Takasuka *et al.*
(submitted soon)

Differential optimal temperatures for growth of larval anchovy and sardine: A potential mechanism for regime shifts?

Akinori Takasuka [1], Yoshioki Oozeki [1], Ichiro Aoki [2], Ryo Kimura [3], Hiroshi Kubota [1], Takashi Yamakawa [2]

[1] *National Research Institute of Fisheries Science, Fisheries Research Agency*
[2] *Graduate School of Agricultural and Life Sciences, University of Tokyo*
[3] *Ministry of Agriculture, Forestry and Fisheries*

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Takasuka *et al.*
(submitted soon)

Questions

Preliminary question

Why does a subtle environmental change trigger a drastic fish regime shift?

Key question

Why do anchovy flourish and sardine collapse during the same ocean regime and vice versa?

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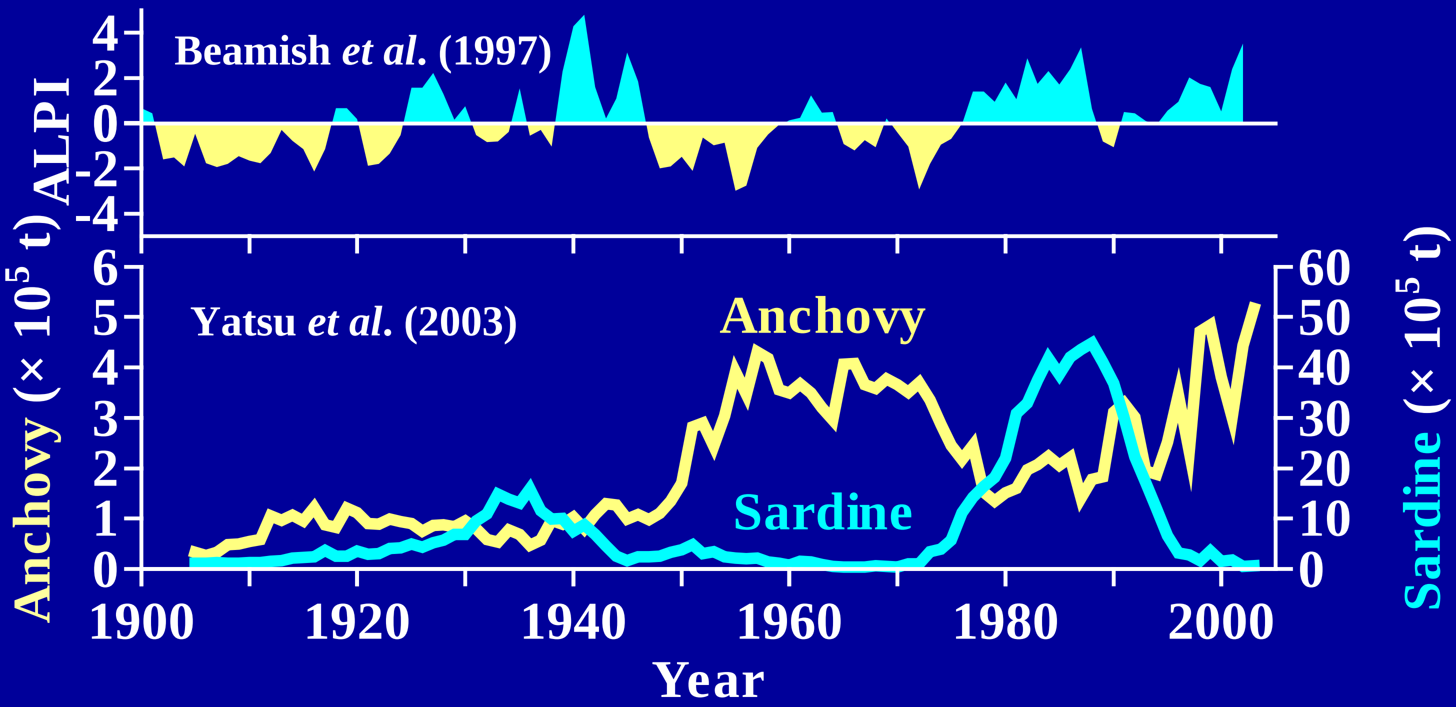
Fish regime shift

Climate and fish regime shift

- Climate impacts fisheries.
- A mystery of the ocean is the out-of-phase stock oscillations between sardine and anchovy.
- 'Fish regime shift' has been attributed to 'ocean regime shift'.



Catch histories of Japanese anchovy *Engraulis japonicus* and Japanese sardine *Sardinops melanostictus*, corresponding to Aleutian low pressure index.

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Climate cascade

Scenario for sardine Noto & Yasuda (1999, 2003), Yasuda *et al.* (1999), Yatsu *et al.* (2003), Nakata & Hidaka (2003), …	Sardine's flourish (Sardine regime)	Sardine's collapse (Anchovy regime)
Aleutian low pressure (in winter)	Intensified	Weakened
Sea surface temperature (in the Kuroshio Extension region)	Lower	Higher
	Cool	*Warm*
Mixed layer (in the Kuroshio Extension region)	Deeper	Shallower
Primary production	Higher	Lower
Zooplankton biomass	Higher	Lower
Food availability for larvae	Higher	Lower
Larval survival rate	Higher	Lower
Recruitment	Success	Failure
Stock of sardine	Flourish	Collapse

Physical process

Biological process

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Questions

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Growth–survival

‘Growth–survival’ paradigm during early life stages

- **‘Growth–mortality’ hypothesis (Anderson 1988)**
- **Faster growing larvae are more likely to survive in the sea.**

Three growth-related mechanisms

- **‘Bigger is better’ hypothesis (Miller *et al*. 1988)**
  Size: negative size-selective mortality
- **‘Stage duration’ hypothesis (Chambers & Leggett 1987, Houde 1987)**
  Time: high mortality larval stage duration
- **‘Growth-selective predation’ hypothesis (Takasuka *et al*. 2003, 2004)**
  Growth rate (*per se*): direct impacts on vulnerability to predation

In theory, …

- **These are independent of and synergistic with one another.**
- **Even subtle variations in growth rates potentially cause extreme fluctuations in survival probability and recruitment.**

Climate cascade

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(submitted soon)

Scenario for sardine Noto & Yasuda (1999, 2003), Yasuda *et al.* (1999), Yatsu *et al.* (2003), Nakata & Hidaka (2003), …	Sardine's flourish (Sardine regime)	Sardine's collapse (Anchovy regime)
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Food availability for larvae		
Growth rate		
Larval survival rate		
Recruitment	Success	Failure
Stock of sardine	Flourish	Collapse

Physical process

Biological process

Amplifier

'Growth–survival' paradigm

- 'Bigger is better'
- 'Stage duration'
- 'Growth-selective predation'

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Objectives

Relationship between growth rates during early life history stages and sea temperature was examined for Japanese anchovy and Japanese sardine.

Engraulis japonicus VS *Sardinops melanostictus*

'Growth-optimal temperature' hypothesis:
A potential mechanism for fish regime shift?

Takasuka *et al.*
(submitted soon)

Materials and Methods

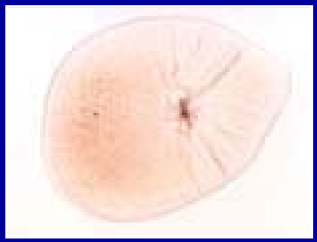
Samples

- **Larval Japanese anchovy *Engraulis japonicus***

  - A portion of samples are identical to those in the previous studies: Aoki & Miyashita (2000), Takasuka & Aoki (2002), Takasuka *et al*. (2003, 2004, 2004), Takasuka & Aoki (in review)

- **Larval Japanese sardine *Sardinops melanostictus***

  - A portion of samples are identical to those in the previous study: Oozeki & Zenitani (1996)
  - Supplemented by Hiroya Sugisaki (Tohoku National Fisheries Research Institute)



Growth rates

- **Sagittal otolith microstructure analysis**
- **Recent 3 day mean growth rates directly before capture**
- **Back-calculation by the biological intercept method**

Relationship between recent growth rates and sea surface temperature at the time of capture

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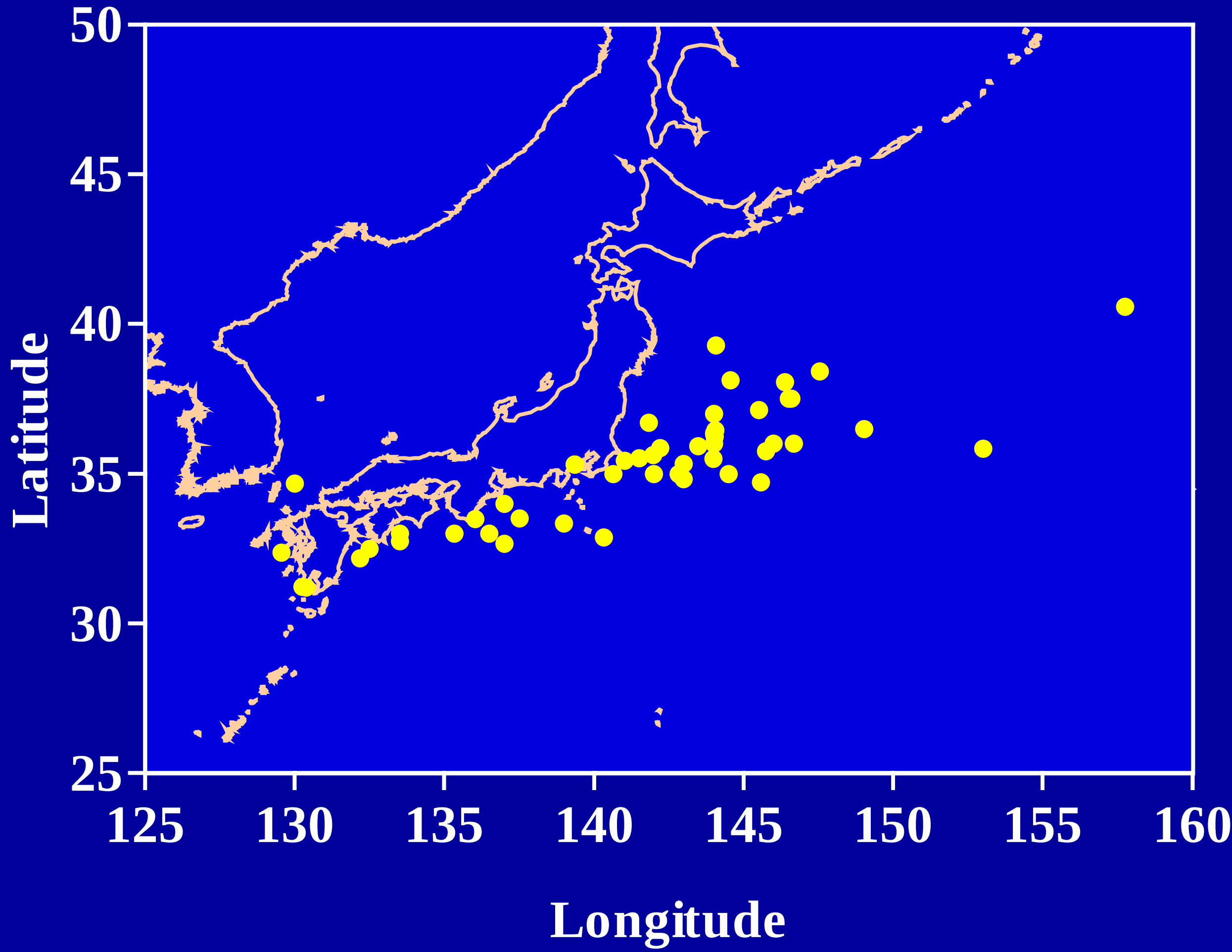
Samples

