibut tagged from 1994 to 1997 and recovered near Kodiak Island (IPHC area 3A in Fig. 2). Because these halibut were released and recaptured in the same area with relatively known oceanic conditions, the test could in principle compare  $\delta^{18}\text{O}$  variations with bottom temperature measurements. Secondly, even if male and female halibut from the same area have no differences in  $\delta^{18}\text{O}$ , their  $\delta^{13}\text{C}$  values might vary with sex because female halibut are larger and mature later than males. To test this hypothesis, we selected seven female and four male halibut from Gulf of Alaska for comparison.

We randomly selected 40 Pacific halibut otoliths from two intervals and two IPHC regulatory areas 3A and 2B (cf. Fig. 2) for stable isotope analysis. All the fish were 13 years old, with the body fork length from 85 to 150 cm (Table 1). These samples were collected in June–July of 1980 and 1993, from water depths from 200 to 250 m. To avoid the confusion of age reading (some starting from January, others from July), we discarded the last annual otolith zone from the age series during microsampling. These selections provide at least 5 years (ages 8–12) during which the halibut were non-migratory (Skud, 1977). Data from fish collected in 1980 and 1993 were thus suitable for testing the bottom environmental conditions at the time of the 1977 and possible 1990 regime shifts.

Halibut otoliths were first cleaned in a supersonic water bath for about 15 min, rinsed with ethanol, and then air-dried. After slight polishing, samples were placed in a mold consisting of an aluminum base and strips with reference lines. After positioning otoliths in the mold, black-pigmented fiberglass resin was added and allowed to harden overnight. Hardened blocks were sectioned using a Micro-Matic precision slicing machine, with automatic controls on speed and direction. For the convenience of polishing individual otoliths, sections were cut into blocks measuring about 15 mm × 10 mm × 5 mm. Each otolith section

Table 1  
Summary of stable oxygen and carbon isotope analyses of halibut otoliths (all fish listed were 13 years old)

Sample	Sex	Length (cm)	$\delta^{18}\text{O}$ range (‰)	S.D.	$\delta^{13}\text{C}$ range (‰)	S.D.
<i>1980 otoliths</i>						
Area 3A						
1214	F	149	0.54 to 2.08	0.57	-1.84 to -0.62	0.38
1281	F	149	0.25 to 1.93	0.46	-2.30 to -0.36	0.53
1285	F	146	0.88 to 2.16	0.41	-1.96 to +0.87	0.96
1290	F	140	0.89 to 2.59	0.54	-2.31 to +0.17	0.80
1334	F	138	0.95 to 1.92	0.28	-2.44 to -0.29	0.70
1342	F	143	0.77 to 2.51	0.53	-2.62 to -0.01	0.76
1343	F	133	1.28 to 1.92	0.20	-2.41 to -1.13	0.40
1344	F	135	1.10 to 2.57	0.55	-2.42 to -0.06	0.71
Area 2B						
0058	F	124	0.69 to 2.08	0.44	-2.38 to -0.17	0.70
0102	F	150	-1.46 to 1.95	1.24	-1.87 to -0.20	0.55
0208	F	128	1.65 to 2.39	0.26	-2.22 to -0.22	0.53
0215	F	142	1.21 to 2.45	0.41	-2.39 to -0.62	0.57
0264	F	92	1.54 to 2.78	0.36	-1.53 to -0.72	0.25
0323	F	118	0.64 to 2.17	0.52	-2.72 to -1.01	0.57
0338	F	126	0.39 to 2.30	0.65	-2.21 to -0.47	0.57
0085	F	146	1.13 to 2.08	0.35	-1.48 to +0.78	0.79
<i>1993 otoliths</i>						
Area 3A						
00090	F	135	1.05 to 2.50	0.54	-2.05 to -0.26	0.50
00100	F	114	0.20 to 2.37	0.73	-3.24 to -0.82	0.89
00220	F	110	1.07 to 2.06	0.30	-2.27 to -1.23	0.31
00285	F	92	0.85 to 2.38	0.55	-2.84 to -1.14	0.52
00310	F	132	1.52 to 2.37	0.32	-1.83 to -0.53	0.43
00585	F	97	0.87 to 2.19	0.37	-2.72 to -1.59	0.36
00670	F	107	1.05 to 2.22	0.40	-2.61 to -1.12	0.42
00070	M	101	0.49 to 2.40	0.65	-1.73 to -0.66	0.34
00200	M	81	1.13 to 2.19	0.39	-3.15 to -1.27	0.58
00205	M	78	-0.43 to 2.35	1.02	-3.28 to -1.10	0.71
00315	M	93	1.02 to 2.41	0.54	-2.69 to -0.64	0.57
Area 2B						
10340	F	93	0.69 to 2.39	0.64	-2.40 to -0.96	0.48
10342	F	115	0.49 to 2.49	0.76	-2.66 to -0.97	0.58
10358	F	125	0.87 to 2.75	0.70	-2.28 to -0.55	0.47
10378	F	85	0.42 to 2.49	0.57	-2.56 to -0.92	0.57
10384	F	116	1.22 to 2.58	0.51	-2.74 to -0.84	0.55
10386	F	114	1.26 to 2.73	0.42	-2.61 to -0.65	0.48
10388	F	136	1.02 to 1.68	0.23	-2.48 to -0.81	0.55
10142	F	97	0.92 to 2.32	0.56	-3.07 to -1.24	0.74
10178	F	113	1.11 to 2.30	0.46	-2.27 to -0.63	0.52
10092	M	84	0.38 to 2.39	0.81	-1.84 to -0.60	0.39
10104	M	83	0.81 to 2.60	0.64	-2.17 to -0.45	0.60
10130	M	108	0.84 to 2.73	0.72	-2.86 to -0.80	0.56
10272	M	89	0.67 to 2.45	0.63	-2.12 to -0.49	0.61

