Modeling recruitment variability of Pacific saury (*Cololabis saira*) using an individual-based model

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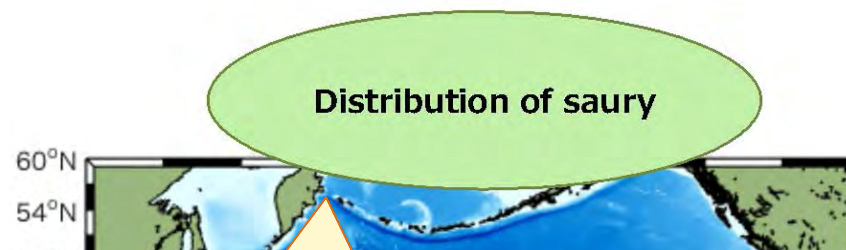
Pacific saury (*Cololabis saira*)



Ecologically & commercially important fish

Outline

Environment
↓
Growth

To examine the effects of environmental conditions on the growth.

- ## Introduction
  - "What is Pacific saury"
  - Problem & Solution
  - Objective
- ## Method & Materials
  - Explanation of the Model
  - Observation data
- ## Results
  - Model-observation data comparison
  - Temporal variation in growth factors
  - Spatial variation in growth
- ## Discussion
  - **Processes responsible for the growth differences**

Growth
↓
Survival

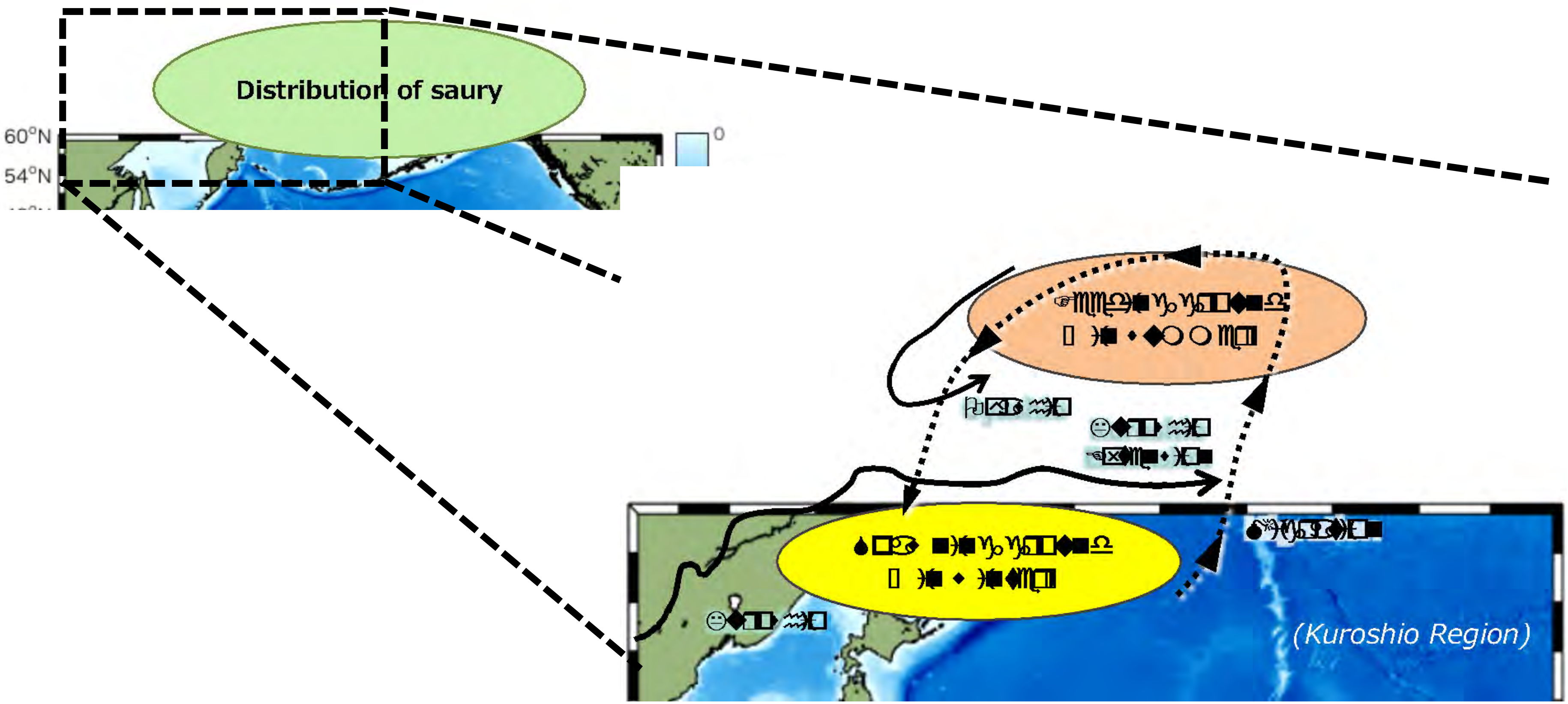
To examine the survival process of saury.

- ## (part of) Results
  - Parameterizing natural mortality

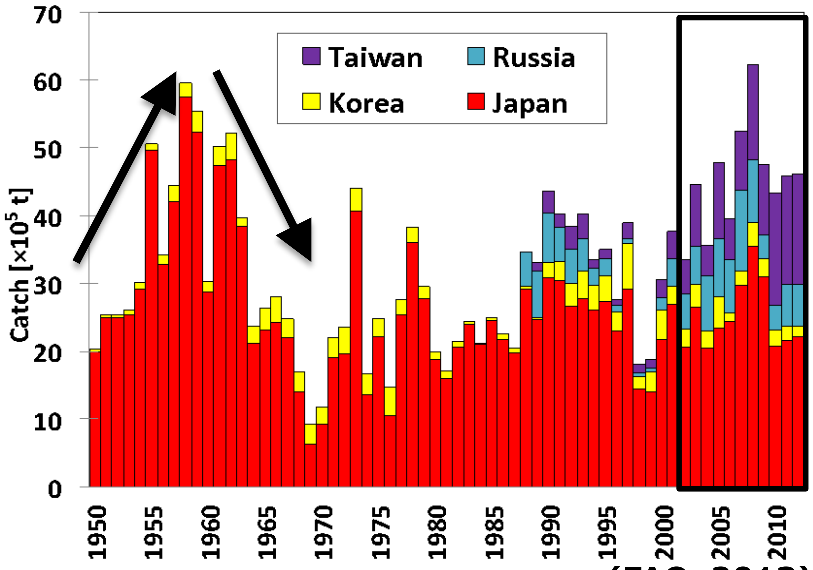
Life cycle of Pacific saury

- Target area: **Coast of Japan – 160°W**)
- 3 spawning seasons:
  Kuroshio region (winter), Transition Zone (autumn & spring)

(Watanabe and Lo, 1988)



Catch of Pacific saury



(FAO, 2013)

- Ecologically important as forage fish in the NP, and commercially important in Japan & other Asian countries.
  - Interannual variability in catch : **Large** (FAO, 2013)
  - Interannual variability in length & weight : **Large** (Kosaka, 2000; Resource assessment survey, 2015)

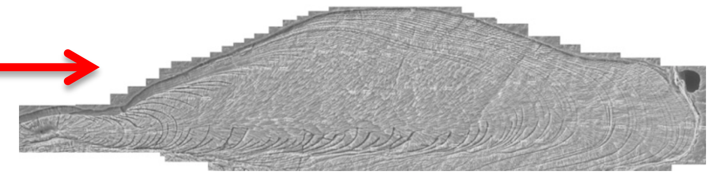
The mechanism of the variability in both growth & population is **not clear**

- The growth & survival in early life stages seemed to be associated with the large environmental variability. (Watanabe et al., 1997, 2003)

Need to investigate the recruitment processes in early life stages

Problem & Solution

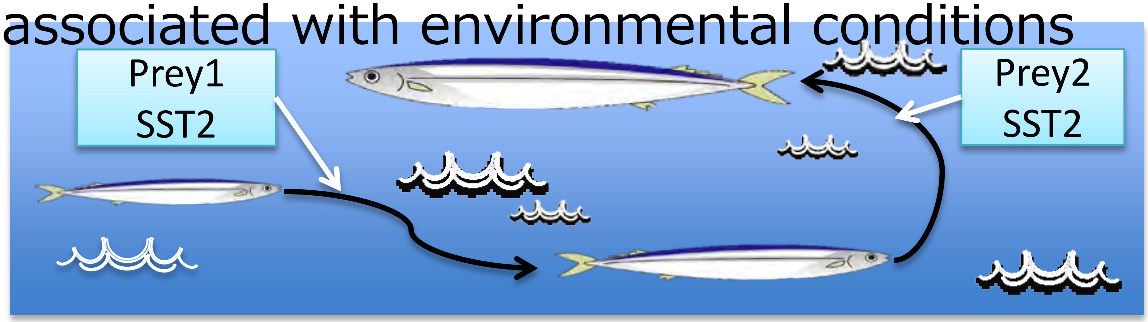
The growth could be estimated from <u>otolith analyses</u>.



