End-to-End Modeling of Marine Ecosystems: can the people and data keep up with the computers?

Kenneth Rose
Louisiana State University

What is End-to-End?

Travers et al. (2007):

(1) aims to represent the entire food web and the associated abiotic environment

(2) requires the integration of physical and biological processes at different scales

(3) implements two-way interaction between ecosystem components

(4) accounts for the dynamic forcing effect of climate and human impacts at multiple trophic levels

Rose (2013):

(1+) multiple species or functional groups be represented at each of the key trophic levels and that top predators in the system are included

(4+)representation of the physics be such that it can be modified by climate inputs and that the human aspect (e.g. fishery) be represented in a dynamic (state-dependent) manner

Development of a Climate-to-Fish-to-Fishery Model:

Implementation in the Eastern Pacific Sardine and Anchovy System

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LSU

RUTGERS UNIVERSITY
MARINE & COASTAL SCIENCES

Ecosystem Studies of Sub-Arctic Seas
ESSAS

CAPaBLE

GLOBEC

CalCOFI est. 1949

NSF

CIB
CENTRO DE INVESTIGACIONES BIOLÓGICAS DEL NOROESTE, S.C.
www.cibnor.gob.mx

ARSC DoD Supercomputing Resource Center

NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

FRA
Fisheries Research Agency

SCRIPPS INSTITUTION OF OCEANOGRAPHY
UC San Diego

INSTITUTO ESPAÑOL DE OCEANOGRAFÍA

CAMEO
COMPARATIVE ANALYSIS OF MARINE ECOSYSTEM ORGANIZATION

LSU

OCEANOGRAPHY & COASTAL SCIENCES
LOUISIANA STATE UNIVERSITY

DoD HPC Modernization Program
SOLVING THE HARD PROBLEMS

North Pacific Marine Science Organization

APN
Asia-Pacific Network for Global Change Research

THE UNIVERSITY OF CALIFORNIA 1868
LET THERE BE LIGHT

INTER-AMERICAN INSTITUTE FOR GLOBAL CHANGE RESEARCH
IAI

NOAA HPCC
High Performance
Computing and
Communications

UAF
UNIVERSITY OF ALASKA FAIRBANKS

Enrique N. Curchitser
Rutgers University

Jerome Fiechter
University of California – Santa Cruz

Kate Hedstrom
Arctic Region Supercomputing Center

Miguel Bernal
FAO – Rome

Sean Creekmore
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Alan Haynie
National Marine Fisheries Service

Dave Checkley
Scripps Institute

Sam McClatchie
National Marine Fisheries Service

Chris Edwards
University of California – Santa Cruz

Tony Koslow
Scripps Institute - CALCOFI

Shin-ichi Ito
Fisheries Research Agency

Salvador Lluch-Cota
CIBNOR (Mexico)

Francisco Werner
NOAA Fisheries - SWFSC

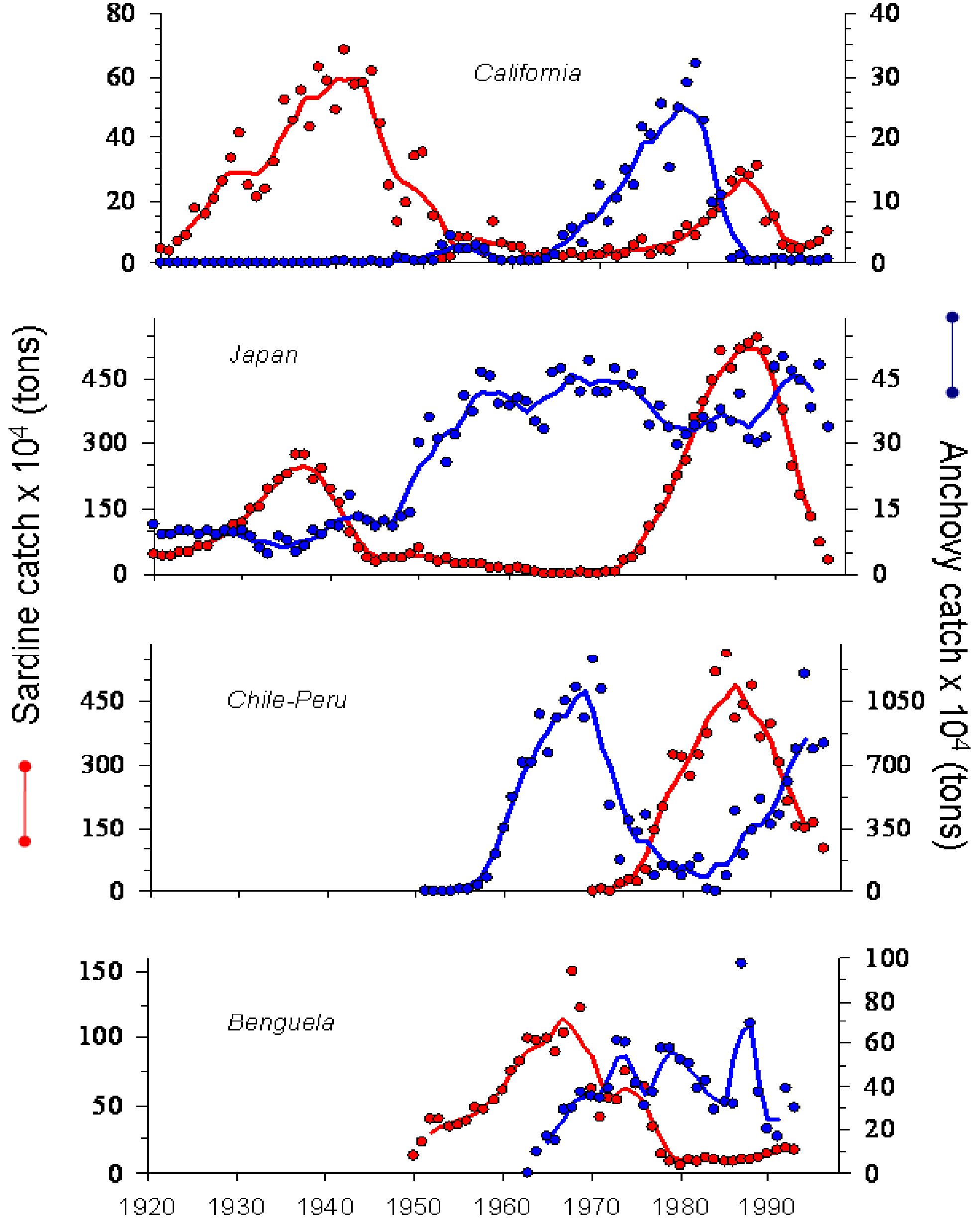
Introduction

- Much emphasis on climate to fish linkages
  - Global change issues
  - Bottom-up, middle-out, top-down controls
- Perceived inadequacies of single-species approach
- Increasing pressure for ecosystem-based considerations in management
- Continuation of the NEMURO effort
  - Multi-species, individual-based, physics to fish model
  - Proof of principle

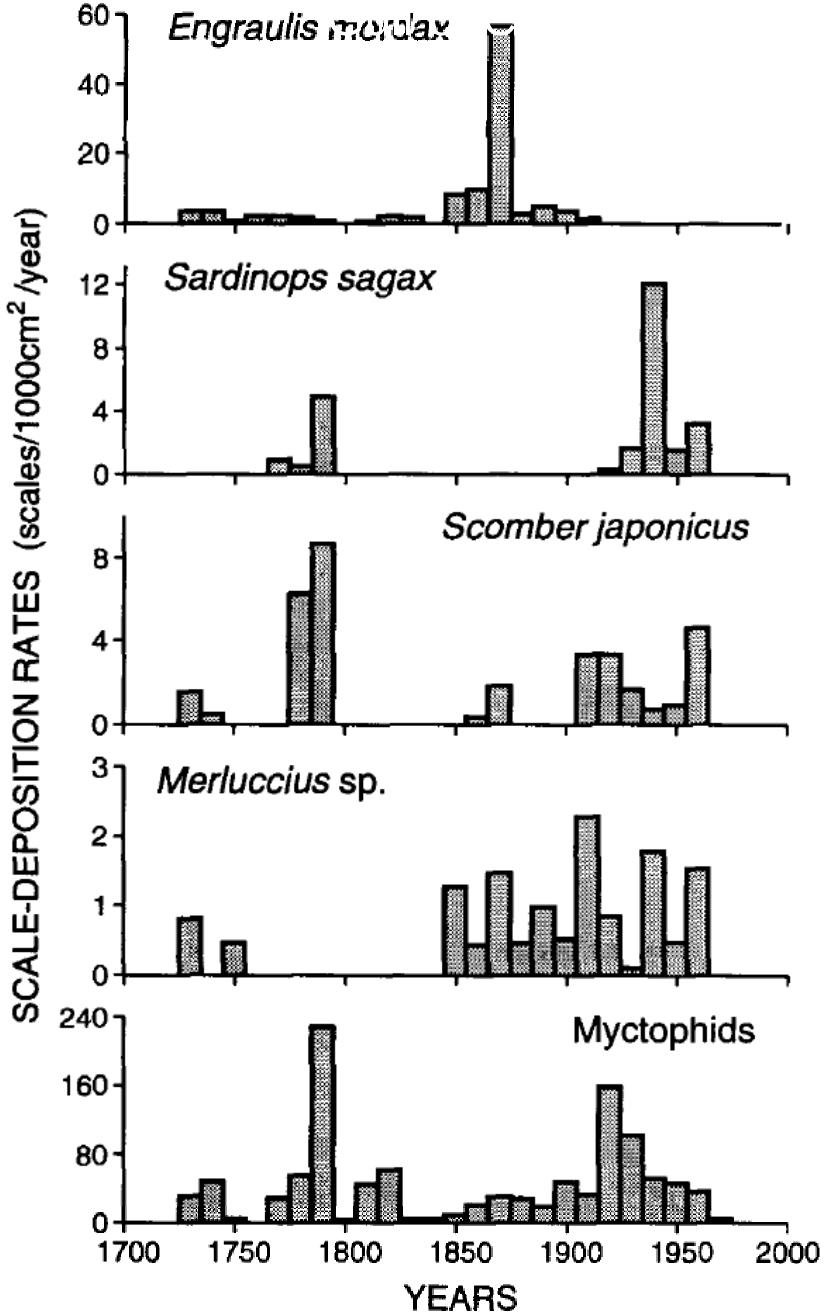
Proof of Principle

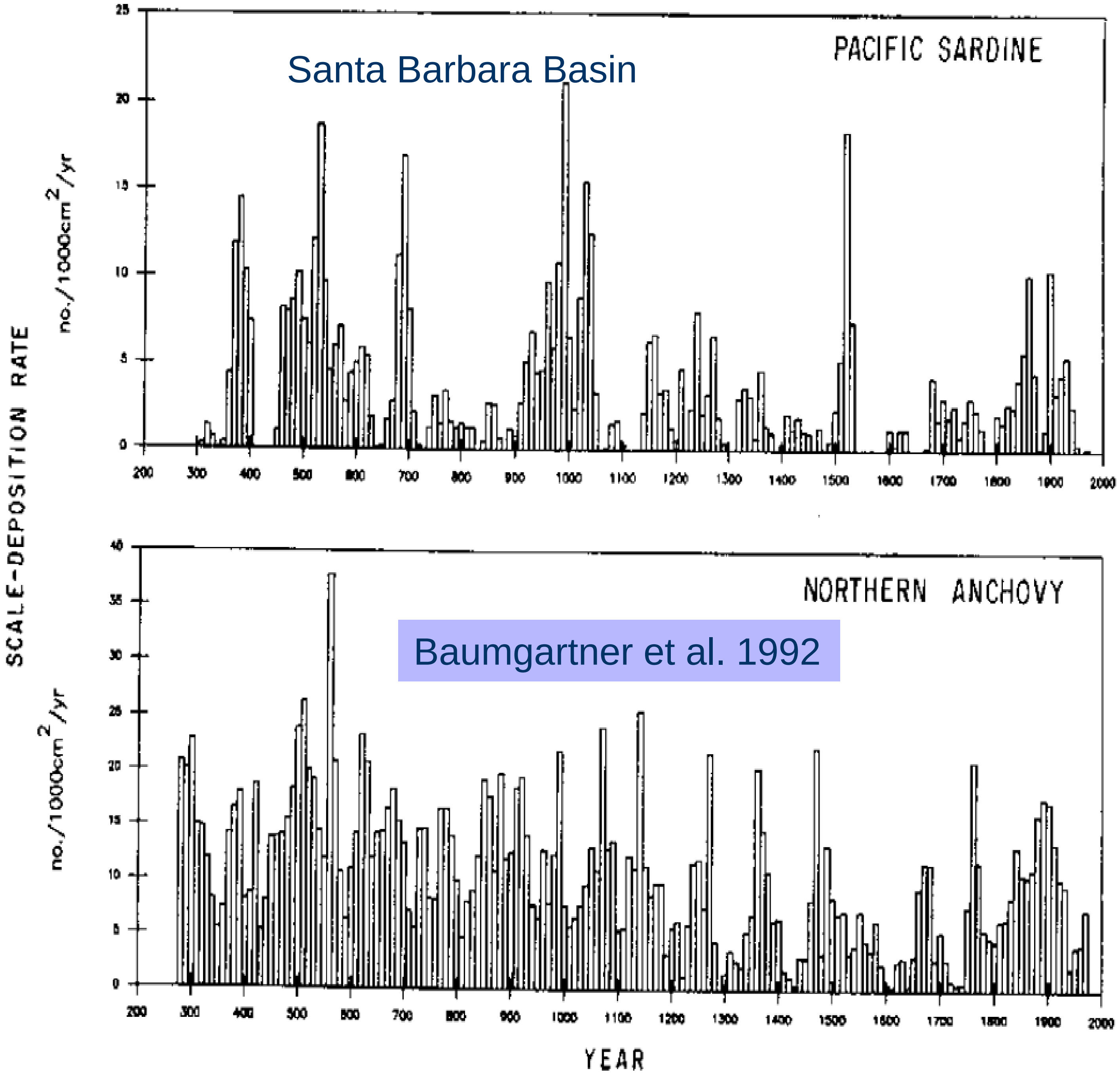
- Sardine – anchovy population cycles
  - well-studied
  - teleconnections across basins

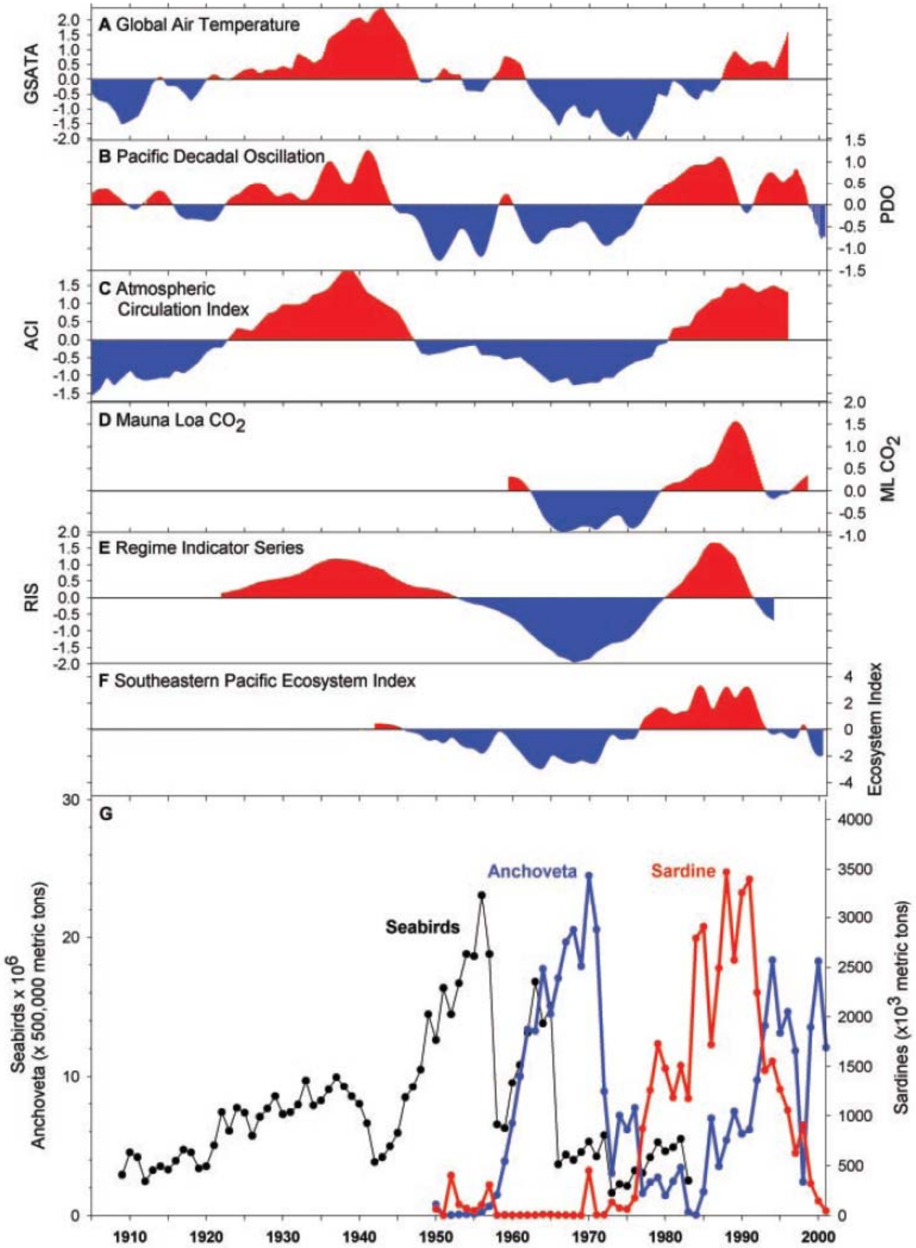
- Good case study
  - Forage fish tightly coupled to NPZ
  - Important ecologically and widely distributed
  - Cycles documented in many systems
  - Recent emphasis on spatial aspects of cycles

