Ecosystem Modelling at Ocean Station P: What Have We Learned About the Subarctic NE Pacific?

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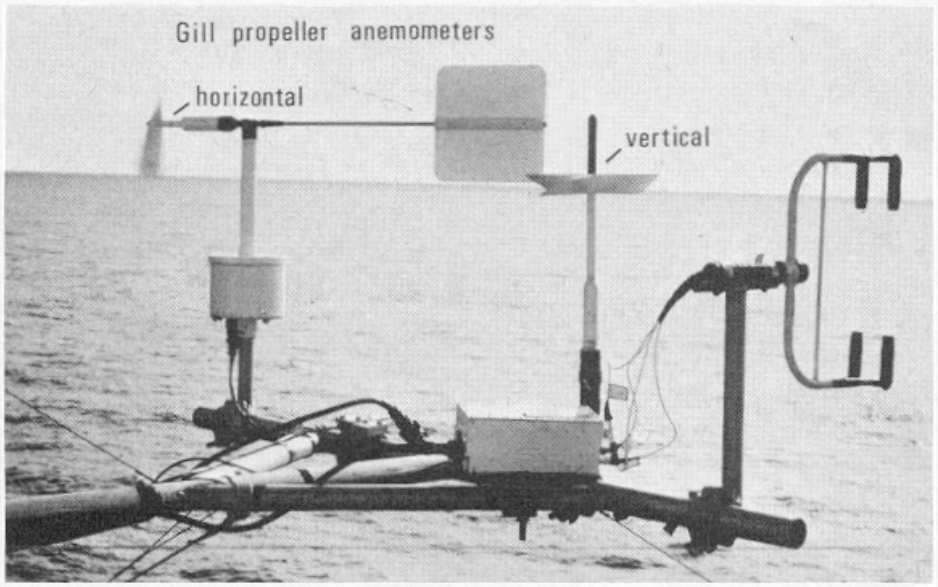
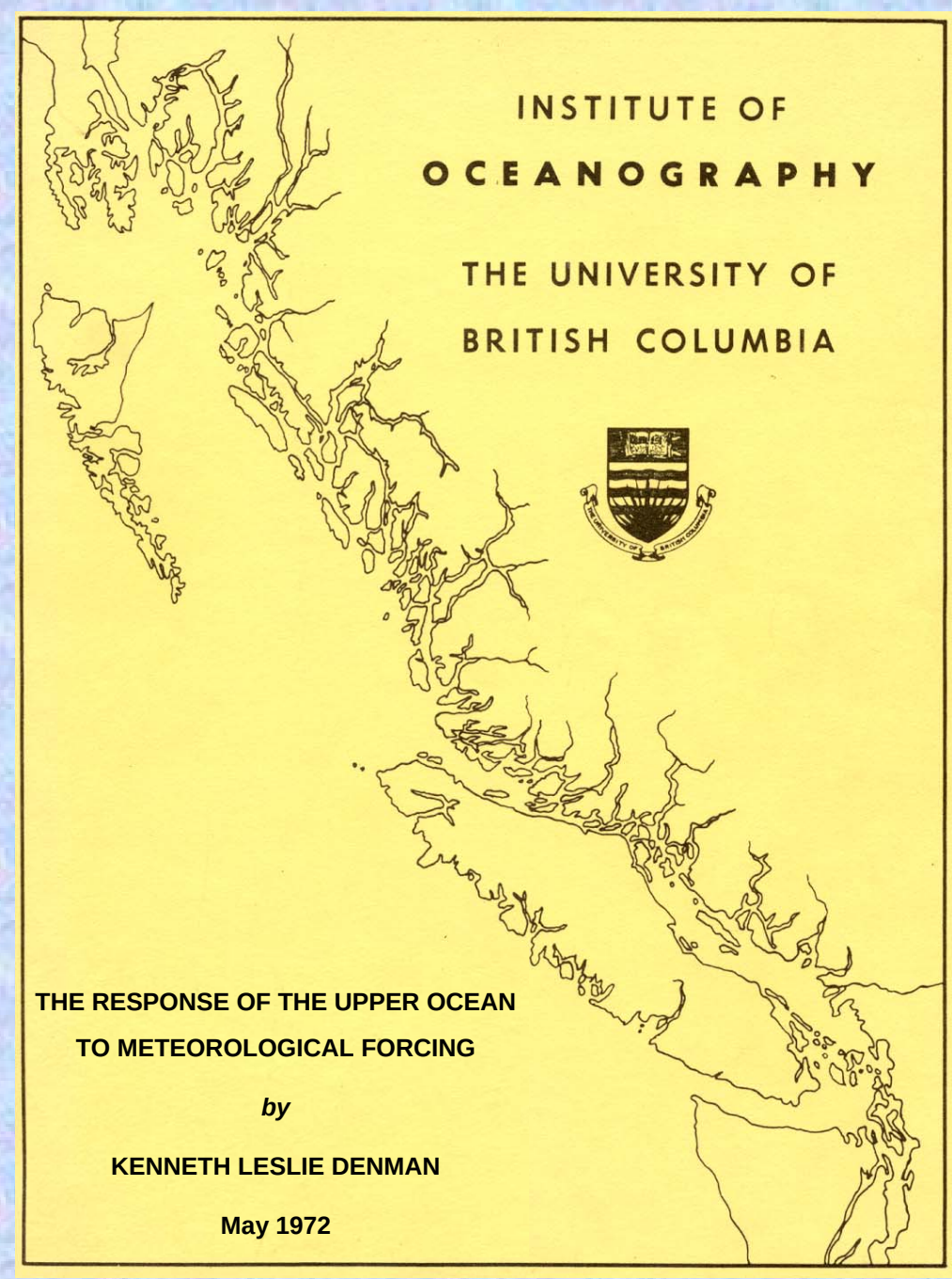
Outline of Talk

- Modelling philosophy
- Legacy of Weathership programme 1956-81
- The subarctic NE Pacific – an HNLC region
- Adding biogeochemistry – Fe & Si
- Coupling physics + biology – variable forcing
- Adding complexity – enough data?
- Future challenges
  - *responses to a changing climate*
  - *ecosystem effects of a more acidic ocean*

Near the Beginning: 1970



The Canadian weathership CCGS *Vancouver*. The location of the instrument on which the propeller anemometers were mounted is indicated.



Our Modelling Philosophy

- A model captures mathematically our 'conceptual' models of how an ecosystem works
  - *allows testing of questions / hypotheses*
- A model is an integrative data analysis tool
  - *pulls together observations of different facets of system*
  - *requires observations to be expressed in same units*
- Models need observations: Line P / Station P provided invaluable background of observations
  - *for design and execution of special intensive projects*
  - *for development and evaluation of first, mixed layer models and later, ecosystem/biogeochemical models*

Legacy of the Weathership Programme

Weathership 1956-81	Transition	SUPER	JGOFS GLOBEC SOLAS/SERIES
John Strickland, Tim Parsons, Cary McAllister, Robin LeBrasseur John Tully, Sus Tabata. Larry Giovando CS Wong	John Parslow John Fulton Mike Miyake Steve Pond Bill Large Steve Emerson Richard Matear	Charlie Miller Bruce Frost Dave Mackas Ann Gargett Ken Denman Mike Landry Pat Wheeler Karl Banse Mary-Jane Perry Mike Dagg etc.	Paul Harrison, CS Wong, Frank Whitney, Phil Boyd, Maurice Levasseur & Many others

This is an incomplete list

Observations from the Weathership Era

A High Nitrogen – Low Chlorophyll (HNLC) region

- **The upper ocean has high nitrate concentrations all year round**
- **Phytoplankton chlorophyll concentrations are low all year < 0.5 mg-Chl m^{-3}**
  - ***no spring bloom***
- **Clear annual cycle in**
  - ***primary production***
  - ***mesozooplankton abundance***
- **Surface O_2 supersaturation in spring / summer**

Observations from the Weathership Era

A High Nitrogen – Low Chlorophyll (HNLC) region

- The upper ocean has high nitrate concentrations all year round
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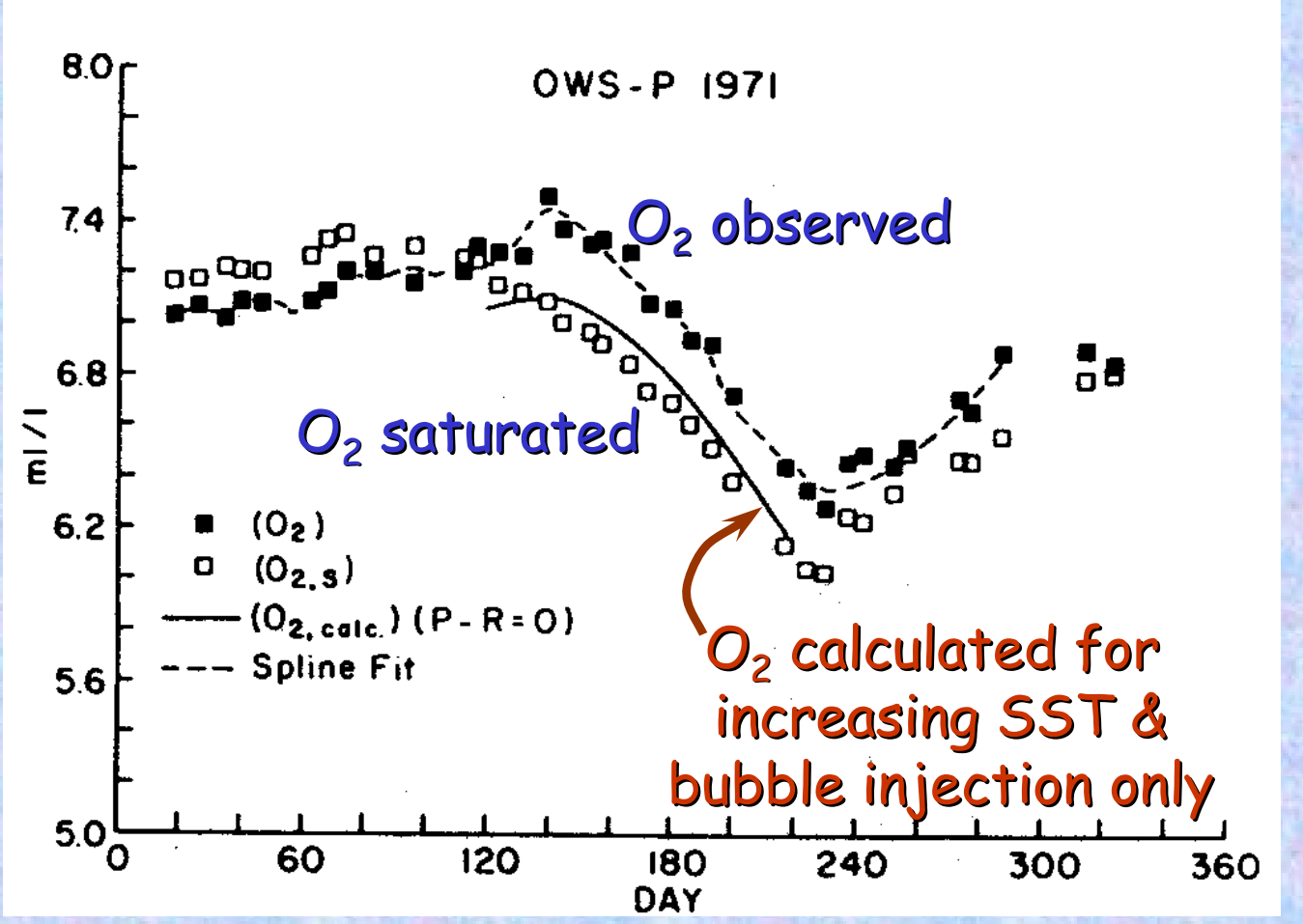
  - *no spring bloom*
- There are lots of mesozooplankton
- Clear annual cycle in
  - *mesozooplankton abundance*
  - *primary production*
- **Surface O_2 supersaturation in spring / summer**

Excess O_2 Supersaturation = (P - R)

May - August:

Excess O_2 from Primary Production, all years in record from 1969-78. Later confirmed through Argon obs., a biologically-inert analogue of Oxygen.



Emerson, S., 1987. J. Geophys. Res. 92(6).
Modelled by Thomas et al., 1990, 1993, Deep-Sea Res.

****** See poster by Roberta Hamm and Steve Emerson ******

Why Is There No Spring Bloom?

Shallow winter ML

→ Sufficient winter PP for microzooplankton

→ Grazing control by microzooplankton

→ No spring bloom

Evans and Parslow, 1985. Biol. Oceanogr. 3, 327.

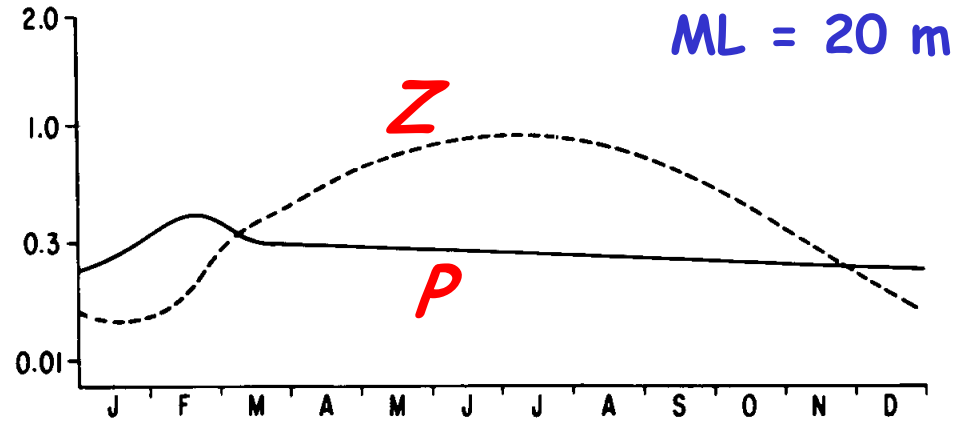


FIGURE 4. The annual cycle for a mixed layer depth of 25 m.

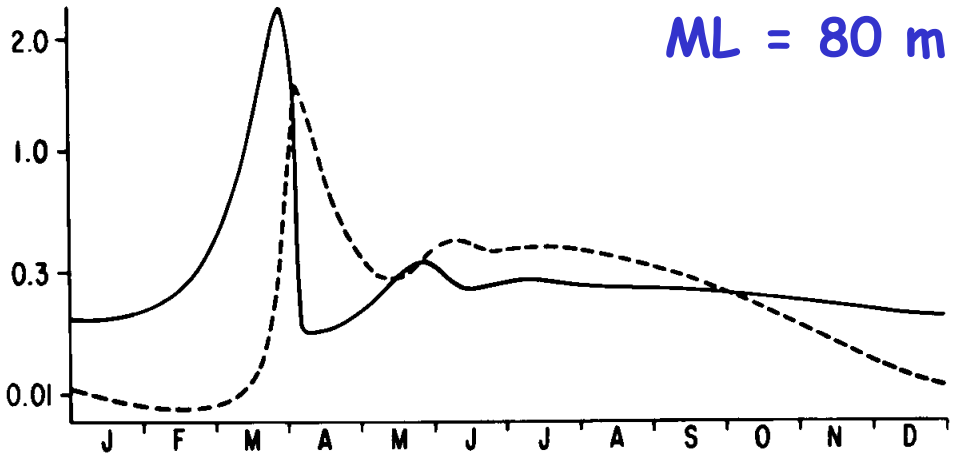
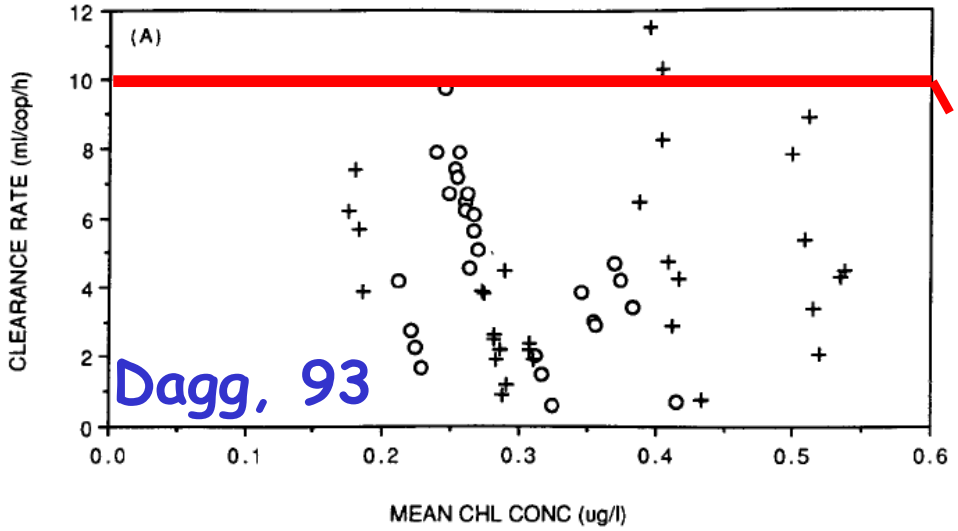


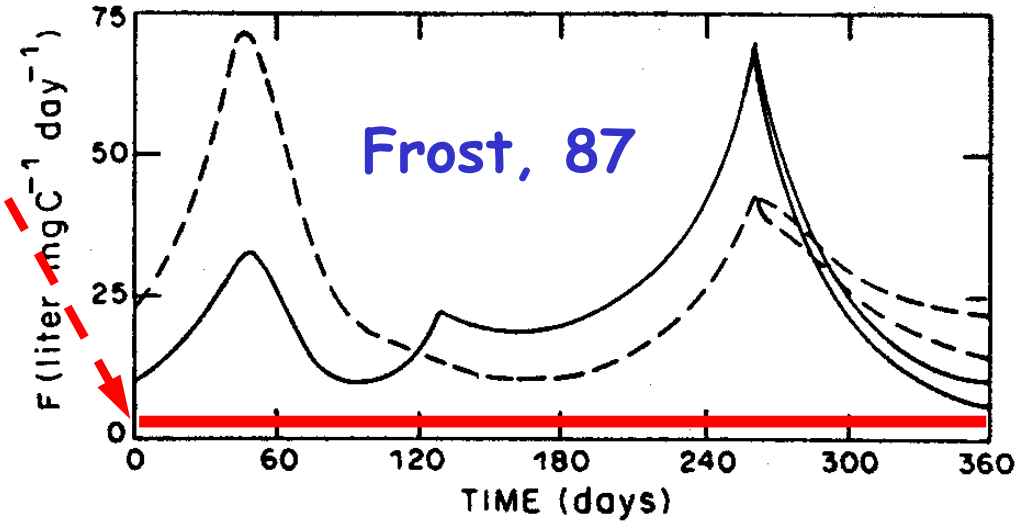
FIGURE 5. The annual cycle of Model 2 corresponding to a mixed layer depth of 80 m.

