Export production from ocean color

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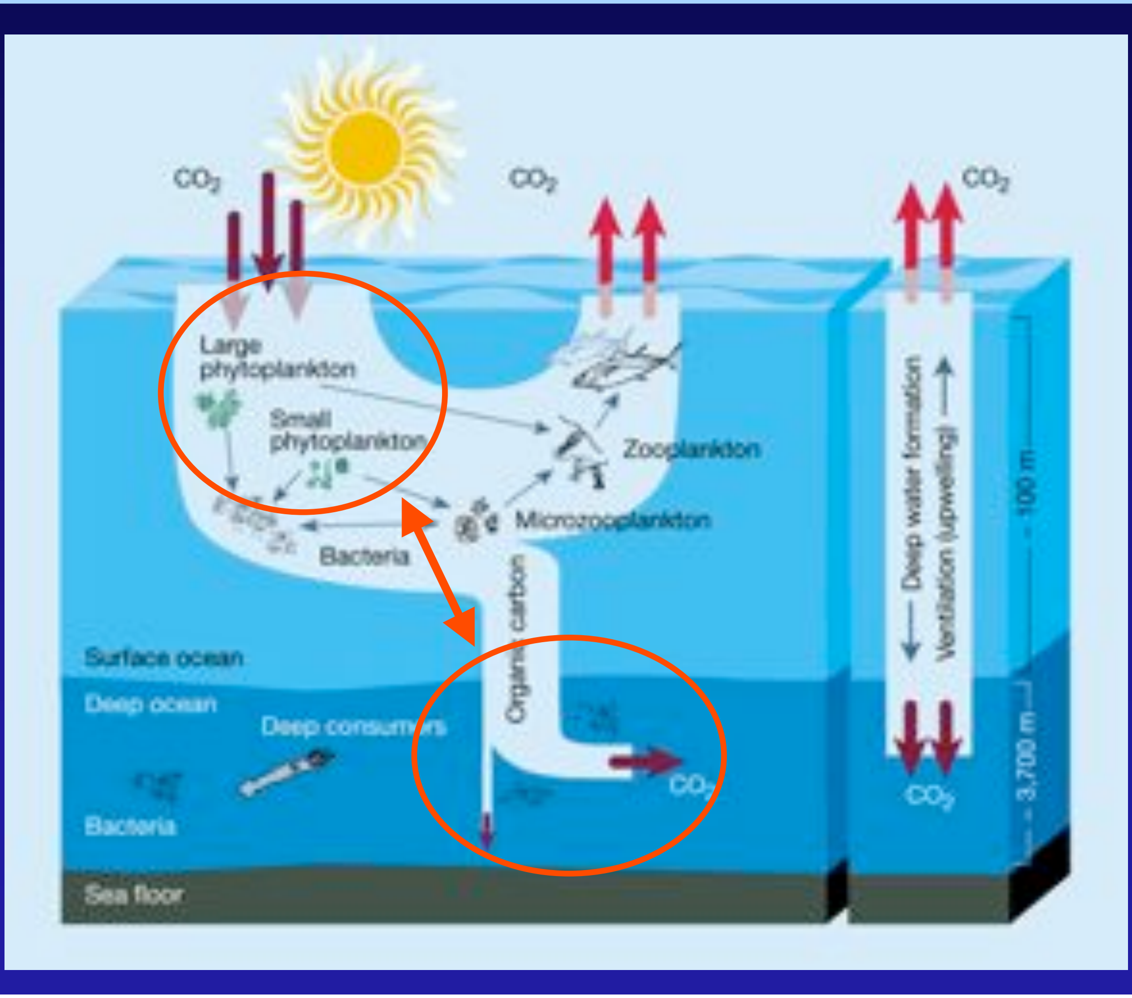
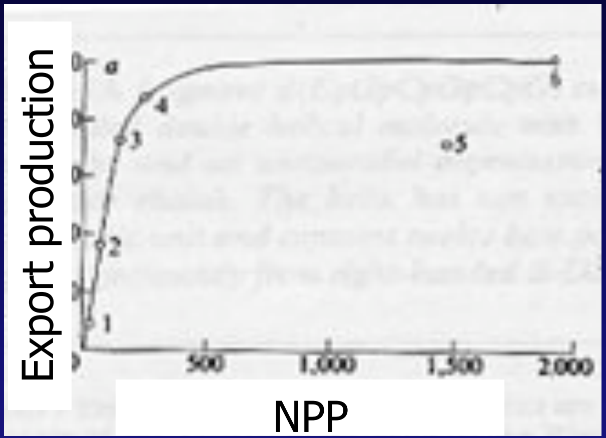
Why? (1)

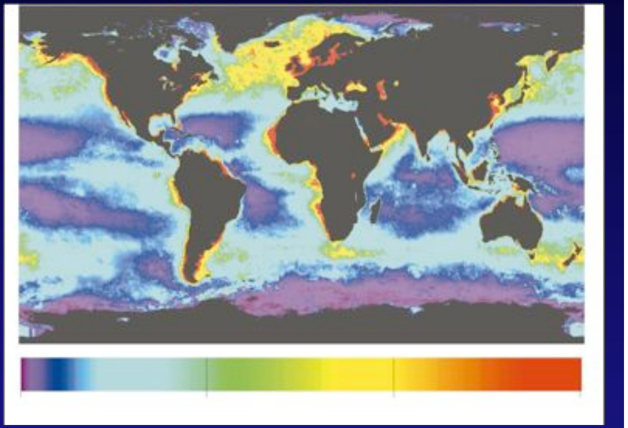
What is the fate of net primary production (NPP)?
(i.e., export v. recycling)

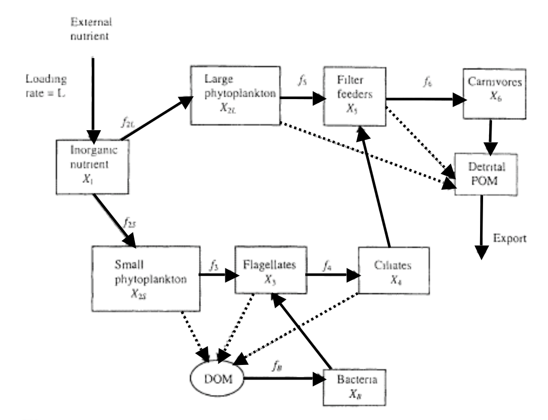


from Chisholm (2000)

Why? (2)







In situ observational studies

- ^{15}N incubations
- Sediment traps
- Geochemical balances
- ^{234}Th inventories

Eppley & Peterson (1979)
Suess et al. (1980)
Buesseler et al. (1998)