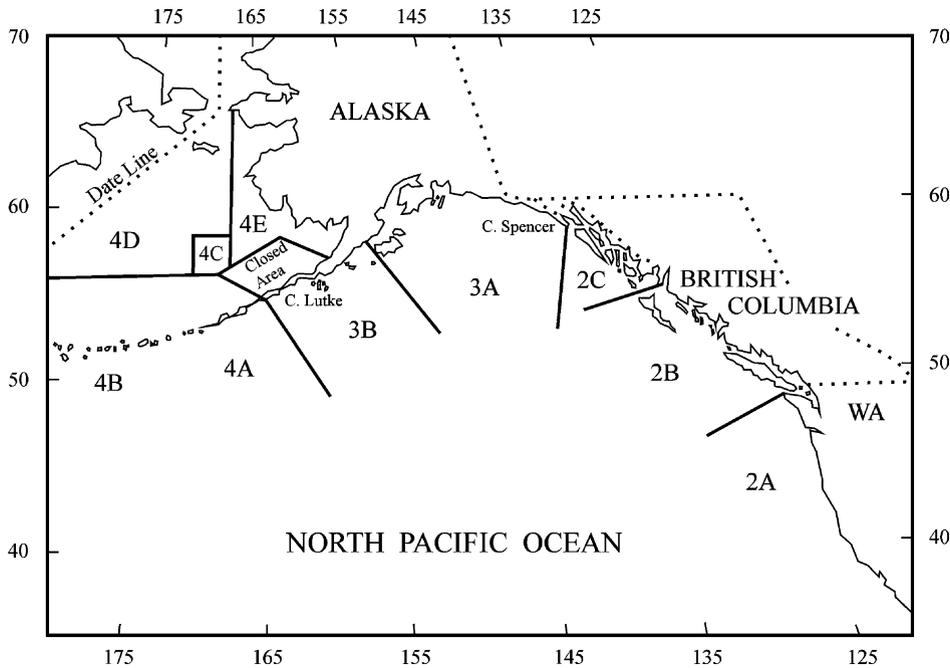


Fig. 2. Location map of the IPHC regulatory areas in the North Pacific ocean.

was polished with care until the annual growth zones became visible (cf. Fig. 1). During microsampling, a core was removed from each annual otolith zone that mainly covered the summer portion of the annulus by using the Dremel method (Gao, 1999). At least 50  $\mu\text{g}$  of aragonite material were extracted from each core for stable isotope analysis.

Once an annual zone was cored, the powder was carefully tapped onto aluminum foil and placed in a metal cup. The otolith section and the sampling bit were cleaned after each core using an Aero-Duster gas. The aragonite powder was analyzed using an Auto-carb preparation device coupled to a VG Optima mass spectrometer at the School of Geography and Geology, McMaster University. All the measurements were reported in the standard  $\delta$  notation in permil (‰), for instance,  $\delta^{18}\text{O} = \{[(^{18}\text{O}/^{16}\text{O})_{\text{A}} / (^{18}\text{O}/^{16}\text{O})_{\text{S}}] - 1\} \times 1000$ , where A is the aragonite sample and S the standard (VPDB, Vienna Peedee belemnite). Calibration of isotopic enrichments to VPDB is based on daily analysis of NBS-19 powdered carbonate and the analytical precision is better than 0.06‰ for both  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ .

To compare  $\delta^{18}\text{O}$  with actual temperature variations in Gulf of Alaska, we obtained the ocean bottom temperature profile from GAK 1 Time Series (available at Royer and Weingartner: [www.ims.uaf.edu:8000/gak1/](http://www.ims.uaf.edu:8000/gak1/)) near Seward, Alaska. These CTD (conductivity–temperature–depth) survey data were collected from 1970 to 2000, with the water depth from surface to the bottom of 263 m. We compiled the annual bottom temperatures (mostly 200 and 250 m) for two periods of time, 1975–1979 and 1988–1992, which correspond to 5-year  $\delta^{18}\text{O}$  variations over the 1977 and 1990 regime shifts.

### 3. Results

The carbon isotopic composition of halibut otoliths ranged from  $-3.3$  to  $+0.9\text{‰}$  VPDB, while the oxygen isotopic composition ranged from  $-1.5$  to  $+2.8\text{‰}$  VPDB (Table 1). For the 1993 samples from British Columbia and Gulf of Alaska, there were no significant differences in  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values. However, for the samples collected in a single area, such as

that in Gulf of Alaska, there were significant differences between 1980 and 1993 otoliths in  $\delta^{18}\text{O}$  values ( $t$ -test,  $P < 0.001$ ), but not in  $\delta^{13}\text{C}$  ( $t$ -test,  $P = 0.85$ ). The  $\delta^{18}\text{O}$  values of otoliths of halibut and sablefish (*Anoplopoma fimbria*) in the same region ( $-5.7$  to  $-0.5\text{‰}$  VPDB in  $\delta^{13}\text{C}$  and  $-0.1$  to  $+2.6\text{‰}$  VPDB

in  $\delta^{18}\text{O}$ ; Gao, unpublished data) were similar ( $t$ -test,  $P = 0.301$ ); however, the  $\delta^{13}\text{C}$  of sablefish were significantly lower ( $t$ -test,  $P < 0.001$ ). This suggests that both halibut and sablefish lived in similar oceanic conditions, but might have different food sources or diet (DeNiro and Epstein, 1978).