Why Is There No Nitrate Depletion?

H1: *Grazing control & preferential NH_4^+ uptake reduce NO_3^- drawdown*

1. Grazing by mesozooplankton (copepods) is too small to keep phytoplankton from blooming





Measured clearance rates May, Sept, 1984, 1988

Modelled clearance rates, to maintain constant Chl a 0.3-0.4 mg-Chl m^{-3}

Take 1 copepod C5 to contain ~75 µg-C *[Miller, 1993, Prog. Ocgy]*
then Clearance rate of 10 mL/copepod/hr ≅ 3 L/mg-C/day

Why Is There No Nitrate Depletion?

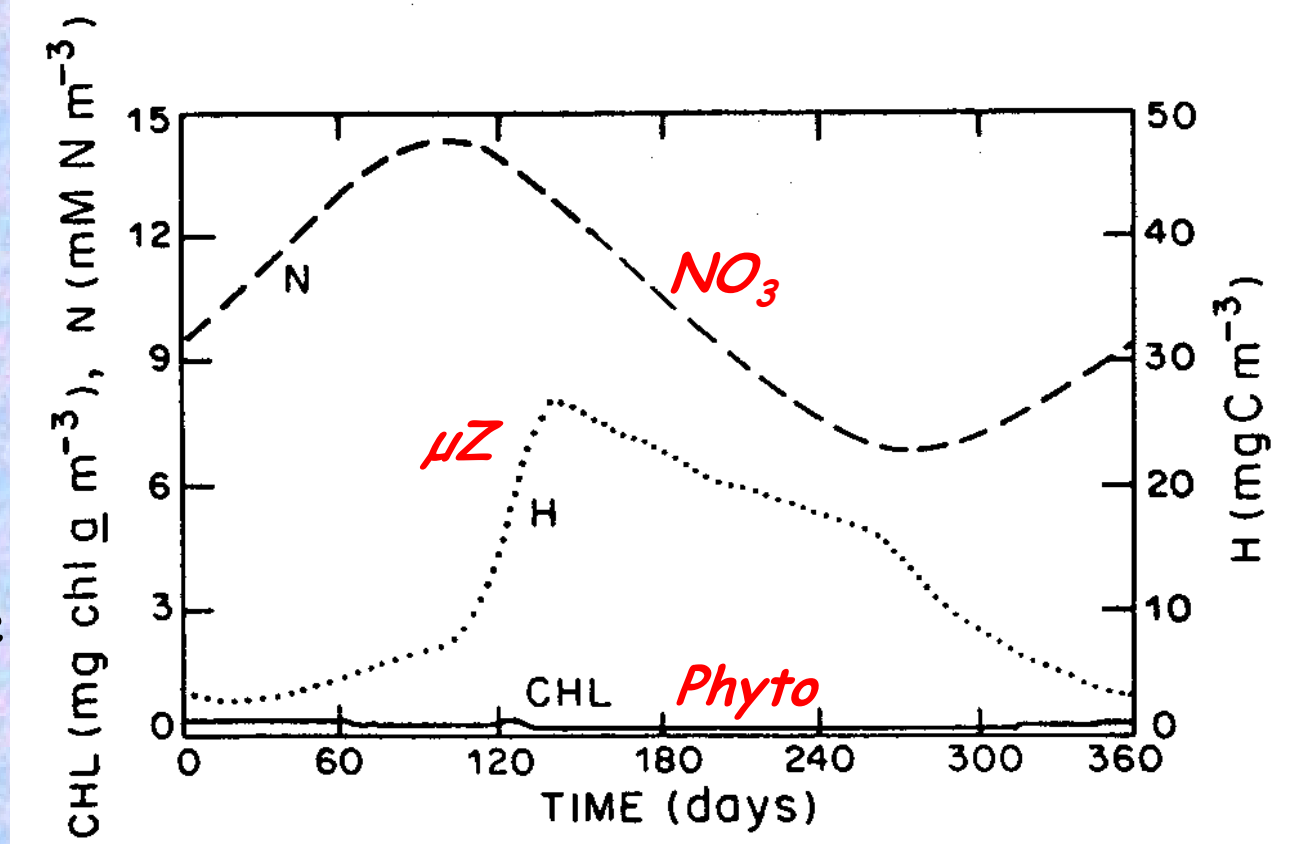
H1: *Grazing control & preferential NH_4^+ uptake reduce NO_3^- drawdown*

2. Grazing by microzooplankton can keep phytoplankton from blooming

Modelled annual OSP cycle requires

- annual cycle in microzooplankton biomass
- grazing rate of *μZ* approaching growth rate of phytoplankton

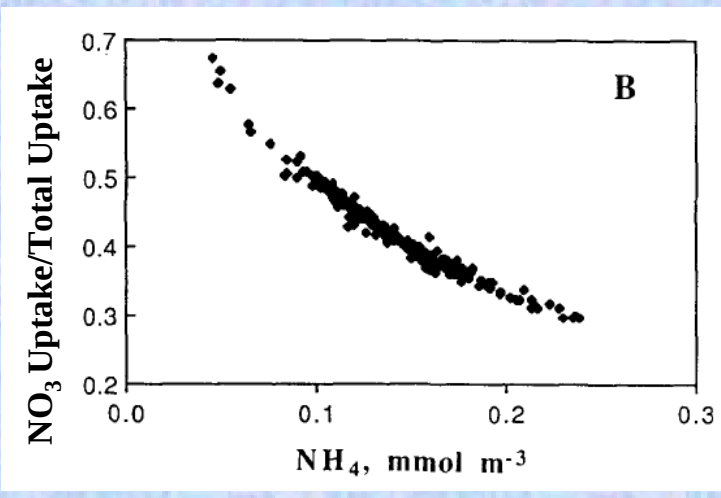
[Frost, 1987, MEPS]

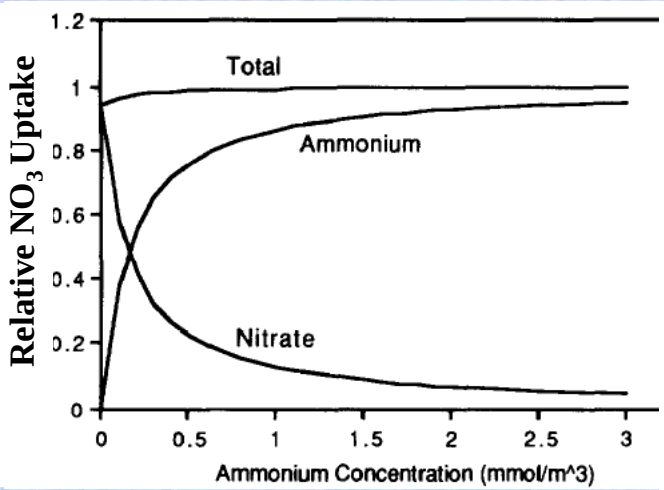


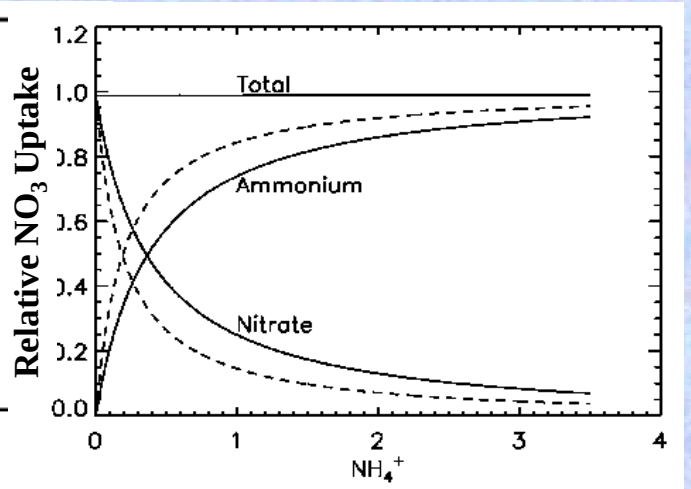
Why Is There No Nitrate Depletion?

H1: *Grazing control & preferential NH_4^+ uptake reduce NO_3^- drawdown*

3. Microzooplankton recycle N by releasing NH_4 which is taken up preferentially over NO_3 by phytoplankton







Modelled as NH_4 inhibition of NO_3 uptake

[Frost, 1993]

Modelled with 'substitution algorithm'

[Fasham, 1995]

Modelled as 'relative preference', after Varela & Harrison, 99

[Denman, 2003]

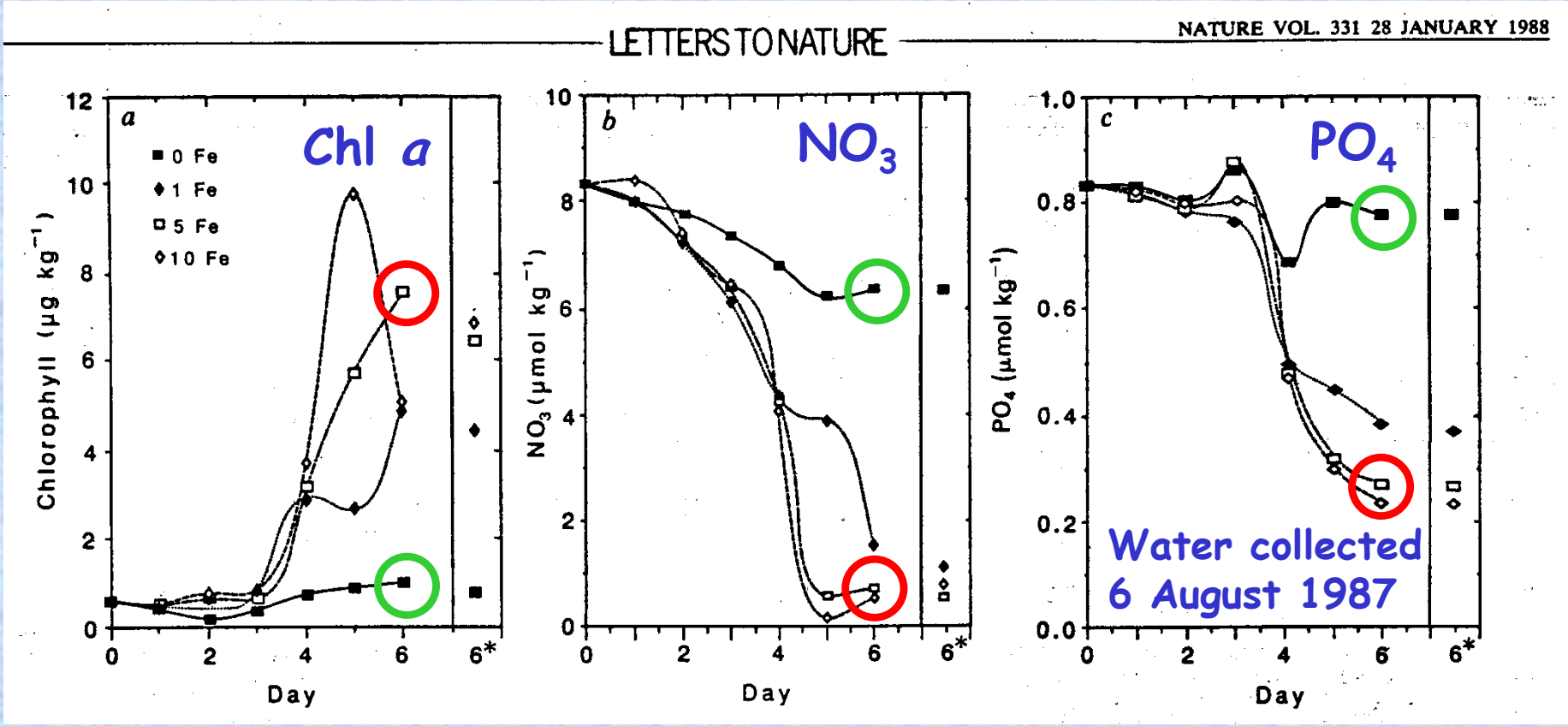
Why Is There No Nitrate Depletion?

H2: *The micronutrient iron limits nitrate uptake and drawdown*

Parsons and Lalli, 1988: " … the seasonal cycle of primary productivity in the North Pacific is limited by low temperature and grazing by micro- and macrozooplankton in the spring and summer, *and possibly by an unidentified nutrient during July and August.*"

Martin and Fitzwater, 1988: *"Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic"*

Surface Fe at OSP Limits Primary Production



No Fe added → little Chl *a* increase, little NO_3 & PO_4 drawdown

5 nmol kg^{-1} Fe added → large Chl *a* increase & NO_3 , PO_4 drawdown

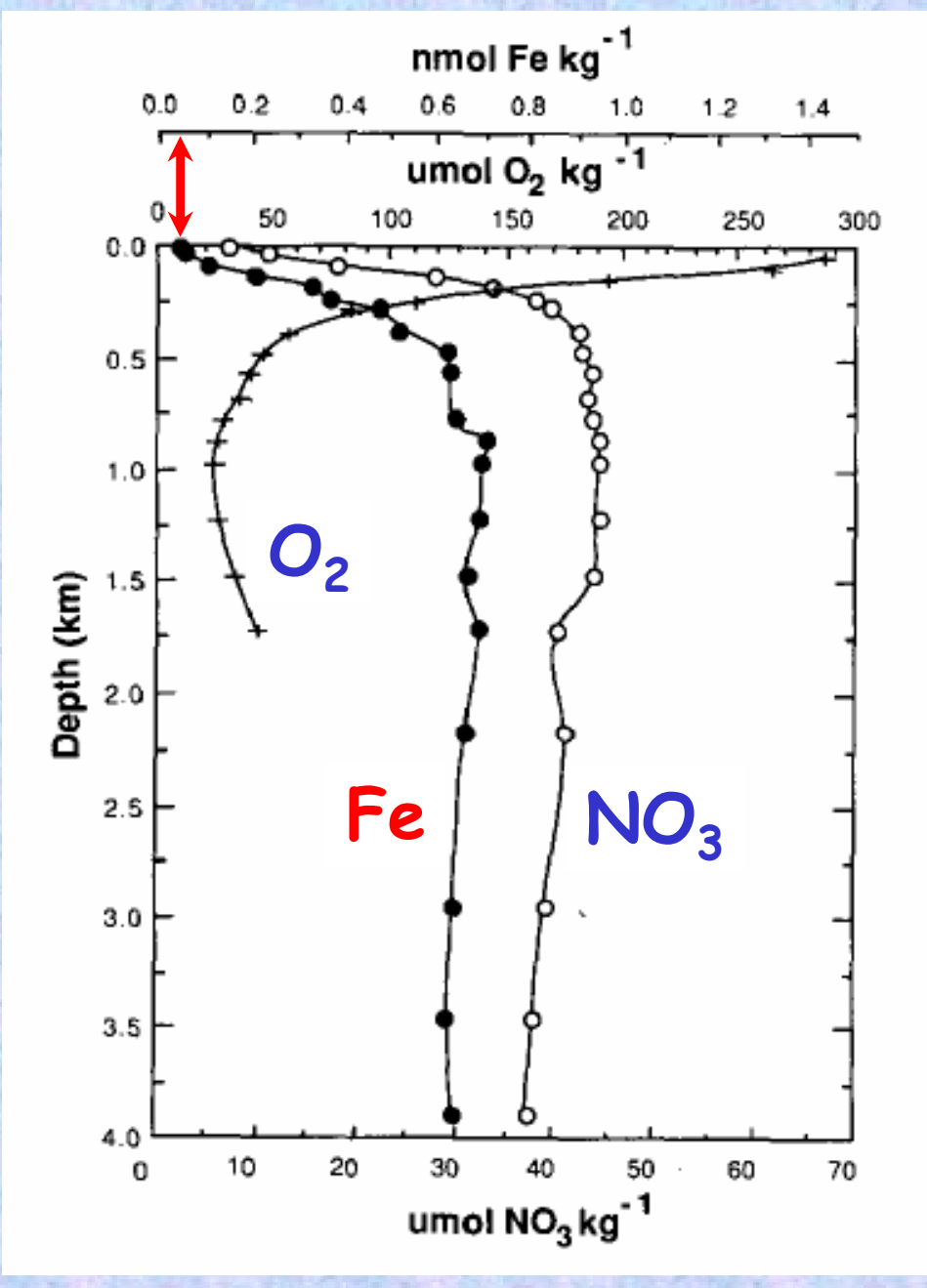
Martin & Fitzwater, 1988. Nature 331.

1988- 20??: The Age of Iron & Silica

Martin et al., 1989.
Deep-Sea Res 36.