Satellite based

- Applications of empirical results
- [Chl], NPP, and SST are not sufficient

Falkowski et al. (1998)
Iverson et al. (2000)
Goes et al. (2000), (2004)

Ecosystem models

- Assumptions
- Simplistic representations

Fasham et al. (1990)
Laws et al. (2000)
Dunne et al. (2005)

How? (1) – CbPM Overview

Carbon-based Production Model (CbPM)

(Behrenfeld et al., 2005; Westberry et al., submitted to GBC)

1. Invert ocean color data to estimate Chl a & $b_{bp}(443)$
   (Garver & Siegel, 1997; Maritorena et al., 2002)

2. Relate $b_{bp}(443)$ to phytoplankton carbon biomass, C

3. Use Chl:C to infer physiology (photoacclimation & nutrient stress)

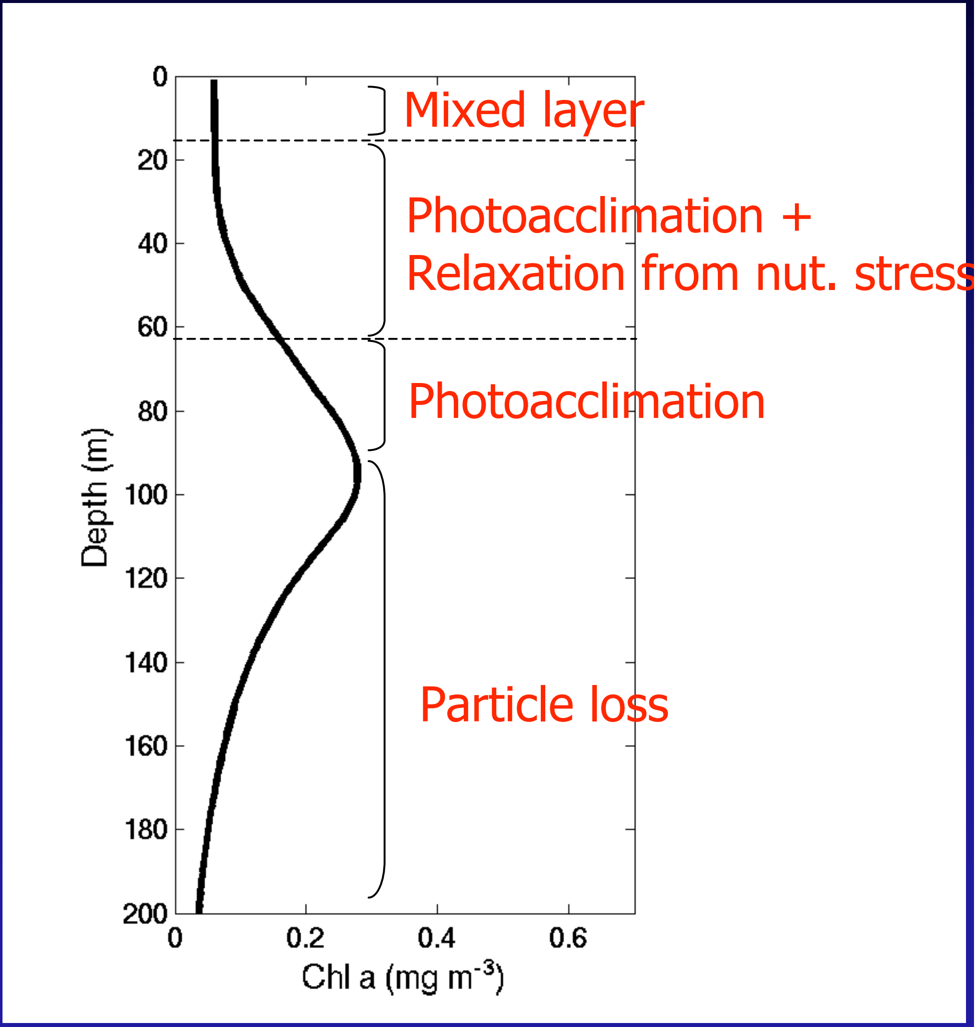
4. Estimate phytoplankton growth rate (μ) and NPP

$$\boxed{NPP = \mu \times C}$$

How? (2) – CbPM Details

We can push model vertically through the water column:

- Spectral accounting for underwater light field
- Cells photoacclimate through the water column
- Nutrient-stress decays as nitracline is neared (using climatological nutrient fields)