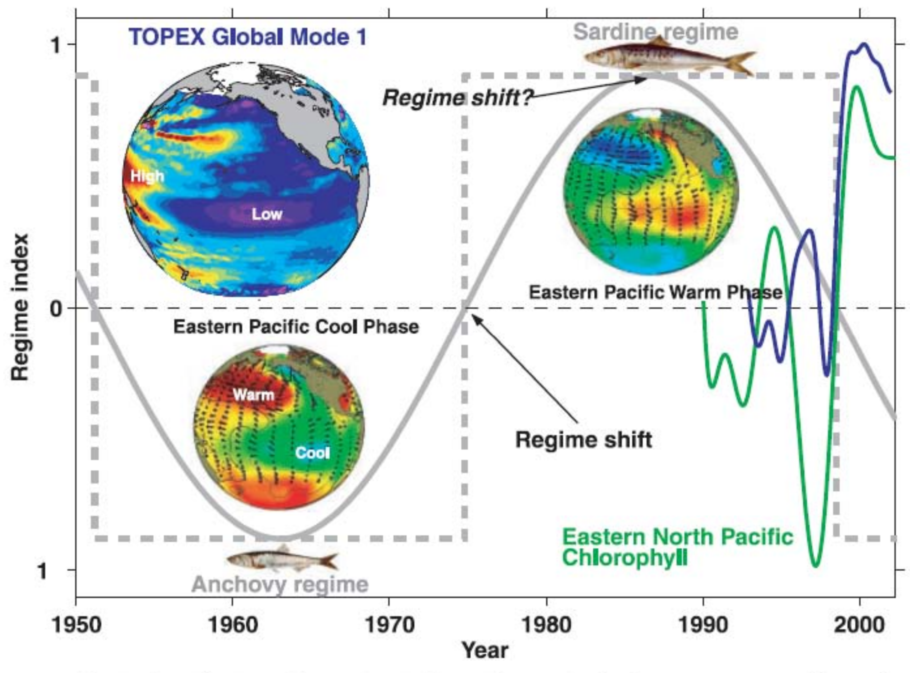


Provided by: Salvador E. Lluch-Cota
Source: Schwartzlose et al., 1999

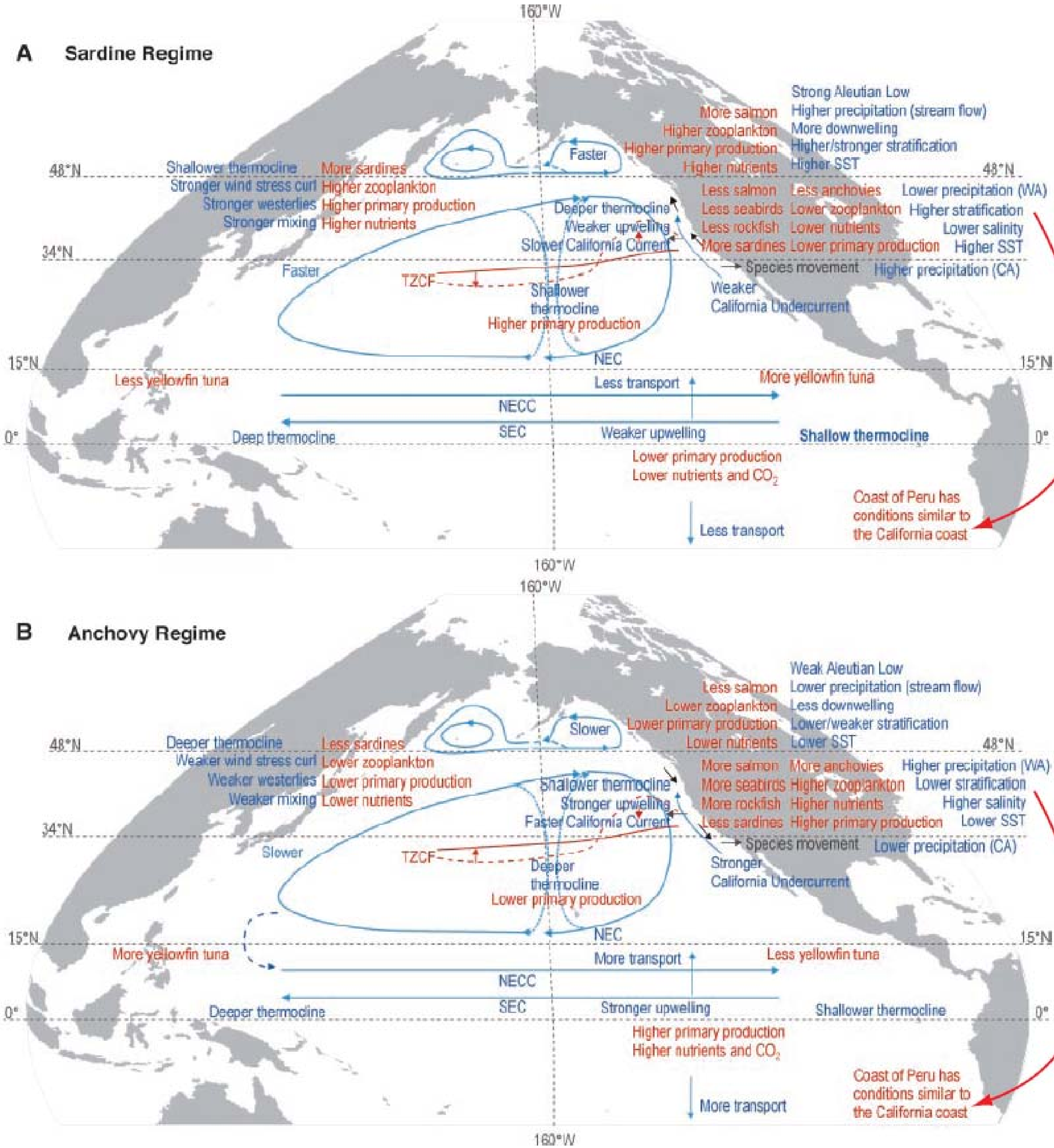

Engraulis mordax
Sardinops sagax
Scomber japonicus
Merluccius sp.
Myctophids
SCALE-DEPOSITION RATES (scales/1000cm2 /year)
YEARS
1700
1750
1800
1850
1900
1950
2000

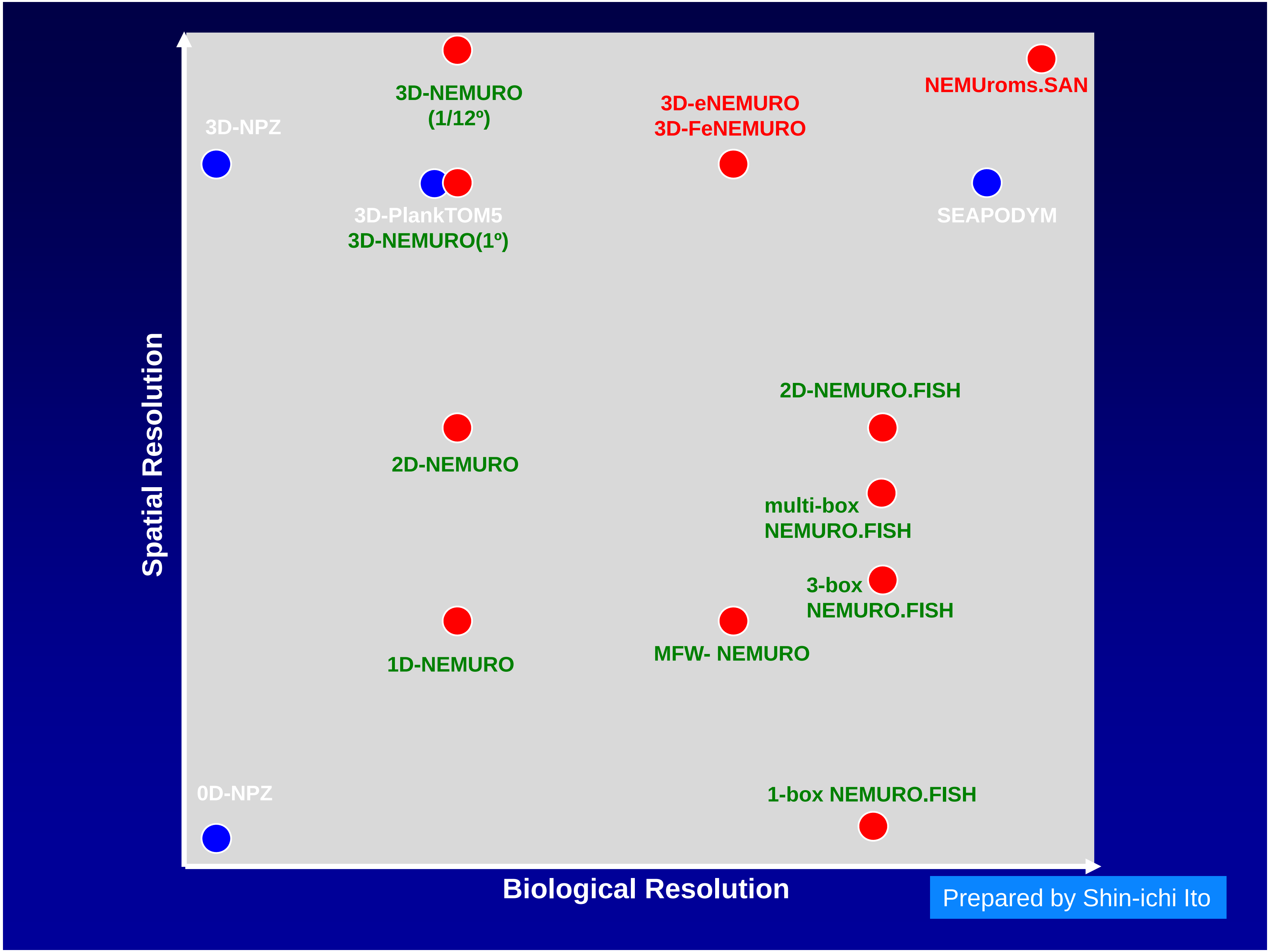

Santa Barbara Basin
PACIFIC SARDINE
NORTHERN ANCHOVY
Baumgartner et al. 1992
SCALE-DEPOSITION RATE
no./1000cm2/yr
YEAR



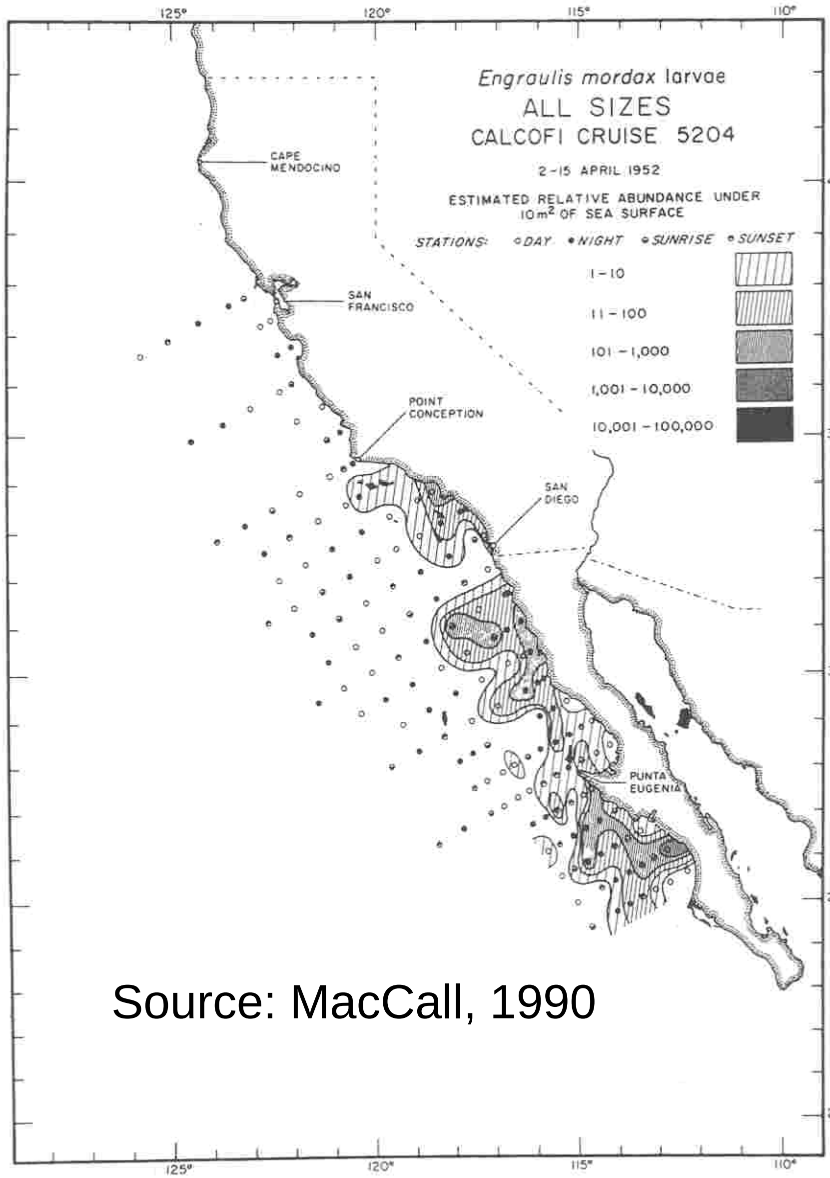


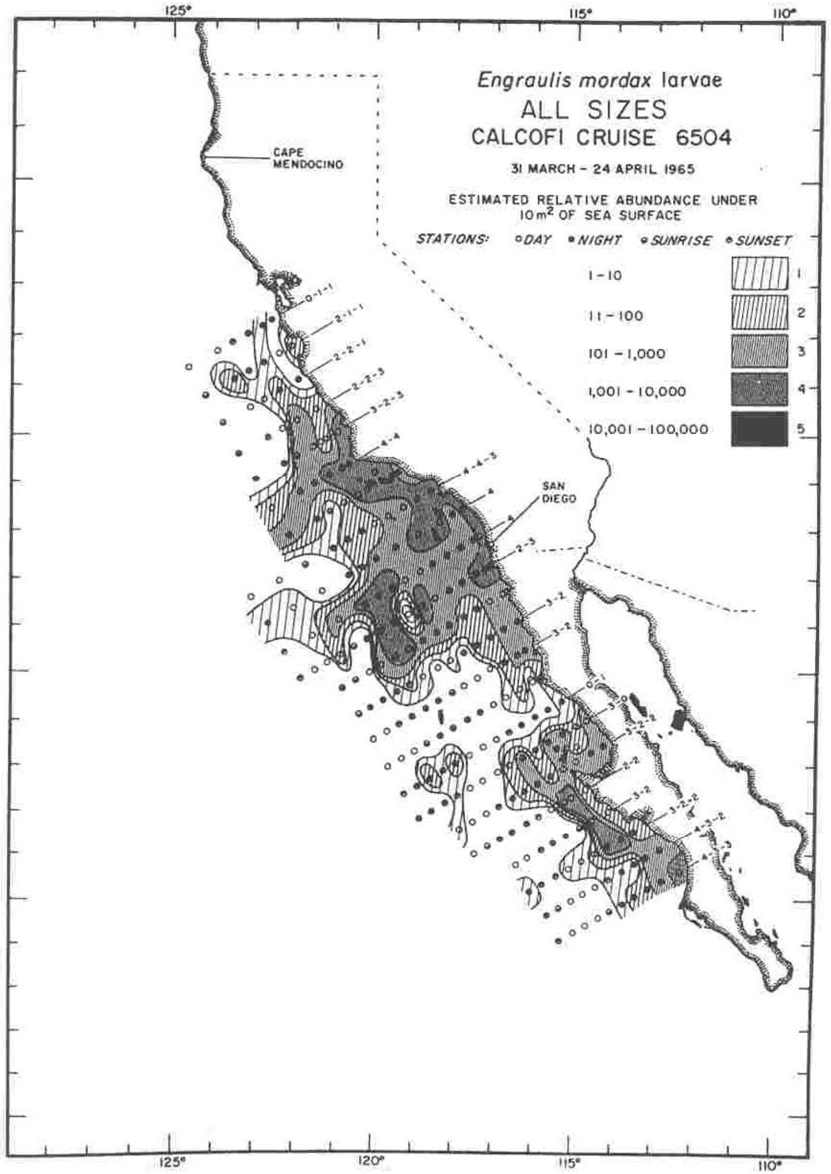
Chavez et al. 2003


A Sardine Regime
Strong Aleutian Low
Higher precipitation (stream flow)
More downwelling
Higher/stronger stratification
Higher SST
More salmon
Higher zooplankton
Higher primary production
Higher nutrients
Faster
Shallower thermocline
Stronger wind stress curl
Stronger westerlies
Stronger mixing
More sardines
Higher zooplankton
Higher primary production
Higher nutrients
Deeper thermocline
Weaker upwelling
Slower California Current
Less salmon
Less seabirds
Less rockfish
More sardines
Less anchovies
Lower zooplankton
Lower nutrients
Lower primary production
Lower precipitation (WA)
Higher stratification
Lower salinity
Higher SST
Higher precipitation (CA)
Species movement
Faster
TZCF
Shallower thermocline
Higher primary production
Weaker California Undercurrent
NEC
Less yellowfin tuna
Less transport
More yellowfin tuna
NECC
SEC
Deep thermocline
Weaker upwelling
Shallow thermocline
Lower primary production
Lower nutrients and CO_2
Less transport
Coast of Peru has conditions similar to the California coast
B Anchovy Regime
Weak Aleutian Low
Lower precipitation (stream flow)
Less downwelling
Lower/weaker stratification
Lower SST
Less salmon
Lower zooplankton
Lower primary production
Lower nutrients
Slower
Deeper thermocline
Weaker wind stress curl
Weaker westerlies
Weaker mixing
Less sardines
Lower zooplankton
Lower primary production
Lower nutrients
Shallower thermocline
Stronger upwelling
Faster California Current
More salmon
More seabirds
More rockfish
Less sardines
More anchovies
Higher zooplankton
Higher nutrients
Higher primary production
Higher precipitation (WA)
Lower stratification
Higher salinity
Lower SST
Lower precipitation (CA)
Species movement
Slower
TZCF
Deeper thermocline
Lower primary production
Stronger California Undercurrent
NEC
More yellowfin tuna
More transport
Less yellowfin tuna
NECC
SEC
Deeper thermocline
Stronger upwelling
Shallower thermocline
Higher primary production
Higher nutrients and CO_2
More transport
Coast of Peru has conditions similar to the California coast
160°W
48°N
34°N
15°N
0°


3D-NEMURO
(1/12º)
3D-eNEMURO
3D-FeNEMURO
NEMUroms.SAN
3D-NPZ
3D-PlankTOM5
3D-NEMURO(1º)
SEAPODYM
Spatial Resolution
2D-NEMURO.FISH
2D-NEMURO
multi-box
NEMURO.FISH
3-box
NEMURO.FISH
1D-NEMURO
MFW- NEMURO
0D-NPZ
1-box NEMURO.FISH
Biological Resolution
Prepared by Shin-ichi Ito

California Current





Source: MacCall, 1990


MARINE and
COASTAL SCIENCES

Why IBM for Fish

- Natural unit in nature
- Allows for local interactions and complex systems dynamics
- Complicated life histories
- Experience (memory) is important
- Plasticity and size-based interactions
- Conceptually easier movement

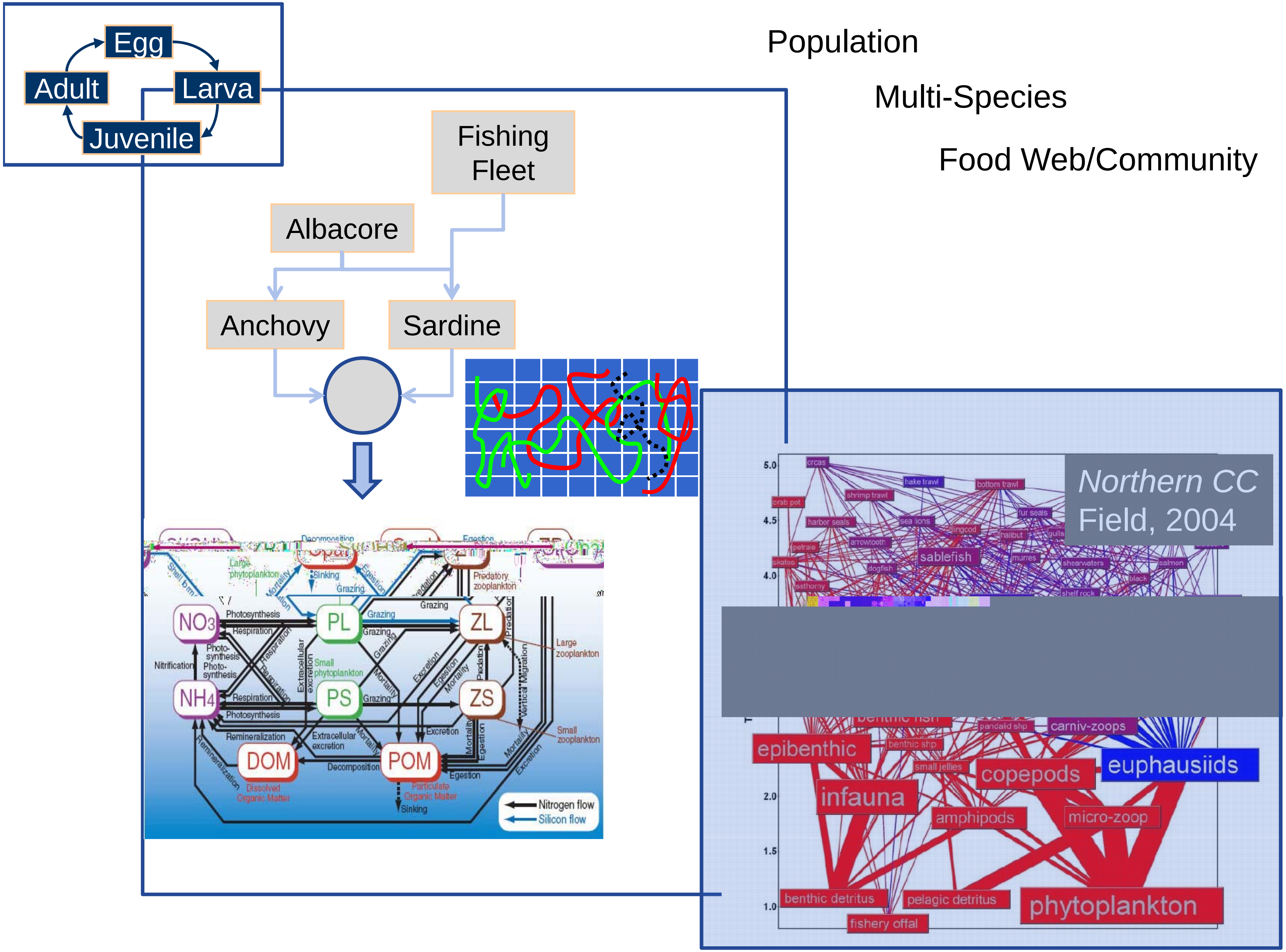
Challenge

- How to combine models with different temporal and spatial scales
- No general theory
  - Modeling as judgement
- Including human dimensions
- Working across disciplines

