EXPLORING BIOGEOGRAPHY AND COMPETITIVE ADVANTAGE/DISADVANTAGE IN A GLOBAL ECOSYSTEM MODEL

Stephanie Dutkiewicz

Jason Bragg[1], Mick Follows,
Oliver Jahn, Andrew Barton,
Fanny Monteiro[2], Penny Chisholm

Massachusetts Institute of Technology
Program in Atmospheres, Oceans and Climate

1. now at CSIRO, Canberrra
2. now at Univ. Bristol

OUTLINE OF TALK

- model description
  - physical/biogeochemistry/ecosystem
- emergent model biogeography
  (given suitable trade-offs, environment selects ecosystem structure)
- environment role in selective pressures that might shape the course of evolution

MODEL DESCRIPTION

•3-D MIT ocean general circulation model (Marshall et al, JGR 1997)

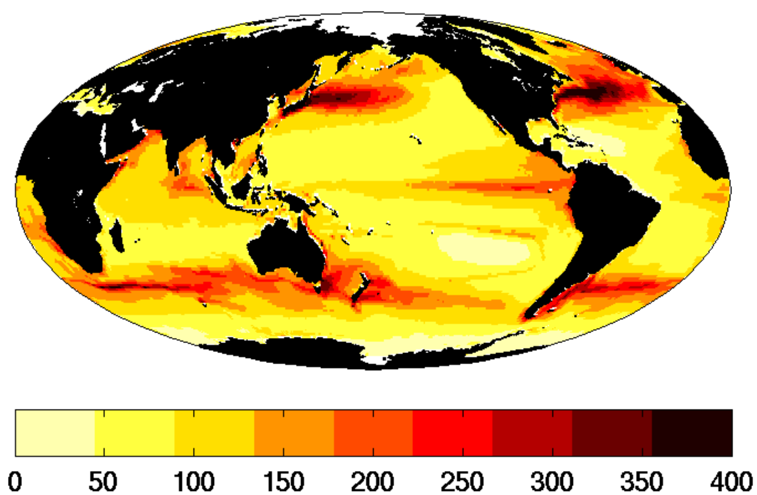
•global 1°x1° horizontal, 22 levels in vertical (10m-500m)

•physics: ECCO state estimates (Wunsch+Heimbach, Physica D 2007)

•biogeochemistry: N,P,Si,Fe

•ecosystem: many phytoplankton, 2 zooplankton

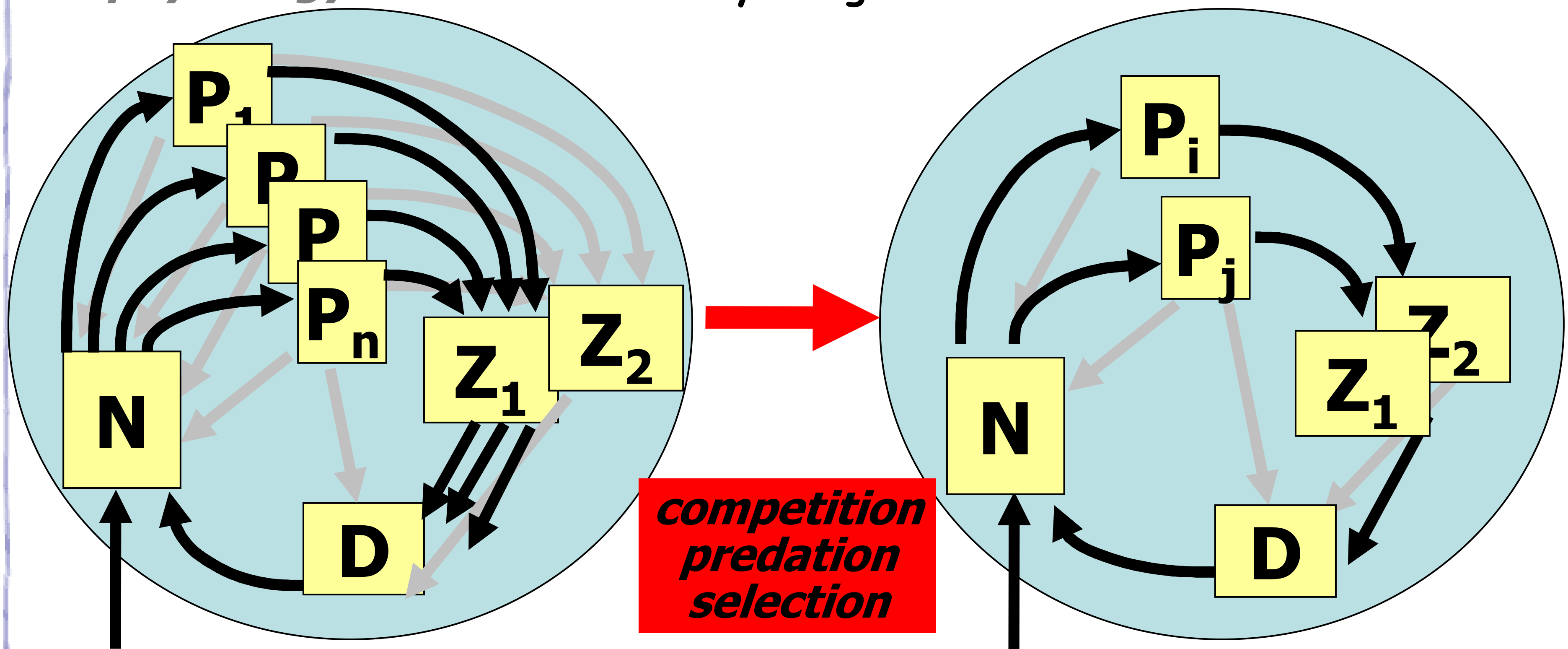
Model Primary Production ($gC/m^2/y$)



MODEL DESCRIPTION

genetics and physiology

parameters of growth rate are randomly assigned



physical and chemical environment

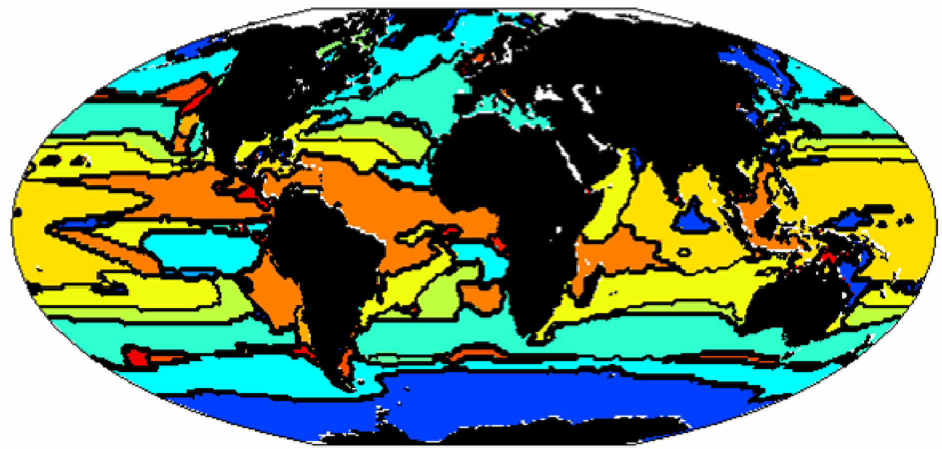
n can by 100's

MORE ON ECOSYSTEM MODEL:
Follows et al, Science, 2007;
Dutkiewicz et al, GBC, 2009

EMERGENT MODEL BIOGEOGRAPHY

Dominant phytoplankton type

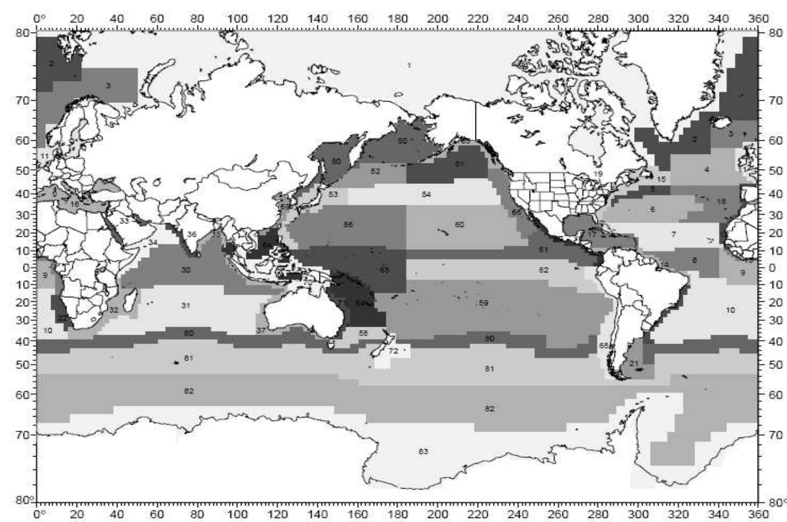
"biomes"



