Tunas in hot water: forecasts of population trends for two species of tuna under a scenario of Climate Change

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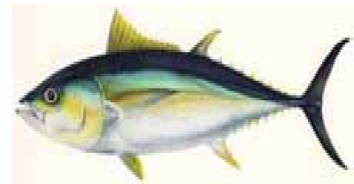
❖ GLOBEC-CLIOTOP Working Group 4

Outline

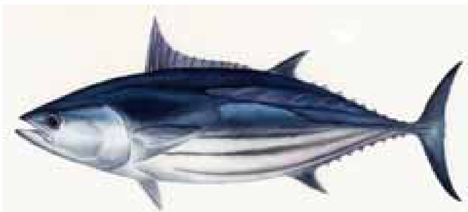
Tunas in hot water

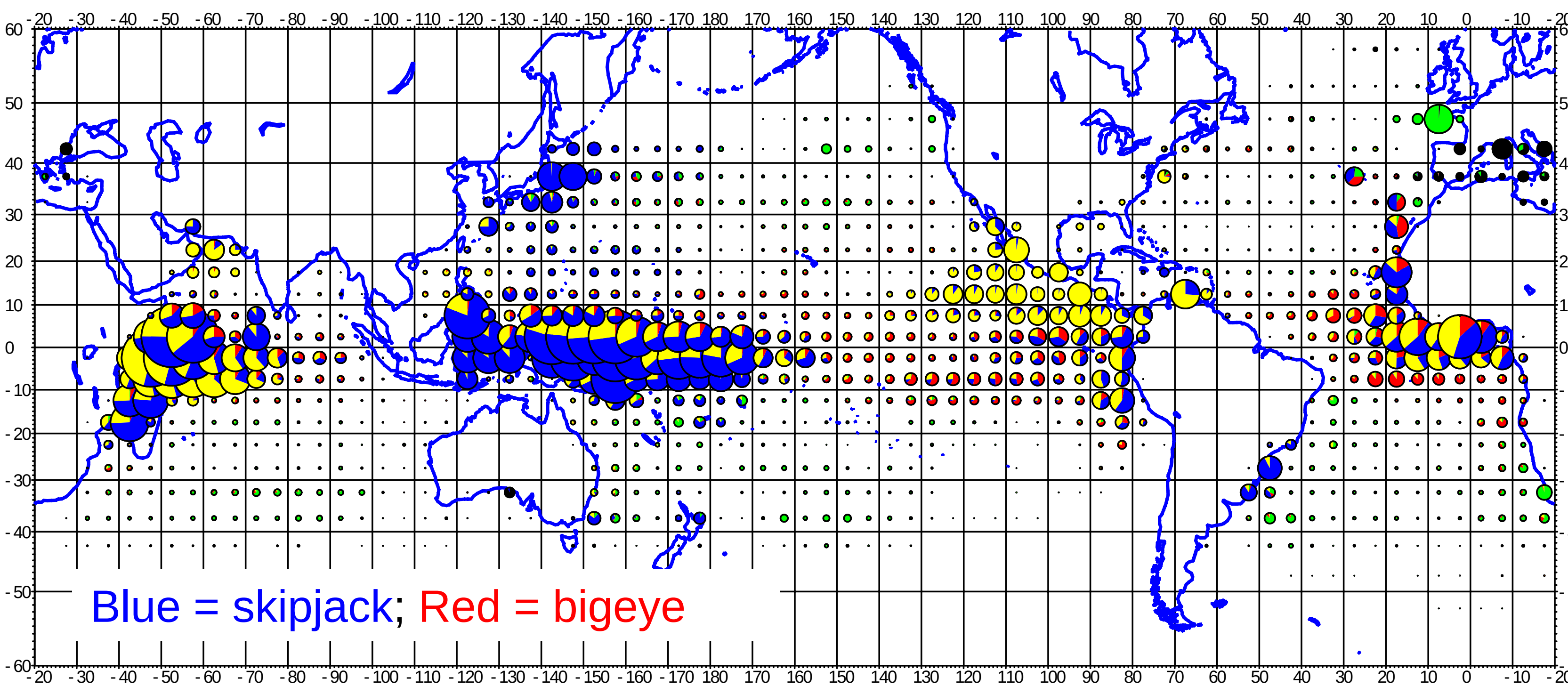
- What is a tuna?
- End-to-end ecosystem modeling (SEAPODYM, briefly)
- Parameters optimization and hindcast simulations
- Confidence and uncertainty
- Forecast: and the winner is …
- So what?

Tunas

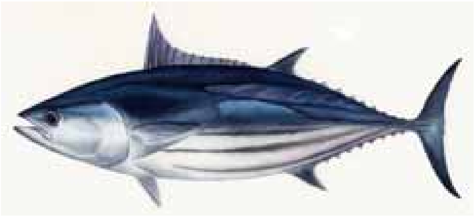
Skipjack (*Katsuwonus pelamis*) vs Bigeye (*Thunnus obesus*)



Fisheries



Skipjack (*Katsuwonus pelamis*) vs Bigeye (*Thunnus obesus*)

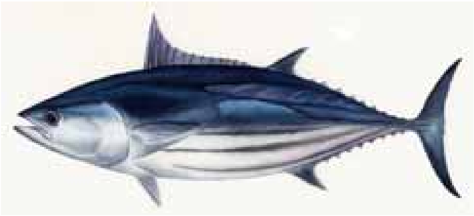


Biology

Skipjack		Bigeye
4 yrs +	← Lifespan →	12 yrs (+)
75 cm / 20 kg	← Max size / weight →	180 cm / 225 kg
10-12 months	← Age at maturity →	2.5 years
Very high	← Fecundity →	Very high
~0.4 per month	← Natural mortality →	~0.1(-) per month
Micronekton	← Food →	Micronekton

Tunas

Skipjack (*Katsuwonus pelamis*) vs Bigeye (*Thunnus obesus*)



Ecology

Skipjack		Bigeye
Warm! 20 – 30 ^oC	← Thermal habitat →	Extended! 10-30 ^oC
Low! >3-4 ml l^{-1}	← Oxygen tolerance →	Good! >1.5 ml l^{-1}
0-200 m	← Vertical habitat →	0-1000 m
Tropical	← Spatial distribution →	Tropical to sub-temperate

CLS PFRP SPC

Spatial Ecosystem And Populations Dynamic Model

Bio-physical environment

Primary Production, Euphotic depth

3-layer data:
Temperature, currents, Oxygen

Mid-trophic sub-model

Predictions

Six forage components:
epi-pelagic
Migrant and non-migrant meso-pelagic
Migrant, non-migrant and highly-migrant bathypelagic

Fishing data

Pole-and-line: tropical and sub-tropical gears

Purse seine: associated and unassociated fleets

Longline: Shallow, deep, …

TADR tuna model

Eqns for 0-3 month old juveniles:
spawning, foraging, passive transport, survival, mortality, cannibalism

Eqns for 1-X quarter old adults:
recruitment, foraging, migrations, ageing, natural and fishing mortality

Predictions

Tuna spatial distributions, **catch** and **length frequencies** time series

Optimization:
Preliminary sensitivity analysis
Constructing cost function according to data distribution minimization, parameter estimation and errors.

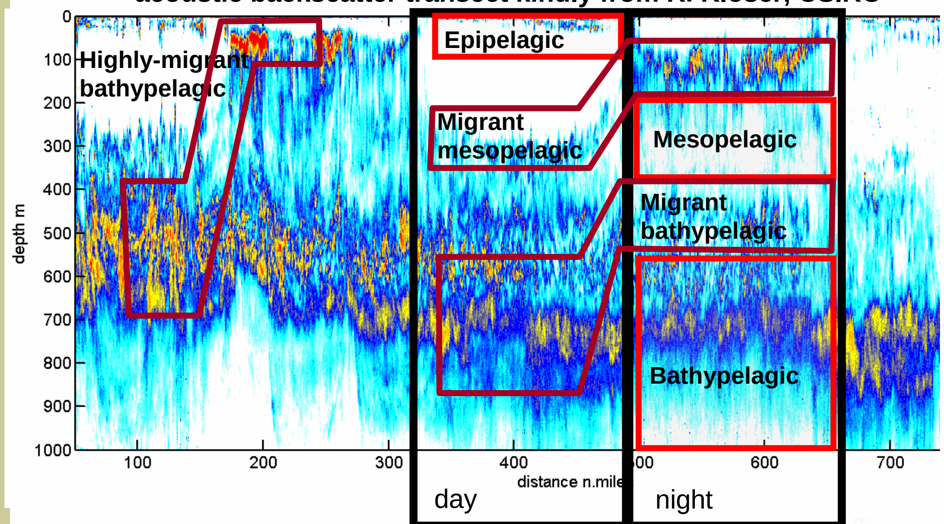
Estimates of model parameters

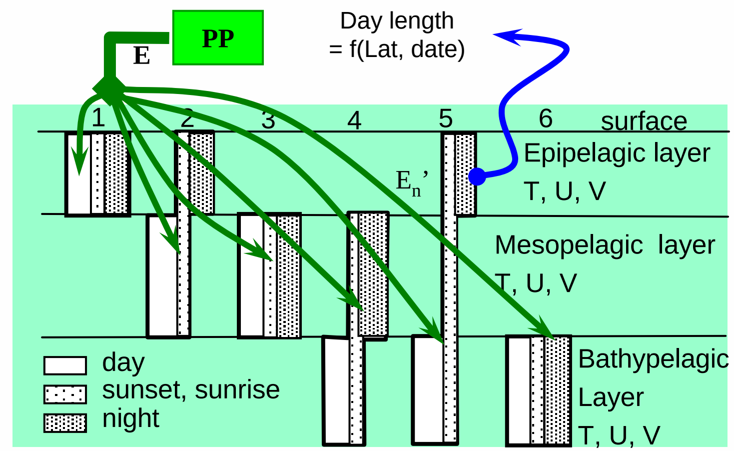
Reference:

Senina, I., Sibert, J., Lehodey, P. (*in press*). Parameter estimation for basin-scale ecosystem-linked population models of large pelagic predators: Application to skipjack tuna.

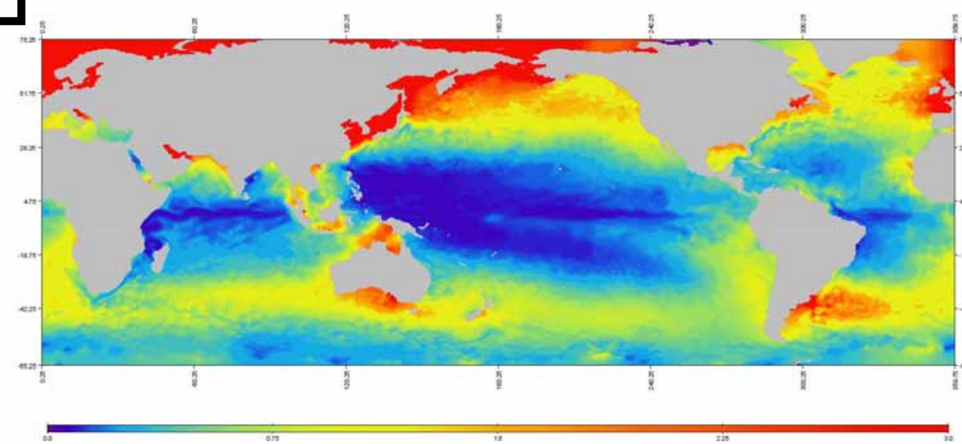
Prey: Micronekton

acoustic backscatter transect kindly from R. Kloser, CSIRO





6 functional groups
in 3 vertical layers



Epipelagic micronektonic group

References:

Lehodey et al 1998. *Fish. Oceanog.*

Lehodey, P., 2001. *Prog. Oceanog.*

Lehodey, Murtugudde, Senina. (submitted). Scaling laws for modelling mid-trophic functional groups and their control on predator dynamics.