Population

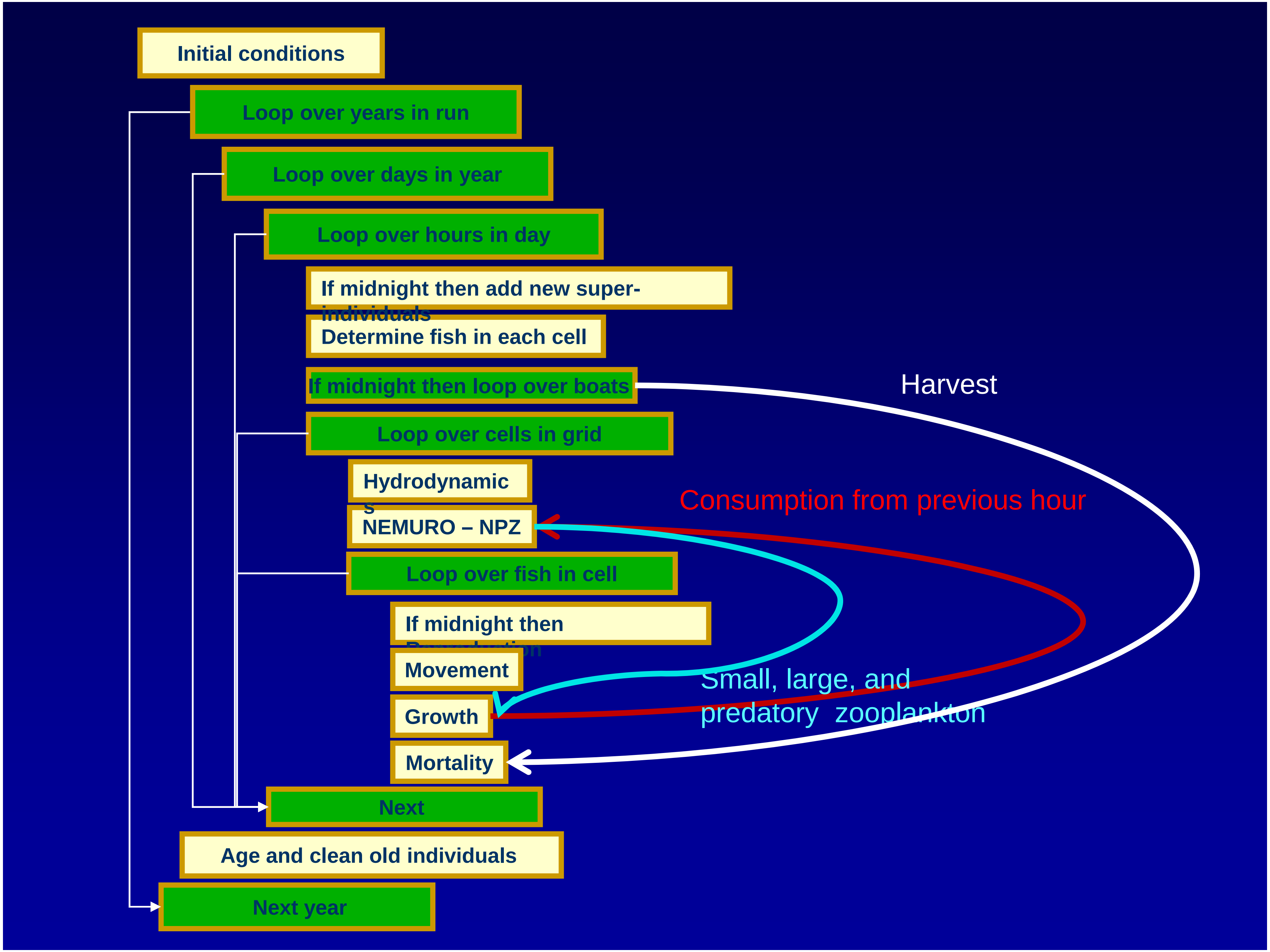
Multi-Species

Food Web/Community



Coupled Models

- Model 1: 3-D ROMS for physics
- Model 2: NEMURO for NPZ
- Model 3: Multiple-species IBM for fish
- Model 4: Fishing fleet dynamics
- Today: progress to date
  - Solved many of the numerical and bookkeeping
  - Next is to add realistic biology

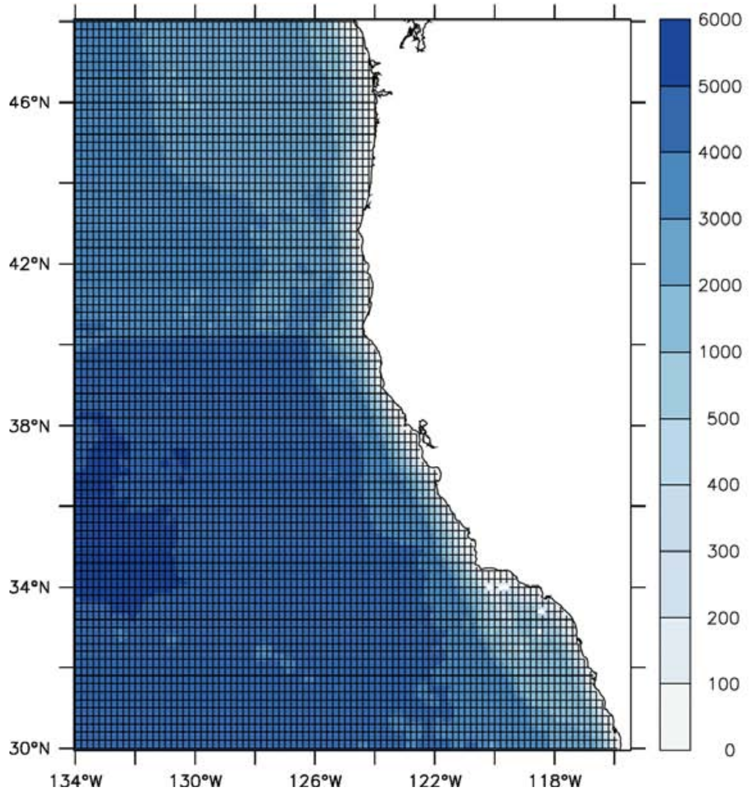

Initial conditions
Loop over years in run
Loop over days in year
Loop over hours in day
If midnight then add new super-individuals
Determine fish in each cell
If midnight then loop over boats
Harvest
Loop over cells in grid
Hydrodynamics
Consumption from previous hour
NEMURO – NPZ
Loop over fish in cell
If midnight then Reproduction
Movement
Small, large, and predatory zooplankton
Growth
Mortality
Next
Age and clean old individuals
Next year

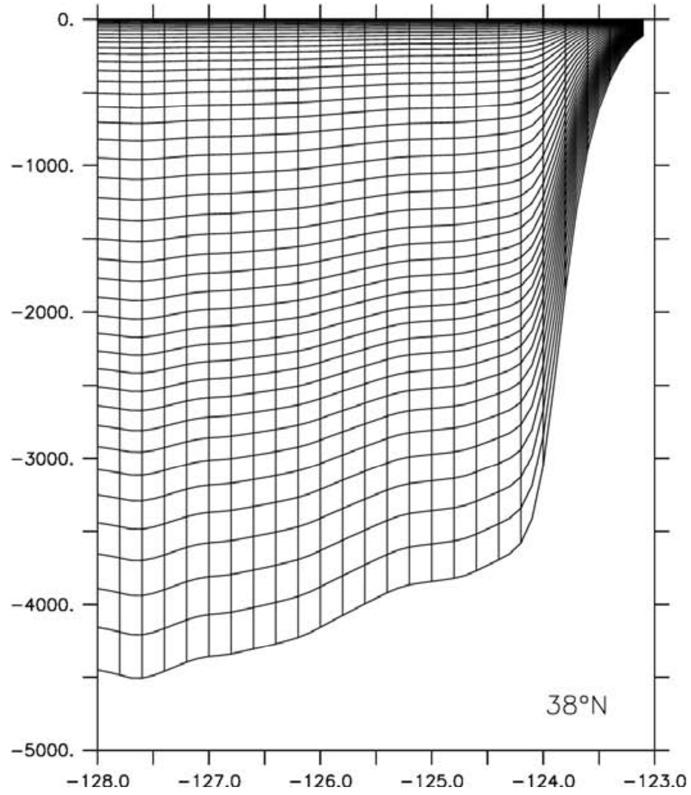
Model 1: ROMS

- Grid:

  10 km

  42 levels

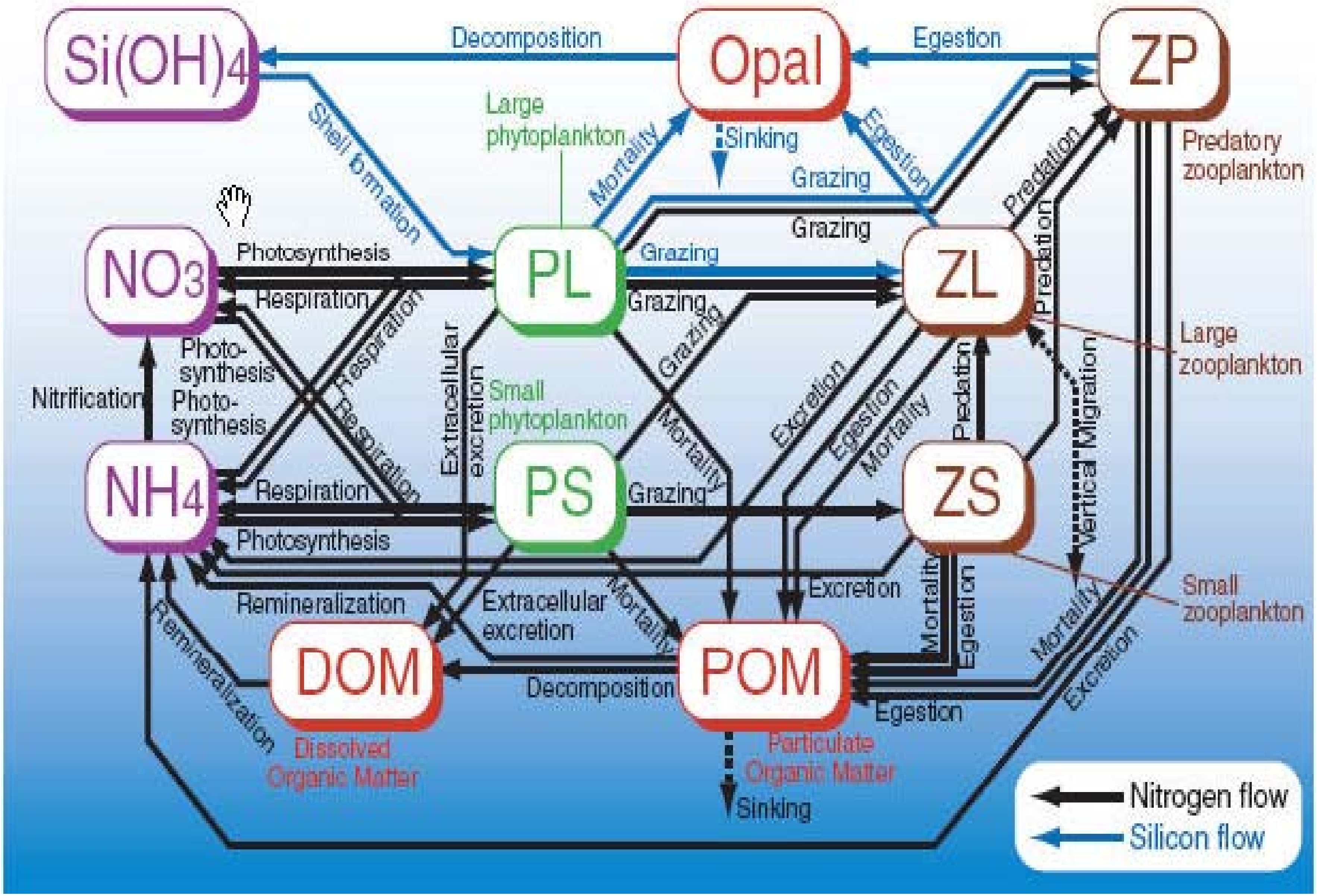




- 900 s

- Run duration: 40 years (1958-2007)

Model 2: NEMURO



Model 3: Fish IBM

Species Types

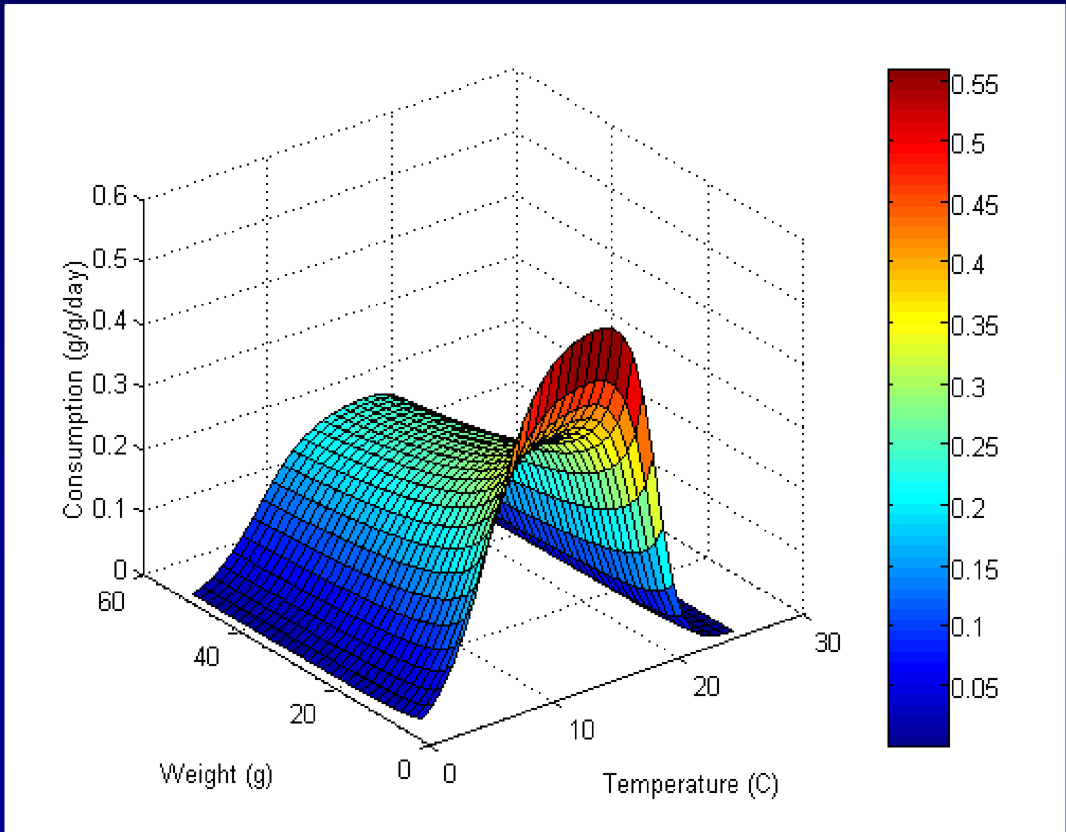
- Sardines and anchovy – fully modeled
  - Reproduction, growth, mortality, movement
  - Competitors (food, space) and predators
- Migratory predator
  - Enter and exit the grid
  - Movement and consumption of sardine and anchovy only
  - “albacore”

Fish IBM: Full members

- Life cycle framework
  - Easy to say, creates bookkeeping challenge
  - Cannot keep adding new fish to the model

- Vital processes:
  - Growth ⟸ ROMS temp and NEMURO zoop
  - Development ⟸ ROMS temp
  - Reproduction ⟸ ROMS temp
  - Mortality ⟸ constant, starvation, predation, fishing
  - Movement ⟸ ROMS transport and temp; kinesis

$$W_{t+\Delta t} = W_t + [(A \cdot C - R) \cdot W_t \cdot \left(\frac{e_f}{e_z}\right) - \frac{E}{e_f}] \cdot \frac{\Delta t}{86400}$$



E was computed as J/day based on whether a batch was produced at midnight

Condition and projected J needed for a batch

Batch developed based on temperature

Resting period

Fish IBM: Mortality

- Fish eating fish
  - Individual albacore eating individual fish
- Natural (background)
- Harvest of sardine
  - Individual fishing boats
- $Worth_{i,t+1} = Worth_{i,t} e^{-\sum M_i}$

Movement

- A major challenge is modeling movement
  - Eggs and larvae maybe reasonably simulated with particle-tracking
  - Juveniles and adults require behavioral approaches

- Wide range of temporal and spatial scales
  - Often scales determined by other submodels
  - Compatibility issues

Movement

- Many approaches have been proposed
  - $X(t+1) = X(t) + V_x(t)*\Delta t$
  - $Y(t+1) = Y(t) + V_y(t)*\Delta t$
  - $Z(t+1) = Z(t) + V_z(t)*\Delta t$
  - Determine the cell

Fish IBM: Movement

- Eggs, yolk-sac, and larvae move by physics
  - assumed at surface for now
- Juveniles and adults move by behavior
  - Day-to-day
  - Seasonal migrations
- Each individual has a continuous x, y, and z position
- Position mapped to 3-D grid every 900 sec to determine cell location and local conditions

Kinesis Movement

(Humston et al. 2004)

- X and Y velocities of each individual is computed daily and applied every 900 sec

- Kinesis behavior (response to temperature and food)

$$V_x = I_x + R_x$$

$$V_y = I_y + R_y$$

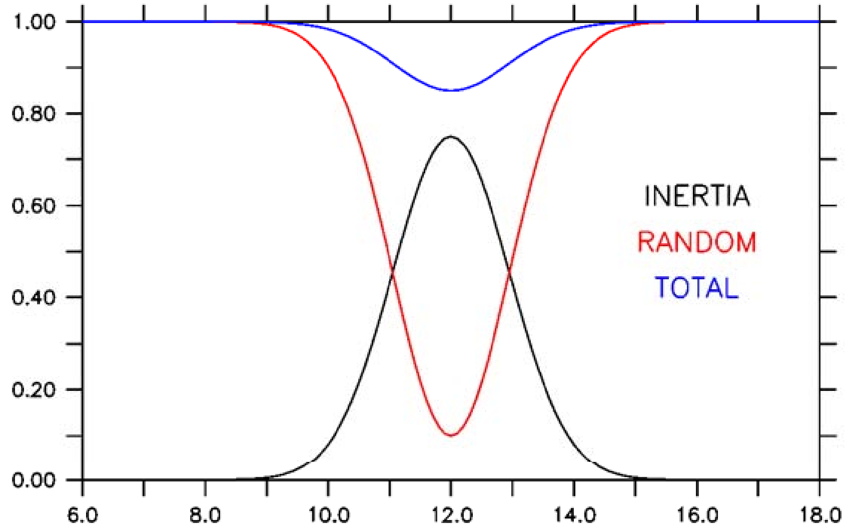
$$V_z = I_z + R_z$$

- Kinesis is the sum of random (R) and inertial (I) velocities (happiness)