Dutkiewicz et al.,GBC, 2009

Coloured regions indicate dominance by a phytoplankton type.
(Note there are several types that co-exist - Barton et al. Science, in press)

reminiscent of Longhurst provinces



EMERGENT MODEL BIOGEOGRAPHY

Trade off in choices of parameters

- opportunists/r-strategists:
  grow fast, but require
  high nutrients
  (e.g. diatoms)

- gleaners/K-strategist:
  slower growing, but
  require little nutrients
  (e.g. prokaryotes)

EMERGENT MODEL BIOGEOGRAPHY

Dominant phytoplankton type

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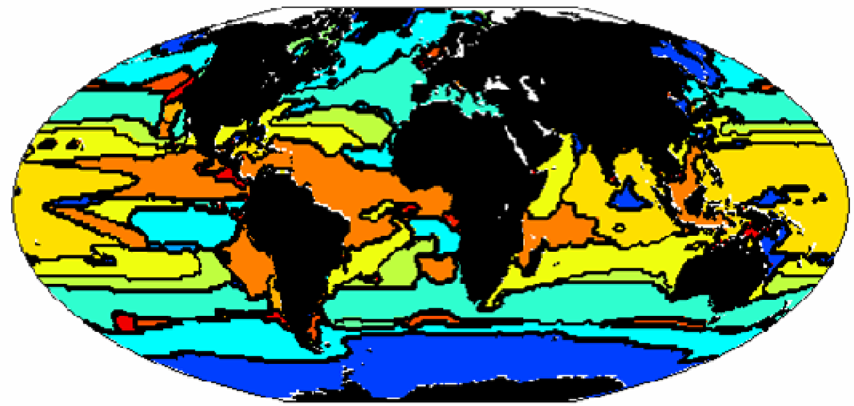
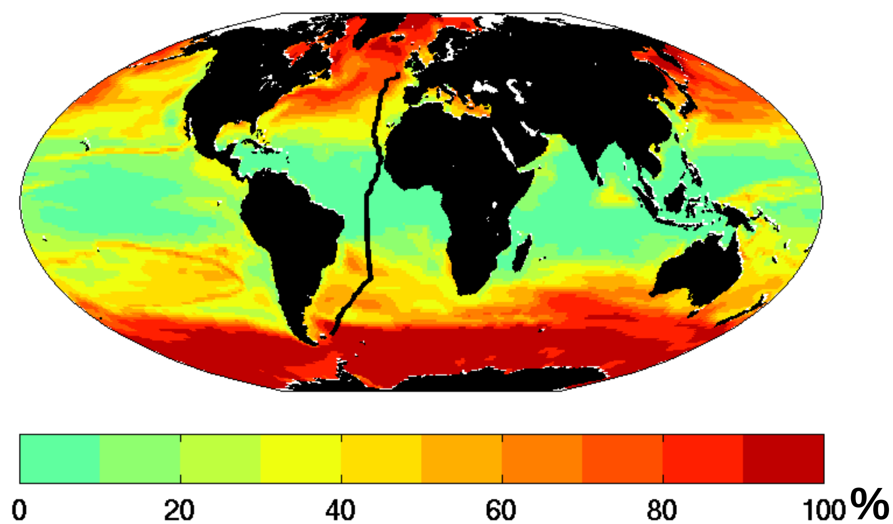


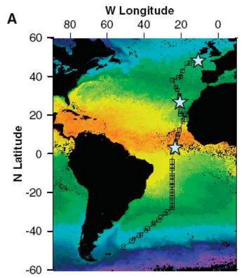
Percent of biomass made up of opportunists

green=mostly gleaners
red= mostly opportunists



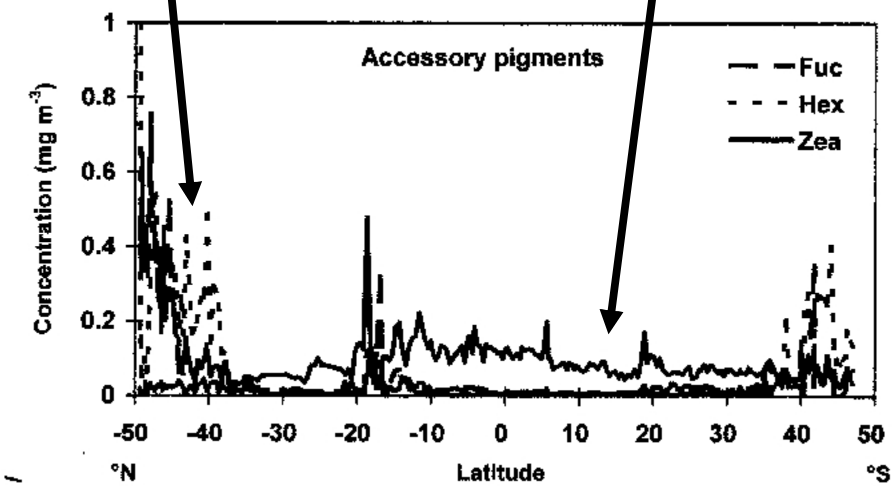
Dutkiewicz et al.,GBC, 2009

EMERGENT MODEL BIOGEOGRAPHY



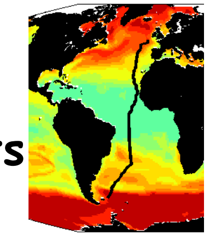
larger phyto

prochlorophytes

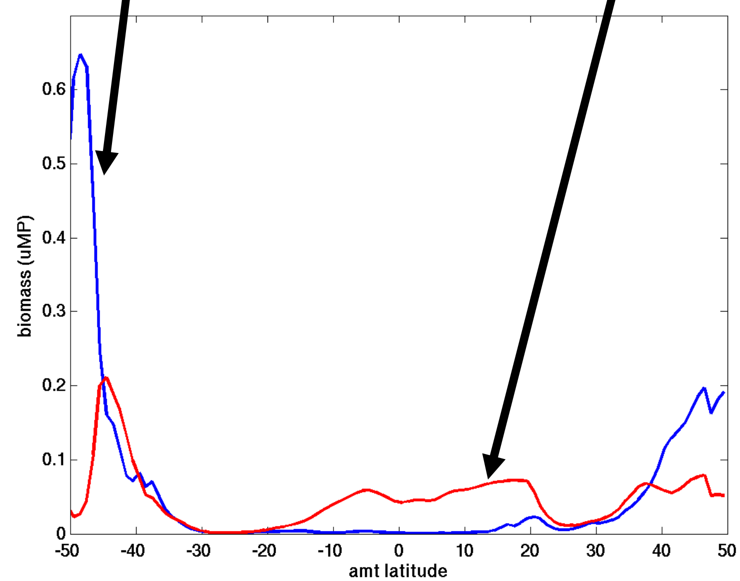


OBSERVATIONS

opportunists (blue)



gleaners (red)



MODEL

Aiken et al.,2000

Dutkiewicz et al.,GBC, 2009

EMERGENT MODEL BIOGEOGRAPHY

Trade off between gleaners

- *Synechococcus*/pico-eukaryotes: use NO_3
- *Prochlorococcus:* cannot use NO_3, but needs less nutrients to grow

Follows et al, Science, 2007

Trade off for nitrogen fixing

- Diazotrophs: fix nitrogen, but at cost of growing slower, and requiring more iron

Monterio et al, GBC, submitted

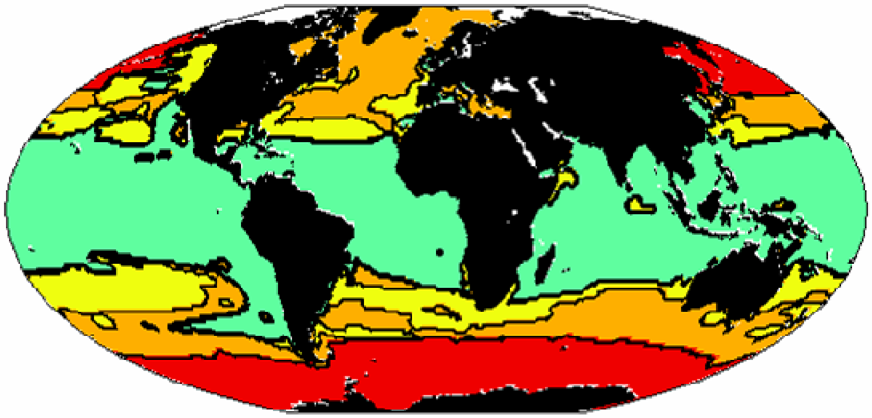
EMERGENT MODEL BIOGEOGRAPHY

- By putting in appropriate trade-offs (the "results" of evolutionary processes) we can get selection by environment

