

Finally, Figure 3.16 demonstrates results of the customized herring model for a p value of 0.6375, and for a run where the multispecies functional response to three prey types was activated using the parameters (k1, k2 and k3) shown in Figure 3.16, as well as the seasonal energy density algorithm. Note that to implement the multispecies functional response feature the line “con=0.75\*gcmax” in the FORTRAN code needs to be commented out.

### **Trends in size-at-age: some ideas for hypothesis testing**

Douglas Hay has data for size-at-age of Pacific herring over several decades. Over the last 20 years, the mean size-at-age has decreased at several locations for fish aged greater than 3 years. However, the mean size-at-age for ages 1–3 years did not show a significant decrease which may result from difficulties in sampling small fish (*i.e.* gear selectivity). In agreement to the observed

size-at-age data, measurements from scale annuli collected over the same period from larger herring also showed no consistent decrease in growth for fish during the first 3 years of life. This decrease in size-at-age first appears when herring can begin to eat euphausiids in addition to copepods (age 3+). Generally, when euphausiids are abundant, the predation on herring by other piscivores that also eat euphausiids is reduced. Given this double benefit of more available food and less predation, the growth of herring should be highly sensitive to euphausiid production. The predatory zooplankton (ZP) compartment in the NEMURO model was designed to represent euphausiids.

Thus the coupled NEMURO-herring bioenergetics model could be used to examine the effects of temperature and other physical forcings (*e.g.*, Pacific Decadal Oscillation) on the production of euphausiids and thereby on the size-at-age of herring.

## **4.0 Saury group report and model results**

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The members of “team saury” were D. Huang, C. Hong, Y. I. Zuenko, T. Katukawa, T. Azumaya, S. Chiba, M. Fujii, M. J. Kishi, K. Tadokoro, M. B. Kashiwai, Y. Yamanaka, T. Okunishi, A. Tsuda, D. Mukai, M. Inada, T. Aiki and S. Ito.

According to the life history of Pacific saury, S. Ito proposed to have saury bioenergetics model coupled with the ecosystem model composed of a three- ocean-box model which corresponds to Kuroshio, Oyashio, and the mixed water region. But the three-box model is a little complicated to start with. As a first step we started from a coupled saury bioenergetics-ecosystem model with

one box, and adapted the same type of governing equations for bioenergetics model as the ones for Pacific herring.

Model parameters are discussed for applying the model to Pacific saury. Here we report the discussion summary and model results.

### **Life history stages**

Pacific saury are spawned in the Kuroshio and the mixed water region from autumn to spring. The larvae are advected to the Kuroshio extension region and juveniles migrate to the Oyashio region

through the mixed water region. After sufficient feeding in the Oyashio region, they migrate back to the spawning region. The swimming activity, feeding habitat and metabolism are different according to the life history stages. Odate (1977) and Kosaka (2000) divided the Pacific saury life history stages according to knob length (KL) (Table 4.1).

**Table 4.1** Life stages of Pacific saury after Odate (1977).

Stage	Knob length
larvae	< 2.5 cm
juvenile	2.5 - 5.9 cm
earlier young	6.0 - 9.9 cm
later young	10.0 - 14.9 cm
small	15.0 - 19.9 cm
adult	> 20.0 cm

About the earlier stage growth, Watanabe and Kuji (1991) reared the saury larvae from hatching and they showed that it takes 60 days to grow to 79 mm KL. Watanabe *et al.* (1988) analyzed the growth rate of Pacific saury and they showed that it takes about 100 days to grow to 100 mm KL. According to their result, it takes about 180 days to become adult saury. Suyama *et al.* (1996) showed lower growth rate and it takes about 200 days to become an adult. For simplicity, only three life stages are assumed in the saury bioenergetics model (Table 4.2).

