

Bioenergetics Model of the Japanese Chum Salmon (*Oncorhynchus keta*) Growth

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A reduction of body size of Japanese chum salmon (*Oncorhynchus keta*) was observed in the 1990s. In order to investigate causes of body size reduction, a bioenergetics model was developed for immature and maturing chum salmon. We assumed that sea surface temperature (SST) and prey zooplankton density were possible factors to reduce fish body size. Information on SST and prey zooplankton density in waters along the migration route of Japanese chum salmon (Urawa 2000, 2004; Azumaya and Ishida 2004) were obtained from the World Ocean Database (WOD) 2001 (O'Brien et al. 2002) and North Pacific Ecosystem Model Used for Regional Oceanography (NEMURO) embedded in 3-D physical model (Aita et al. 2007).

NEMURO (Fig. 1) was developed by PICES Model Task Team (Megrey et al. 2002). In this model, silicate is included as a nutrient as well as nitrogen, and ontogenetic vertical migration is applied to Copepoda (ZL in Figure 1). If it is embedded into a Global model, however, there are some technical difficulties. Figure 2 shows the time dependent features and anomalies of annual average plankton biomass and primary production, where PS, small phytoplankton (flagellate); PL, large phytoplankton (diatom); ZS, small zooplankton (foraminifera); ZL, large zooplankton (copepod); ZP, zooplankton predator (krill and jelly fish). After the regime shift, the biomass of phytoplankton and zooplankton and nutrient concentration increased dramatically as did primary production, except for ZS which increased slightly.

Our bioenergetics model (Fig. 3) was based on models for Pacific herring (*Clupea pallasii*) and Pacific saury

Fig. 1. North Pacific Ecosystem Model for Regional Oceanography (NEMURO) developed by PICES Model Task Team.

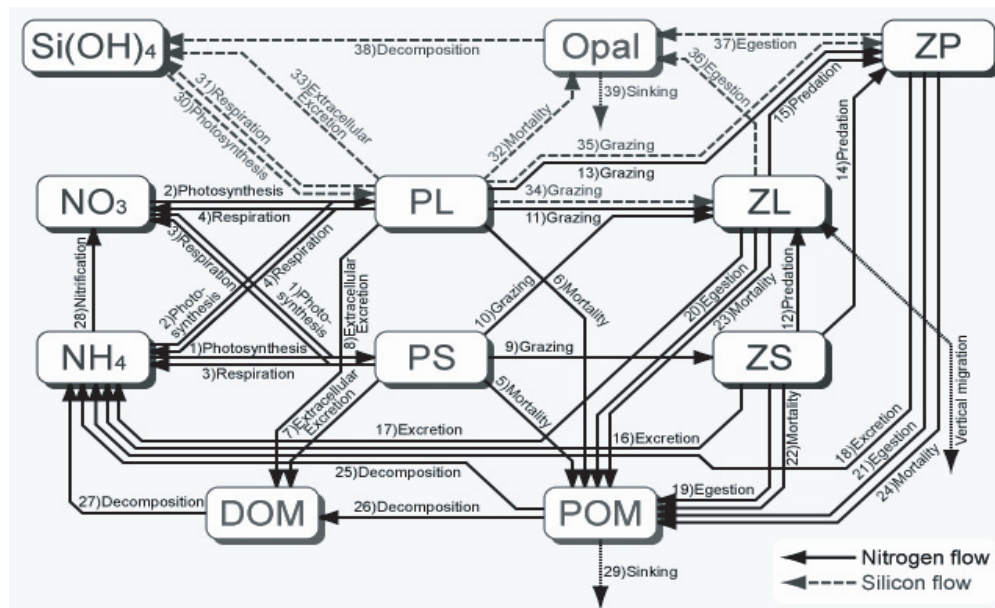


Fig. 2. Time dependent features of anomalies of annually averaged PS, PL, ZS, ZI, and ZP biomass, nitrate and silicate concentrations, and primary production in the upper 150 m in 6 regions of the Bering Sea (after Aita et al. 2007).