"Every things is everywhere, but, environment selects" Lourens Bass-Becking

Dominant functional type

Green=*Prochloroccus*
Yellow=other small
Orange=other large
Red=diatoms



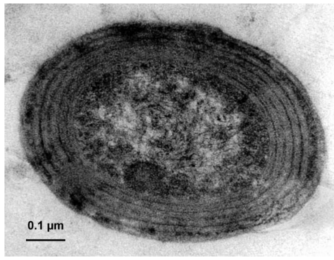
Dutkiewicz et al.,GBC, 2009

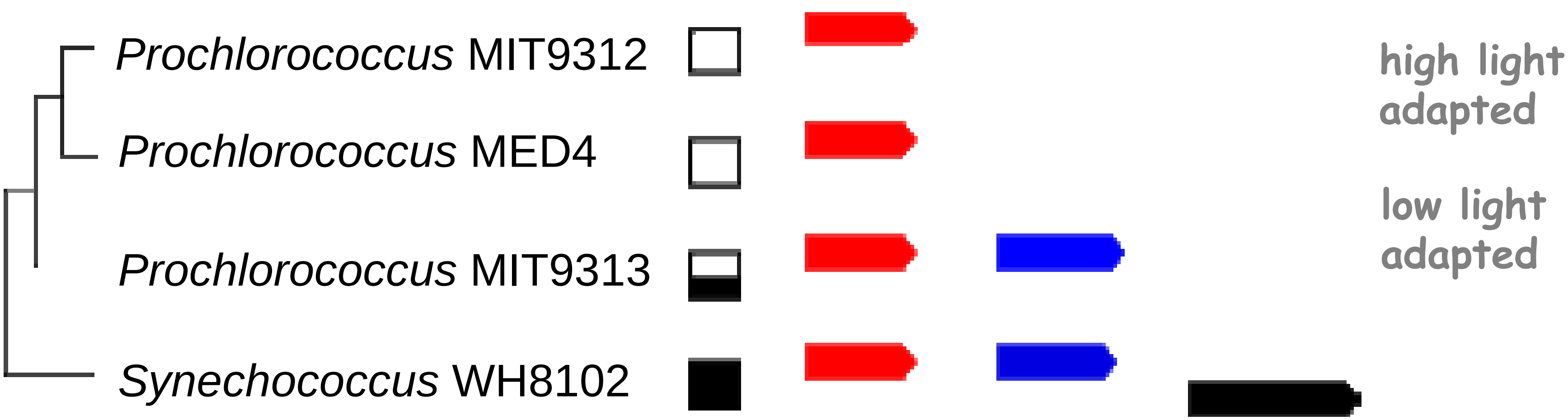
EMERGENT MODEL BIOGEOGRAPHY

- By putting in appropriate trade-offs (the "results" of evolutionary processes) we can get selection by environment

> "Every things is everywhere, but, environment selects" Lourens Bass-Becking

- Now instead of setting some trade offs, we use the model to offer insight into selective pressures that may help shape the course evolution





Rocap *et al.* 2003

N sources for growth:

- □ NH_4
- ⬓ NH_4, NO_2
- ■ NH_4, NO_2, NO_3

$NO_3 \xrightarrow{narB} NO_2 \xrightarrow{nirA} NH_4 \xrightarrow{glnA} \rightarrow \rightarrow$ amino acids

Moore *et al.* 2002

though nitrate gives idea of distribution we can find no statistical association with inorganic nitrogen compounds

Why have *Prochloroccus* lost ability to use nitrate, nitrite?

- **disadvantage is small?**
  NH_4 abundant, NO_3, NO_2 scarce

- **there are advantages?**
  costs of maintaining NO_3 and NO_2 use?

Aim: - to 'rewind the tape of life' to a point where picoplankton structured by *I, T* traits
- use ocean ecosystem model to study disadvantage of losing N use abilities

Bragg et al, PloS One, 2010

MUTATION EXPERIMENTS

$$\frac{dP}{dt} = \mu P - mP - \varepsilon\mu P$$

$$\frac{dP_m}{dt} = +\varepsilon\mu P + (\mu + \Delta\mu)P_m - mP_m$$

P	parent population
P_m	mutant
μ	growth rate
m	loss rate
ε	proportion of divisions becoming mutants
$\Delta\mu$	mutation affect on growth

For ε <<1 and small perturbation around steady state

$$\frac{dP_m}{dt} \approx \Delta\mu P_m + \varepsilon\mu P$$

MUTATION EXPERIMENTS

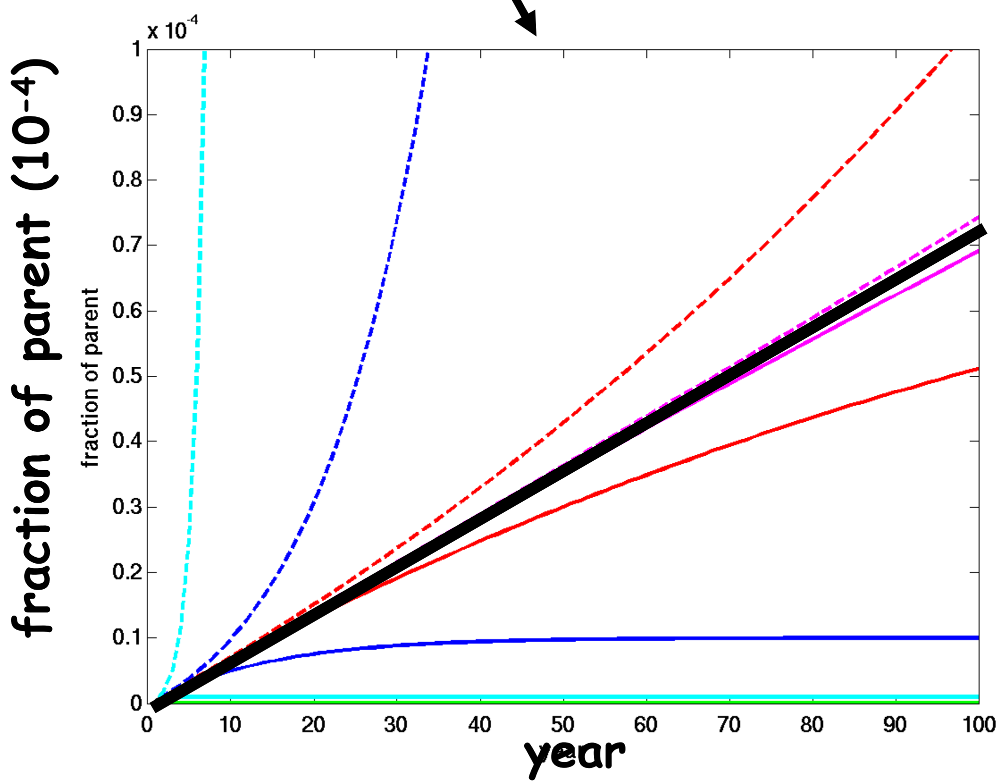
gain mutants:
accumulates quicker, and will eventually take over from parent