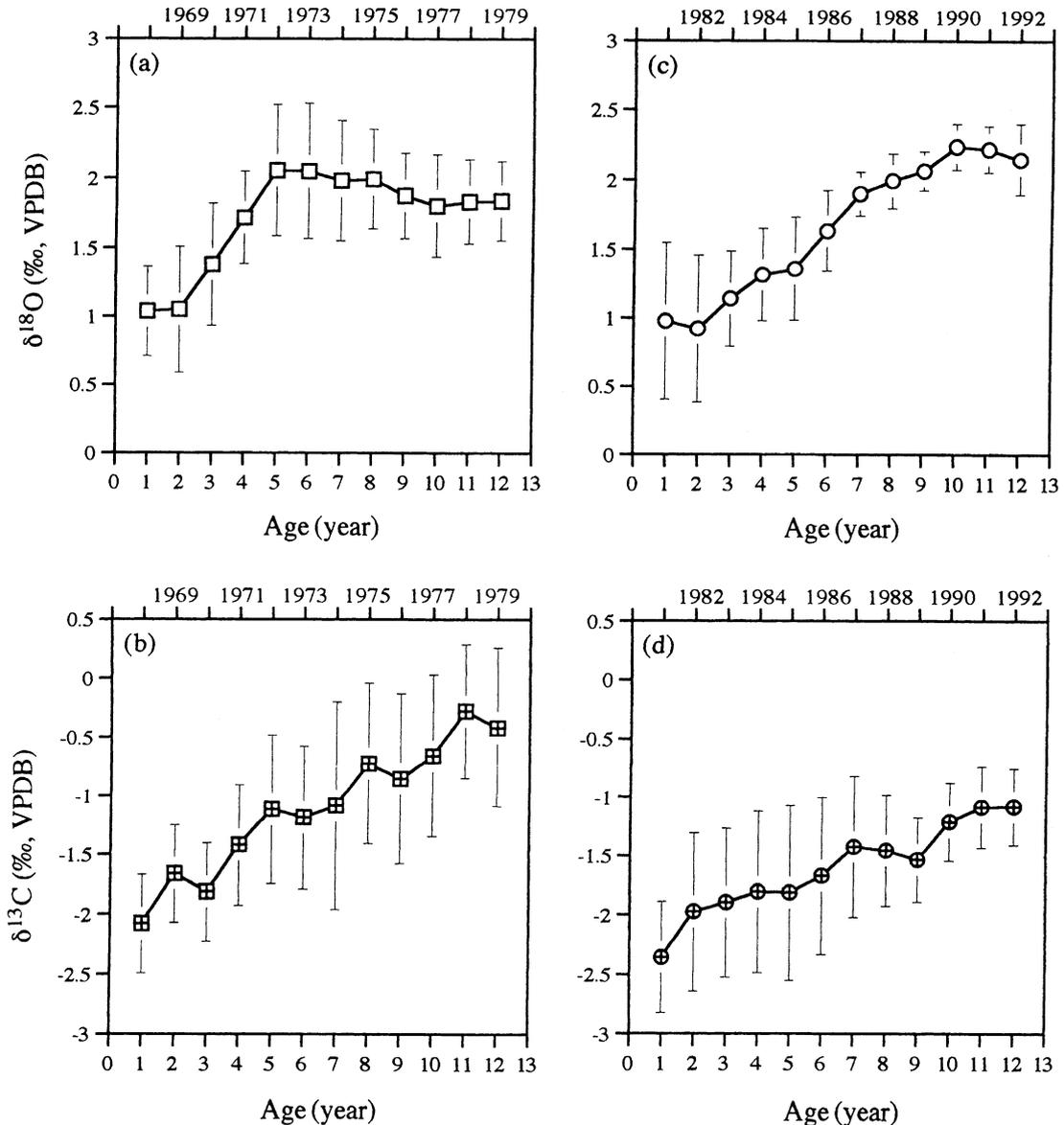


Fig. 3. The average  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values for otoliths of female halibut from Gulf of Alaska (area 3A) in 1980 and 1993 collections (error bar = 1 S.D.): (a)  $\delta^{18}\text{O}$  variations from 1980 samples; (b)  $\delta^{13}\text{C}$  variations from 1980 samples; (c)  $\delta^{18}\text{O}$  variations from 1993 samples; (d)  $\delta^{13}\text{C}$  variations from 1993 samples.

The annual  $\delta^{18}\text{O}$  variations averaged over 8 and 11 otoliths from halibut captured in 1980 and 1993 from Gulf of Alaska showed two stages: a lower  $\delta^{18}\text{O}$  (0.9–1.1‰ VPDB) stage and a higher  $\delta^{18}\text{O}$  (1.8–2.3‰ VPDB) stage (Fig. 3). Differences in  $\delta^{18}\text{O}$  values are consistent with the movements offshore and counter-migration of juveniles from the shallow, warm waters to the deeper, colder adult environment (Skud, 1977). Similar results have been found in other fish species. For instance, the life history of Pacific sockeye salmon (*Oncorhynchus nerka*) has been clearly depicted by their isotopic variations measured at half-year intervals from fresh water ( $\delta^{18}\text{O}$  values as low as -14.2‰ VPDB) to marine ( $\delta^{18}\text{O}$  values close to 0‰ VPDB) settings, and the latter is extremely uniform (Gao and Beamish, 1999).

The transition from lower  $\delta^{18}\text{O}$  values of the juvenile halibut to higher values in the adult stage was different for the two time periods (Fig. 3a and c). Otoliths from the 1980 captures showed a transition of  $\delta^{18}\text{O}$  values from age 2 to 5; thereafter the  $\delta^{18}\text{O}$  values remained stable. Transition for the 1993 otoliths occurred from age 3 to 7 or 8;  $\delta^{18}\text{O}$  values did not become invariant until around age 9. Variations of  $\delta^{13}\text{C}$  in halibut otoliths, in contrast, did not show any transition except for a consistent increase from the juvenile halibut to the adult stage (Fig. 3b and d). Overall, the long-term  $\delta^{18}\text{O}$  records were shown in decadal scales consisting of two lows and two peaks over the time series: the late 1960s (around 0.9‰ VPDB) and early 1980s (0.9–1.0‰ VPDB) lows and 1972–1979 (1.8–2.0‰ VPDB) and 1988–1992 (2.1–2.3‰ VPDB) peaks. The low oxygen isotope ratios are recorded in young halibut in both the data sets, and high ratios are reflected in adult halibut.

For fish released and recaptured in the same areas, we analyzed five otoliths from halibut tagged in the eastern Aleutian islands and four otoliths from halibut tagged near Kodiak Island (Table 2). The ages of recovered halibut ranged from 9 to 13 years. In both the cases,  $\delta^{18}\text{O}$  values of the first-year halibut (i.e., aragonite samples taken from the first annulus) were separated between the Aleutian and Kodiak samples (Fig. 4). Similarly, the  $\delta^{18}\text{O}$  values of adult fish (i.e., the annuli for ages 8–11) were also different for the two areas, and different from the age-one samples. We selected the oldest three ages available from the otoliths when examining the  $\delta^{18}\text{O}$  values of adult