Predators : tunas

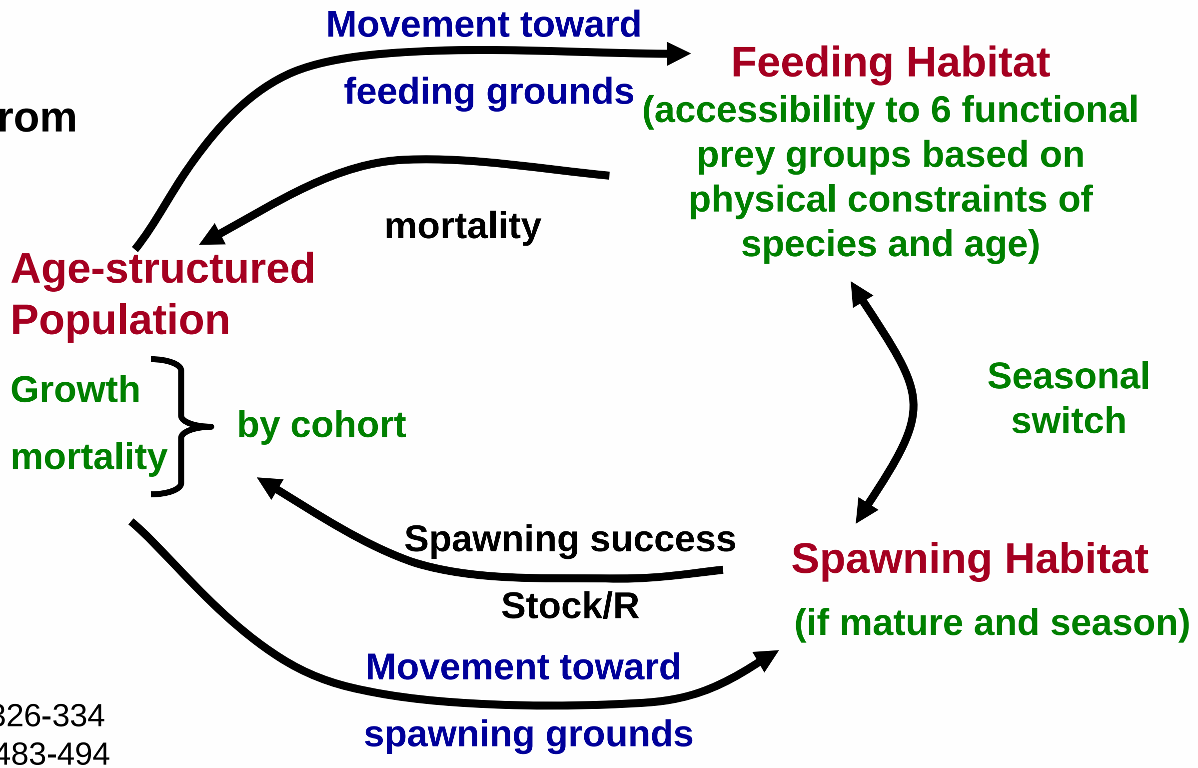
Spatial dynamics of tuna populations are based on habitats definition

Eulerian approach:

movement is modelled from

Advection-diffusion

equations



References:

Bertignac et al., 1998. *Fish. Oceanog.*, **7**, 326-334
Lehodey et al., 2003. *Fish. Oceanog.*, **12**, 483-494
Lehodey, Senina, Murtugudde, submitted.

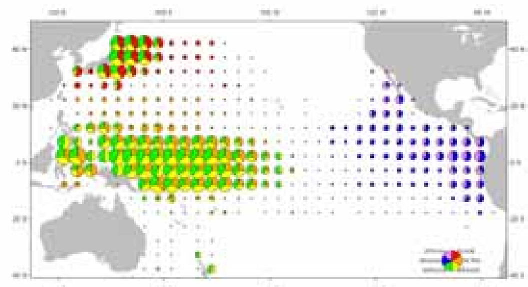
Parameters optimization

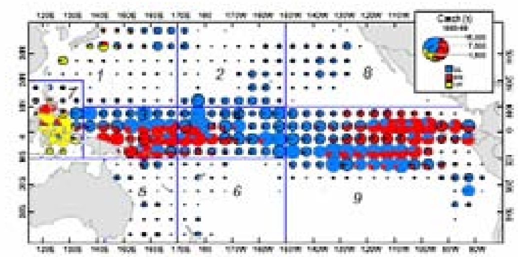
Data

Fishing data:

- Spatially-disaggregated monthly catch data

Skipjack = 4 purse-seine and 2 pole-and-line fisheries (original data on 1-deg resolution)
Bigeye = idem skipjack + 15 long-line fisheries (original data on 5-deg resolution)





- Quarterly length frequencies data for each fishery

Bio-physical input dataset:

- coupled physical-biogeochemical reanalysis from Earth Science System Interdisciplinary Center, University of Maryland, USA (R. Murtugudde)

Note: with fixed definition of vertical layers (0-100m, 100-400m, 400-1000m)

Time period for optimization experiment:

- 1984-2004: 2 deg x 2 deg x month

Parameters optimization

Method

- Model predictions:
  - total catch by fleet and size (month x 2 deg)

- The task of finding the optimal parameterization of the numerical model by fitting its prediction to observation consists in maximizing the likelihood function (or commonly, minimizing negative log-likelihood).

- Numerical estimation
  - Quasi-Newton minimization of negative log of joint likelihood
  - Derivatives of likelihood function with respect to all estimated parameters computed by adjoint methods

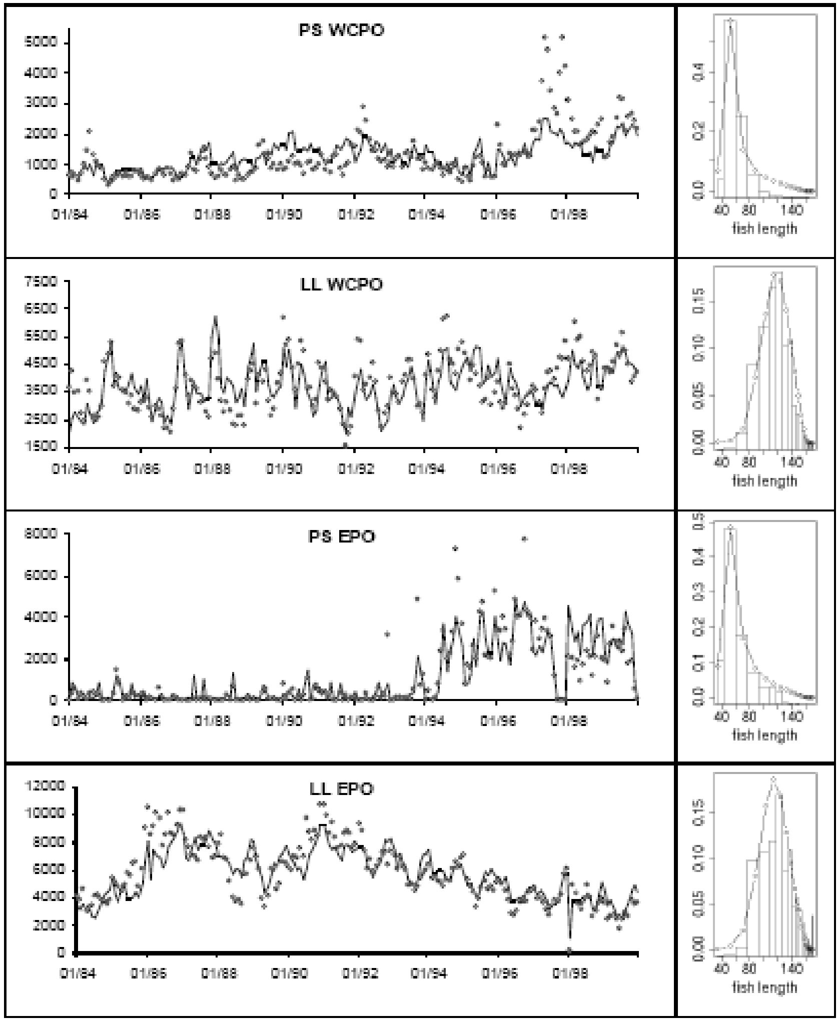
Senina, I., Sibert, J., Lehodey, P. (in press). Parameter estimation for basin-scale ecosystem linked population models of large pelagic predators: Application to skipjack tuna. *Prog. Oceanog.*

Parameters optimization

Estimated parameters

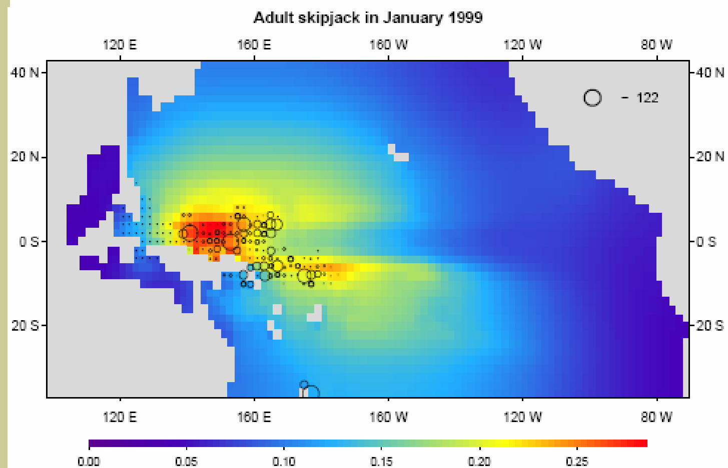
	θ	Skipjack	Bigeye
Natural mortality	β_p	0.296 ± 0.0018	0.073 ± 0.0005
	M_{max}	0.5*	0.25 ± 0.003
	β_s	-0.044 ± 0.0015	-0.097 ± 0.008
	A	31*	80.6 ± 0.008
Spawning habitat	σ_0	3.5*	0.82 ± 0.012
	T_0	30.5 ± 0.0047	26.2 ± 0.013
	α	0.1*	0.63 ± 0.02
	BH_a	0.5*	0.0045 ± 6e-4
Adult habitat	σ_a	2.62 ± 0.0015	2.16 ± 0.004
	T_a	26*	13 ± 0.004
	$\hat{O}$	3.86 ± 0.0009	0.46 ± 0.0006
Movement	D_{max}	0.4 ± 0.005	0.22 ± 0.002
	V_{max}	1.3 ± 0.006	0.32 ± 0.002
Fishing parameters: catchabilities & selectivities			