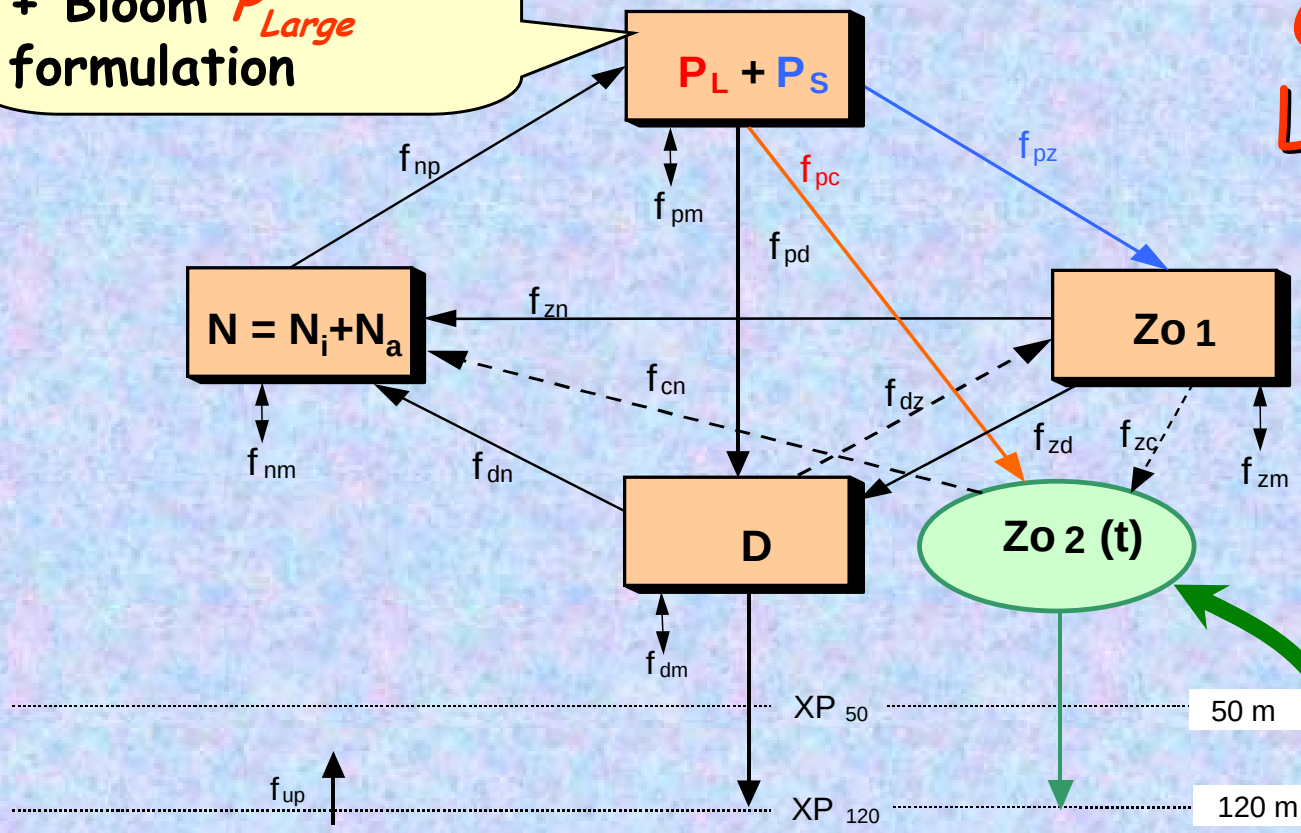
Surface Fe at OSP
< 0.1 nmol kg^{-1}

[Water collected 5 August 1987]



Coupled 1D Mixed Layer + Ecosystem Models

Background P_{Small} + Bloom P_{Large} formulation

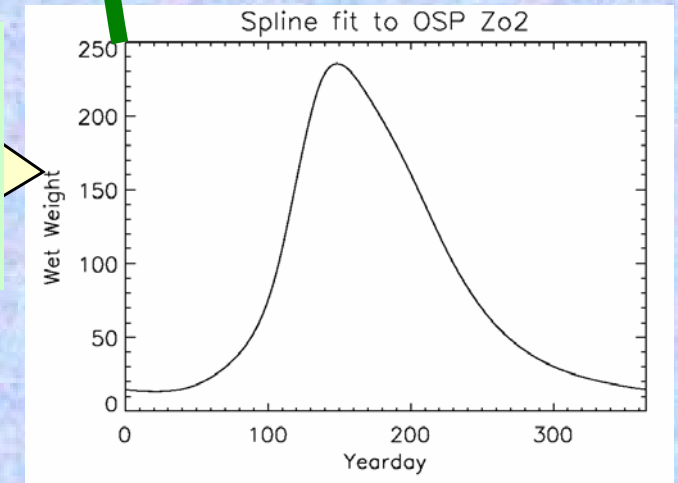


Denman and Peña, 1999 & 2002.

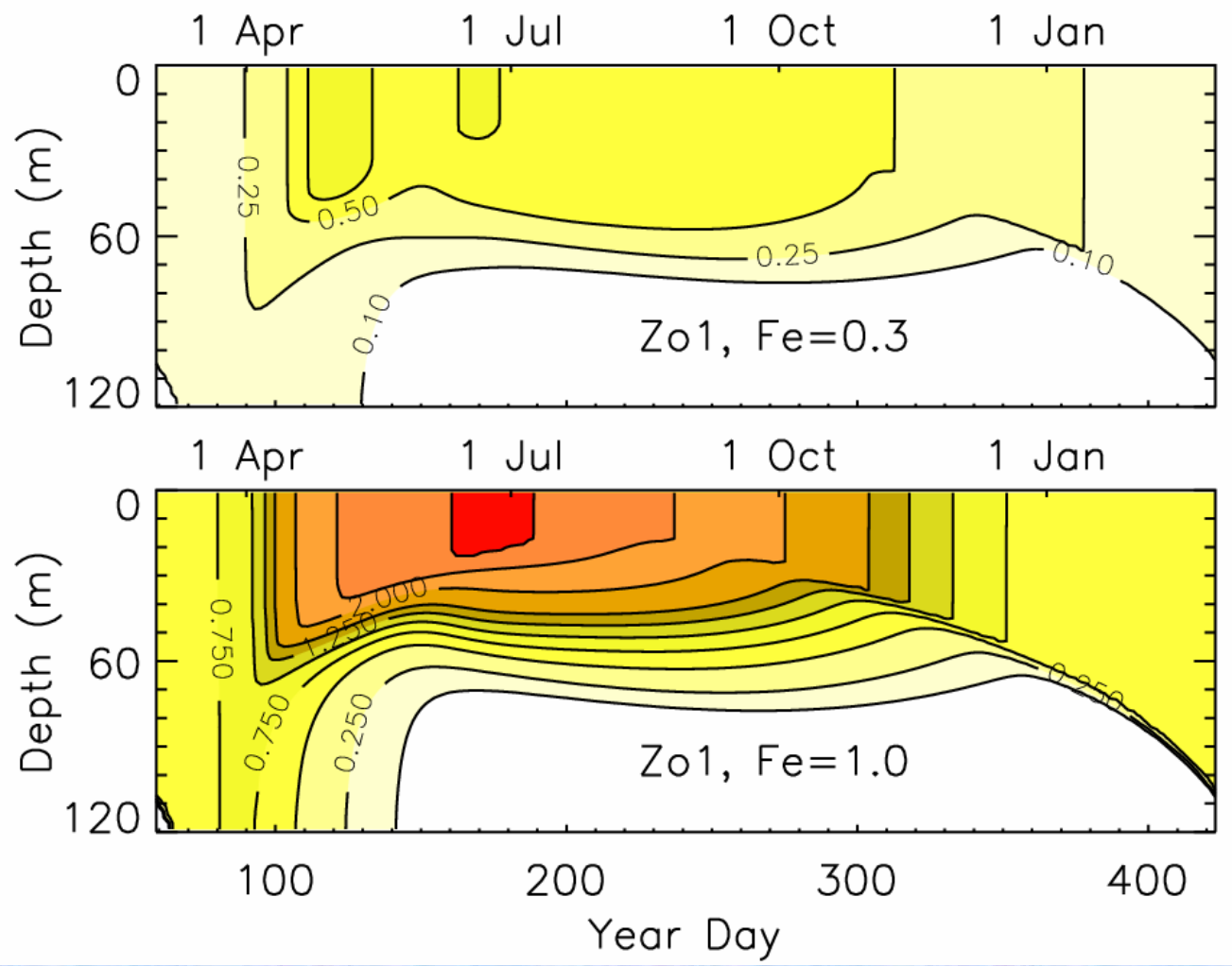
Denman 2003, & Peña 2003

- Fe limitation imposed as a cap on PP rate (i.e. no Fe budget)
- physiological rates temperature dependent

term observations at Ocean Station P.



Fe Addition: Microzooplankton *Zo1*



Fe limited

Not Fe limited

In both models, 5°C warming and Fe fertilization affected *Zo1* biomass and export of particles, but not *Ph* biomass

SERIES:
A Purposeful Fertilization Experiment

A purposeful 'experiment' provides the opportunity to perturb the system in a controlled way and observe the response

- We model the oceanic response to the Fe fertilization
- Extrapolate the model another 6 months beyond the cessation of sampling
- Show effects of different processes added 1 at a time

Model With Two Size Classes of Phytoplankton

PLUS
- Inorganic Carbon cycle
- Silica cycle

P_S small phytoplankton

P_L large phytoplankton ie diatoms

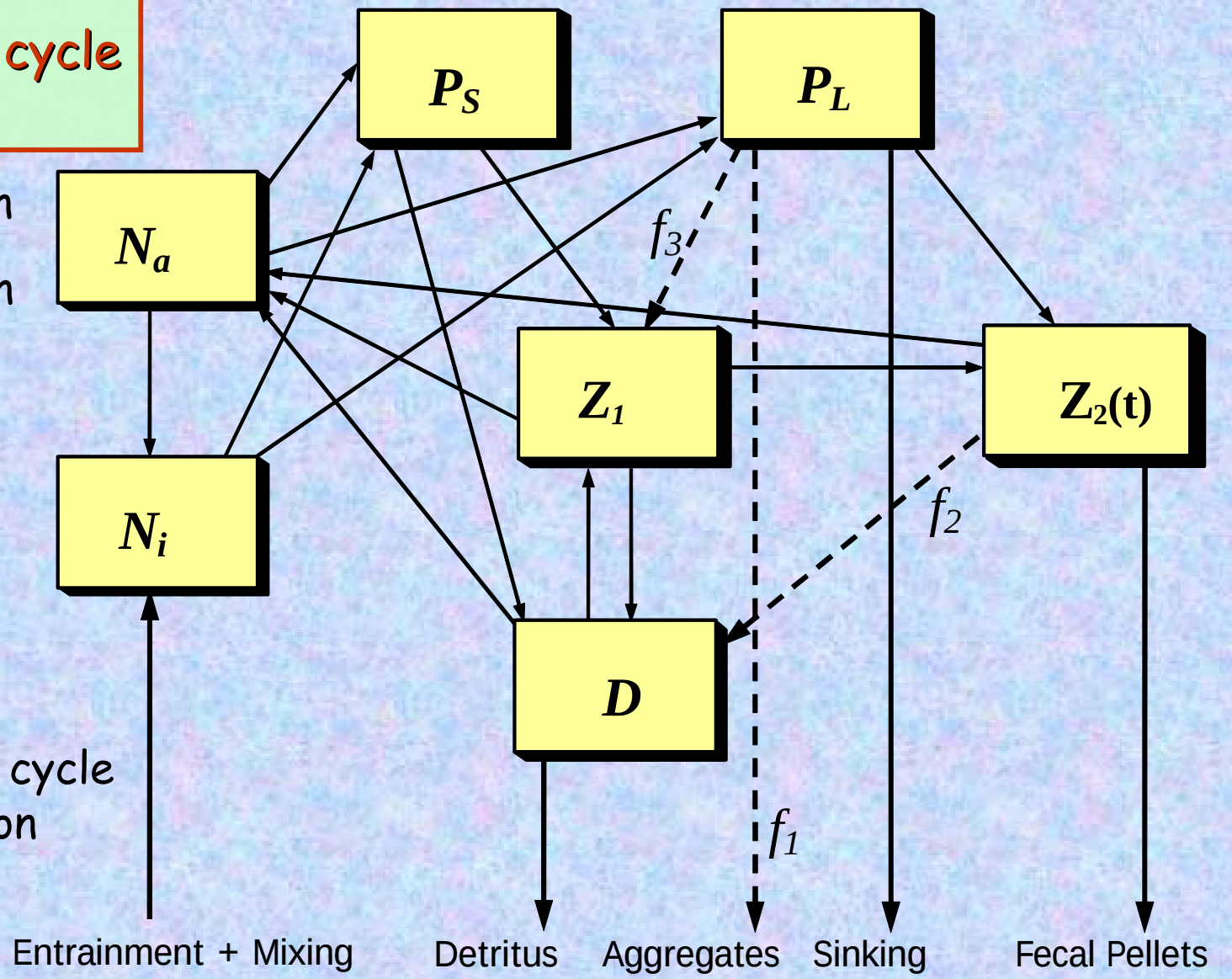
N_i nitrate

N_a ammonium

D detritus

Z_1 microzooplankton

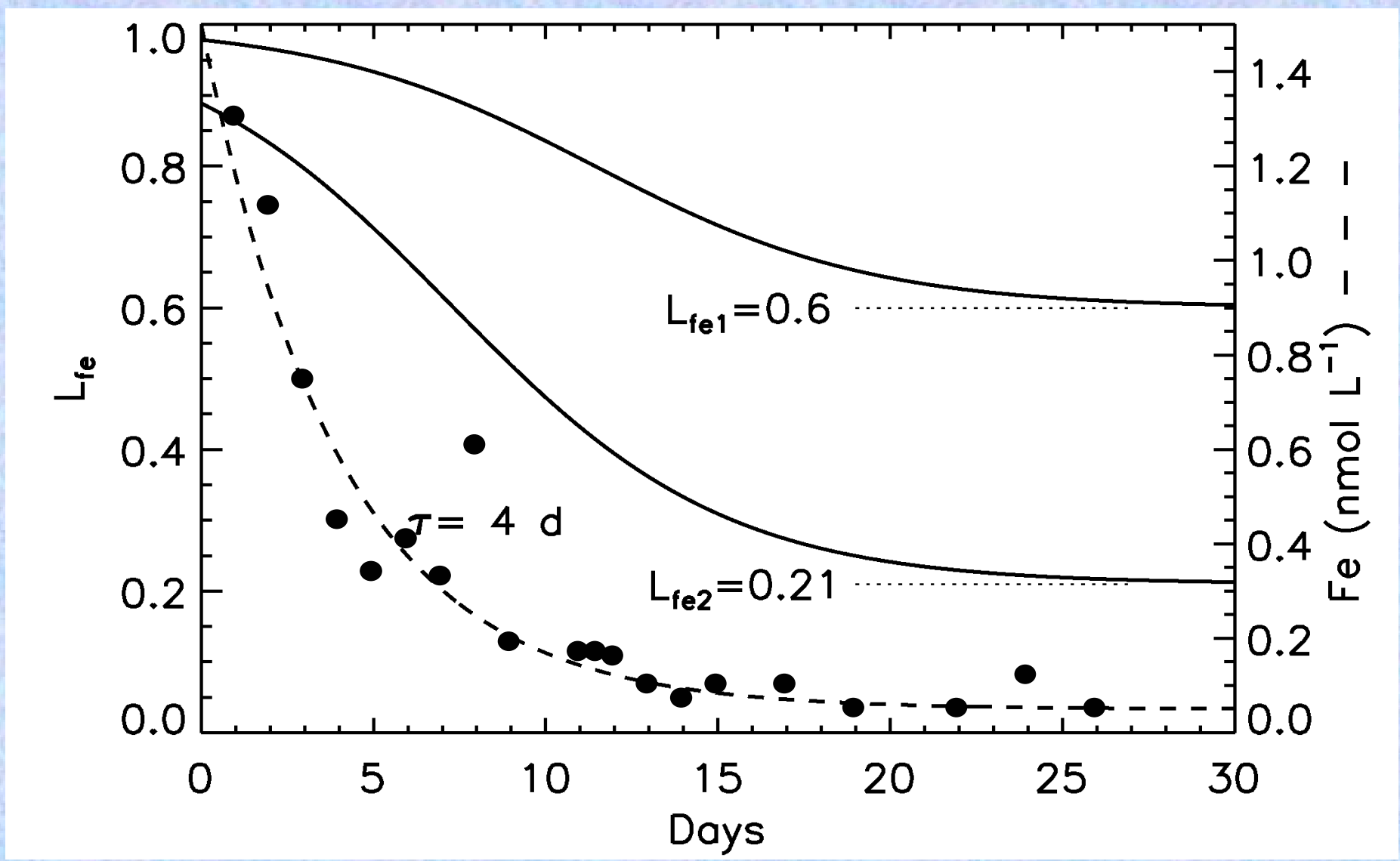
$Z_2(t)$ specified annual cycle of mesozooplankton



Peña, 2003; Monahan and Denman, GBC, 2004; Denman, Voelker, Peña and Rivkin, DSR II, in press.