**Westberry et al., (in review GBC)

How? (2) – CbPM Details

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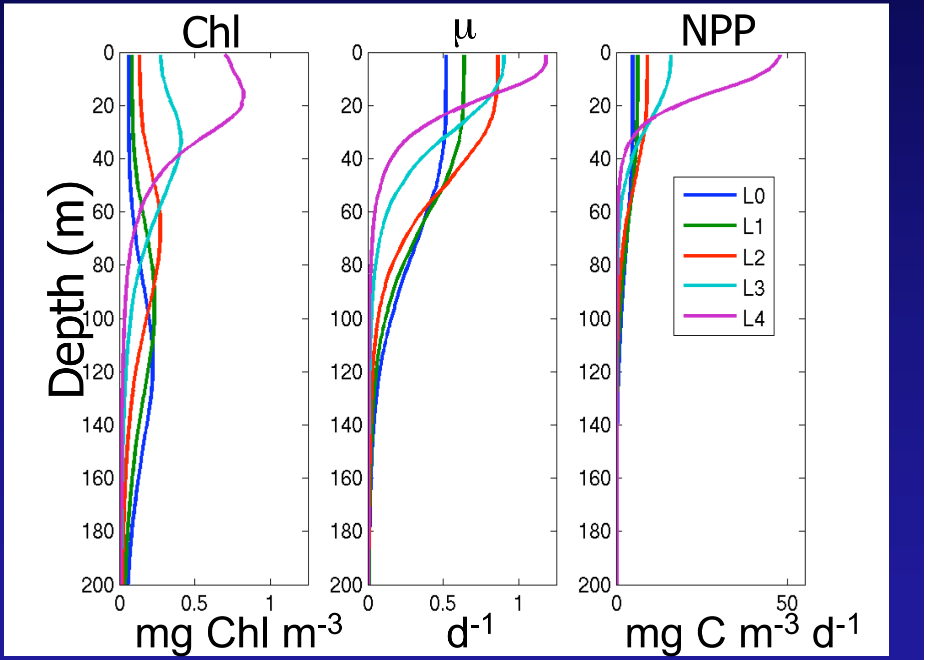
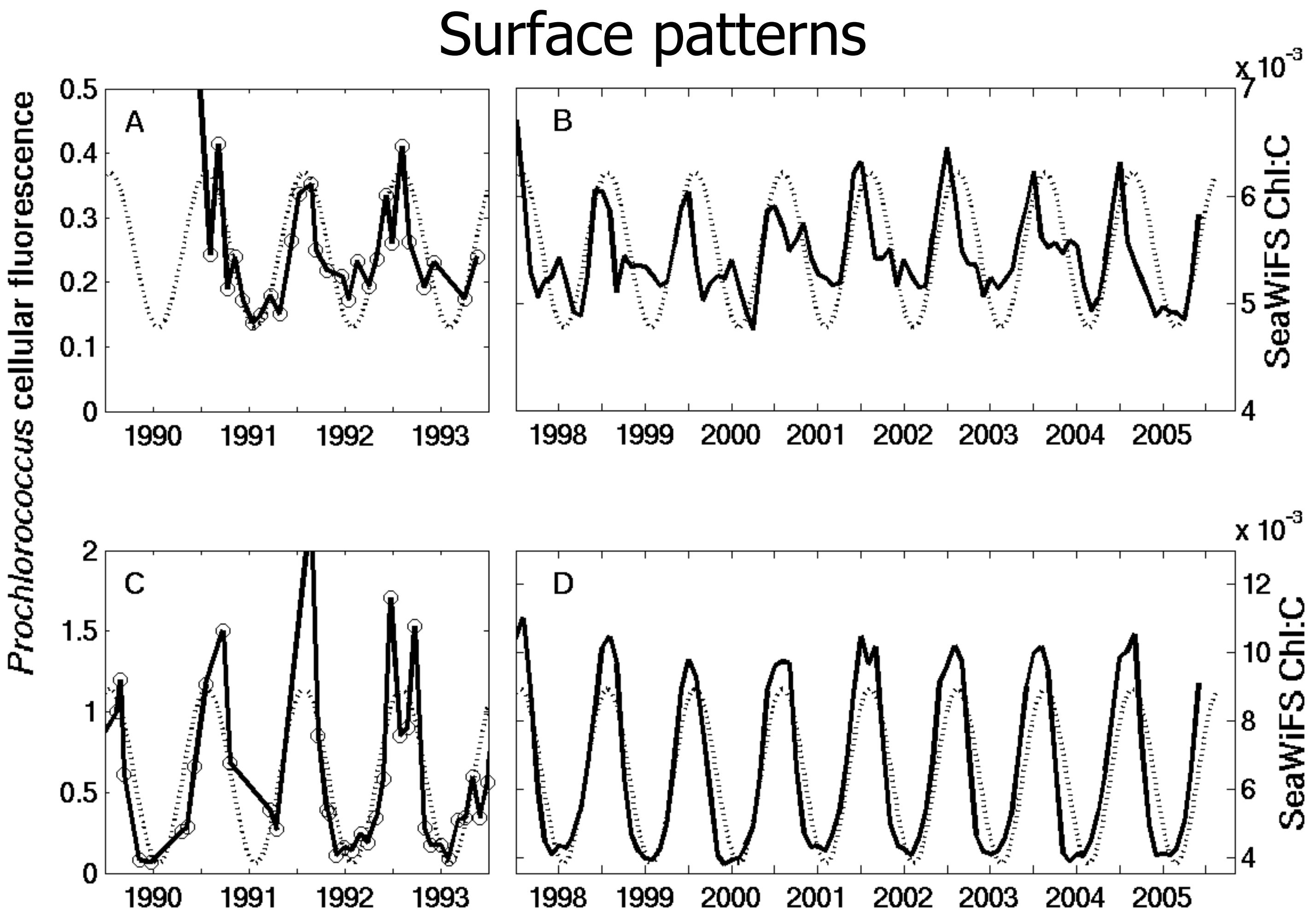


**Westberry et al., (submitted to GBC)

CbPM (1) – Results & Validation



Surface patterns

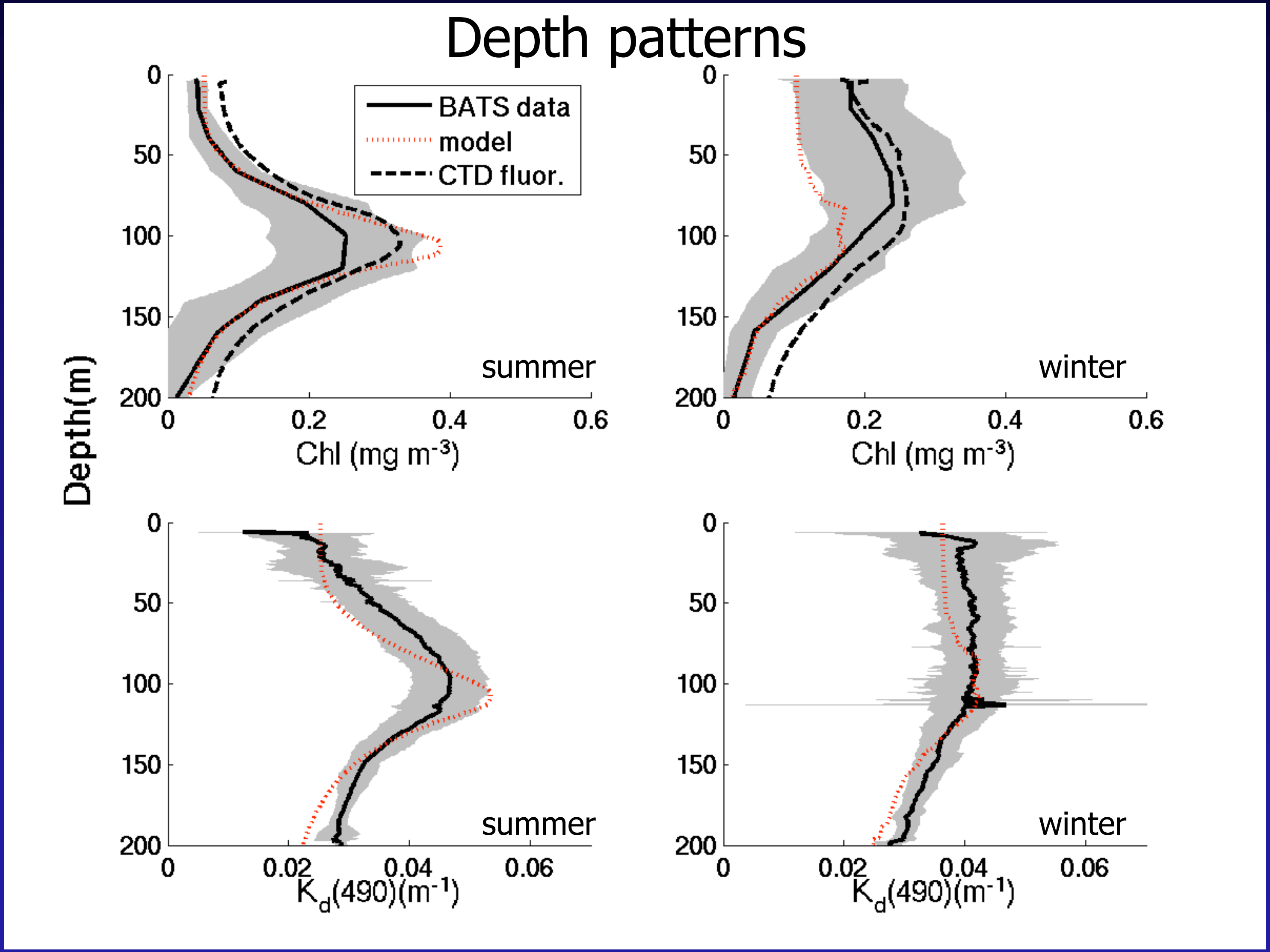
Data from Winn et al. (1995); Durand et al. (2001)