50 stations in total, 1990–2004



Larval anchovy

- All seasons
- 34 samples
- 2041 larvae
- 6–35 mm SL

Larval sardine

- Jan.–Jun.
- 30 samples
- 766 larvae
- 8–35 mm SL

Sampling areas and stations for larval Japanese anchovy and Japanese sardine.

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Materials and Methods

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- **A portion of samples are identical to those in the previous studies: Aoki & Miyashita (2000), Takasuka & Aoki (2002), Takasuka *et al*. (2003, 2004, 2004), Takasuka & Aoki (in review)**

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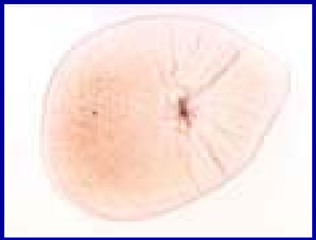

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Takasuka *et al.*
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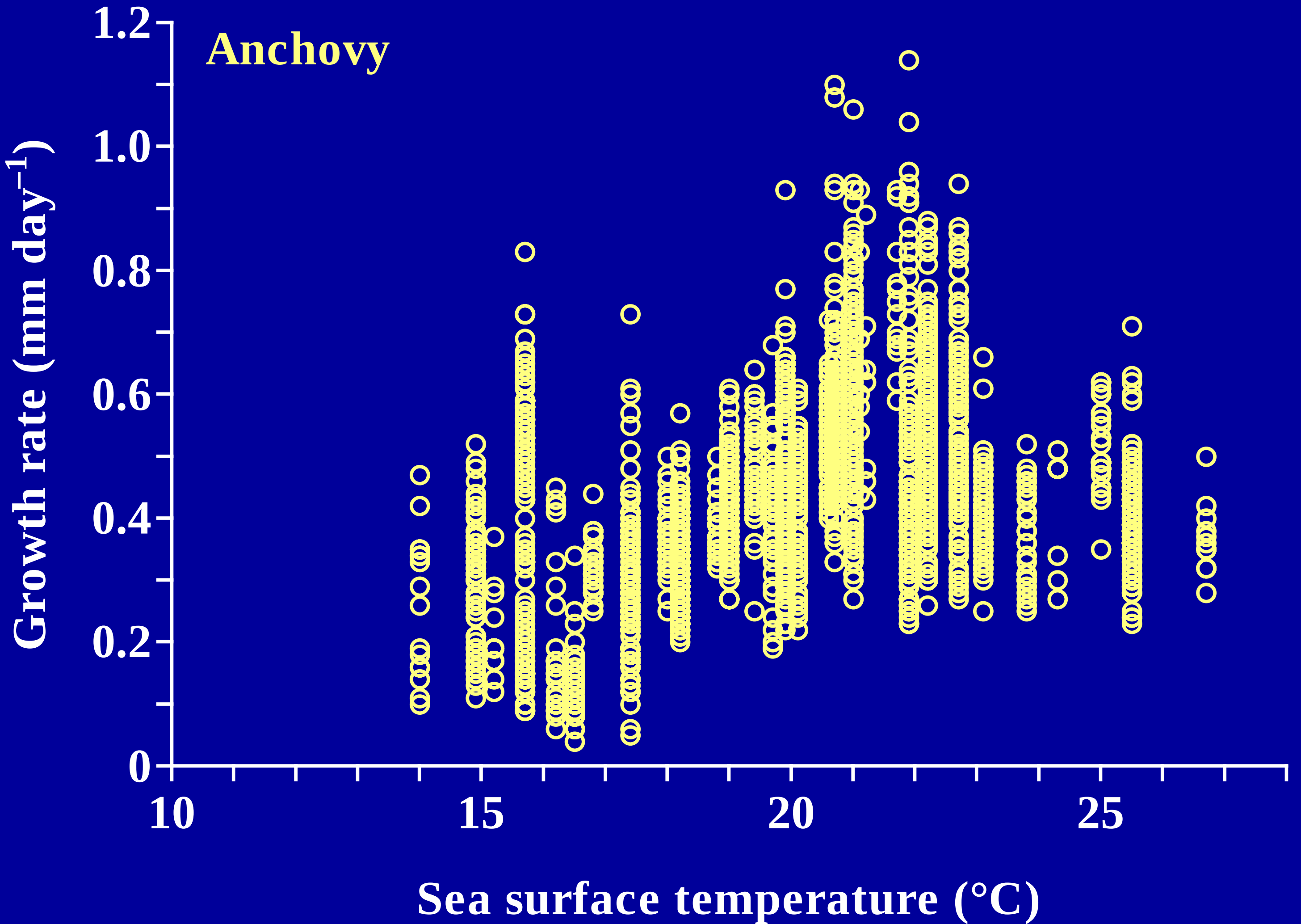
Growth–SST for anchovy



Relationship between recent 3 day mean growth rates and sea surface temperature for larval Japanese anchovy.