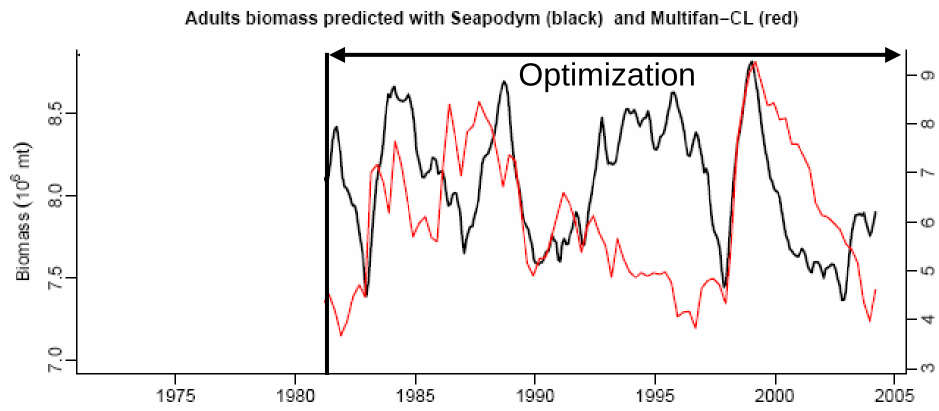
± st.dev; * fixed



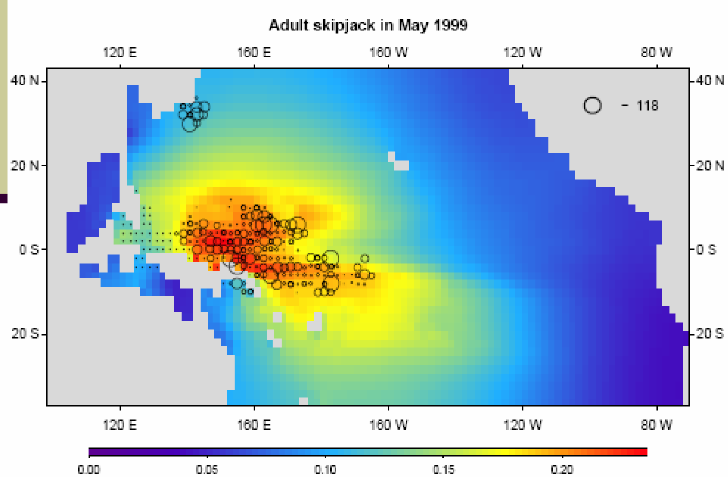
Hindcast simulations

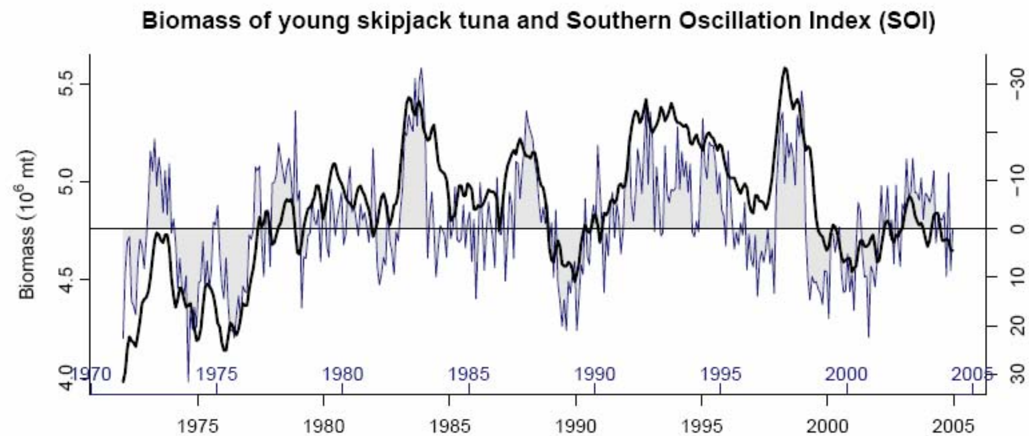
Pacific skipjack





* MULTIFAN-CL: statistical stock-recruitment model

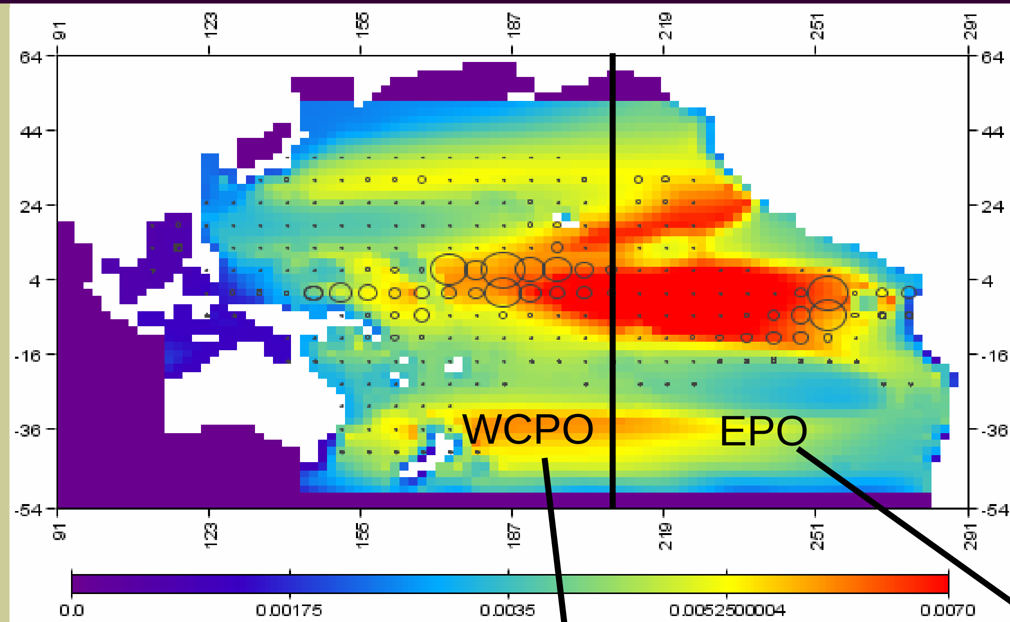




Time series of skipjack biomass is lagged by 8 months backward

Hindcast simulations

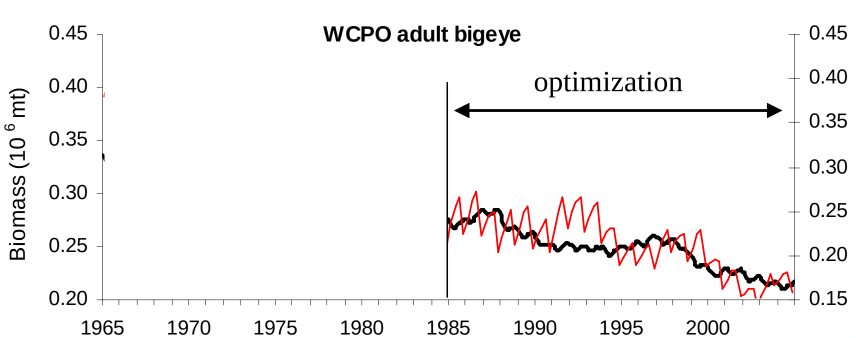
Pacific bigeye stock

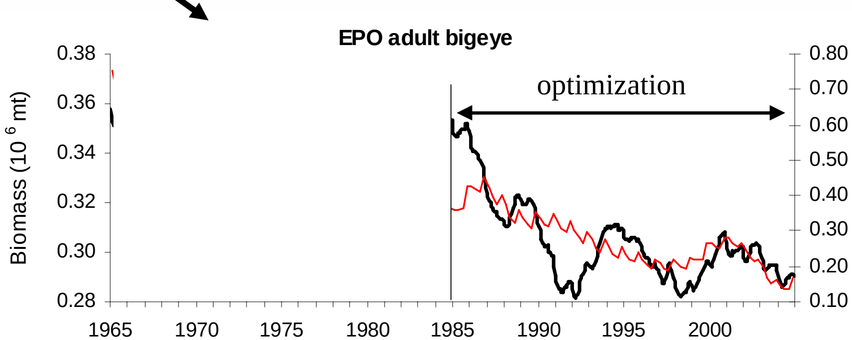


- Predicted distribution of adult biomass and observed (circles) longline catch

Black curve: SEAPODYM

Red curve: Statistical Stock-recruitment model (MULTIFAN-CL)





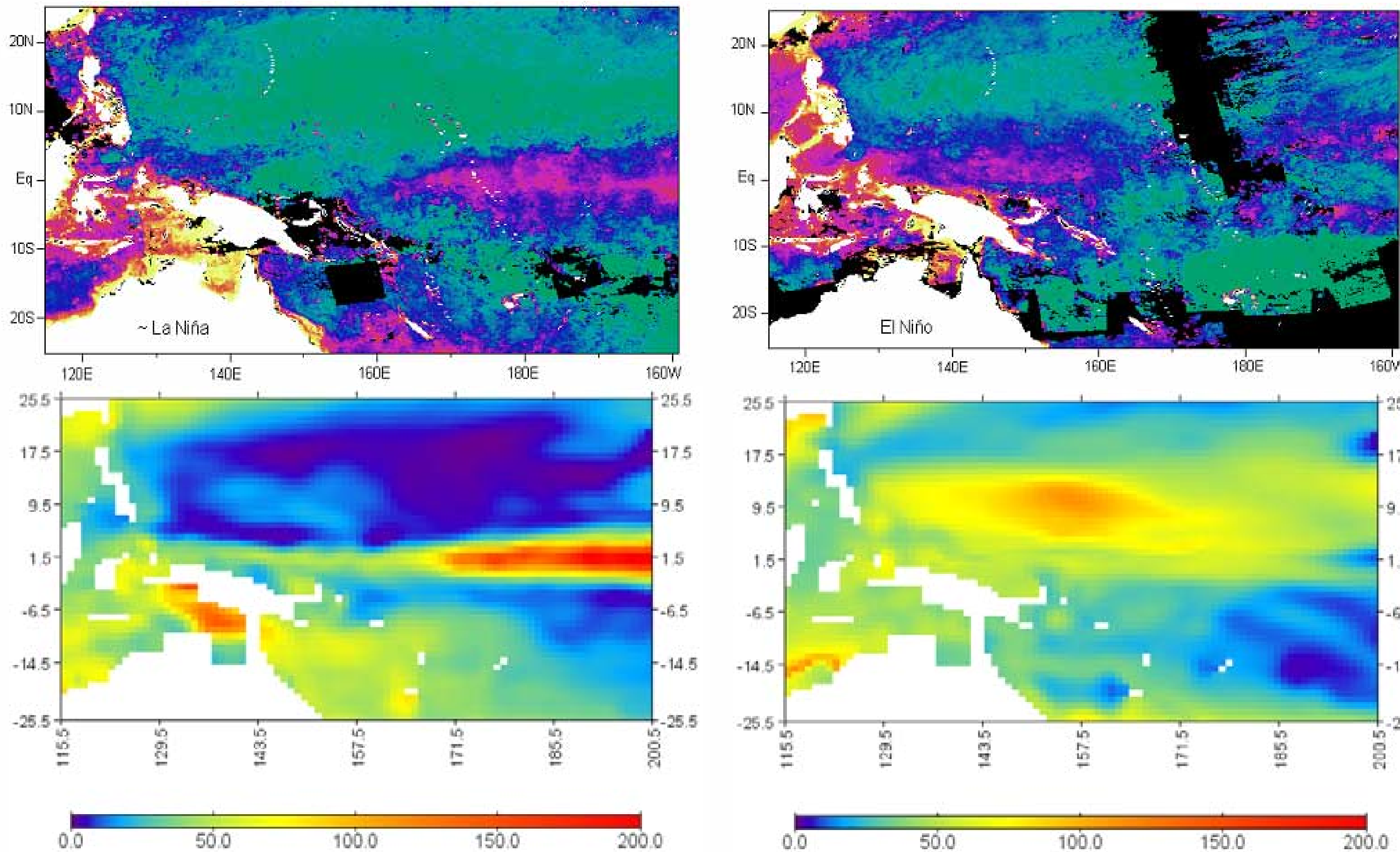
Confidence / uncertainty

Environmental forcing data set

La Niña | **El Niño**

Observation Satellite

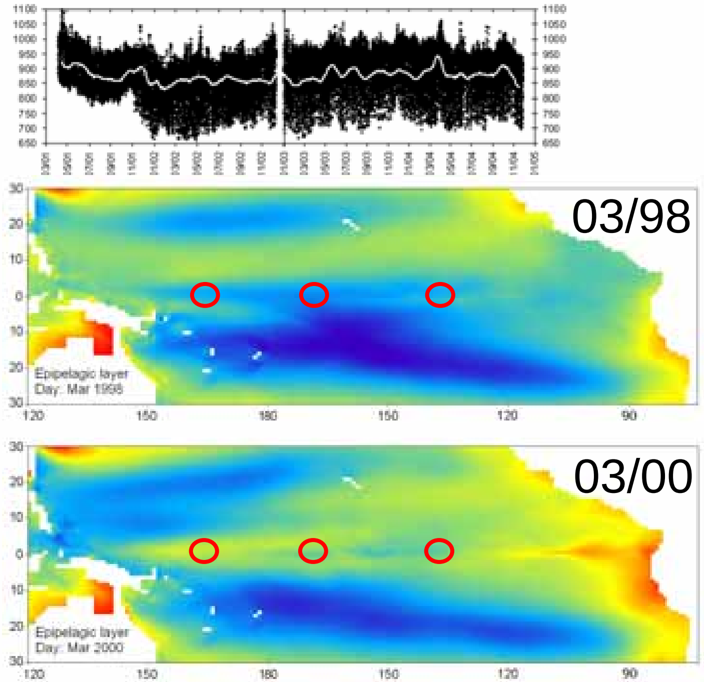
Prediction model



Confidence / uncertainty

Micronekton

ADCP data (Mc Phaden, Radenac et al.)