HOT

BATS

**Westberry et al., (submitted to GBC)

CbPM (2) – Results & Validation



BATS

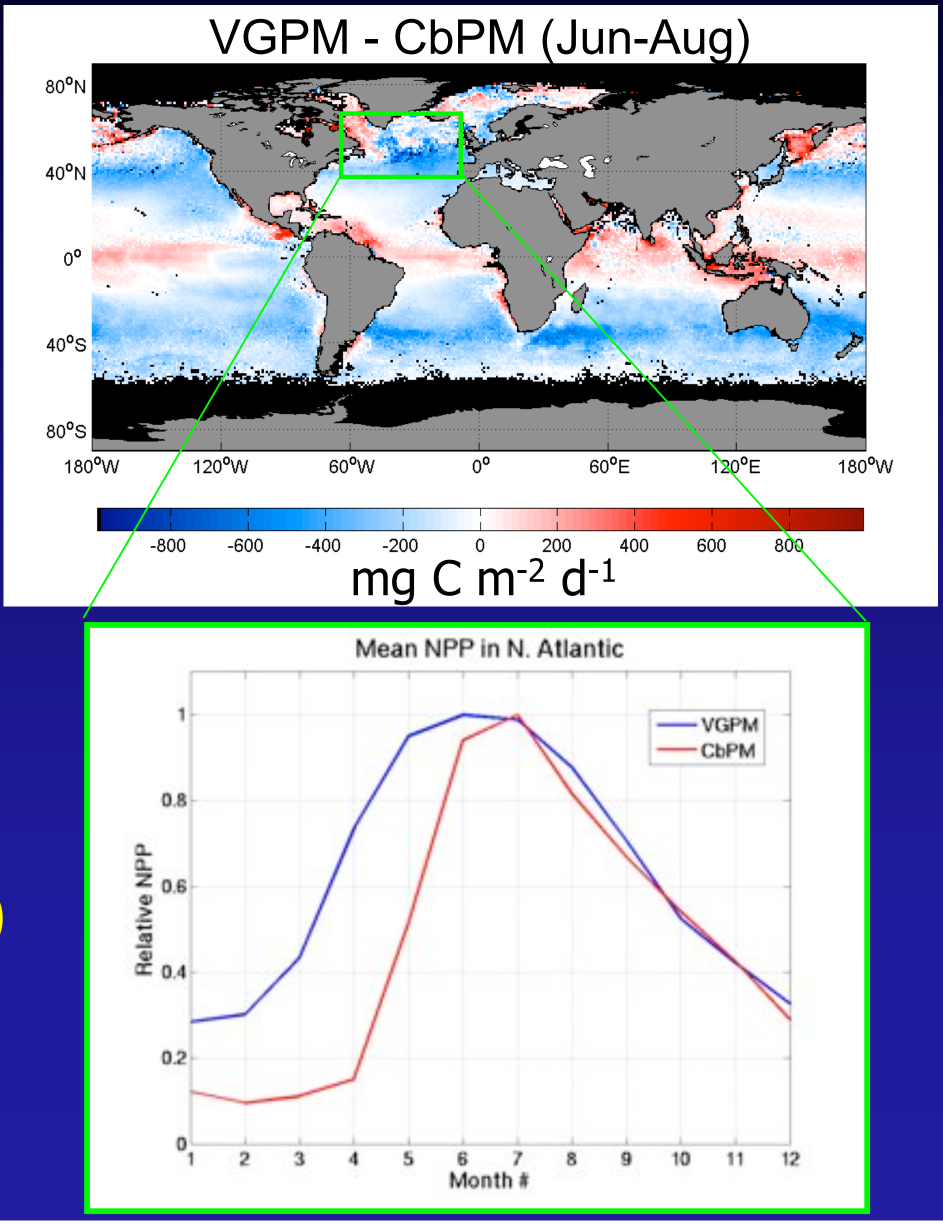
BATS

**Westberry et al., (submitted to GBC)

CbPM (3) - ∫NPP Patterns

- Both spatial AND temporal patterns of NPP are different wrt Chl-based model (VGPM, Behrenfeld and Falkowski, 1997)

- Onset and peak of blooms can be delayed (~1-2 months)