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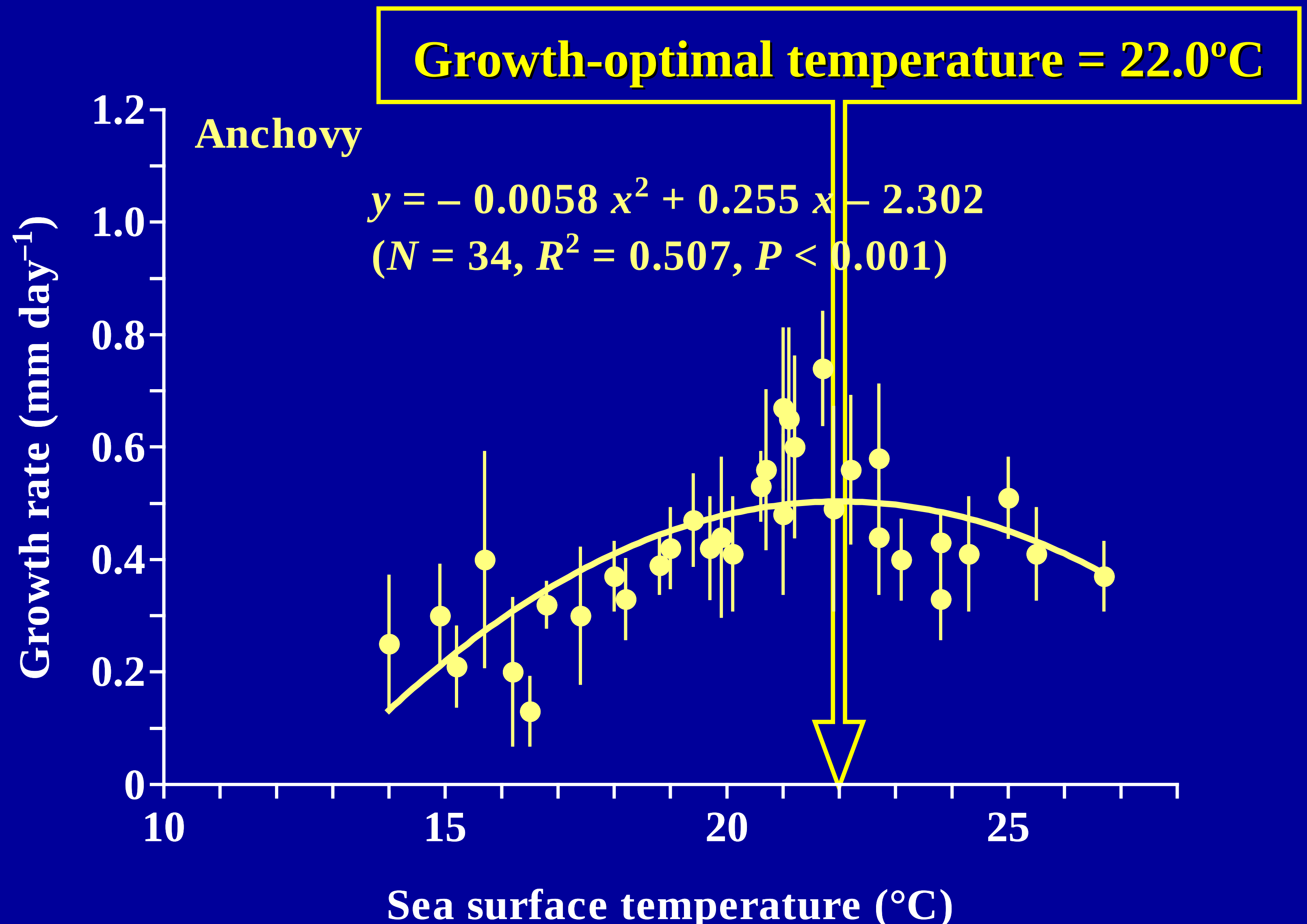
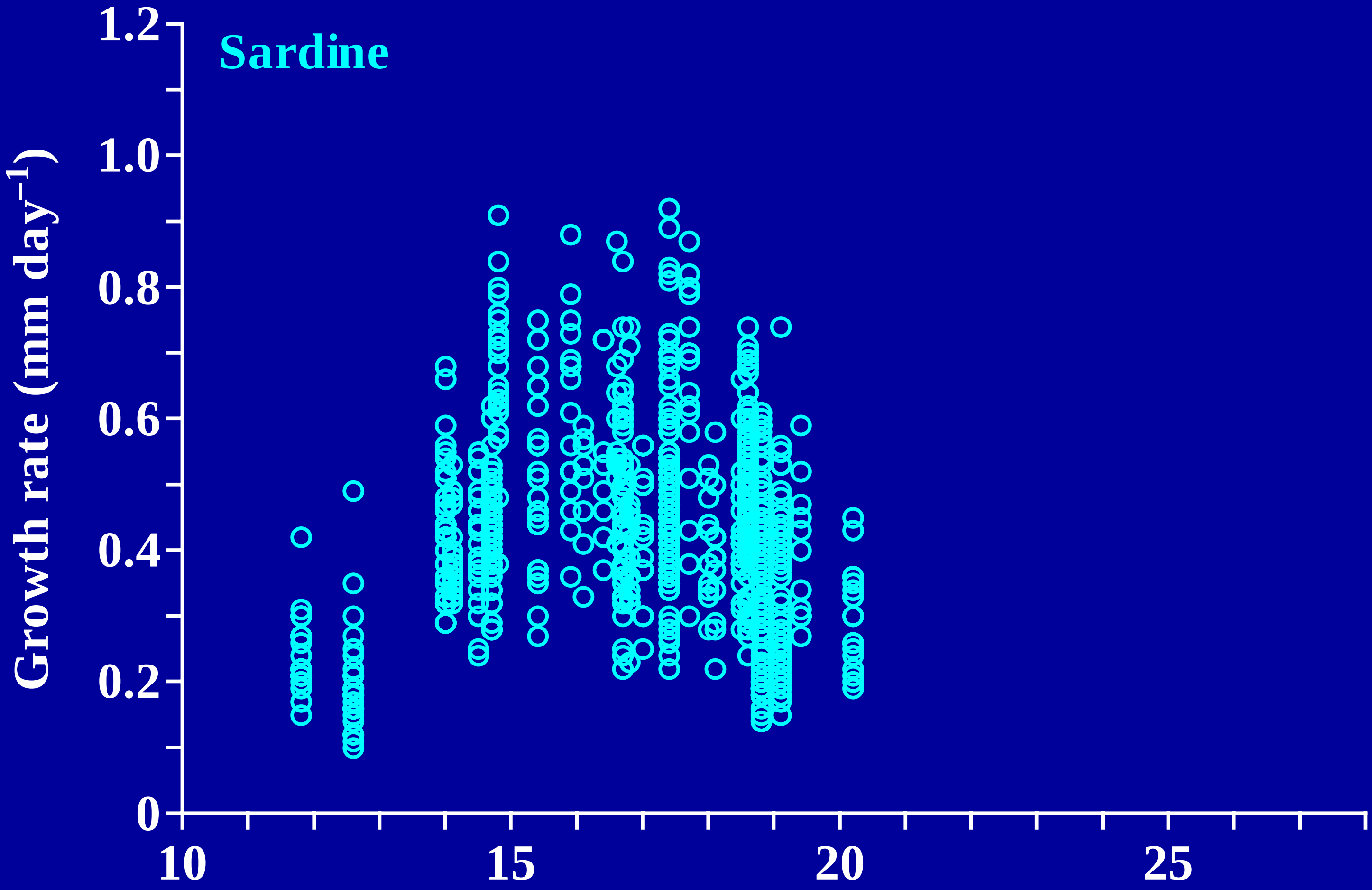
Growth–SST for anchovy



Relationship between recent 3 day mean growth rates and sea surface temperature for larval Japanese anchovy.

Takasuka *et al.*
(submitted soon)

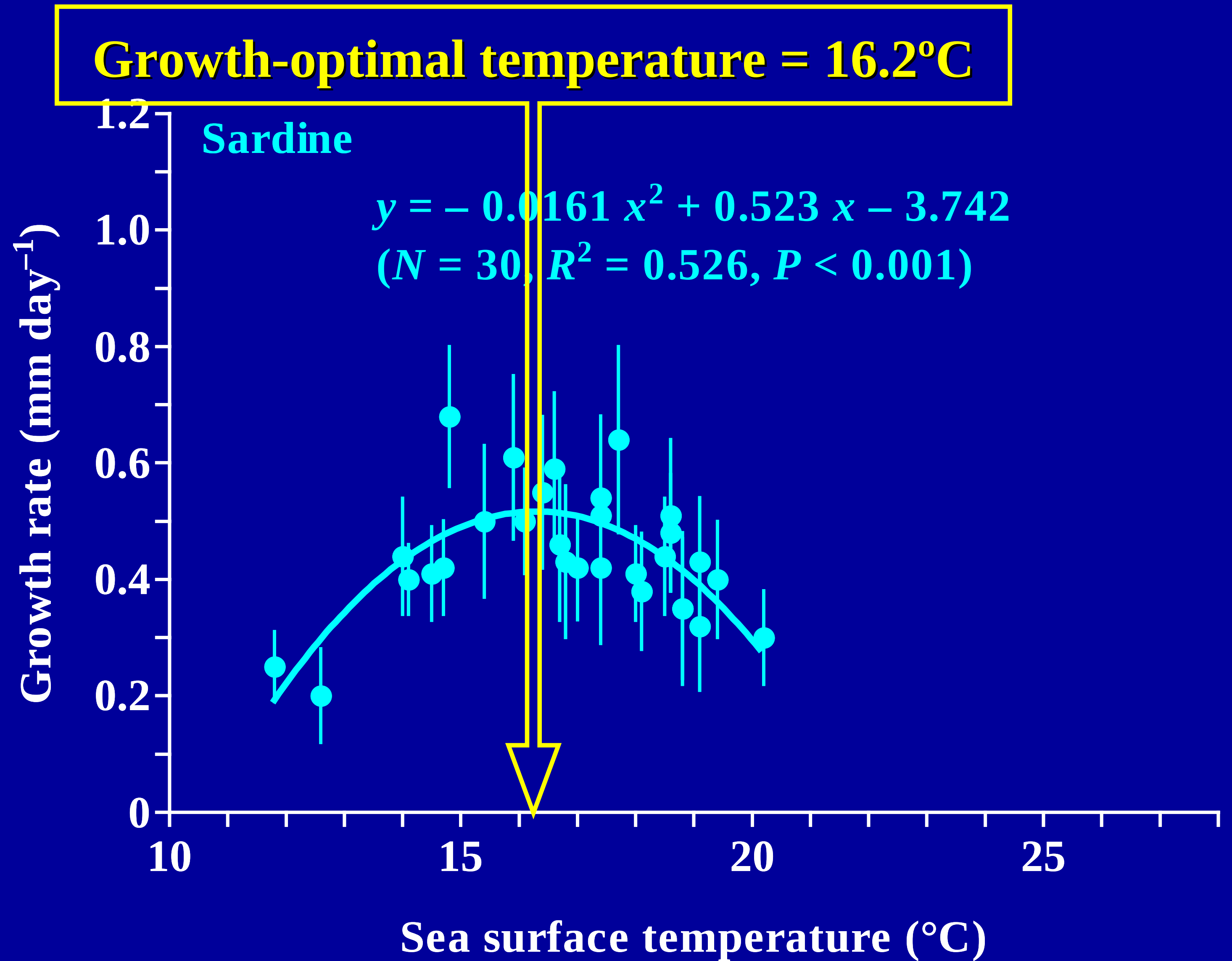
Growth–SST for sardine



Relationship between recent 3 day mean growth rates and sea surface temperature for larval Japanese sardine.

Takasuka *et al.* (submitted soon)