(Kurita et al., 2004; Oozeki et al., 2004; Takasuka et al., 2014, 2016 etc)

→ **<u>However</u>**, the growth trajectory & environmental conditions experienced are **not clarified from otolith analyses alone**.

Need to investigate **the spatio–temporal variability in growth & migration** of fish associated with environmental conditions **comprehensively.**

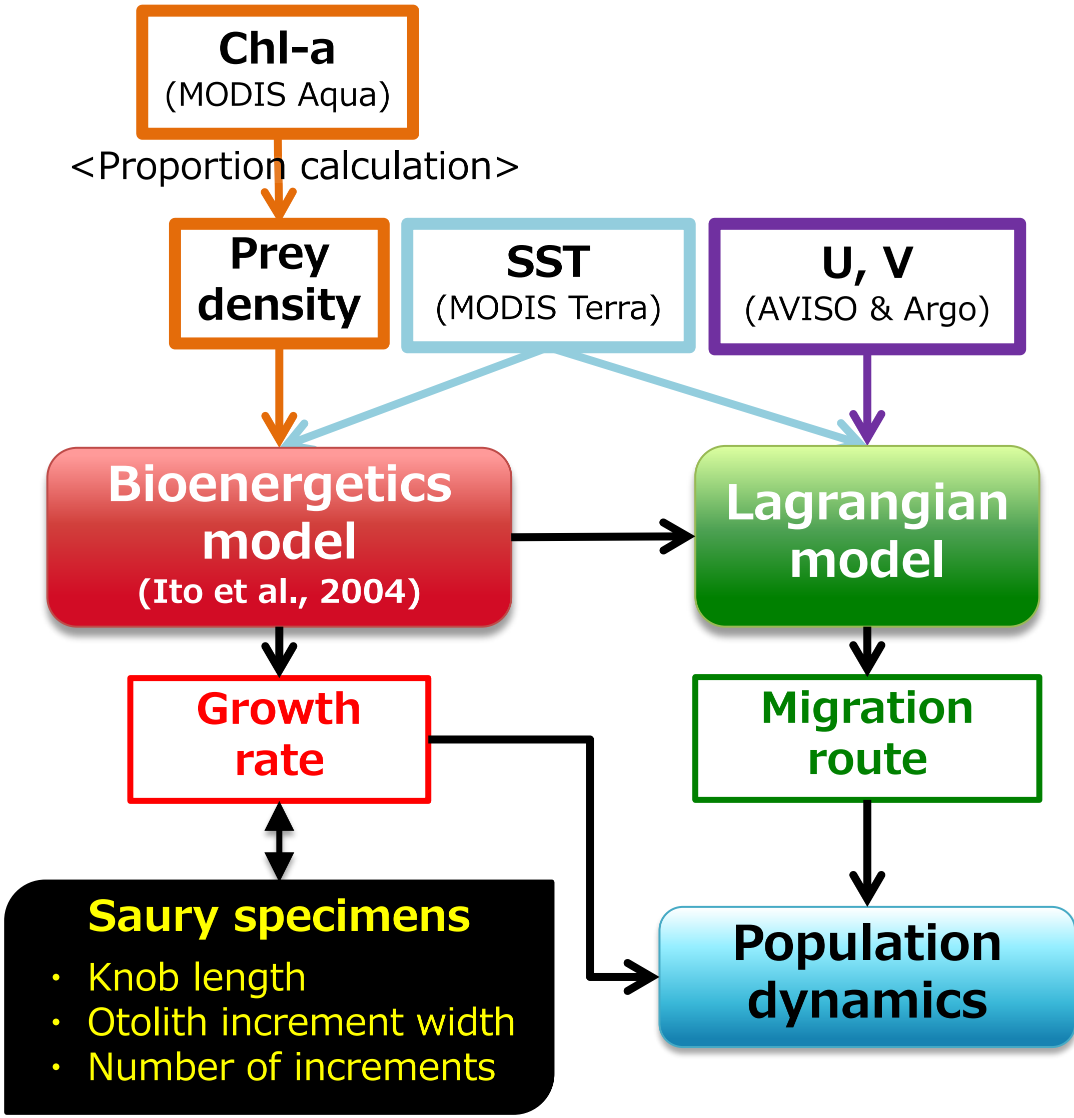


Objective

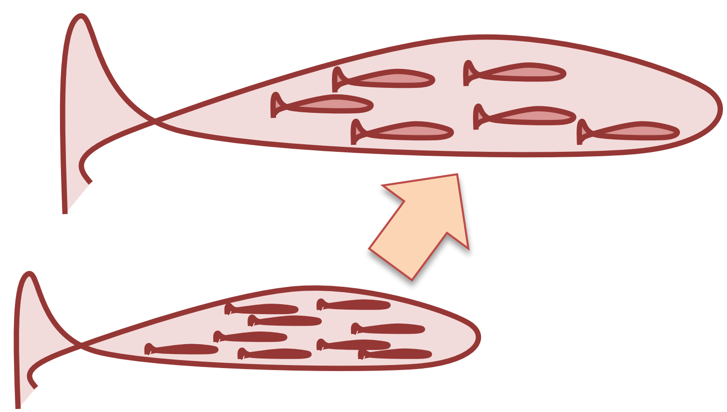
- To clarify effects of environmental conditions on growth of Pacific saury in relation to their migration route

Individual based-model + Otolith microstructure analyses

Individual-based model



- **Calculate the growth** using a bioenergetics model (Ito et al., 2004) and **migration route** using a Lagrangian model.
- **Validate** & **analyze** the growth & migration route



Bioenergetics model

➢ The model is based on a model that reproduces **the growth pattern of the fish weight.** (Ito et al., 2004)

$$\frac{dW}{dt} = (C - R - SDA - F - E - P) \cdot \frac{Cal_{zoo}}{Cal_{fish}} \cdot W$$

$$C = C_{MAX} \cdot \rho \cdot f(T)$$

C_{MAX} : the maximum consumption rate

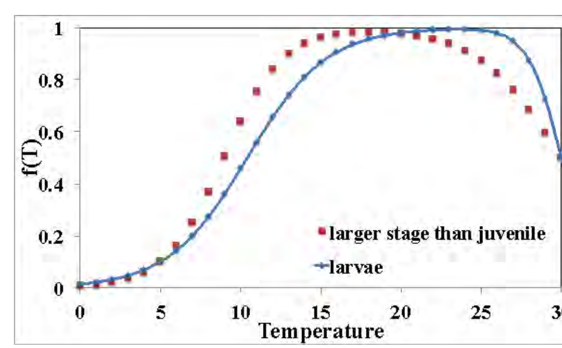
ρ : **prey density** dependent function ($0 \leqq \rho \leqq 1$)

Zooplankton

$f(T)$: **temperature** dependent function ($0 < f(T) < 1$)

※ ρ or $f(T) \rightarrow 1$: favorable environment for growth

The behavior of *f (T)*

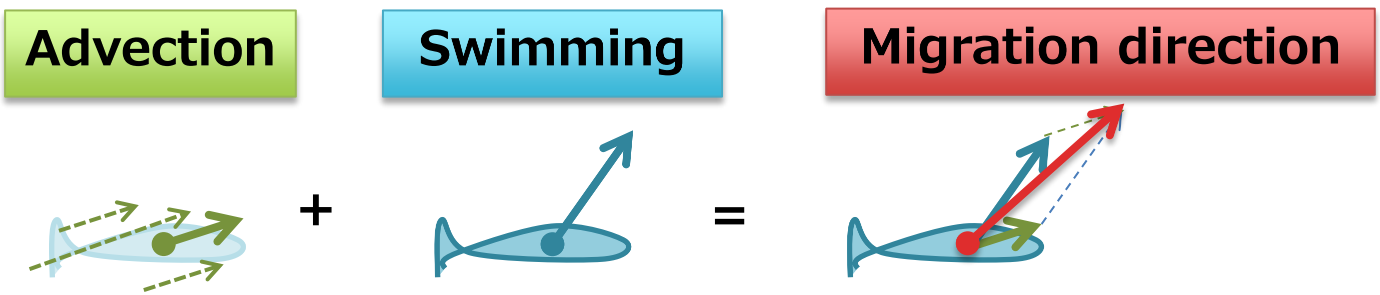


Lagrangian model

- **Set up for the migration**

  (a) L ≤ 2.5cm : advection only

  (b) L > 2.5cm : advection & swimming



Model saury individuals swim at speed of **two times their body length per second**

- **Either of the two, depending on the maturity and season:**

  (b-1) Feeding migration

  (b-2) Spawning migration

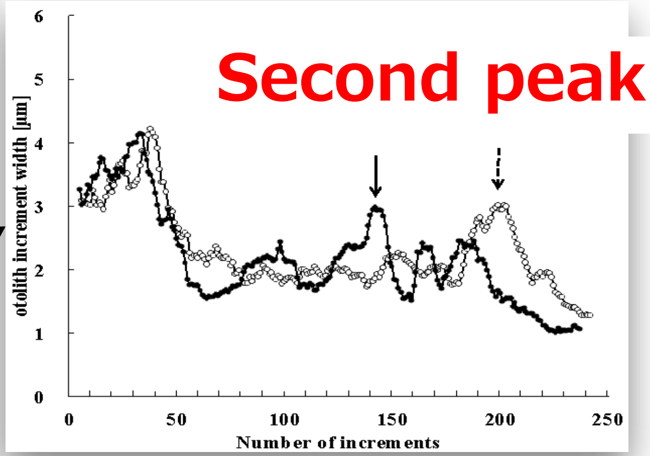
Observation data

- **Otolith microstructure analyses data** (Suyama et al., 2012)