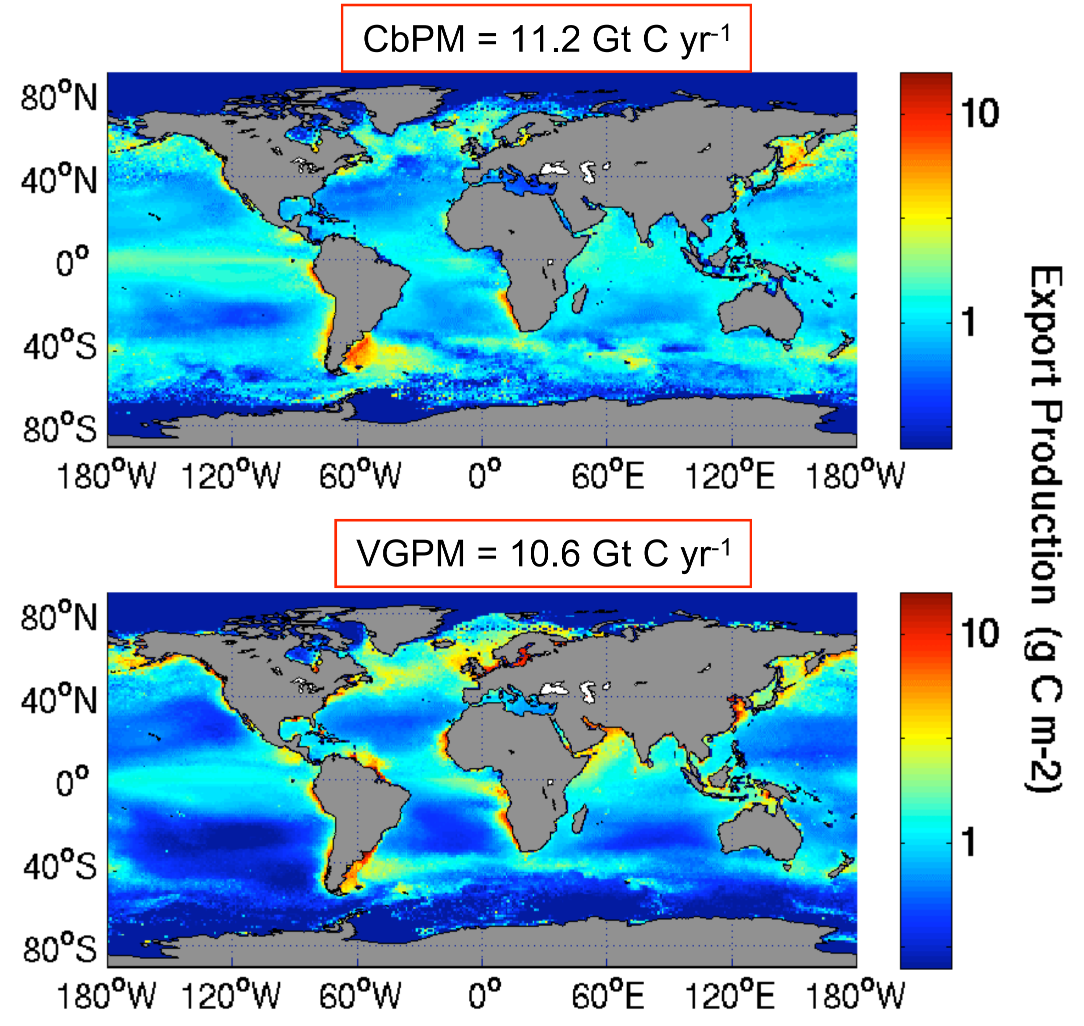
How to assess export?

1. Apply **new** CbPM patterns to existing empirical export algorithms (i.e., Laws et al., 2000; Dunne et al., 2005)

2. Use biomass (C) and growth rate (μ) in addition to NPP to construct a mass balance for phytoplankton C in the mixed layer

Export – empirical (1)

- Annual particle export predicted from Laws et al. (2000)



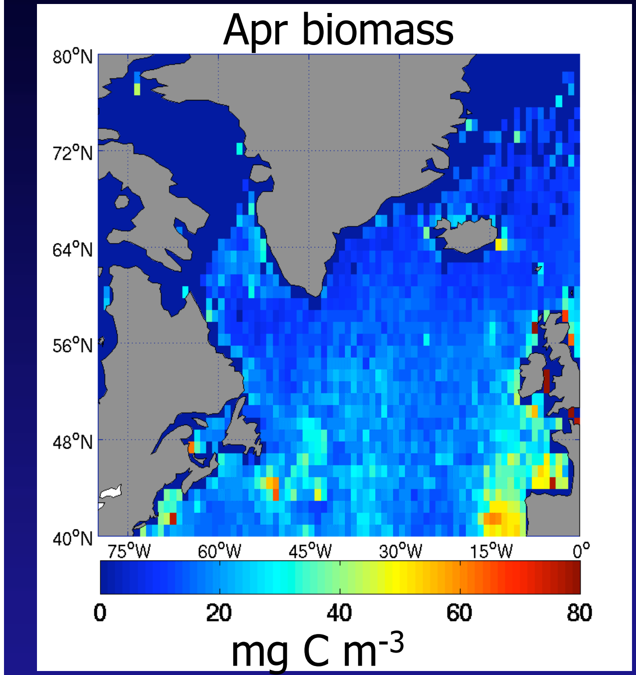
Export – empirical (2)

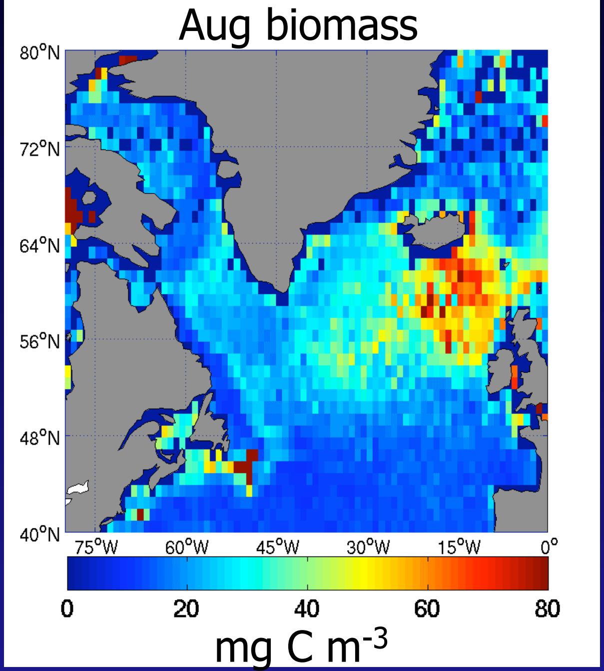
Fraction of total export

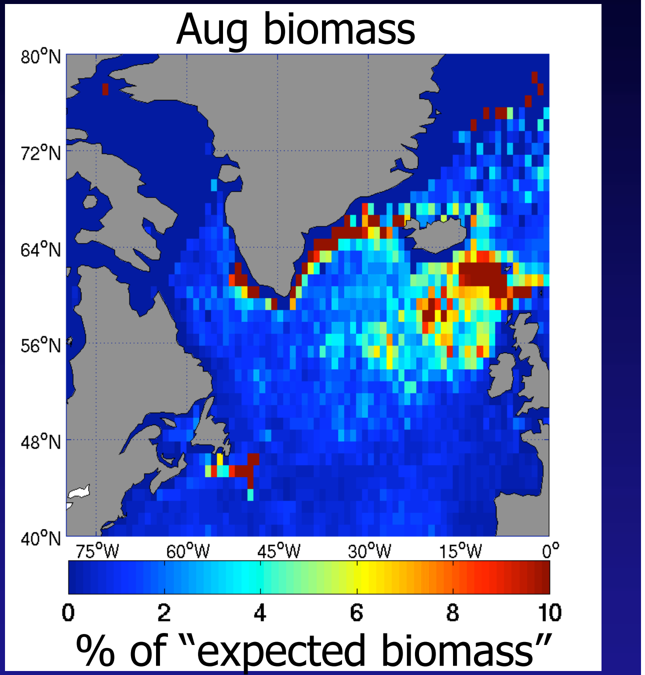
	VGPM	CBPM
> 60°N	46%	22%
30°N - 60°N	22%	19%
0° - 30°N	10%	11%
0° - 30°S	8%	12%
30°S - 60°S	6%	14%
> 60°S	8%	23%
Total (Gt C yr^{-1})	10.6	11.2