$$\Delta\mu > 0$$

$$\frac{dP_m}{dt} \approx \Delta\mu P_m + \varepsilon\mu P$$

$$\Delta\mu = 0$$

null mutant:
steady accumulation

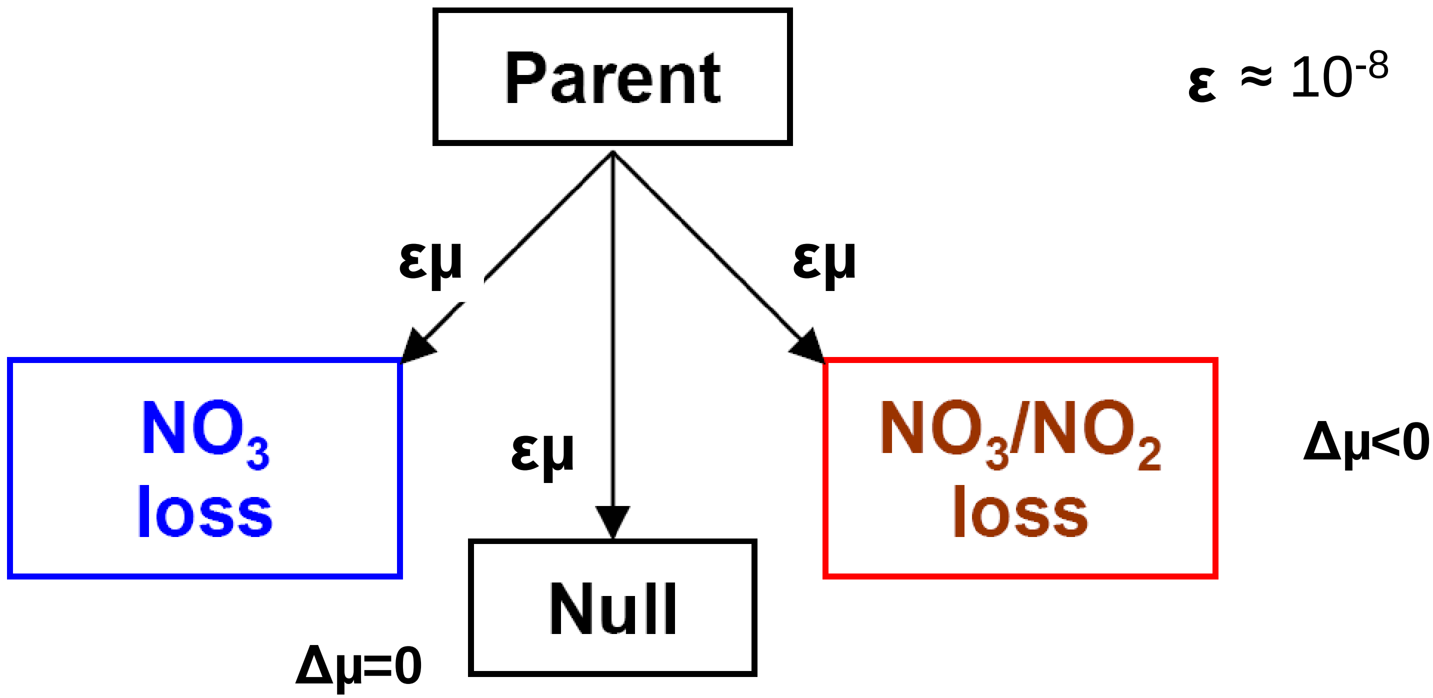


$$\Delta\mu < 0$$

loss mutants:
accumulates slower, will never take over from parent but may reach substantial portion

MUTATION EXPERIMENTS

- 15 gleaners/18 opportunists initialized
- model run for three years
- then, mutants produced by growth of gleaner parents
- mutants are identical to parents except for N use ability

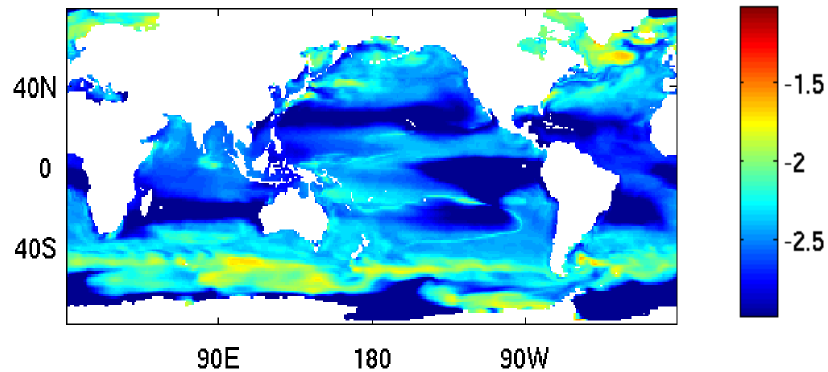


Bragg et al, PloS One, 2010

MUTATION EXPERIMENTS

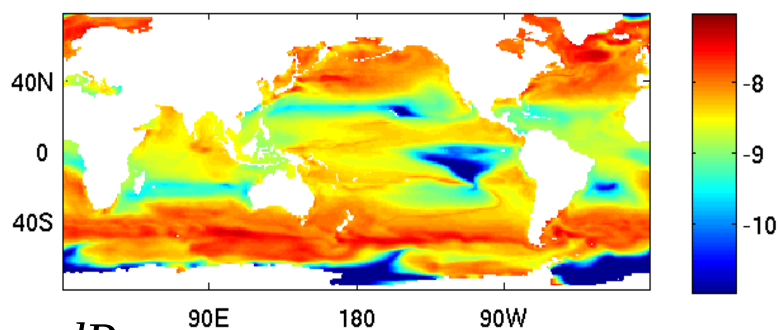
picoplankton (gleaners) after 2 years of mutation

parents



$\log_{10}$ biomass (μM P)

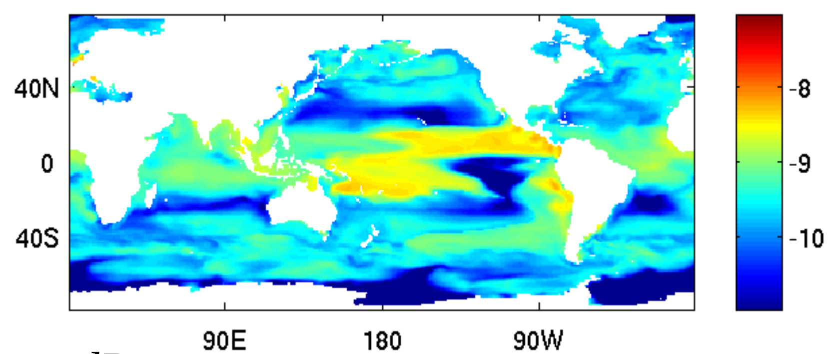
null mutants



$$\frac{dP_m}{dt} \approx +\varepsilon\mu P$$

Δμ=0

NO_3/NO_2 loss mutants



$$\frac{dP_m}{dt} \approx \Delta\mu P_m + \varepsilon\mu P$$

Δμ<0

Where is $\Delta\mu$ sufficiently small?

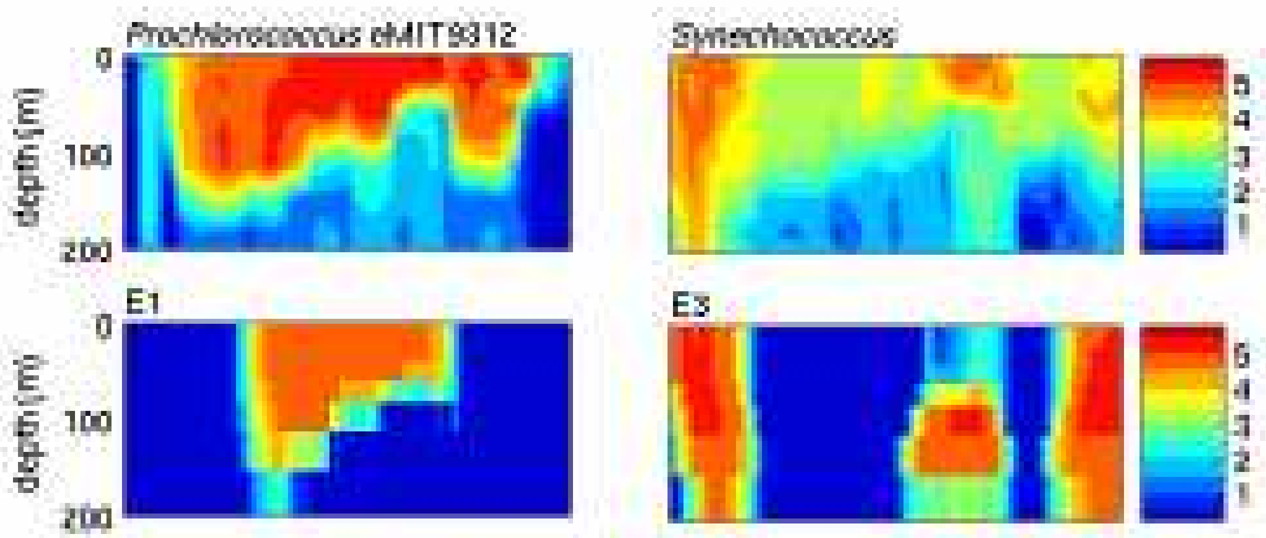
Bragg et al, PloS One, 2010

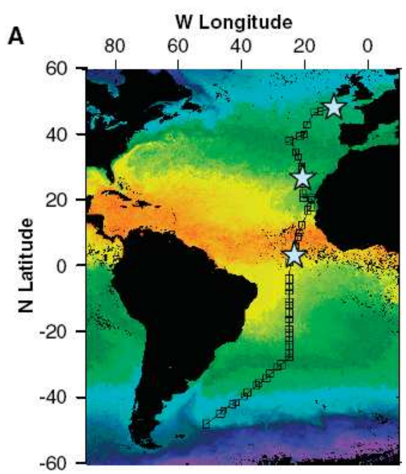
MUTATION EXPERIMENTS

Bragg et al, PloS One, 2010

OBSERVATIONS
(Johnson et al. Science, 2006)
log10(cells/ml)

MODEL PARENTS
(designated by geographical distribution)