Table 2  
Otoliths of tagged halibut used for test in the present study

Tag number	Release year	Release age	Recover year	Recover age	Year of liberty
Area 4A ⇔ 4A					
22428	1985	5	1992	12	7
20623	1985	2	1992	9	7
23454	1985	5	1992	12	7
23103	1985	6	1992	13	7
21666	1985	4	1992	11	7
Area 3A ⇔ 3A					
57244	1994	8	1997	11	3
51113	1994	8	1997	11	3
53868	1994	7	1997	11	4
55665	1994	8	1997	11	3

halibut to minimize influence from the transition period. As expected, the typically colder water of the Bering Sea–Aleutian region is consistent with the higher  $\delta^{18}\text{O}$  values of the Aleutian samples compared with the lower  $\delta^{18}\text{O}$  values from the warmer central Gulf of Alaska.

The  $\delta^{18}\text{O}$  values from 5-year average (ages 8–12) of female halibut otoliths from the two sampling intervals displayed distinct isotopic variations (Fig. 5), corresponding to the 1977 and 1990 calendar years, respectively. The data demonstrated a 0.2–0.3‰ VPDB increase in  $\delta^{18}\text{O}$  from 1977–1979 to 1990–1992 in

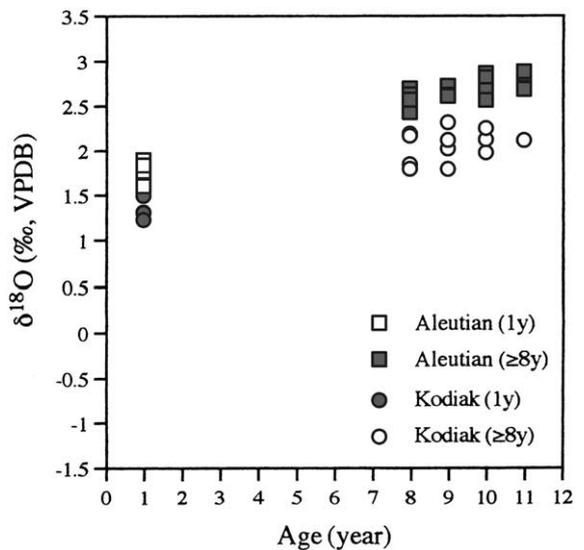
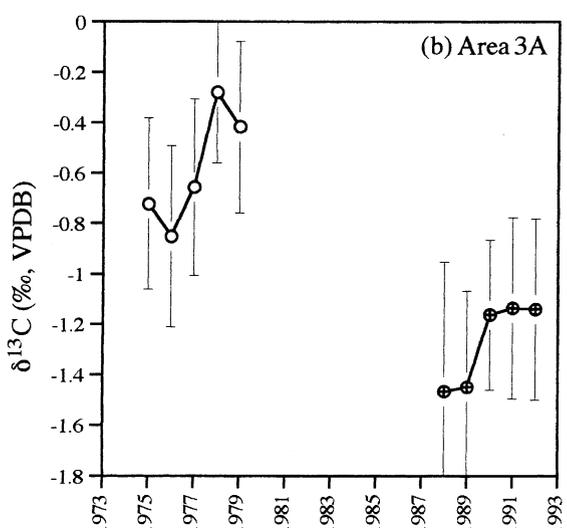
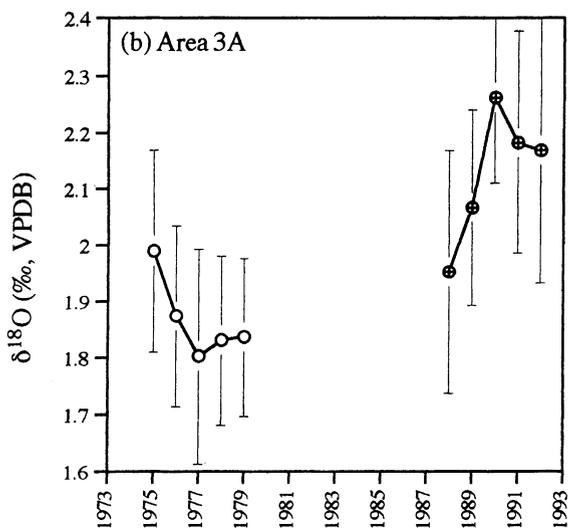
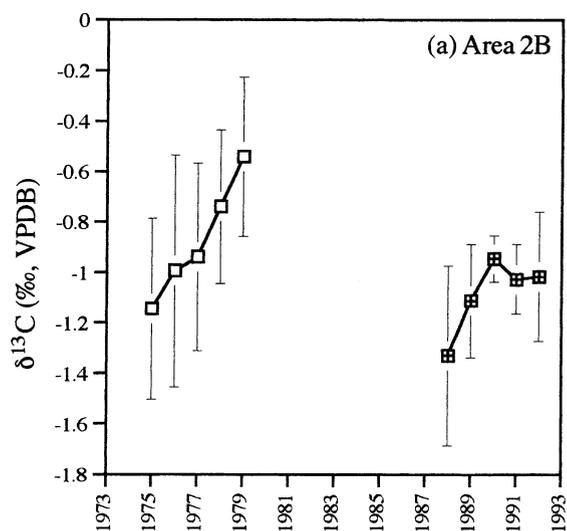
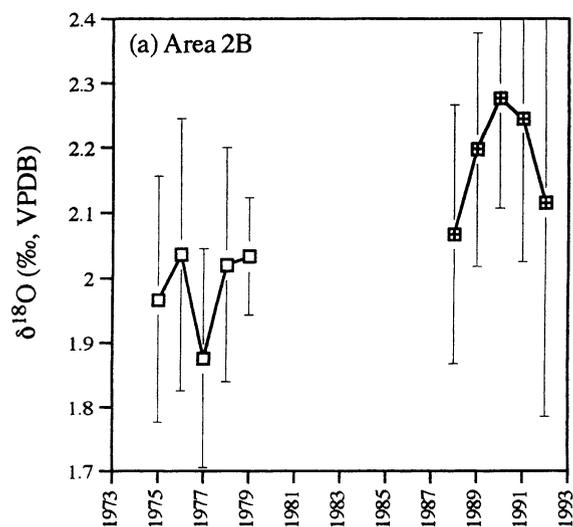