- CbPM suggests much more NPP in So. Ocean and less in N. hemisphere high latitudes and upwelling regions

NPP to Export – mechanistic (1)

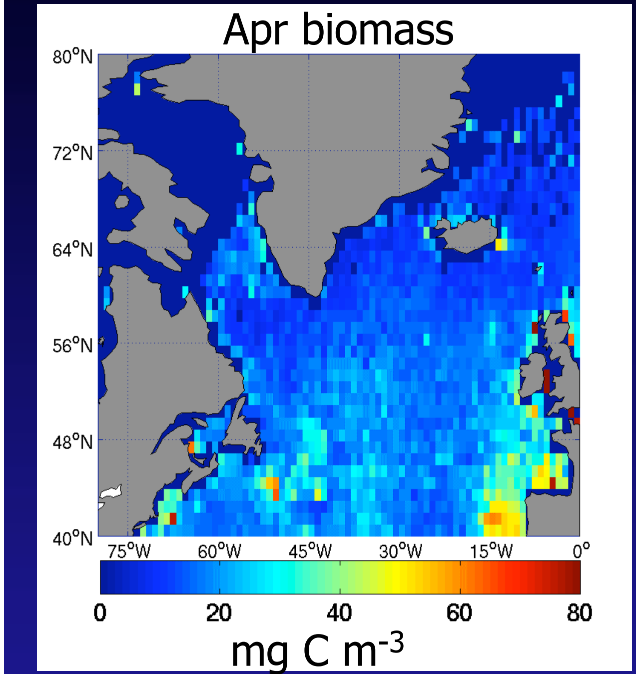

Apr biomass

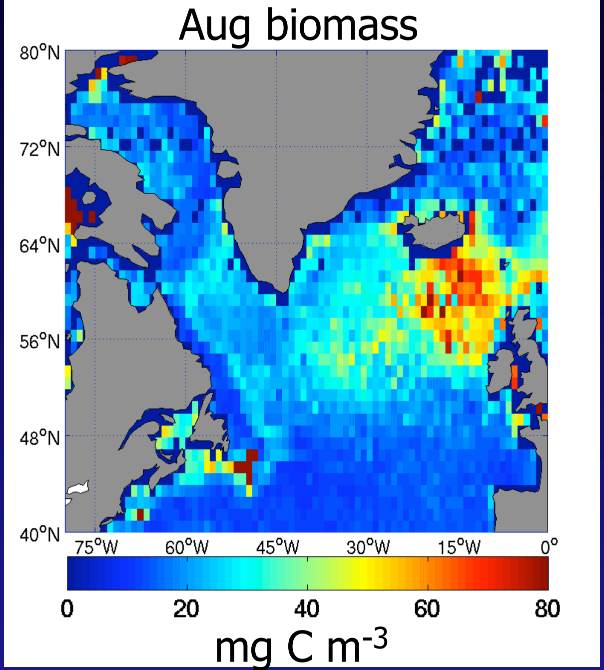

Aug biomass

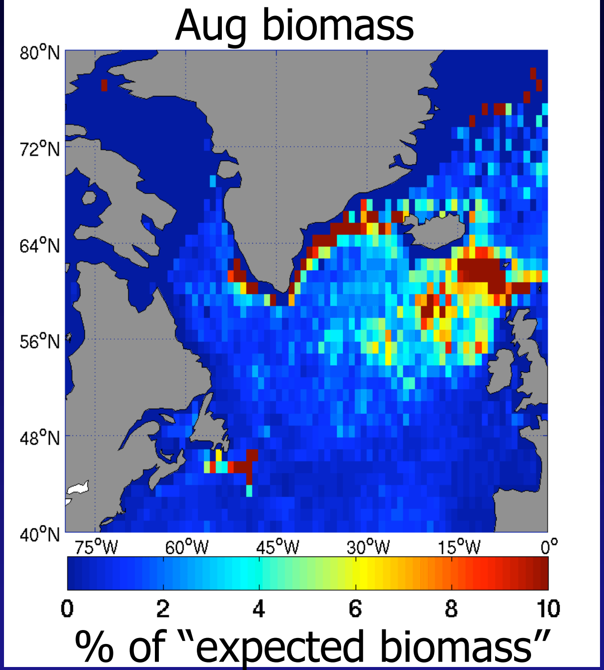

Aug biomass

$$\underbrace{\frac{dC}{dt}}_{\text{Biomass accumulation}} = \underbrace{\mu C}_{\text{NPP}} - \underbrace{[advection + dilution + export + recycling]}_{\text{Losses}}$$

NPP to Export – mechanistic (1)


Apr biomass

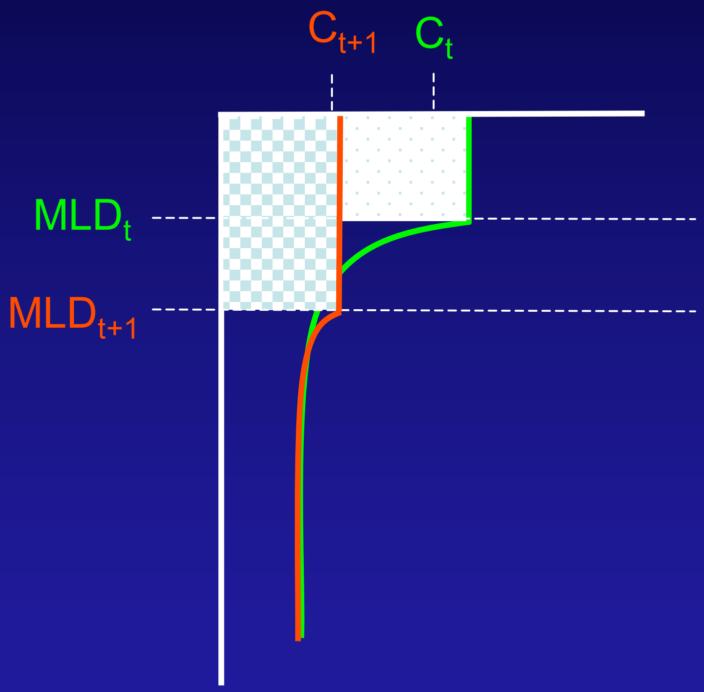

Aug biomass


Aug biomass

$$\underbrace{\frac{dC}{dt}}_{\text{Biomass accumulation}} = \underbrace{\mu C}_{\text{NPP}} - \underbrace{[\xcancel{\lambda_{adv}} + \boxed{\lambda_{dil}} + \lambda_{sink} + \lambda_{graz}]}_{\text{Losses}}$$