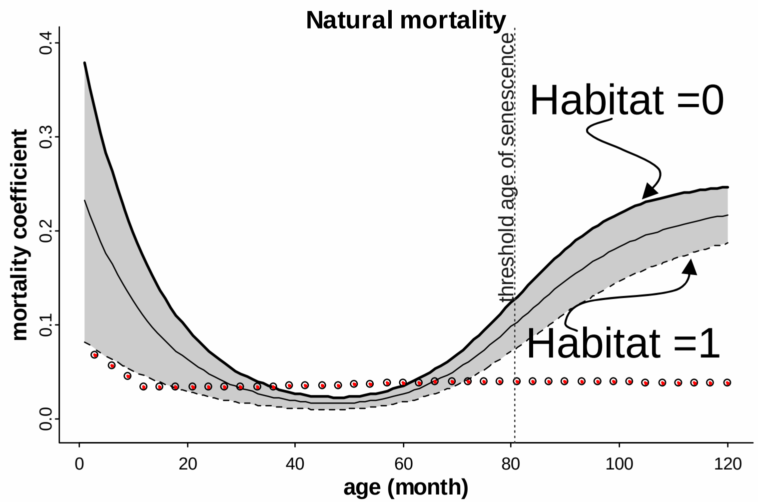


- In all cases, fluctuations of ADCP time series are shifted by several months relatively to the primary production

- Micronekton (tuna forage) predicted time series are in phase with ADCP data

Coherence in parameter estimates

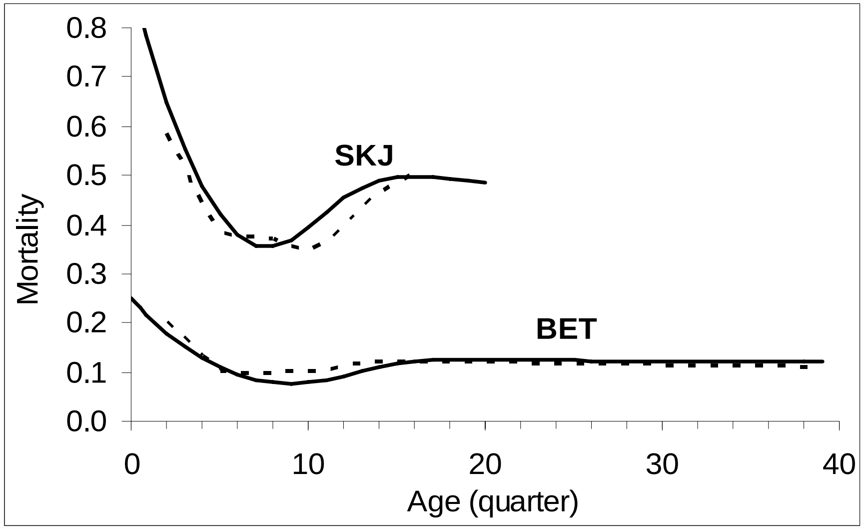
Natural mortality rates



	θ	Skipjack	Bigeye
Natural mortality	β_p	0.296 ± 0.0018	0.073 ± 0.0005
	M_{max}	0.5*	0.25 ± 0.003
	β_s	-0.044 ± 0.0015	-0.097 ± 0.008
	A	31*	80.6 ± 0.008

✓ In average, converging with independent studies

!! Values at early stages are correlated with spawning coefficient (lack of data)

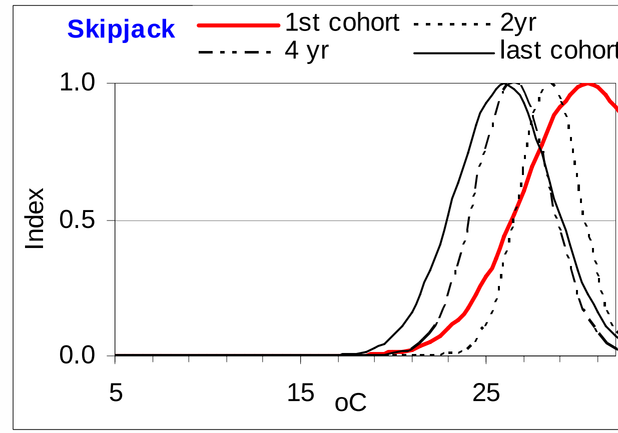


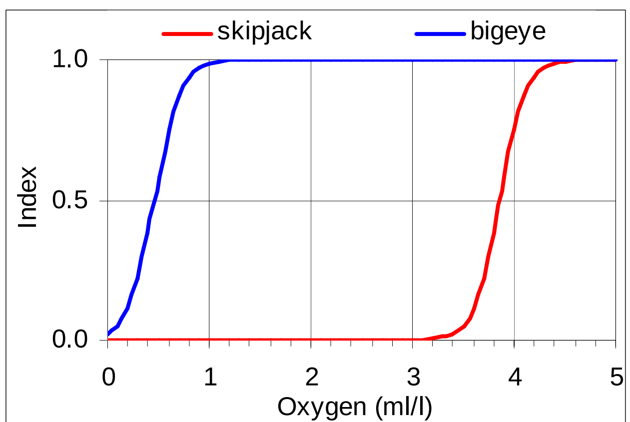
Confidence / uncertainty

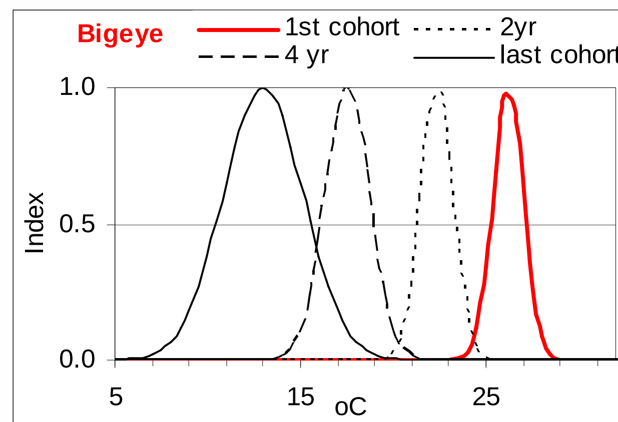
Coherence in parameter estimates

Thermal habitat and oxygen tolerance

	θ	Skipjack	Bigeye
Spawning habitat	σ_0	3.5*	0.82 ± 0.012
	T_0	30.5 ± 0.0047	26.2 ± 0.013
Adult habitat	σ_a	1.62 ± 0.0015	2.16 ± 0.004
	T_a	26*	13 ± 0.004
	$\hat{O}$	3.86 ± 0.0009	0.46 ± 0.0006







<u>Oxygen:</u>

✓ok for bigeye

✓ok for skipjack

<u>Temperature:</u>

✓ok for bigeye

!! difficult for skipjack

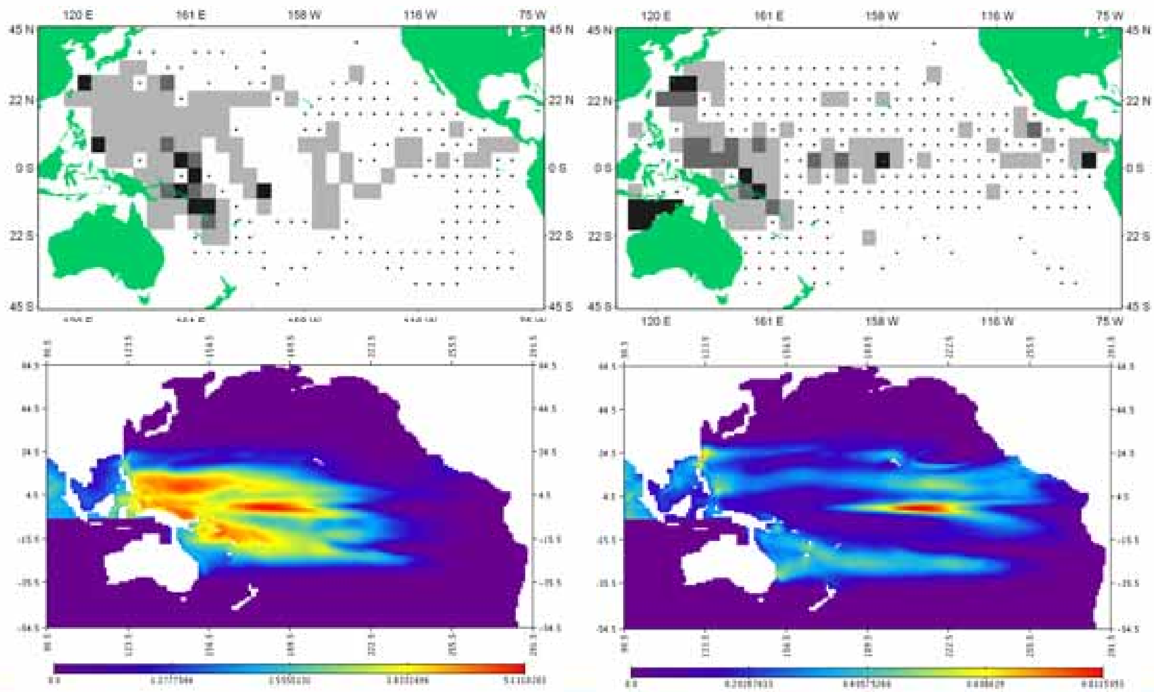
Confidence / uncertainty

Coherence in parameter estimates

larvae survival leading to recruits

The number of larvae recruited in each cell of the grid at each time step is the product of a Beverton-Holt relationship coefficient linking the number of larvae to the density of mature fish and the spawning index I_s

I_s: combines the effect of temperature and a measure of the trade-off ratio between food (~PP) and predators (micronekton) of larvae



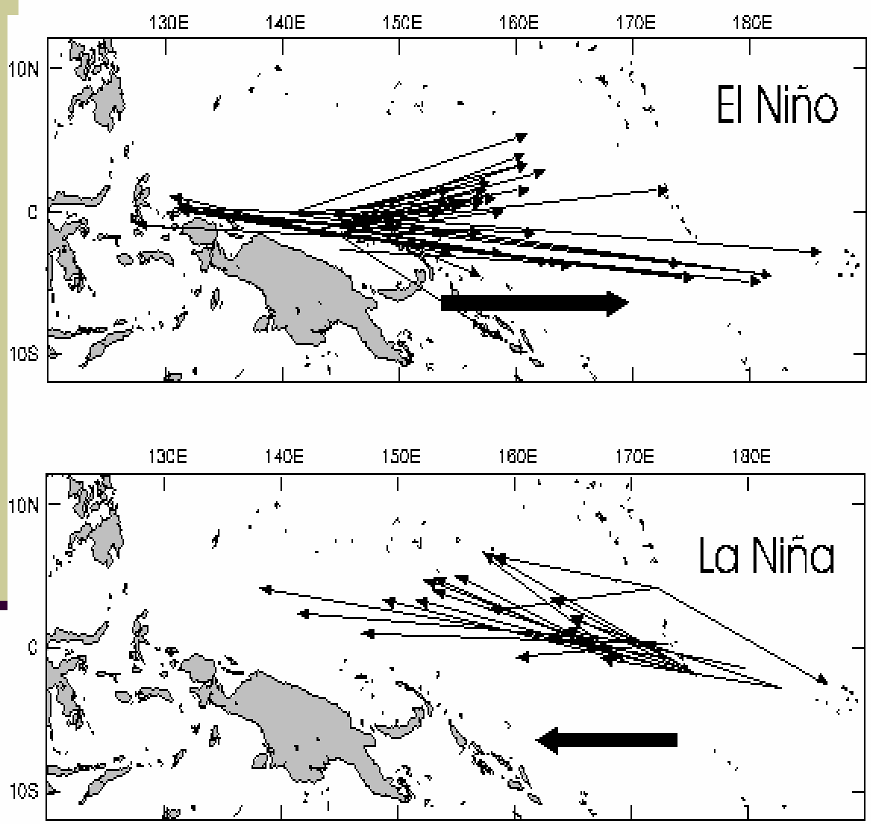
✓General agreement with existing (limited) data