Fig. 4. The  $\delta^{18}\text{O}$  patterns from otoliths of halibut tagged from the eastern Aleutian islands (area 4A) and the Kodiak island (area 3A).



Calendar year

Calendar year

Fig. 5. Average  $\delta^{18}\text{O}$  values of female halibut otoliths for the ages 8–12 over the 1977 and 1990 regime shifts (error bar = 1 S.D.): (a)  $\delta^{18}\text{O}$  variations from British Columbia (area 2B); (b)  $\delta^{18}\text{O}$  variations from Gulf of Alaska (area 3A).

British Columbia, and a 0.3–0.4‰ VPDB increase in  $\delta^{18}\text{O}$  for Gulf of Alaska. In both the areas,  $\delta^{18}\text{O}$  values apparently increased during the presumably stable ocean regime as defined between 1977 and 1990. Distinct isotopic shifts also occurred in  $\delta^{13}\text{C}$  values (Fig. 6). In British Columbia,  $\delta^{13}\text{C}$  values from

Fig. 6. Average  $\delta^{13}\text{C}$  values of female halibut otoliths for the ages 8–12 over the 1977 and 1990 regime shift periods (error bar = 1 S.D.): (a)  $\delta^{13}\text{C}$  variations from British Columbia (area 2B); (b)  $\delta^{13}\text{C}$  variations from Gulf of Alaska (area 3A). Different  $\delta^{13}\text{C}$  shifts between areas 2B and 3A indicate that  $\delta^{13}\text{C}$  values are not directly related to regime shifts.

1977–1979 to 1990–1992 varied in the similar range, with an increasing trend occurred across the 1977 and 1990 periods. Values of  $\delta^{13}\text{C}$  from 1977 to 1979 for Gulf of Alaska were about 0.6‰ VPDB higher than