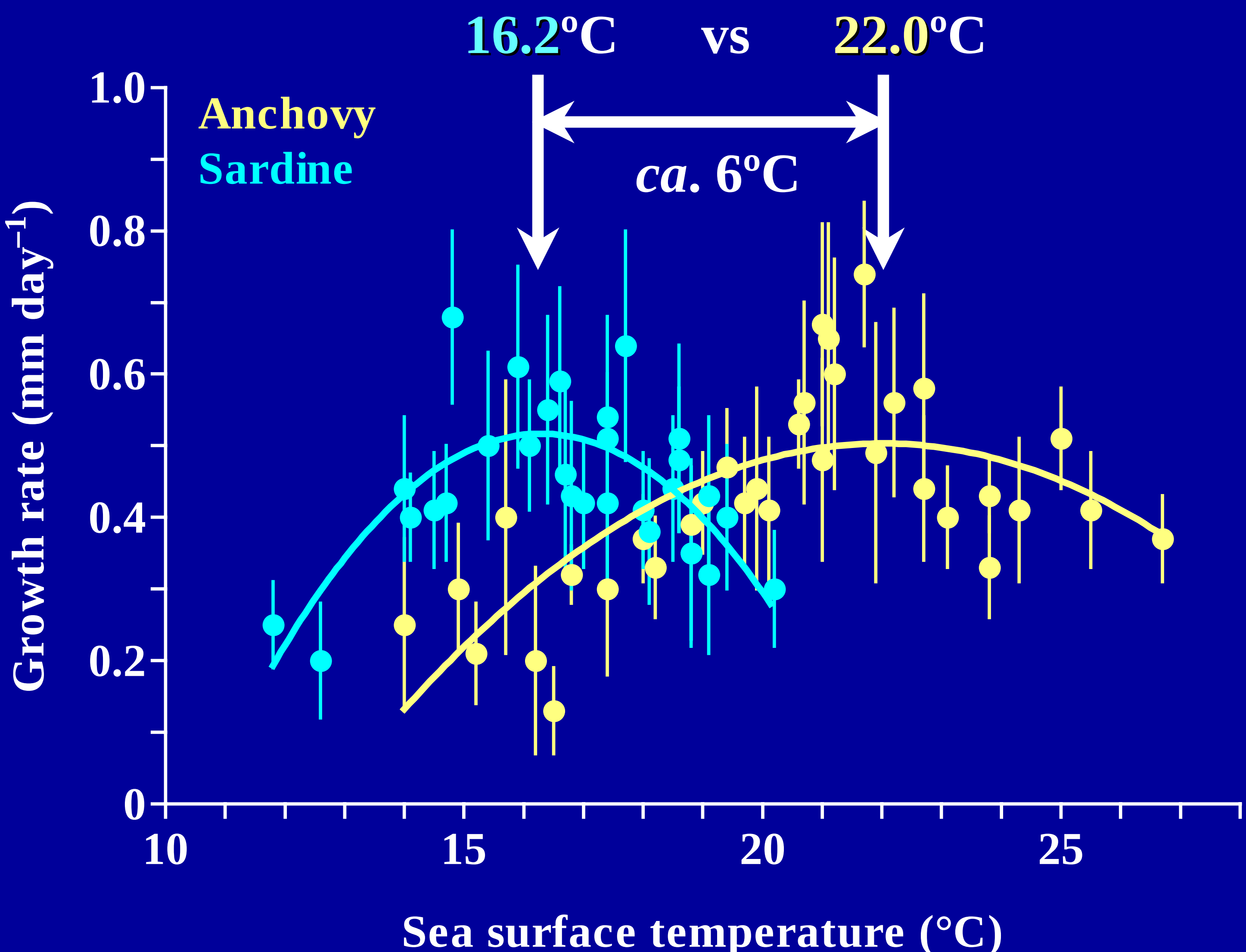
Growth–SST for sardine



Relationship between recent 3 day mean growth rates and sea surface temperature for larval Japanese sardine.

Takasuka *et al.*
(submitted soon)

Anchovy vs Sardine



Relationship between recent 3 day mean growth rates and sea surface temperature for larval anchovy and sardine.

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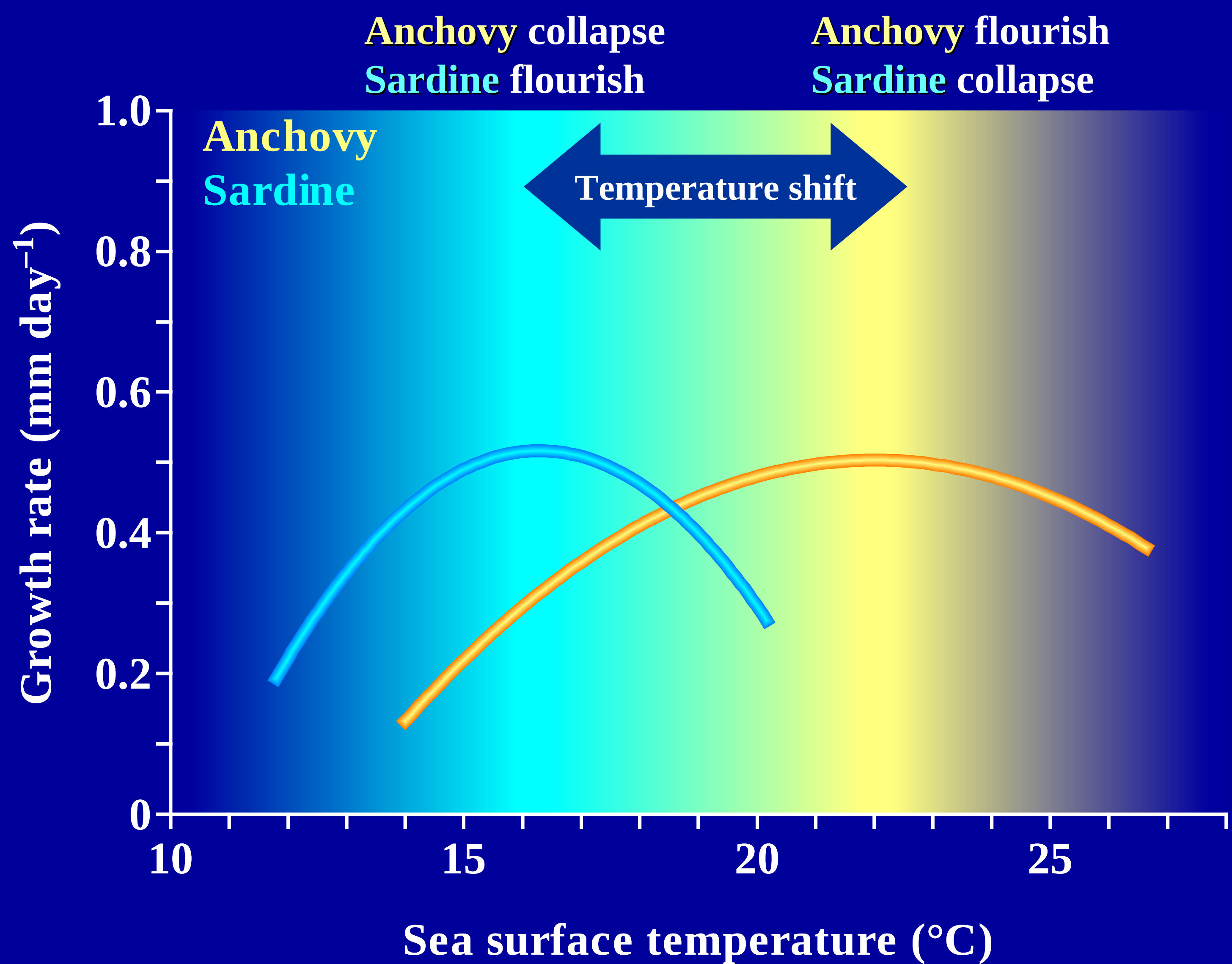
(submitted soon)

Mechanism



Conceptual framework of a potential mechanism for fish regime shift by the differential growth-optimal temperatures.

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(submitted soon)

Issues raised

In summary, …

- In the western North Pacific, the warm anchovy regime has shifted to the cool sardine regime and back (e.g. McFarlane, *et al.* 2002).
- Differential optimal temperatures for larval growth rates can explain the fish regime shift at least theoretically, if they experience exactly the same environments.

However, …

- The spawning seasons differ between anchovy and sardine.
- The SST ranges differed in the present samples.

What temperatures are they likely to experience?

Is the difference in growth-optimal temperatures (*ca*. 6°C) really significant?

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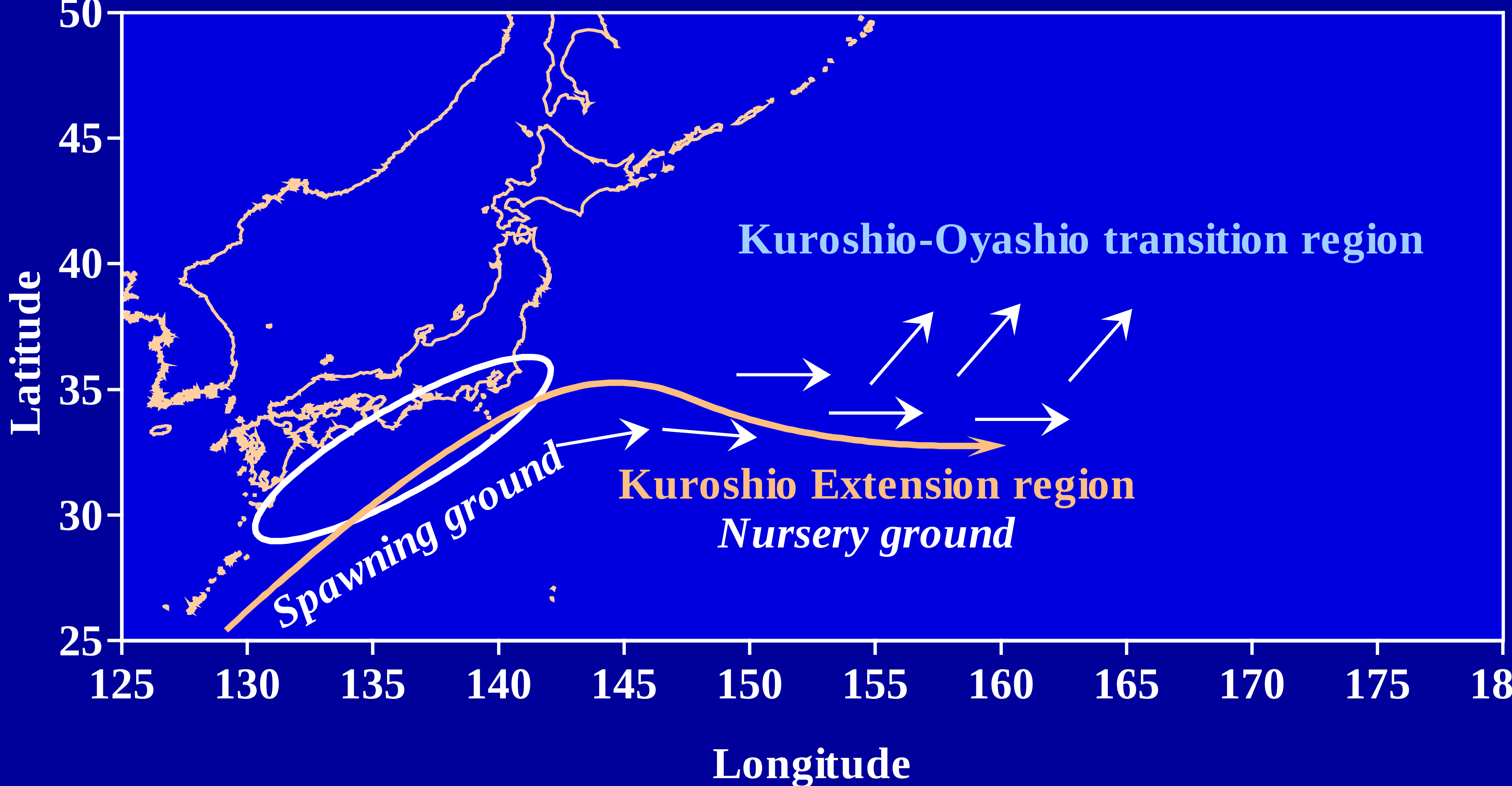
General early life history



Conceptual diagram of the general pattern of spawning ground, transport and migration for anchovy and sardine.