Fish IBM: Kinesis Movement

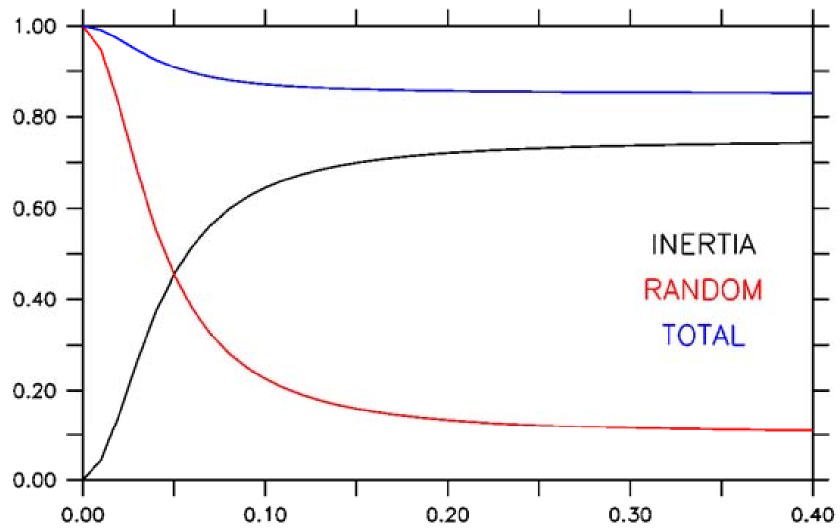
- Inertial:

$$I_x = V_x(t-1) \times f(TorP)$$



- Random:

$$R_x = r \times g(TorP)$$



Model 4: Fishing Fleet

- 100 boats and 5 ports - sardine
- Day boats so complete a trip in 24 hours
- Daily evaluation
- Compute expected net revenue (ENR) based on:
  - Perceived CPUE (10-day average)
  - Price per pound
  - Cost per km
  - Return to nearest port

Numerical Details

- Major numerical and bookkeeping challenges
- Solving everything simultaneously
  - Two-way coupling between fish and zooplankton
- We are working within ROMS source code, using the available particle tracking features

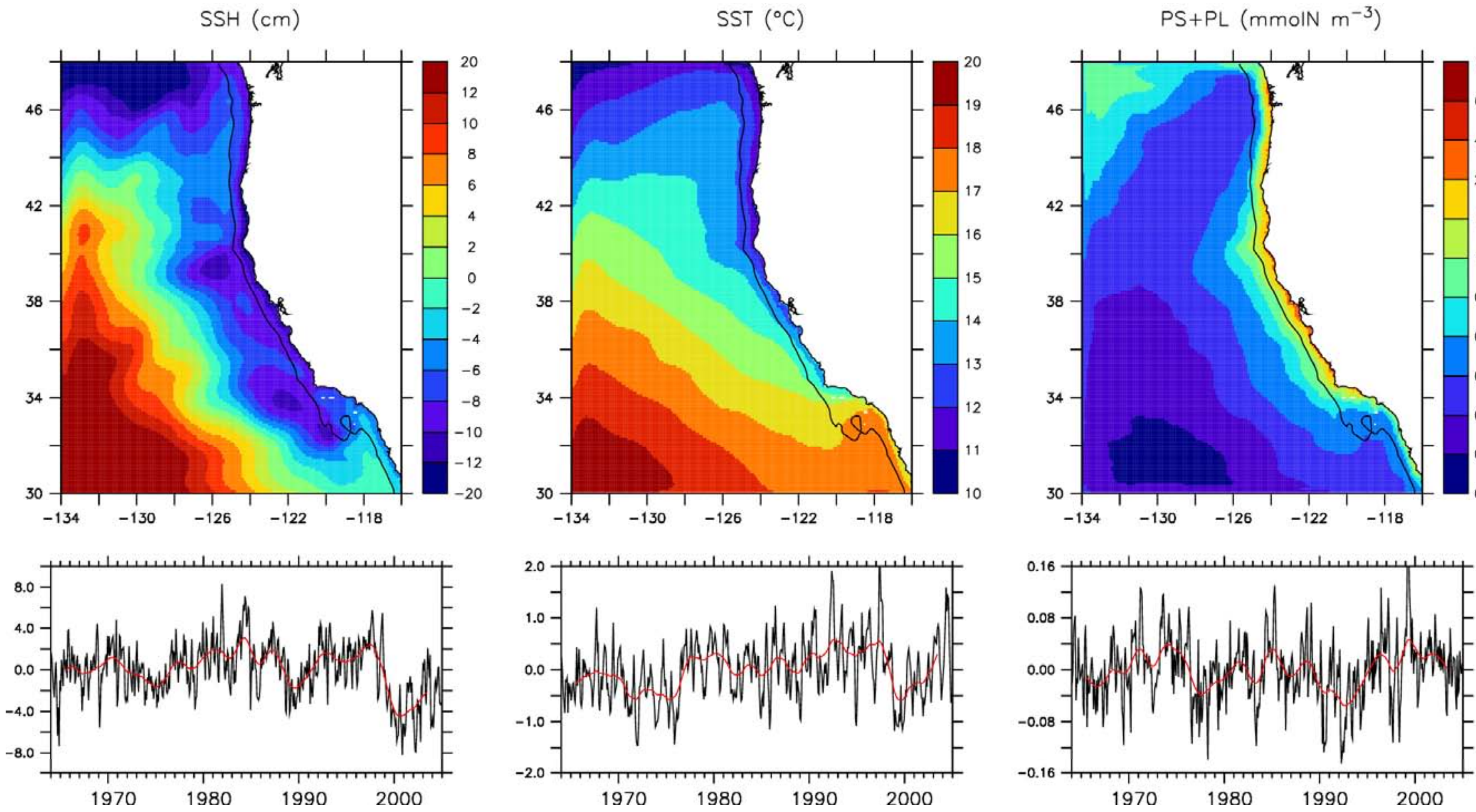
Numerical Details

- Computing speed, mass balance, Eulerian with Lagrangian, and full life cycle
  - Interpolate zooplankton fields - correct removal
  - “halo” computing for albacore to eat fish on different processor
  - Super-individual approach (adult produce young who become adults)

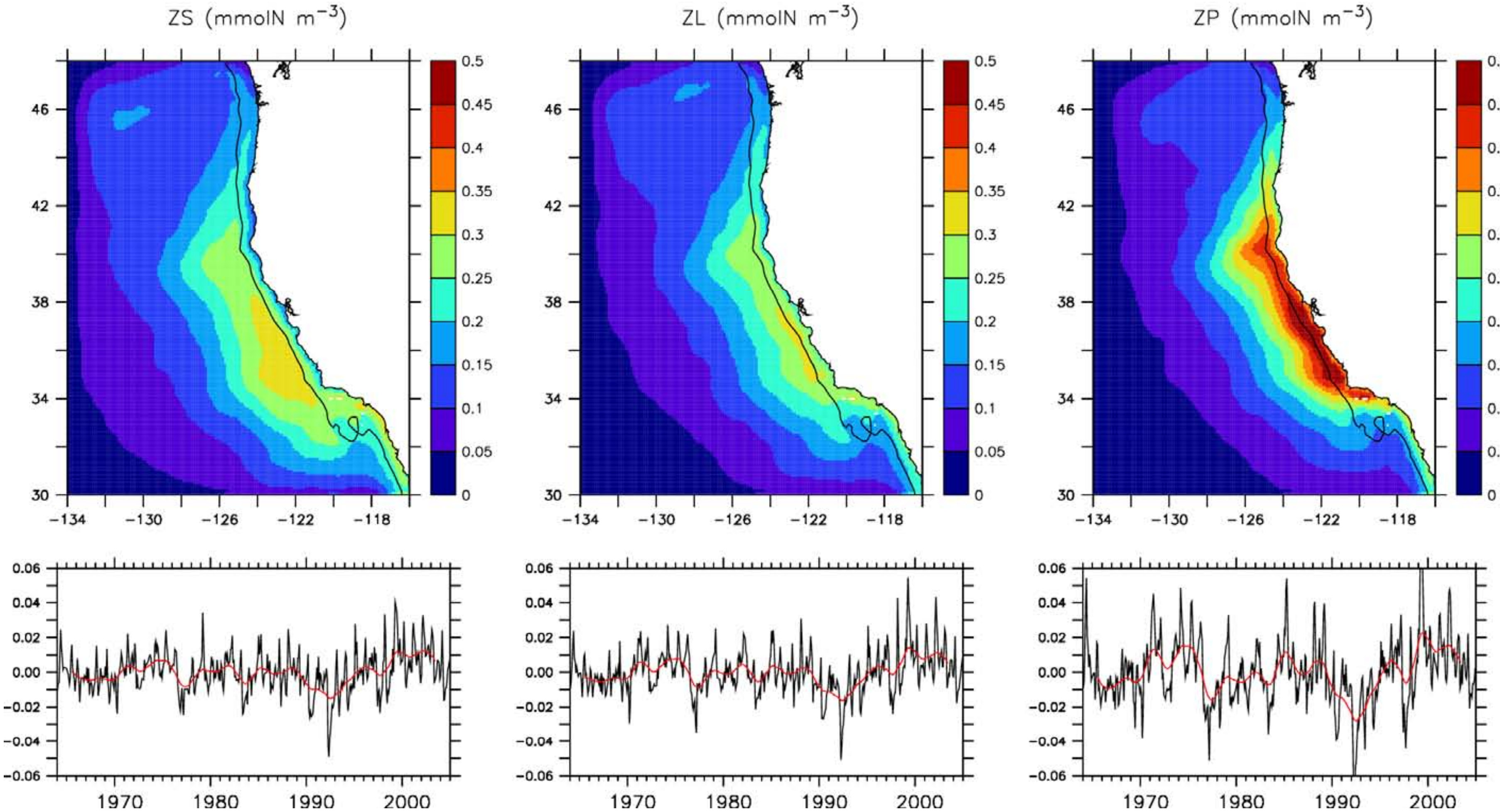
- Code is thousands of lines

Model Simulations

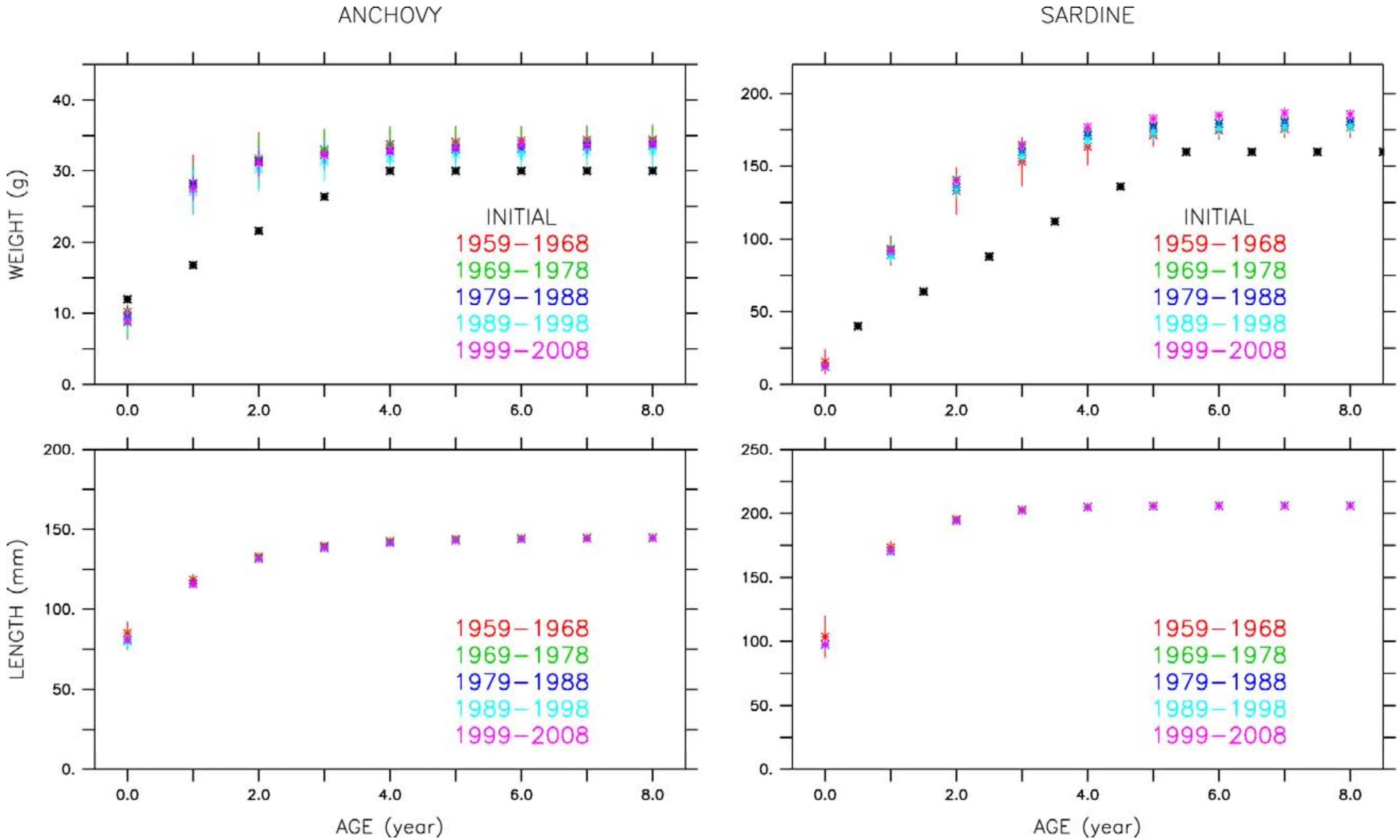
- Fully coupled model
- 1958 to 2007
- Parallel computing (MPI)
  - UC Shared Research Computing Services (ShaRCS) - Berkeley
  - 128 CPUs (Xeon 2.4 GHz, 272 nodes, 8 cores/node, 3 GB/core)
  - 40-year run with 20,000 super-individuals takes ~2 days
  - NCAR BigBlue, DOE Artic Computing Center; Earth Simulator

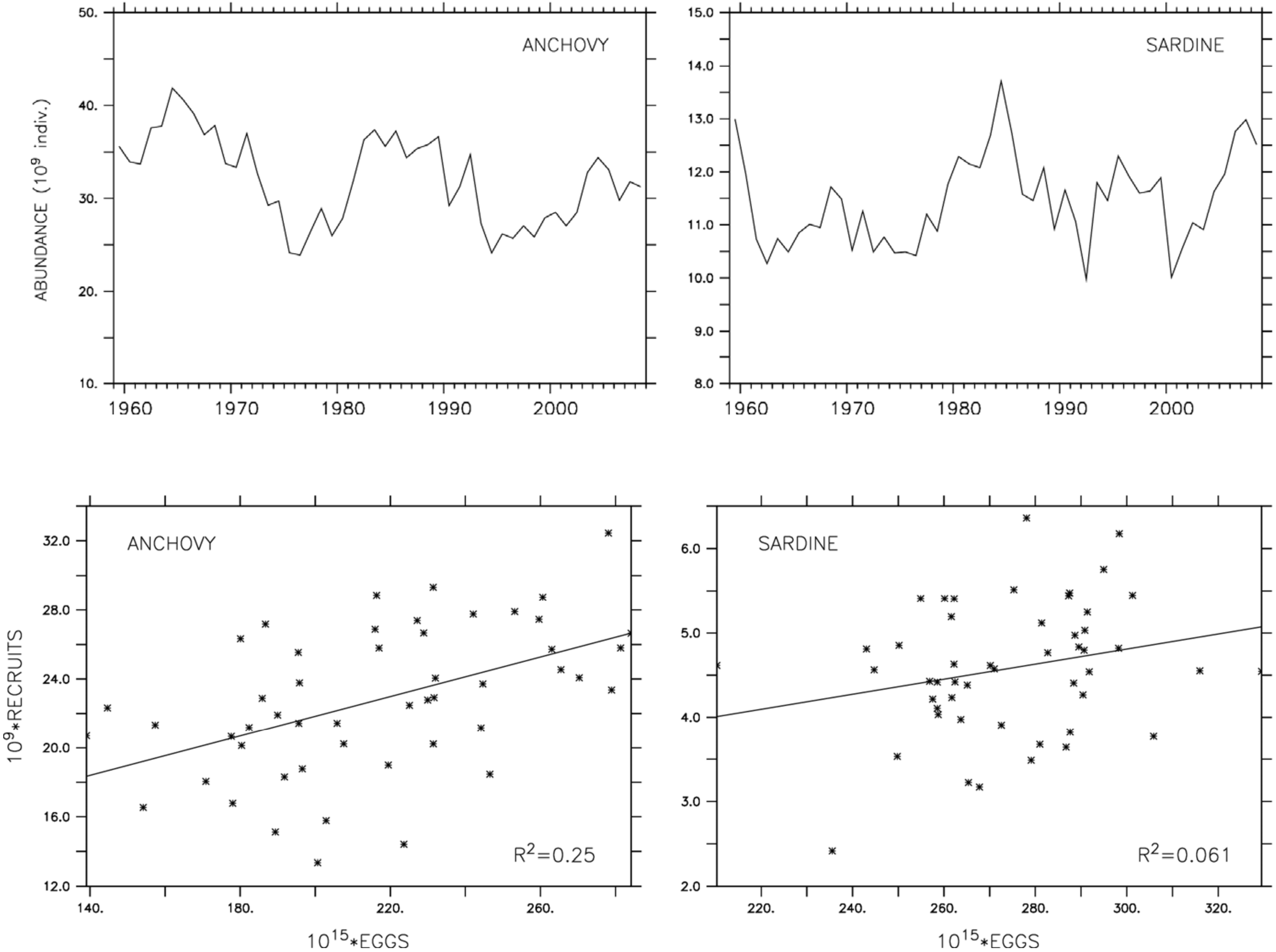


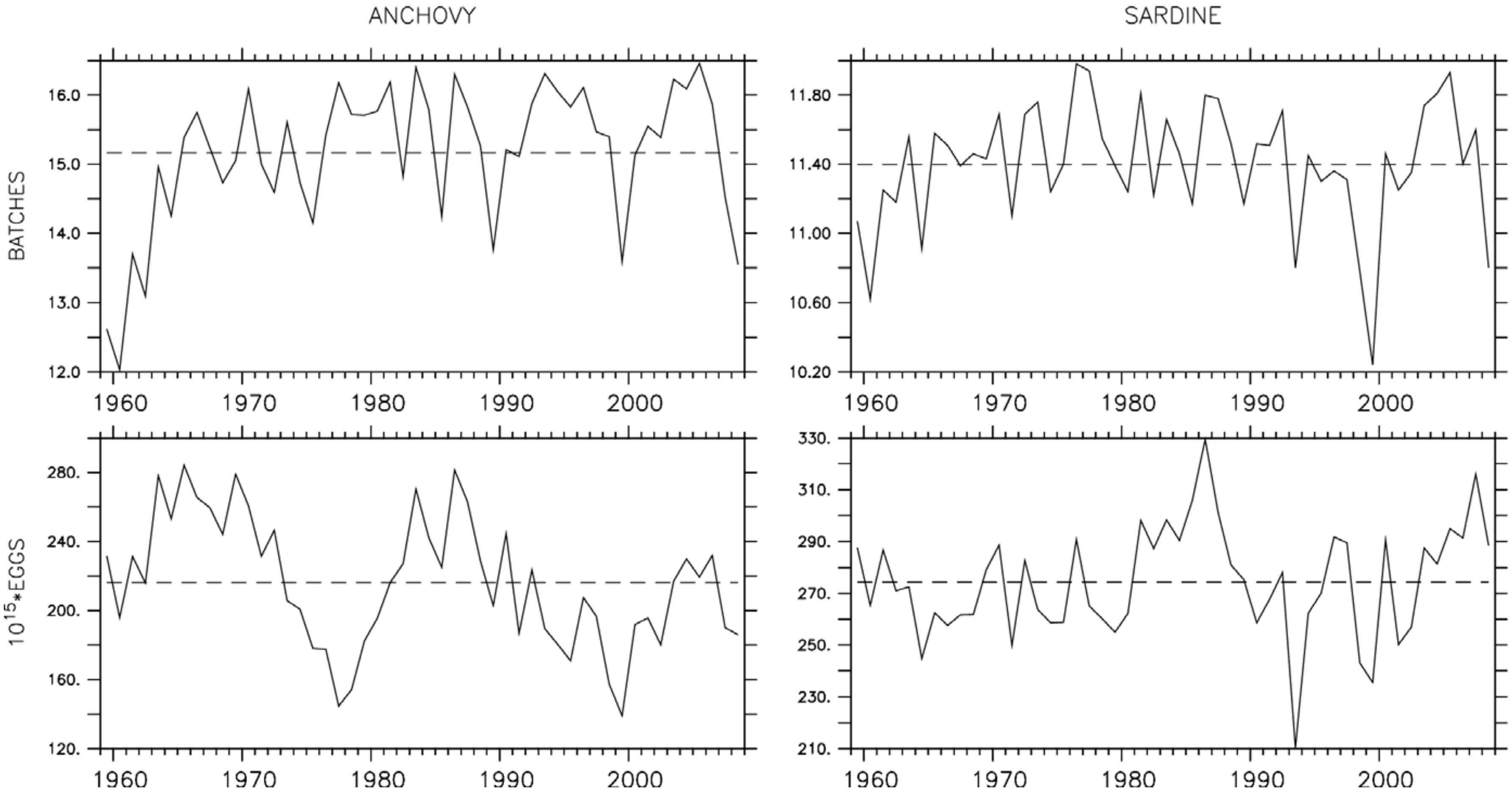
SSH (cm)
SST (°C)
PS+PL (mmolN m^{-3})
20
12
10
8
6
4
2
0
−2
−4
−6
−8
−10
−12
−20
19
18
17
16
15
14
13
11
10
6.3
2.5
1.6
1
0.63
0.4
0.25
0.16
0.1
46
42
38
34
30
−134
−130
−126
−122
−118
8.0
4.0
0.0
−4.0
−8.0
2.0
1.0
−1.0
−2.0
0.16
0.08
0.00
−0.08
−0.16
1970
1980
1990
2000

