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Female maturity, reproductive potential, relative distribution, and growth compared between arrowtooth flounder (*Atheresthes stomias*) and Kamchatka flounder (*A. evermanni*) indicating concerns for management

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Summary

Arrowtooth flounder (*Atheresthes stomias*) and Kamchatka flounder (*A. evermanni*), major piscivorous predators in the eastern Bering Sea and Aleutian Islands, are morphologically similar. Consequently the two species have been managed together as a species complex using the length- and age-at-maturity derived from Gulf of Alaska arrowtooth flounder, which had been the only available maturity estimates. However, there could be serious management consequences if the two species matured at significantly different ages and fork lengths. Therefore, this study was conducted during 2007 and 2008 to determine if there were significant differences in maturation between the two species. Significant differences in size and age of female maturation and growth were found. The age and length of 50% maturity ($A_{50,}$ $L_{50,}$ respectively) for arrowtooth flounder females is 7.6 years of age and 480 mm in body length. In comparison, $A_{50,}$ L_{50} of Kamchatka flounder females is 10.1 years of age and 550 mm, meaning that Kamchatka flounder has a significantly lower reproductive potential than arrowtooth flounder. The large difference in reproductive potential indicates that managing the two species together as a species complex using the reproductive characteristics of arrowtooth flounder, was not conservative for Kamchatka flounder. This study also determined that arrowtooth flounder maturation was consistent between the Gulf of Alaska and eastern Bering Sea populations.

Introduction

Arrowtooth flounder (*Atheresthes stomias*) and Kamchatka flounder (*A. evermanni*) are major predators of fish and invertebrates in the eastern Bering Sea. There had been no directed fishery for either species until a fishery developed for Kamchatka flounder in 2009. Both species are taken as bycatch in other fisheries. The congeners are morphologically very similar but differ in the placement of the upper eye and the number of gill rakers. The left eye of the arrowtooth flounder is located on the upper margin of the head and is visible from the ventral or blind side of the body; the left eye of the Kamchatka flounder is located nearer to the right eye and is not visible from the blind side of the body. Arrowtooth flounder and Kamchatka flounder also differed in the abundance of males relative to females. Arrowtooth flounder males represent <40% of the estimated total arrowtooth flounder biomass, which has been attributed to males having a higher natural mortality than females (Wilderbuer and Turnock, 2009; Wilderbuer et al., 2010a). By comparison Kamchatka flounder males and females are approximately equal in abundance (Rooper and Wilkins, 2008; Hoff and Britt, 2009). This suggests that Kamchatka flounder males have a lower natural mortality than arrowtooth flounder males, however no male Kamchatka flounder age data are currently available for comparison. Distribution of arrowtooth flounder and Kamchatka flounder overlap in the Bering Sea, Aleutian Islands, Sea of Okhotsk, and the Kamchatka Peninsula (Mukhametov and Orlov, 2002; Rooper and Wilkins, 2008; Wilderbuer et al., 2010b). Highest abundance of arrowtooth flounder occurs in the Gulf of Alaska (Stark, 2008), which has no Kamchatka flounder. Distribution of the two species complex in the eastern Bering Sea is more strongly related to the spatial extent of cold bottom temperatures than to species abundance (Spencer, 2008); bottom temperatures <2°C are avoided. A pool of cold water <2°C has bisected the eastern Bering Sea since 2006 (Spencer, 2008; Lauth, 2010; Wilderbuer et al., 2010a), restricting the distribution of these species to the outer strata of the continental shelf and the upper continental slope. The Gulf of Alaska does not have a cold pool, thus allowing the wide distribution of arrowtooth flounder.

This study was conducted by the Alaska Fisheries Science Center (AFSC) to provide the age- and length-at-maturity estimates needed to establish sustainable and reasonable management regulations for the eastern Bering Sea arrowtooth and Kamchatka flounders.