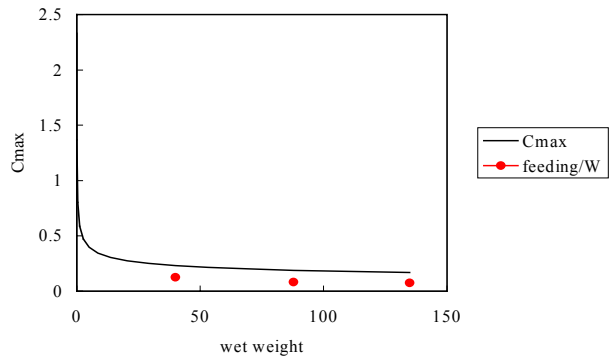
**Table 4.2** Life stages of Pacific saury in the saury bioenergetics model.

Stage	Age
larvae and juvenile	< 60 days
young and premature	60-180 days
adult	> 180 days

#### Maximum consumption rate $C_{MAX}$

Because adult Pacific saury are too difficult to rear in laboratories, there is no experimental estimation of consumption rate. Field data showed the

average ration of the Pacific saury are 5.0 gww/day/individual for 20 cm, 7.2 gww/day/individual for 26 cm, and 10.2 gww/day/individual for 30 cm saury (Kurita and Sugisaki; in preparation). These data were estimated in the Oyashio region. Comparing this with observational data, we adapted 0.6 for  $a_c$  and -0.256 for  $b_c$  parameters. Figure 4.1 shows the  $C_{MAX}$  curve and observational value of ration per unit wet weight of the Pacific saury.

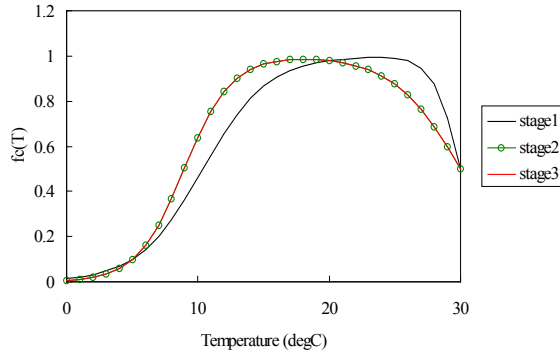


**Fig. 4.1**  $C_{MAX}$  curve and observational value of ration per unit wet weight of the Pacific saury.

#### Temperature dependency for $C_{MAX}$

Oozeki (in preparation) analyzed the relationship between saury growth rate and environmental factors using the same field data reported in Watanabe *et al.* (1997). His result showed positive contributions from surface temperature and food density to growth rate. The SST range was between 16-22°C. Oozeki and Watanabe (2000) reared Pacific saury in the laboratory with different water temperatures and found a strong dependence of growth rate on temperature. The temperature range was between 12-24°C.

For adult saury we have no measures of growth rate at different temperatures. But the habitat temperature is between 16 and 20°C. We adapted the following values for the temperature dependency parameters for  $C_{MAX}$  of Pacific saury (Table 4.3). Figure 4.2 shows the temperature dependence function for each stage.



**Fig. 4.2** Temperature dependence function of consumption rate of Pacific saury for each life stage.

**Table 4.3** Temperature dependency parameters for  $C_{MAX}$ .

		Stage 1	Stage 2	Stage 3
te1	Temperature for xk1 (in °C)	5	5	5
te2	Temperature for xk2 (in °C)	20	16	16
te3	Temperature for xk3 (in °C)	26	20	20
te4	Temperature for xk4 (in °C)	30	30	30
xk1	Proportion of $C_{MAX}$ at te1		0.10	
xk2	Proportion of $C_{MAX}$ at te2		0.98	
xk3	Proportion of $C_{MAX}$ at te3		0.98	
xk4	Proportion of $C_{MAX}$ at te4		0.5	

### Swimming speed

Although we do not have actual data on swimming speed of Pacific saury, other small pelagic fish swim at speeds of several times their body length per second. We assumed the normal swimming speed is two times of the knob length (nearly same as body length) per weight (Fig. 4.3).