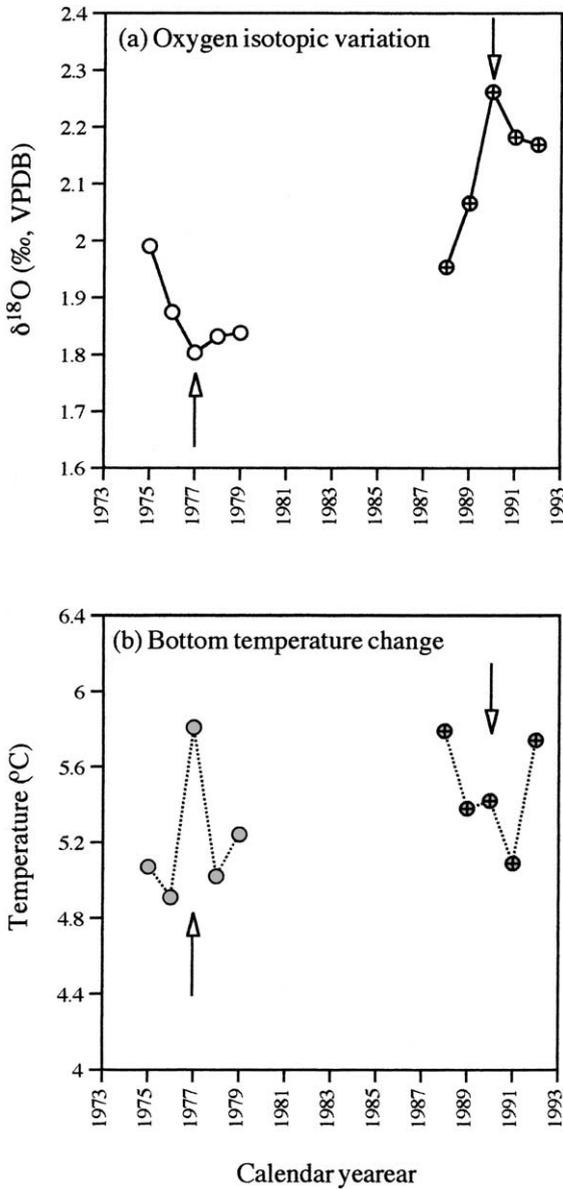


Fig. 7. The 5-year  $\delta^{18}\text{O}$  variation (cf. Fig. 5b) and bottom temperature profile (mostly 200 and 250 m) over the same period from GAK 1 Time Series near Seward, AK. On the average, about 1 °C temperature change occurred during the 1977 and 1990 regime shifts.

for the 1990–1992 period (Fig. 6b). Ocean bottom temperature analyses comparing from 1975–1979 to 1988–1992 showed changes consistent with the 5-year  $\delta^{18}\text{O}$  variations in Gulf of Alaska (Fig. 7).

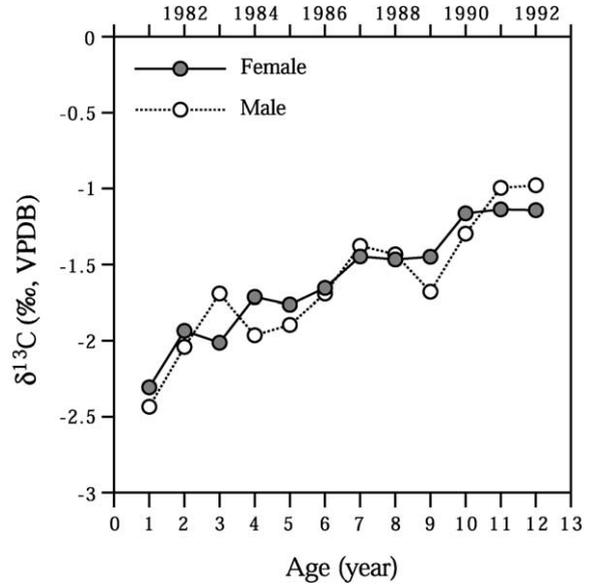


Fig. 8. Comparison of mean  $\delta^{13}\text{C}$  values for female and male halibut from area 3A, showing similar patterns of isotopic variation over time.

From 1975 to 1979, about 1 °C temperature increase occurred in 1977. Similarly, there was approximately a 1 °C decrease from 1988 to 1991. This indicates that the 1977 regime shift might have a warming impact on Gulf of Alaska, whereas a cooling regime shift might occur around 1990.

During the study we mainly used otoliths of female halibut to examine stable isotopic signatures for regime shifts (cf. Table 1) because most archived otolith collections in IPHC are females. Was isotopic composition mainly from females representative of the whole halibut population?  $\delta^{13}\text{C}$  values of female halibut otoliths from Gulf of Alaska were very similar to those of male halibut (Fig. 8), indicating that the sexual dimorphism in halibut is not a problem in stable isotope analysis.

#### 4. Discussion

The Thompson–Burkenroad debate (Skud, 1975), on the decline and subsequent increase in the Pacific halibut population between 1920 and 1940, is a well known debate in fisheries management. Thompson took the view that changes in halibut abundance

could be solely attributed to fishing pressure, while Burkenroad ascribed most of the variability to climatic forcing. Skud (1975) reviewed the debate and concluded that neither was entirely correct and that, most likely, both the factors were at work, a conclusion echoed by Hilborn and Walters (1992). Beamish (1995) recently emphasized the importance of marine environmental impacts on fish population dynamics. For example, Brodeur and Ware (1992) demonstrated that the standing stock of zooplankton has doubled in Gulf of Alaska between the 1950s and 1980s. Beamish and Bouillon (1993) concluded that the large-scale trend in salmon production from 1925 to 1989 is not primarily the result of fishing effort, management actions or artificial rearing, but the result of environmental influences. Mantua et al. (1997) showed that the northeast Pacific undergoes discrete changes in environmental conditions over scales of two or three decades. These investigations suggest that the consequences of the most recent regime shifts in marine ecosystems are dramatic and pervasive.