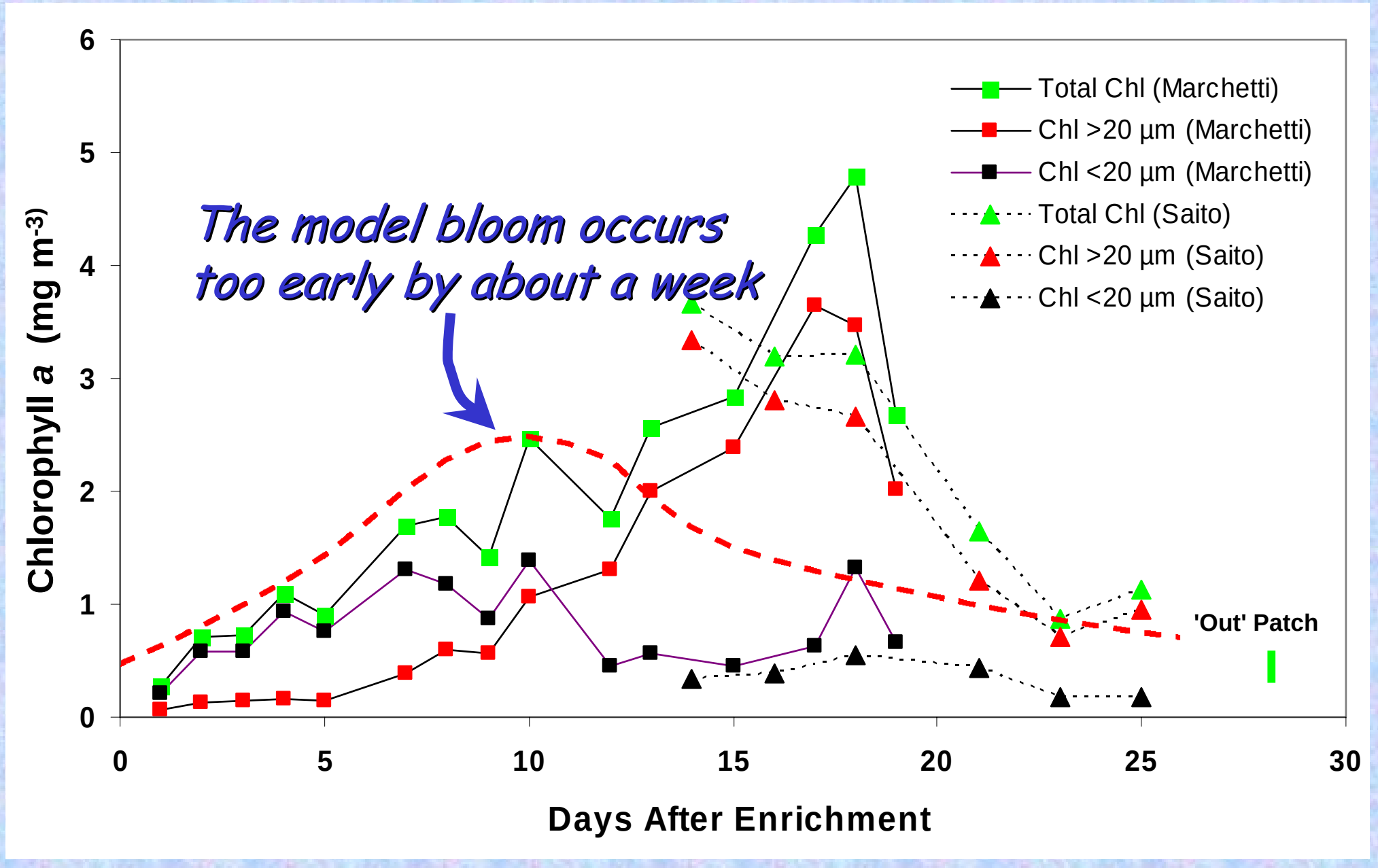
Fe Limitation: Michaelis-Menten Curve

Based on dashed line fit to Fe observations following fertilization

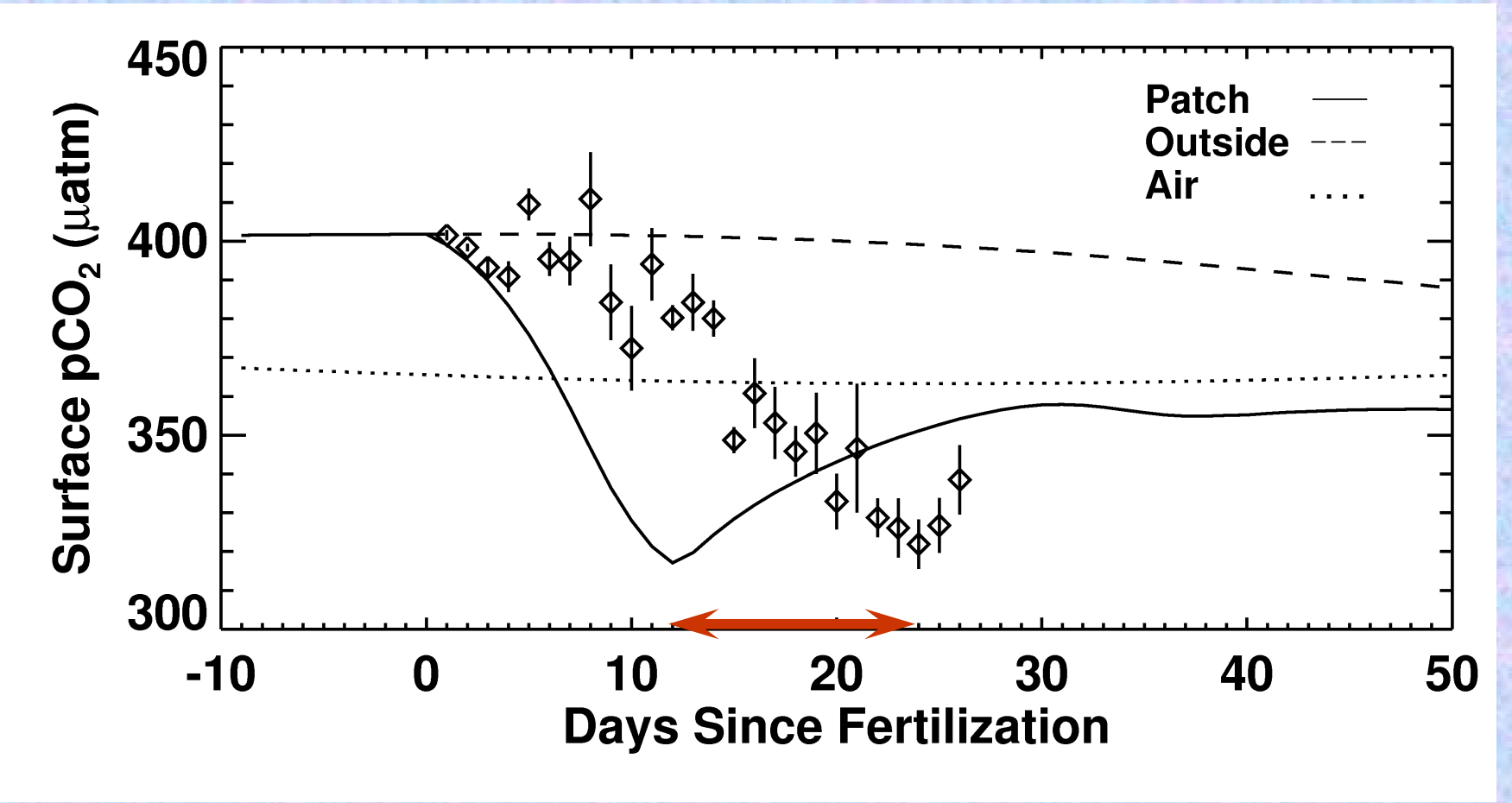


Fe concentrations redrawn from Boyd et al. 2006, Limnol. Oceanogr.

'Standard' Fertilization Simulation



The pCO_2 Drawdown Following Fertilization



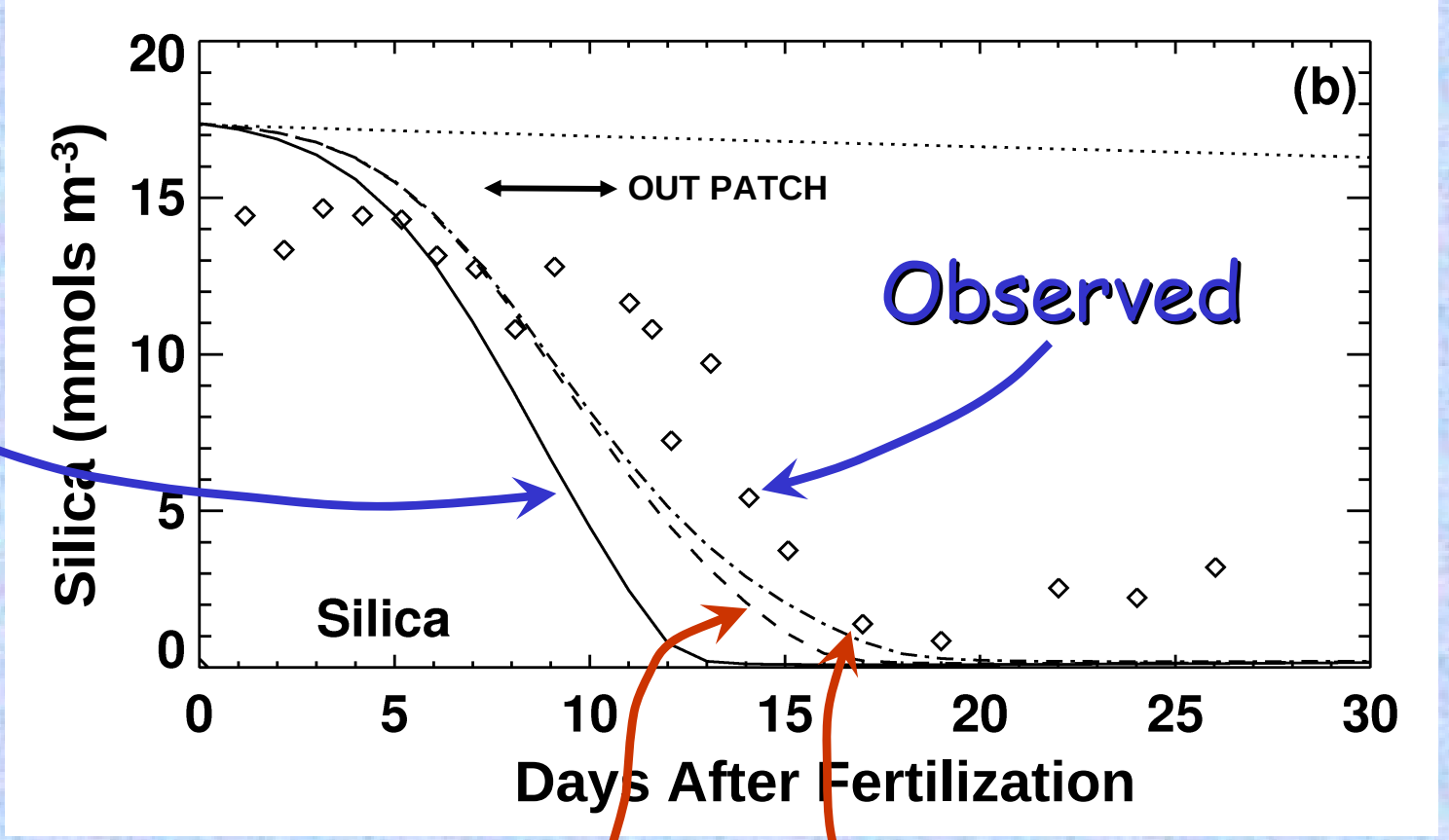
Right magnitude but EARLY

[but this 'patch' does not mix with its surroundings]

Data from Wong et al., DSR II, in press

Silica Drawdown by Diatom Uptake

Model Si:N uptake fixed



Si:N uptake ratio varies with Fe availability
- *Silica limitation delayed ~3 days*

[Takeda et al, in press, use threshold shift in Si:N uptake ratio]

[Data from Boyd et al. 2006, L&O]

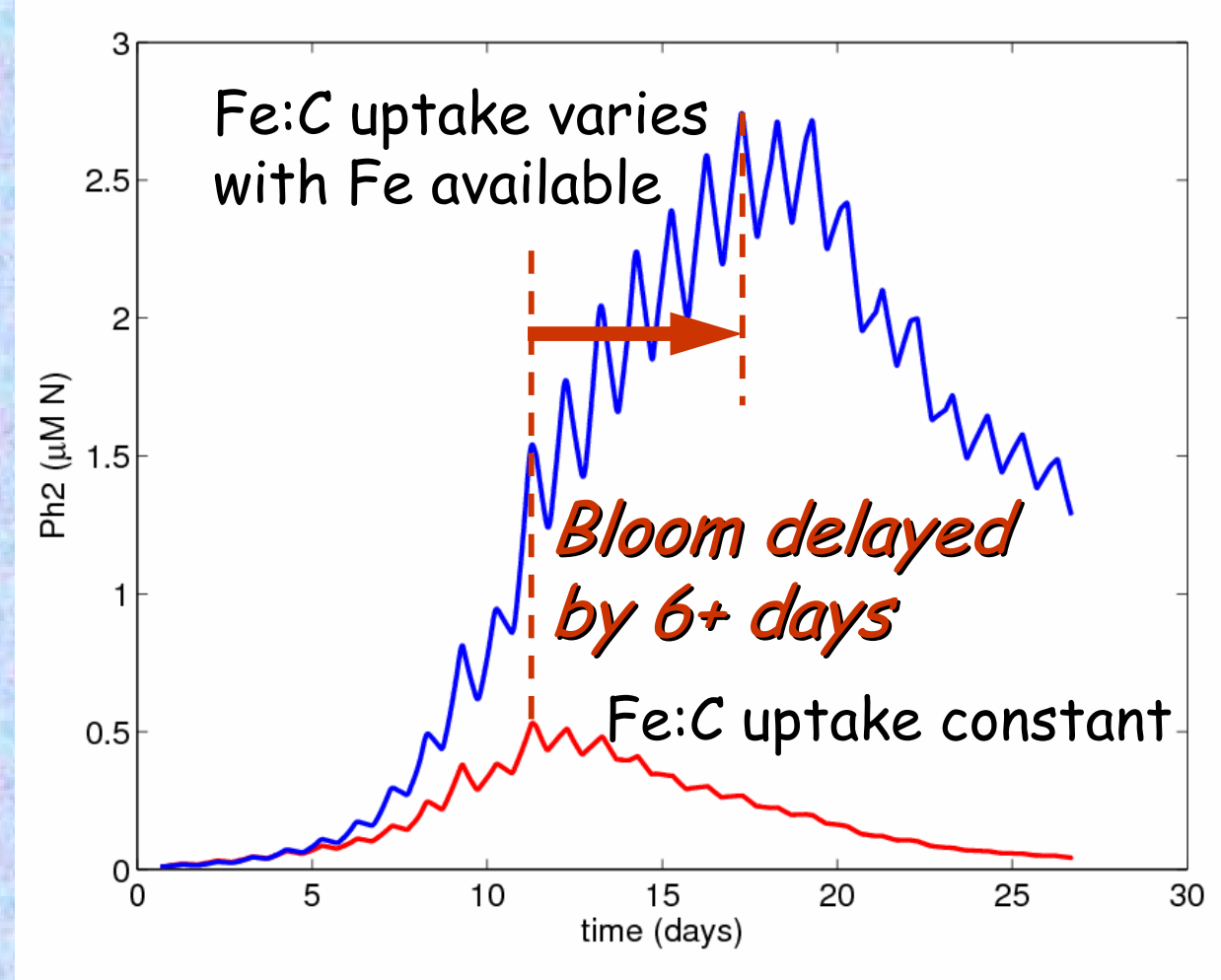
Silica redissolution rate depends on temperature
- *Silica limitation delayed ~1 more day*

But bloom delayed only 1-2 days

Adding Cell 'Quota' for Fe Uptake Relative to C & N Uptake

Diatoms *'Ph2'* take up more Fe relative to C than they need when there is lots of Fe available
- then they use it up later

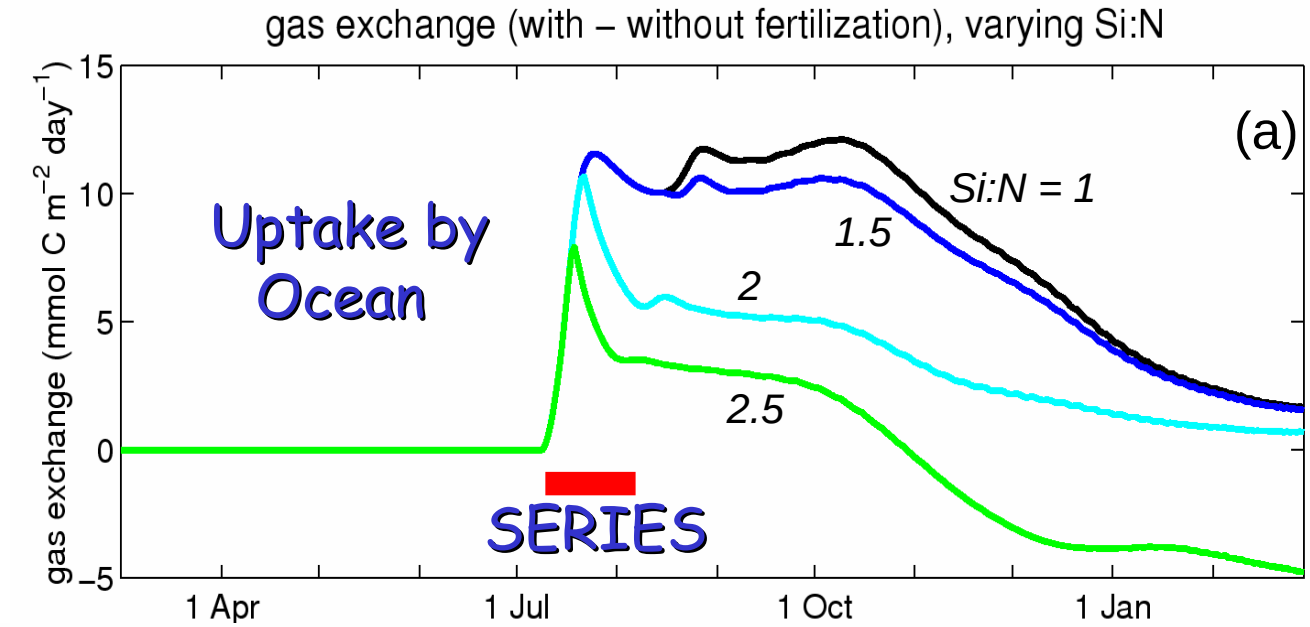
C. Voelker has implemented this 'Droop' model in a preliminary manner

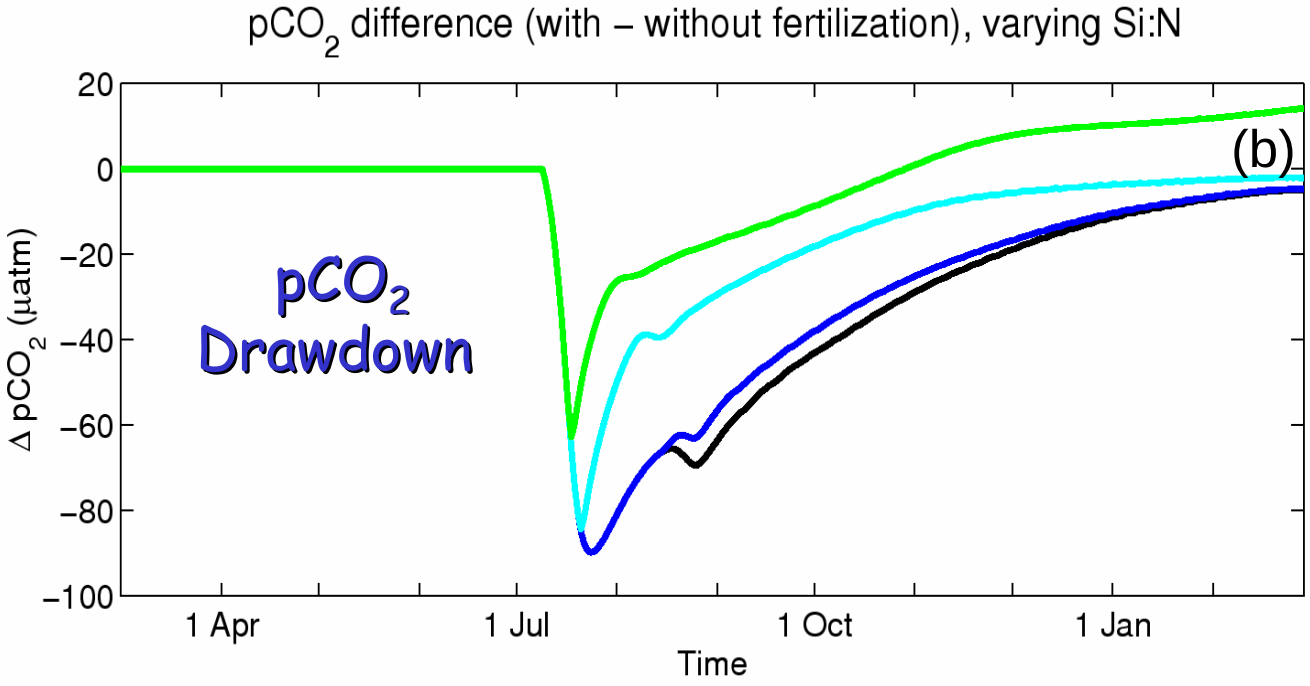


Uptake of CO_2 After Fe Fertilization

Role of Silica vs Iron

High Si:N uptake could cause early Si depletion so long term effect of Fe fertilization would be emission of more CO_2





How Important is Variability in Physical Forcing?