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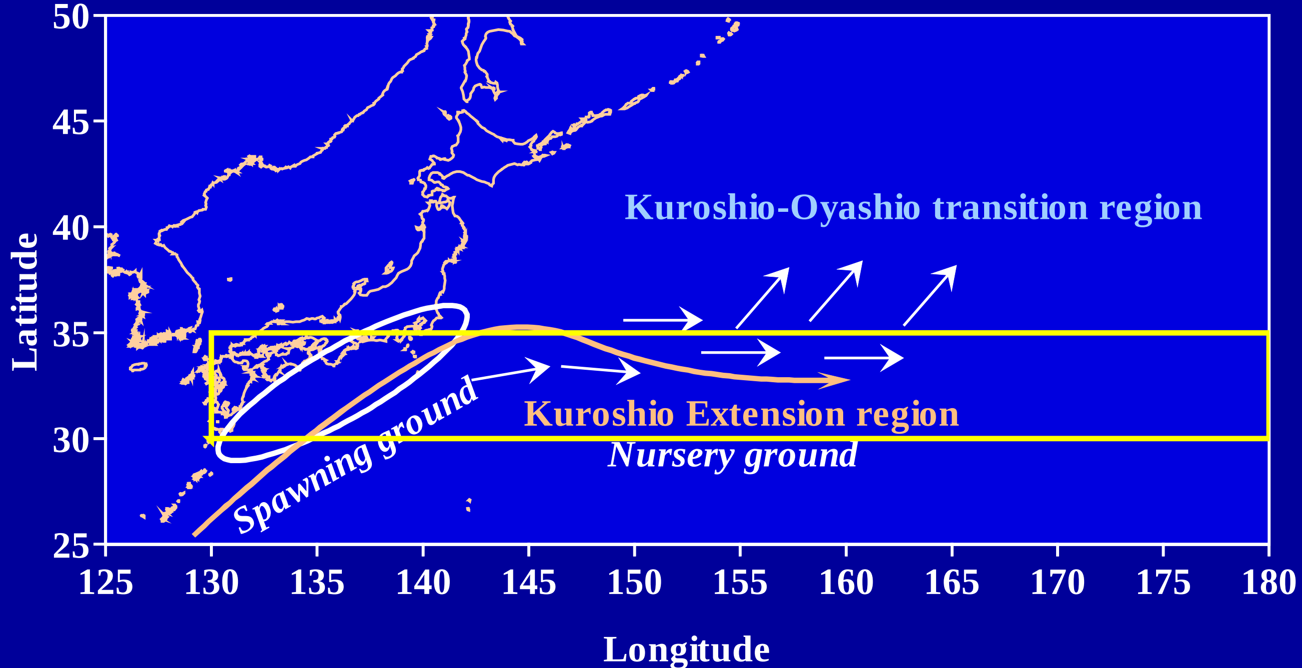
(submitted soon)

Sea surface temperature

Nursery ground

- *Consideration*: Offshore transport
  Different peaks of hatching
- *Assumption*: Spawning seasons are invariable annually.
  Larvae are transported physically.
- **Mean SST in the Kuroshio Extension region (30–35ºN, 130–180ºE)** (prepared by Tomowo Watanabe)



30–35ºN
130–180ºE

Larval anchovy
- Apr.–May

Larval sardine
- Feb.–Mar.

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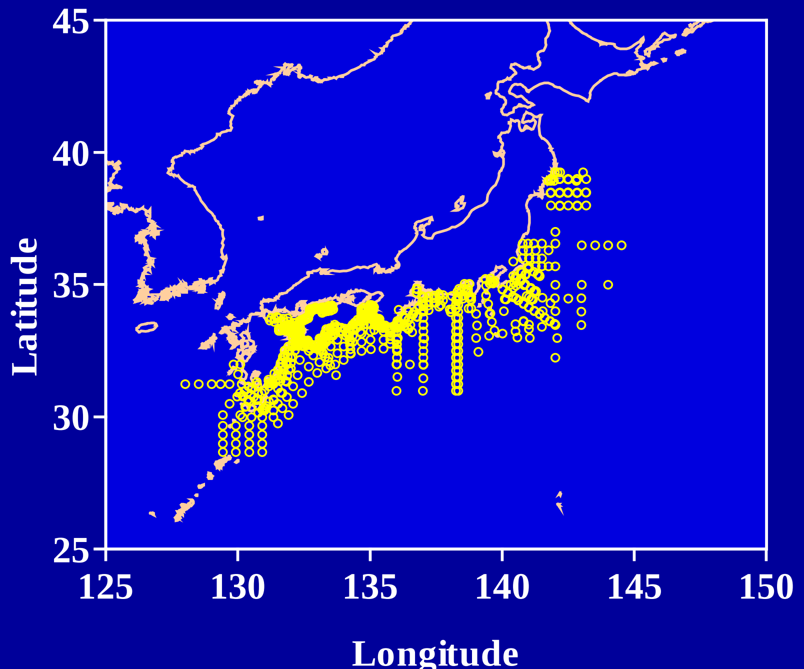
Sea surface temperature

Spawning ground

- *Consideration*: Temporal and spatial dynamics of the SST at the time of hatching
- *Assumption*: Temperatures in the spawning ground regulate growth rates after hatching.
- **Egg-density-weighted mean SST** from a newly developed database.



Egg sampling

Larval anchovy
Larval sardine

- All seasons
- All stations
- Annual mean

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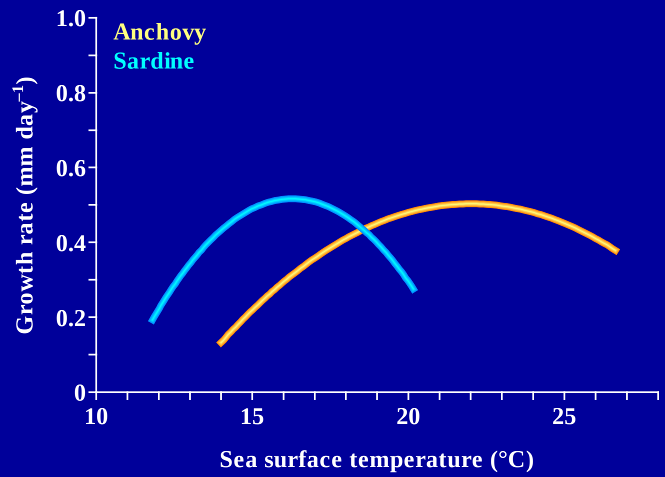
Retrospective test

Growth rate conversion

- Larval growth rates were converted from SST data, using the growth–SST relationships, for anchovy and sardine.
- Temporal shifts of the converted growth rates were compared with Catch history data and RPS data.



Time series data

- Catch history (1905–2003) (arranged by Akihiko Yatsu)
- Recruitment per spawning biomass (RPS) (1976–2003)

(from the stock assessment reports)

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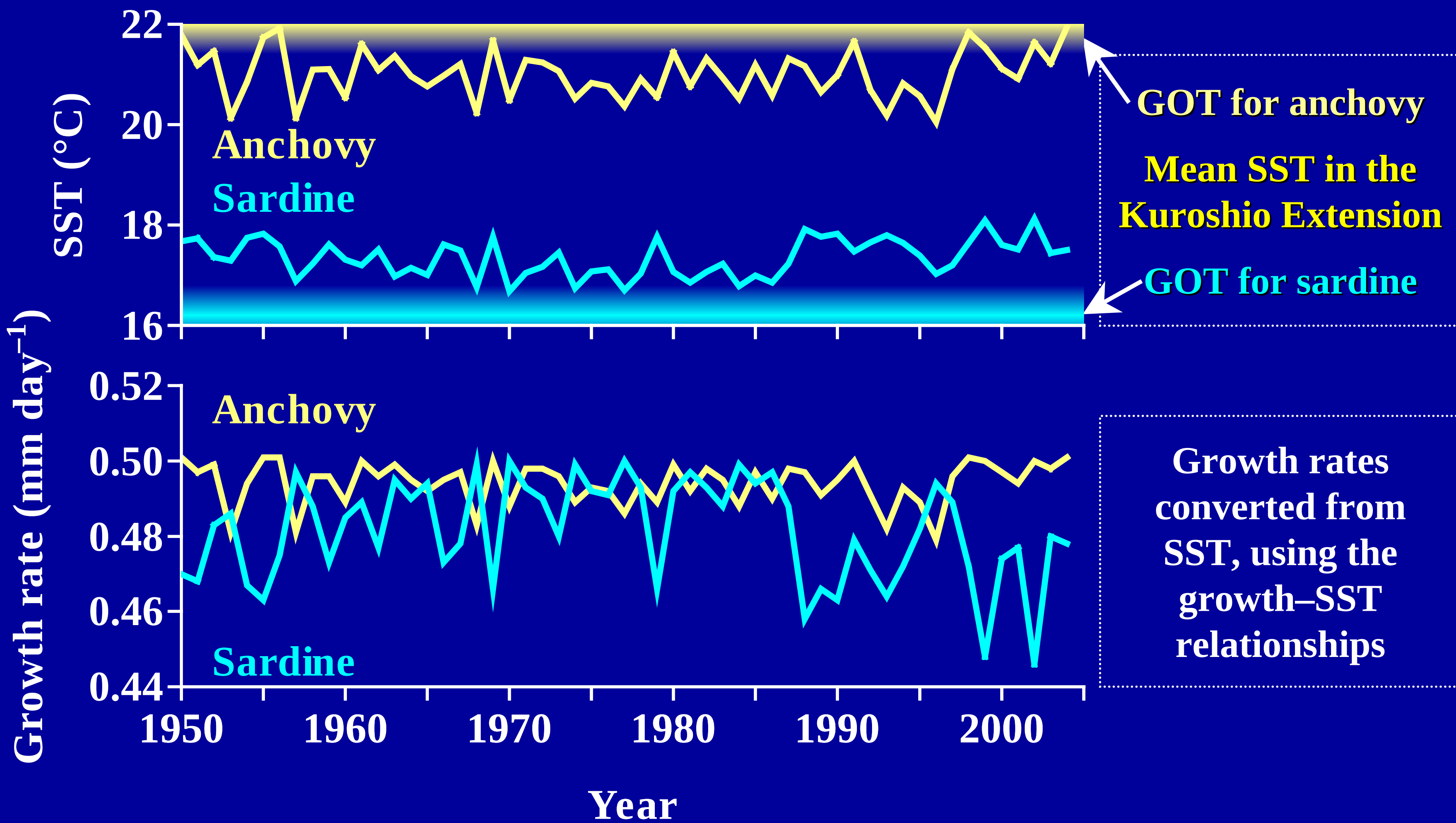
Nursery ground



Mean SST in the Kuroshio Extension region and the converted growth rates for larval anchovy and sardine.