! Difficulties for skipjack in parameters optimization

Confidence / uncertainty

Coherence in parameter estimates

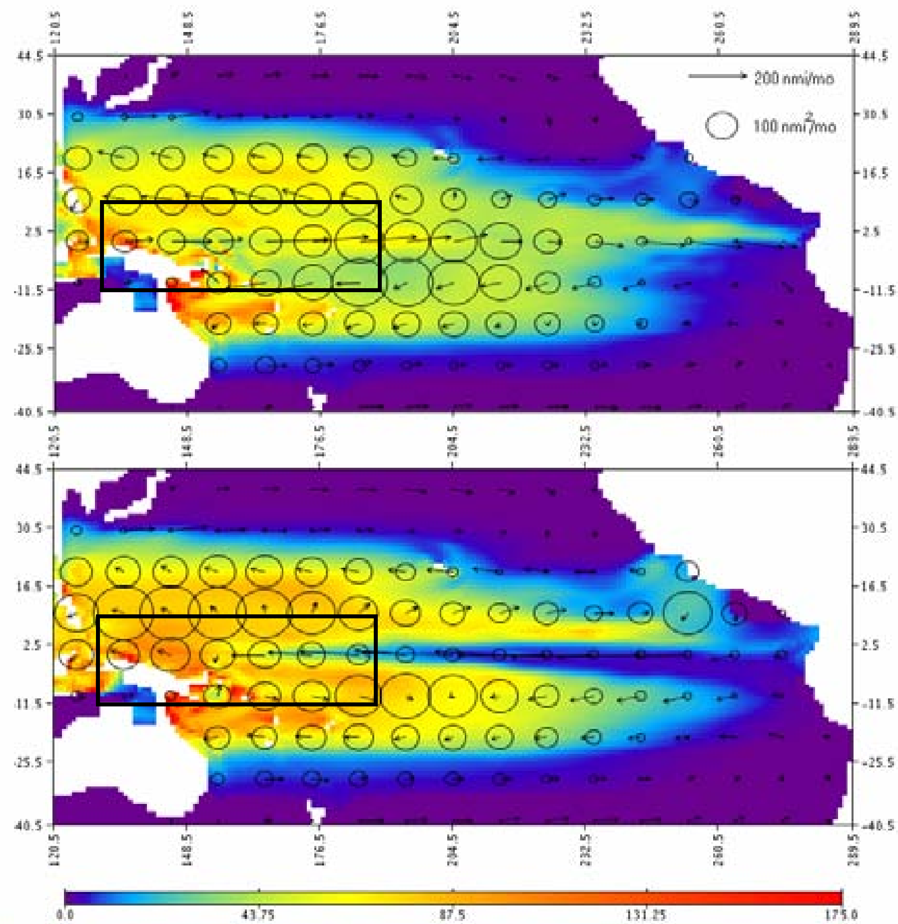
Movements



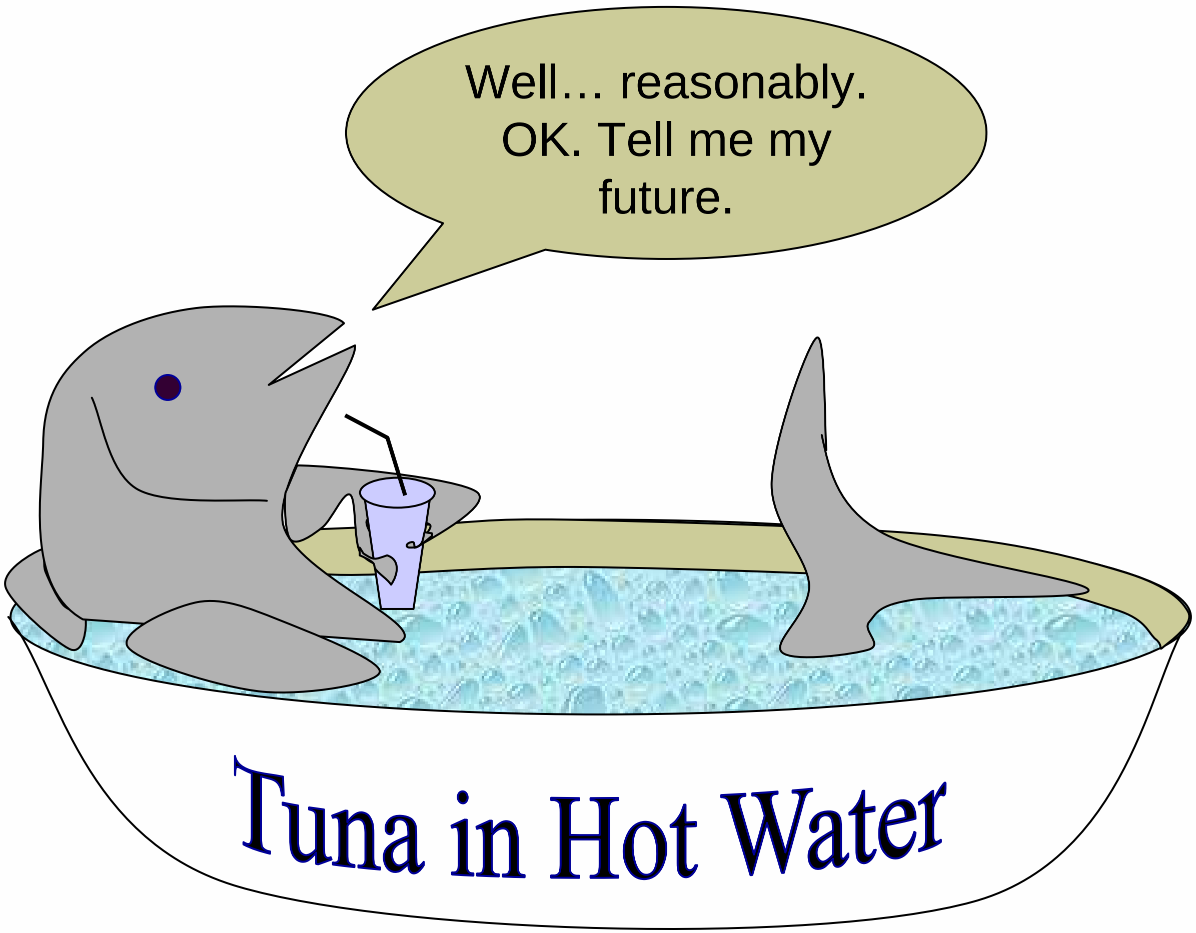
Observed movement from skipack tagging data

(Lehodey et al. 1997, Nature)

Skipjack



Are you confident with this model ?



Forecast: IPSL Simulation

Ocean Reanalysis vs Climate Simulation

Ocean Reanalysis

3D-forcing | *Atmospheric reanalysis* heat flux, wind

↓

Ocean General circulation Model

↓

Ocean Biogeochemical (Nutrient-Phyto-Zoo-Detritus) Model

Realistic seasonal, inter-annual and decadal variability in time and space (e.g. reproduce El Niño / La Niña years, PDO shifts, NAO, ...)

Climate Simulation

Atmospheric CO_2 concentration | **1D-forcing**

↓

Atmospheric model (*LMDZ*)

Land surface Model *(ORCHIDEE)*

Coupler (OASIS)

Ocean General circulation Model *(OPA)*

Sea-ice model (*LIM*)

↓

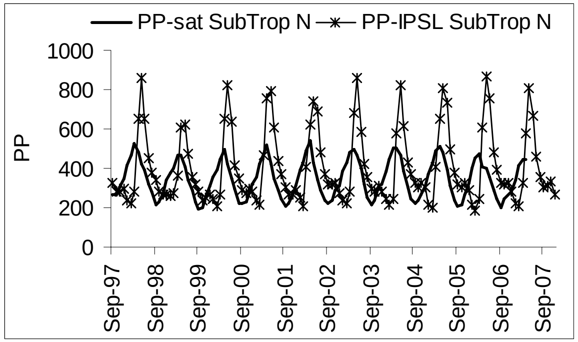
Ocean Biogeochemical (NPZD) Model

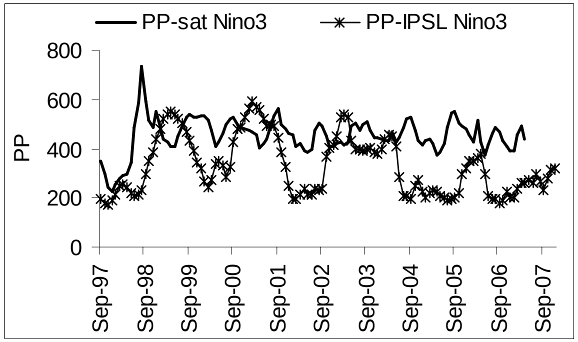
Realistic seasonal variability

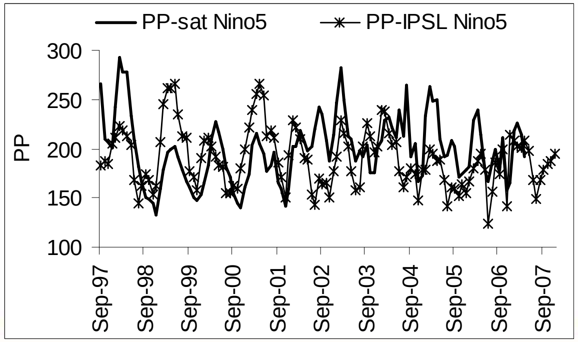
Realistic internal frequency at inter-annual and decadal scale, but not necessarily coinciding with observed variability