McClain et al. 1996, JGR

- 30 years met. forcing, including wind stress curl (upwelling)

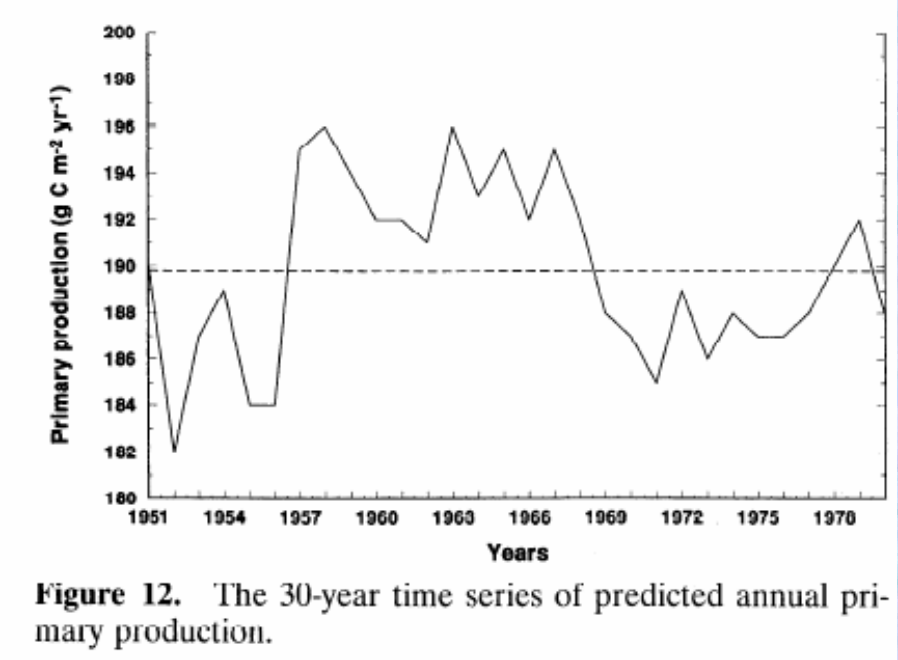
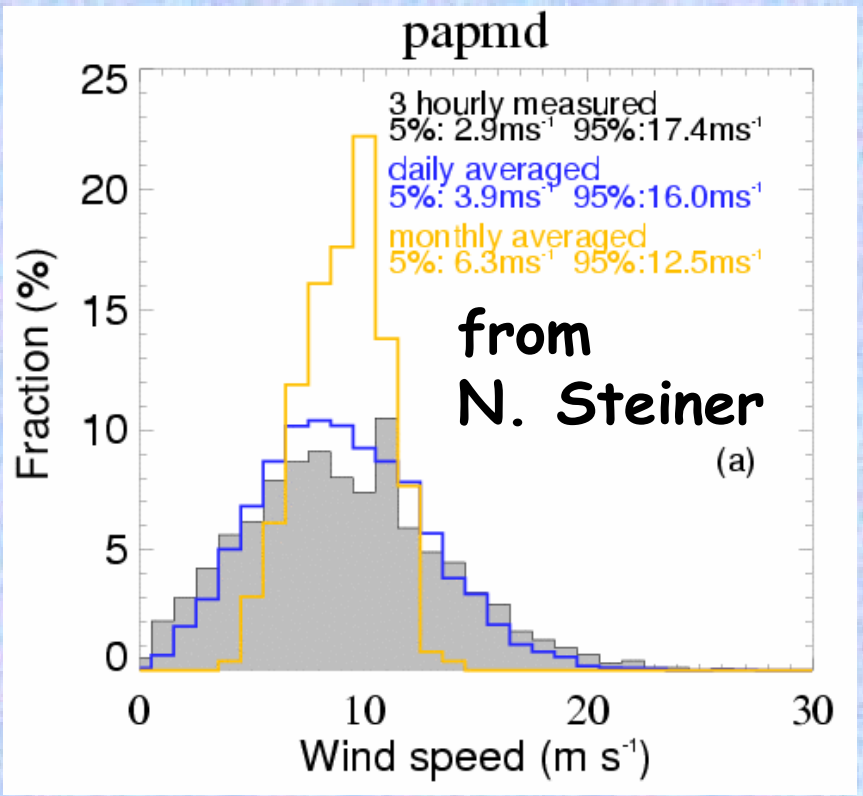


Figure 12. The 30-year time series of predicted annual primary production.

Variability of modelled annual PP < ±4%

Monahan & Denman 2004, GBC

- stochastic forcing model from 21 years 3-hourly met. forcing, including cloud fraction, winds, temperature, humidity
- constant degree of Fe limitation



3-hourly data matter

Variability in Meteorological Forcing

- Large variability in standing stocks
- Low variability in XP in Fe limited OSP
- Higher variability in XP in Fe replete 'coastal' regime, e.g. line P4

See Adam Monahan's poster for more

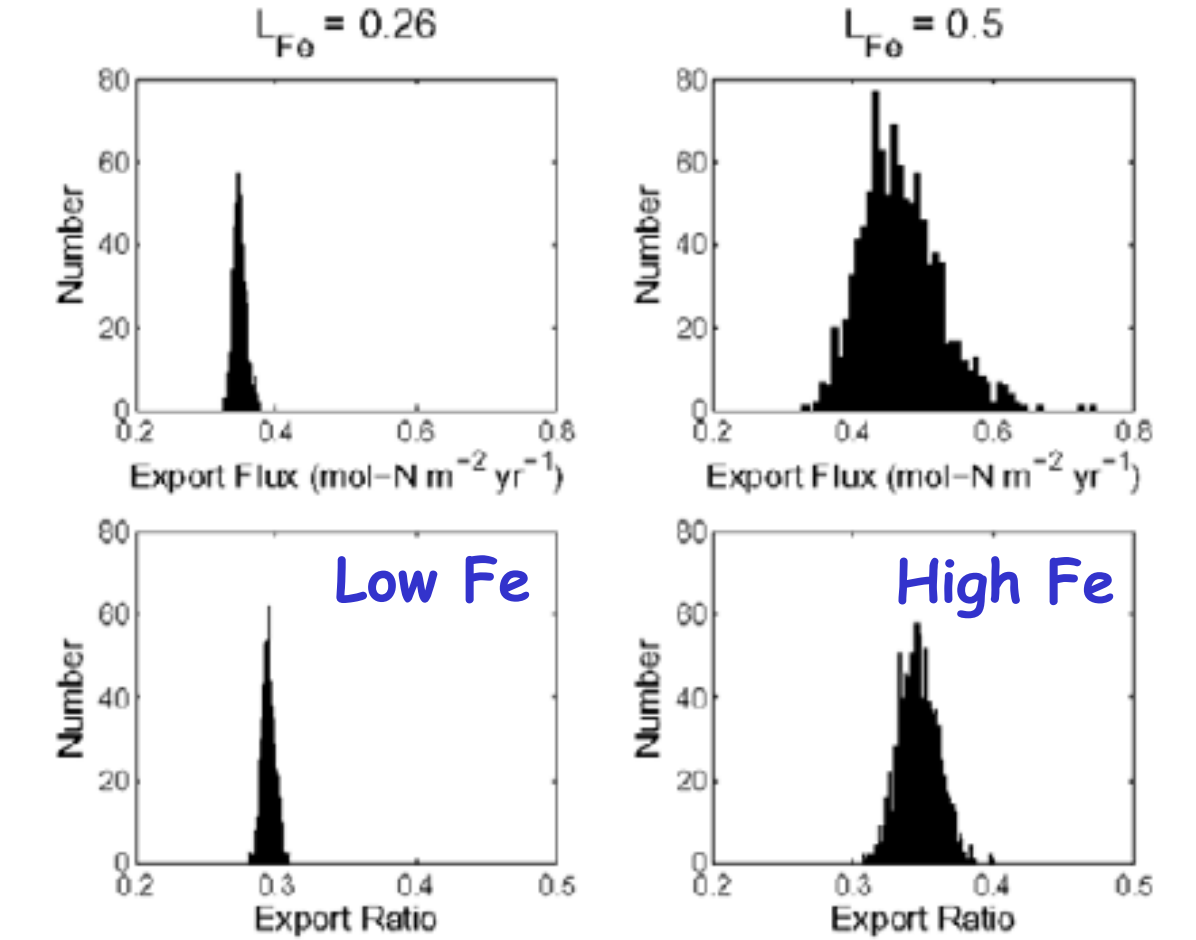


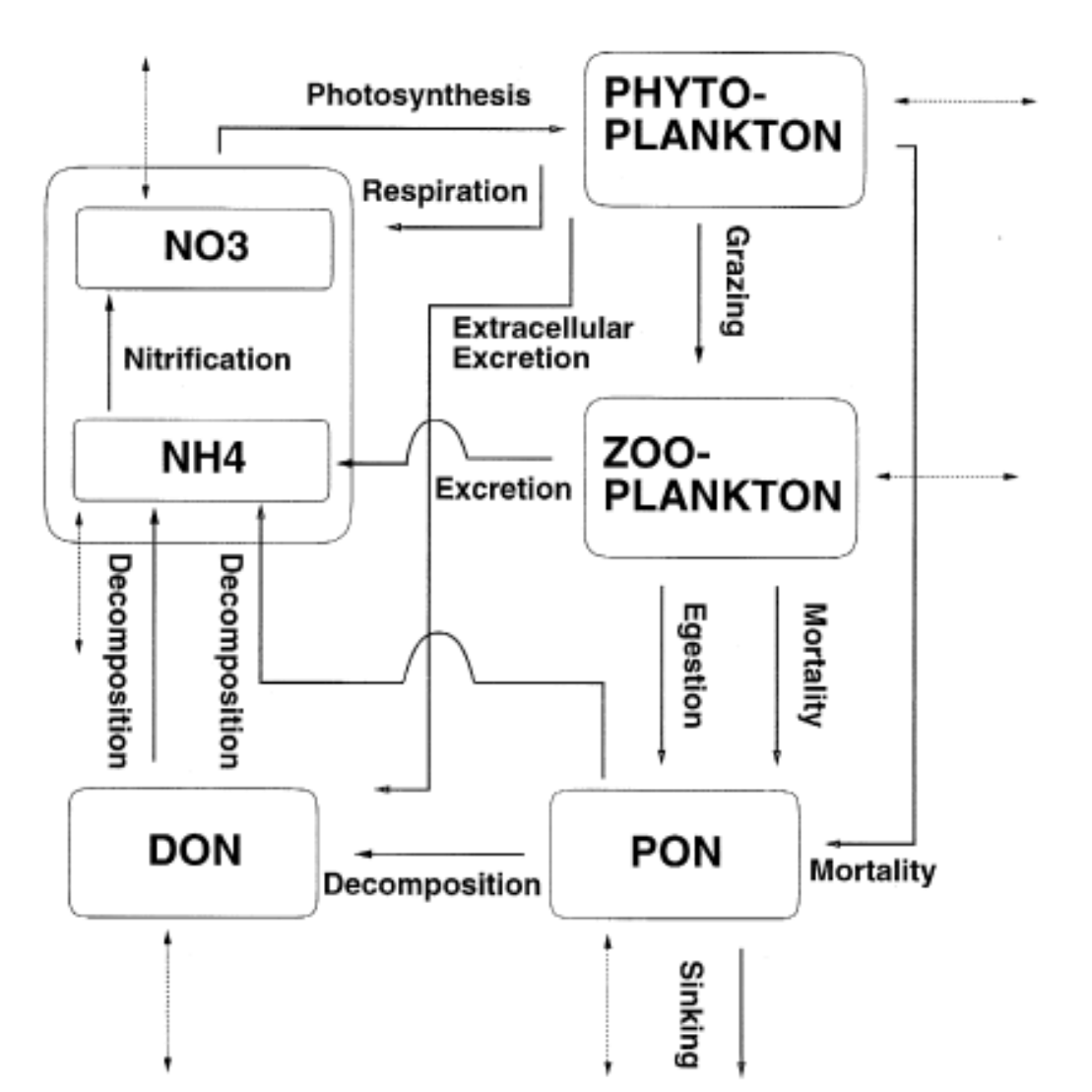
Figure 16. Histograms of export fluxes and export ratios for 1000-year integrations in the iron-limited and nitrogen-limited regimes.

Monahan & Denman 2004, GBC

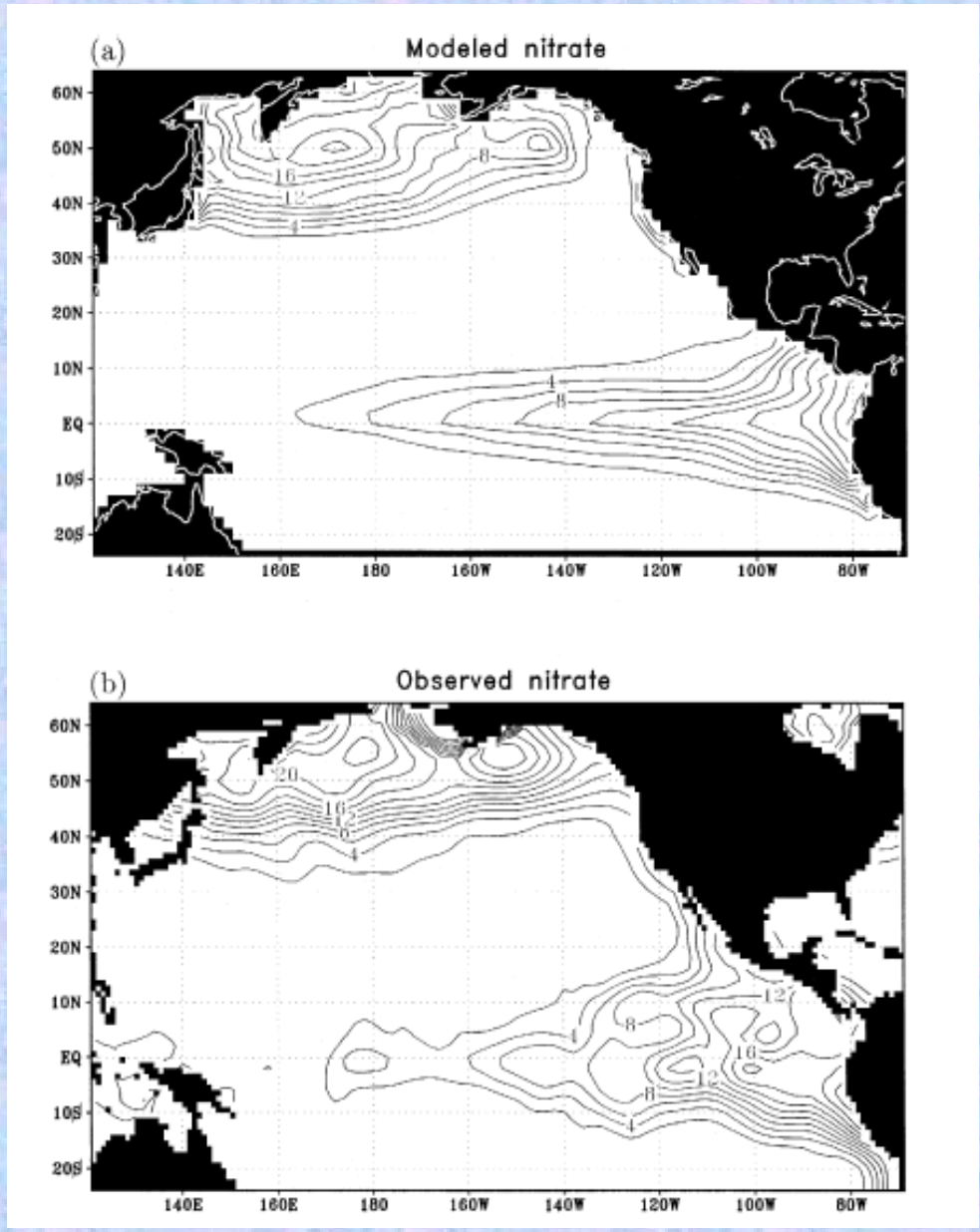
Can 3-D Models Reproduce the Subarctic and Subtropical Gyre Ecosystems?

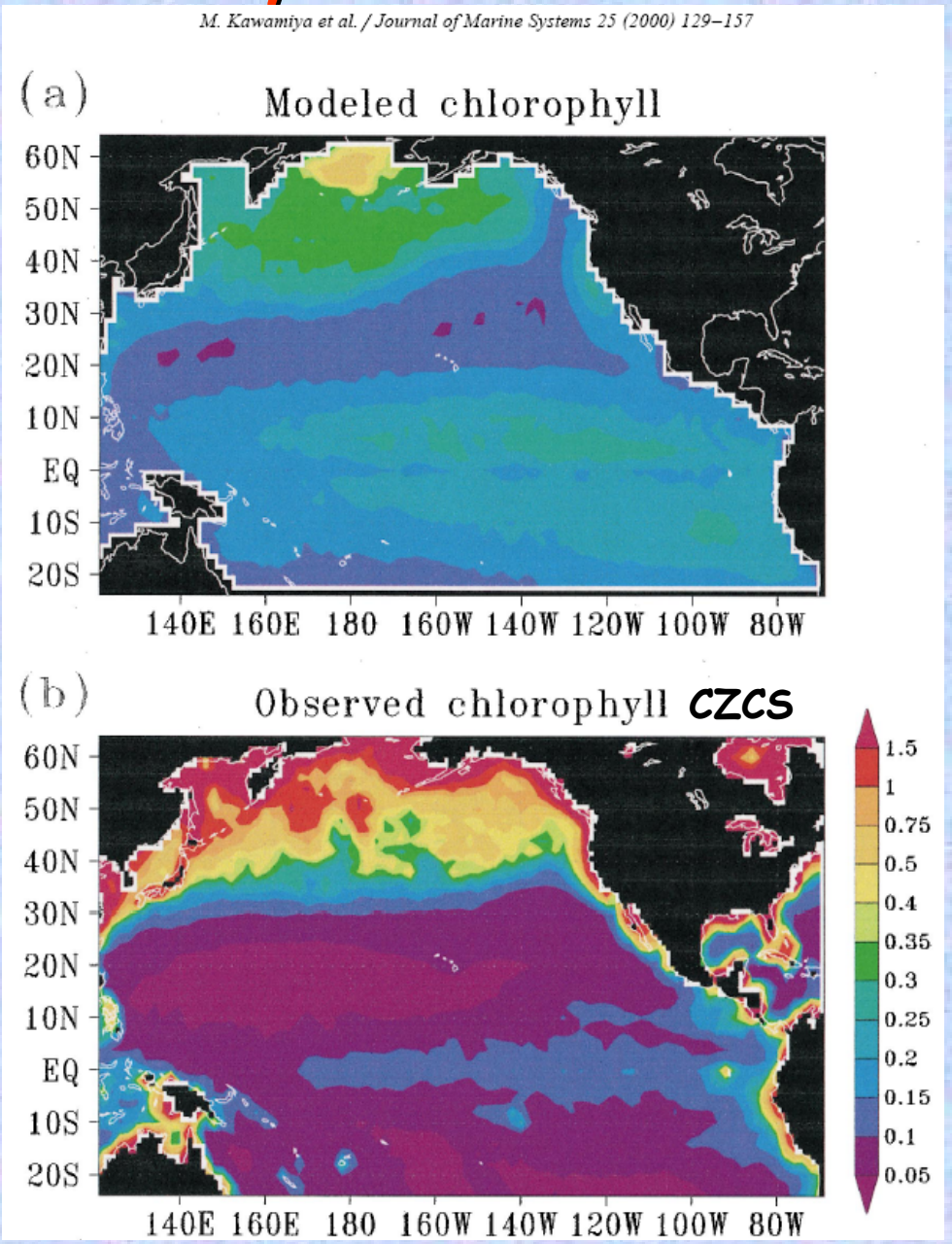
1-D:
Kawamiya, et al., 1995, 1997

3-D:
Kawamiya, et al., 2000a, b



Can 3-D Models Reproduce the Subarctic and Subtropical Gyre Ecosystems?