Sampling date	06/07 – 06/29/2006
Sampling area	38°N-44°N, 140°E-165°W
Numbers of samples	**35 samples** of age-1 saury
Hatching date	**01/15 – 02/15/2005** (Kurita et al., 2004)
Measurement items	Knob length
	Otolith increment width
	Number of increments (= age in days)

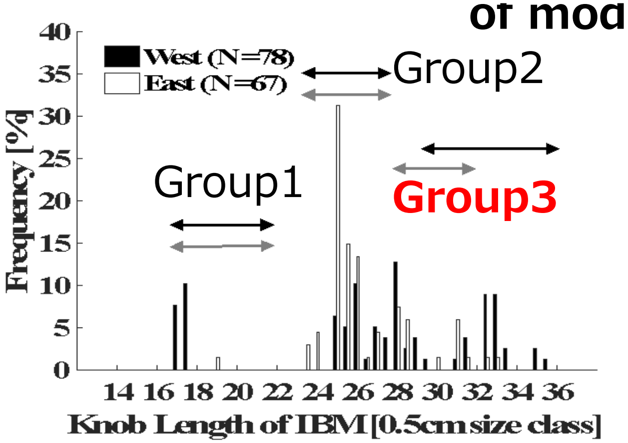
match start time of

Calculation 02/01/2005

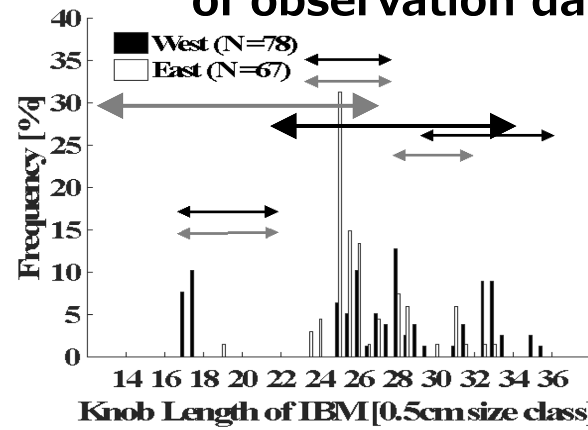


Model & Observation data

Length frequency distribution of model



Length frequency distribution of observation data



Validation ①

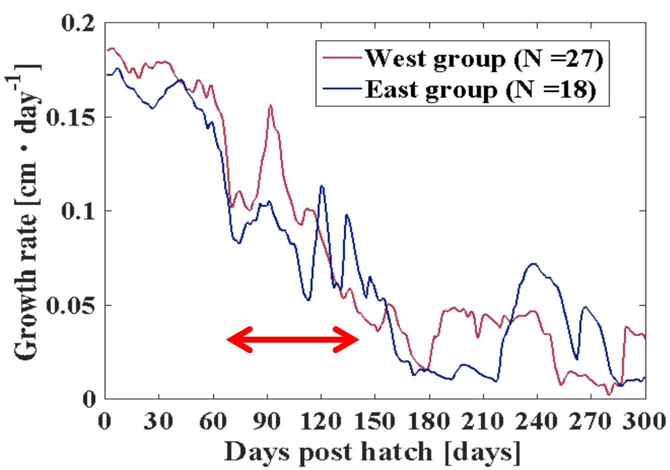
Knob length
- Range
- West > East

Consistent with observation data

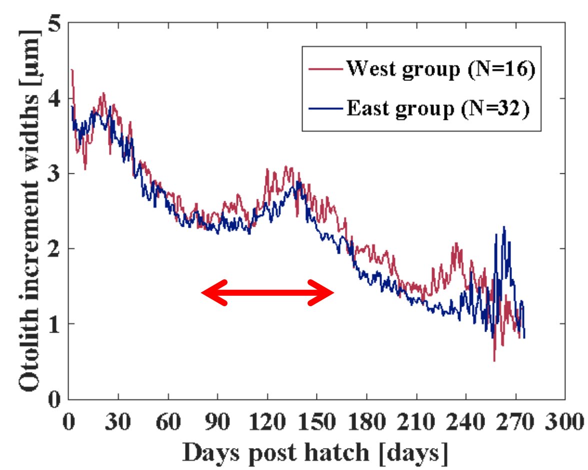
Validation ②

second peak

Growth trajectory of group3

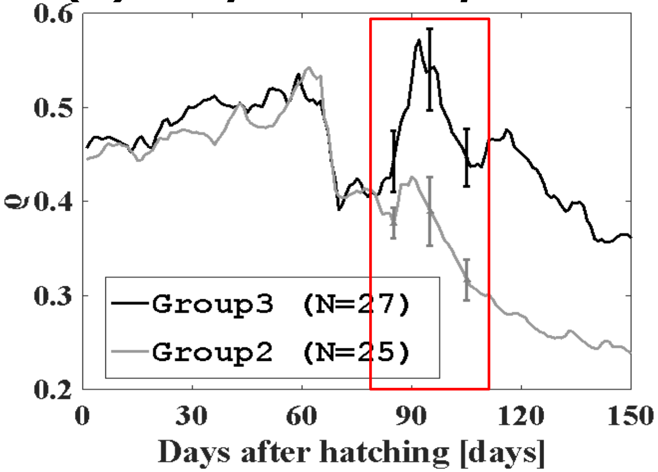


Otolith increment widths

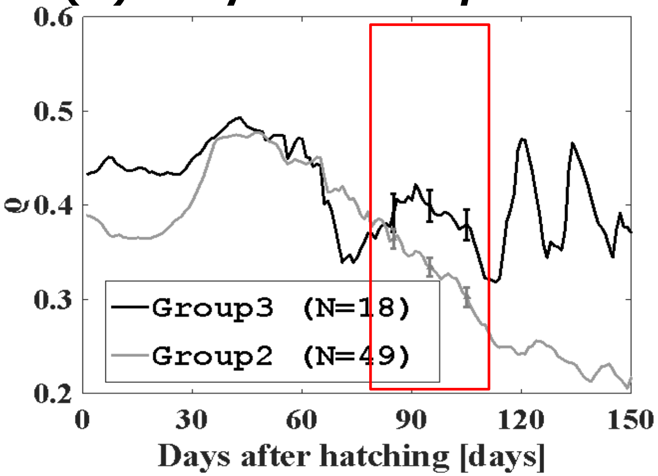


Determinant of the growth difference

(a) Western & group2 / & group3
(1) Prey function ρ



(b) Eastern & group2 / & group3
(1) Prey function ρ

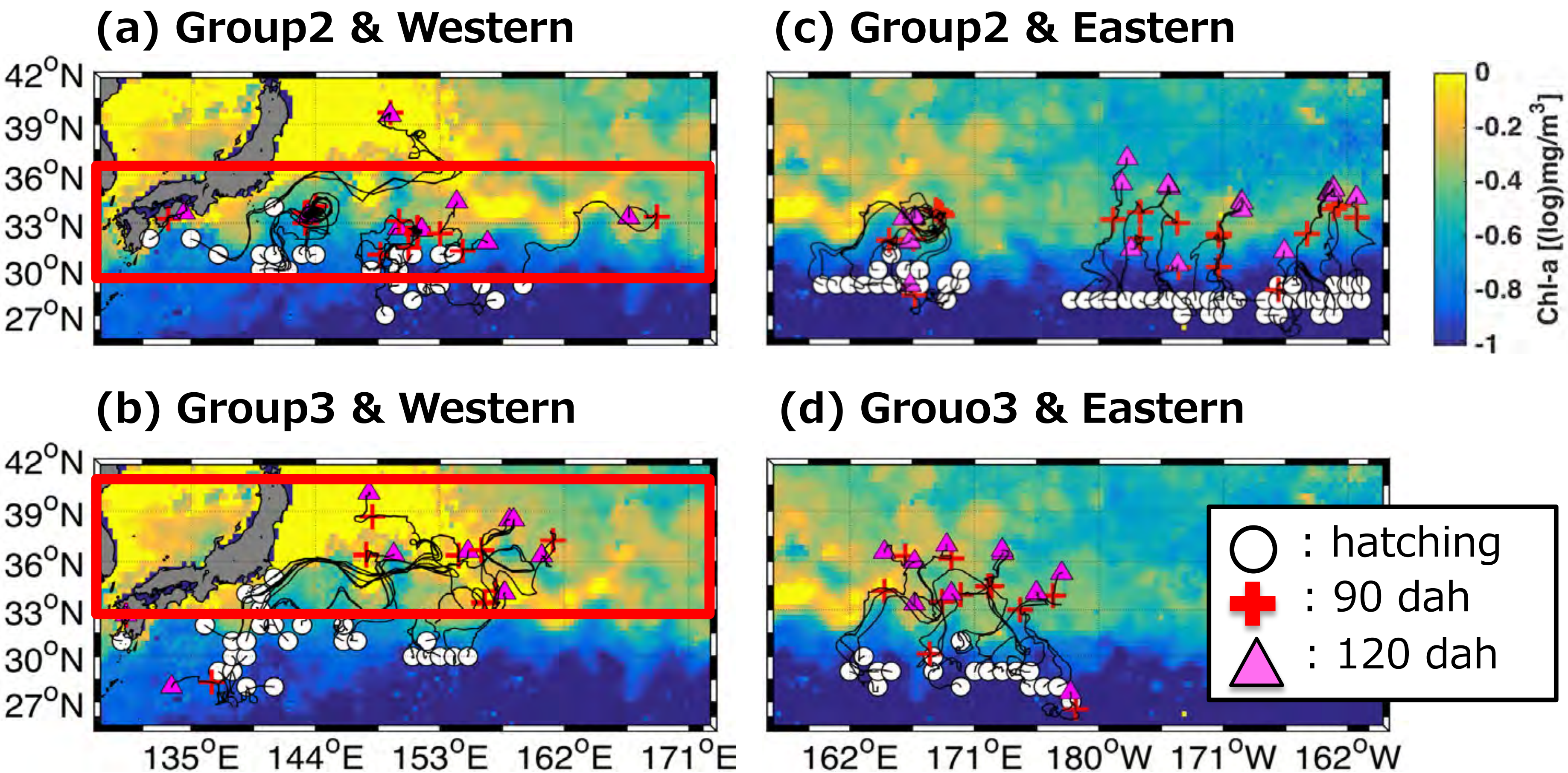


Prey density

$$C = C_{MAX} \cdot \rho \cdot f(T)$$

- We compare group3 with group2.
- In the growth rate, the significant difference arises at 105–115dah.
  (dah: days after hatching)
- The variability in growth rate is mainly controlled by **consumption term, C & Respiration term, R**