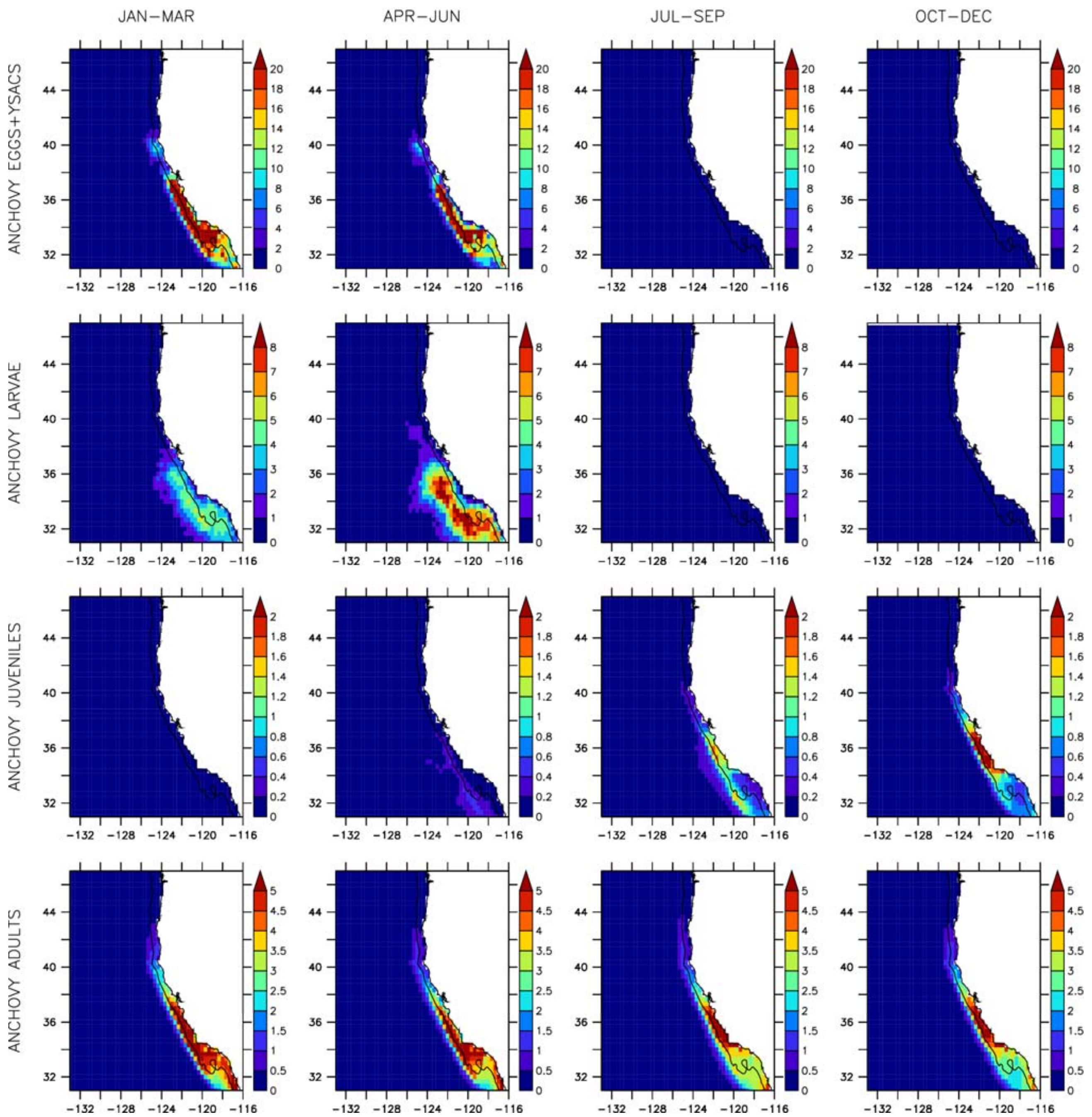


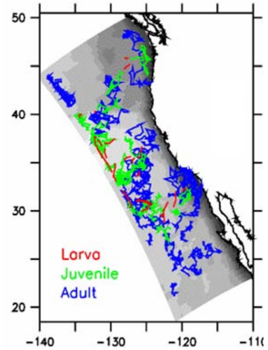
ZS (mmolN m^{-3})
ZL (mmolN m^{-3})
ZP (mmolN m^{-3})
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
46
42
38
34
30
−134
−130
−126
−122
−118
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
1970
1980
1990
2000

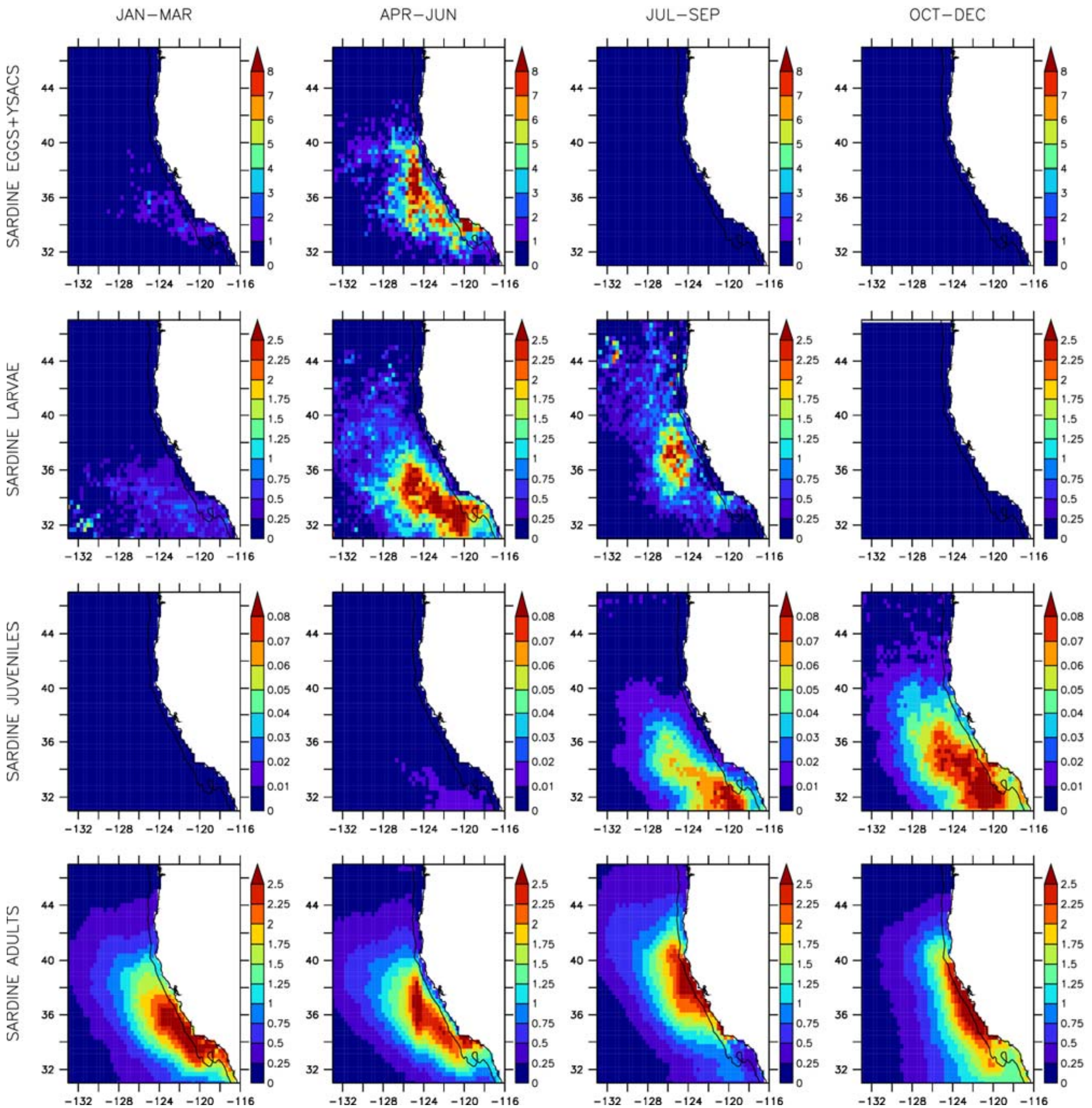

ANCHOVY
SARDINE
WEIGHT (g)
LENGTH (mm)
AGE (year)
AGE (year)
INITIAL
1959−1968
1969−1978
1979−1988
1989−1998
1999−2008
INITIAL
1959−1968
1969−1978
1979−1988
1989−1998
1999−2008
1959−1968
1969−1978
1979−1988
1989−1998
1999−2008
1959−1968
1969−1978
1979−1988
1989−1998
1999−2008

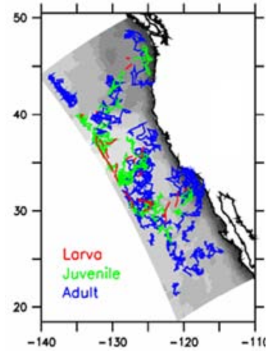

ANCHOVY
SARDINE
ABUNDANCE (10^9 indiv.)
1960
1970
1980
1990
2000
ANCHOVY
SARDINE
10^9*RECRUITS
R^2=0.25
R^2=0.061
10^15*EGGS
10^15*EGGS

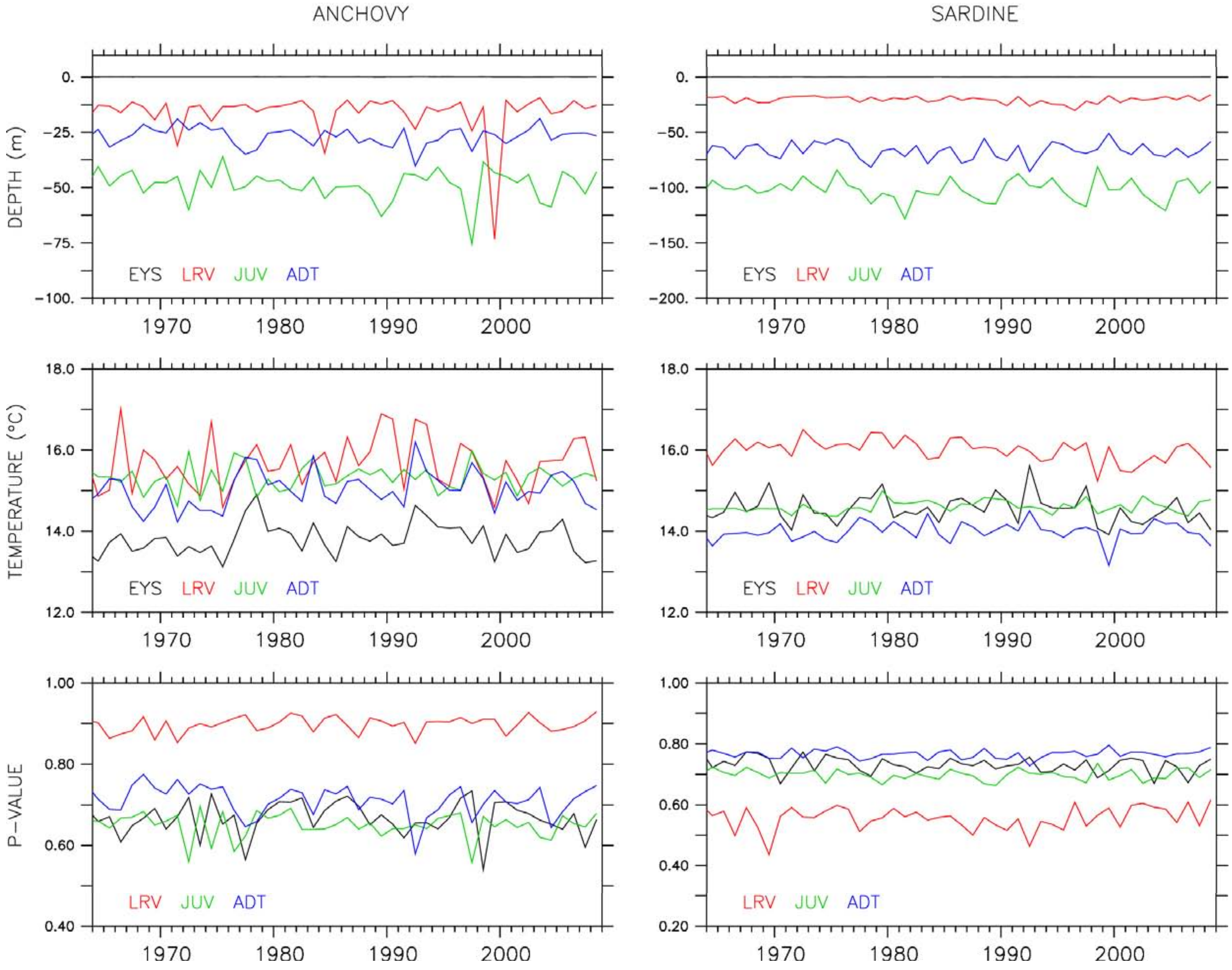

ANCHOVY
SARDINE
BATCHES
10^15*EGGS
12.0
13.0
14.0
15.0
16.0
10.20
10.60
11.00
11.40
11.80
120.
160.
200.
240.
280.
210.
230.
250.
270.
290.
310.
330.
1960
1970
1980
1990
2000

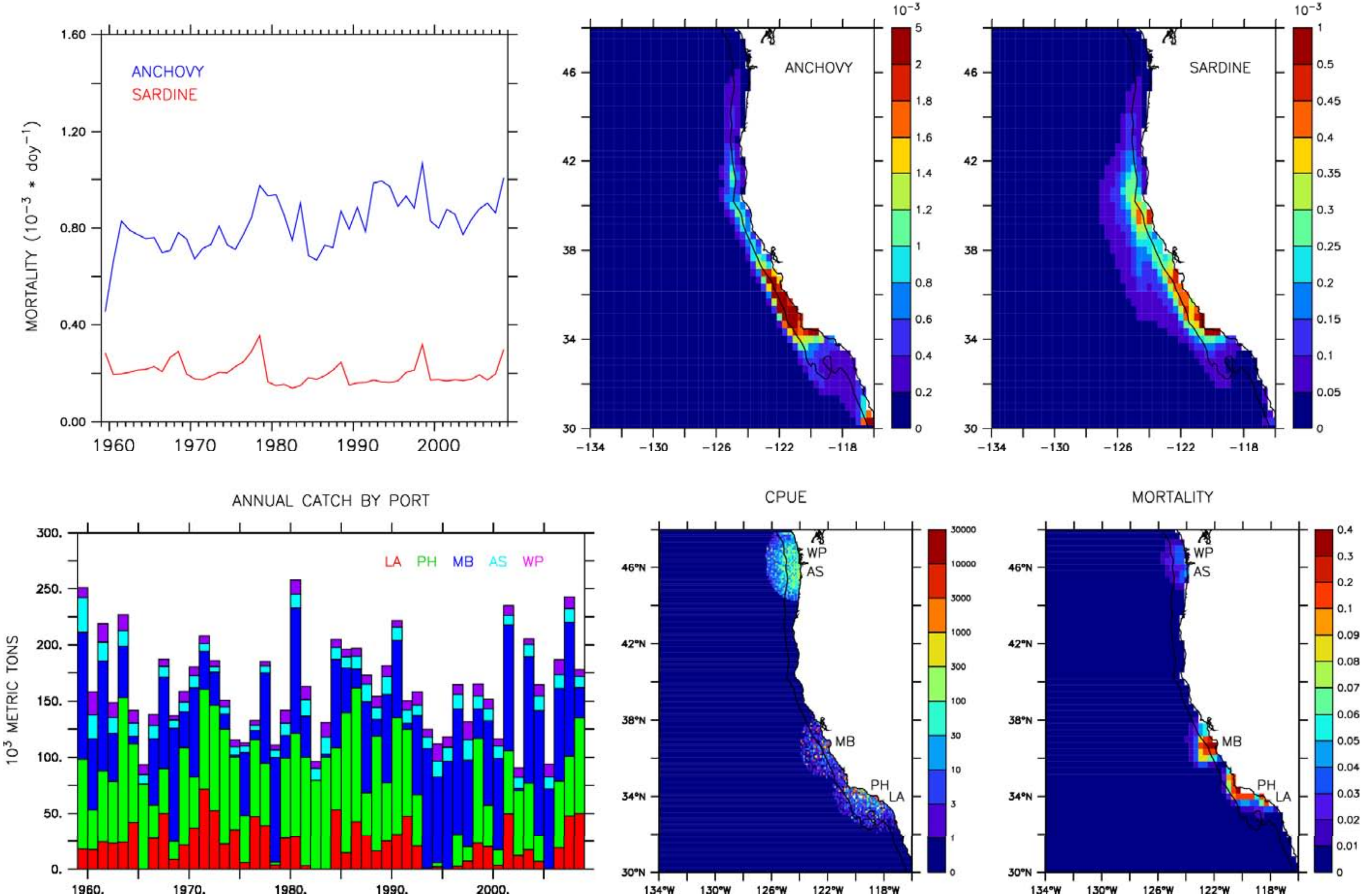

JAN–MAR
APR–JUN
JUL–SEP
OCT–DEC
ANCHOVY EGGS+YSACS
ANCHOVY LARVAE
ANCHOVY JUVENILES
ANCHOVY ADULTS


Larva
Juvenile
Adult

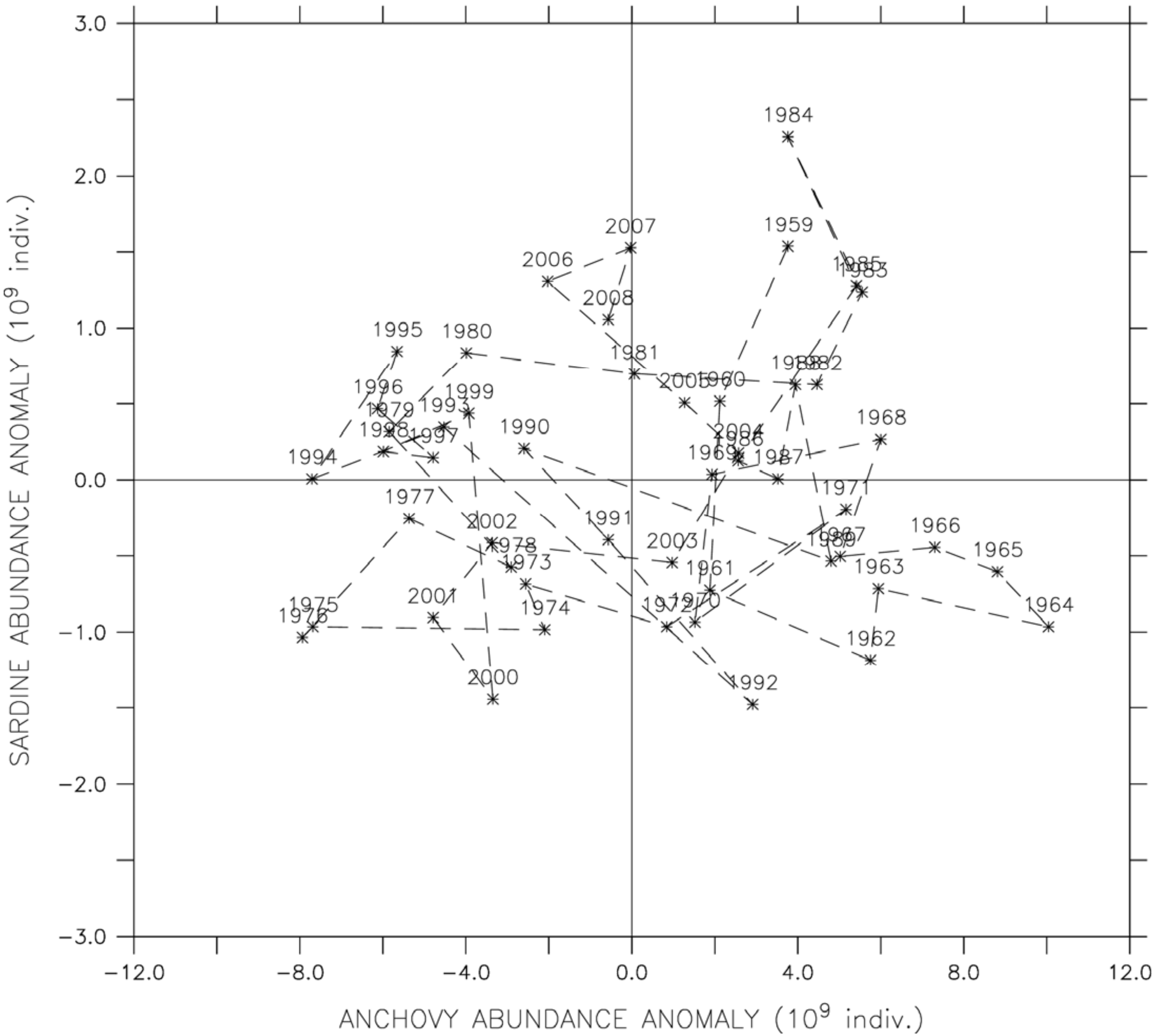

JAN–MAR
APR–JUN
JUL–SEP
OCT–DEC
SARDINE EGGS+YSACS
SARDINE LARVAE
SARDINE JUVENILES
SARDINE ADULTS


Larva
Juvenile
Adult


ANCHOVY
SARDINE
DEPTH (m)
TEMPERATURE (°C)
P−VALUE
EYS LRV JUV ADT
LRV JUV ADT
0.
−25.
−50.
−75.
−100.
−150.
−200.
12.0
14.0
16.0
18.0
0.20
0.40
0.60
0.80
1.00
1970
1980
1990
2000