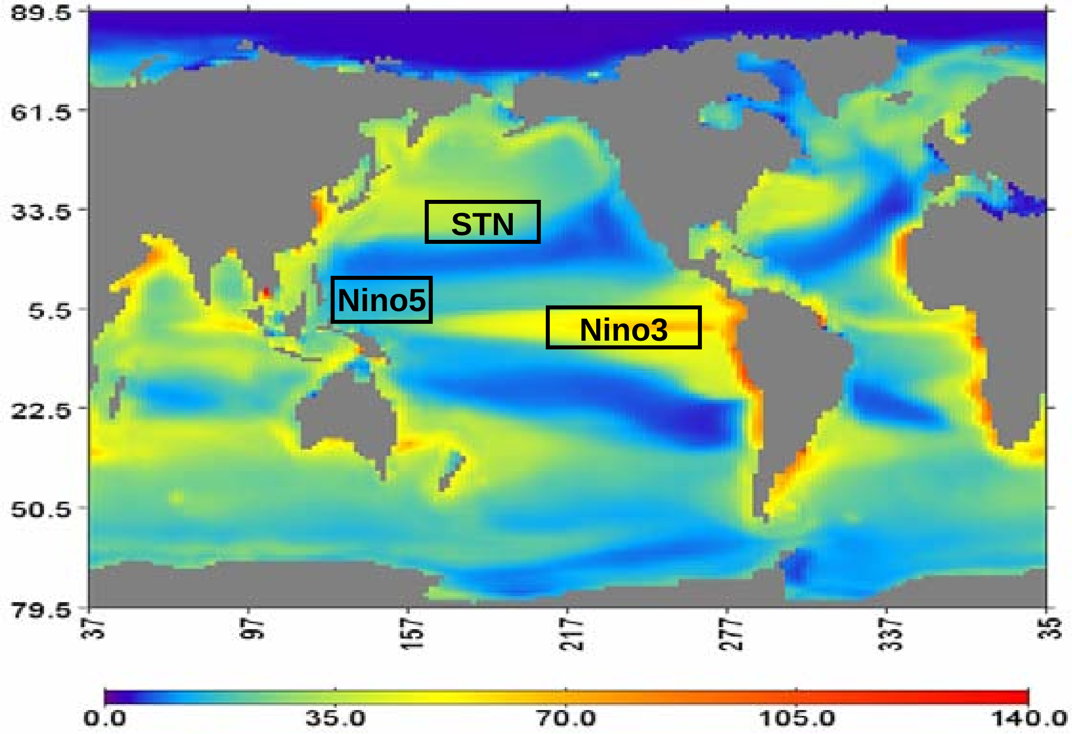
Forecast: IPSL Simulation

Ex: Primary production









Comparison with primary production deduced from Satellite data (*Behrenfeld and Falkowski, 1997*)

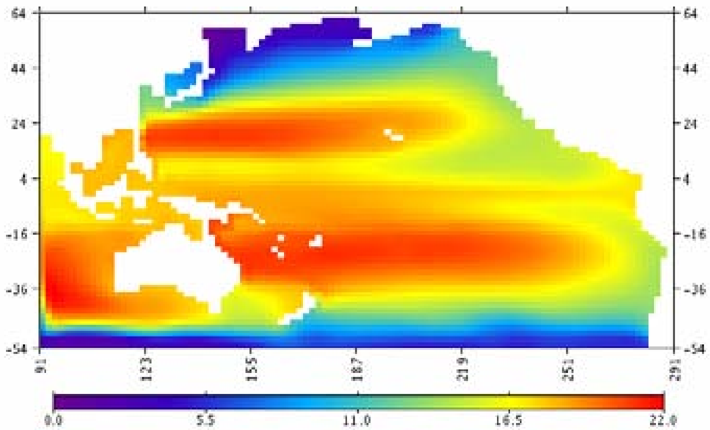
Ref.: Schneider, Bopp et al., 2007. Spatio-temporal variability of marine primary and export production in three global coupled climate carbon cycle models. *Biogeosciences Discussion*, **4**: 1877–1921

Forecast: IPSL Simulation

PFRP

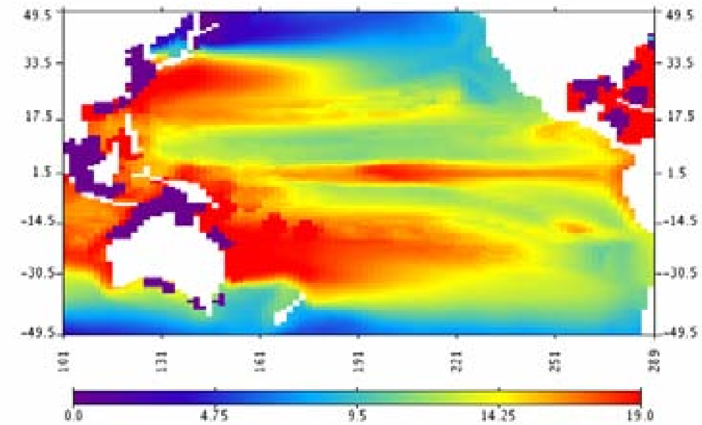
Changes in forcing fields

ESSIC

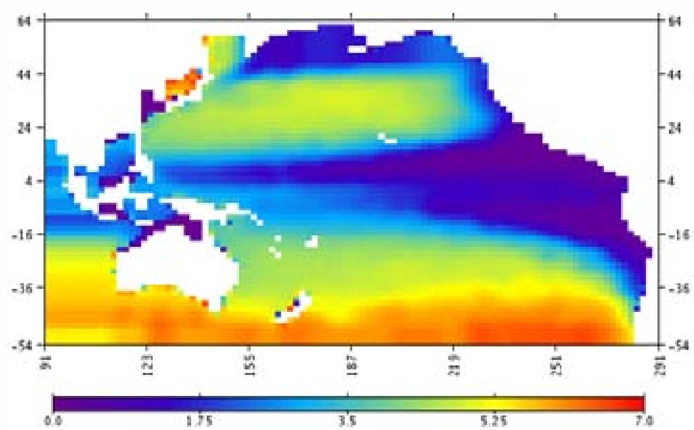


Constant depth of layers

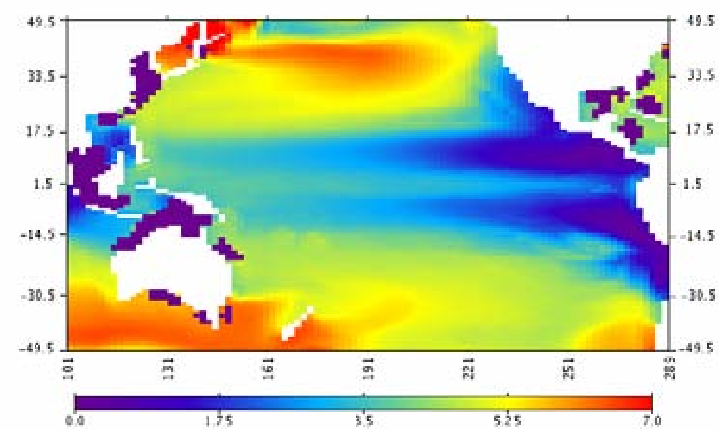
IPSL



Definition of vertical layers by euphotic depth



Levitus seasonal climatology for oxygen



IPSL predicted monthly oxygen outputs

Forecast: IPSL Simulation

PFRP

Revising parameters optimization

Bigeye

θ	F	ESSIC	IPSL
β_p	Natural mortality	0.073	0.083
M_{max}		0.25	<u>0.3</u>
β_s		-0.097	-0.11
A		80.6	75.8
σ_0		0.82	**0.21**
T_0	Spawning habitat	26.2	26.5
α		0.63	0.69
BH_a		0.0045	<u>0.009</u>
σ_a	Adult habitat	2.16	2.74
T_a		13	**9.94**
[illegible]		0.46	**1.05**
D_{max}	Movement	0.22	0.11
V_{max}		0.32	0.4
Fishing parameters			

Skipjack

θ	F	ESSIC	IPSL
β_p	Natural mortality	0.296	0.1
M_{max}		0.5*	0.5*
β_s		-0.044	-0.1
A		31*	31*
σ_0	Spawning habitat	3.5*	3.5*
T_0		30.5	29.5
α		0.1*	0.1*
BH_a		0.5*	0.5*
σ_a	Adult habitat	2.62	2.1
T_a		26*	26*
[illegible]		3.86	**5.46**
c	Movement	0.4	0.27
V_{max}		1.3	0.95
Fishing parameters			

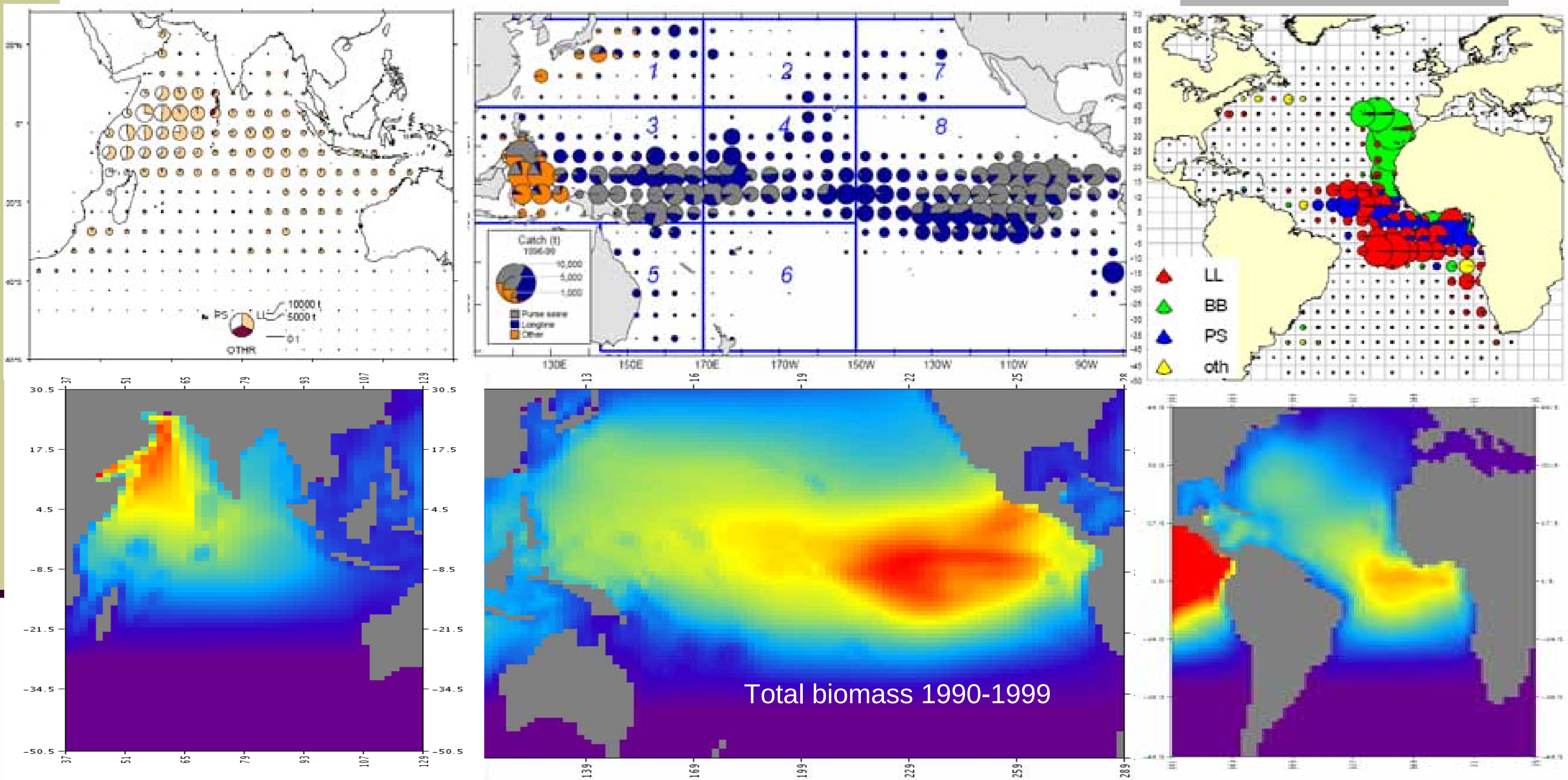
The estimated biology reflects the environment

Bigeye has a long life span and extended habitat strongly influenced by seasonal variability, facilitating the revision of parameters with CC simulation

Skipjack has a short life-span, with equatorial core habitat influenced by ENSO variability: it is much more difficult to revise parameters optimisation with CC simulation