- Before 105dah, the variability in C & function ρ **synchronize** and significant differences in group3 & group2 occur **during 80–90 dah**.
- West group <u>experiences the good-food condition earlier</u> than east group.

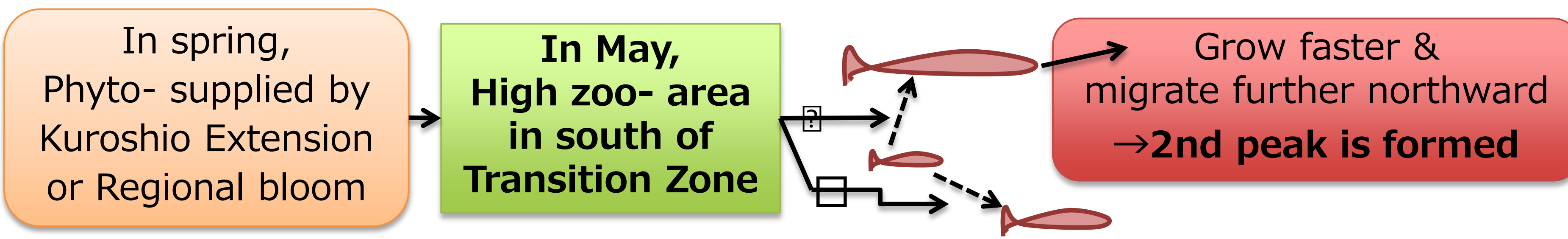
Migration route of each group



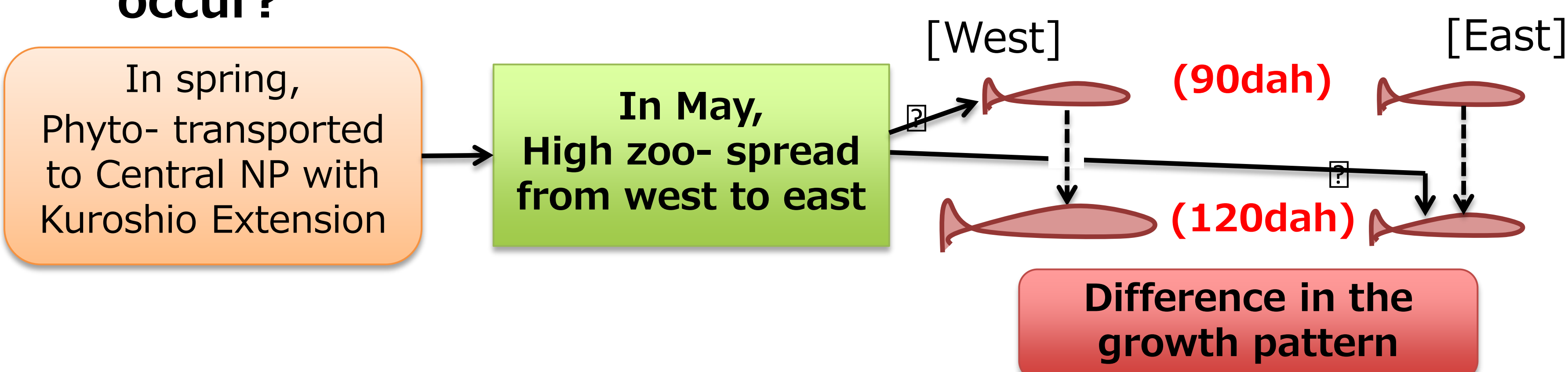
- At 90 dah (05/10/2006), the distribution of the group3 in the western side is found in the north of those of group2

Two controlling processes of growth

➢ **“How does the difference in growth of the larger & smaller groups occur?”** (Group3) (Group2)



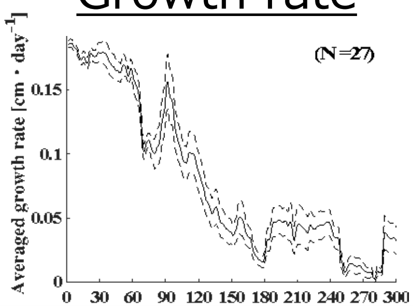
➢ **“How does the difference in growth of the west & east groups occur?”**

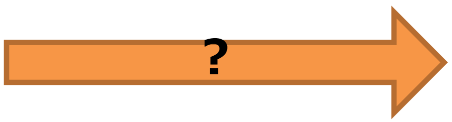


"Parameterizing natural mortality"

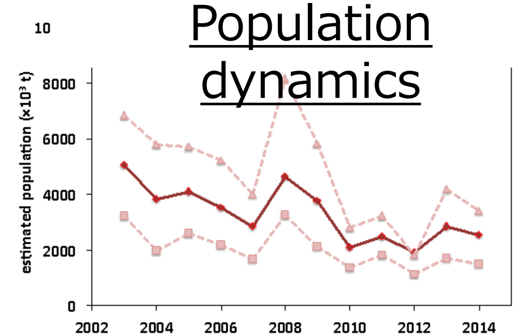
- Next question is, "**How does the growth & migration of saury affect population dynamics?**"

Growth rate



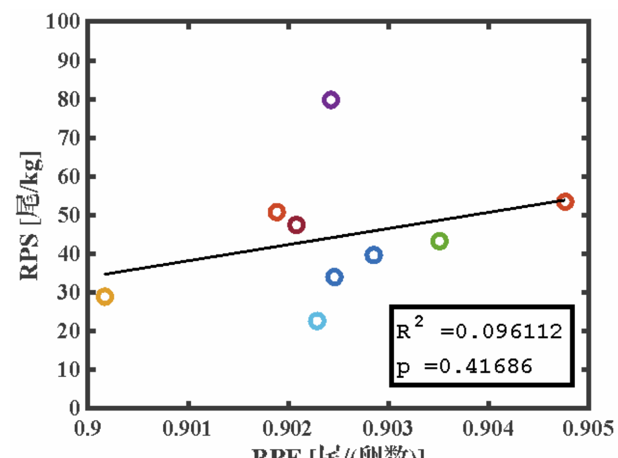


Population dynamics

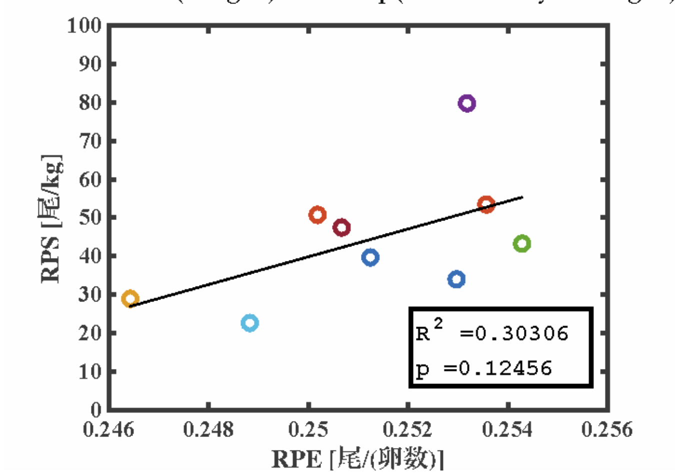


To answer this question, we parameterize natural mortality using growth & growth rate in the model

$$M = 5 \cdot 10^{-11} \times (Weight)^{-0.01} \times \exp(9.5 \cdot dW7days / Weight)$$



$$M = 5 \cdot 10^{-10} \times (Weight)^{-0.001} \times \exp(9.5 \cdot dW3days / Weight)$$