Kawamiya et al, 2000a,b

Can 3-D Models Reproduce the 1976 'Regime Shift'?

a) Surface Nitrate

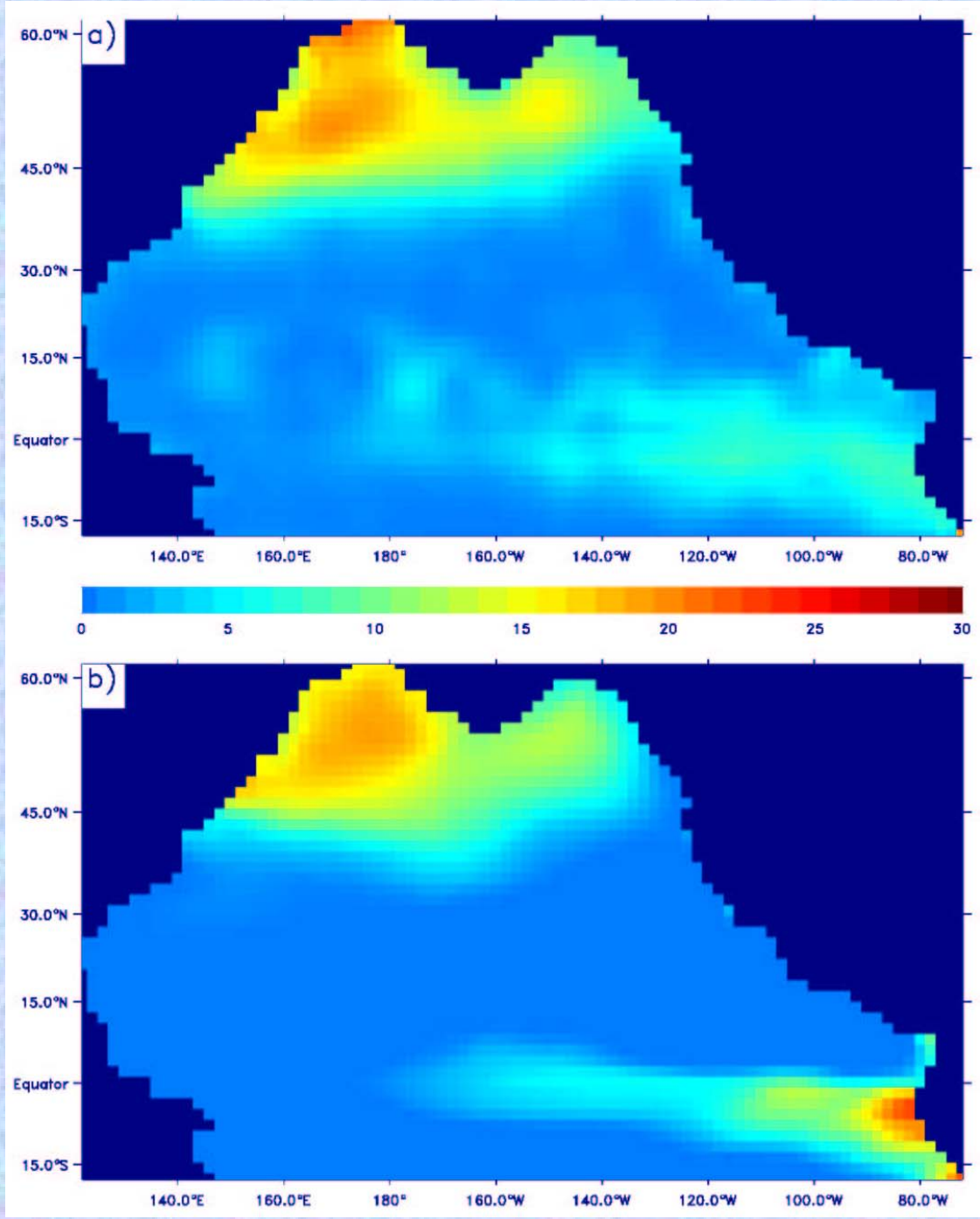
World Ocean Atlas 1994

b) Surface Nutrient

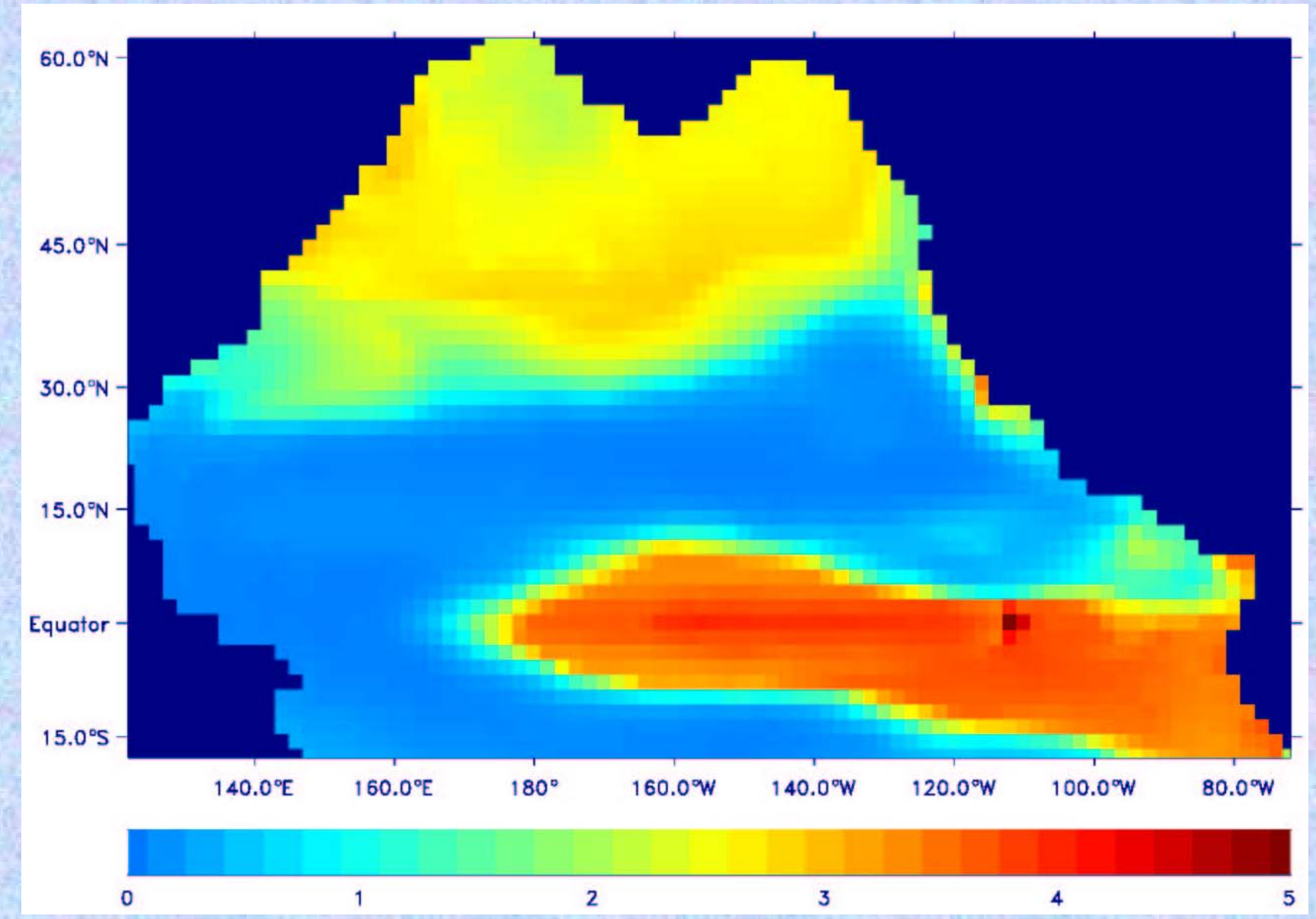
Model output Year 3
1952-88 forcing

Haigh, Denman & Hsieh, 2001

- isopycnic model
- 4 component ecosystem

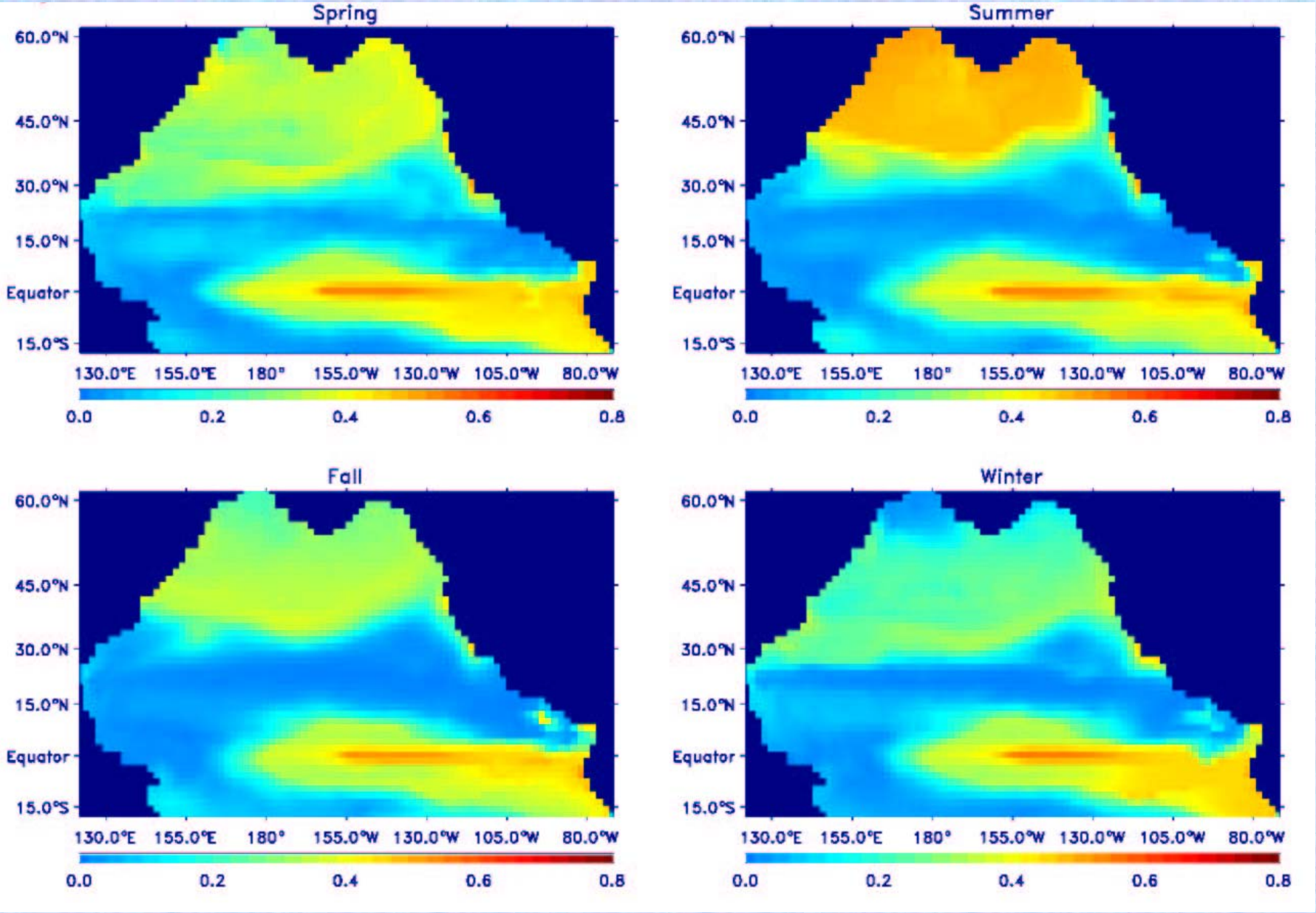


Annual Primary Production – Upper 100m



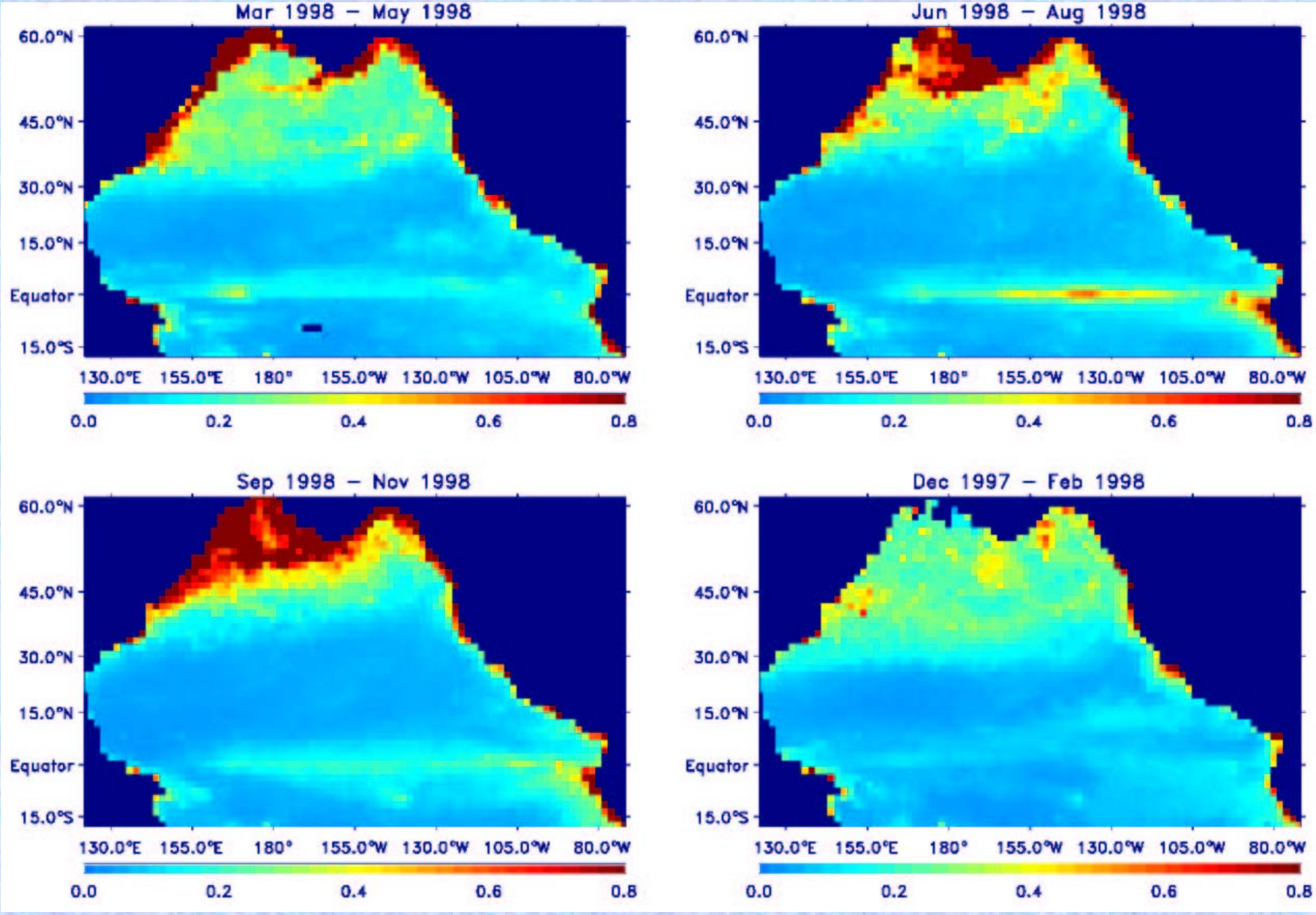
Haigh, Denman & Hsieh, 2001

Seasonal Averaged Phytoplankton in Mixed Layer



No iron limitation in model

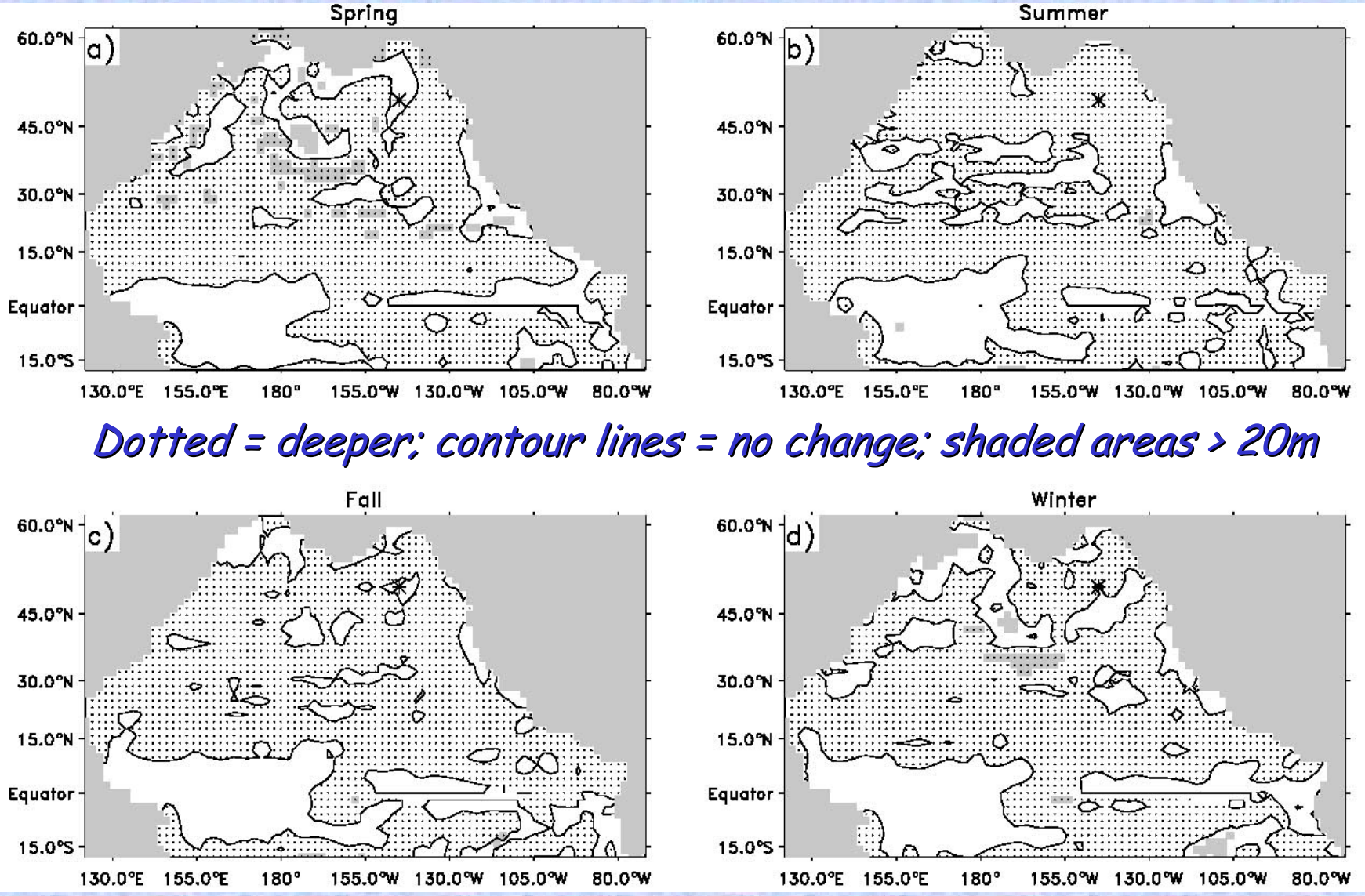
Seasonal SeaWiFS Chlorophyll 1997-98