Materials and methods

All collections were made by the AFSC aboard the NOAA ship *Miller Freeman* in the eastern Bering Sea, using bottom-trawling gear with a cod end mesh opening of 8.9 mm. The Kamchatka flounder collections were made from 5 through 7 October 2007 (n = 112), and the arrowtooth flounder collections from 19 through 26 February 2008 (n = 175, Fig. 1). The collections consisted of whole ovaries, each pair of sagittal otoliths, and fork length measurements from three to seven females within each 10 mm interval of total body length larger than 180 mm. Each 10 mm length category extends over a range of +5 to −5 mm, on the fork length measurement scale. The sampling protocol, histological processes, ovary maturity classifications, and ageing methods followed those described in Stark (2007). Females designated as mature were those classified into ovary maturity stages: cortical alveoli, vitellogenesis, advanced yolk, hydrated, and postovulatory follicles. The maturity collections provide representative samples of

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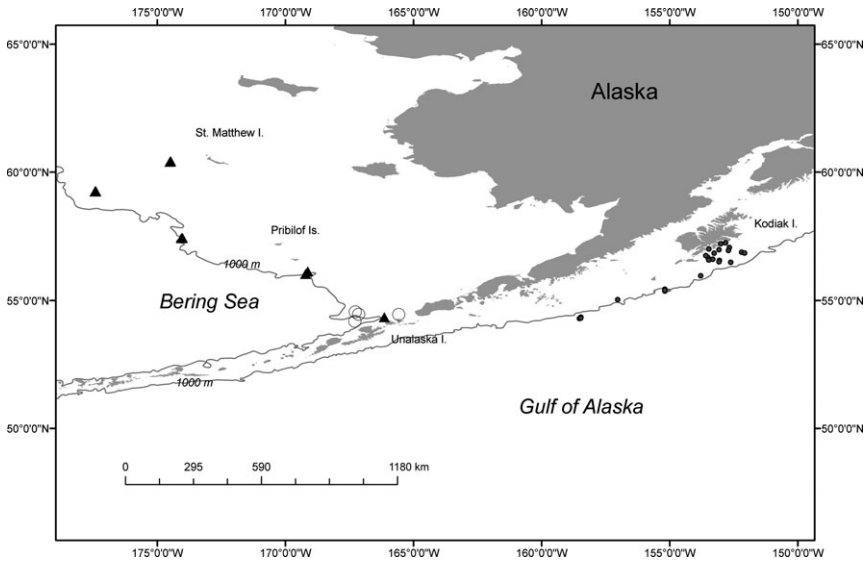

Fig. 1. Station locations for Alaska Fisheries Science Center maturity study collections of arrowtooth flounder and Kamchatka flounder. Arrowtooth flounder collections from Gulf of Alaska study, 2002 and 2003 (♦). Present study collections from Bering Sea, February 2008, of arrowtooth flounder (○), and October 2007 for Kamchatka flounder (▲)

each species state of maturation, and there is a low probability that spent females were misclassified as immature because of the low incidence of arrowtooth flounder spawning and lack of Kamchatka flounder spawning. All age determinations were made by the AFSC's Age and Growth Program (Kimura et al., 2007). The methods include sectioning each otolith through the nucleus, and heating the otolith to increase the contrast between the growth (transparent) and opaque layers. The growth layers are considered to be the annuli, and are delineated using a dissecting microscope.

The procedures utilized S-PLUS software (version 2000 Professional release 3, MathSoft Inc., Cambridge, MA). Maturity was estimated as a function of length and age by fitting a logistic function to the maturity data with generalized linear modeling (Venables, 1997). Variance of age (A_{50}) and total body length (L_{50}) at 50% maturity were estimated for the Kamchatka flounder and arrowtooth flounder maturity collections using bootstrapping (Efron and Tibshirani, 1993) based on 200 resamplings with replacement of the maturity, age, and length data. Differences between the Kamchatka flounder and arrowtooth flounder A_{50} and L_{50} were tested with a Z-test (Sokal, 1969). The same procedures were used to determine if arrowtooth flounder A_{50} and L_{50} differed between the eastern Bering Sea and previously reported results (Stark, 2008) for the Gulf of Alaska, from a 2002 and 2003 maturity study. A Z-test was used to determine if there were significant differences between species in their preferred distribution by depth or by seawater temperature, which could lead to differences in sexual maturation. The comparison utilized AFSC survey data from the eastern Bering Sea shelf collected annually from 2004 through 2009, the Bering Sea slope from 2004, 2006 and 2008 and the Aleutian Islands from 2004 and 2006 (n = 32707 fish).

Length at age was described by the von Bertalanffy growth function, which used non-linear least-squares fitted to L_T and age data (Venables, 1997). Between-sex and between-area differences in growth were tested by first fitting the von Bertalanffy model with a term distinguishing each category, and again for the categories combined. The likelihood ratio of the two models was then determined for each category (Kimura, 1980). Significance of the likelihood ratio was tested to determine if growth differed by species or between arrowtooth flounder in the eastern Bering Sea and Gulf of Alaska. The Gulf of Alaska comparison utilized unpublished data from an AFSC 2002 and 2003 maturity study (Stark, 2008). Age composition of specimens was compared between the two species using a Chi-squared test.