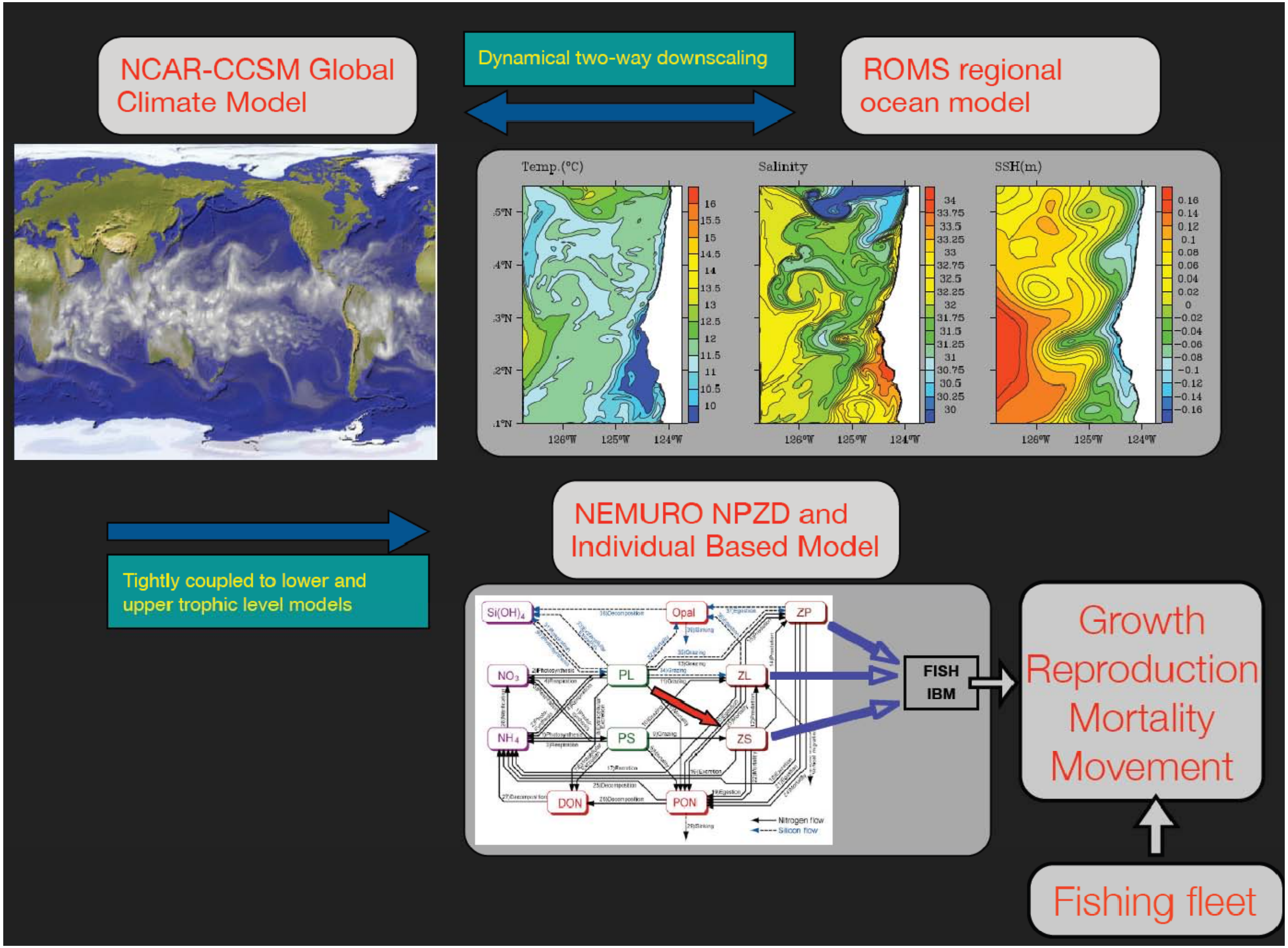
ANCHOVY
SARDINE
MORTALITY (10^-3 * day^-1)
1.60
1.20
0.80
0.40
0.00
1960
1970
1980
1990
2000
10^-3
ANCHOVY
SARDINE
ANNUAL CATCH BY PORT
LA PH MB AS WP
10^3 METRIC TONS
300.
250.
200.
150.
100.
50.
0.
CPUE
MORTALITY
WP
AS
MB
PH
LA



SARDINE ABUNDANCE ANOMALY (10^9 indiv.)
ANCHOVY ABUNDANCE ANOMALY (10^9 indiv.)

Next Steps

- It can be done – proof of principle
  - Bookkeeping solved
  - Linkages operating (interpolation)
  - Parallel computing working
- Parallel effort for Oyashio-Kuroshio system underway (Dr. Ito)
- Implementation within Earth System Model


NCAR-CCSM Global Climate Model
Dynamical two-way downscaling
ROMS regional ocean model
Temp.(°C)
Salinity
SSH(m)
126°W
125°W
124°W
NEMURO NPZD and Individual Based Model
Tightly coupled to lower and upper trophic level models
Si(OH)4
Opal
ZP
NO3
PL
ZL
NH4
PS
ZS
DON
PON
Nitrogen flow
Silicon flow
FISH IBM
Growth
Reproduction
Mortality
Movement
Fishing fleet

So is it Useful?

- Include important differences in the species
- Extensive historical data for model evaluation
- Evaluate hypotheses of cyclic dynamics
  - Bottom-up: transport and circulation
    - retention, eddies, upwelling, source water
  - Bottom-up: temperature optima and NPZ (food)
  - Top-down: loopholes, predator shift, fisheries

End-to-End Modeling of Marine Ecosystems: can the people and data keep up with the computers?

Kenneth Rose
Louisiana State University

Introduction

- Accelerating interest in end-to-end models
- End-to-end means climate to physics to fish to fisheries to people
- Conceptually and politically attractive

Introduction

- To date, physics-NPZ and fish models were developed separately
- Meet at zooplankton (fish food)
  - Closure term for NPZ
  - Assumed available for fish
- Advances in each seemed out-of-phase
- Today: thoughts about end-to-end modeling

Why now?

- Advances in data collection
  - Spatially-detailed data
  - Behavioral measurements

- Continued increases in computing power

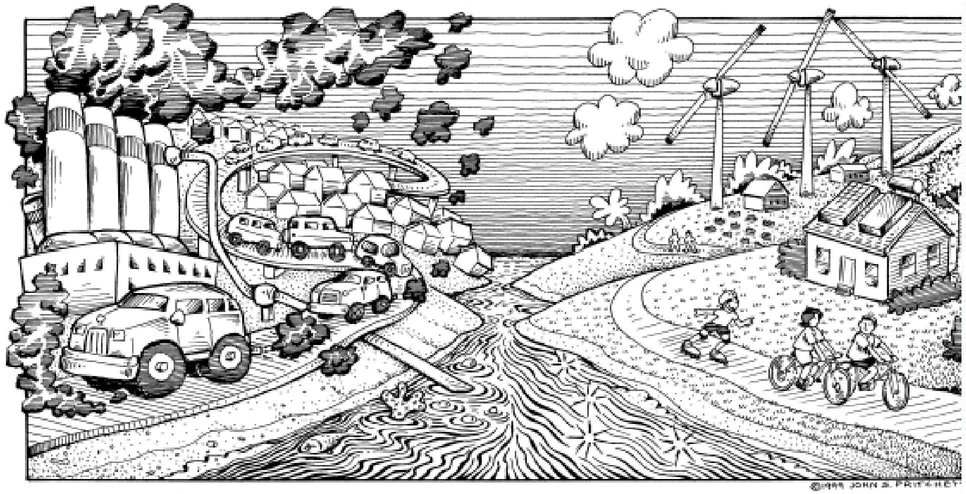
- Advances in modeling
  - Physics: meso-scale features in decadal runs
  - Fish: individual-based, fine-scale observations

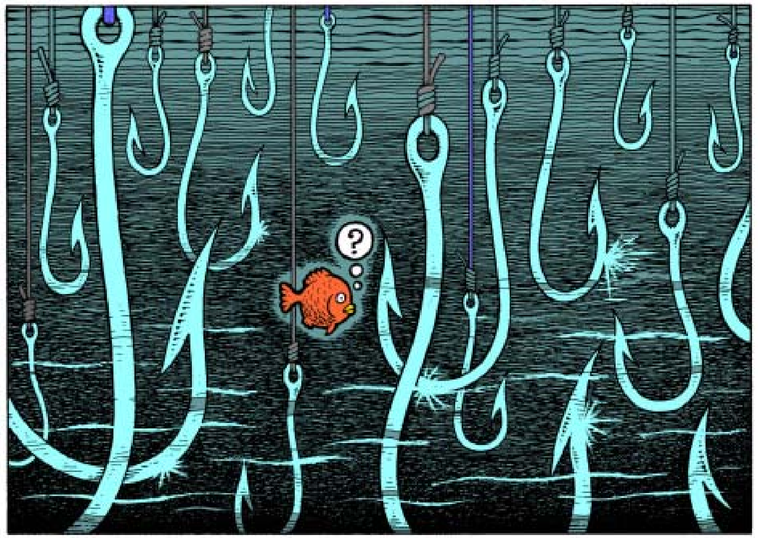
Technical: Computing

- Computing power is constantly surprising us (especially older scientists)

- Super-computers,
  OPENMP

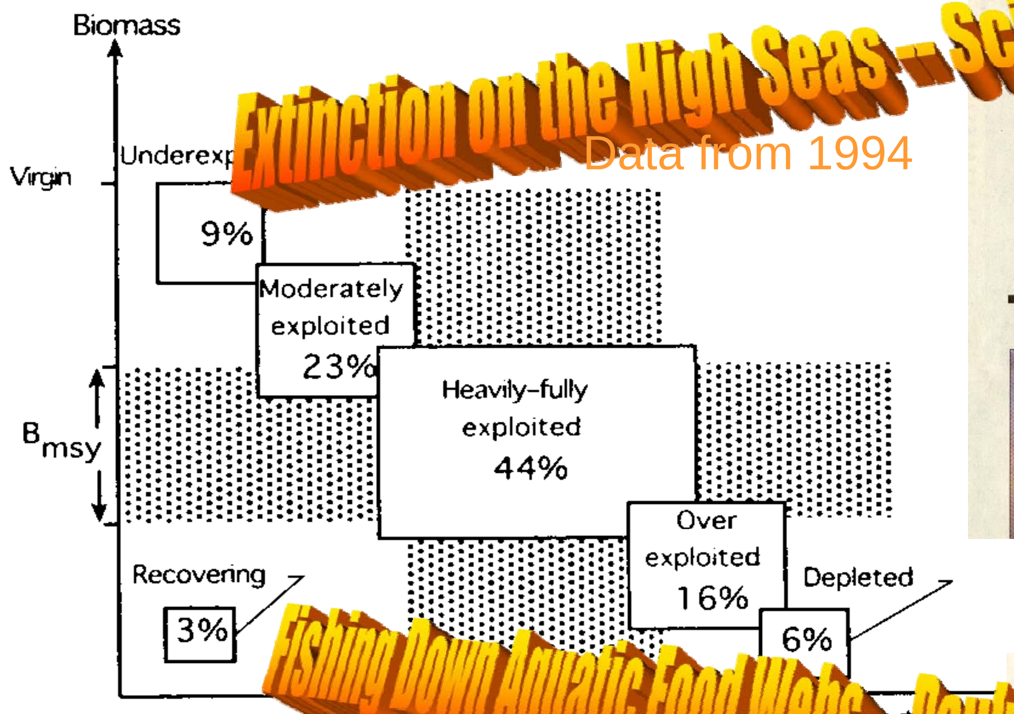
What's Changed?





Extinction on the High Seas -- Science 1997

Data from 1994



esources: Proportion
ted, moderately or full
overing. Source: FA

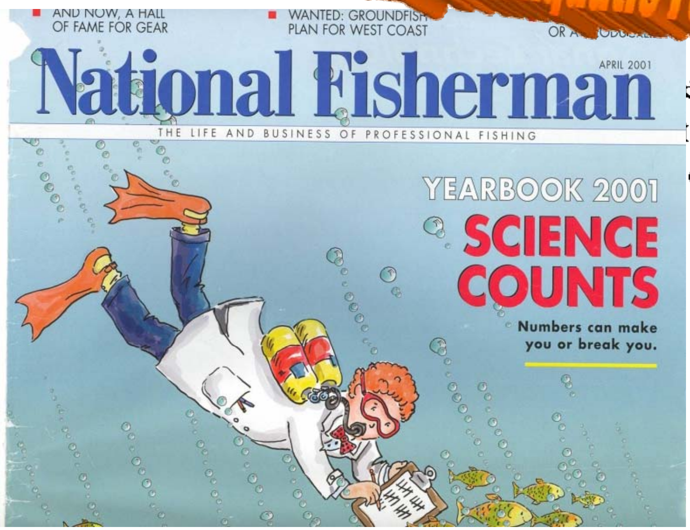
1996!

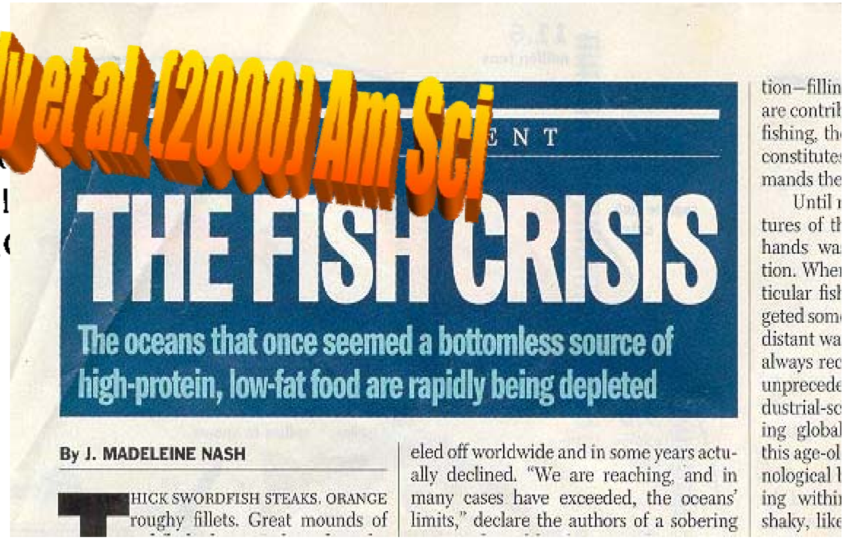

The Times-Picayune
MARCH 28, 1996

PART 5 OF 8
OCEANS of TROUBLE
ARE THE WORLD'S FISHERIES DOOMED?