Provided by the SeaWiFS Project, NASA/Goddard Space Flight Center & ORBIMAGE

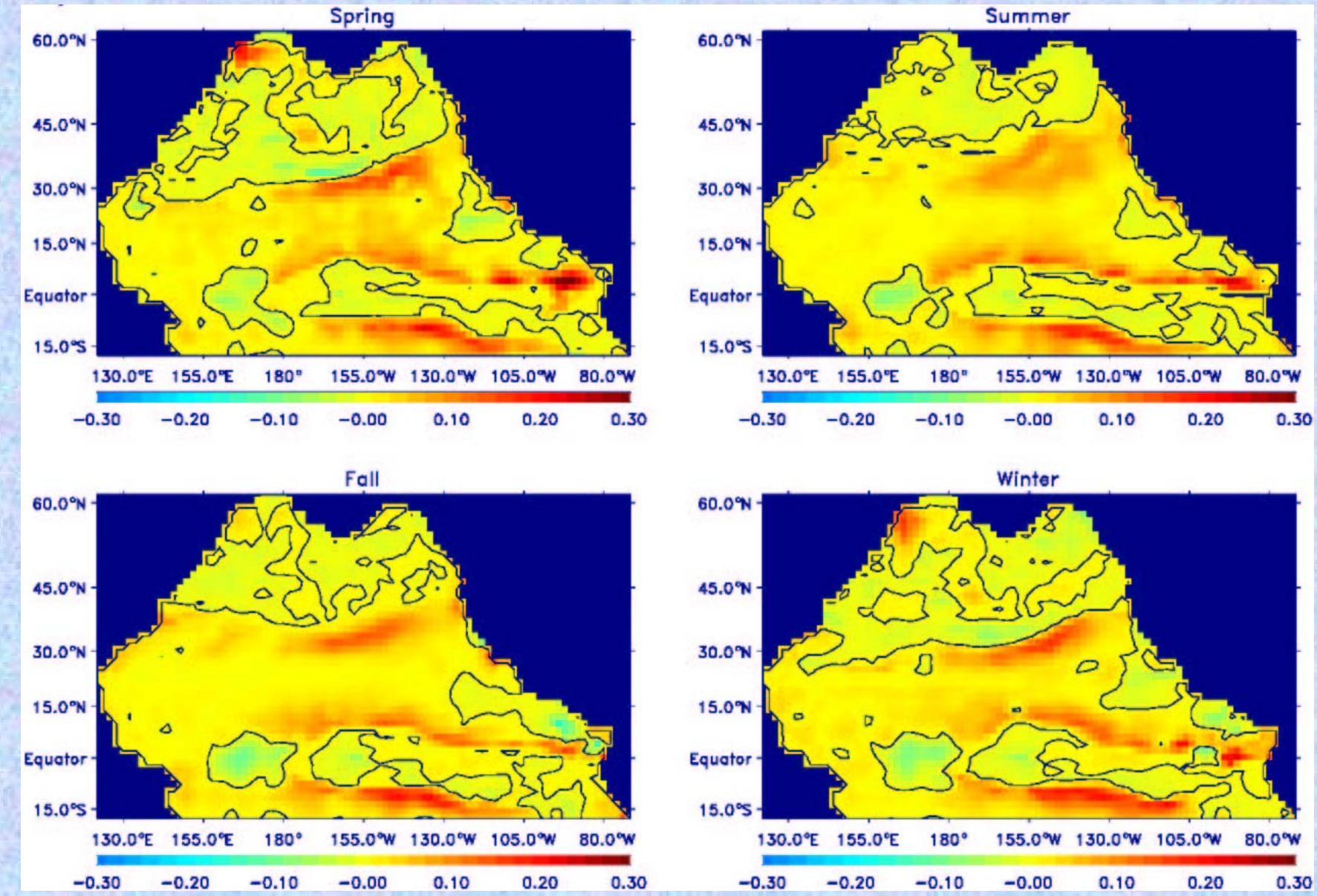
SeaWiFS first year 1997-98 atypical due to El Niño?

Post – Pre 1976 Mixed Layer Depths

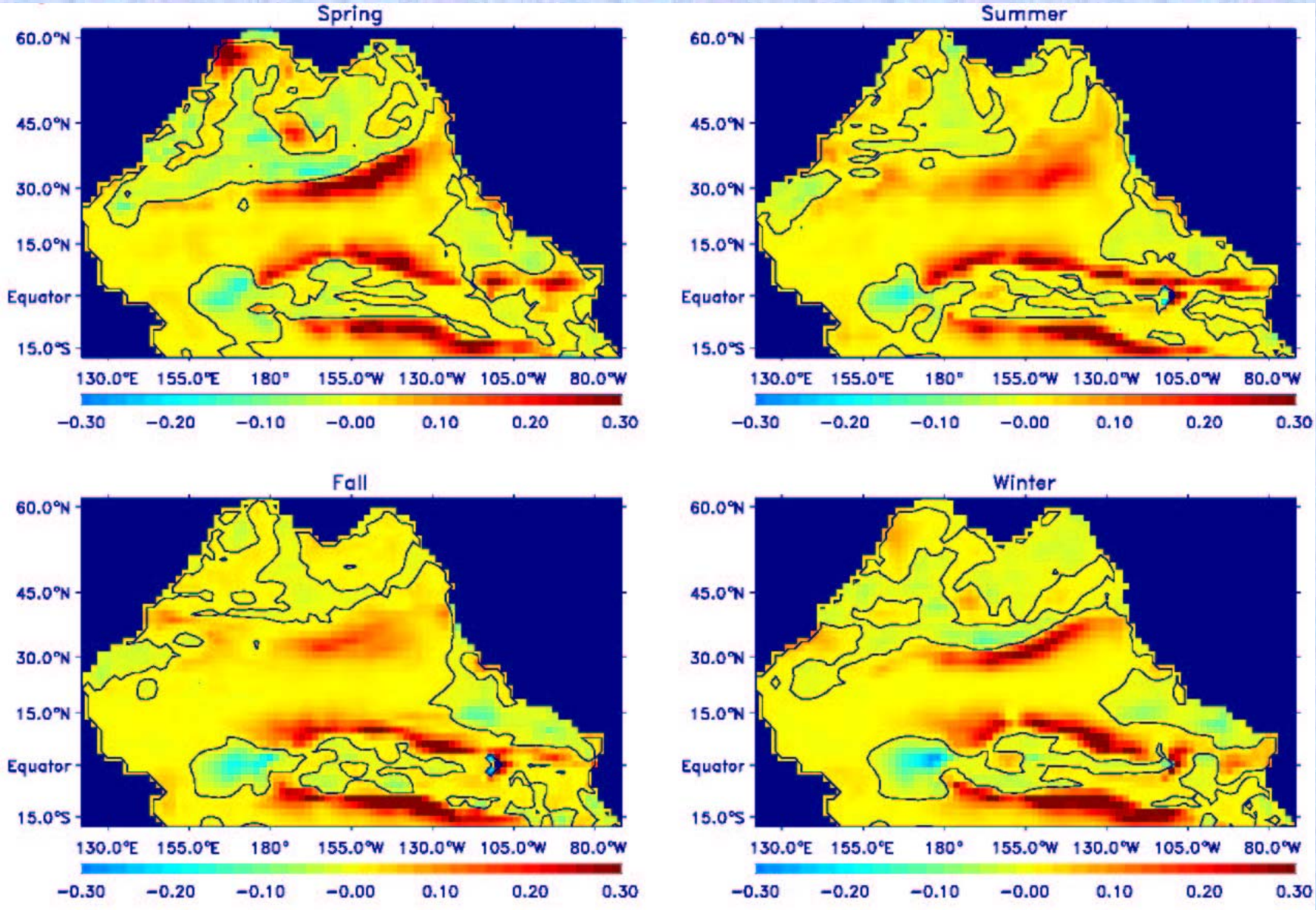


Dotted = deeper; contour lines = no change; shaded areas > 20m

Model Phytoplankton: Difference Between ML Post-76 and Pre-76 Fields

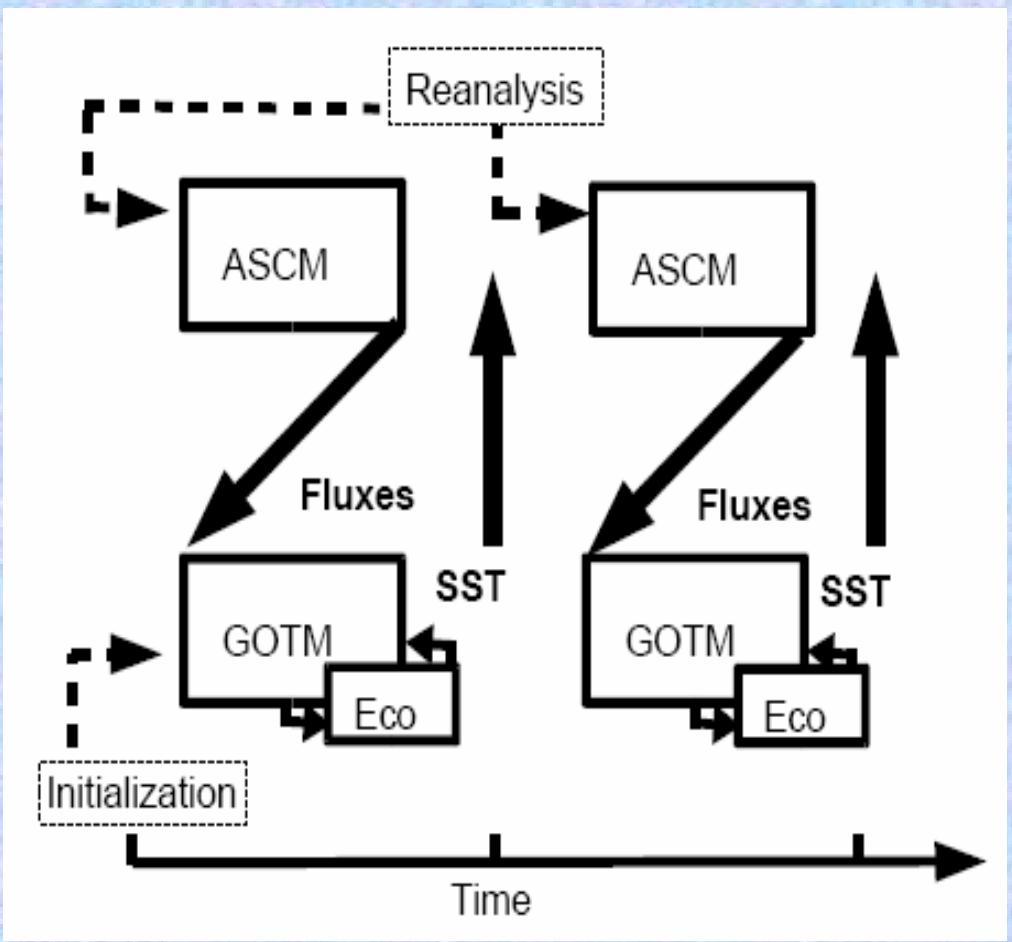


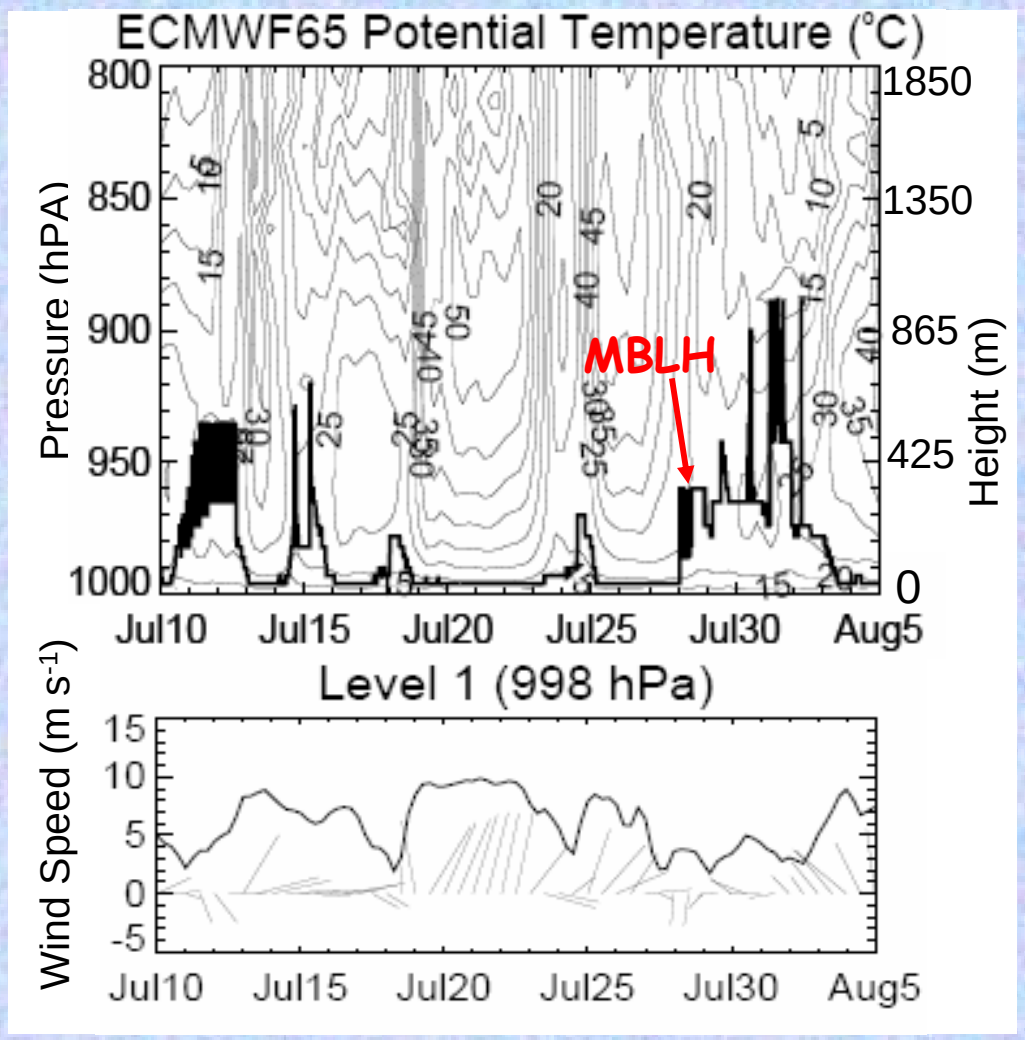
Model Zooplankton: Difference Between Top 100m Post-76 and Pre-76 Fields



A Coupled Atmosphere-Ocean Boundary Layer Model

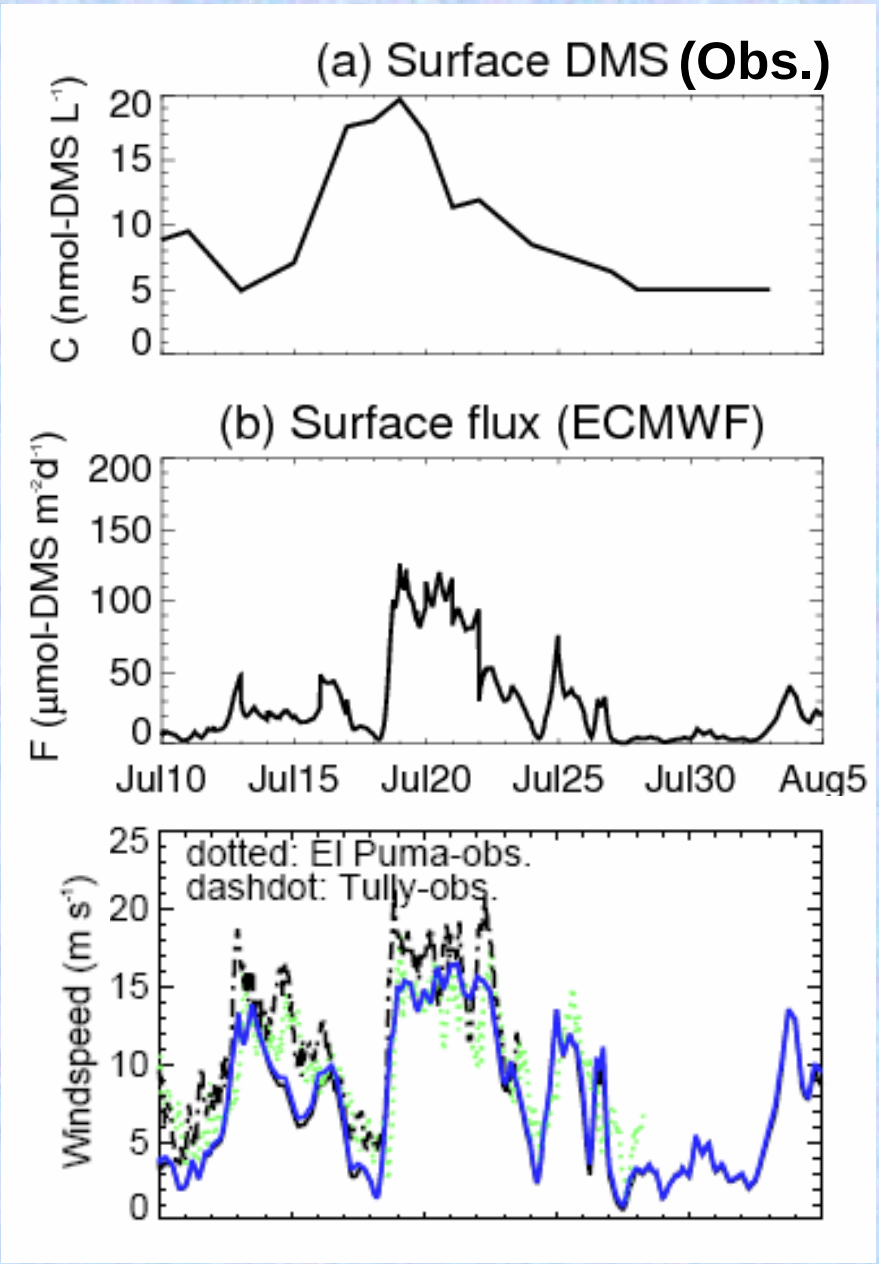
'The Response of the Lower Atmosphere to Oceanographic Forcing'

