Potential biological mechanisms of anchovy and sardine alternations: Species-specific temperature optima and synergistic factors

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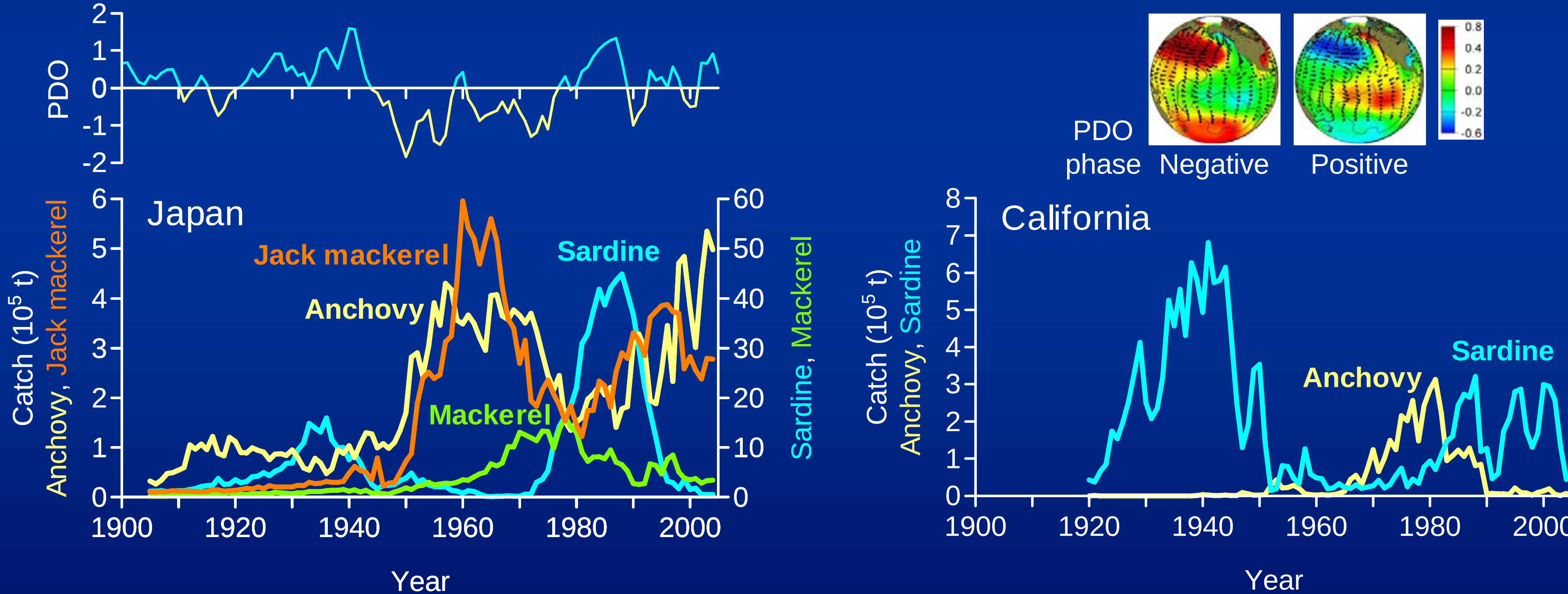
Multi-species regime shift

Climate changes and multi-species regime shifts

- Small pelagic fish have exhibited cyclic population dynamics in the complex marine ecosystems worldwide.
- The patterns have been associated with climate changes.
- However, the biological processes have remained unclear.



Multi-species regime shifts of small pelagic fish and synchronous anchovy and sardine alternations under the reversed temperature regimes across the Pacific in response to Pacific Decadal Oscillation (PDO) (Mantua et al. 1997).

Questions

Preliminary question

Why do even subtle environmental changes sometimes trigger drastic fish regime shifts?

Key question

Why do anchovy flourish and sardine collapse or *vice versa* under the same ocean regime?

Target question

Why were anchovy and sardine regime shifts synchronous across the Pacific?

Extended question

Why do some species show synchronous patterns, while others show out-of-phase patterns?

First, we explored the simplest and most direct pathway to explain the biological processes of multi-species regime shifts.

Topic

Differential optimal temperatures for growth rates during early stages between anchovy and sardine

Preliminary question

Why do even subtle environmental changes sometimes trigger drastic fish regime shifts?

Key question

Why do anchovy flourish and sardine collapse or *vice versa* under the same ocean regime?

Objectives

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

Engraulis japonicus VS. *Sardinops melanostictus*

"Optimal growth temperature" hypothesis:
A potential biological mechanism for anchovy and sardine regime shifts?

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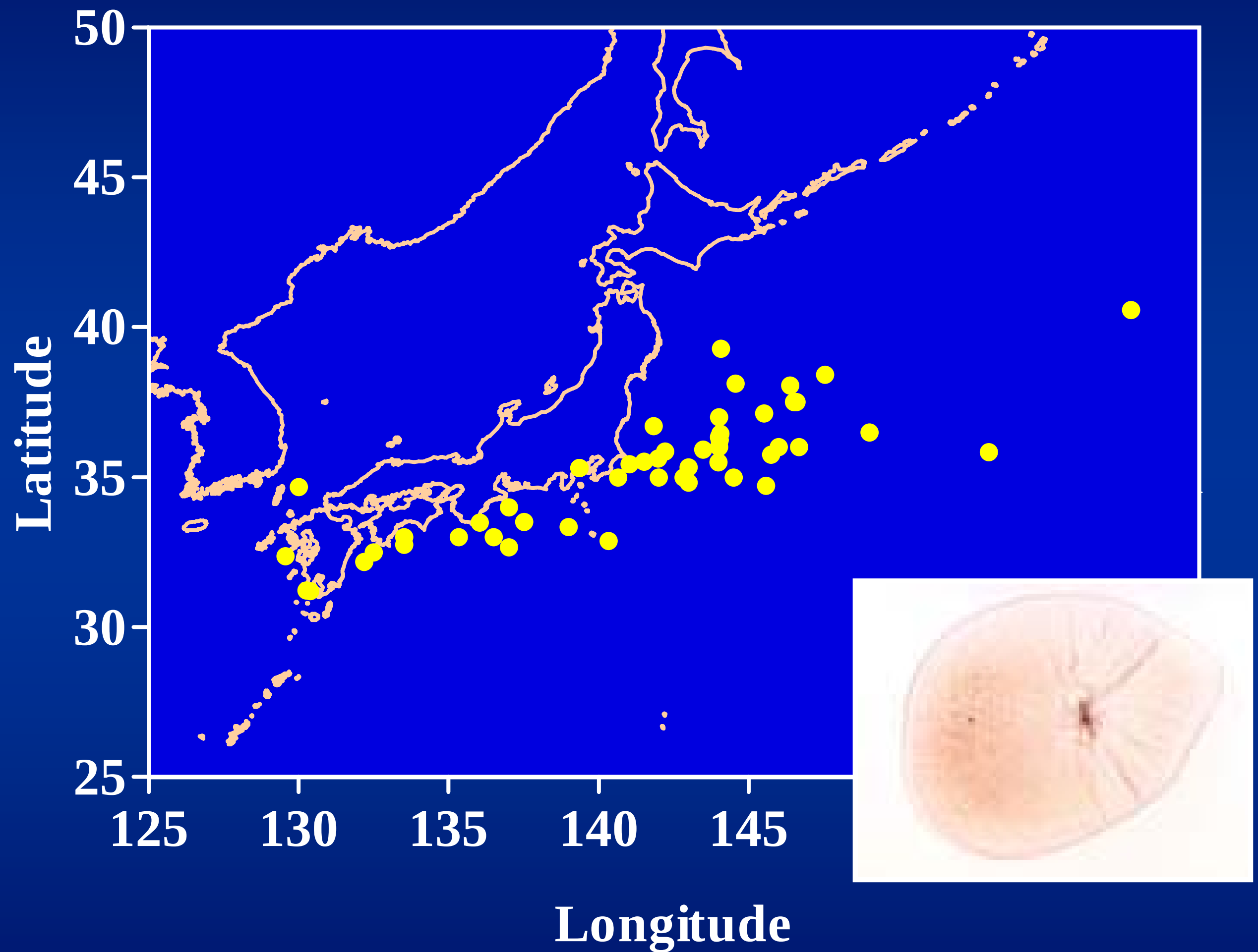
Samples

At 50 stations during 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 Japanese anchovy and sardine larvae in the western North Pacific.

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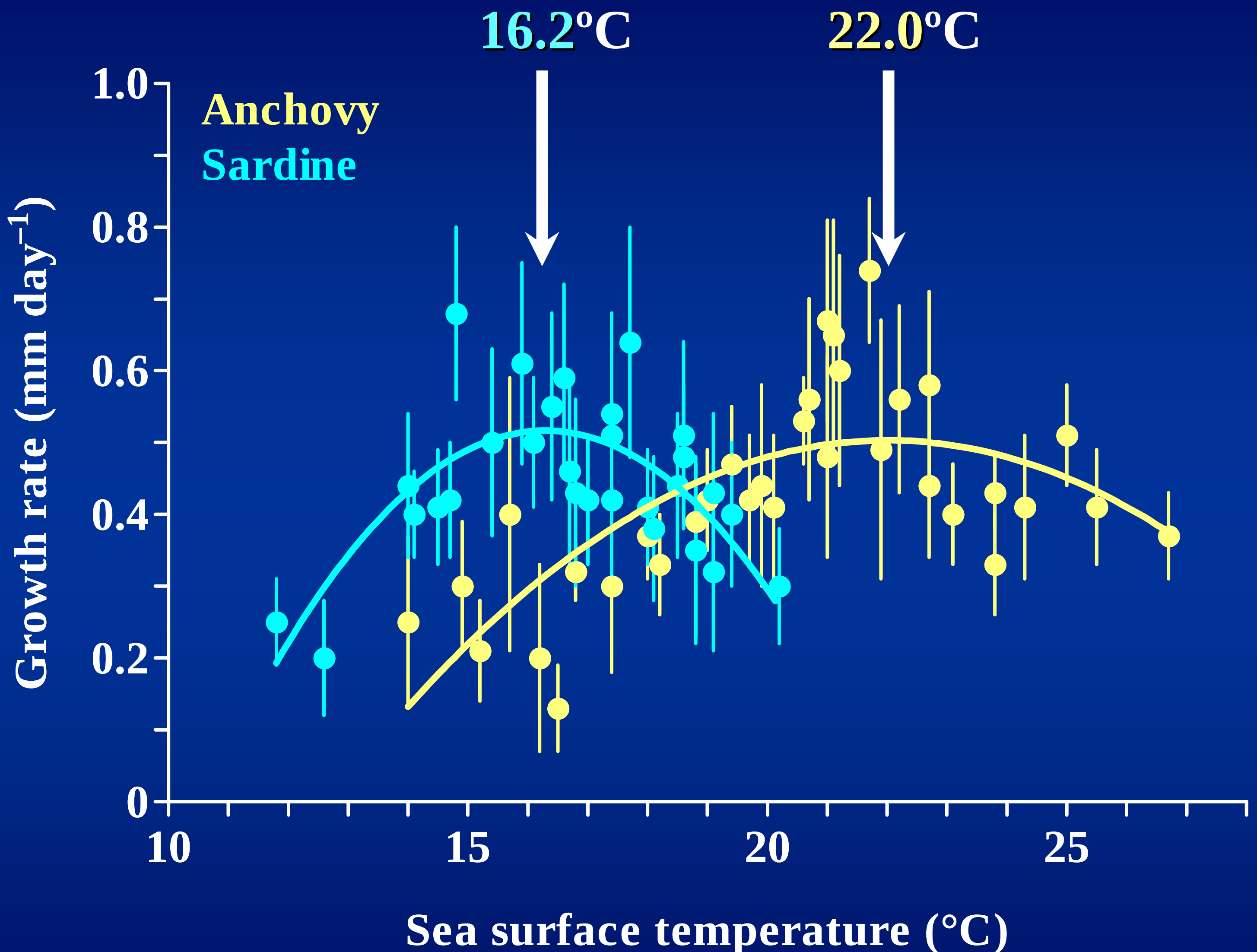
Anchovy vs. Sardine