Forecast: IPSL Simulation

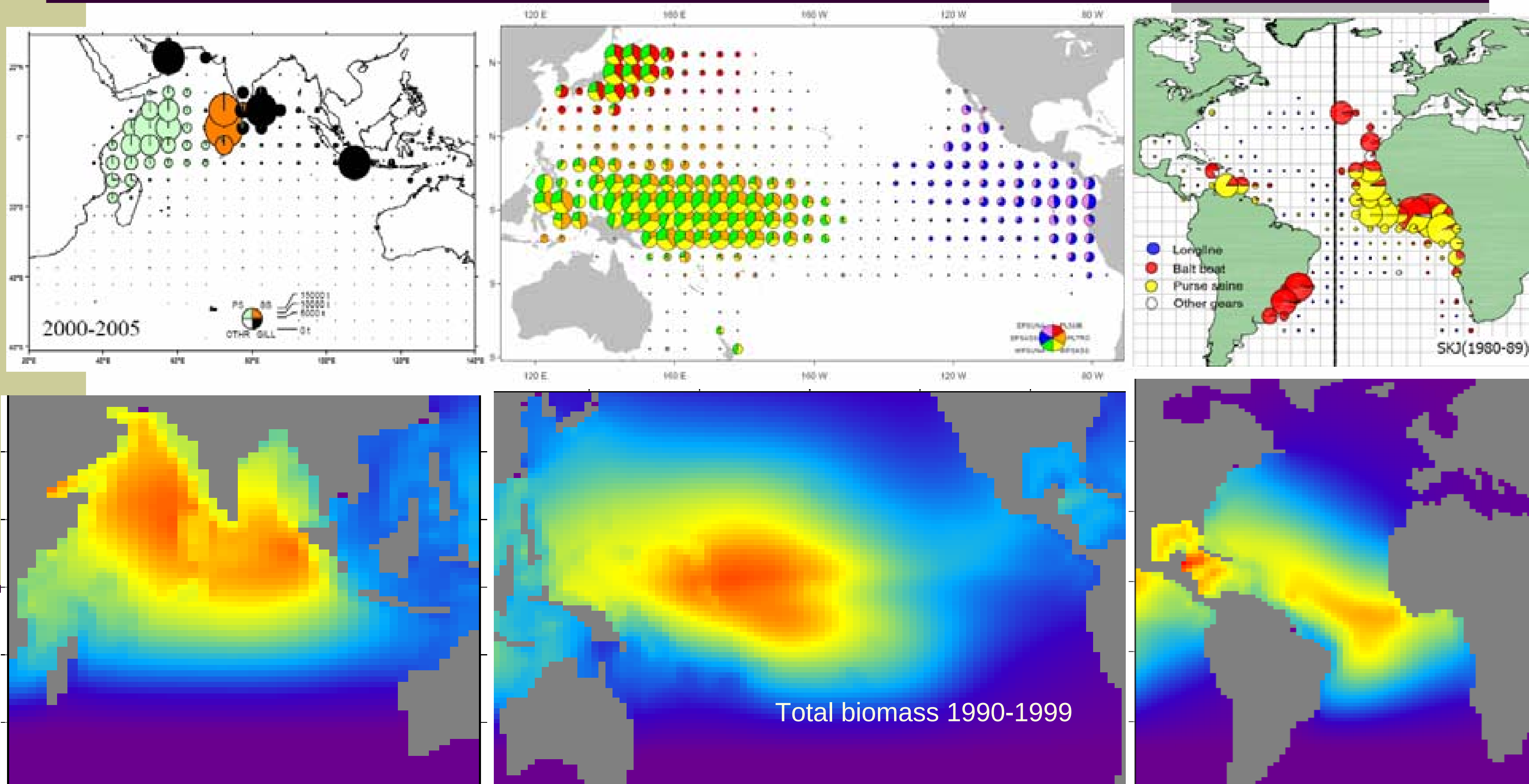
BIGEYE: Global average predicted distribution



For bigeye, model gives superficially realistic predictions in other oceans using parameters estimated from Pacific populations

Forecast: IPSL Simulation

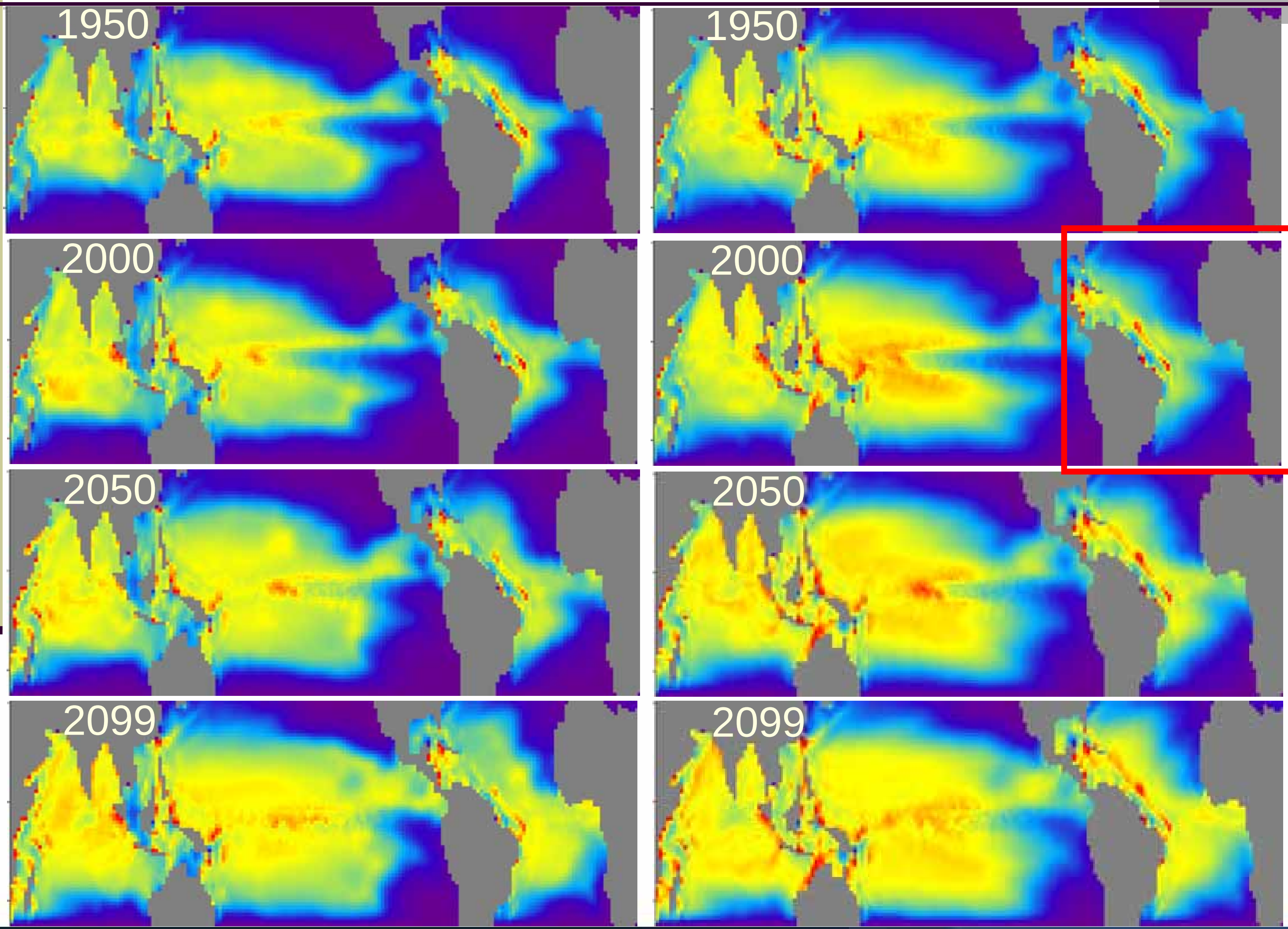
SKIPJACK: Global average predicted distribution



For skipjack, Pacific parameterization gives less convincing “visual correlation” (based on catch distribution) in other Oceans

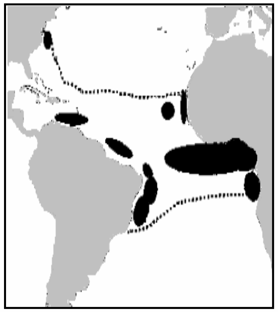
Trends

Larvae distribution



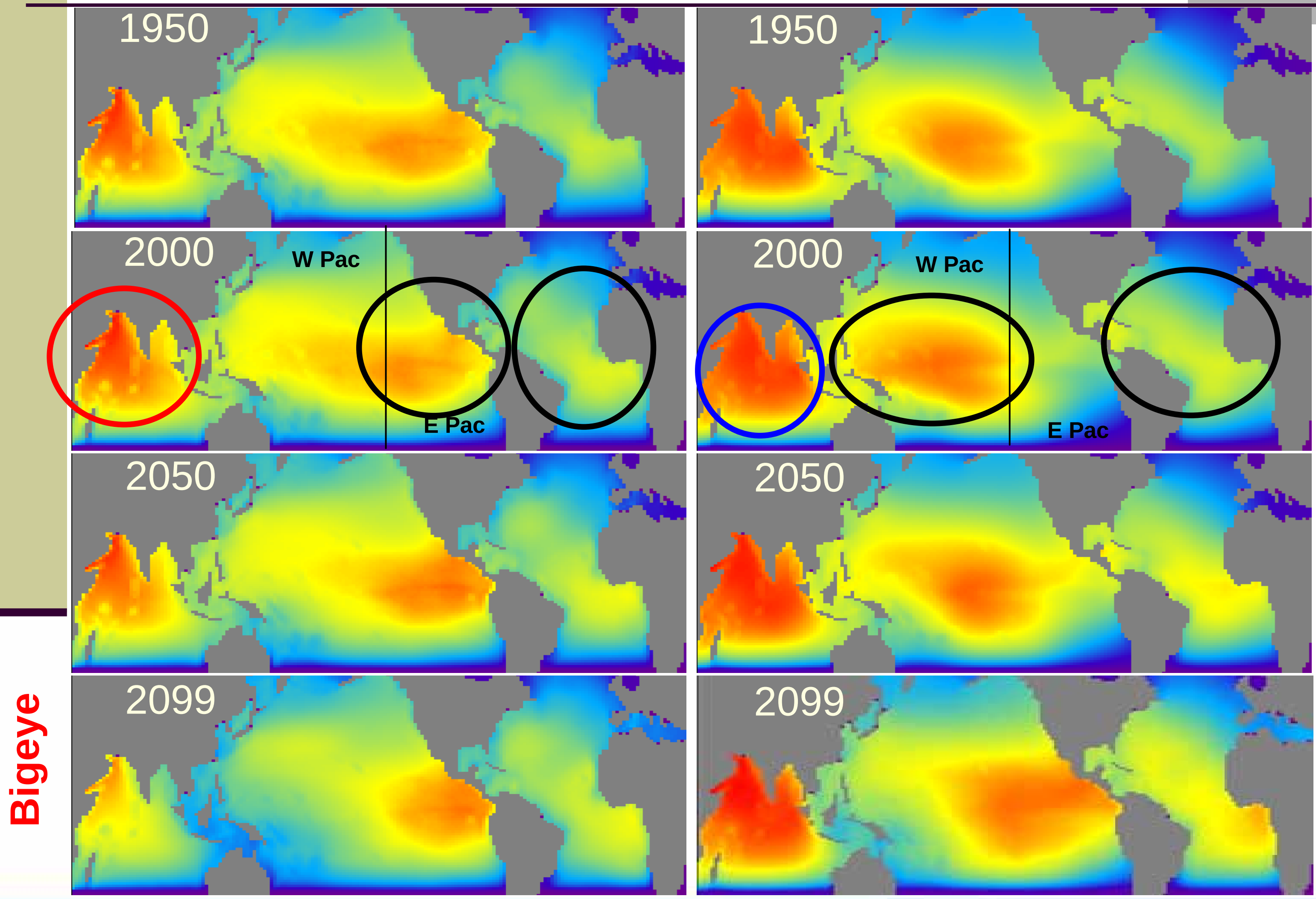
Bigeye

Skipjack



Spawning sites (black) and larvae distribution (between dotted lines). From ICCAT report (1999)