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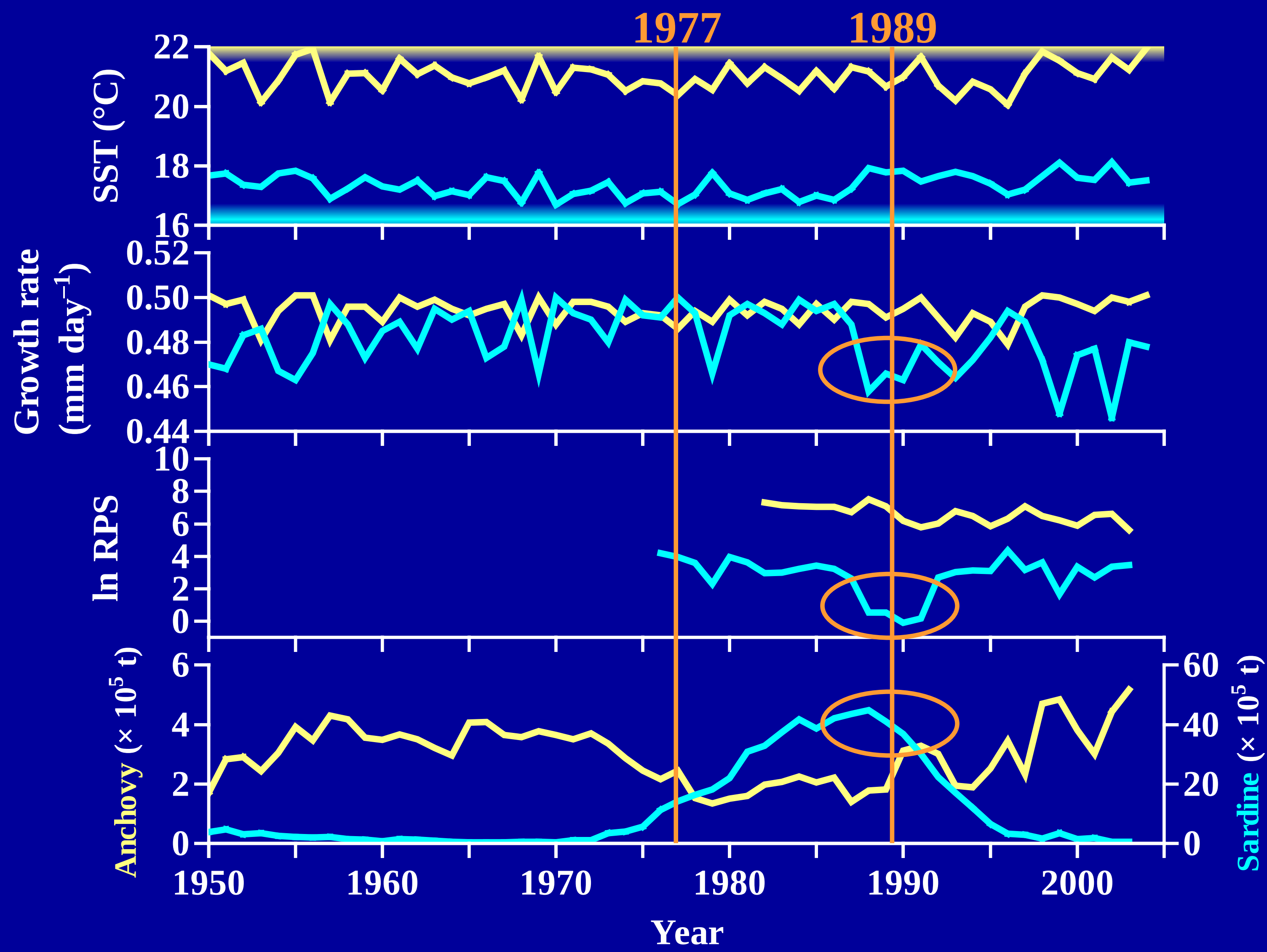
(submitted soon)

Time series data



Times series data of mean SST in the Kuroshio Extension region, larval growth rates converted from SST, RPS and catch history for anchovy and sardine.

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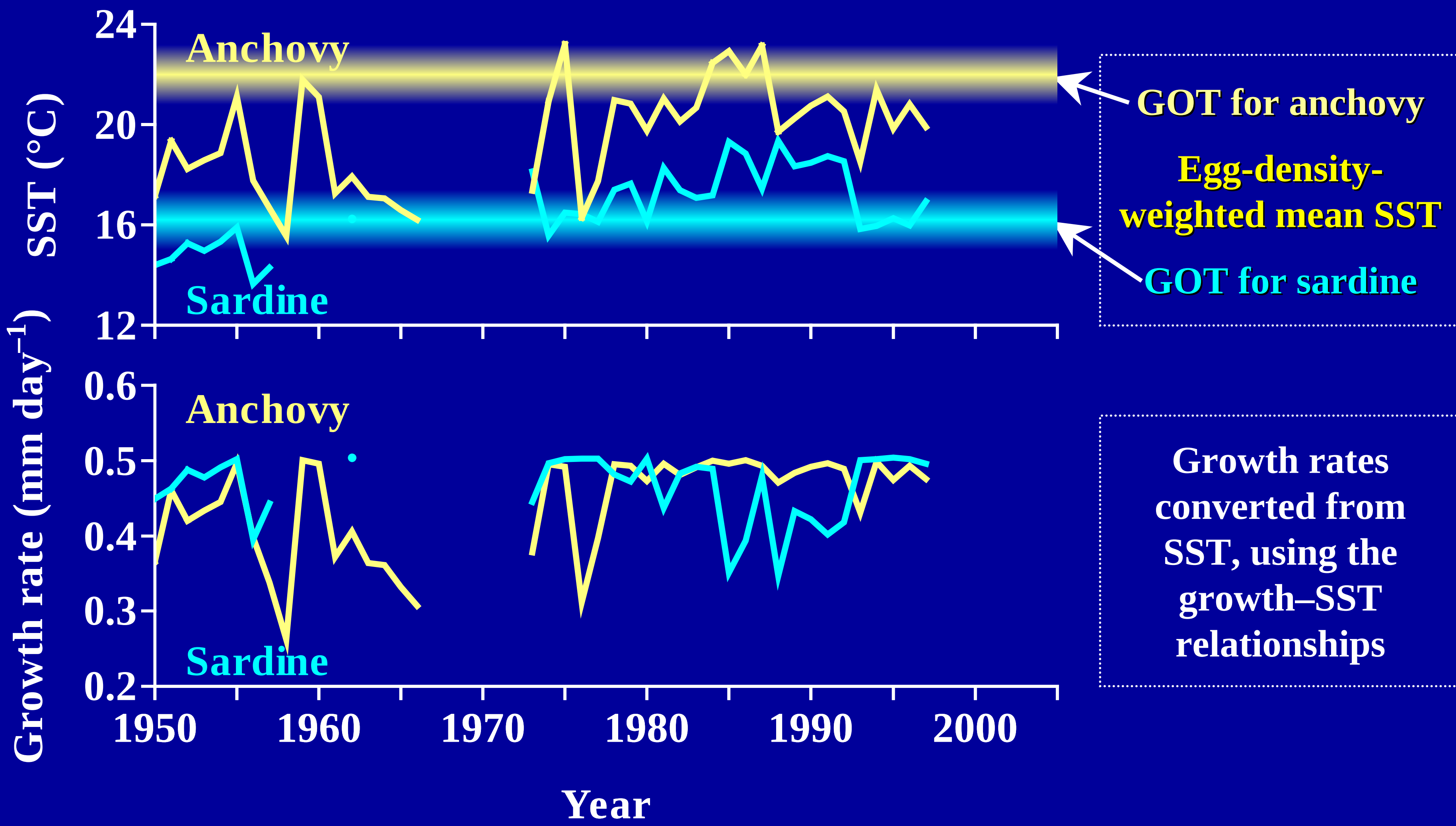
(submitted soon)

Spawning ground



Egg-density-weighted mean sea surface temperature and the converted growth rates for larval anchovy and sardine.