Conclusion

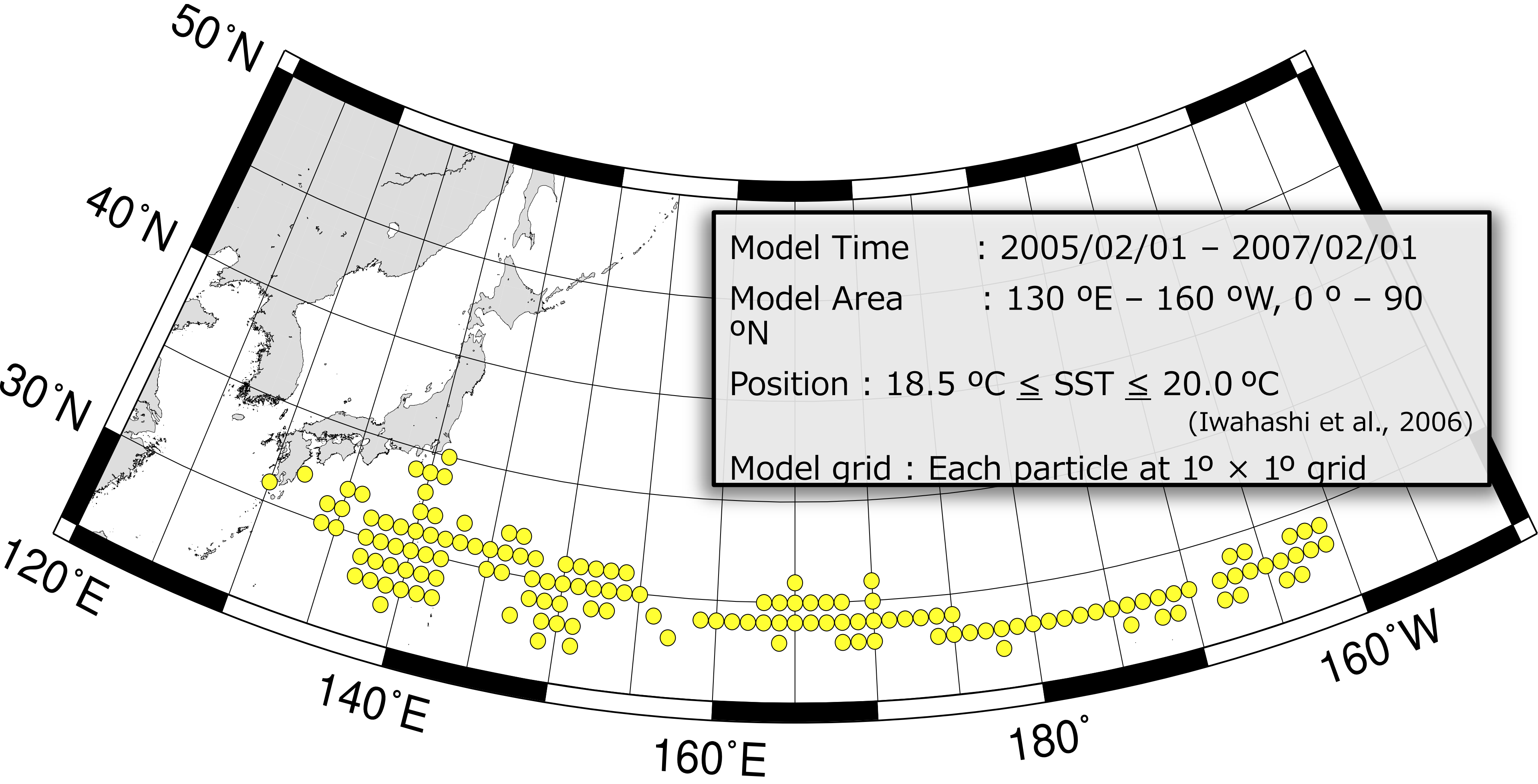
1) The model in this study represent the growth pattern of saury and this outputs are consistent with some knowledge derived from some previous study.

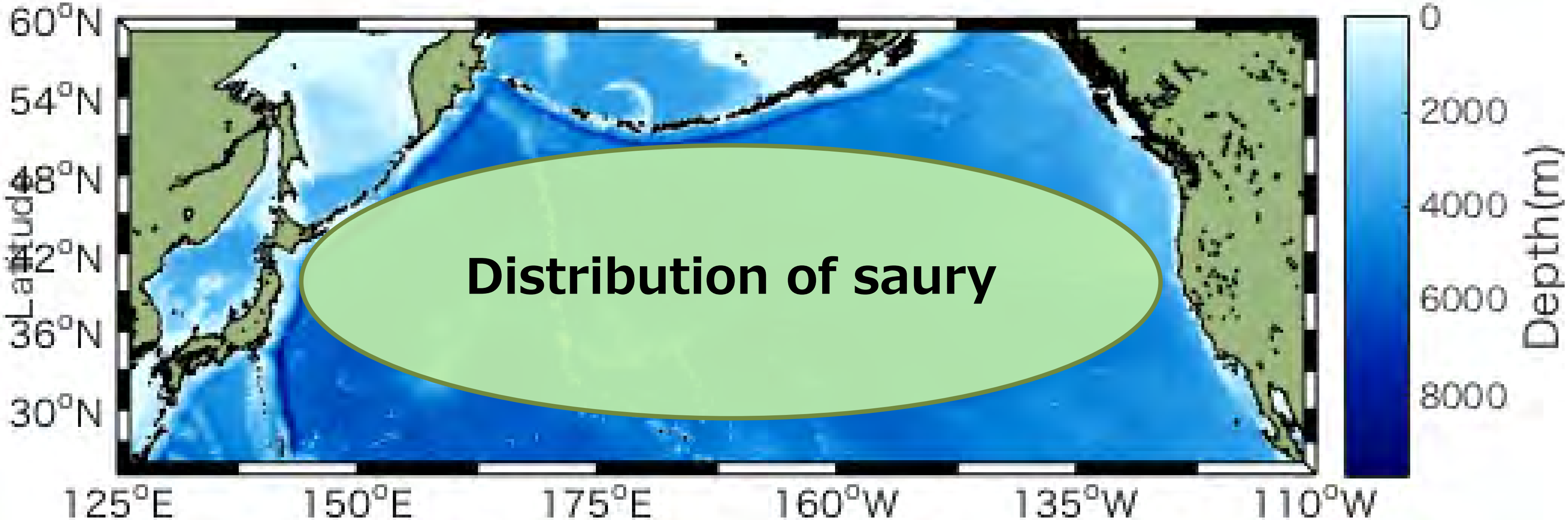
2) The growth rate during planktonic stage controlled northward migration of juveniles.

3) The difference between the growth of the saury in the eastern & western sides is determined by 90days after hatching

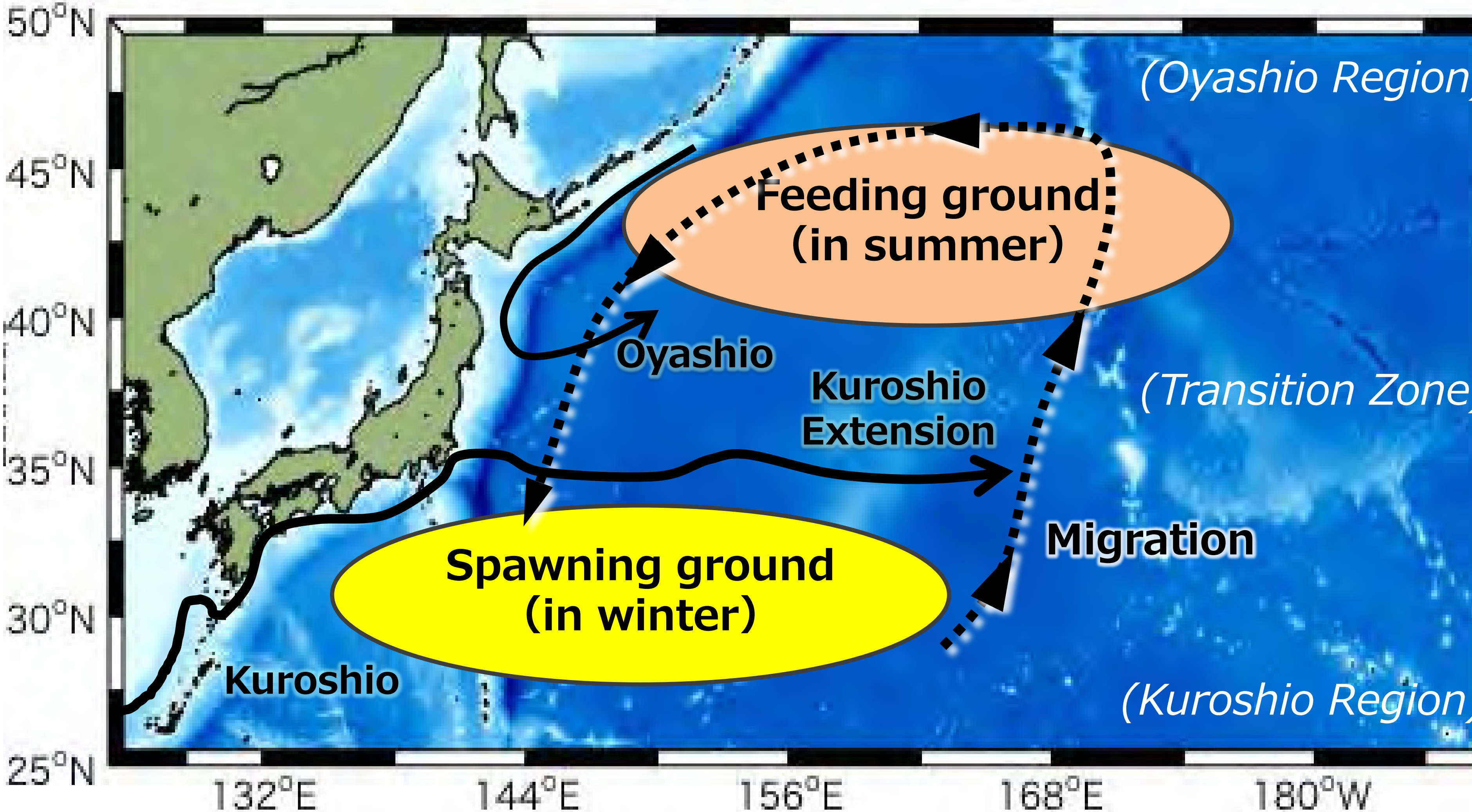
4) The variability in the recruitment might be affected by both body size & growth rate