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

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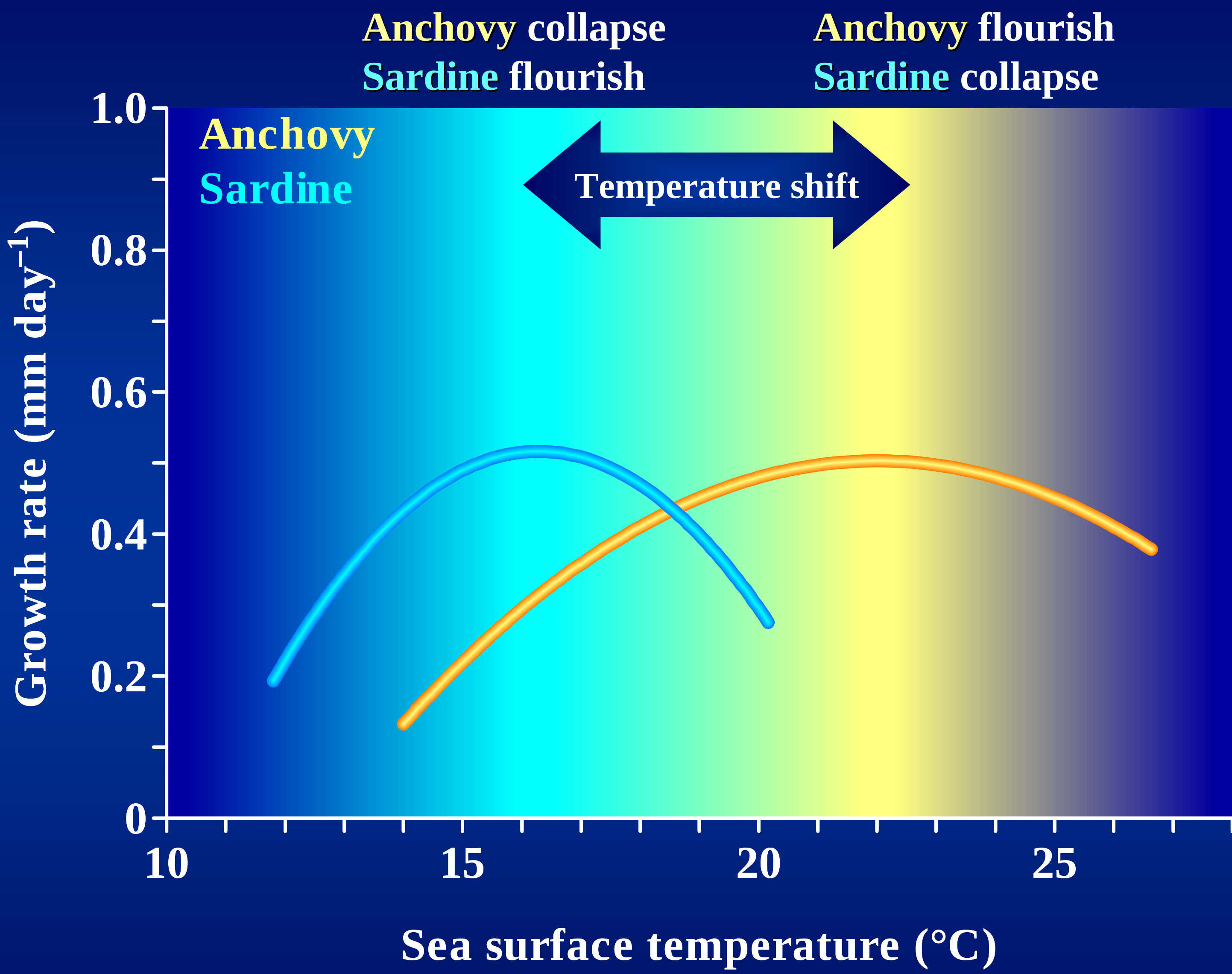
Mechanism



Conceptual framework of a potential mechanism for fish regime shifts based on the differential optimal growth temperatures.

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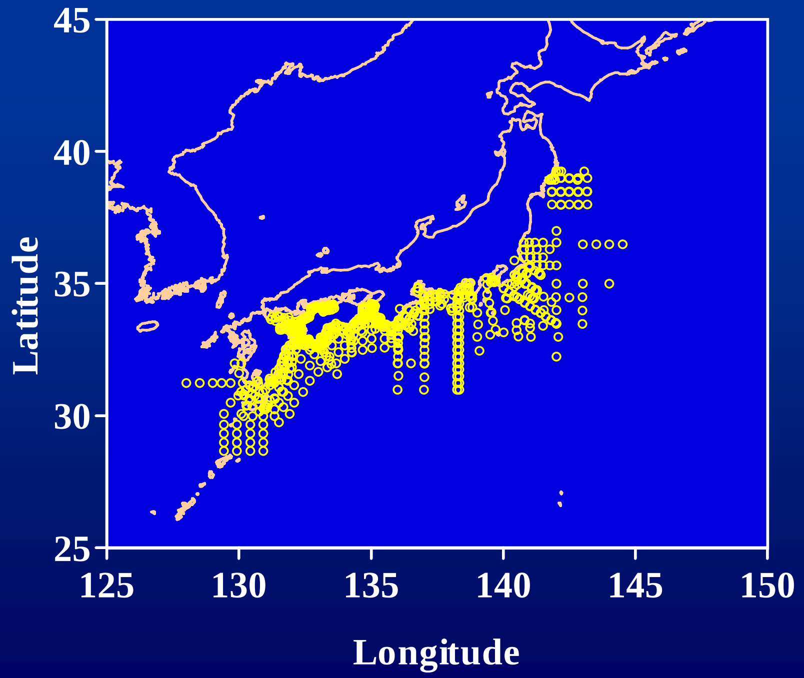
Ambient temperature

What temperatures are they likely to experience?
Is the difference in optima really significant?

Spawning ground

- ***Assumption*: Sea surface temperatures (SSTs) in the spawning regulate larval growth rates after hatching.**
- **Egg-density-weighted mean SSTs for anchovy and sardine**



Egg and larval surveys
Anchovy eggs
Sardine eggs

- **Off the Pacific coast**
- **From 1978 to 2004**
- **All seasons**
- **All stations**
- **Annual mean**

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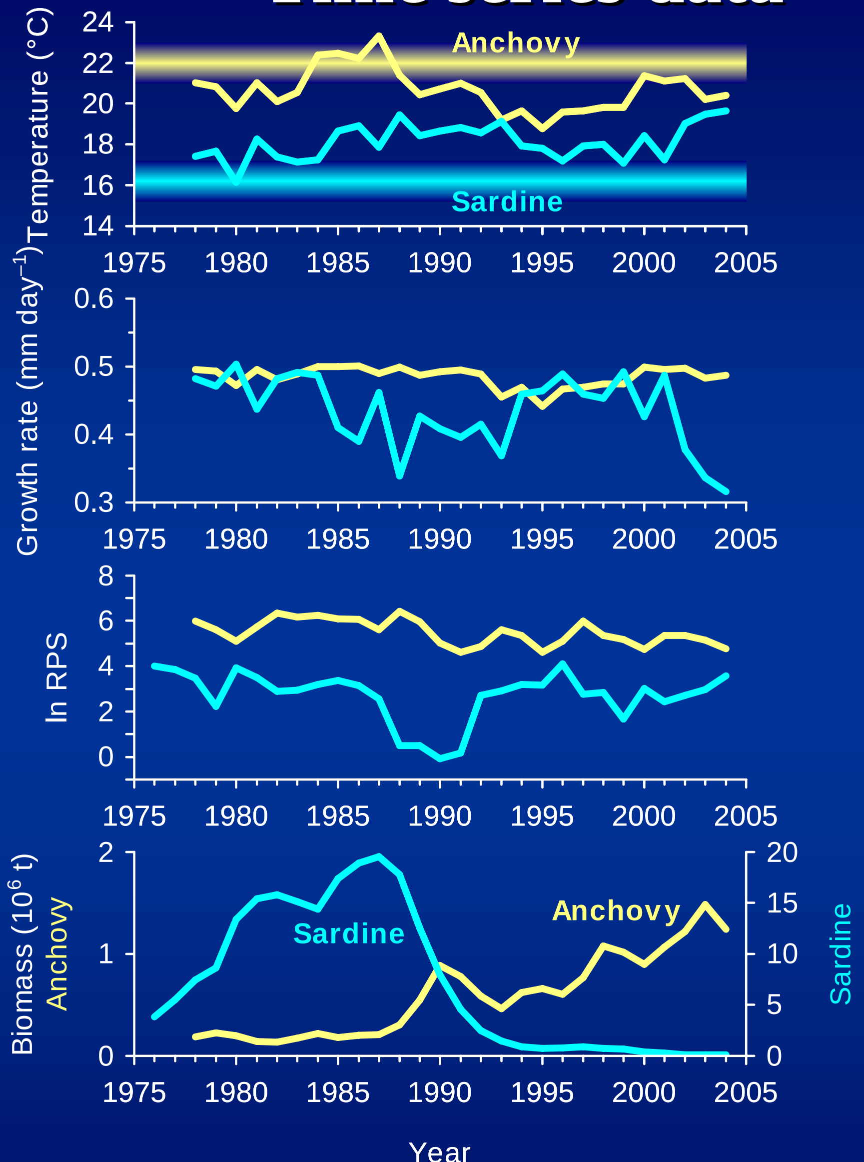
Time series data



Egg-density-weighted mean SST

Growth rate converted from SST

Recruitment per spawning biomass (RPS) as a larval survival index

Biomass

Retrospective test of the hypothesis with the times series data of egg-density-weighted mean SST, growth rate, RPS and biomass for anchovy and sardine.

Hypothesis proposed

"Optimal growth temperature" hypothesis

- Potential biological mechanism for anchovy and sardine alternations.
- The theory is independent of and synergistic with the existing hypotheses.
- Optimal temperature would provide a necessary condition rather than a sufficient condition.

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

Topic

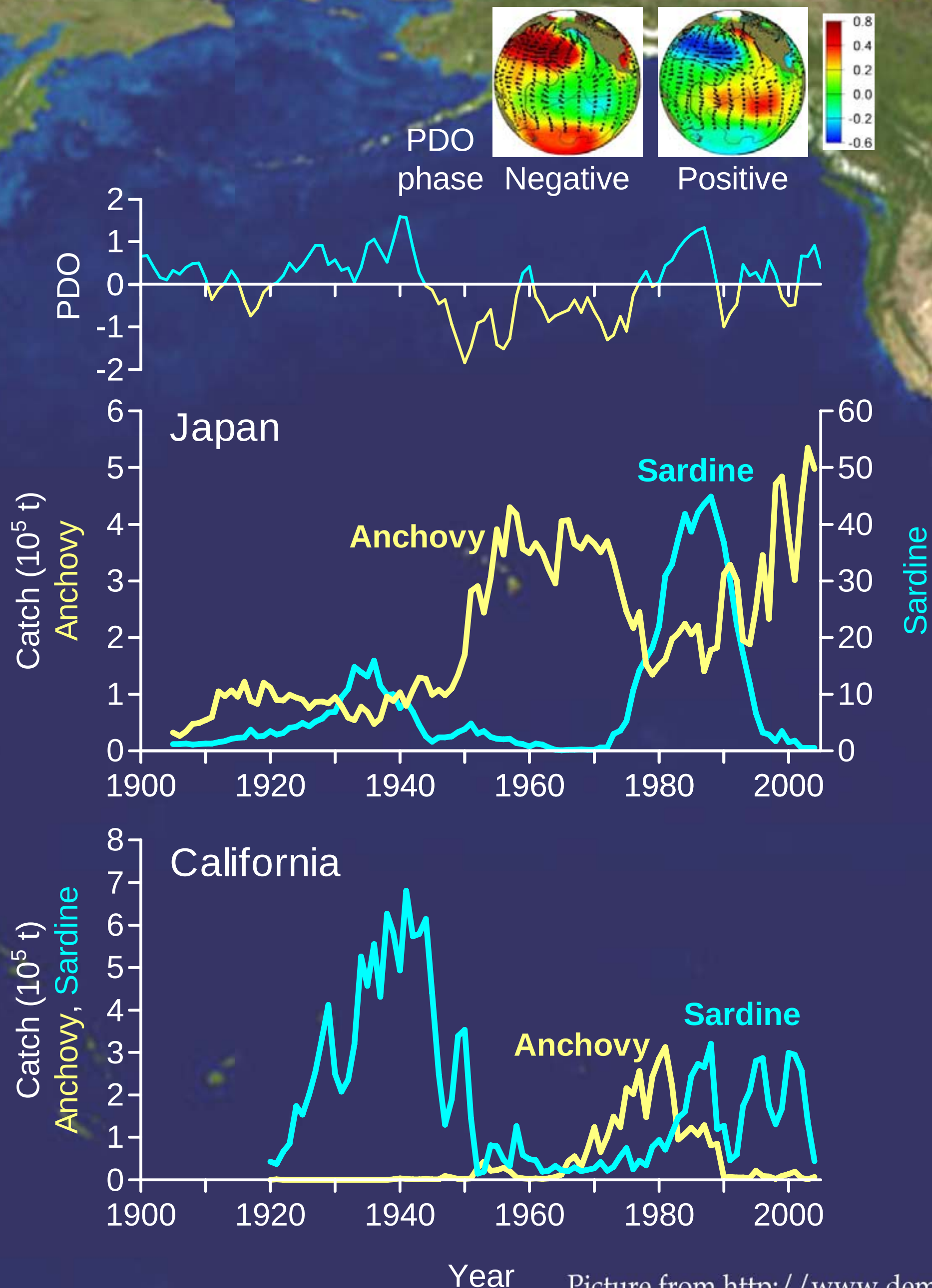
Contrasting spawning temperature optima of anchovy and sardine between opposite sides of the Pacific

Target question

Why were anchovy and sardine regime shifts synchronous across the Pacific? (despite the reversed temperature regimes)

Picture from http://www.demis.nl

East–West paradox



Picture from http://www.demis.nl

Objectives

Why were anchovy and sardine regimes synchronous across the Pacific?