$$U = 2.0 \text{ KL}$$

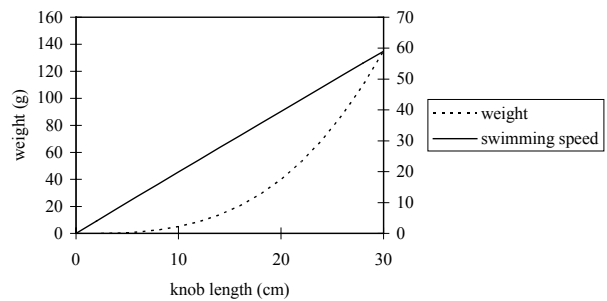
On the other hand, the wet weight (g)-knob length (cm) relation was proposed by Kosaka (2000) as:

$$\begin{aligned} & \text{larvae and juvenile} \\ \log W &= -2.069 + 2.42439 \log L \\ & \text{earlier young} \\ \log W &= -2.483 + 3.06174 \log L \\ & \text{later young} \\ \log W &= -2.335 + 2.93760 \log L \\ & \text{small} \\ \log W &= -2.688 + 3.22526 \log L \\ & \text{adult} \\ \log W &= -2.685 + 3.21229 \log L \end{aligned}$$

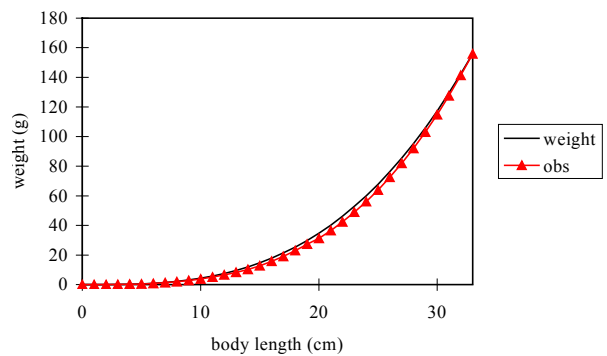
Figure 4.4 shows the wet weight-knob length relation curves of Kosaka (2000). If we adapt the simple one curve for all stages, it becomes

$$W = (KL / 6.13)^3$$

and the curve will look like Figure 4.4. The broken line in Figure 4.3 shows the same curve.



**Fig. 4.3** Swimming speed (cm/s) and wet weight (g) as a function of body length (cm).



**Fig. 4.4** Wet weight (g)-knob length (cm) relation curves of Kosaka (2000) (red) and fitting curve (black).

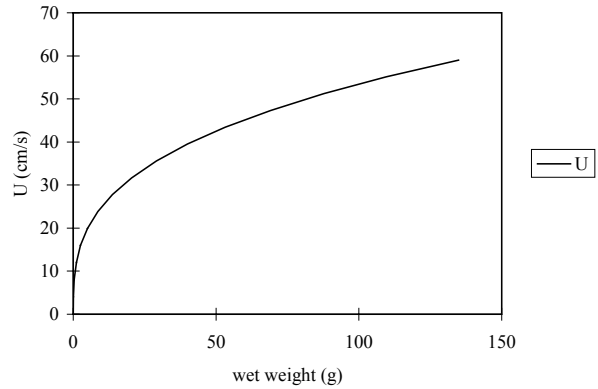
The last equation could be rewritten as

$$KL = 6.13 W^{0.33}$$

and the swimming speed becomes

$$U = 12.3 W^{0.33}$$

and we adapted 12.3 as  $a_A$  parameter when the temperature is higher than 12°C and 0.33 for  $b_A$  value. For temperatures less than 12°C we adapted 2.0 as  $a_A$ . The weight - swimming speed relation looks like Figure 4.5 when the temperature is higher than 12°C.



**Fig. 4.5** Wet weight (g)-swimming speed (U-cm/s) relation curve for higher temperature.

The parameters we adapted for Pacific saury bioenergetics model are summarized on Table 4.4.