Initial condition of model





60°N
54°N
48°N
42°N
36°N
30°N
Latitude
125°E
150°E
175°E
160°W
135°W
110°W
0
2000
4000
6000
8000
Depth(m)
Distribution of saury


50°N
45°N
40°N
35°N
30°N
25°N
132°E
144°E
156°E
168°E
180°W
(Oyashio Region)
Feeding ground
(in summer)
Oyashio
Kuroshio
Extension
(Transition Zone)
Migration
Spawning ground
(in winter)
Kuroshio
(Kuroshio Region)

Environmental data

➢ Satellite data

- SST : MODIS Terra ・ 9km × 9km ・ Weekly
- Chl–*a* concentration : MODIS Aqua ・ 9km × 9km ・ Weekly
- Sea surface velocity : $0.25^{o} \times 0.25^{o}$ ・ Weekly (Nakamura et al. 2015)

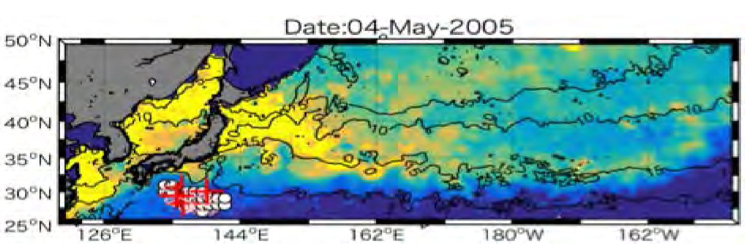
➢ Method of interpolating

(1) Using Gaussian interpolation of SST & Chl-*a* data (Segawa, K, 2000)

(2) Masked by $1/3^{o}$ map from AVISO

(3) Chl–*a* concentration 1.0 [mg chl.a/ m^3] → (Ikeda et al., 2008) → prey density

Proportion calculation



Small zooplankton ZS : 0.38 [g/ m^3]
Large zooplankton ZL : 0.75 [g/ m^3]
Gelatinous plankton ZP : 0.15 [g/ m^3]

Set up of bioenergetics model

- **Calculate weight growth rate of an individual per time**
  - Refer to Ito et al. (2004) for information on each parameter
  - dW/dt < 0 → $L_t = L_{t-1}$

    dW/dt > 0 → $L_t = 6.13 \cdot W_t^{0.33}$ t: time step

- Feeding habit

  → set up every length class

  (Sugisaki and Kurita, 2004)

Length [cm]	Half-saturation constants for each zooplankton compartment K_{ij}	Vulnerability coefficients for each zooplankton compartment v_{ij}		
		ZS	ZL	ZP
~2.5	0.10	1.0	0.0	1.0
2.5~14.9	0.30	1.0	1.0	0.0
~14.9 (ZL concetration ≧0.05)	0.60	0.0	1.0	1.0
~14.9 (ZL concetration <0.05)	0.60	1.0	1.0	1.0

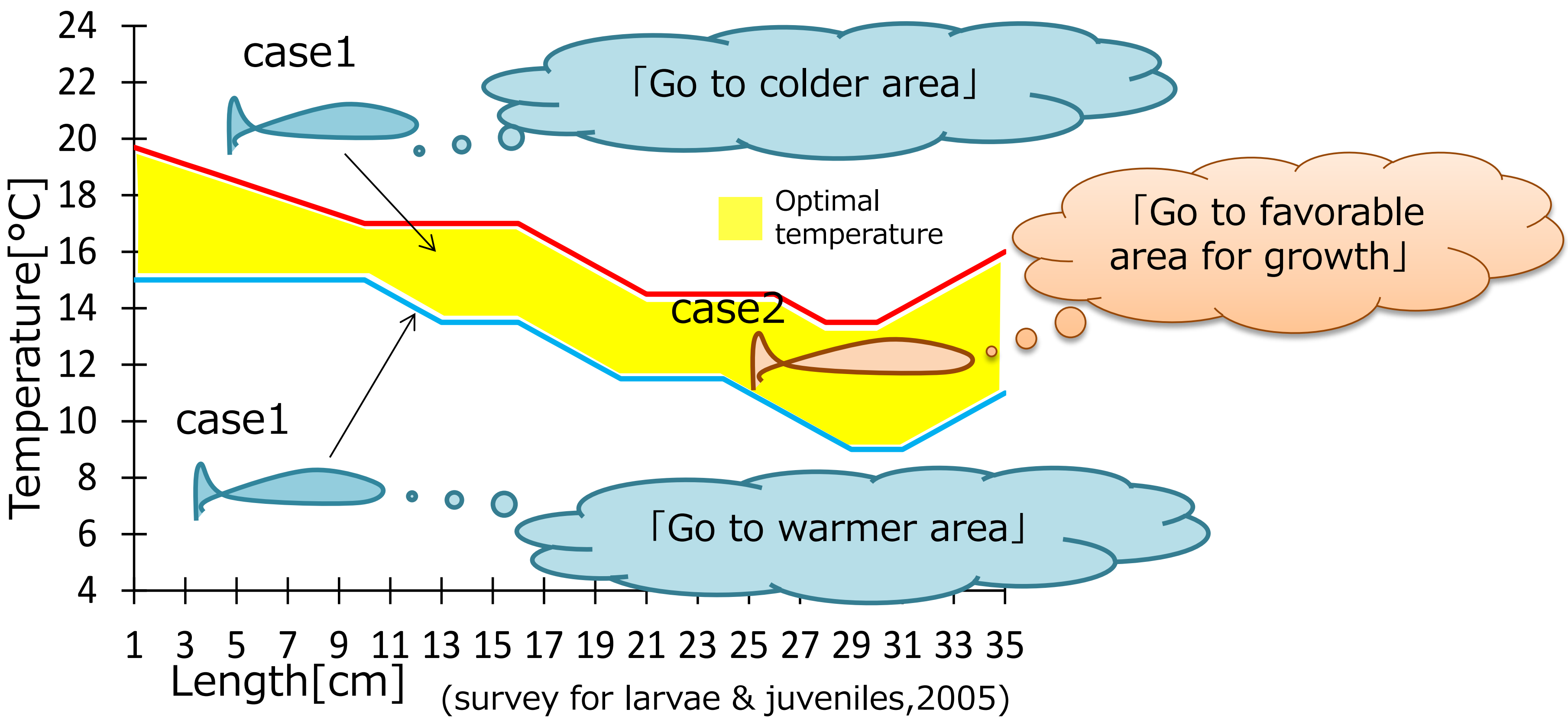
ZS : Small zooplankton (ciliates)
ZL : Large zooplankton (copepods)
ZP : Predatory zooplankton (gelatinous plankton, euphausiids or krill)