A preliminary step toward basin-scale synthesis

- **Spawning temperature optima were compared between Japanese anchovy and sardine in the western North Pacific.**

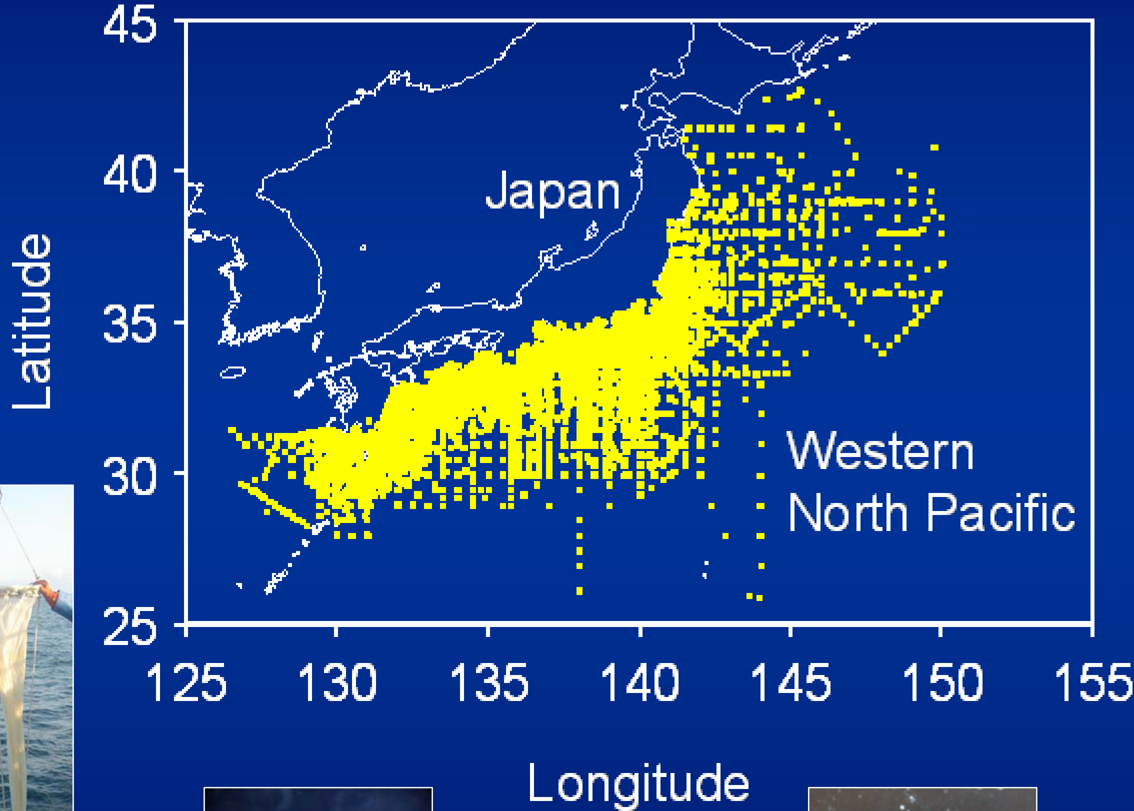
- **The results were compared with those in the California Current by Lluch-Belda *et al*. (1991).**

Western Boundary Current system vs. Upwelling system

Picture from http://www.demis.nl

Data

Long-term data set of egg and larval surveys



- **Off the Pacific coast of Japan**
- **Past 27 years (1978–2004)**
- **102,905 tows**
- **Over 3,000 tows per year**

Sampling stations of the historical egg and larval surveys off the Pacific coast of Japan from 1978 to 2004.

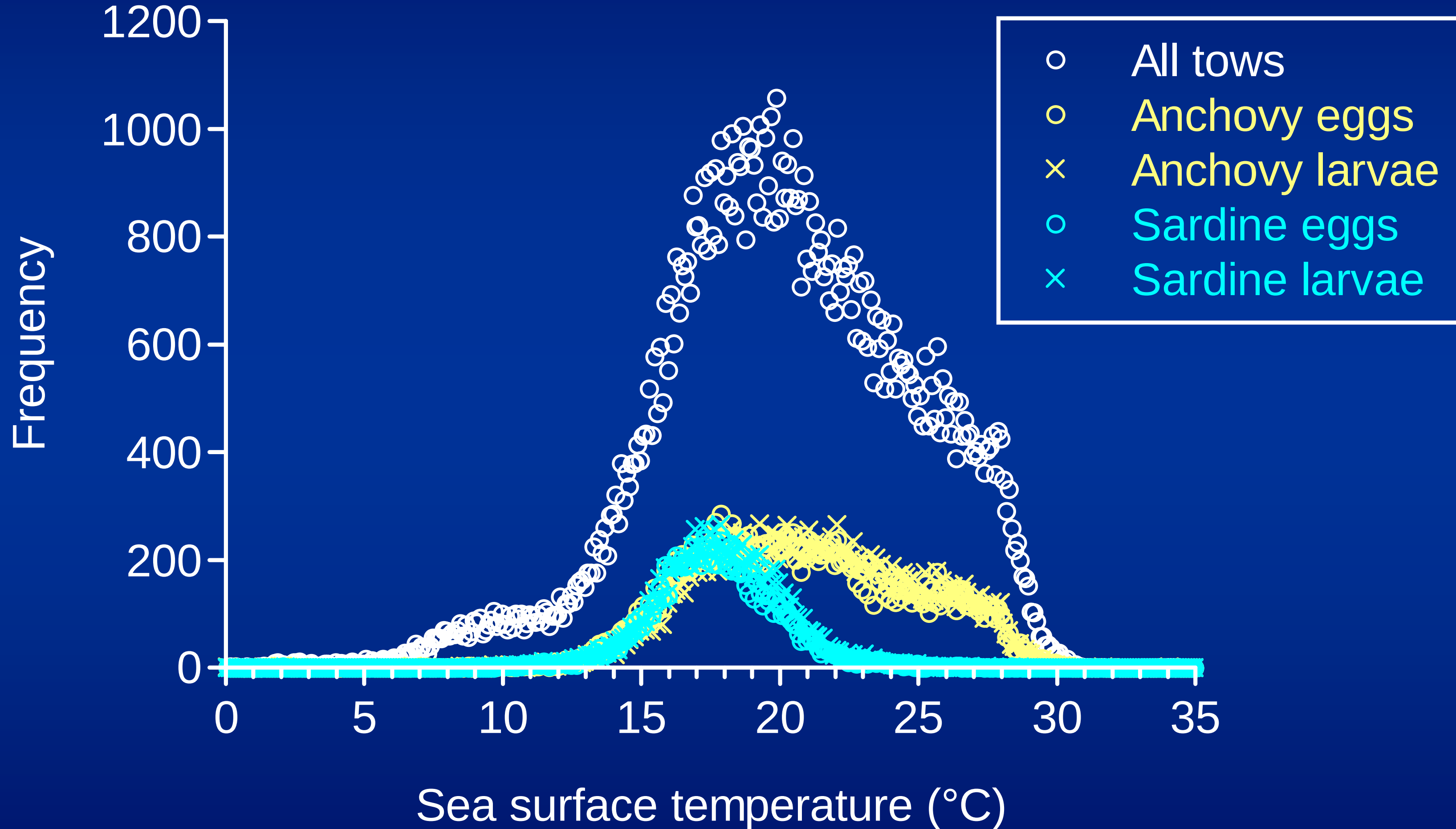
Takasuka *et al.*

Frequency

The methods of Lluch-Belda *et al.* (1991)

(1) All samples were classified into SST intervals of 0.1ºC.

(2) They were sorted for "positive" samples for anchovy and sardine eggs and larvae.



Frequency distributions of plankton samples (stations) classified into the sea surface temperature intervals of 0.1ºC.

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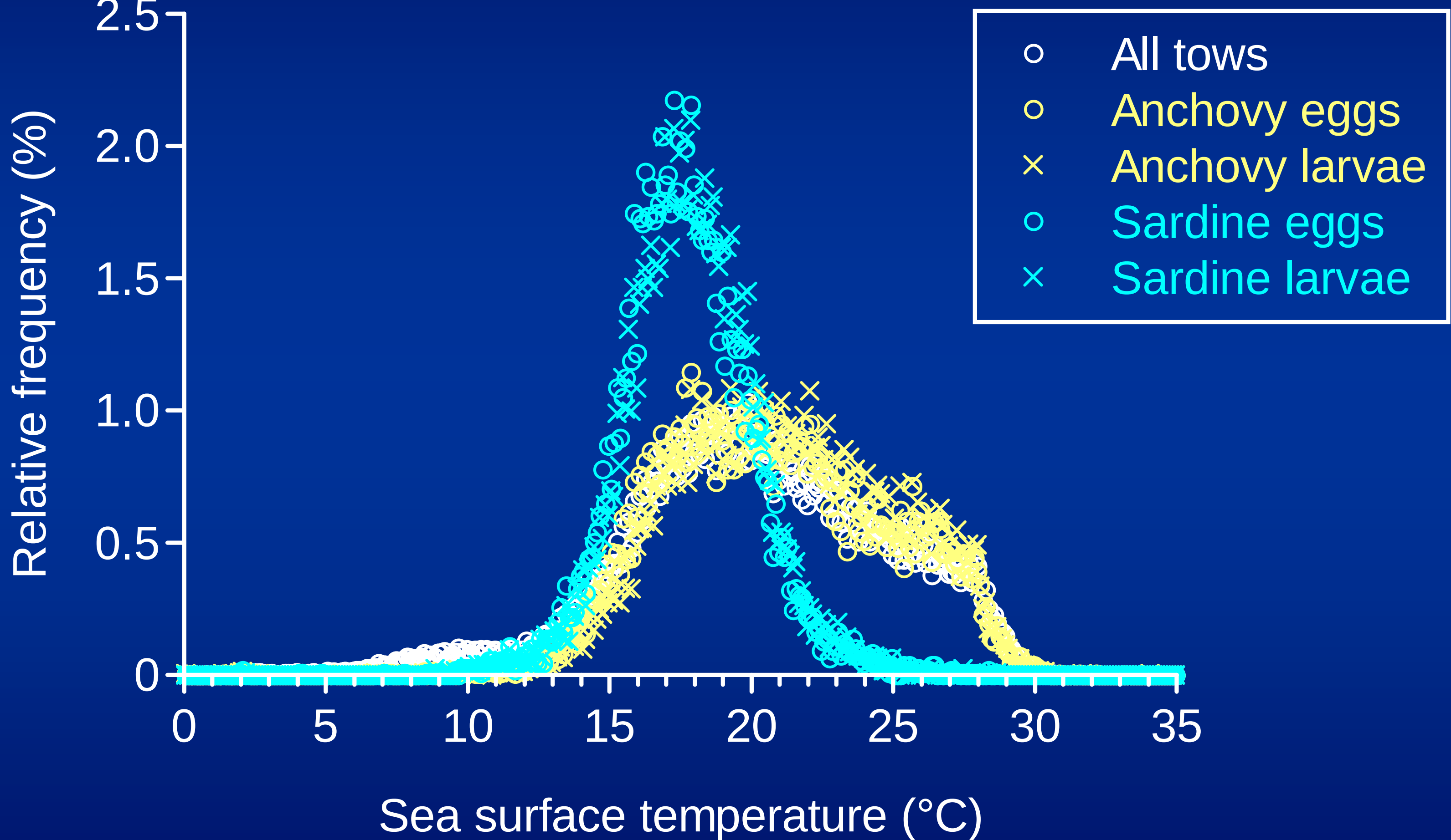
Relative frequency

The methods of Lluch-Belda *et al.* (1991)