Results

The specimen age composition of this study was similar (P = 0.35) for both species. However, there were significant differences between species in sexual maturation. Female arrowtooth flounder reached 50% maturity at 7.6 years of age (Table 1, Fig. 2). In contrast, Kamchatka flounder matured at a significantly (P < 0.001) older age, reaching 50% maturity (A_{50}) at 10.1 years of age. Similarly, the physical size at which each species matured differed significantly (P < 0.001). The fork length at which 50% of the females reached maturity (L_{50}) was 480 mm for arrowtooth flounder, compared to 550 mm for Kamchatka flounder (Table 2, Fig. 3). The significant differences in maturation between the arrowtooth flounder and Kamchatka flounder were probably not related to differences in the species distributions by depth

Table 1
Female arrowtooth flounder (*Atheresthes stomias*) and Kamchatka flounder (*A. evermanni*) age-at-maturity results based on ovary histology samples (n), eastern Bering Sea, by date of collection. Parameters of logistic equation used to fit data: B (slope of the line) and A (Y intercept), variance (square of standard deviation of B and A), covariance (product of standard deviations of B and A and covariance between them), age (years) at which 50% of females were expected to reach sexual maturity (A_{50}), and variance of A_{50}

	Species and date of collection	
	Arrowtooth flounder February 2008	Kamchatka flounder October 2007
n	165	111
B	1.03	0.73
A	−7.86	−7.32
σ^2 (B)	0.00	0.00
σ^2 (A)	1.70	2.24
Cov (B, A)	0.00	0.00
A_{50}	7.64	10.10
$\sigma^2(A_{50})$	0.07	0.40

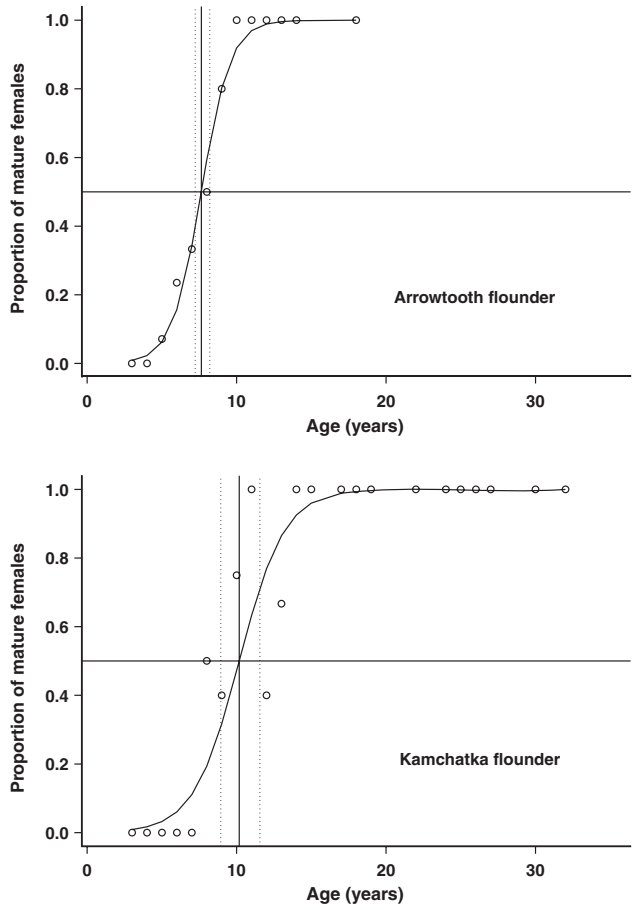

Fig. 2. Maturity estimated as a function of age for arrowtooth flounder (*Atheresthes stomias*) and Kamchatka flounder (*A. evermanni*) by fitting a logistic function to the maturity data based on the arrowtooth flounder February 2008 (n = 165) and Kamchatka flounder October 2007 (n = 111) maturity collections. Mean age at 50% maturity (solid vertical lines) = 7.6 years for arrowtooth and 10.1 years for Kamchatka flounders. Dotted vertical lines = 95% confidence limits