MUTATION EXPERIMENTS

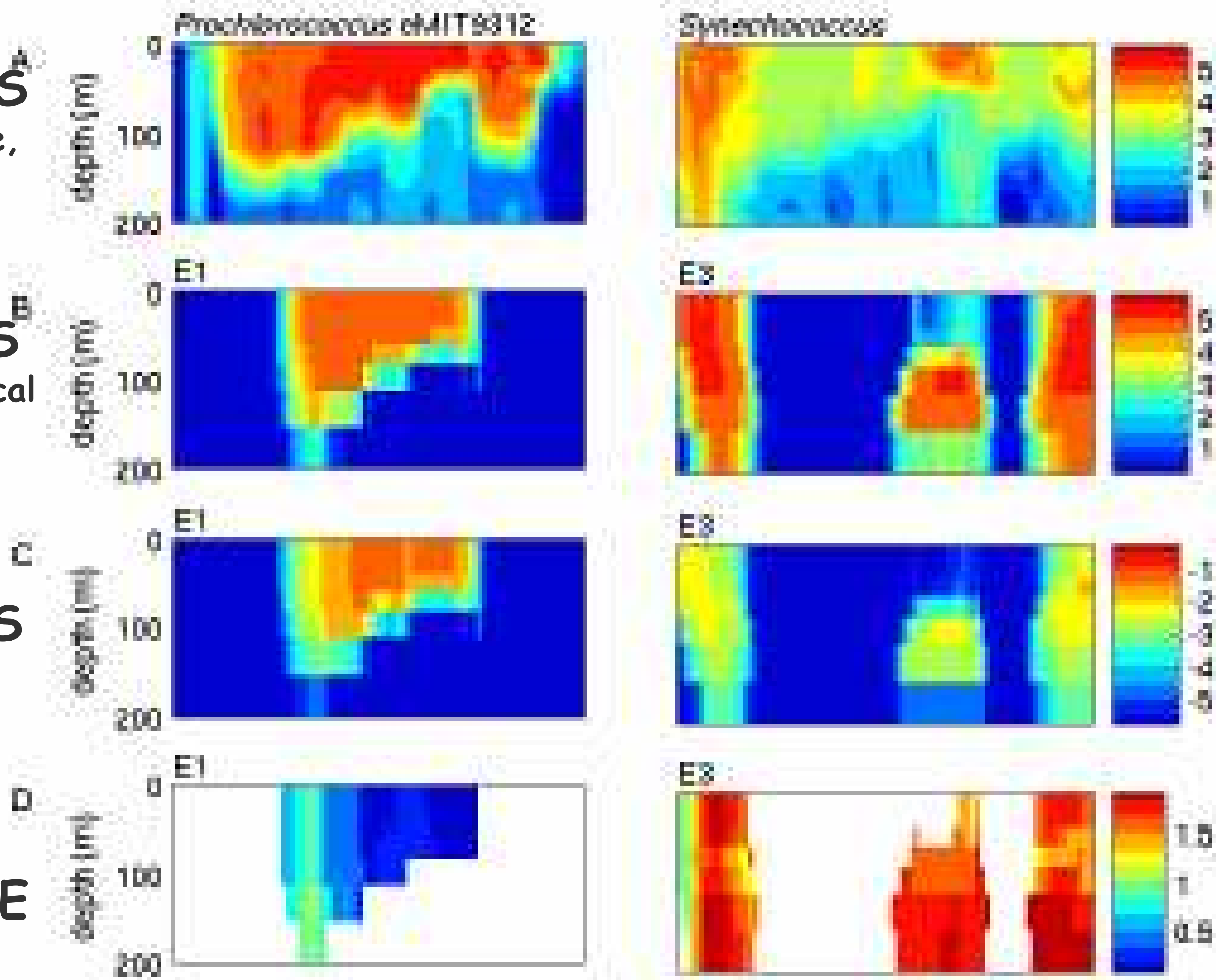
Bragg et al, PloS One, 2010

OBSERVATIONS
(Johnson et al. Science, 2006)
log10(cells/ml)

MODEL PARENTS
(designated by geographical distribution)

LOSS MUTANTS

INDICES OF DISADVANTAGE
log10(null/mutant)

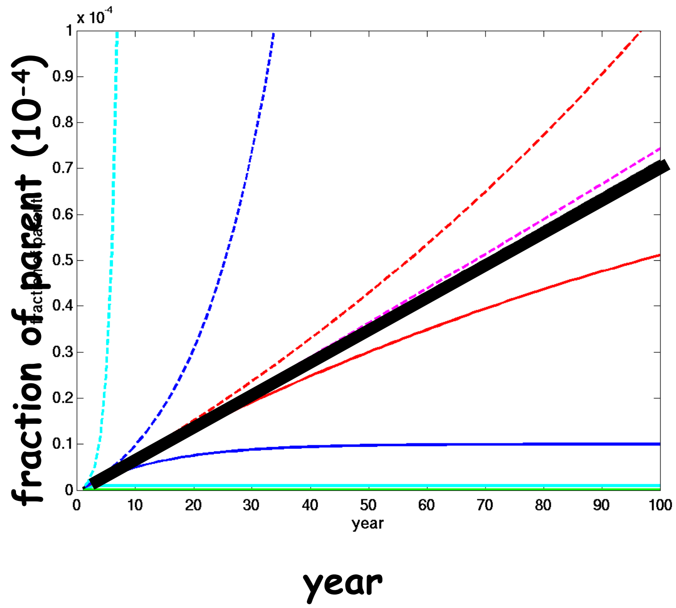


lower values (blues) indicate less disadvantage

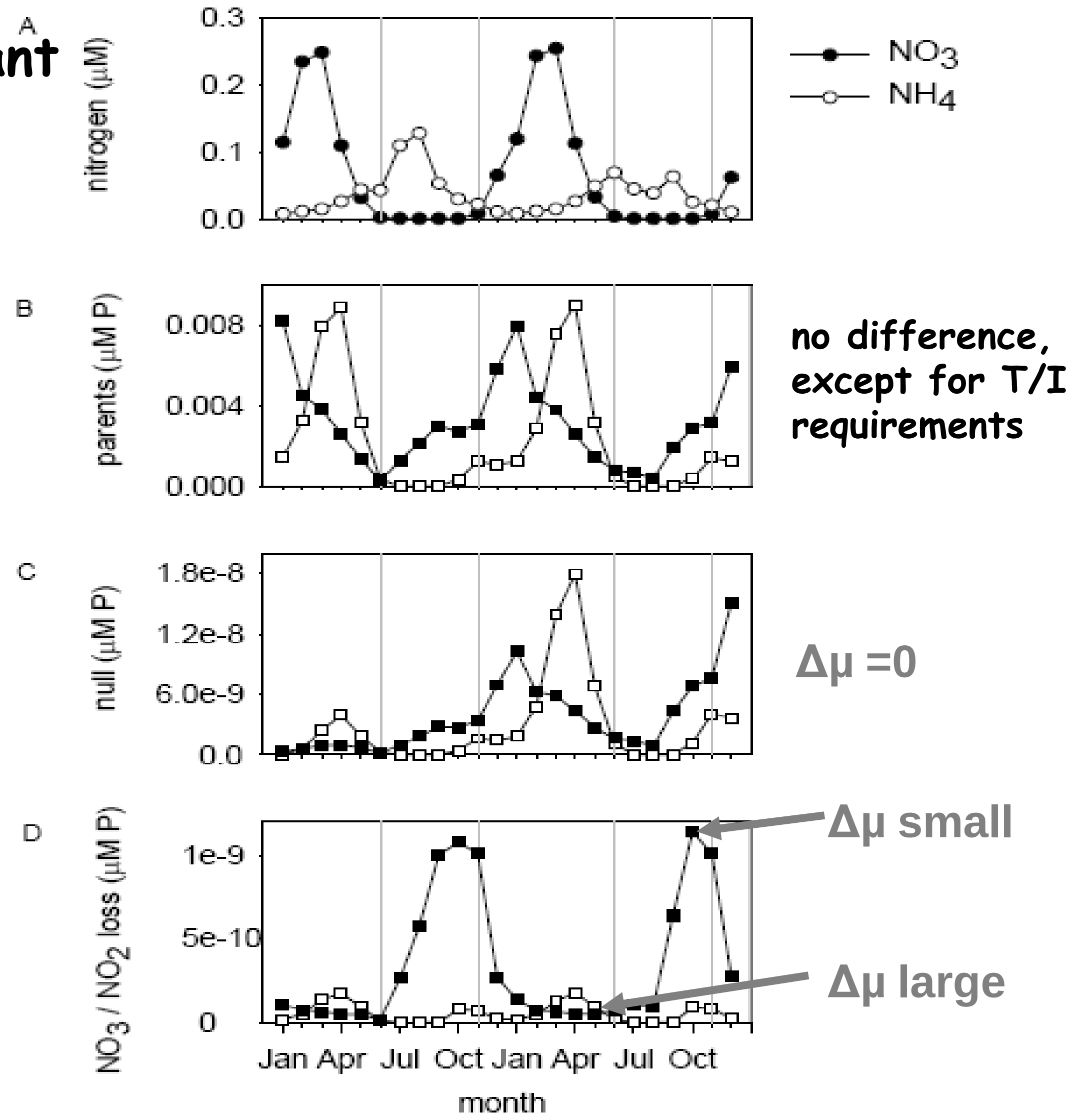
MUTATION EXPERIMENTS

Bragg et al, PloS One, 2010

Temporal distribution important (BATS-type location)