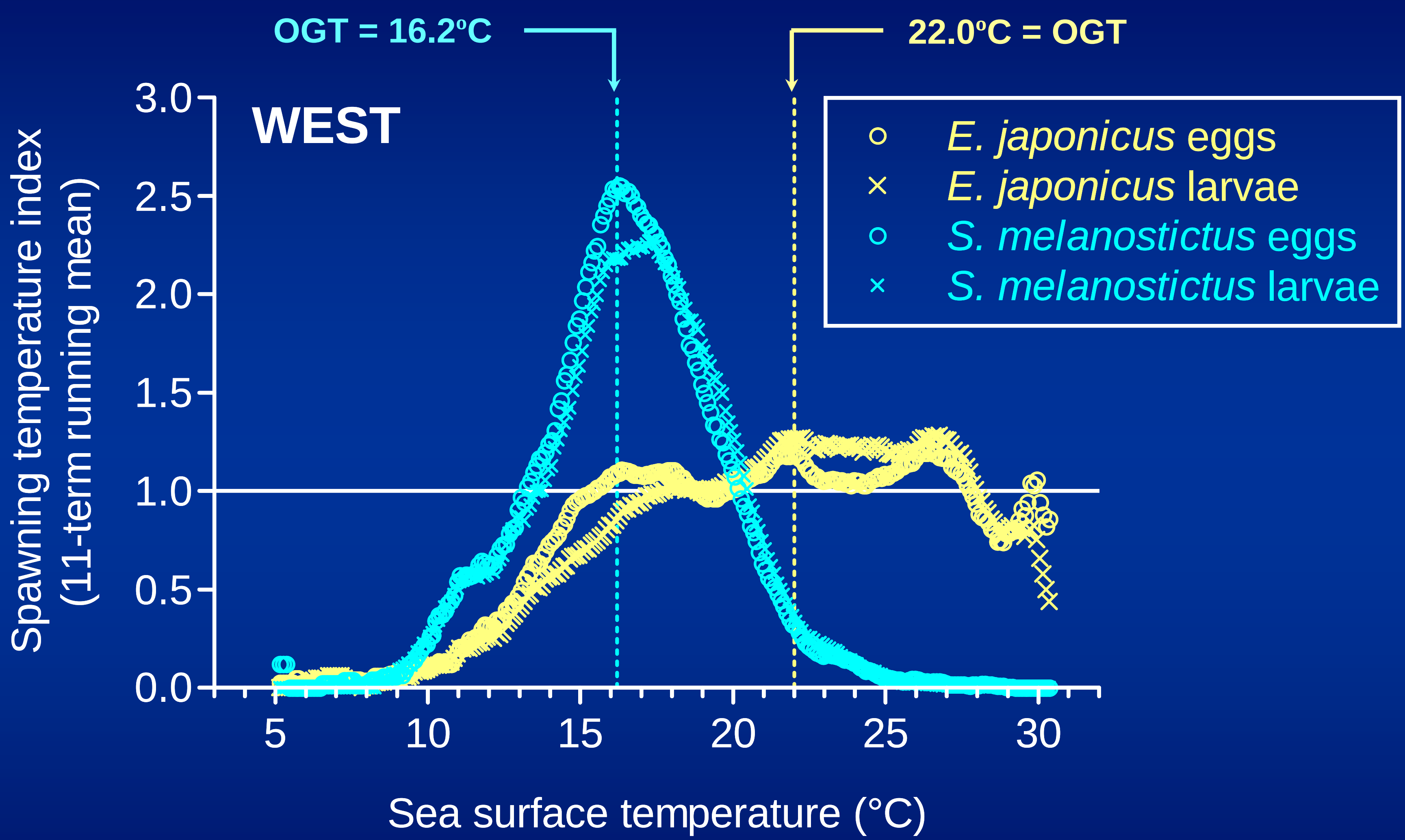
(3) **Spawning temperature index** (quotient) was calculated as **ratio of relative frequencies of 'positive' samples vs. all samples** for each SST interval.

(4) Assumption: The value of index > 1.0: Preferred or selected



Relative frequency distributions of plankton samples (stations) classified into the sea surface temperature intervals of 0.1ºC.

Western North Pacific



Spawning temperature index for Japanese anchovy (*E. japonicus*) and sardine (*S. melanostictus*) in the western North Pacific.

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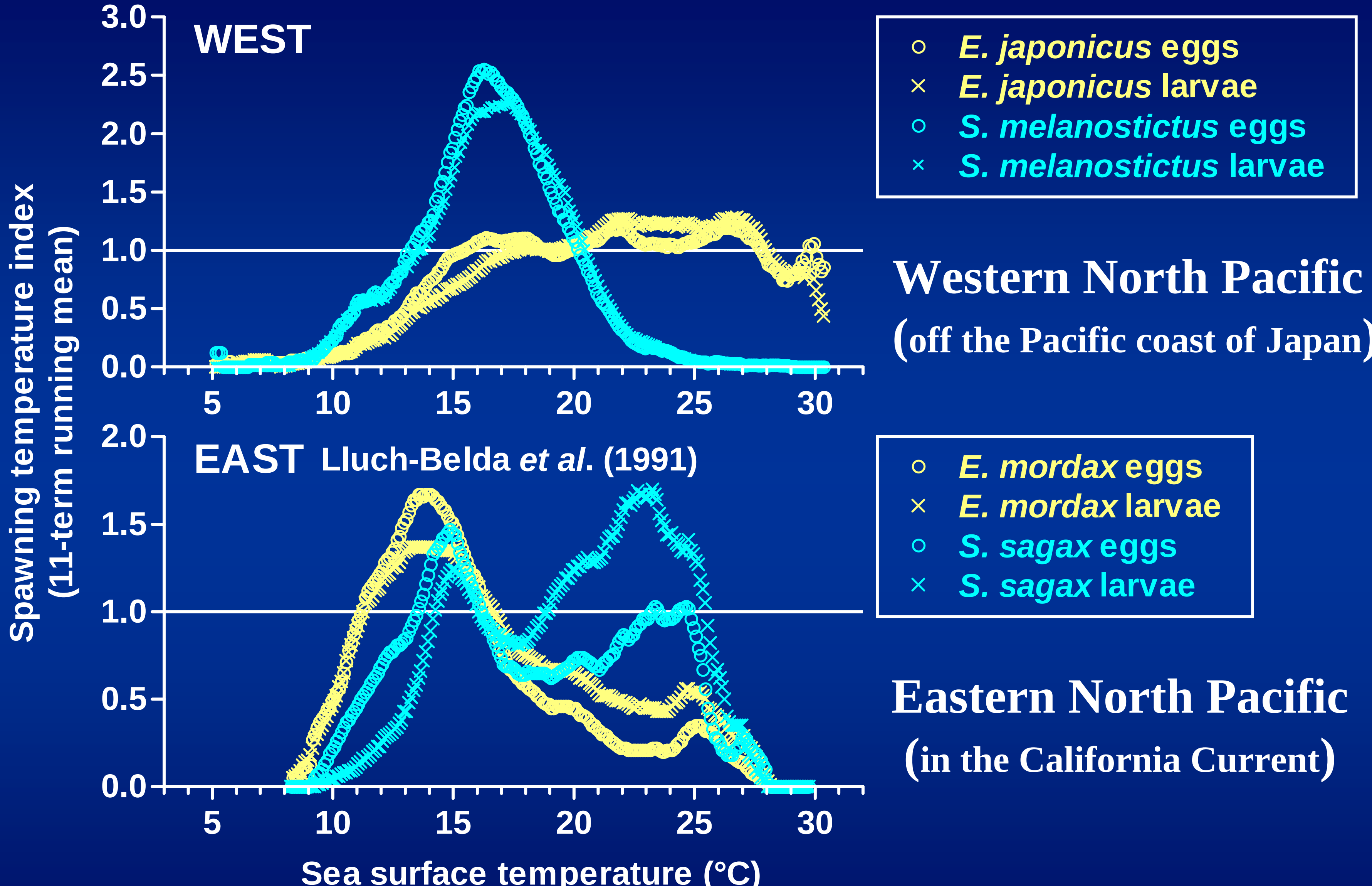
East–West



Temperature optima for anchovy and sardine spawning: Contrast between the western and eastern sides of the Pacific.

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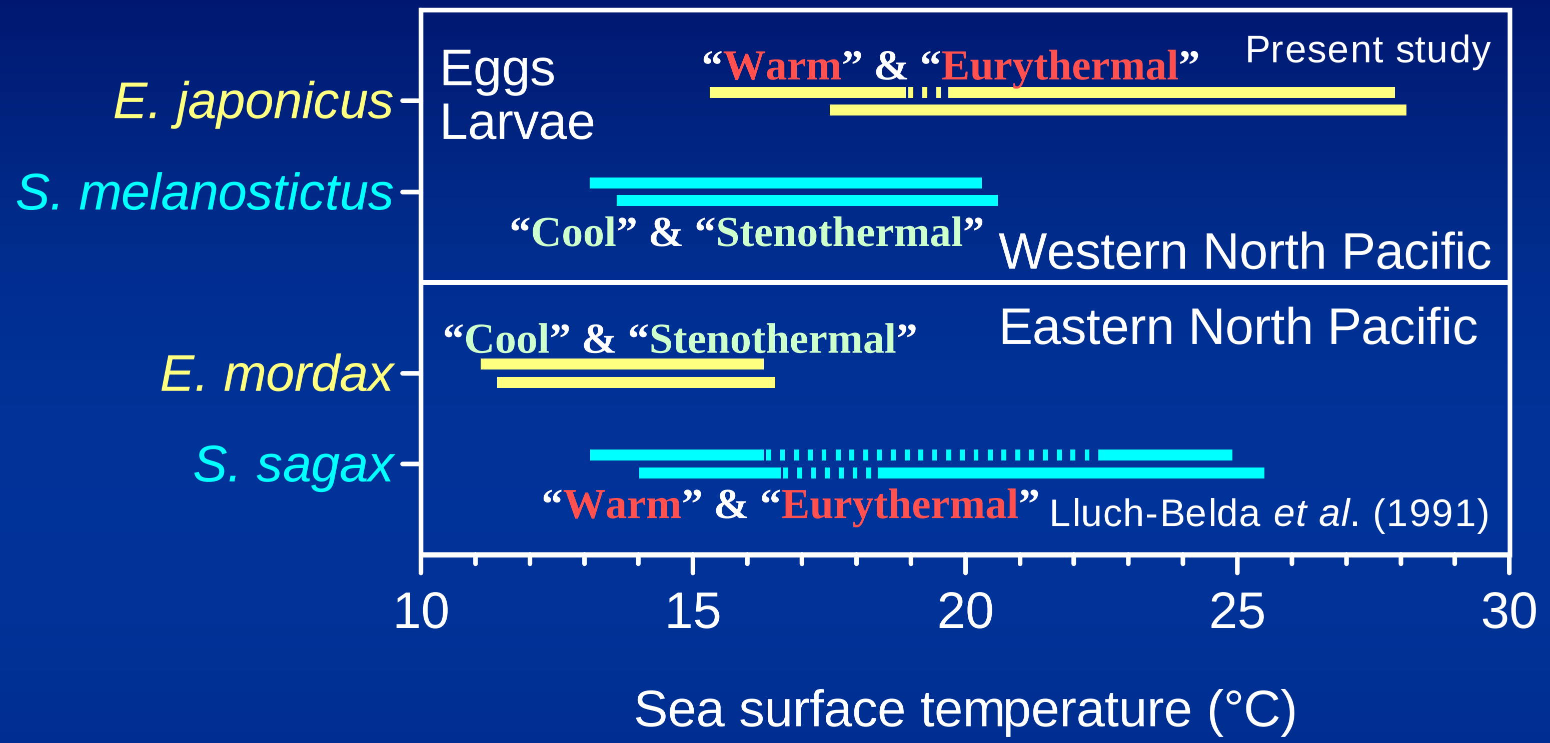
East–West

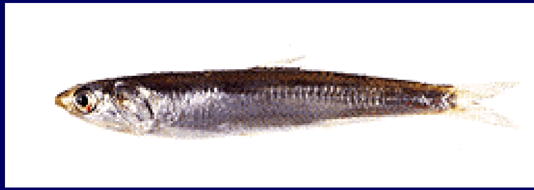
Spawning temperature index > 1.0

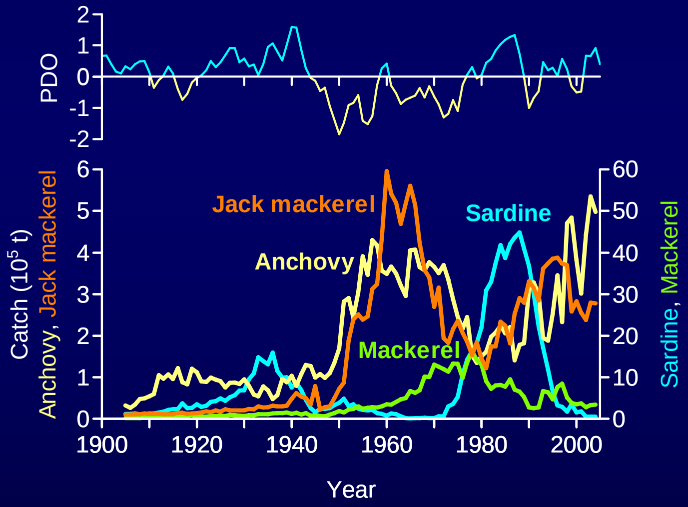


Reversed **species-specific temperature optima under the** ***reversed*** **temperature regimes would provide a possible theoretical solution to the** ***synchronous*** **alternations across the Pacific.**

Topic

Multi-species regime shifts reflected in spawning temperature optima of small pelagic fish in the western North Pacific





Extended question

Why do some species show out-of-phase patterns, while others show synchronous patterns?