**Table 4.4** Summary of parameter values used in the saury bioenergetics model.

Symbol	Parameter description	Value
<b>Consumption, <math>C_{MAX}</math></b>		
$a_C$	Intercept for $C_{MAX}$ at $(te1+te3)/2$	0.6
$b_C$	coefficient for $C_{MAX}$ versus weight	-0.256
$te1$	Temperature for $xk1$ (in °C)	5, 5, 5
$te2$	Temperature for $xk2$ (in °C)	20, 16, 16
$te3$	Temperature for $xk3$ (in °C)	26, 20, 20
$te4$	Temperature for $xk4$ (in °C)	30, 30, 30
$xk1$	Proportion of $C_{MAX}$ at $te1$	0.10
$xk2$	Proportion of $C_{MAX}$ at $te2$	0.98
$xk3$	Proportion of $C_{MAX}$ at $te3$	0.98
$xk4$	Proportion of $C_{MAX}$ at $te4$	0.5
<b>Metabolism, R</b>		
$a_R$	Intercept for R	0.0033
$b_R$	Coefficient for R versus weight	-0.227
$c_R$	Coefficient for R versus temperature	0.0548
$d_R$	Coefficient for R versus swimming speed	0.03
S	Coefficient for Specific Dynamic Action	0.175
<b>Swimming speed, U</b>		
$a_A$	Intercept U (< 12 °C) (in cm/s)	2.0
$a_A$	Intercept U ( $\geq$ 12 °C) (in cm/s)	12.3
$b_A$	Coefficient U versus weight	0.33
$c_A$	Coefficient U versus temperature (< 12 °C)	0.149
$c_A$	Coefficient U versus temperature ( $\geq$ 12 °C)	0.0
<b>Egestion and excretion, F and E</b>		
$a_F$	Proportion of consumed food egested	0.16
$a_E$	Proportion of consumed food excreted	0.10

**Multispecies functional response (by saury size groups)**

V <sub>11</sub>	Vulnerability of prey group 1 to predator 1	1.0
V <sub>12</sub>	Vulnerability of prey group 2 to predator 1	0.0
V <sub>13</sub>	Vulnerability of prey group 3 to predator 1	0.0
K <sub>11</sub>	Half saturation constant for prey group 1 to predator 1 (g wet weight/m <sup>3</sup> )	100.0
K <sub>12</sub>	Half saturation constant for prey group 2 to predator 1 (g wet weight/m <sup>3</sup> )	100.0
K <sub>13</sub>	Half saturation constant for prey group 3 to predator 1 (g wet weight/m <sup>3</sup> )	100.0
V <sub>21</sub>	Vulnerability of prey group 1 to predator 2	1.0
V <sub>22</sub>	Vulnerability of prey group 2 to predator 2	1.0
V <sub>23</sub>	Vulnerability of prey group 3 to predator 2	0.0
K <sub>21</sub>	Half saturation constant for prey group 1 to predator 2 (g wet weight/m <sup>3</sup> )	100.0
K <sub>22</sub>	Half saturation constant for prey group 2 to predator 2 (g wet weight/m <sup>3</sup> )	100.0
K <sub>23</sub>	Half saturation constant for prey group 3 to predator 2 (g wet weight/m <sup>3</sup> )	100.0
V <sub>31</sub>	Vulnerability of prey group 1 to predator 3	0.0
V <sub>32</sub>	Vulnerability of prey group 2 to predator 3	1.0
V <sub>33</sub>	Vulnerability of prey group 3 to predator 3	1.0
K <sub>31</sub>	Half saturation constant for prey group 1 to predator 3 (g wet weight/m <sup>3</sup> )	100.0
K <sub>32</sub>	Half saturation constant for prey group 2 to predator 3 (g wet weight/m <sup>3</sup> )	100.0
K <sub>33</sub>	Half saturation constant for prey group 3 to predator 3 (g wet weight/m <sup>3</sup> )	100.0

start day is February 1st

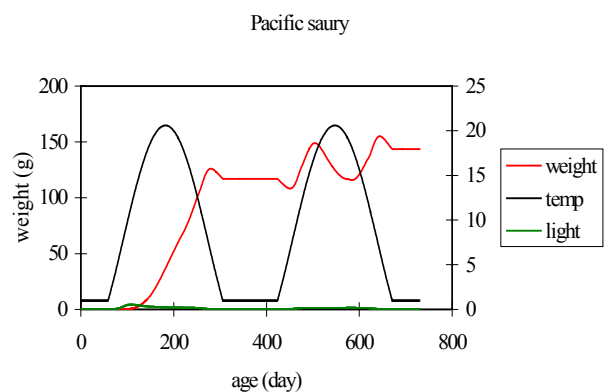
stage 1	0-50mm	0-30days
stage 2	50-200mm	30-150days
stage 3	>200mm	150day-720days

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## Model result

The parameters which are revised for the Pacific saury were used to integrate the bioenergetics model coupled with the ecosystem model. Figure 4.6 shows the result of the integration, and shows that the weight of saury reached 120 g after one year. This seems reasonable for Pacific saury. The model shows a high growth rate around 13°C water temperature. This corresponds to the habitat temperature in the Oyashio region during the feeding season.