Export – Dilution

- Mixed layer phytoplankton C lost due to dilution



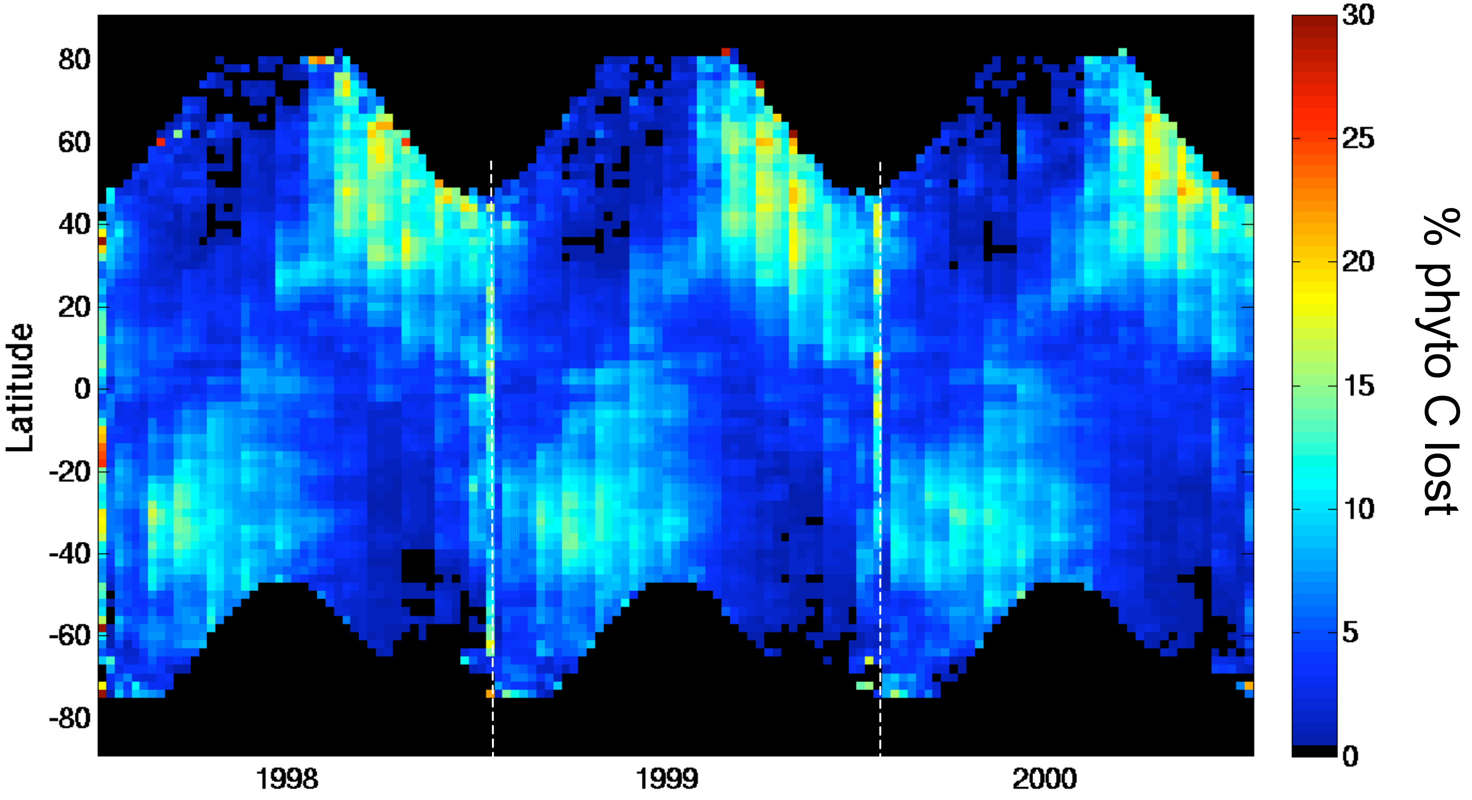
$$\lambda_{dil} = \frac{\int_0^{MLD_t} C_z \, dz}{MLD_{t+1}} \left(MLD_{t+1} - MLD_t \right)$$

$$C_t \, MLD_t = C_{t+1} \, MLD_{t+1}$$

NOTE: only valid when mixed layer deepens. No corresponding process when mixed layer shoals

Export – Dilution

- Change (%) in ML phytoplankton C due to ML deepening



Export – mechanistic (2)

$$\underbrace{\frac{dC}{dt}}_{\text{Biomass accumulation}} = \underbrace{\mu C}_{\text{NPP}} - \underbrace{[\cancel{\lambda_{adv}} + \lambda_{dil}\checkmark + \lambda_{sink} + \lambda_{graz}]}_{\text{Losses}}$$

$$\lambda_{sink} + \lambda_{graz} \propto \frac{d[nuts]}{dt}$$

- World Ocean Atlas 2005 $NO_3(z)$
- 8day SeaWiFS-derived phytoplankton C and μ (1/3°)