TRAWLING INTO TROUBLE

Fishing Down Aquatic Food Webs -- Pauly et al. (2000) Am Sci




THE FISH CRISIS

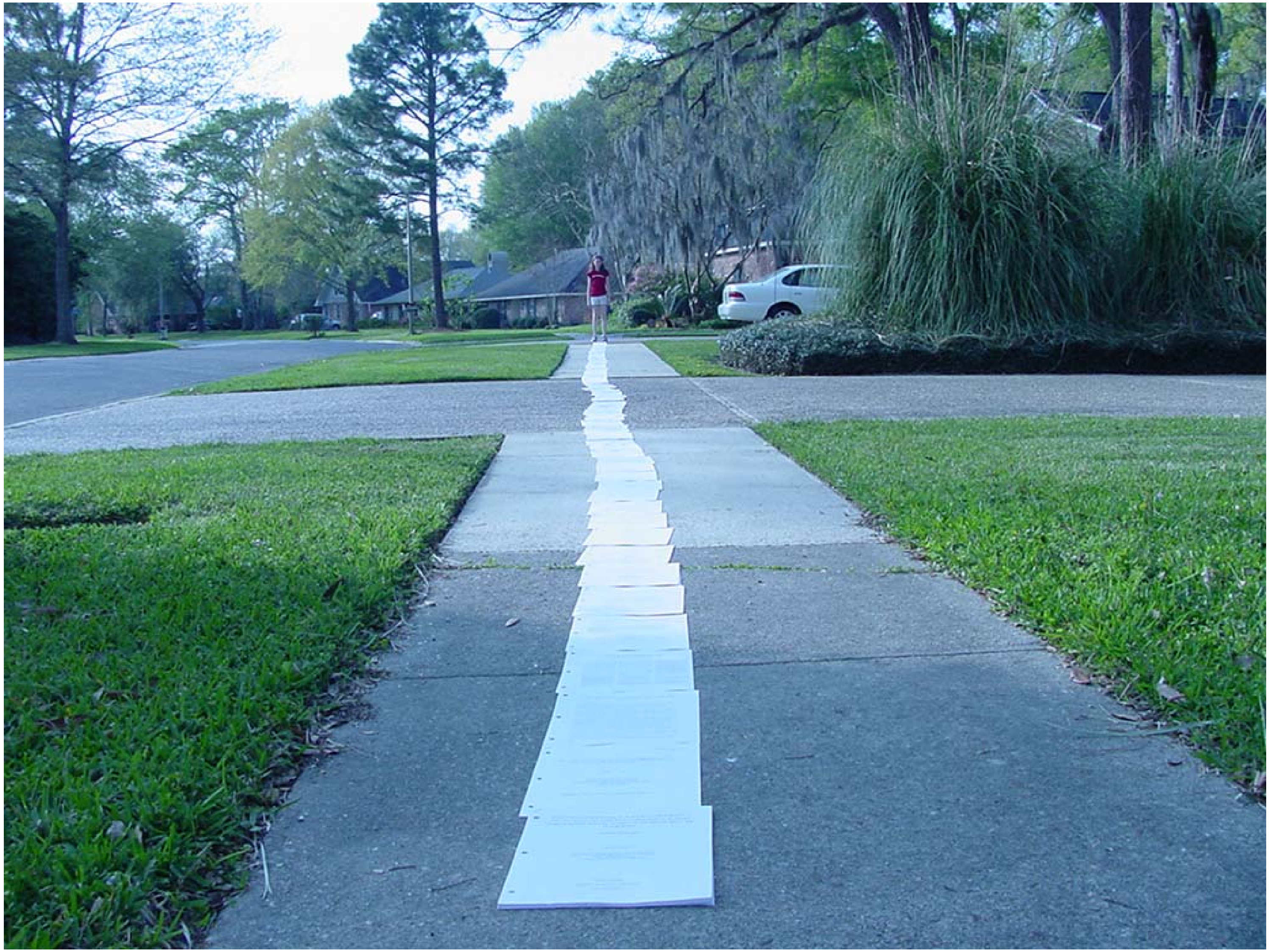
The oceans that once seemed a bottomless source of high-protein, low-fat food are rapidly being depleted

By J. MADELEINE NASH

THICK SWORDFISH STEAKS. ORANGE roughy fillets. Great mounds of

eled off worldwide and in some years actually declined. "We are reaching, and in many cases have exceeded, the oceans' limits," declare the authors of a sobering

Preparation documents sent to review panel members for the Gulf of Mexico Red Snapper stock assessment



One Solution

- Coupled models that can address bottom-up, top-down, and side-ways issues
- Climate change effects on fish
- Perceived fisheries management crisis due to simple single-species approach
- Ecosystem-based management (whatever that means)

Challenge

- How to combine models with different temporal and spatial scales
- No general theory
  - Modeling as art
- Including human dimensions
- Working across disciplines

Journal of Marine Systems 81 (2010) 171–183

Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

Approaches to end-to-end ecosystem models

Elizabeth A. Fulton *

CSIRO Marine Research, GPO Box 1538, Hobart, Tasmania 7001, Australia

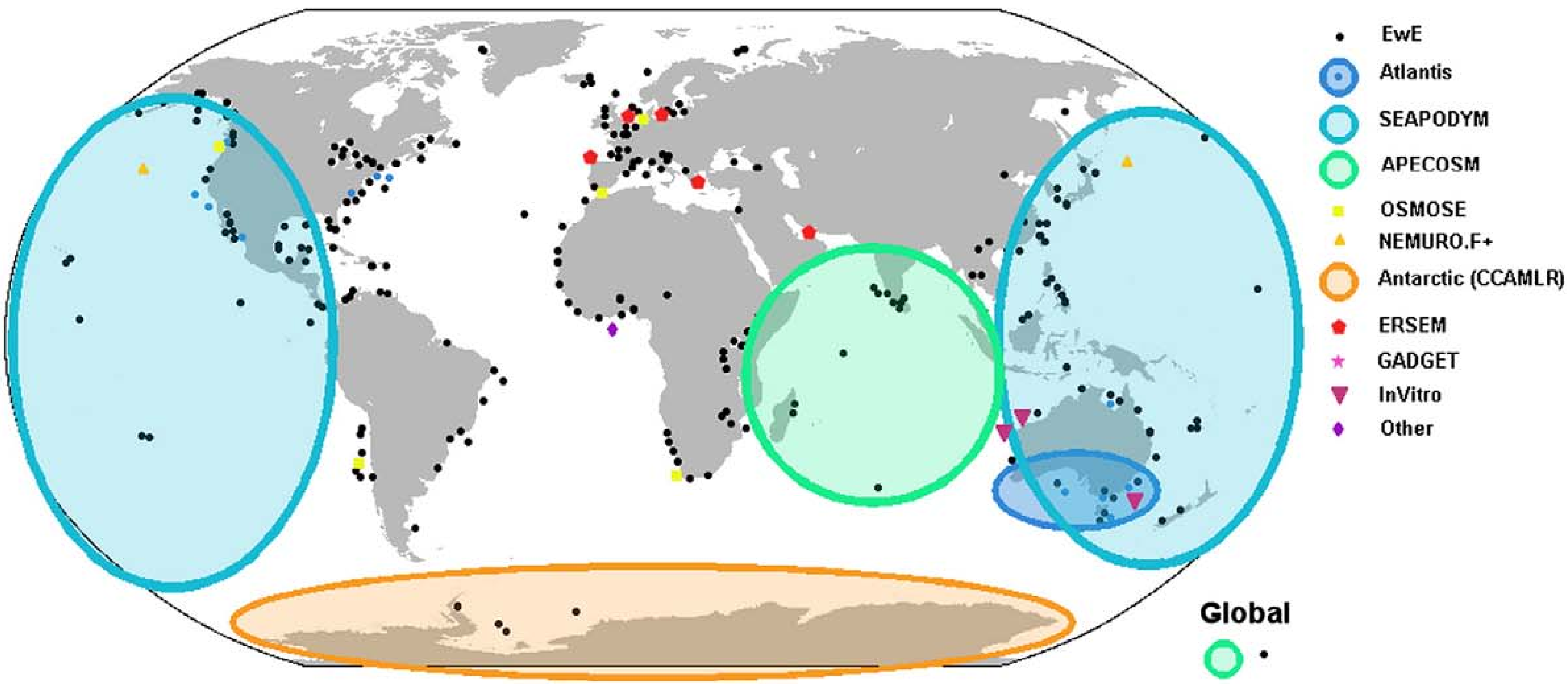


Fig. 3. Map of end-to-end models implemented to date (many more have been proposed or are in early development).

End-To-End Models for the Analysis of Marine Ecosystems: Challenges, Issues, and Next Steps

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MENG ZHOU
Department of Environment, Earth, and Ocean Sciences, University of Massachusetts, Boston, Massachusetts 02125, USA

"Bridging the gap between lower and higher trophic levels"
February 2009
Plymouth, England
AMEMR and MEECE

Issues

(1) Zooplankton

Shift from biochemical cycling to fish food

(2) New Organisms

Macroinvertebrates

Demersal fish species

People

Issues

(3) Scaling

Determining the appropriate temporal, spatial, and biological scales for a model is always challenging

Now,

- Hydrodynamics on minute scales
- Organisms that live for days to decades
- 10^{-12} to 10^{6} grams
- Fast processes (e.g., larval feeding) for decades
- Fine-scale but large domain and near coasts
- Interspecific interactions – community ecology has failed us

Issues

(4) Acclimation and adaptation

(5) Behavioral movement

Ecological Modelling 250 (2013) 214–234

Contents lists available at SciVerse ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Evaluating the performance of individual-based animal movement models in novel environments

Katherine Shepard Watkins*, Kenneth A. Rose

Department of Oceanography and Coastal Sciences, Energy, Coast, and Environment Building, Louisiana State University, Baton Rouge, LA 70803, United States

(6) Software

C and FORTAN

Hinders advances

Issues

(7) Solution and numerics

- Two-way coupling
- Super-individuals
- Full life cycle
- Eulerian and Lagragian
- Density-dependence
- Computing

Issues

(8) Model confidence

Physics people need to relax a bit

(9) Interdisciplinary Efforts

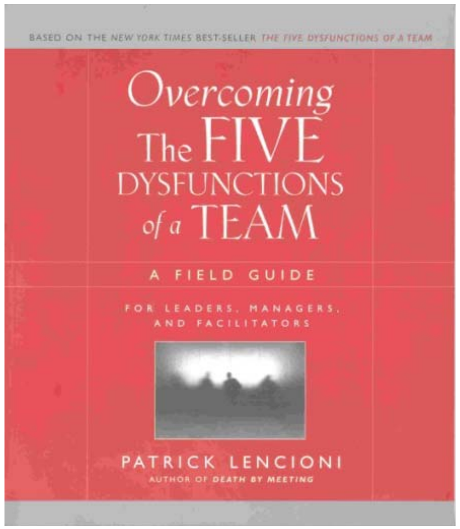
Move from multi to interdisciplinary

Adjustment of plans based on others

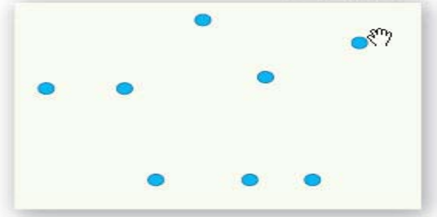
Issue 9

Barabasi 2005

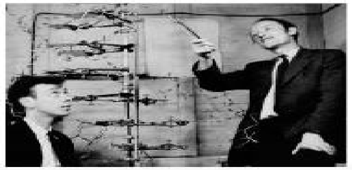
"You should check your e-mails more often. I fired you over three weeks ago."

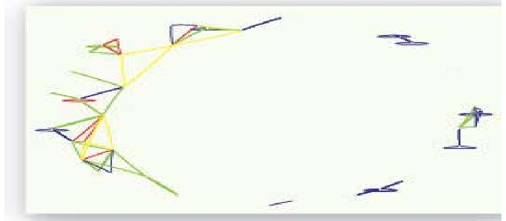


Galileo Newton
Darwin Einstein

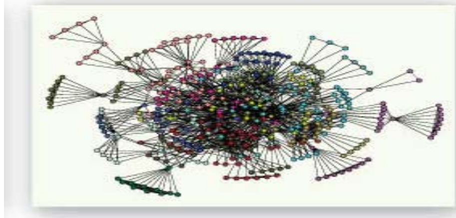


Crick and Watson





International Human Genome Sequencing Consortium



Conclusions

- Ingredients are now available
- It can (should) be done!!
  - Decisions are being made, without the best information
- Challenges:
  - Technical (computing, algorithms, data)
  - Institutional
  - People

Rose (2012) End-to-end models for marine ecosystems: Are we on the precipice of a significant advance or just putting lipstick on a pig? *Scientia Marina* 76:195-201.

What we want to avoid

Over-promise
Repackage poorly performing submodels
Frakenmodel
Call everything "end-to-end"

Community-based effort
Collaborative
Caution and thoughtful
Face our weaknesses

Unsolicited Advice

- Do not love your model - it will not love you back
- Do not apologize for your model
- Take ownership and responsibility of the model, while respecting its history
- You should know what the mathematics is and the solution method you are using
- Precision versus accuracy and relative predictions versus forecasting

Unsolicited Advice

- Very carefully use computer costs as basis for assumptions
- Learn to program in a sequential language
- Test codes with known problems in modules
- Try to break the model and then treat model simulations as an experiment

Unsolicited Advice

- Lead the audience from model output to final figures you show
- Know your audience
- Know the details of model even if you inherited it from someone else
- Simple assumptions are the most important
- Hidden assumptions will get you

Unsolicited Advice

- Understand why results occurred
- Trace history of model before the most recent paper
- Respect data but not wait for it
- Embrace variability, feedbacks, and interactions
- Learn how to bound the answers

End-to-End Modeling: Simulating Movement of Fish over Spatial and Temporal Scales:

if fish were dumber and people were smarter
Is it the journey or the destination?

Kenneth Rose
Louisiana State University
Baton Rouge, LA USA

Movement

- A major challenge is modeling movement
  - Eggs and larvae maybe reasonably simulated with particle-tracking
  - Juveniles and adults require behavioral approaches

- Wide range of temporal and spatial scales
  - Often scales determined by other submodels
  - Compatibility issues

Movement

- Many approaches have been proposed
  - $X(t+1) = X(t) + V_x(t)$
  - $Y(t+1) = Y(t) + V_y(t)$
  - $Z(t+1) = Z(t) + V_z(t)$
  - Determine the cell

- Quite confusing because of non-standard descriptions and terminology for V_x, V_y, and V_z
  - Random walk
  - Run and tumble
  - Event-based
  - Restricted-area
  - Kinesis
  - ANN

Movement Issues

- Fixed parameters preventing adaptive and phenotypic variation in behavior
- Edge effects on finite grids
- Stranding and oscillatory movements
- Weakly convergent parameter values
- Non-unique pattern matching

Issues

- Renegade individuals
- Bifurcated movement patterns
- Short-cut solutions that use geography
- Compromise behaviors from multiple cues
- ***Calibration and validation***

Major Issue

- If we are to use these methods to simulate management actions and climate change, then the methods must capture the response to cue(s)
- Little investigation of performance of any of these approaches under novel conditions
- We will explore this issue in more detail

Calibration and Validation

- Challenge: Calibration data are rarely available at the necessary scale
- Genetic algorithms calibrate without data by evolving a population with parameters that produce fit movement
- GAs assume fish inherit movement instincts that maximized fitness in previous generations
- Examples: ANNs (Huse and Giske 1998; Huse and Ellingsen 2008; Mueller et al. 2010), neighborhood search (Giske et al. 2003), rule-based (Huse 2001)

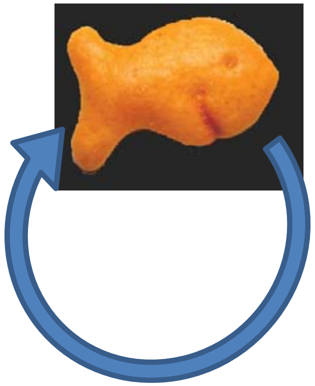
Calibration and Validation

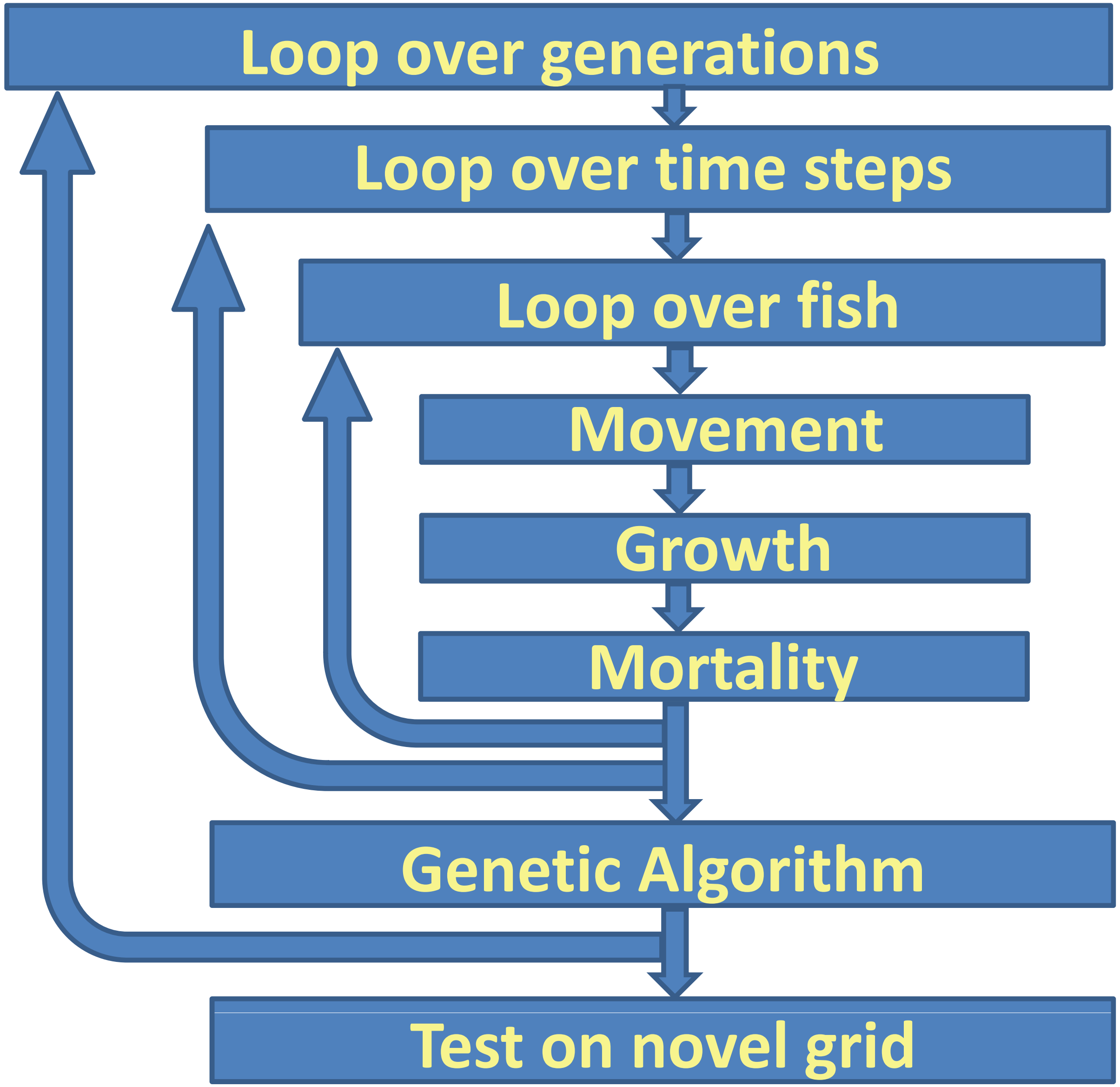
- Calibrate 4 movement models (neighborhood search, kinesis, event-based, and run-tumble) with a GA in four 2-D environments

- Evaluate the performance of each calibrated sub-model in novel conditions

Model Structure

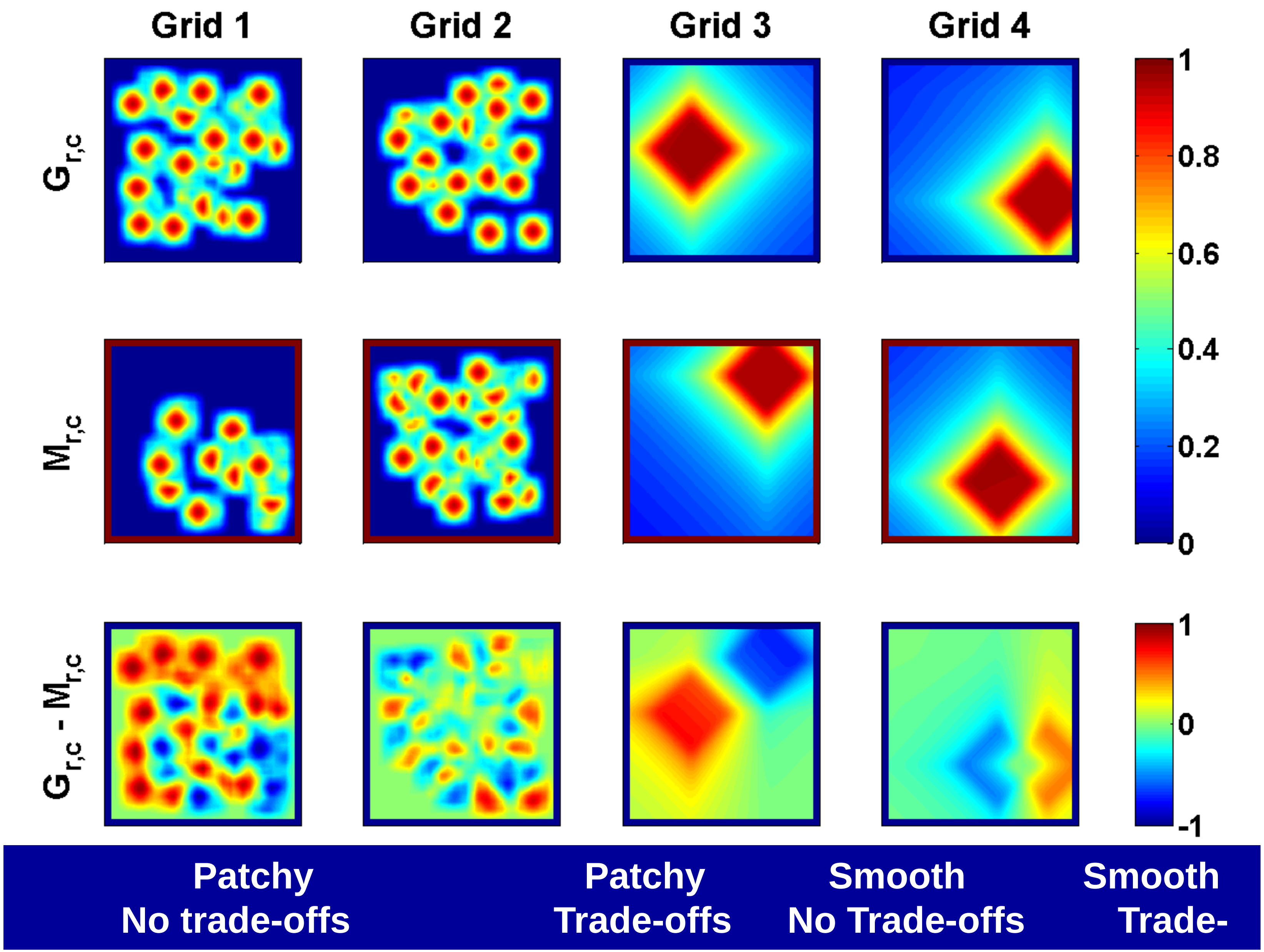
Simplified Hypothetical Species





<u>Scale</u>

Grid: 540 x 540 cells
Cells: 5 m^2
Time step: 5 minute
Generation: 30 days
Initial size = 73.3 mm
Initial worth = 100 fish
3000 super-individuals