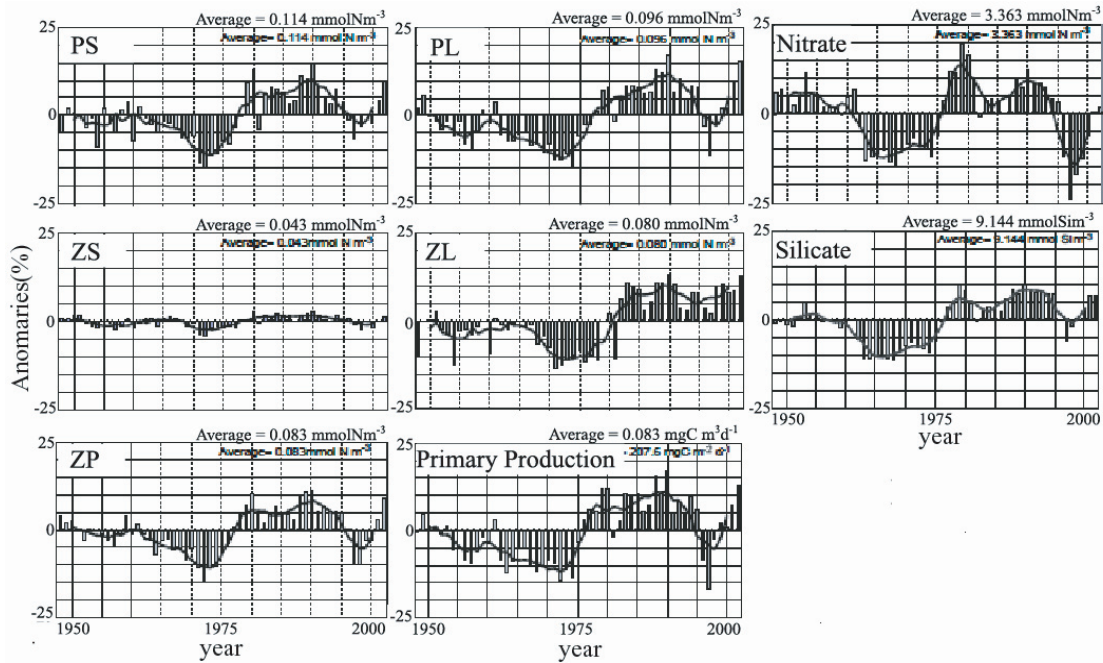


Fig. 3. The governing equation of chum salmon bioenergetics.

$$\frac{dW}{W \cdot dt} = [C - (R + SDA + F + E)] \cdot \frac{CAL_z}{CAL_f}$$

where
W: wet weight of fish (wwg)
t: time(day)
C: consumption(g prey · g fish⁻¹ · d⁻¹)
R: respiration or losses through metabolism(g prey · g fish⁻¹ · d⁻¹)
SDA: specific dynamic action (g prey · g fish⁻¹ · d⁻¹)
F: egestion or losses due to feces (g prey · g fish⁻¹ · d⁻¹)
E: excretion or losses of nitrogenous excretory wastes (g prey · g fish⁻¹ · d⁻¹)
CAL_z, *CAL_f*: caloric equivalent of zooplankton (cal · g zooplankton⁻¹) and fish(cal · fish⁻¹)

$C = C_{MAX} \cdot C_p \cdot f_c(T)$
 where
C_{MAX}: the maximum specific feeding rate (g prey · g fish⁻¹ · d⁻¹)
C_p: prey density dependence function for consumption
f_c(T): temperature dependence function for consumption

Table 1. Life stages of Japanese chum salmon in the bioenergetics model.

Stage	Ocean age	Period	Region
1	0-1	12/1-5/31	W. North Pacific
2	1	6/1-11/30	Bering Sea
3	1-2	12/1-5/31	E. North Pacific
4	2	6/1-11/30	Bering Sea
5	2-3	12/1-5/31	E. North Pacific
6	3	6/1-10/31	Bering Sea

Fig. 4. Schematic view of the three oceanic spatial domains and the numbers of life stages of Japanese chum salmon simulated in the model. The three domains correspond to the western North Pacific, Bering Sea, and eastern North Pacific Ocean.