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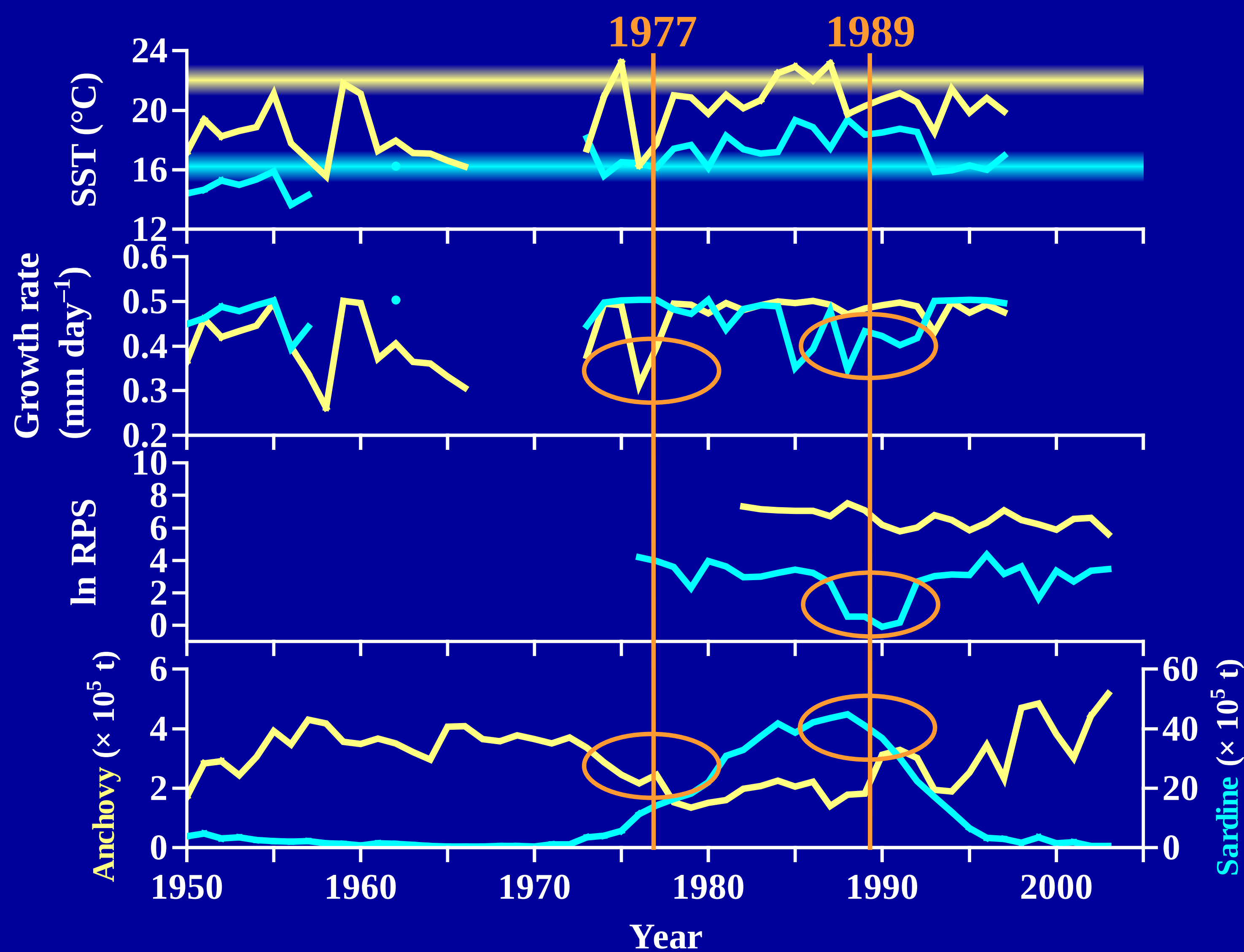
(submitted soon)

Time series data



Times series data of egg-density-weighted mean SST, larval growth rates converted from SST, RPS and catch history for anchovy and sardine.

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(submitted soon)

Preliminary question

Why does a subtle environmental change trigger a drastic fish regime shift?

Theoretical solution

- **The ‘growth–survival’ paradigm has been incorporated into the the ‘climate cascade’.**
- **Even a subtle temperature shift potentially trigger a drastic fish regime shift.**
- **The growth-related mechanisms serve as an amplifier.**

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Key question

Why do anchovy flourish and sardine collapse during the same ocean regime and vice versa?

Differential optimal temperatures for larval growth rates

- **Differential optimal temperatures for growth rates were demonstrated between larval Japanese anchovy (22ºC) and larval Japanese sardine (16ºC).**
- **Temperatures which larvae are assumed to experience have fluctuated mainly between 16 and 22ºC.**
- **Temporal shifts of the growth rates converted from such temperatures seemed to correspond to fish regime shifts at least to some extent.**

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Hypothesis proposed

'Growth-optimal temperature' hypothesis

- Potential biological mechanism for fish regime shift
- The theory is independent of and synergistic with the existing hypotheses.

I. 'Growth–survival' paradigm
II. Direct temperature impacts
III. Differential growth-optimal temperatures

A possibility of collaboration:
Reversed growth-optimal temperatures in the eastern North Pacific?
East meets West in the fish regime shift?

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(submitted soon)

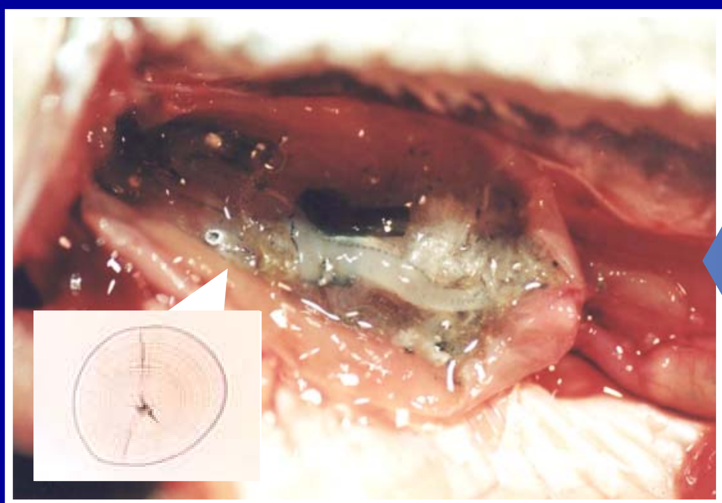
PICES XI in China

Is a slower growing larval Japanese anchovy actually removed by predation at a given moment in the sea?

(Takasuka *et al*. 2003, 2004, 2004)

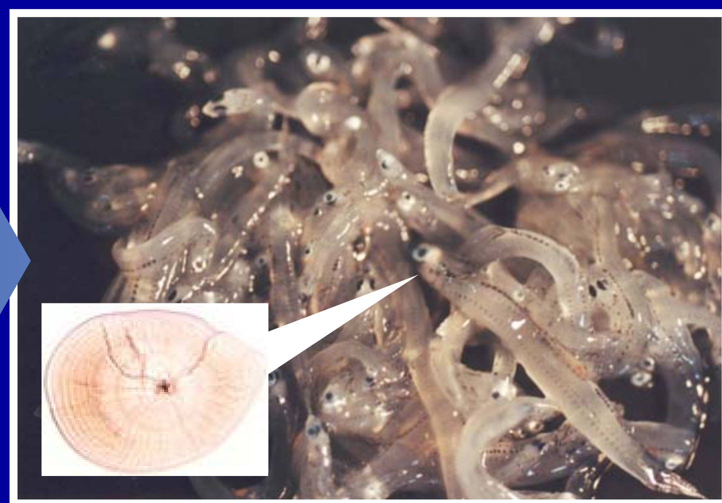
- **Growth rates were compared between the larvae dissected from the stomach contents of the predators and the larvae captured simultaneously with the predators.**

Ingested larvae



Comparison

Surviving larvae



- **The ingested larvae had lower growth rates than the surviving larvae even at the same size at a given moment in the sea.**

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Growth–survival

How strongly do growth rates influence survival?

Functional mechanisms of the paradigm

‘Bigger is better’ (but we know ‘bigger is not always better’)

- **In specific conditions, the selection is intensive.**

‘Stage duration’

- **Simulation studies by Houde (1987, 1989) suggested that 0.2–0.3 mm day^{-1} growth variation can cause over 100-fold survival probability (accumulated effects).**

‘Growth-selective predation’

- **Our previous studies and preliminary analysis suggested that declines in growth rates can lead to 2–5 times vulnerability to predation (at maximum) at a given moment.**

- **Predation is the primary and direct source of mortality.**
- **All of the mechanisms should be predator-specific.**
- **Substantial quantitative data will be required.**

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(submitted soon)

Incidental question

Why does the stock of sardine fluctuate greater than that of anchovy?

Response of growth rates to temperature

- **Responses of growth rates to sea temperature seemed drastic for larval sardine and moderate for larval anchovy.**
- **Larval sardine may be more susceptible to temperature shift than larval anchovy.**
- **This seems consistent with the fact that the stock of sardine has fluctuated about 10-fold greater than that of anchovy around Japan.**

- **Further studies will be required to prove the above.**
- **Are differences in longevity more important?**

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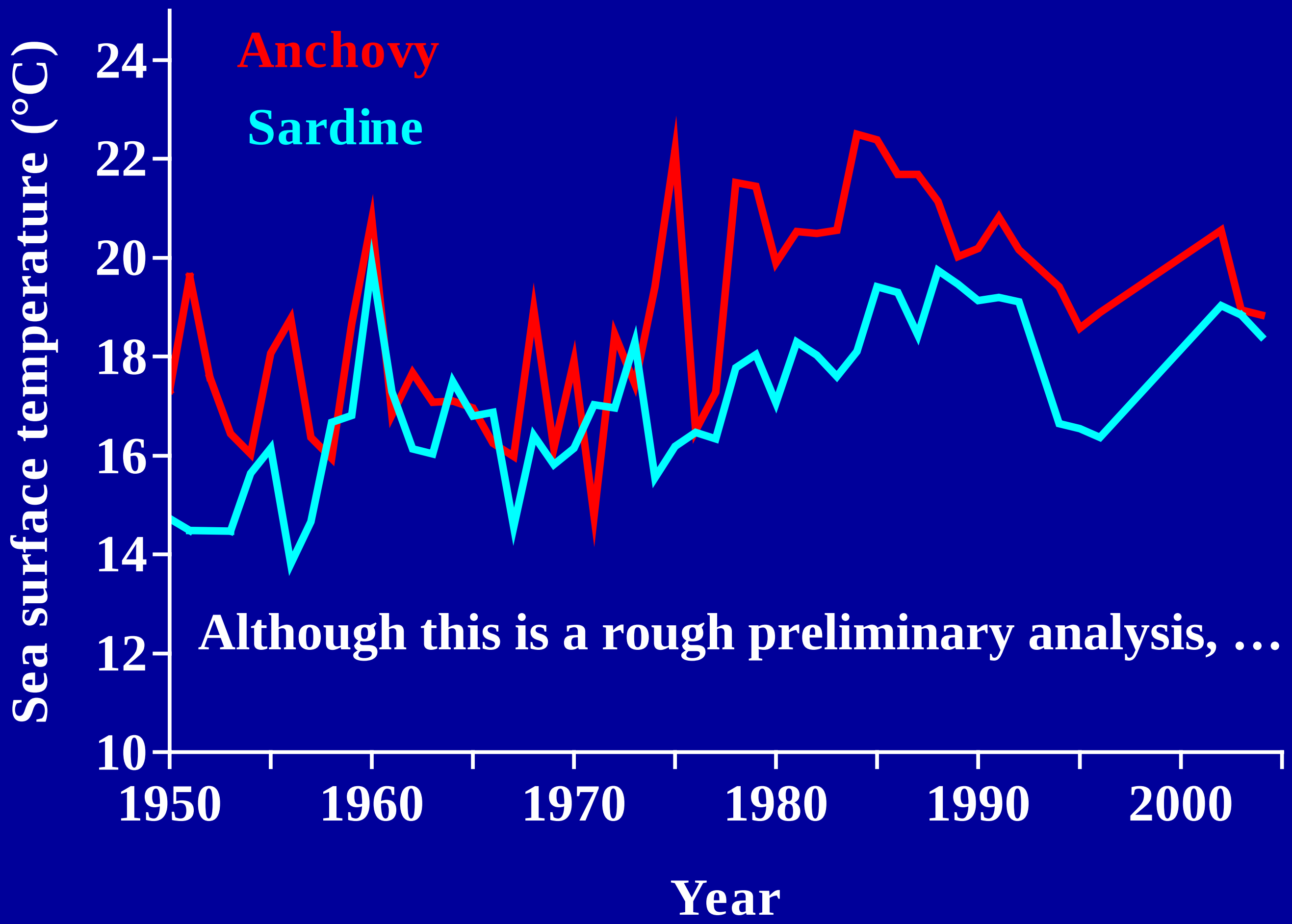
(submitted soon)