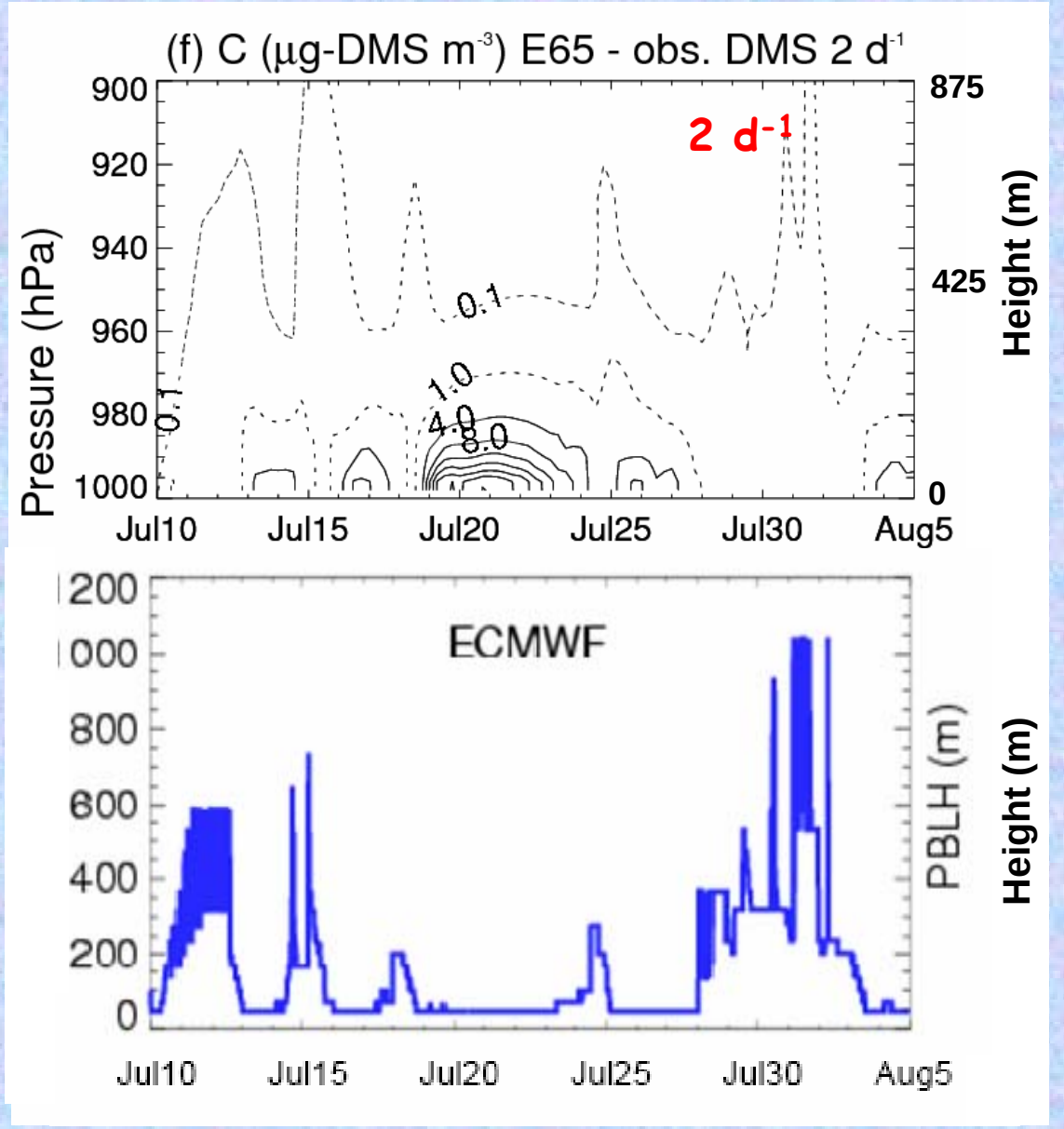




From Steiner et al., Deep-Sea Res II, in press.

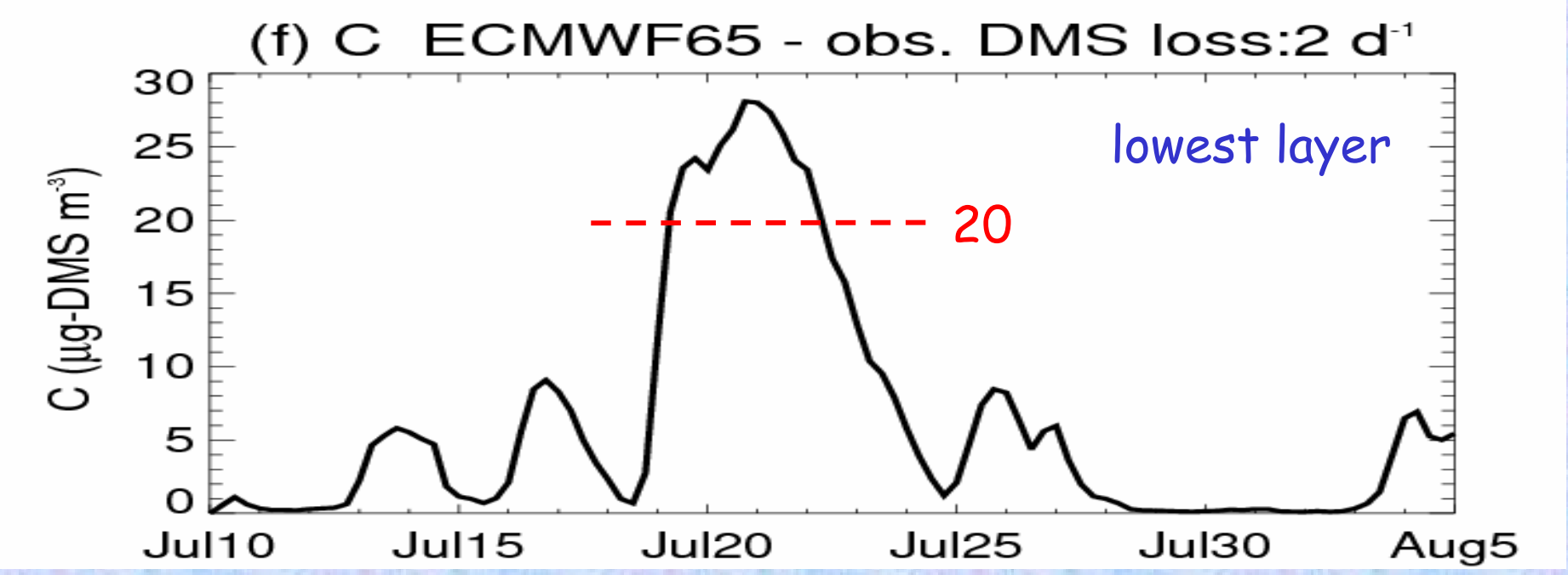
DMS Flux & Dispersion in MBL





From Steiner et al., Deep-Sea Res II, in press.

DMS: Comparison With Observations



NOTE

- DMS loss rates in MBL have diurnal variation, as they are generally photoactive
- Need to use DMS-specific wind speed dependence for piston velocity ***k***

(Blomquist et al, 2006, GRL)

Only a few observations by Moire Wadleigh, A-L. Norman, et al. 2006 , exceeded 20 µg-DMS m^{-3}

Next Steps for Coupled 1-D Model

- Nadja Steiner is developing a DMS model coupled into the ocean ecosystem model:

  ** See Steiner et al. poster **

  [work with Y. Le Clainche & M. Levasseur]

  ** See talk and posters **

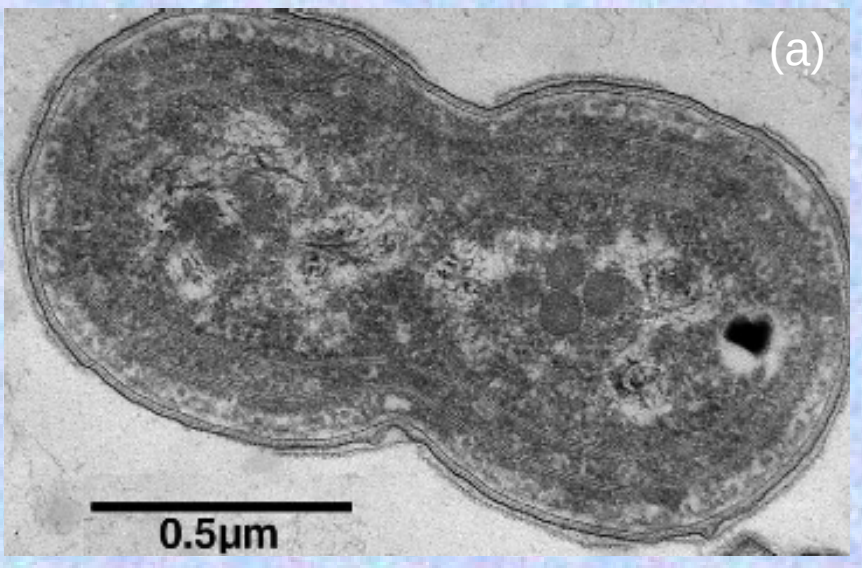
- Implement gas-specific dependencies of pistion velocity *k* on wind, sea state and bubbles

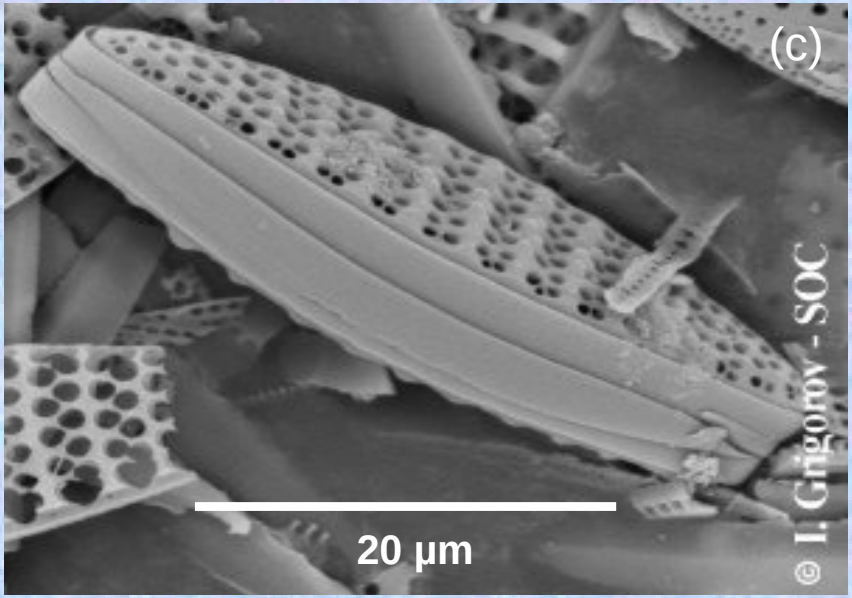
  ** See Svein Vagle talk **

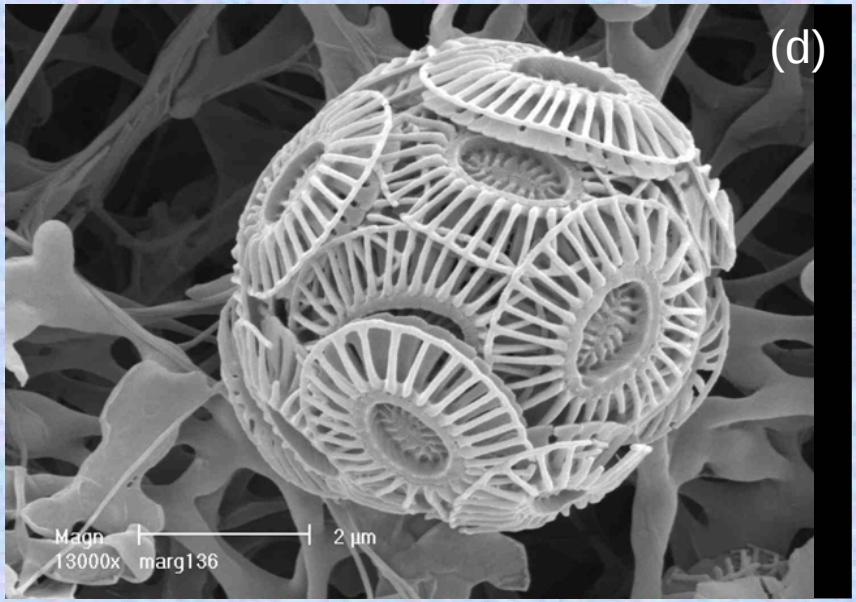
The Future:
1. Make projections of N. Pacific foodwebs responding to climate change

- What is the appropriate level of complexity?
  - *a model's detail may extend beyond observations [e.g. Matear 1995, Denman 2003]*
  - *a model of 'local' phenomena may be overtuned and have poor 'portability' to other regions*
- Global datasets are essential for model development and evaluation, but:
  - *We need to know how complete or 'sparse' are the underlying data*
  - *Is there an 'implicit model' used in their interpolation and extrapolation?*

Need Four 'PFTs': Plankton Functional Types

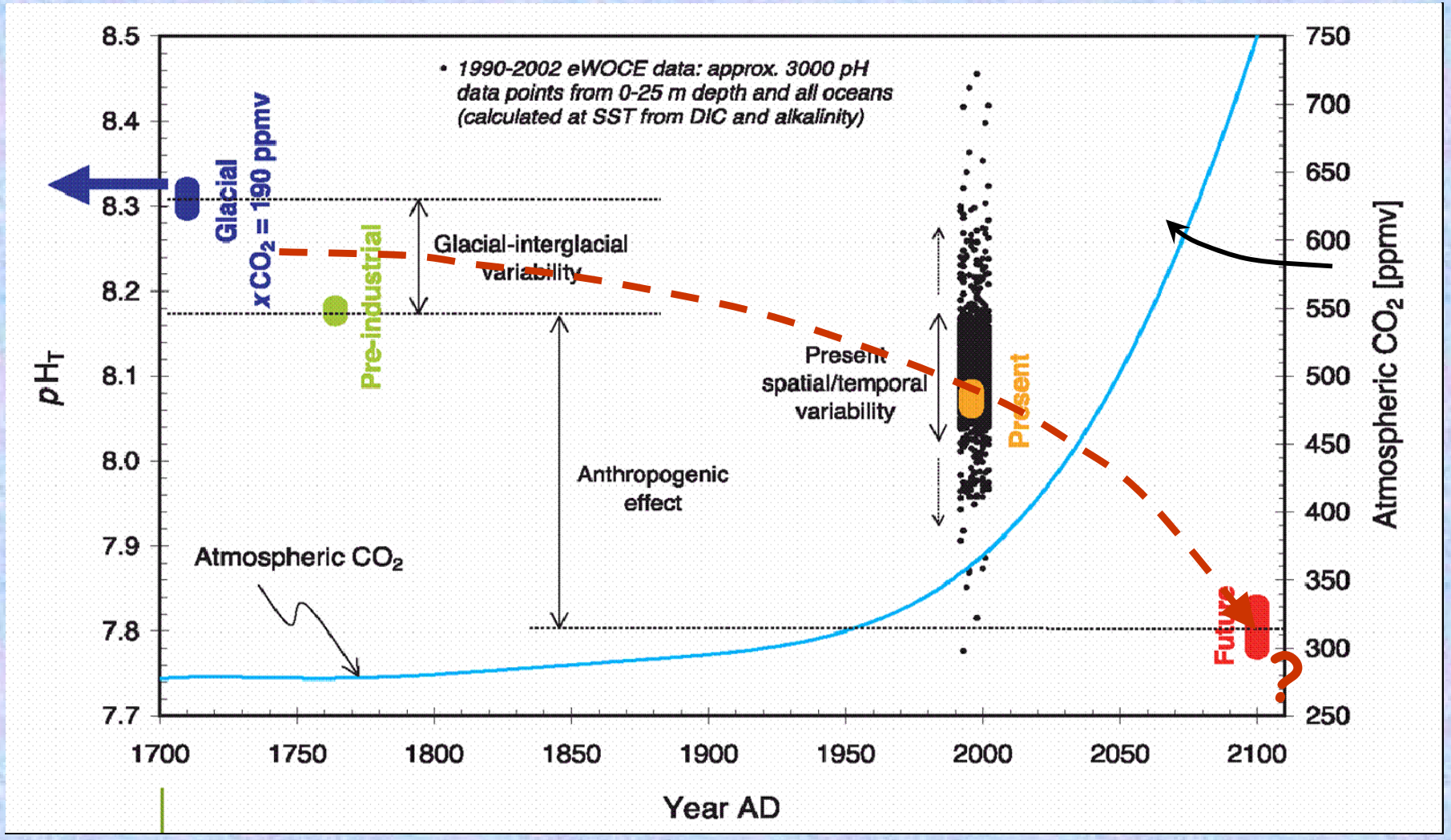






The PARADIGM Group, Oceanography, March 2006

The Future: 2. More CO_2 → Surface pH is Decreasing → Ocean Acidity Increasing



[prepared by Arne Körtzinger (IFM,Kiel) for the IMBER Science Plan on the basis of WOCE data: Schlitzer, 2000]

http://ioc.unesco.org/iocweb/co2panel/Publications.htm

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