Grid 1
Grid 2
Grid 3
Grid 4
$G_{r,c}$
$M_{r,c}$
$G_{r,c}$ - $M_{r,c}$
1
0.8
0.6
0.4
0.2
0
1
0
-1
Patchy
No trade-offs
Patchy
Trade-offs
Smooth
No Trade-offs
Smooth
Trade-

Model Processes

Growth (mm 5-min^{-1})

$G = G_{max} * G_{r,c}$

$L(t+1) = L(t) + G$

$W(t+1) = a * L(t+1)^b$

Mortality (5-min)$^{-1}$

$M = M_{max} * M_{r,c} * M_L$

$S(t+1) = S(t) * e^{-M}$

$$M_L = 1 - \frac{L_i - 73.3}{L_{max} - 73.3}$$

Movement

$\mathbf{X(t+1) = X(t) + V_x(t)}$

$\mathbf{Y(t+1) = Y(t) + V_y(t)}$

cell location (r,c

Reproduction

$E = 55 \cdot S(30) \cdot (421.84 \cdot W(30) + 304.79)$

GA Calibration

- 3000 strategy vectors of parameter values
  - Start with random values for everyone
- Every 30-day generation, select 3000 individuals:
  - P(selection) = $E_i/\Sigma E$
  - Mutate each vector: 6% of parameters, ±0.25
- Use these 1000 vectors for the next generation
- Continue until egg production levels off
- Parameter values should have converged

Restricted Area Search

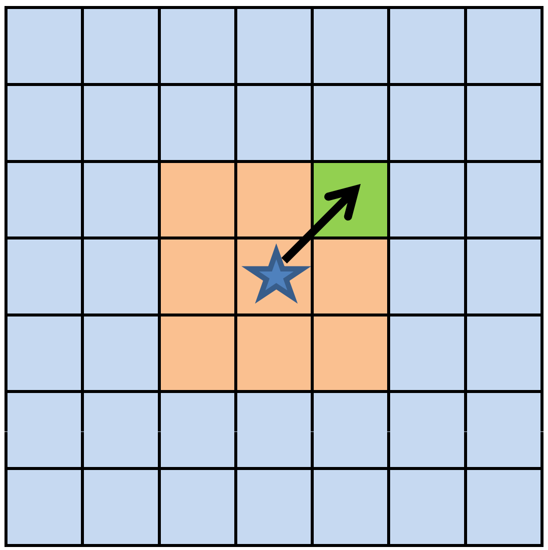
- Rank cells in a D_{hood} cell radius by habitat quality ($Q_{c,r}$)

$$Q_{c,r} = (1-\delta)*(G_{c,r}+n)-\delta*(M_{c,r}*M_L+n)$$

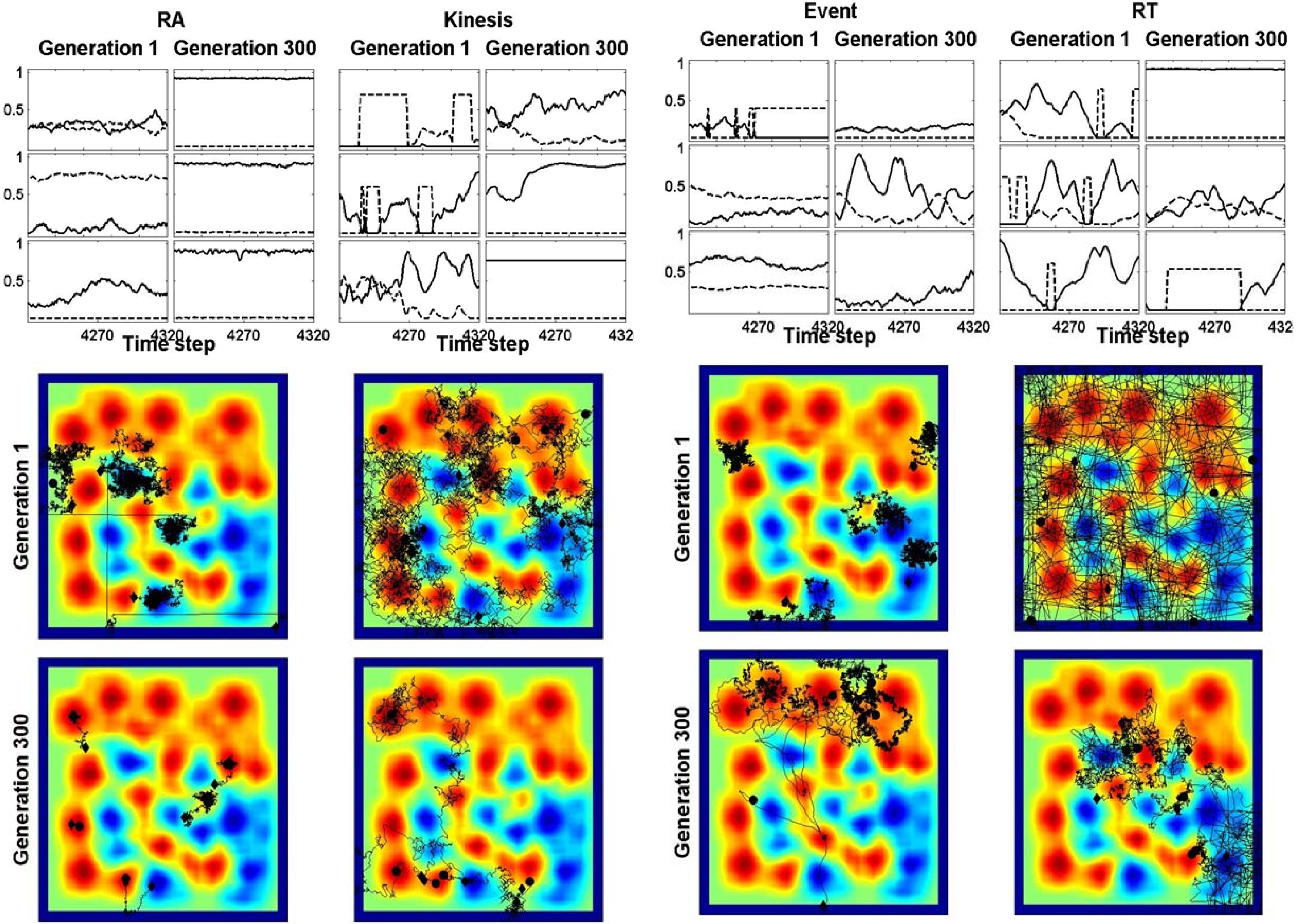
- $n = \left(1 - \frac{1.42}{\sqrt{(c-xcell)^2 + (r-ycell)^2}}\right)$

- Compute Θ = toward the cell with the highest $Q_{c,r}$

$$V_x(t) = (SS + RV_1 \cdot R_{dist}) \cdot \cos(\theta + RV_2 \cdot R_\theta)$$
$$V_y(t) = (SS + RV_1 \cdot R_{dist}) \cdot \sin(\theta + RV_2 \cdot R_\theta)$$

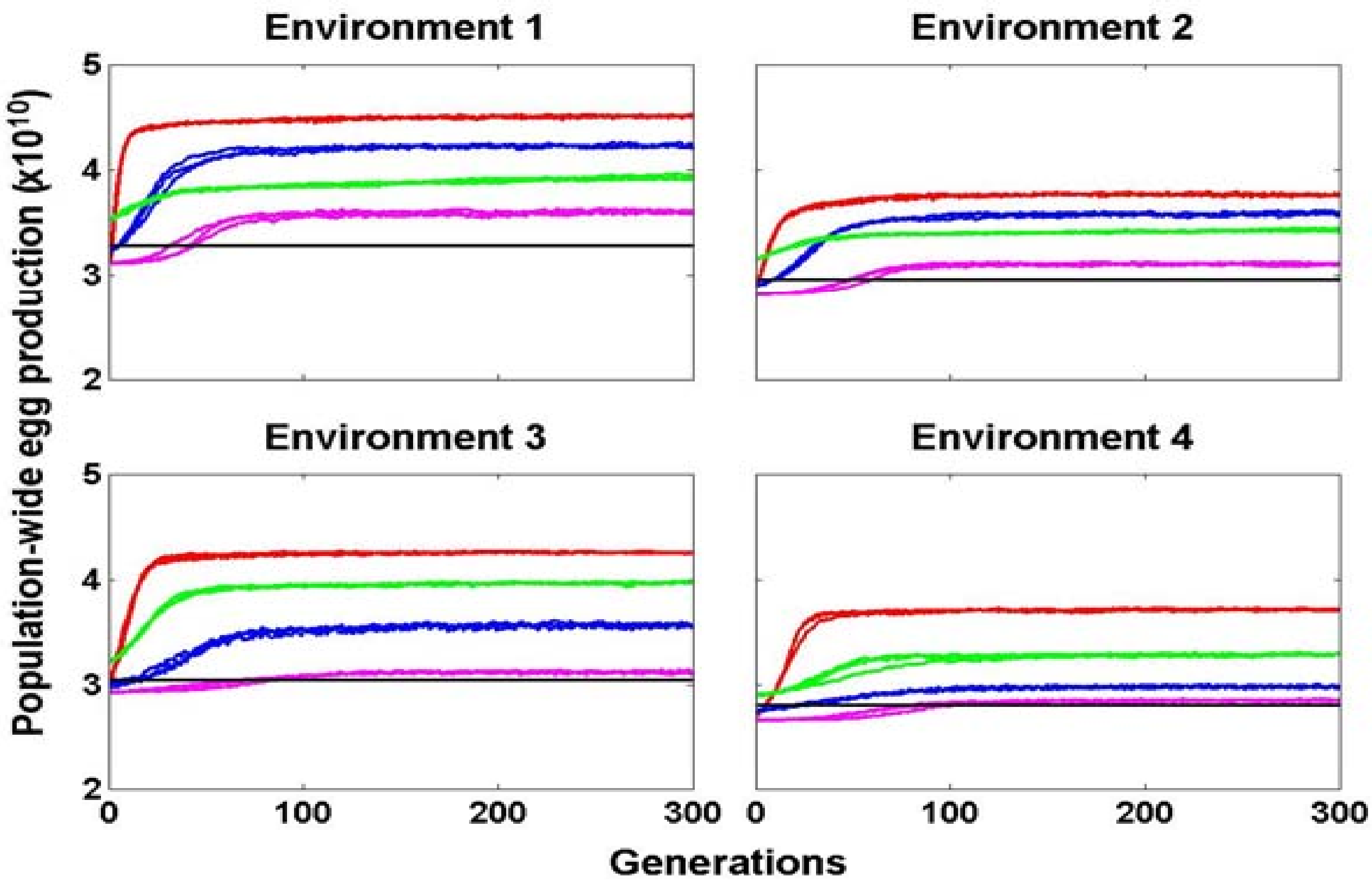


- GA evolves: δ, R_θ, R_{dist}, D_{hood}



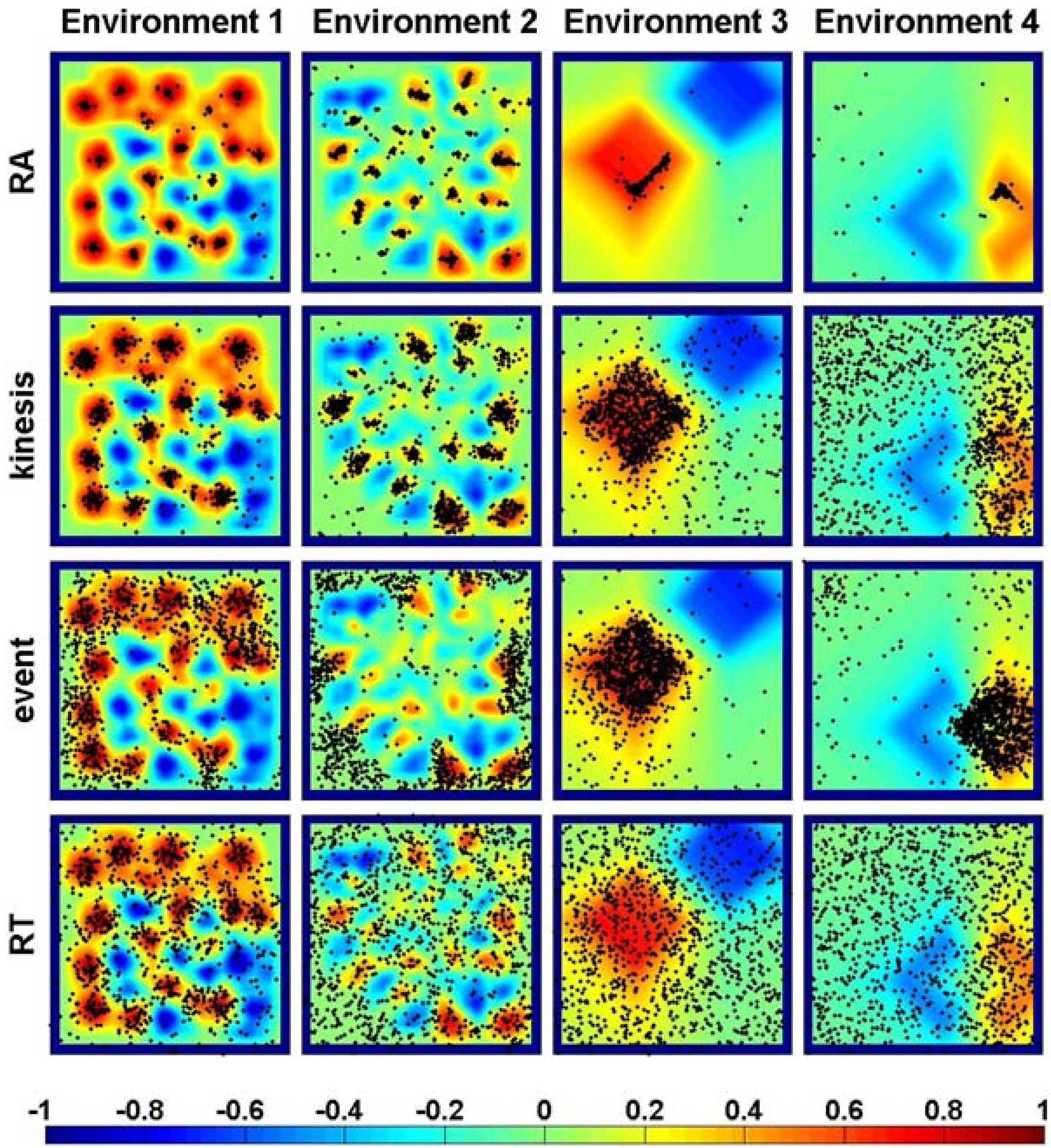
RA
Kinesis
Event
RT
Generation 1
Generation 300
Generation 1
Generation 300
Generation 1
Generation 300
Generation 1
Generation 300
1
0.5
4270
4320
4270
4320
4270
4320
4270
432
4270
4320
4270
4320
4270
4320
4270
432
Time step
Time step
Time step
Time step
Generation 1
Generation 300
Generation 1
Generation 300

Calibration – Fitness Convergence

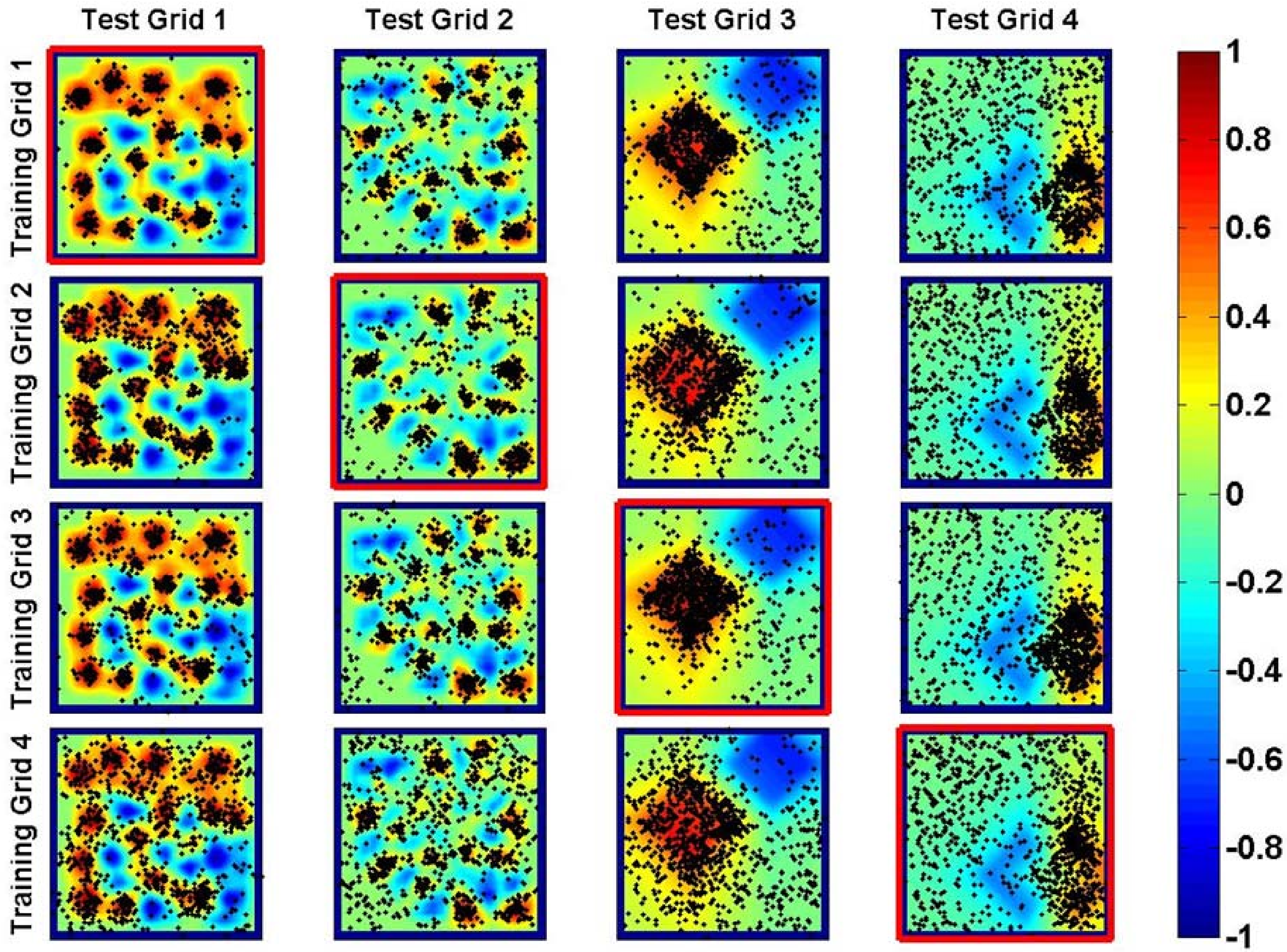


Restricted area, Kinesis , Event-based, Run-tumble

Last day of 300th generation



Kinesis - Testing



Conclusions

- Behavioral movement is a major uncertainty in spatially-explicit models

- Presently, a variety of approaches whose relationships are unclear and developed on different scales

- Our analysis attempted to address this:
  - Calibration - GA
  - Robustness - testing under novel conditions