The well documented 1977 regime shift was characterized by a clear decrease in  $\delta^{18}\text{O}$  values and a slight shift in  $\delta^{13}\text{C}$  values. If the relationship between  $\delta^{18}\text{O}$  variation of otoliths and temperature in seawater (Gao, 1997) was applicable to the study areas, we could infer that the 1977 regime shift was recorded as a warming event in the coastal waters of the northeast Pacific. This conclusion on the character of 1977 regime shift agrees well with previous oceanographic and meteorological studies. Miller et al. (1994) reported that one impact of the 1976–1977 regime shift is about 1–2 °C warming of the waters of the northeast Pacific and Bering Sea. Wooster and Hollowed (1995) concluded that in the eastern North Pacific, winter conditions appear to be alternated between warm and cool eras, with an average period of about 17 years.

A possible 1990 regime shift was also shown by an increase in  $\delta^{18}\text{O}$  values from 1.9 to 2.3‰ VPDB and an increase in  $\delta^{13}\text{C}$  values from –1.5 to –1.0‰ VPDB in both Gulf of Alaska and British Columbia. These isotopic variations were generally small over the last 5-year annulus in otoliths from 1988 to 1992; however, minor  $\delta^{18}\text{O}$  variation from 1.9 to 2.3‰ VPDB would be a distinct signature for adult halibut. The larger  $\delta^{18}\text{O}$  variation from otoliths of sockeye salmon (0.6–0.8‰ VPDB; Gao and Beamish, 1999) than that of halibut (0.3–0.4‰ VPDB; this study)

might be evidence that the isotopic signatures are attributed to the depth effect of the water column, as smaller changes in temperature near the ocean bottom than near the ocean surface.

While the 1977 regime shift represents a temperature increase, the possible 1990 regime shift was recorded as a cooling event. For British Columbia and Gulf of Alaska, our data demonstrated a 0.3–0.4‰ VPDB maximum variation in  $\delta^{18}\text{O}$  from 1977–1979 to 1990–1992, corresponding to a temperature change in bottom seawater of about 2 °C (Gao, 1997). This temperature change over the presumably stable environmental period of 1977–1990 is very close to the bottom temperature profile of about 1 °C observed near Seward, AK. Values of  $\delta^{13}\text{C}$  in both the areas, in contrast, decrease from 1977–1979 to 1990–1992 over the same presumably stable period. Previous otolith studies from Atlantic cod (*Gadus morhua*) suggested that the age at attainment of maximum in  $\delta^{13}\text{C}$  values may mark the time of sexual maturity (Schwarcz et al., 1998). For Pacific halibut, the lifetime  $\delta^{13}\text{C}$  variations do not reach a maximum like cod. Therefore, changes in  $\delta^{13}\text{C}$  values are more likely related to diet than to maturity. Selection of prey or changes in composition of forage fish may have caused the decline in  $\delta^{13}\text{C}$  values. Diet changes are reflected by an increase in  $\delta^{13}\text{C}$  values from juvenile to adult stages (Fry, 1988). The  $\delta^{13}\text{C}$  variations of adult halibut for the 1977–1979 and 1990–1992 periods are different between Gulf of Alaska and British Columbia, suggesting that  $\delta^{13}\text{C}$  values may not be related to regime shifts, but to different metabolic conditions.

In summary, our study has demonstrated that environmental changes can be deduced from stable isotope ratios of Pacific halibut otoliths, and that isotopic signatures reflect known differences in oceanic conditions between the Bering Sea and the Gulf of Alaska during the early 1990s. Lower  $\delta^{18}\text{O}$  values of young halibut and higher values of older halibut are consistent with halibut spending several years on nursery grounds, several years migrating off shore, and periods of small summer-to-summer migrations at older ages (Trumble et al., 1993). There is a small but distinct shift in isotopic signatures of halibut otoliths at the time of known regime shifts; however, the identification of the 1990 regime shift and the estimated 2 °C temperature changes in the bottom environment from the later 1970s to early 1990s need further investigation.

We used a small number of fish from two localities to characterize the broad scale changes in the northeast Pacific. To quantitatively examine bottom temperature changes, one should obtain  $\delta^{18}\text{O}$  variations in seawater to define the possible role of salinity, and calculate the temperatures from isotopes over time (Gao, 1997). Despite these and other concerns, our results show that historic collections of halibut otoliths could provide a new source of data to study historic changes in the marine environment in the North Pacific.

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