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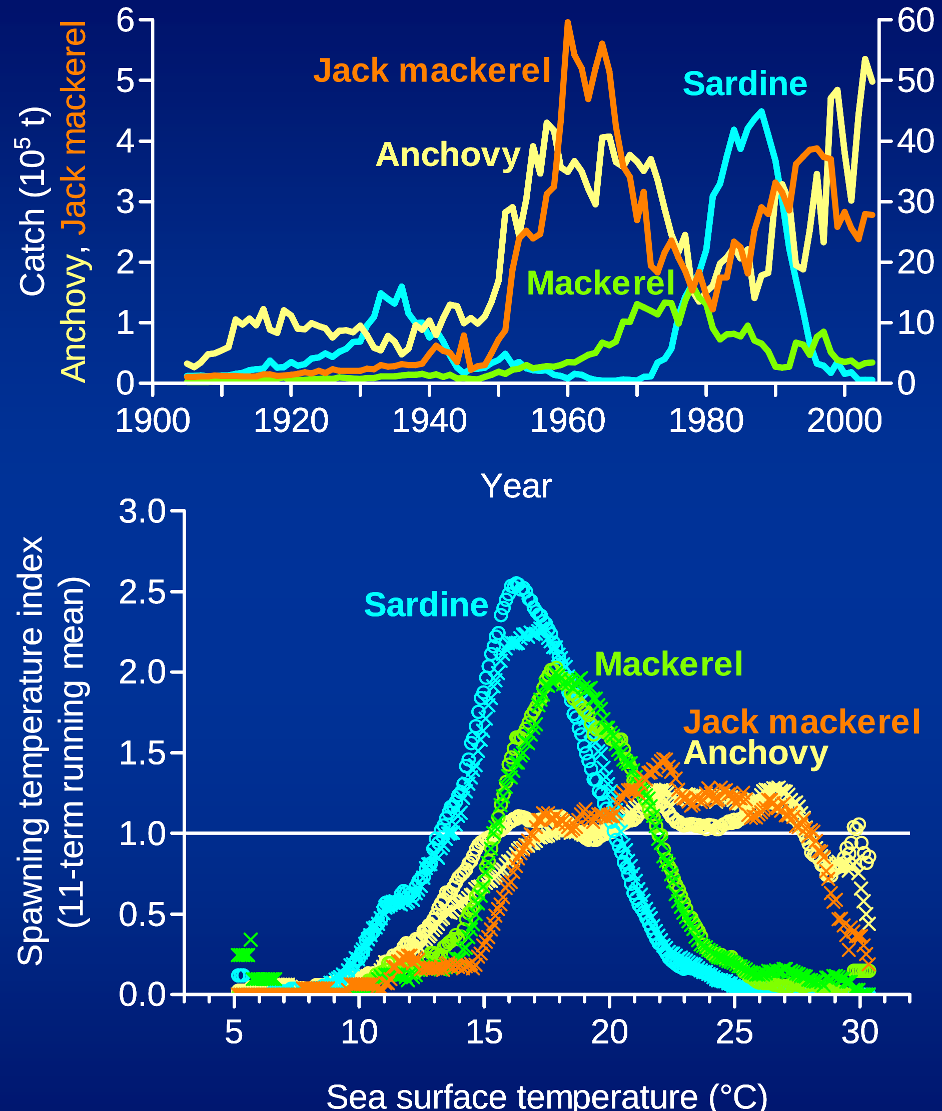
Multi-species comparison



Anchovy

Sardine

Mackerel

Jack mackerel

Similarities and differences in spawning temperature patterns reflect those in the long-term population dynamics patterns.

Implications

Implications

Despite the complex nature of marine ecosystems, …

Temperature-based hypotheses

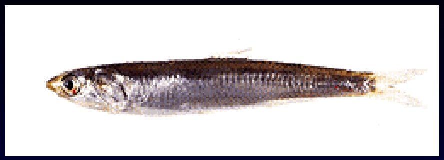
- **The dominant mechanism of the large-scale events may be simple and direct.**
- **Species-specific temperature optima ideas could provide at least a theoretical solution to what has been hard to explain by the other factors.**
- **Direct temperature impacts on fish population dynamics might be greater at the large scales than expected before.**

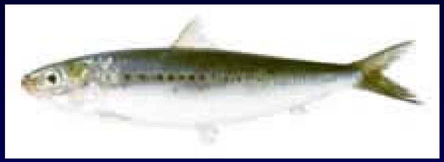
Synergistic mechanisms

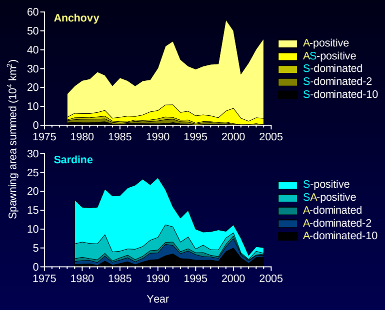
- **No single factor is enough to explain the whole picture.**
- **There should be synergistic effects of the other factors.**
- **In fact, sardine have not yet indicated any sign of recovery, despite the relatively favorable conditions in recent years.**

Topic

Spatial and temporal overlaps of anchovy and sardine spawning in the western North Pacific







Question arising

How much do anchovy and sardine eggs co-occur in the western North Pacific?

Objectives

Sardine's collapse

- Why have not sardine populations recovered?
- A controversial issue: Fishing mortality?
- Another possible aspect: Interspecies interactions

Spawning overlaps

- A possible source of direct competitions during early stages.
- Spawning peaks differ between anchovy and sardine.
- But their spawning seasons can be overlapped.
- Sardine show *ca*. tenfold greater fluctuations than anchovy.
- Spawning grounds and periods indicate expansion/contraction.

As a first step, …

- Spatial and temporal overlaps of anchovy and sardine spawning were described qualitatively and quantitatively.

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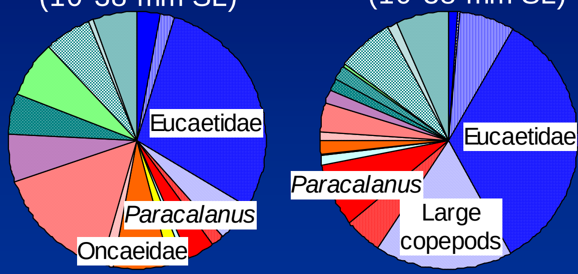
Feeding habit

Tosa Bay
November 2003

Anchovy
(10-38 mm SL)

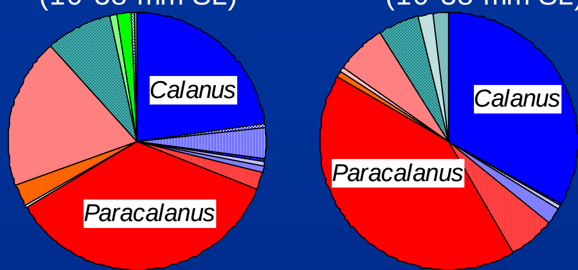
Round herring
(10-38 mm SL)



Tosa Bay
March 2004

Sardine
(10-38 mm SL)

Round herring
(10-38 mm SL)

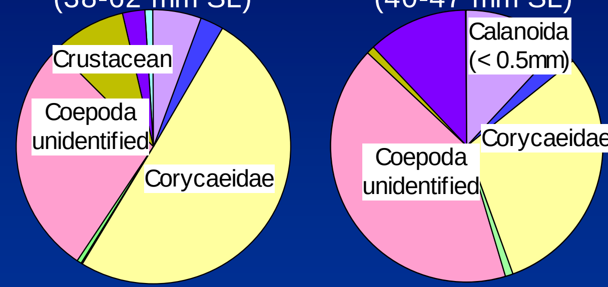


Gut content compositions (% V)

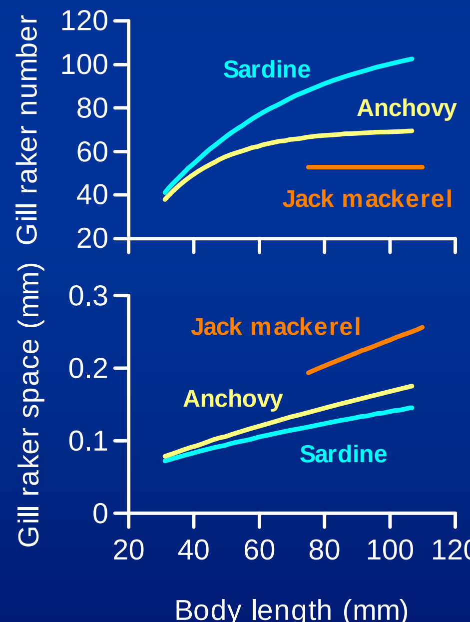
Sagami Bay
March 2004

Anchovy
(38-62 mm SL)

Sardine
(40-47 mm SL)



Stomach content compositions (% N)



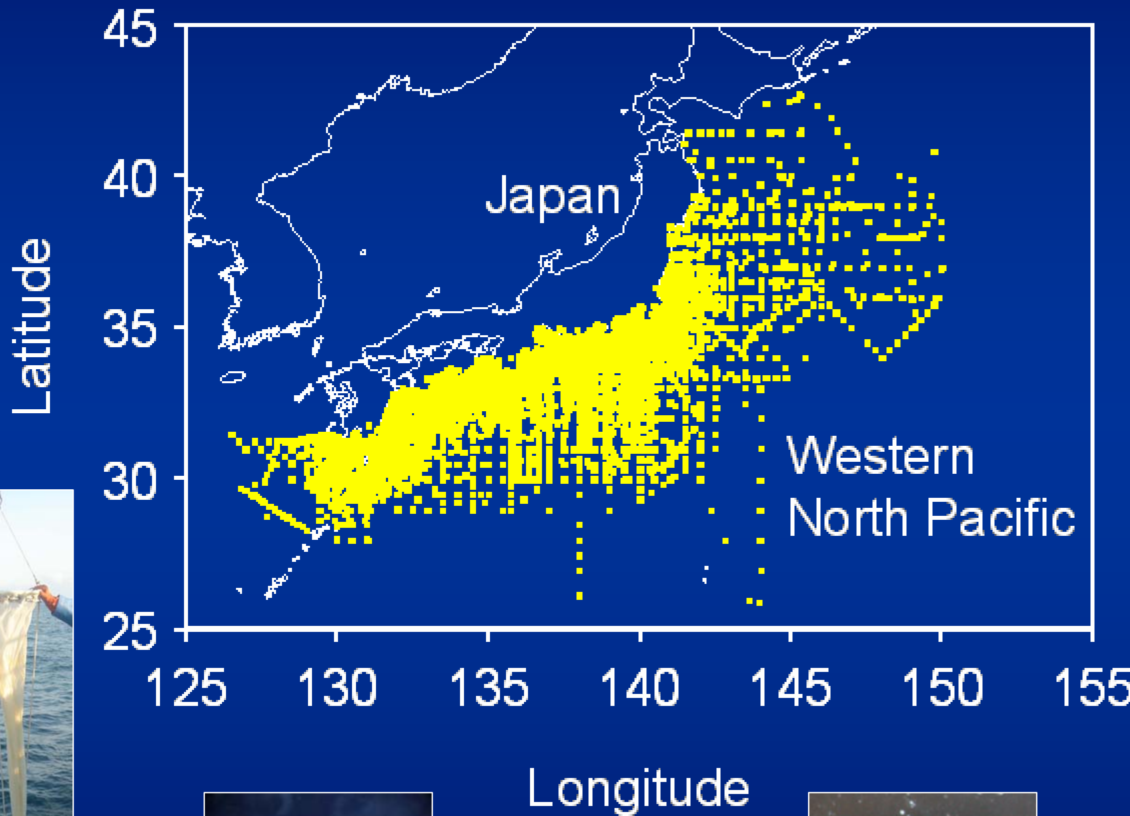
Gill raker morphologies

Poster S7-3017:
Kubota *et al.*
for details

Tanaka *et al.* (2006) in JFB
Tanaka (2006) PhD thesis

Data

Long-term data set of egg and larval surveys



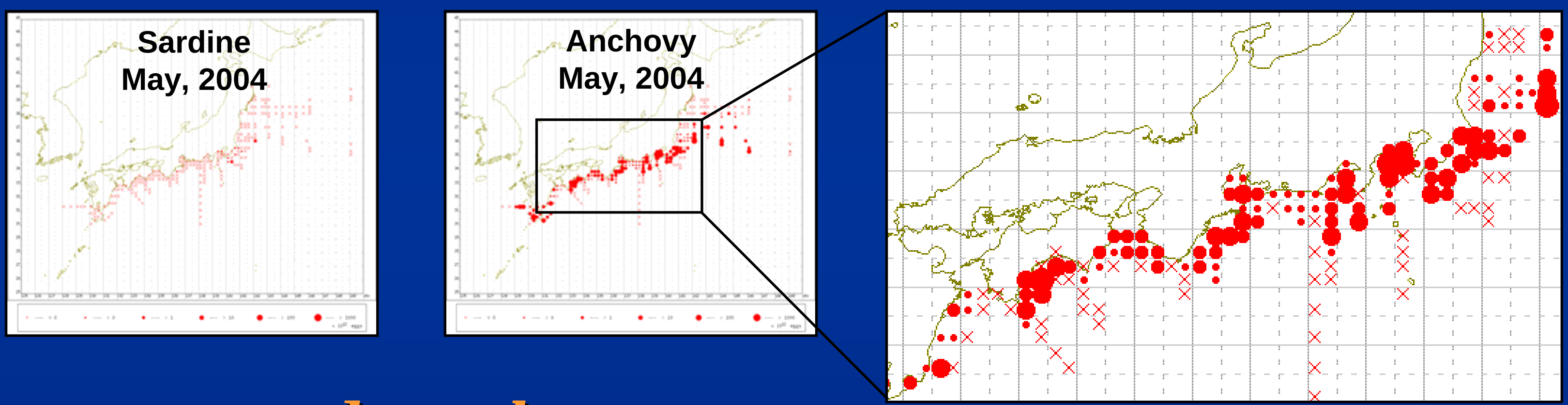
- Off the Pacific coast of Japan
- Past 27 years (1978–2004)
- 102,905 tows
- Over 3,000 tows per year

Sampling stations of the historical egg and larval surveys off the Pacific coast of Japan from 1978 to 2004.