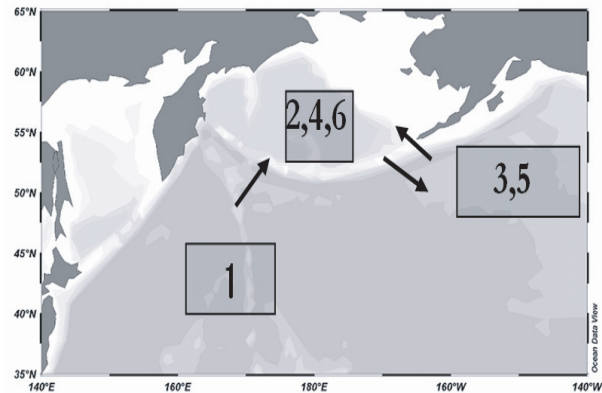


Fig. 5. Temperature dependent function (*f_c(T)*) for stage-1 (thin line), stage -2, 4 (bold line), and stage 3, 5 (broken line).

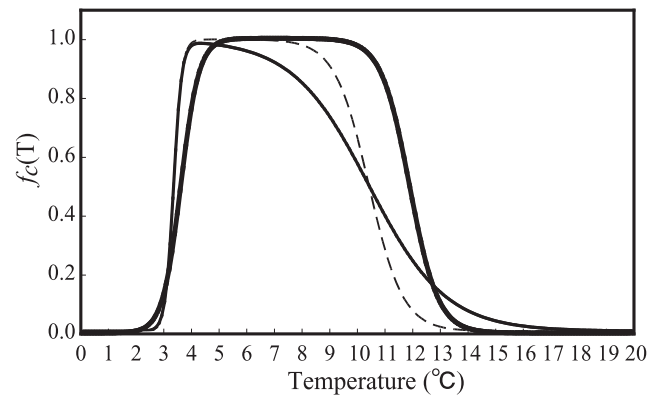


Fig. 6. Simulated body size growth of 1972 and 1991 year classes of chum salmon for cases of control (a), constant prey density with time dependent temperature (b), and constant temperature with time dependent density (c).

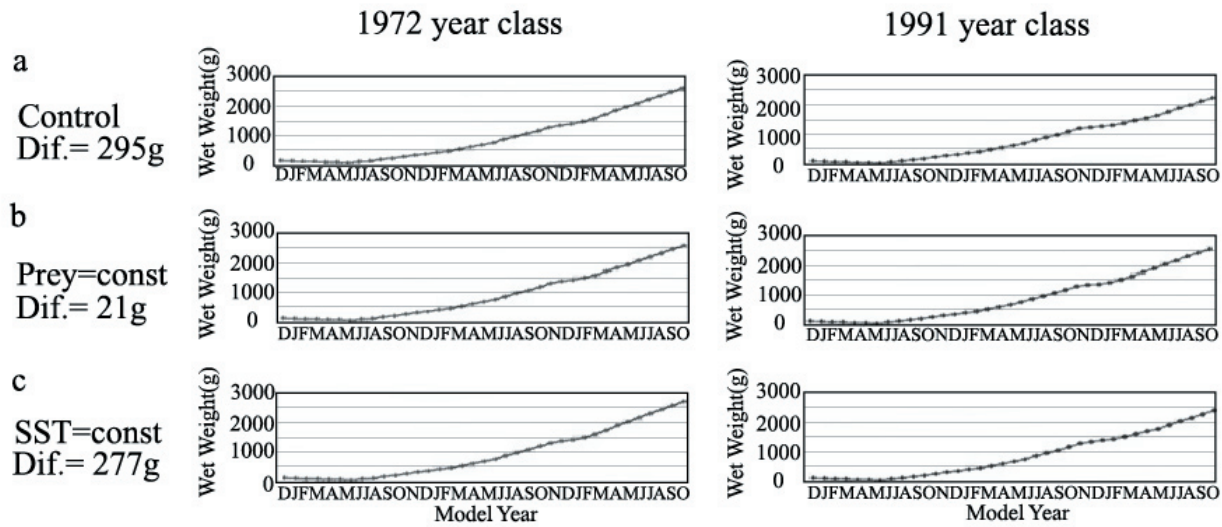


Fig. 7. Time dependent features of $f_c(T)$ (a) and C_r (b) in the equation of consumption for 1971 (open circles) and 1991 (closed circles) year classes of chum salmon.