Adults biomass distribution



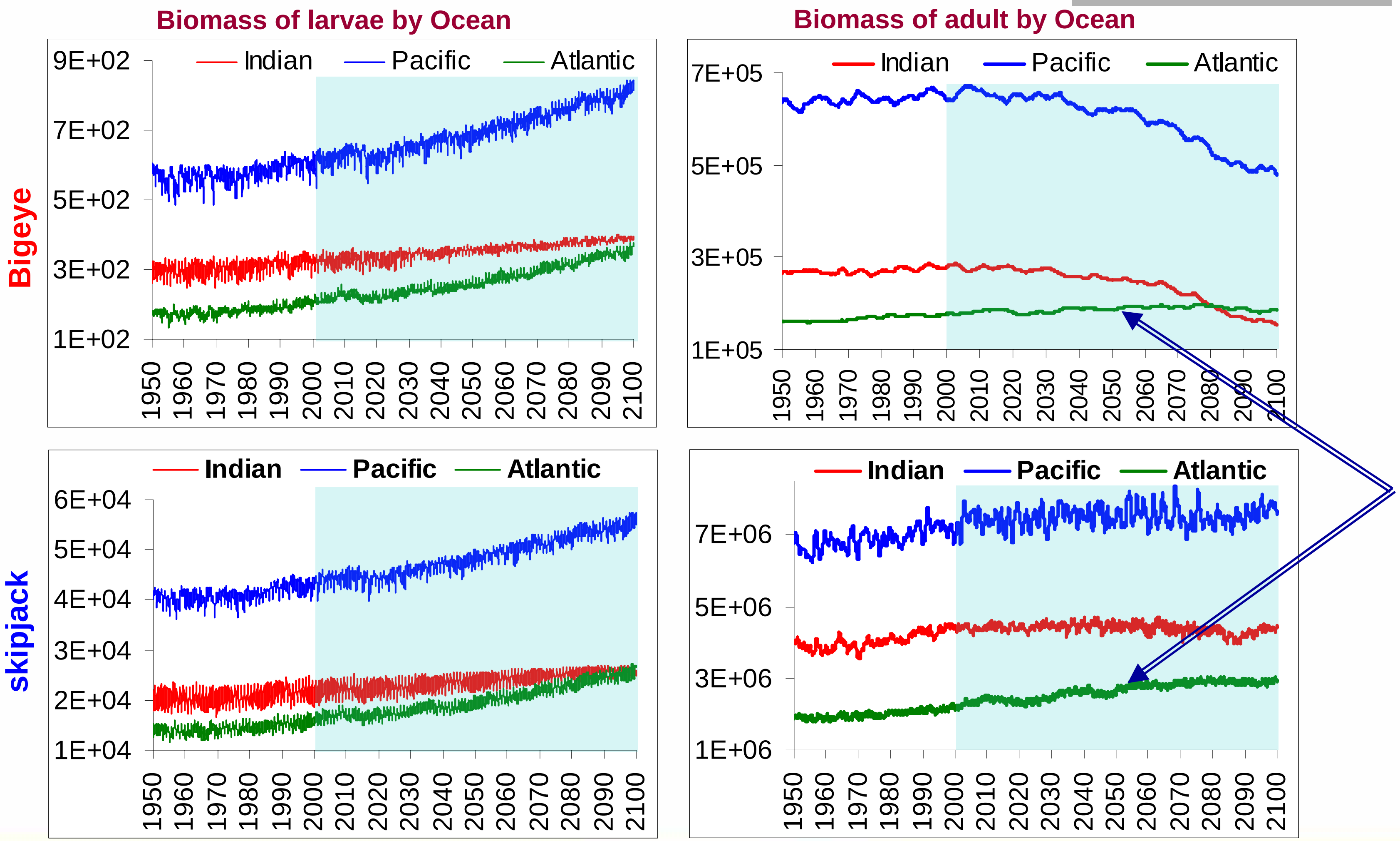
	Bet	Skj
E Pac.	108-142	282-439
W Pac.	117-134	1136-1370
Ind.	115-135	422-489
Atl.	76-103	115-160

Range of annual catch ('000 t) by ocean 2000-04 (FAO,2007)

Tropical Indian O. area ~ ½ trop. W. Pac. area

And the winner is…

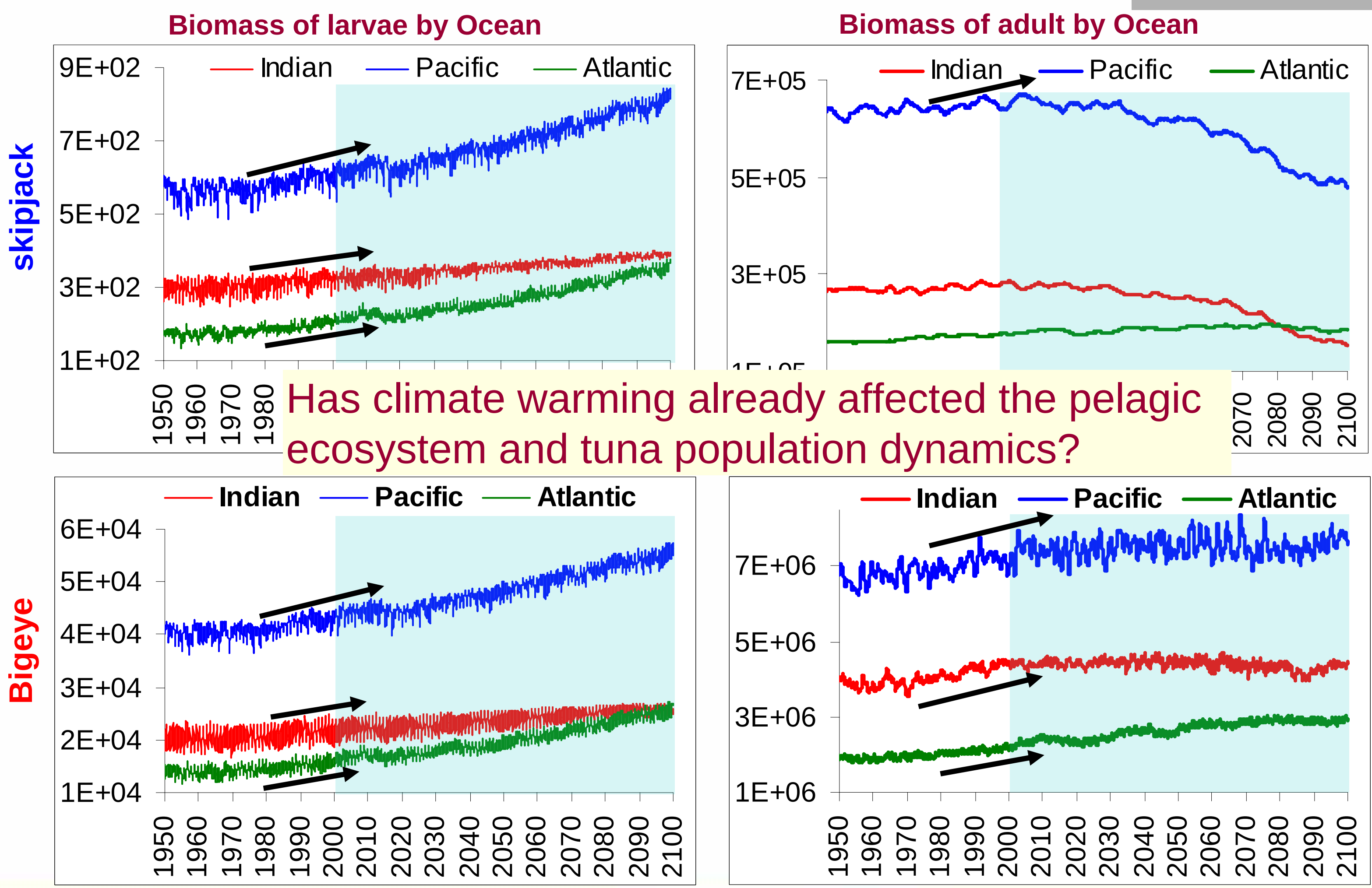
… The Atlantic Ocean?



By the way…

PFRP

Did you notice this?



Has climate warming already affected the pelagic ecosystem and tuna population dynamics?

Conclusions

Summary

Uncertainty

- Single reanalysis and some changes in forcing fields of climate change scenario
- Difficulties in optimization of some parameters for skipjack
- Very few estimate of accuracy of forage components
- Interaction between species?

Confidence

- ✓ Rigorous optimization leads to meaningful biological parameters
- ✓ Many mechanisms in the model based on relative rather than absolute parameterization
- ✓ Predictions in agreement with independent stock assessment estimates (MFCL) including for hindcast simulations
- ✓ Limited and coherent changes in parameter estimates between reanalysis and CC simulations
- ✓Realistic distribution in three oceans with one single (Pacific) parameterization
- ✓ Coherent changes in habitats and dynamic

Conclusions

So what?

Modeling

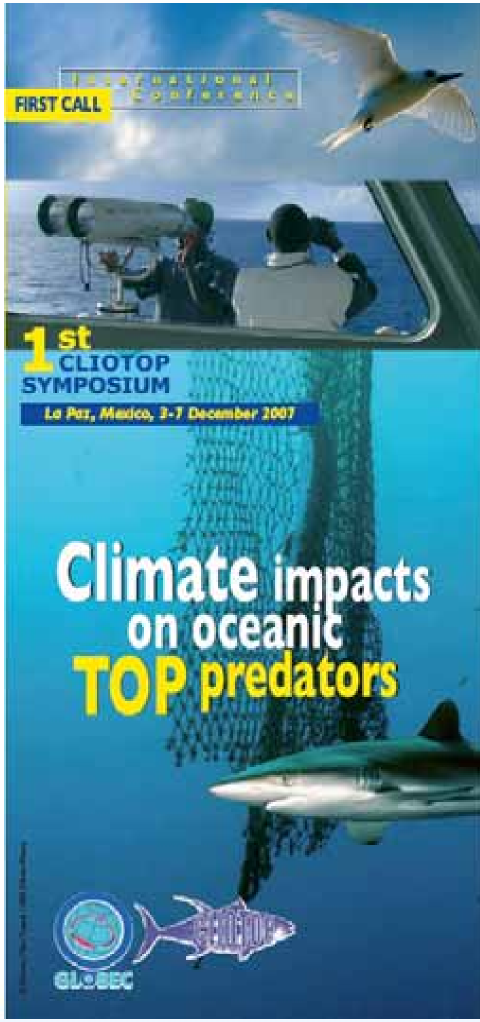
- End-to-end ecosystem modelling is possible by avoiding excessive reductionism.
- Optimized parametrization is key issue to investigate the top-down & bottom-up control of marine ecosystems.
- SEAPODYM will find application in evaluation of tuna fishery management

Climate change simulation

1. We got different (complex) responses by species and Ocean.
2. Despite general increase in larvae abundance, adult biomass decrease in some places but not in others: e.g., increase in the Atlantic, abrupt decrease of bigeye in the Indian and western Pacific… Which mechanisms? thresholds?
3. Tuna populations may have been already impacted by CC. Any evidence of that?
4. Large pelagic highly migratory animals are sentinelle species of the CC. We should monitor these animals carefully.

Conclusions

Next steps



- Compare fishery and climate effects during historical period in Atlantic and Indian O.
- Apply to yellowfin tuna
- Optimization using other reanalysis and simulation products
- Optimization with multi-species for testing species-interaction *(need parallel code)*
- Verify forage components; implement MAAS project (CLIOTOP: next meeting in Bergen, Norway, June 24)
- Forecast fishing effects into the future *(needs model of fishery dynamics, topic for CLIOTOP WG5)*

CLIOTOP web site: http://web.pml.ac.uk/globec/structure/regional/cliotop/cliotop.htm

The End

Thank you