Methods

Egg abundance and spawning area

- Monthly egg abundance calculated in terms of 15'x15' squares.
- Spawning area calculated by summing areas of squares positive for anchovy and/or sardine eggs

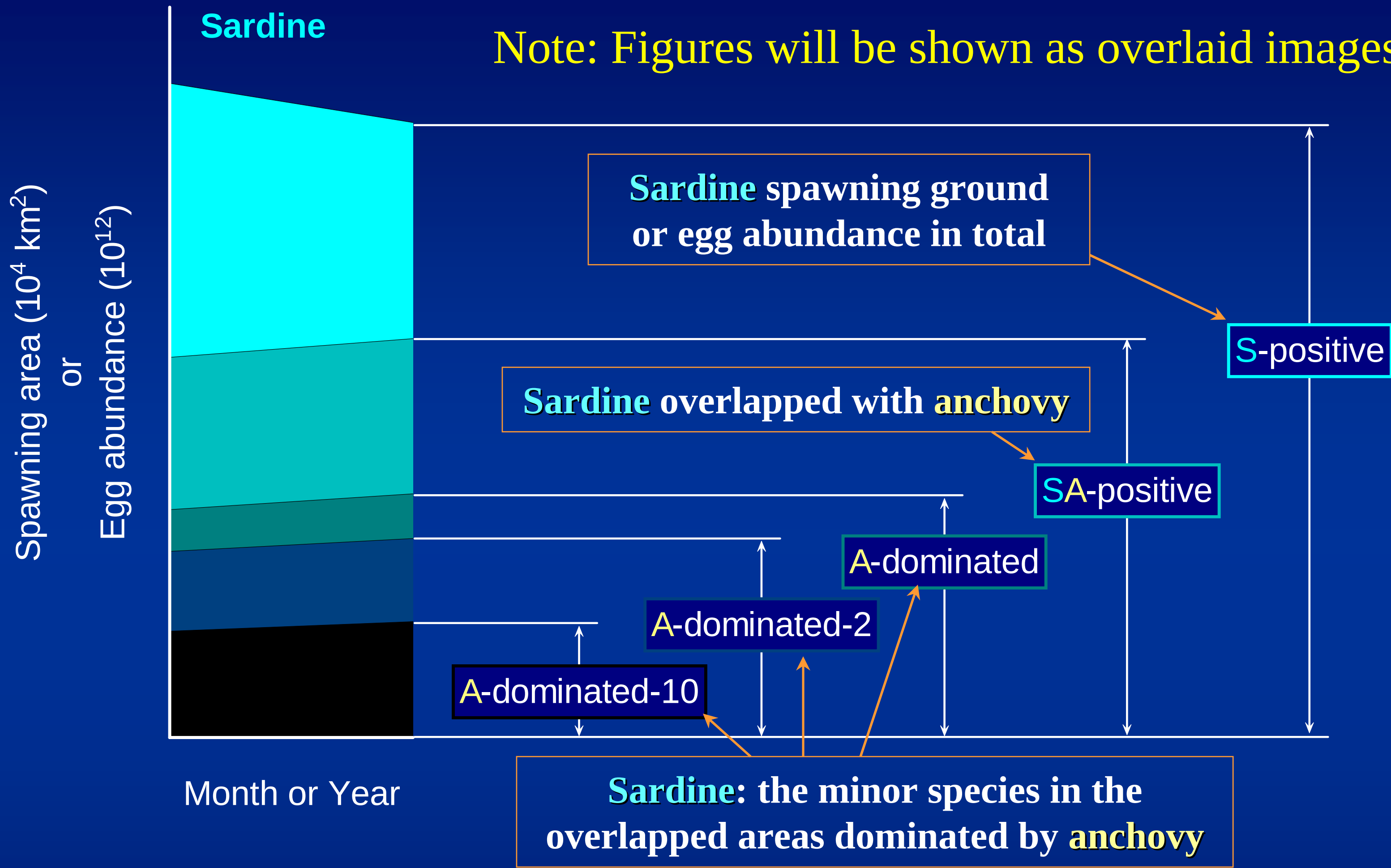


Occurrence and overlap status

- "S-positive": sardine eggs occurred
- "SA-positive": sardine and anchovy eggs co-occurred
- "A-dominated": sardine < anchovy in egg abundance
- "A-dominated-2": sardine < 1/2 anchovy in egg abundance
- "A-dominated-10": sardine < 1/10 anchovy in egg abundance

Methods

Note: Figures will be shown as overlaid images

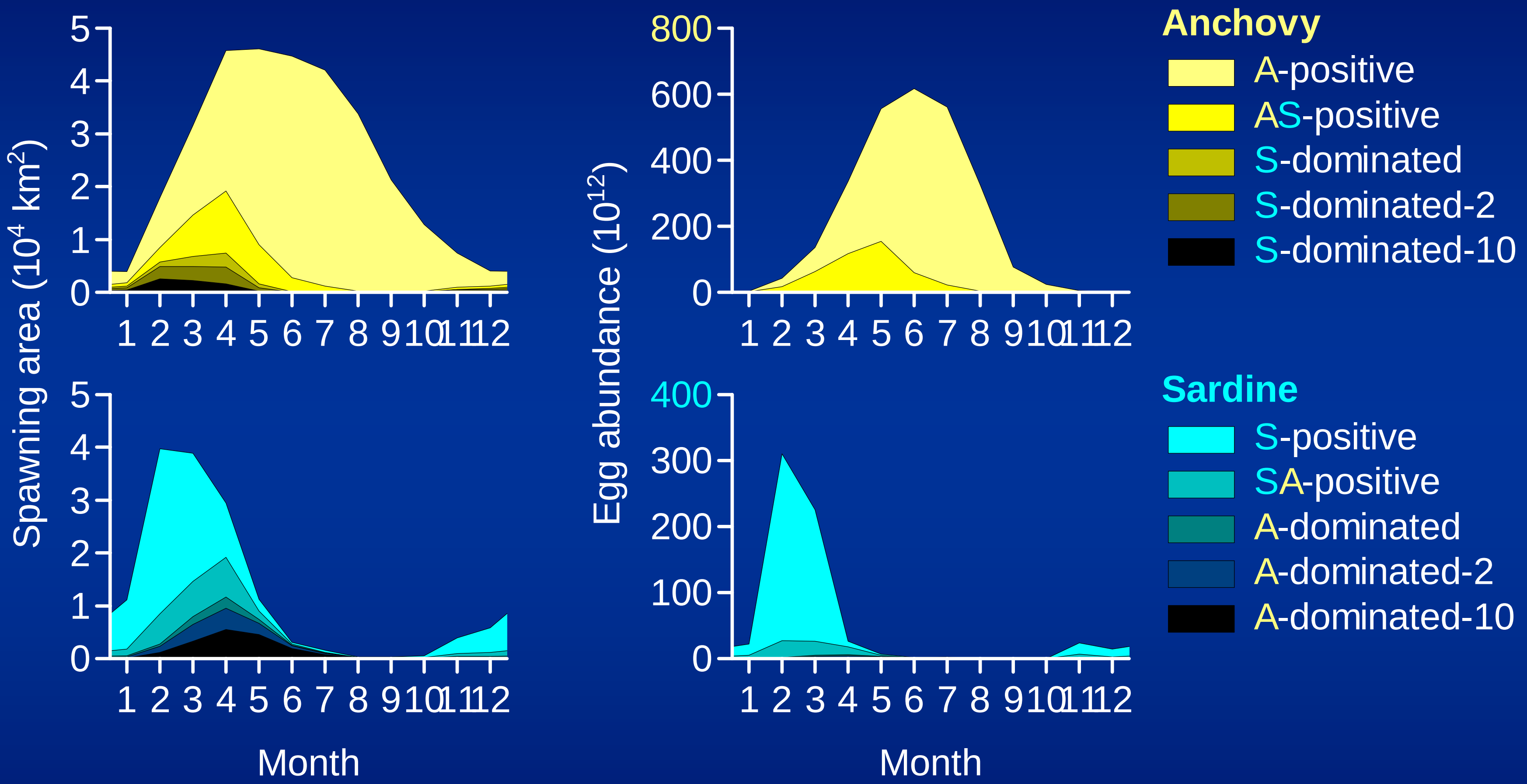


- Spawning area was calculated by summing areas of each category.
- Egg abundance was calculated by summing egg abundances in the areas of each category.

Q: e.g. What is the ratio of sardine egg abundance in the "A-dominated" areas to total sardine egg abundance?

Seasonal changes

Averaged for 27 years



Seasonal changes in spawning areas and egg abundances of anchovy and sardine with a focus on their spawning overlaps.