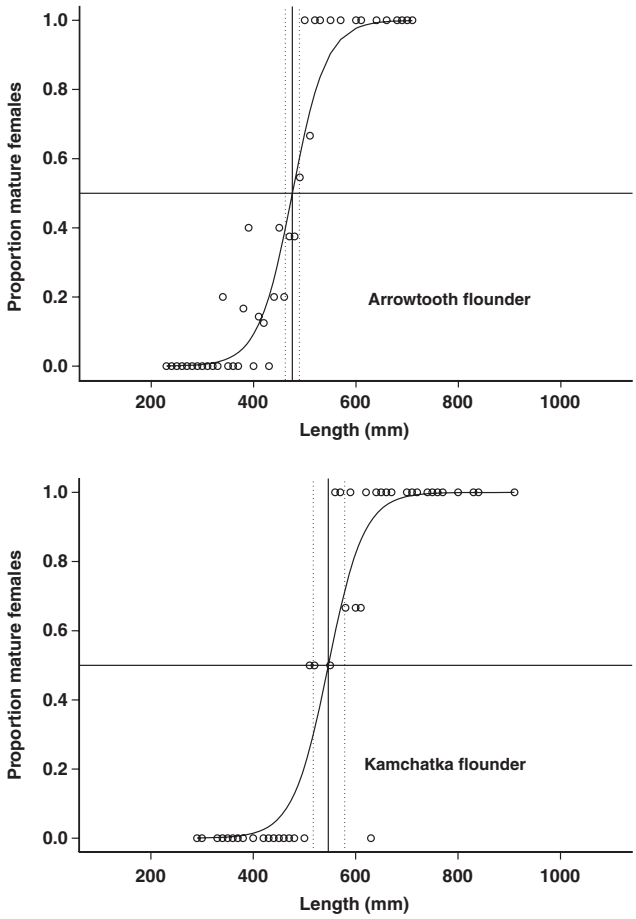

Fig. 3. Maturity estimated as function of fork length for arrowtooth flounder (*Atheresthes stomias*) and Kamchatka flounder (*A. evermanni*) by fitting a logistic function to maturity data based on arrowtooth flounder February 2008 (n = 175), and Kamchatka flounder October 2007 (n = 112) maturity collections. Mean length at 50% maturity (solid vertical lines) was 475.8 mm for arrowtooth and 550.1 mm for Kamchatka flounders. Dotted vertical lines = 95% confidence limits

Table 2
Female arrowtooth flounder (*Atheresthes stomias*) and Kamchatka flounder (*A. evermanni*) length-at-maturity results based on ovary histology samples (n), eastern Bering Sea, by date of collection. Parameters of logistic equation used to fit data: B (slope of the line) and A (Y intercept), variance (square of standard deviation of B and A), covariance (product of standard deviations of B and A and coefficient of correlation between them), fork length (mm) at which 50% of females were expected to reach sexual maturity (L_{50}), and variance of A_{50}

	Species and date of collection	
	Arrowtooth flounder February 2008	Kamchatka flounder October 2007
n	175	112
B	0.03	0.02
A	−14.34	−12.40
σ^2 (B)	4.75	2.71
σ^2 (A)	9.38	26.41
Cov (B, A)	−0.00	−0.00
L_{50}	475.75	550.25
σ^2 (L_{50})	54.92	258.27

(P = 0.60) or sea water temperature (P = 0.65), based on unpublished data from AFSC eastern Bering Sea groundfish surveys. Based on that data, this study found that each species avoided bottom temperatures < 2°C. The arrowtooth flounder maturity results from this study were compared with those from the Gulf of Alaska (Stark, 2008) to determine the consistency of maturation between areas. Arrowtooth flounder in the eastern Bering Sea matured at a similar age (P = 0.75) A_{50} of 7.6 years and similar (P = 0.08) L_{50} of 460 mm as they did in the Gulf of Alaska.

Spawning arrowtooth flounder females represented only 1% of all specimens and were the largest females collected, 610 and 690 mm in body length, and both with hydrated oocytes. These results suggested that February represented the initial month of the annual arrowtooth flounder spawning cycle in the eastern Bering Sea, and that the season was initiated by the population's largest individuals with the other females spawning at a later date. None of the Kamchatka flounders collected were in spawning or post-spawning condition, indicating that October represented a prespawning period in the species' annual spawning cycle.

Arrowtooth flounder matured at a similar length in the Gulf of Alaska and eastern Bering Sea, and also grew at a similar (P = 0.93) rate (0.11 *k*, Fig. 4). Arrowtooth flounder grew significantly (P = 0.02) faster (Table 3, Fig. 5) than Kamchatka flounder (0.07 *k*).