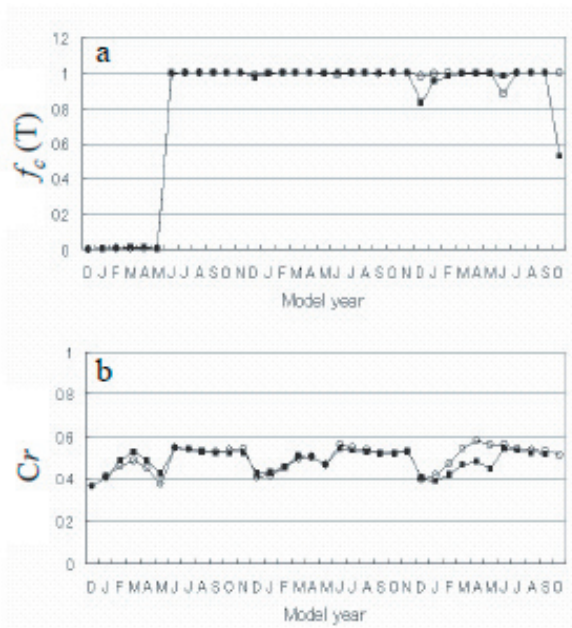
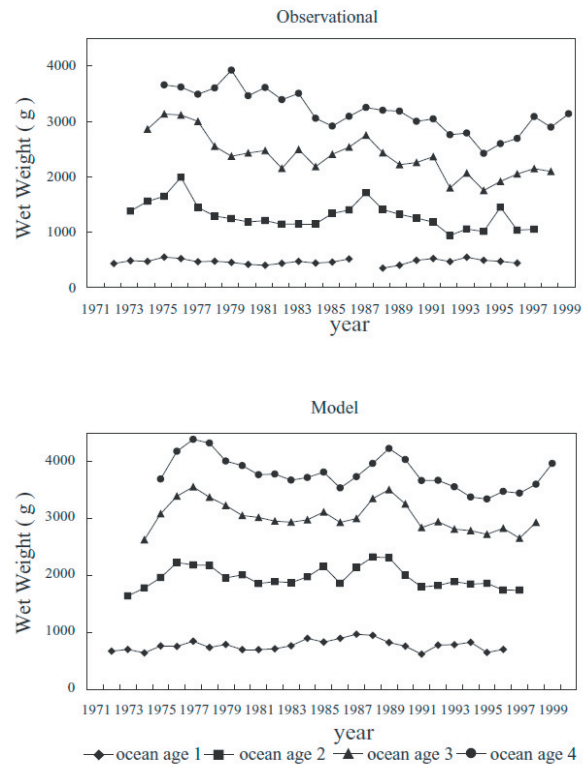


Fig. 8. Time dependent body size of chum salmon in the Bering Sea in the summer of 1971-1999.



(*Cololabis saira*) (Mergrey et al. 2002), using respiration and consumption terms of Ware (1978), Beauchamp et al. (1989) and Trudel et al. (2004). According to Kaeriyama et al. (2004), we used only ZP as a zooplankton predator. The mean period of foraging ocean migration of chum salmon was supposed to be 3 years, thus the life stage was divided into six stages: three stages each for summer and winter (Table 1, Fig. 4). The model reproduced the body size of 1972 and 1991 year classes of chum salmon. We assumed optimum SST for chum salmon in each box and made $f_c(T)$ (Fig. 5).

The zooplankton density of NEMURO, represented in nitrogen unit ($\text{mol N}\cdot\text{L}^{-1}$) and simulated results converted into wet weight (Aita et al. 2007), was too small compared with WOD 2001 (O'Brien et al. 2002). Then, we adjusted the NEMURO value (ZL) (wet weight $\text{g}\cdot\text{m}^{-3}$) as 0.104 using observational data of WOD 2001, and

converted ZP also with the same ratio.

Reproduced wet weight of the 1972 year class was larger than that of 1991 year class (Fig. 6a). The prey density, especially prey zooplankton density during winter in the Gulf of Alaska, was found to influence the body size of ocean age 3 rather than SST (Figs. 6b,c, 7). The simulated results of time dependent features showed a coincident with observations in the Bering Sea (Fig. 8). The growth of ocean age 1 chum salmon did not affect the body size of ocean age 3 or 4 fish, but the body size of ocean age 3 fish was related to that of ocean age 4 fish. These results suggest that the size reduction of Japanese chum salmon in 1990s might be partly affected by prey zooplankton density.

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