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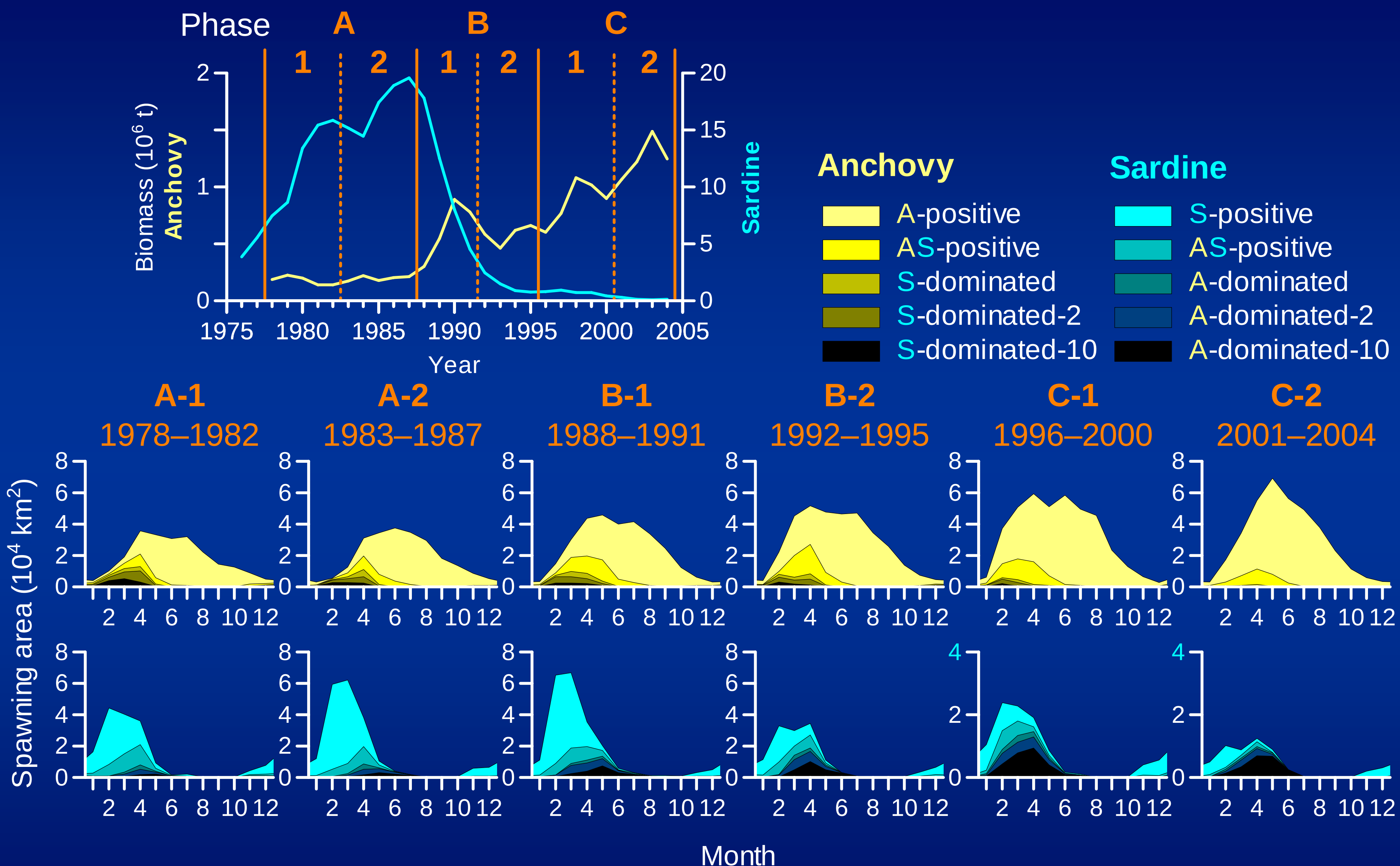
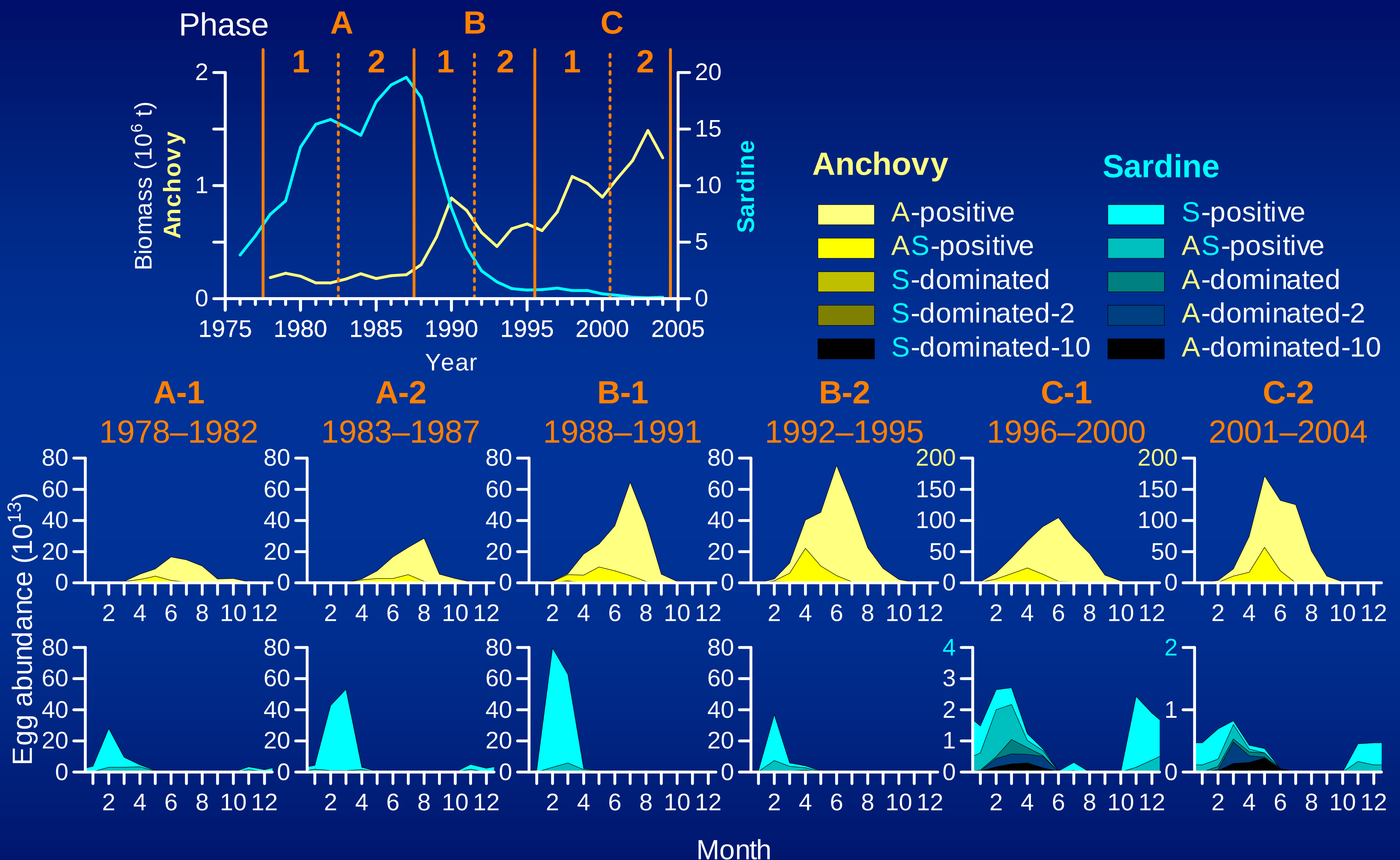
Spawning area



Seasonal changes in spawning areas of anchovy and sardine for different phases with a focus on their spawning overlaps.

Egg abundance



Seasonal changes in egg abundances of anchovy and sardine for different phases with a focus on their spawning overlaps.

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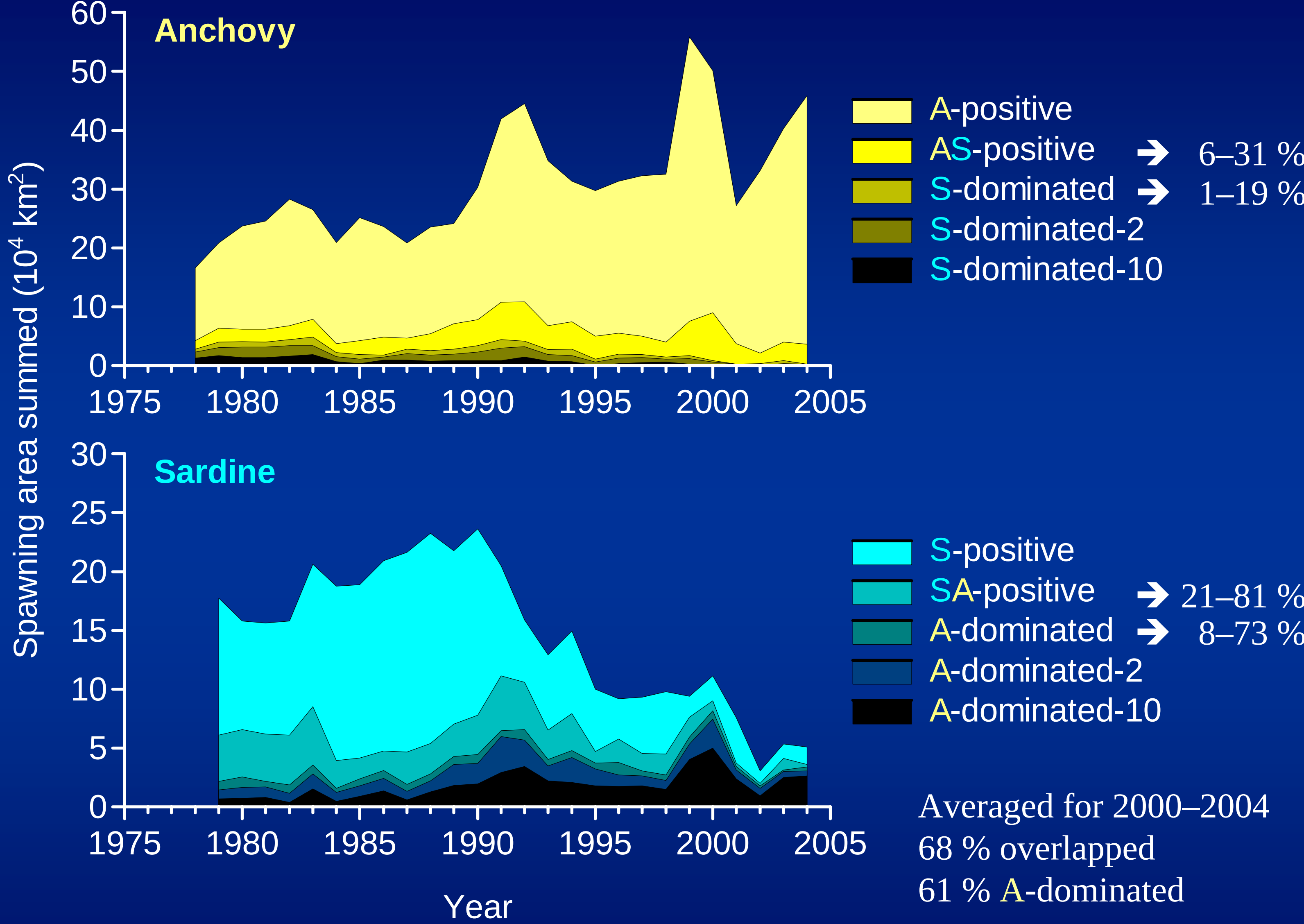
Spawning area summed



Decadal shifts of spawning areas of anchovy (Jan. to Dec.) and sardine (Oct. to Sep.) with a focus on their spawning overlaps.

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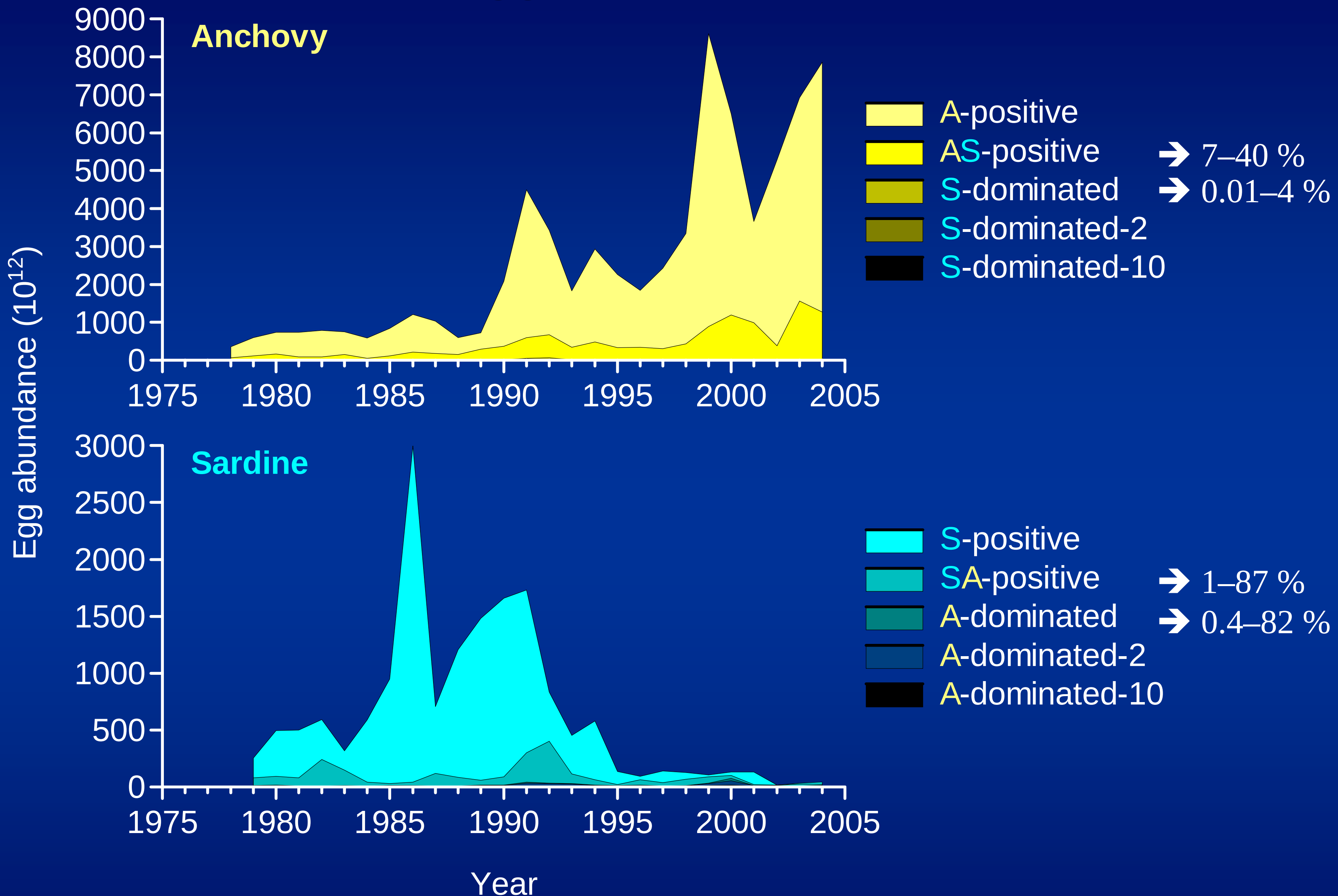
Annual egg abundance



Decadal shifts of egg abundances of anchovy (Jan. to Dec.) and sardine (Oct. to Sep.) with a focus on their spawning overlaps.