$$\frac{dP_m}{dt} \approx \Delta\mu P_m + \varepsilon\mu P$$



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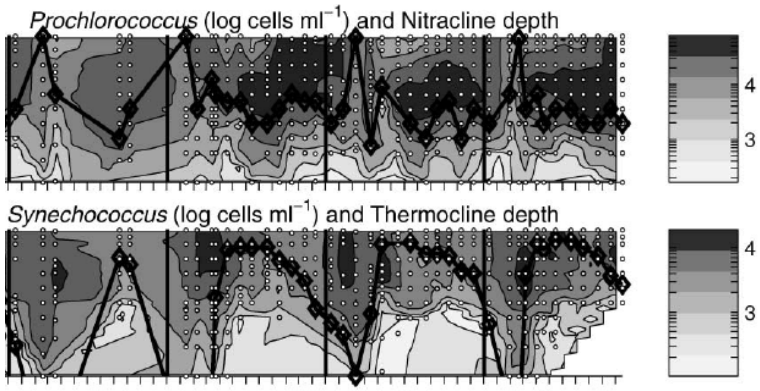
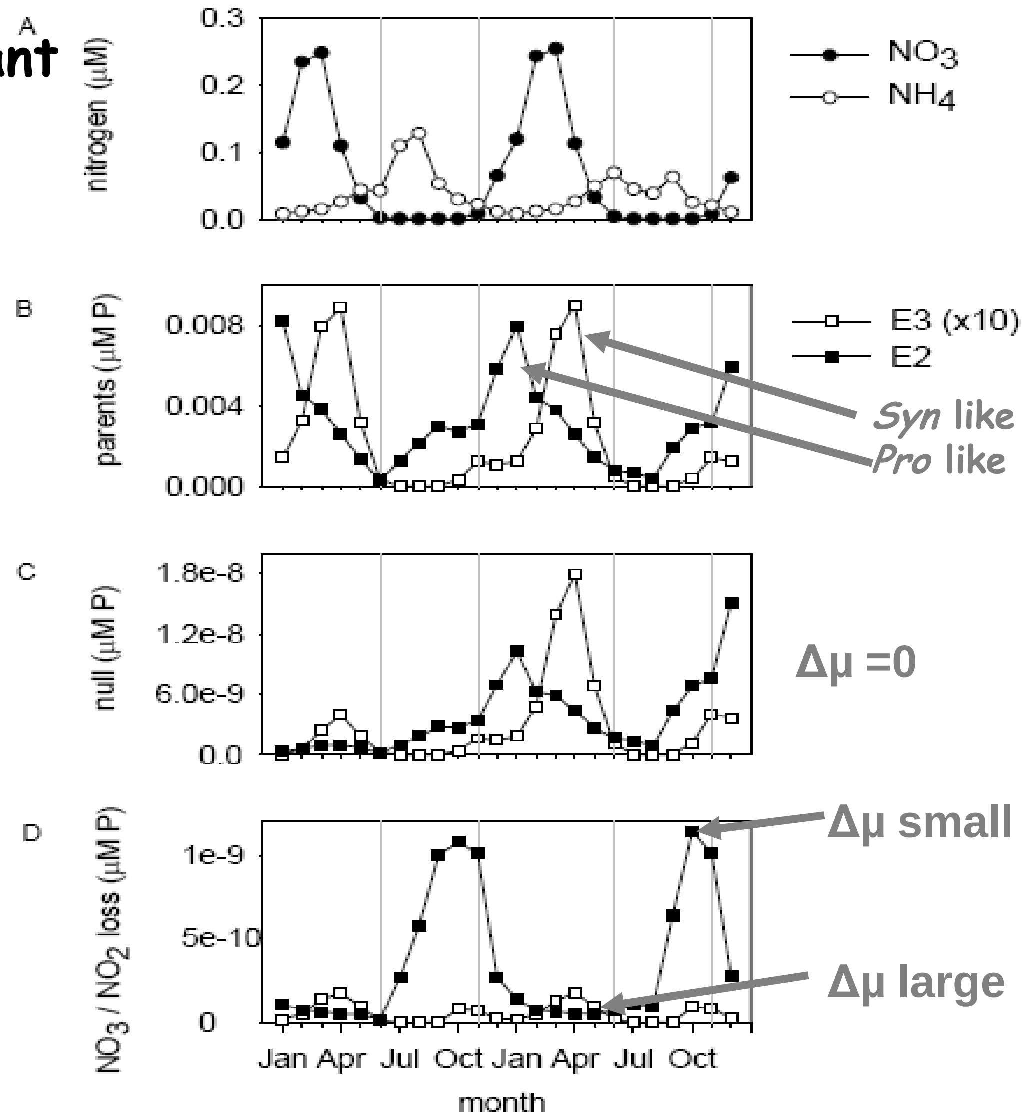
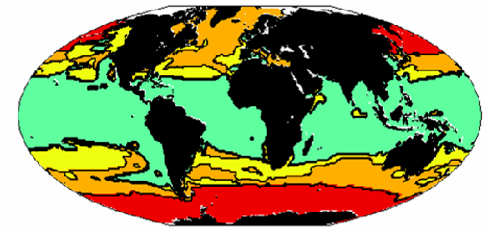


DuRand *et al.* 2001

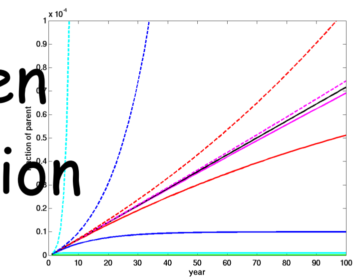


SUMMARY

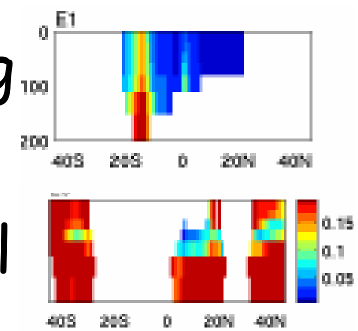
- By putting in appropriate trade-offs (the "results" of evolutionary processes) we can get selection by environment



- Model offers insight into environmentally driven pressures that help shape the course of evolution



- Selective pressures for N use abilities reflect biogeographical and temporal distribution among prokaryotes
  - this includes combinations of physics, chemical environment, competition, and genetic forces



EMERGENT MODEL BIOGEOGRAPHY

Trade off between gleaners

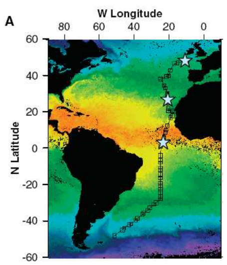
- *Synechococcus*/pico-eukaryotes: use NO_3
- *Prochlorococcus:* cannot use NO_3, but needs less nutrients to grow