Determining direction

- **Setting up swimming direction: (b-1) Feeding migration**

  case1: Out of optimal temperature

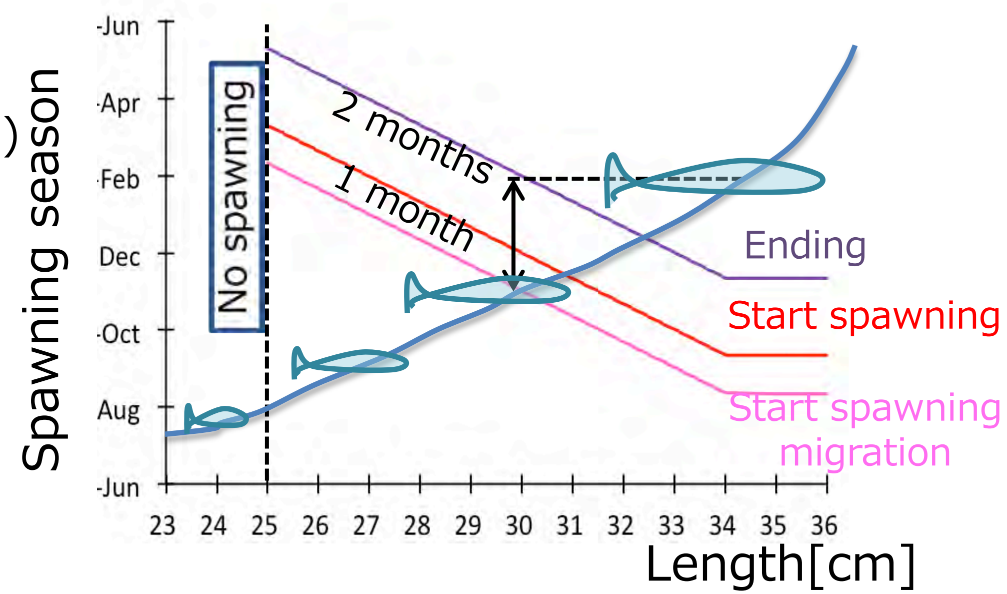
  case2: In optimal temperature

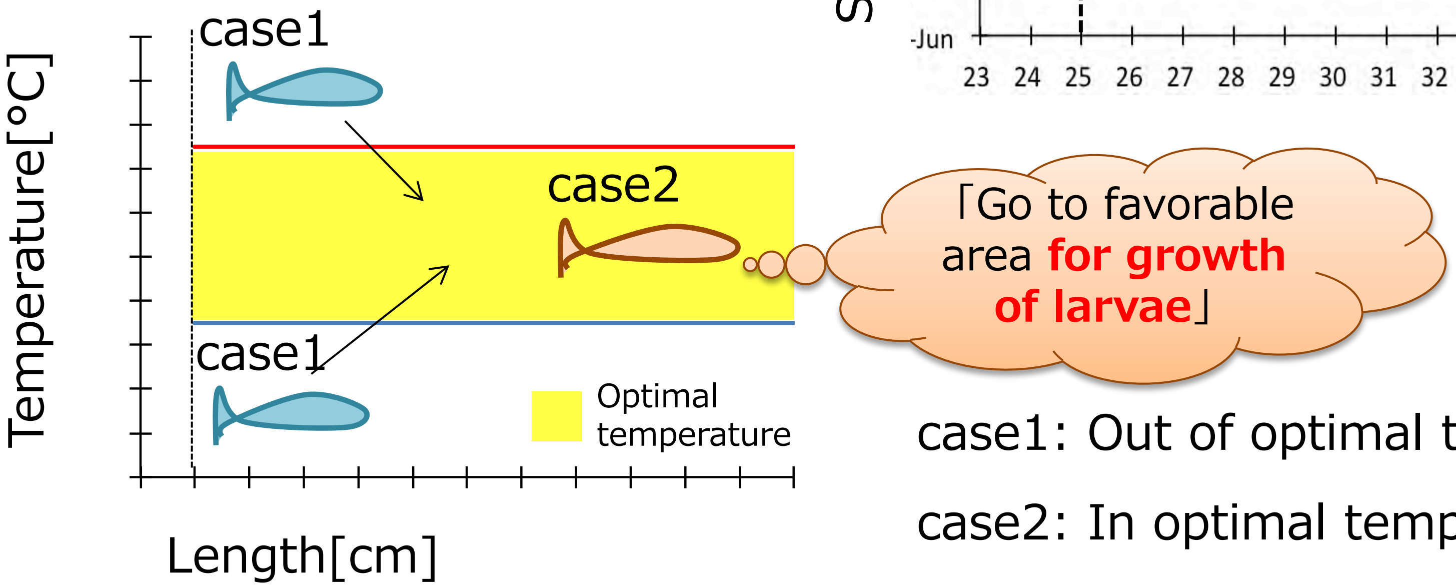


Determining direction

➢ **Setting up swimming direction: (b-2) Spawning migration**

・Set up spawning season
(Mukai et al., 2006)