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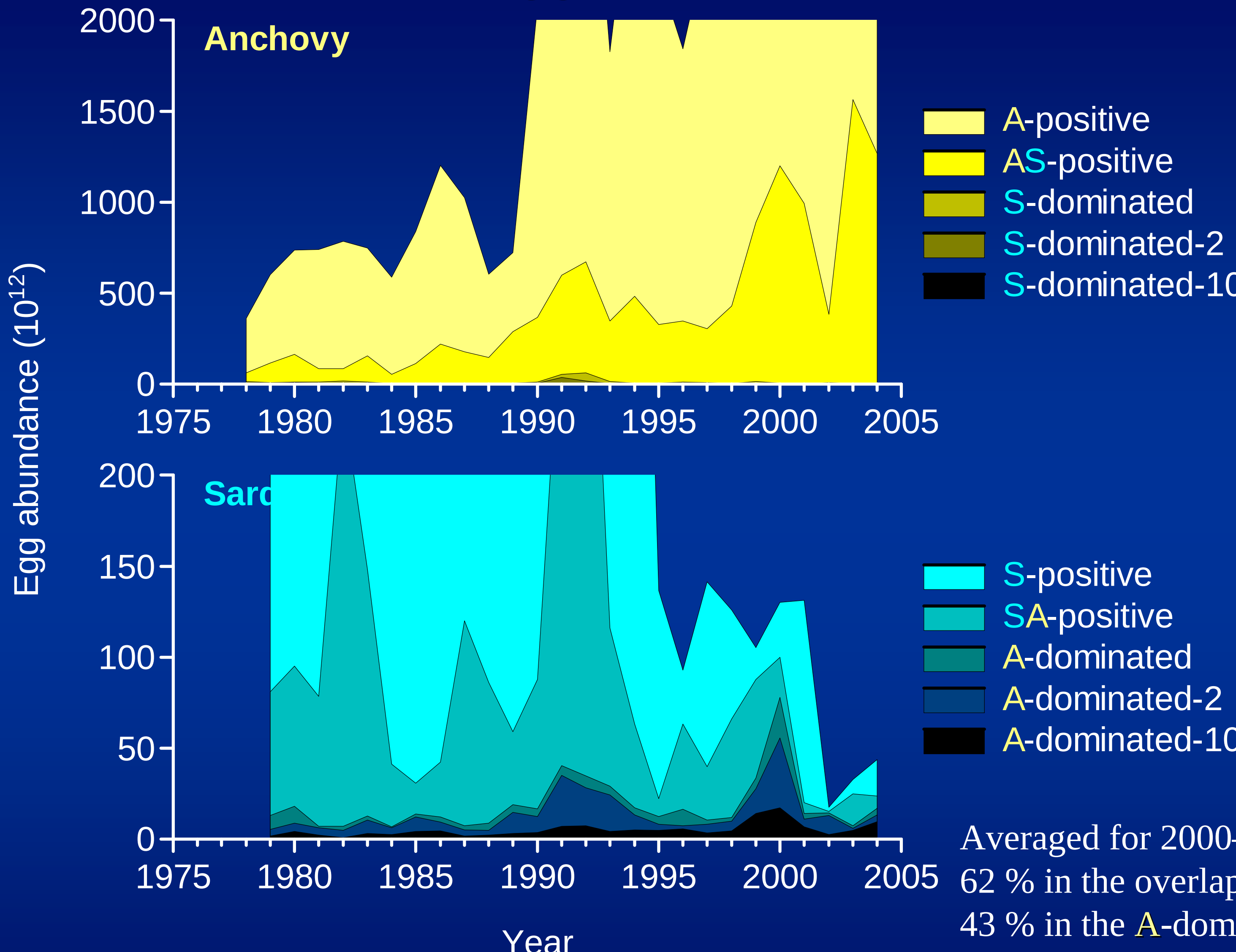
Annual egg abundance



Averaged for 2000–2004
62 % in the overlapped areas
43 % in the A-dominated areas

Decadal shifts of egg abundances of anchovy (Jan. to Dec.) and sardine (Oct. to Sep.) with a focus on their spawning overlaps.

Implications

Spawning overlaps

- **Spawning overlaps were described qualitatively and quantitatively.**
- **Relative contributions of mechanisms would be phase-specific.**
- **Overlaps might be critical for sardine but not for anchovy.**

Factors responsible

- **Spawning periods and temperature optima**
- **Offshore expansion / inshore contraction**

Competition?

- **"School trap" hypothesis (Bakun & Cury 1999): The minor species becomes more minor because of being minor in the mixed-species schools.**

Temperature optima and synergistic factors

- **Sardine could be a "recovery-harder" species than anchovy.**

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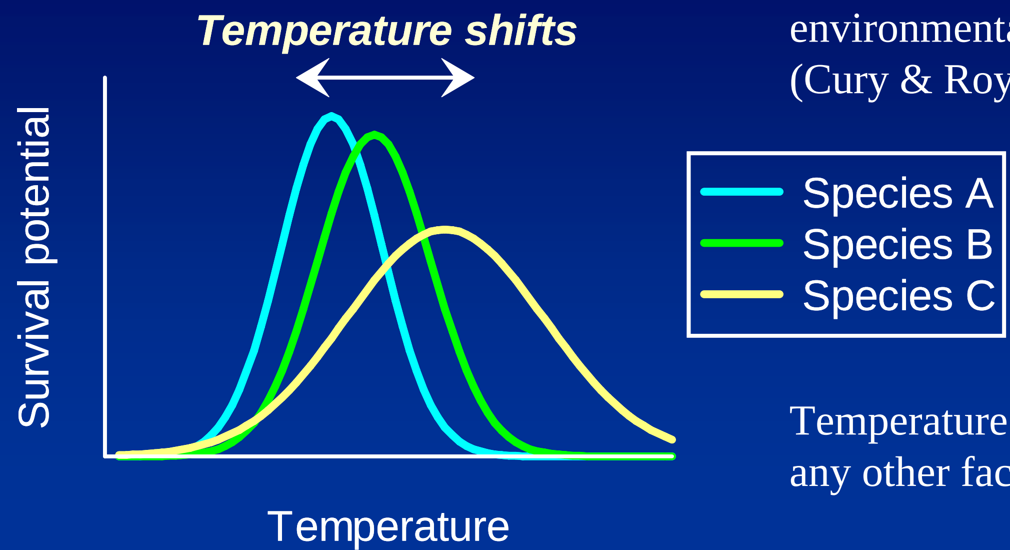
Generalization

An extension of the “optimal environmental window” idea (Cury & Roy 1989 in CJFAS)

Growth rate

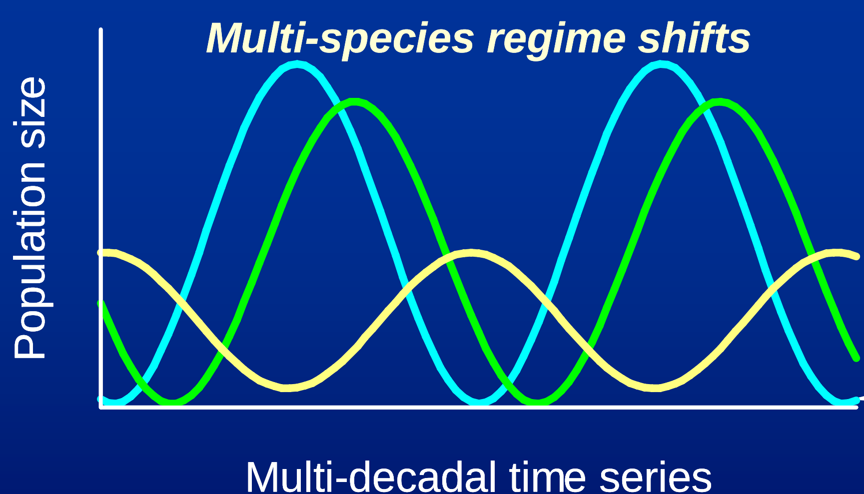
Spawning

Physiological condition



Temperature may be replaced by any other factor.

Relative importance of mechanisms might vary with phases.



Hard to recover with interspecies interactions?

Conceptual framework of multi-species regime shifts based on differential species-specific temperature optima.

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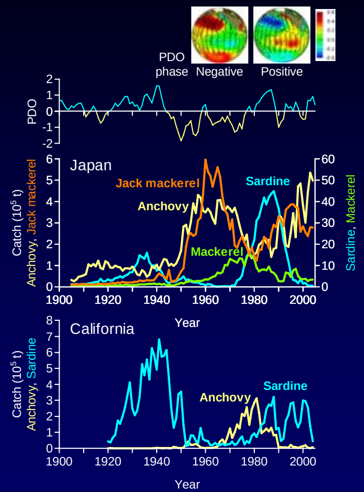
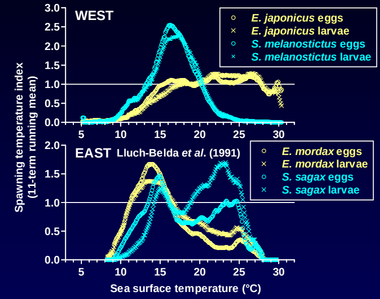
Thank you

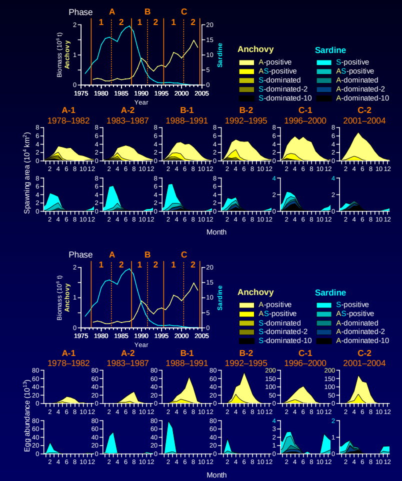
Finish



Multi-species regime shifts

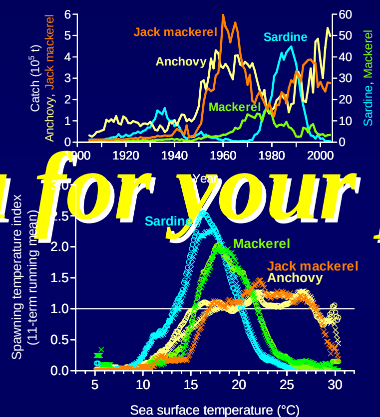


Contrasting spawning temperature optima

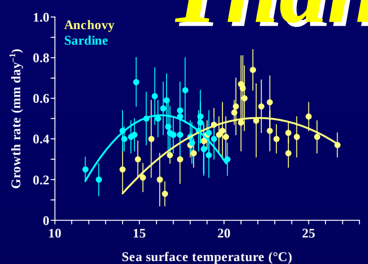


Seasonal changes in spawning overlaps

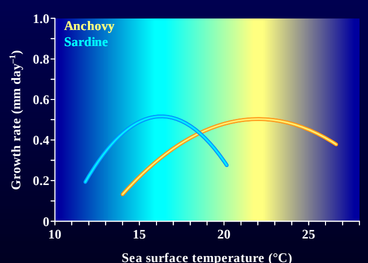
Thank you for your precious time.



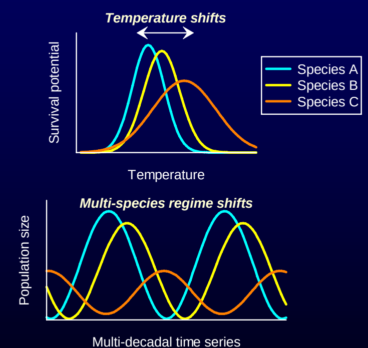
Species-specific temperature optima



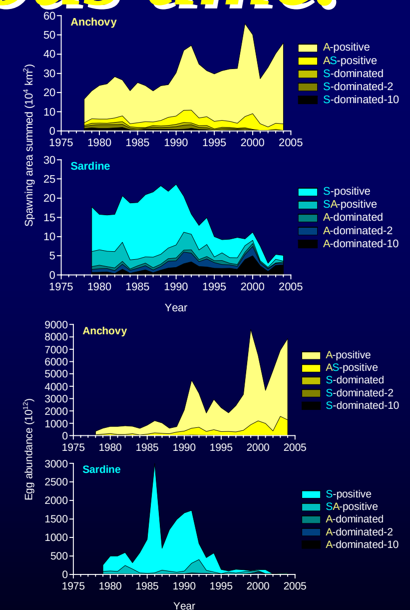
Differential optimal growth temperatures



“Optimal growth temperature” hypothesis



Conceptual framework



Decadal shifts of spawning overlaps