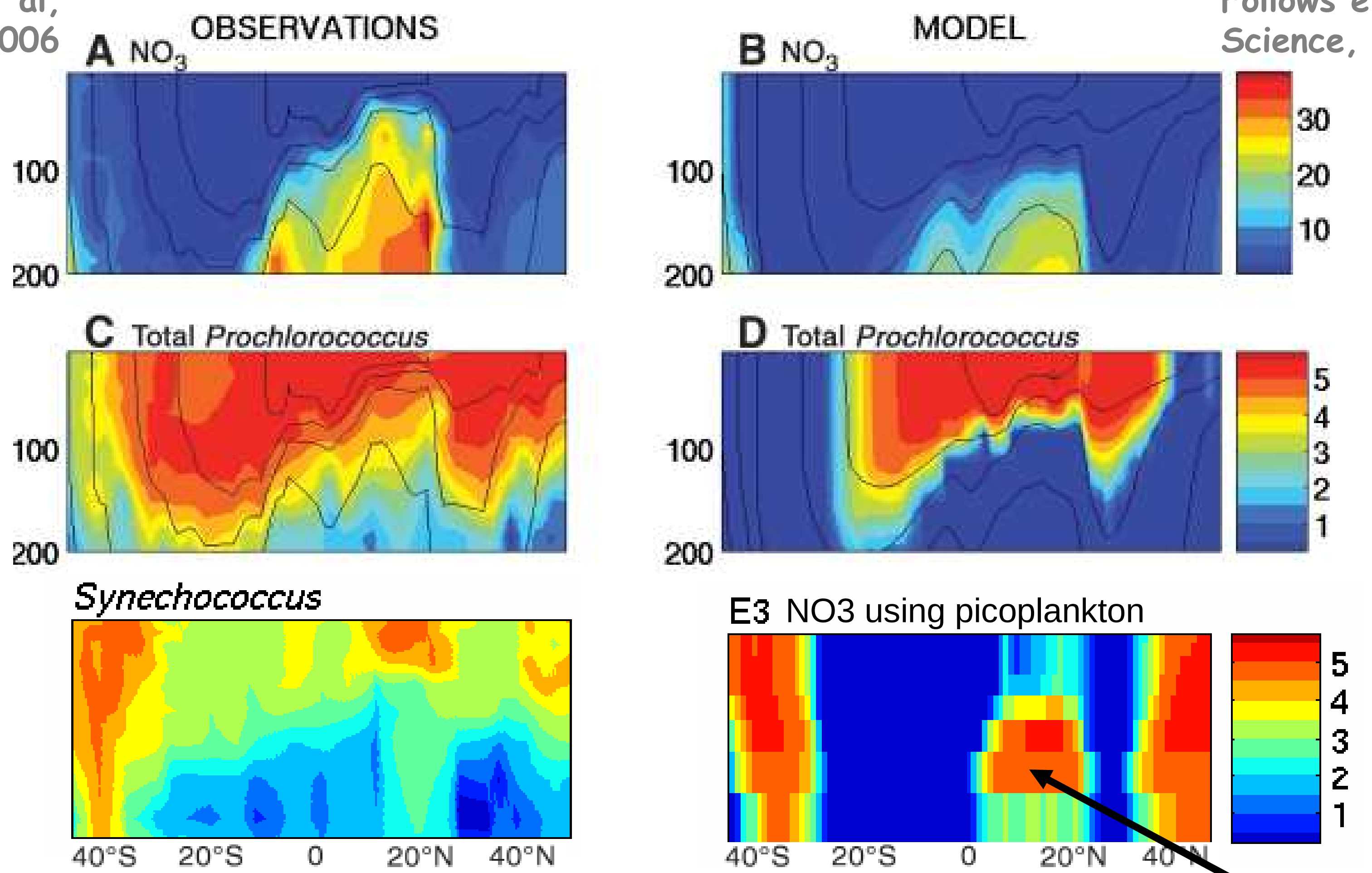
EMERGENT MODEL BIOGEOGRAPHY

Johnson et al, Science, 2006

Follows et al., Science, 2007

AMT13





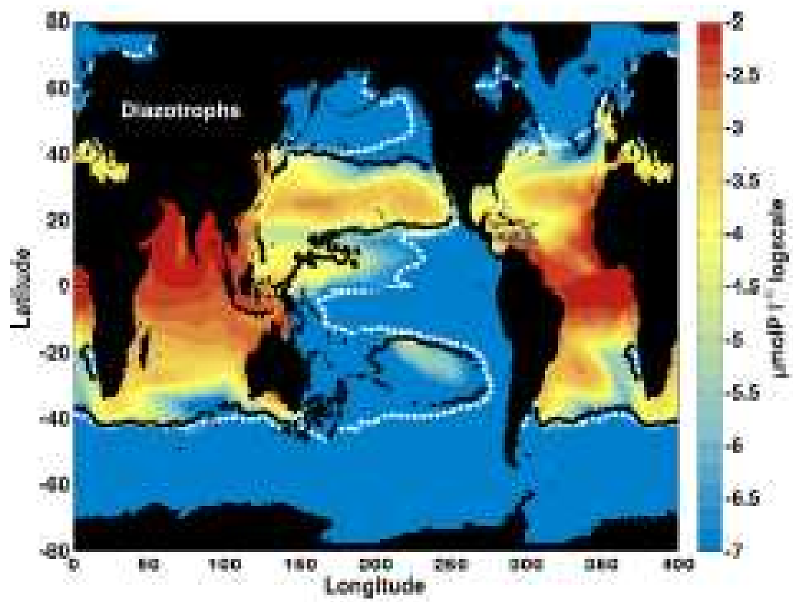
though nitrate gives idea of distribution we can find no statistical association with inorganic nitrogen compounds

pico-eukaryotes

EMERGENT MODEL BIOGEOGRAPHY

<u>Trade off for nitrogen fixing</u>

- Diazotrophs: fix nitrogen, but at cost of growing slower, and requiring more iron



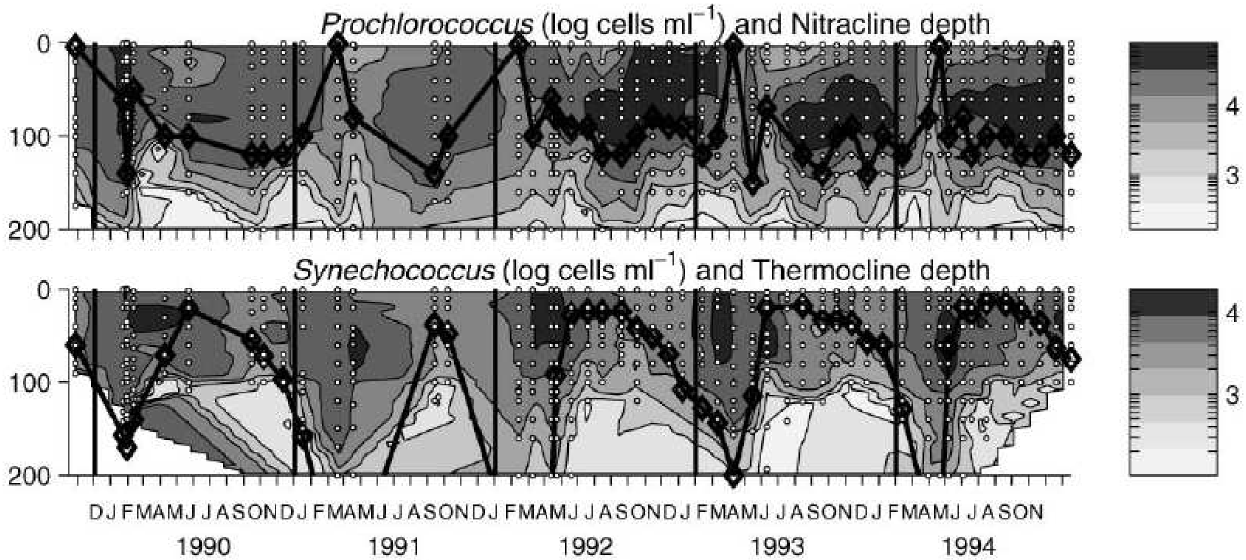
(b) Total diazotroph biomass with R^* contours (Fe in black and PO_4^{3-} in grey) and fixed nitrogen isoline (white dashed line)

Diazotrophs exist where other phytoplankton are nitrogen limited AND there is enough iron and phosphate

Monterio et al, GBC, in prep

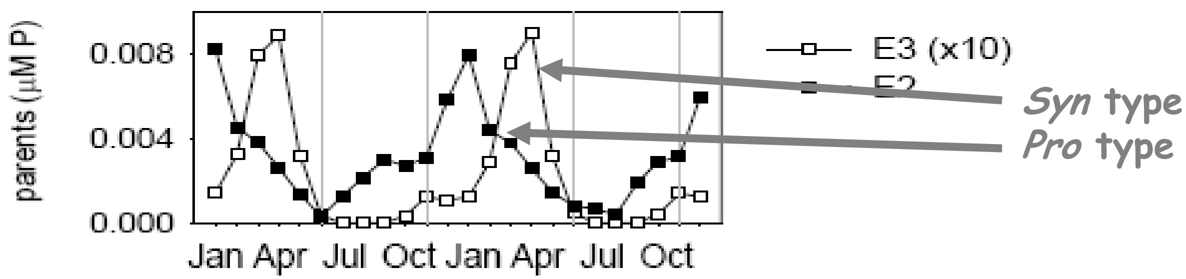
MUTATION EXPERIMENTS

Temporal distribution of *Pro* and *Syn* at BATS (32° N, 64° W)



Pro **bloom when nutricline low (i.e. low nutrients)**
Syn **bloom with thermocline deep (i.e. higher nutrients)**