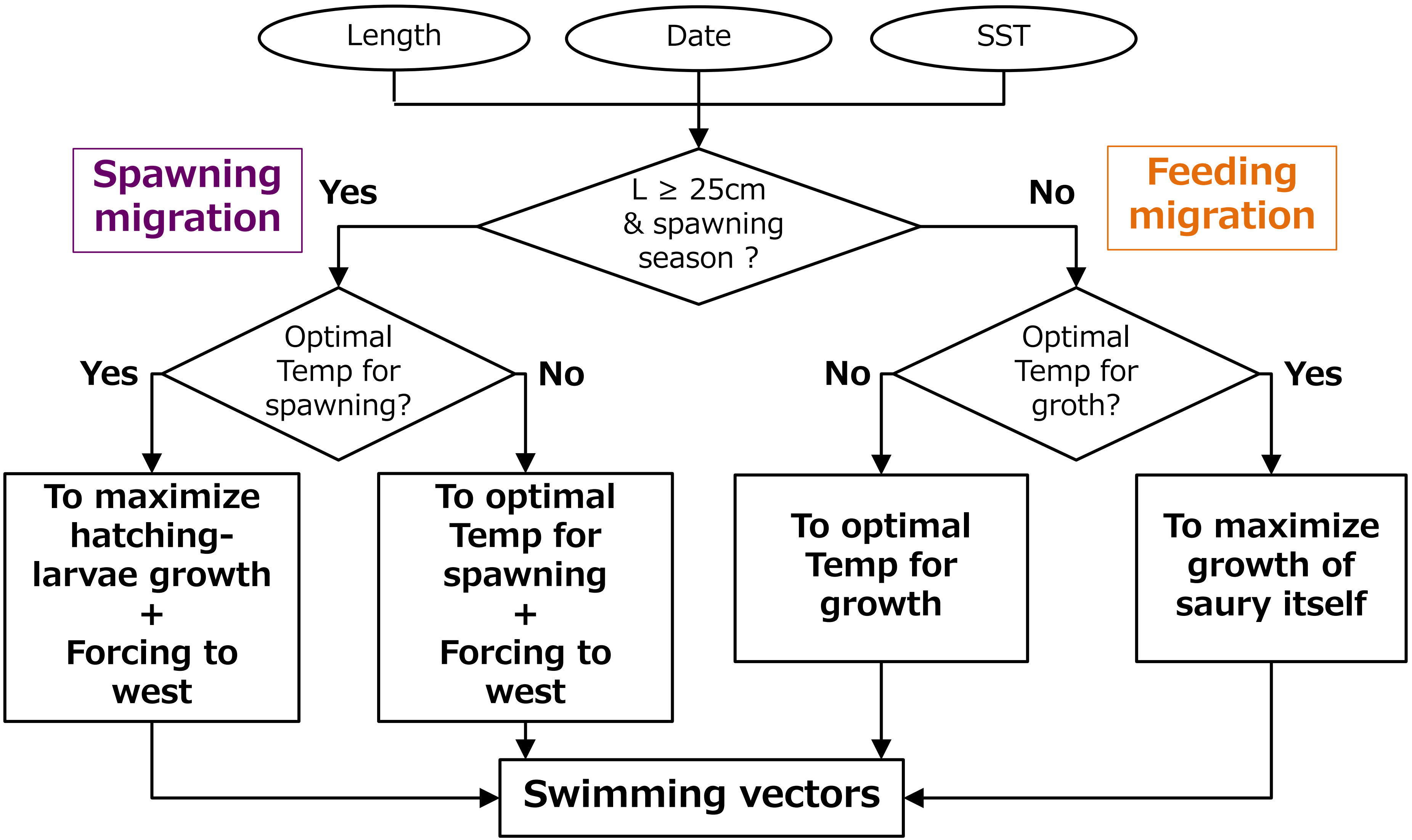




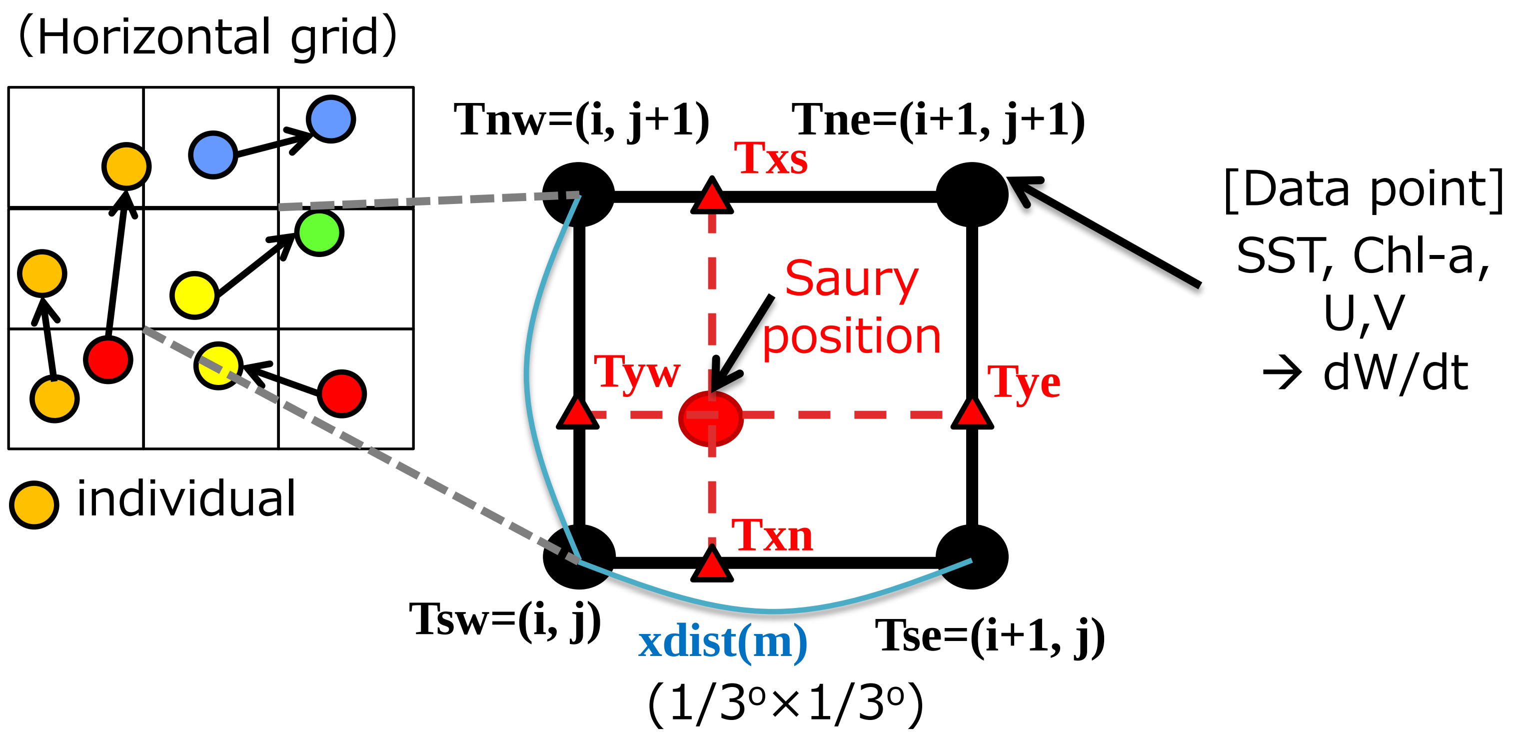
case1: Out of optimal temperature

case2: In optimal temperature

Flowchart of determining direction



spatial interpolation

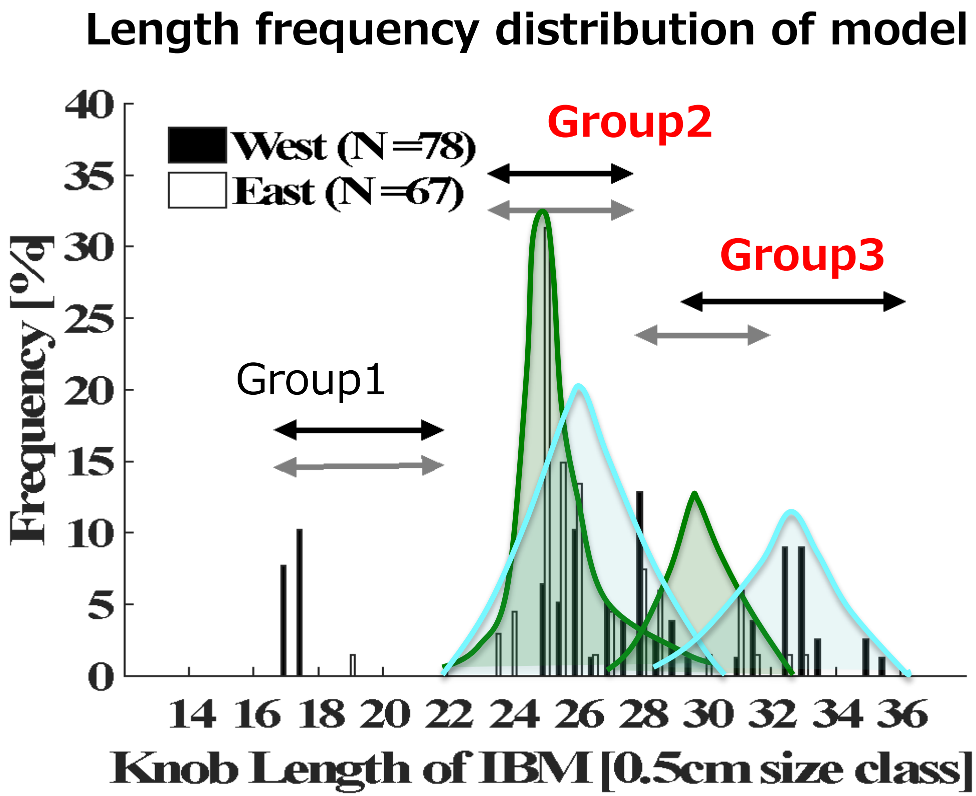


1) Calculate gradient of factors along x-axis & y-axis
1) Convert gradient values to the vectors

   ex = ex / ee (unit vector of x-axis)
   ey = ey / ee (unit vector of y-axis)

3) Swimming velocity = (ex or ey) × speed

Results: Validation



West group (west of 160°E)

Group1: 17≤L<22
Group2: 23≤L<28
Group3: 29≤L<36

East group (east of 160°E)

Group1: 17≤L<22
Group2: 23≤L<28
Group3: 28≤L<32

* Based on length frequency distribution of model, we defined 3 Groups

Basis of parameterization

- Hypothesis on growth & survival:

「Bugger or growing faster individual is better survival」

(Anderson, 1988)

・「Bigger」 → Length (KL) or Weight (W)

・「Growing faster」 → Cumulative growth rate for some days (dW)

(3, 5, 7, 10days)

In addition,

・The direct effects of temperature

・The balance between length & weight

Long length & Low weight

Small length & High weight

- Defined the natural mortality rate

$$M = a \times (W)^b \quad M = a \times \exp(dW) \quad M = a \times \exp(dW \times \frac{1}{W})$$ **etc**

(M: Mortality rate; a,b: coefficient number)

Validation of natural mortality

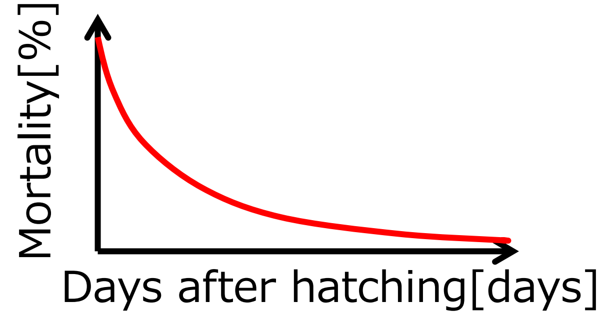
① Determine the form of parameter of natural mortality

Assuming: "Higher mortality rate in earlier life stage"

$$M = a \times (W)^b \qquad M = a \times \exp(dWdt)$$

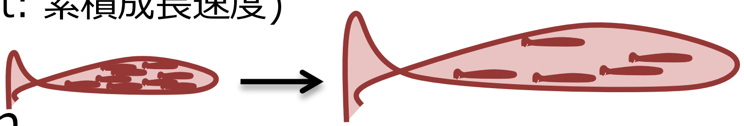
$$M = a \times \exp(dWdt \times \frac{1}{W})$$ **etc**

(M: mortality rate; W: weight;
dWdt: Cumulative growth rate for some days a,b: 定数)



② Calculate the number of age-0 saury in 2004-2012

$$\frac{dN}{dt} = -M \times Nt$$ (M: 死亡率; N:個体数; dWdt: 累積成長速度)



- Egg number / 1 particle : 500 million

③ Examine a correlation between model outputs & observation data

Model : recruitment success index
(Survival numbers of age-0 in Jun / Egg number)

Observation data : RPS (by Fisheries Agency)
(Number of age-0 in next year / spawning biomass in this year)

Goal

Environment

To examine the effects of environmental conditions on the growth.

Growth

To parameterize the natural mortality of saury.

Survival

1) To examine the effects of environmental conditions **on survival through the growth**.
2) To examine the differences of the relationship **between growth and survival in 3 spawning seasons**.

Population dynamics

To study of the effects of environmental conditions **on the population of saury through the growth**

Future works

1) Further parameterizing natural mortality coupling temperature & length

$$M = a \times \exp(dWdt \times \frac{T}{W}) \quad \textbf{etc}$$

In addition to, conduct a sensitivity analysis of these parameters

2) Using the model outputs with high reproducibility, analyze the growth, distribution & growth trajectory at each life stage **to examine the effects of environmental conditions on survival through the growth.**

3) Validate & analyze in case of other season-spawned cohort **to examine differences of the relationship between growth and survival in 3 spawning seasons.**