Recent EWMT



Larval anchovy

- 14.8–22.5ºC
- Mean:18.7ºC

Larval sardine

- 13.8–20.0 ºC
- Mean:17.0ºC

Difference

- –2.2–6.0
- Mean:1.8ºC

Fig. 7. Time series data of egg-density-weighted mean sea surface temperature for larval anchovy and sardine.

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Recent EWMT

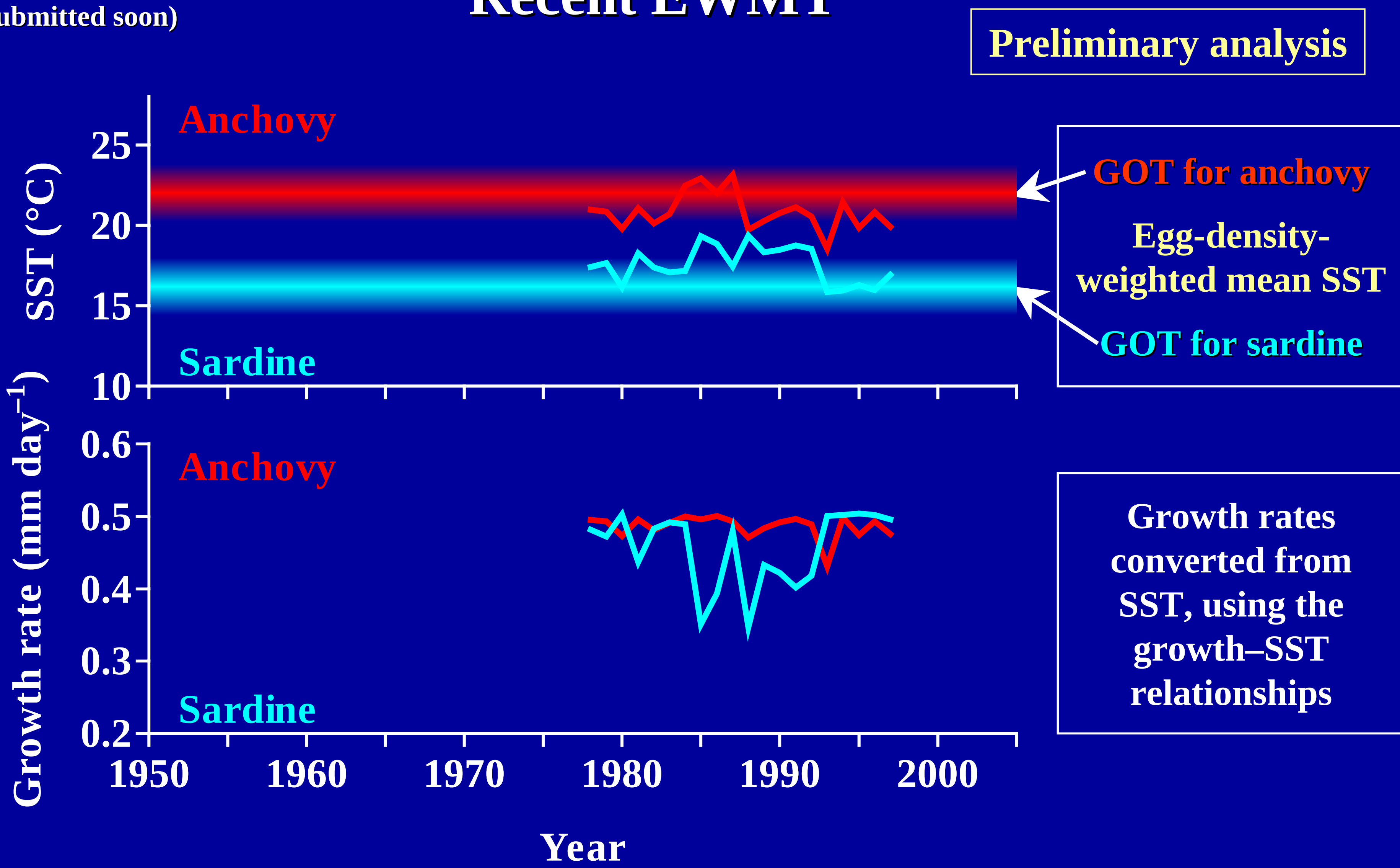

Fig. 10. Egg-density-weighted mean sea surface temperature and the converted growth rates for larval anchovy and sardine.

Recent EWMT

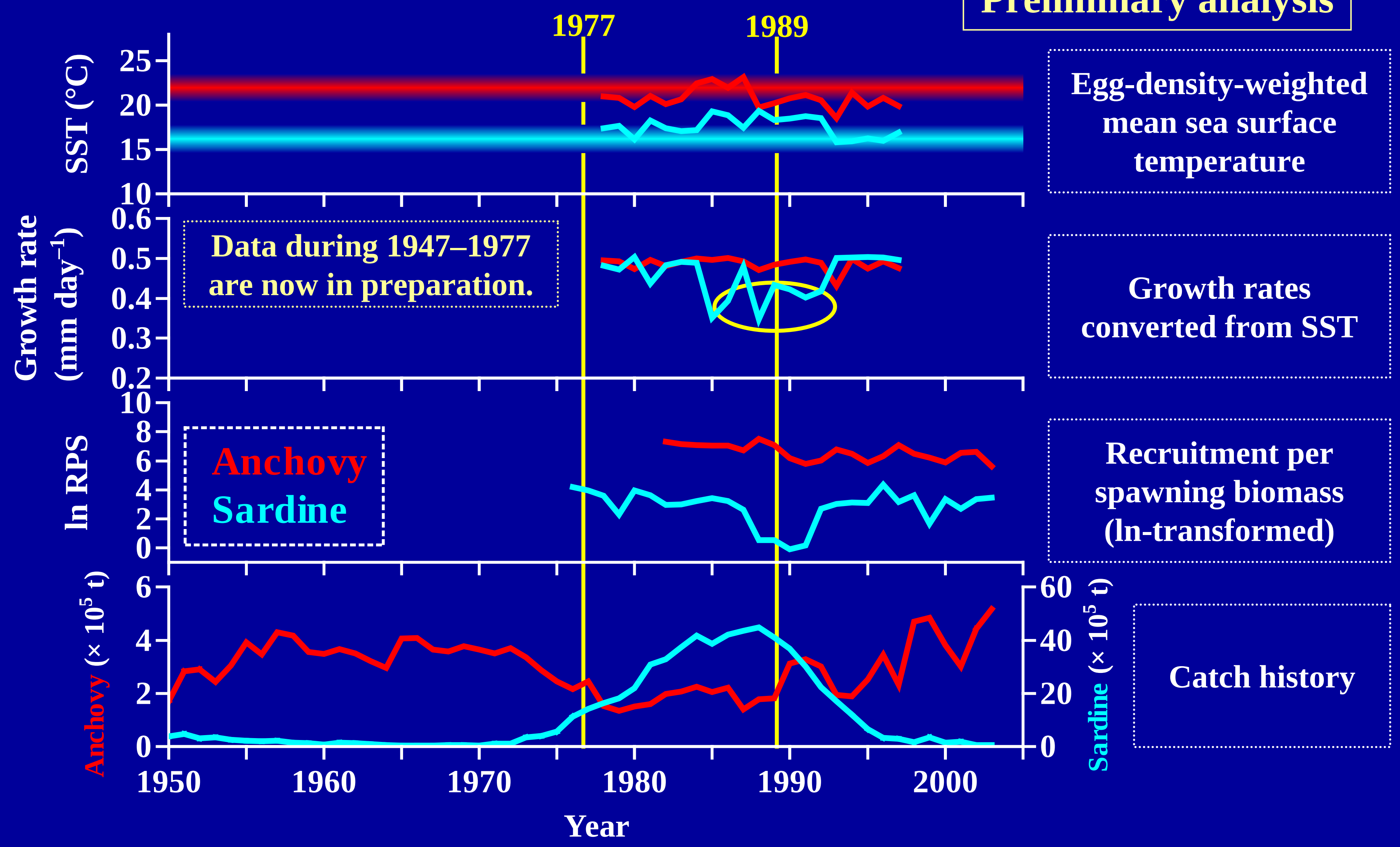

Fig. 11. Times series data of egg-density-weighted mean SST, larval growth rates converted from SST, catch and RPS for anchovy and sardine.