DuRand *et al.* 2001



Bragg et al, PloS One, 2010

MUTATION EXPERIMENTS

gain mutants:
accumulates quicker, and will eventually take over from parent

$$\Delta\mu > 0$$

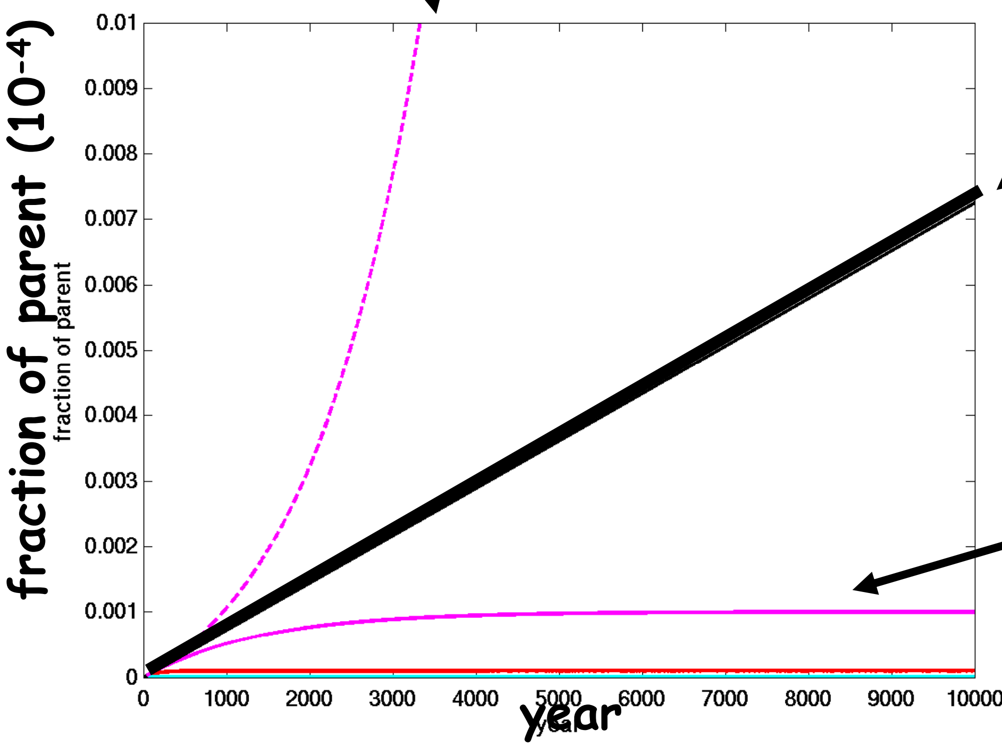
$$\frac{dP_m}{dt} \approx \Delta\mu P_m + \varepsilon\mu P$$

$$\Delta\mu = 0$$

null mutant:
steady accumulation

$$\Delta\mu < 0$$

loss mutants:
accumulates slower, will never take over from parent but may reach substantial portion



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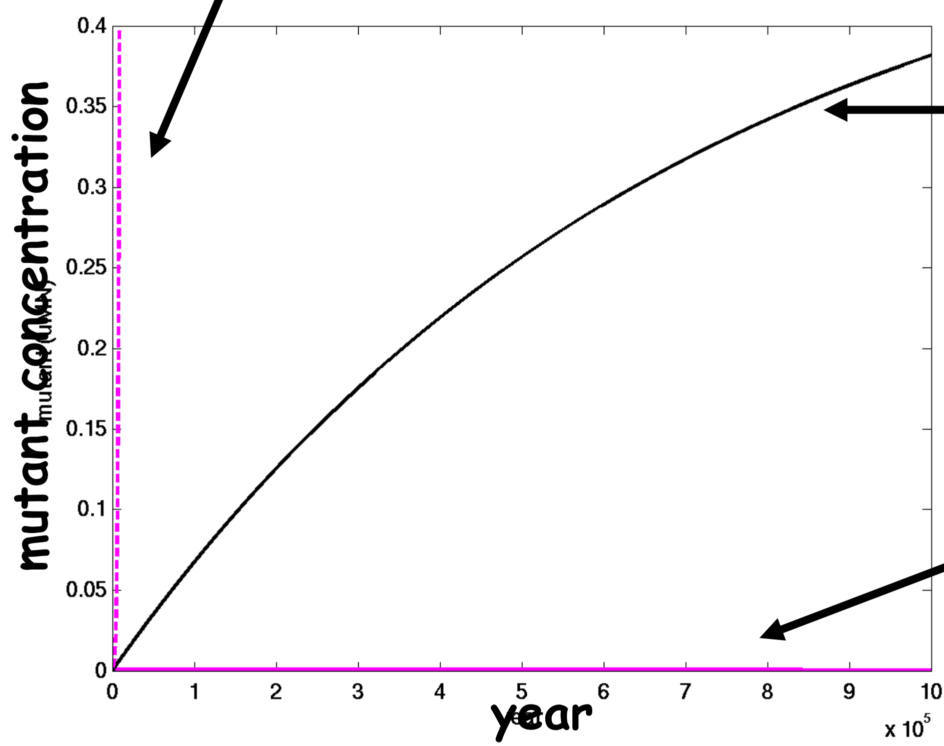

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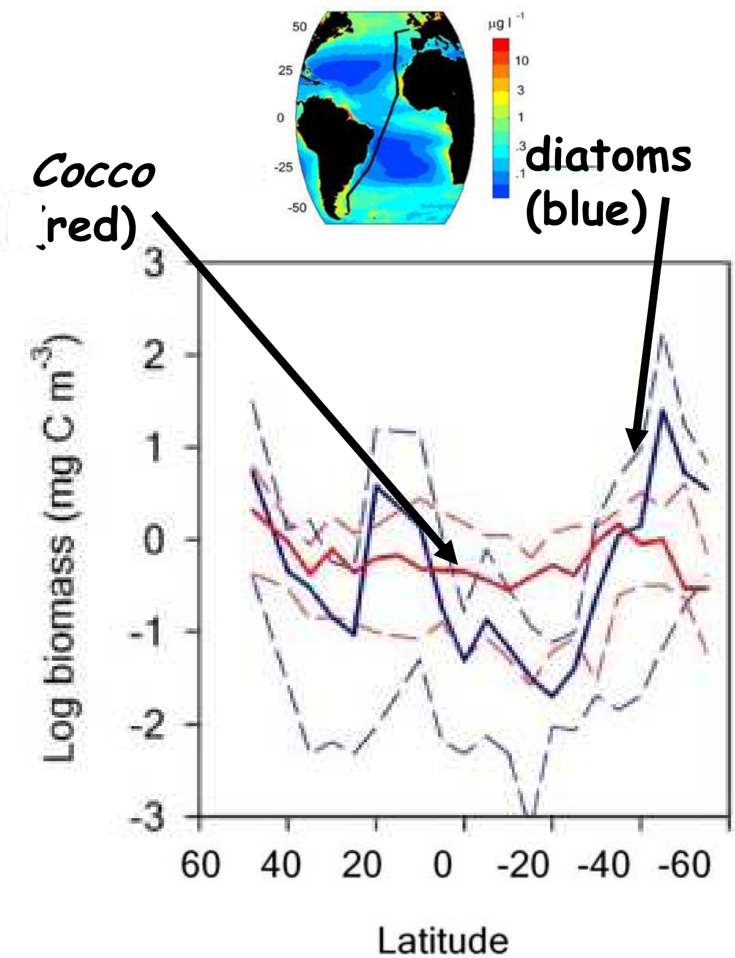
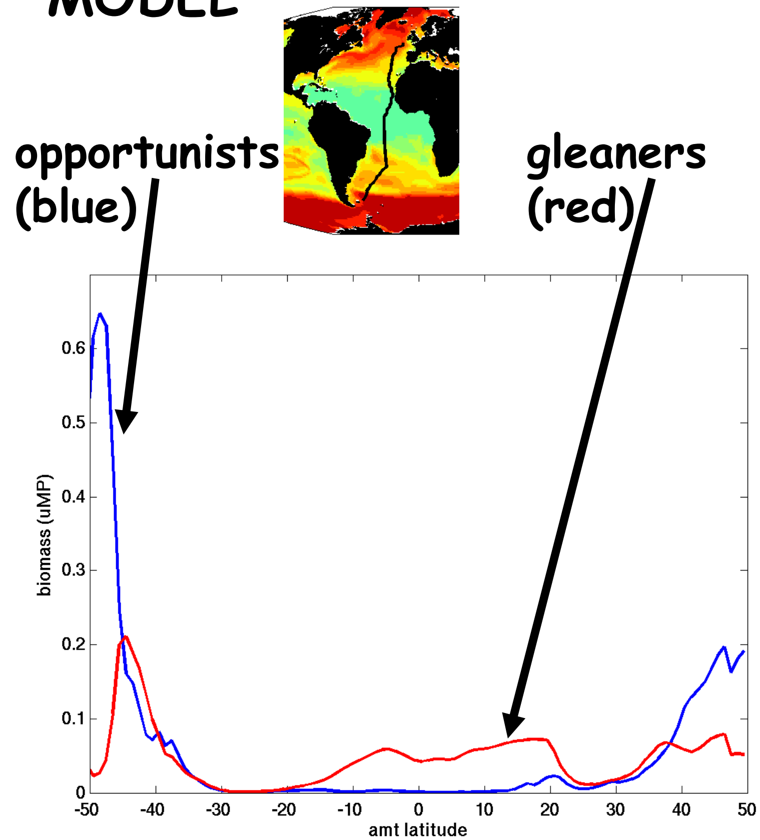
EMERGENT MODEL BIOGEOGRAPHY

OBSERVATIONS



Cermeno et al.,PNAS, 2008

MODEL



Dutkiewicz et al.,GBC, 2009