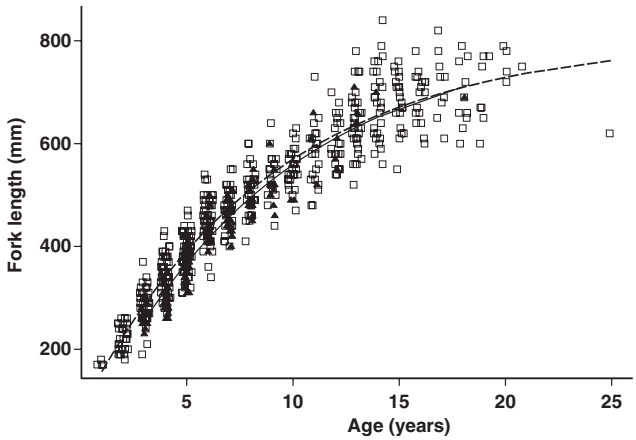

Fig. 4. Female arrowtooth flounder growth based on unpublished Alaska Fisheries Science Center data, Gulf of Alaska, 2003 and 2004 (n = 551, □, – – –), and eastern Bering Sea, 2008 (n = 173, ▲, ——)

Table 3
Arrowtooth flounder (*Atheresthes stomias*) and Kamchatka flounder (*A. evermanni*) fork length at age described by von Bertalanffy growth equation, based on ovary maturity samples (n), Bering Sea, by species and date of collection. Parameters were L_∞ (length at maximum age in mm), k (estimated growth increment), t_0 (theoretical age when fish length is 0), by area

	Species and date of collection	
	Arrowtooth flounder February 2008	Kamchatka flounder October 2007
n	173	111
L_∞(mm)	816.01	883.34
var (L_∞)	2238.14	1218.55
k	0.11	0.07
var (k)	0.00	0.00
t_0	−0.37	−3.63
var (t_0)	0.08	0.44
cov (L_∞,k)	−0.67	−0.29
cov (L_∞,t_0)	−11.08	−19.54
cov (k,t_0)	0.00	0.01

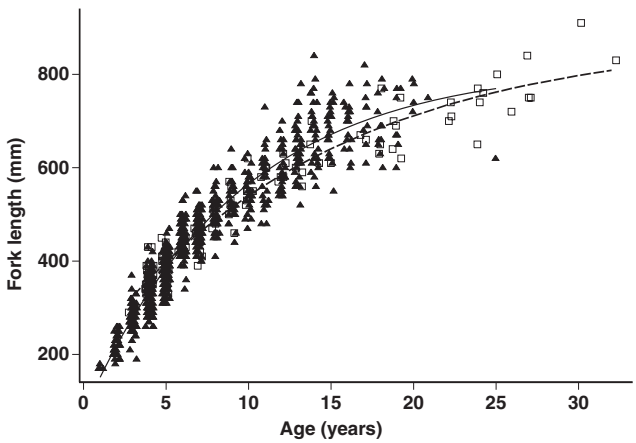

Fig. 5. Female growth based on arrowtooth flounder (*Atheresthes stomias*) 2008 (n = 173, ▲,——) from previous study in Gulf of Alaska, 2002 and 2003, and from present study in the eastern Bering Sea, 2008. Kamchatka flounder growth data from the present study, 2007, eastern Bering Sea (n = 111, □, – – –)

Discussion

Arrowtooth flounder maturity did not differ significantly between the eastern Bering Sea and the Gulf of Alaska, based on the results of this study and a previous study (Stark, 2008). In contrast, Kamchatka flounder females matured at a significantly older age and larger body length and grew significantly more slowly than arrowtooth flounder. The differences are inherent and not related to the distribution of the two species. As a result of the differences in the rate of maturation and growth found by this study, the Kamchatka flounder population would be much more vulnerable to fishing mortality than the arrowtooth flounder population. Kamchatka flounder are also more vulnerable due to their substantially lower overall abundance (129000 t; Wilderbuer et al., 2010b) compared to arrowtooth flounder (406000 t). However, the allowable biological catch and overfishing limit had been set to the combined estimated biomass, which is dominated by arrowtooth flounder. Since 2010, after a fishery developed for Kamchatka flounder, the two species have been managed separately (Wilderbuer et al., 2010b). The maturity results from this study provide for improved management by allowing managers to estimate arrowtooth and Kamchatka flounder spawning biomasses which are essential in stock management models to provide more accurate estimates of the allowable biological catch and overfishing limits. The result would move the two species into management tier 4 that will allow for more precise catch allocations within established overfishing limits.

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