Figure 4.7 shows the interannual experiment of ecosystem-saury coupled model with realistic



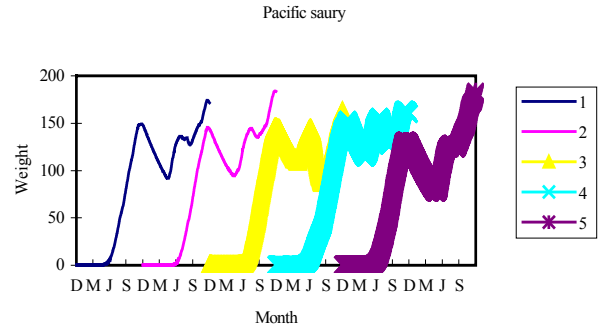
**Fig. 4.6** Result of Pacific saury bioenergetics model. Light is in units of ly/min.

forcing of A7 (Akkeshi line St 7 off Hokkaido, Japan). The model results show low growth rate in the third and fourth year cohort. The result strongly depends on water temperature.

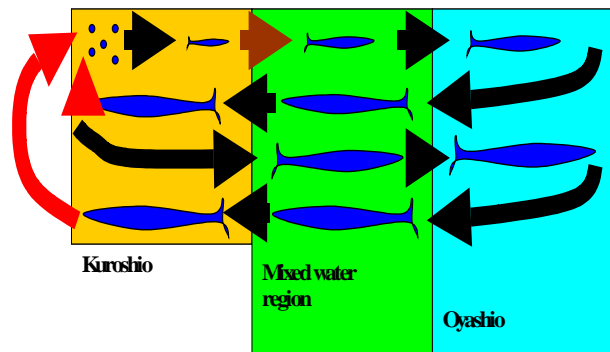
### Future work

This model is not perfect and needs improvements in several respects.

- The weight of the earliest stage is not reproduced well. We should re-parameterize values for this stage.
- More than half of the Pacific saury spawn in the first year and all of them spawn in the second year (Kurita and Sugisaki; in preparation). We should include the effect of spawning in this model.
- In this model only one ocean region is included. But the saury migrate from the subtropical to the subarctic region through the mixed water region, each with its own seasonal cycle of temperature and prey. We should include at least three ocean regions in the ecosystem-saury coupled model. We suggest Figure 4.8 as a prototype three ocean region model. This kind of model is very useful for the analysis of interannual variability of saury growth.



**Fig. 4.7** Result of Pacific saury bioenergetics model with realistic forcing.



**Fig. 4.8** Schematic picture of a three-ocean-box model. This model includes three ocean regions but only one saury bioenergetic model.

## 5.0 Model experiments and hypotheses

Several model experiments were discussed to test hypotheses regarding the effects of climate change. The details of the experiments and hypotheses are described below.

### Space hypothesis

**Geographic variation in fish growth:** Differences in environmental conditions, and resulting differences in lower trophic conditions, can account for the differences in herring growth rates among selected sites in the North Pacific ecosystem. There exist long-term data sets on size-at-age of herring from many locations in the North Pacific. These data sets show that herring growth rates over the past decades have varied consistently among the different locations.

Understanding the extent to which environmental conditions account for these temperature differences in herring growth is important for predicting climate change effects and for effective management of these fisheries in the future.

**Key regions contributing to fish growth and biomass variations:** Pacific saury are spawned in the subtropical and transition zone from autumn to spring, and migrate from the subtropical to the subarctic ocean through a transition zone. The environments of these three regions show different interannual variability, and it is very difficult to distinguish which location (or season) is most important to the interannual variability of fish growth and biomass. We will tune up the NPZ model coupled to the fish growth model with long-