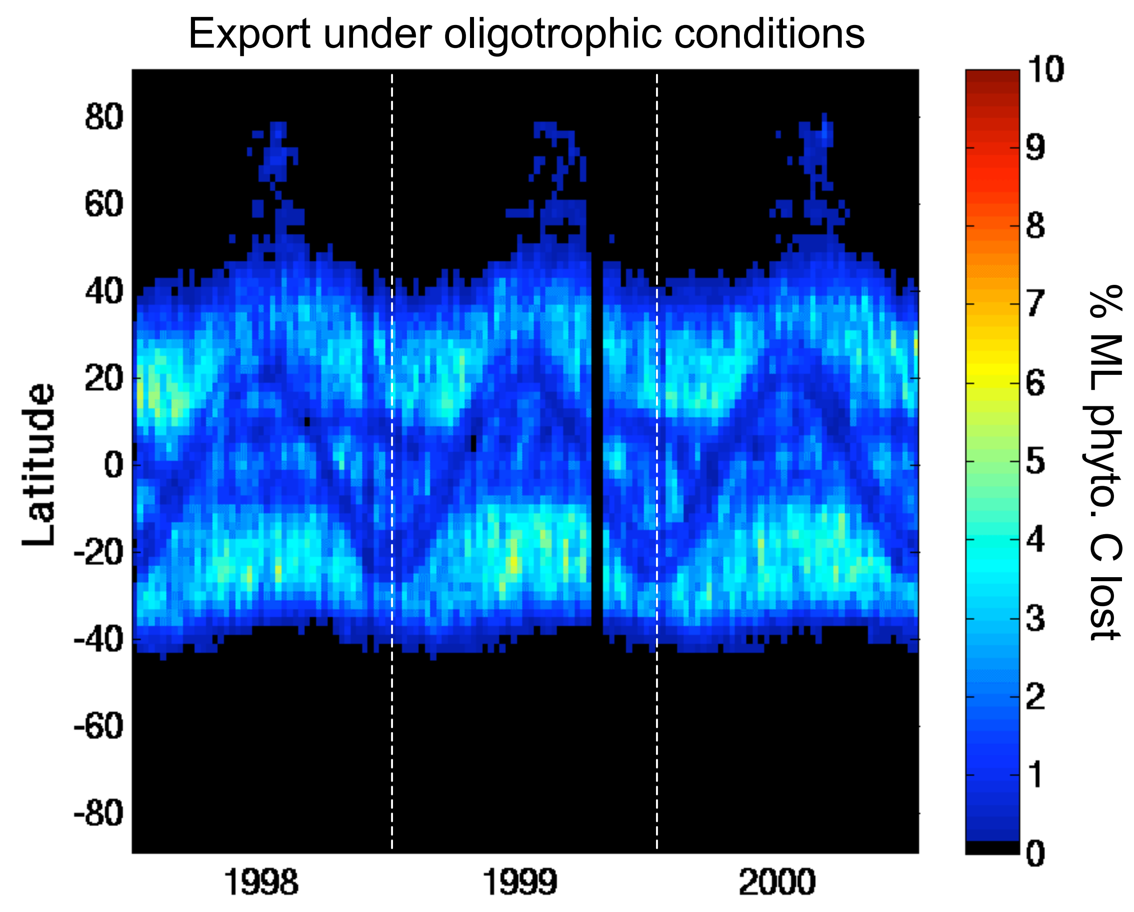
Export – mechanistic (3)

Example 1

$t_1 \longrightarrow t_2$

1. $\frac{dNO_3}{dt} = 0$
2. $\frac{d\mu}{dt} \sim 0$
3. $\frac{dC}{dt} < 0$

$$\lambda_{sink} = \frac{dC}{dt}$$


Export under oligotrophic conditions

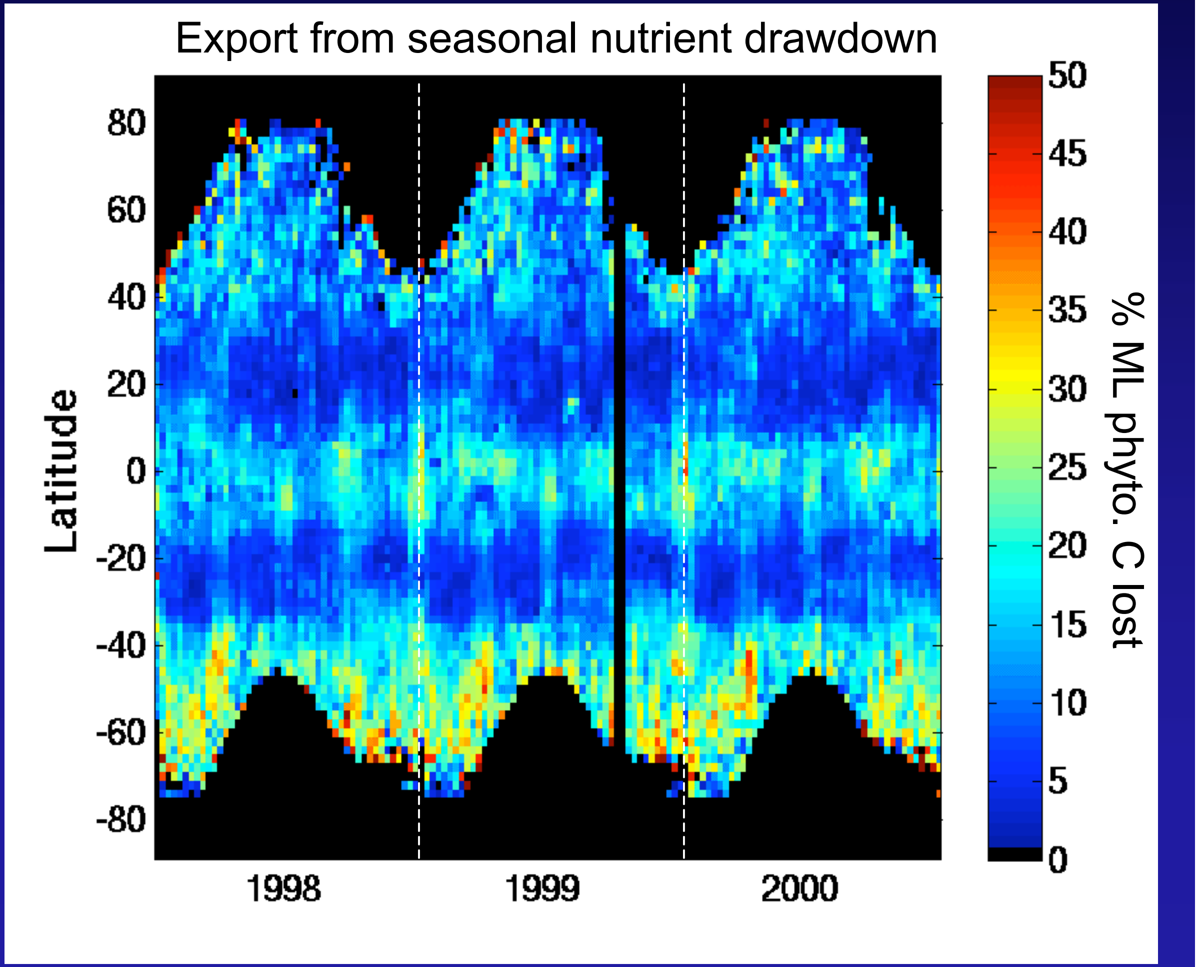
Export – mechanistic (4)

Example 2

$t_1 \longrightarrow t_2$

1. $$\frac{dNO_3}{dt} < 0$$
2. $$\frac{d\mu}{dt} \sim 0$$
3. $$\frac{dC}{dt} \leq 0$$

$$\boxed{\lambda_{sink} = \frac{dNO_3}{dt}\left(\frac{C}{N}\right)}$$



Export – mechanistic (5)

Example 3

$t_1 \longrightarrow t_2$

$$1.\quad \frac{dNO_3}{dt} < 0$$

$$2.\quad \frac{d\mu}{dt} > 0$$

$$3.\quad \frac{dC}{dt} \geq 0$$

???
Need to link dμ/dt to
nutrient drawdown
???

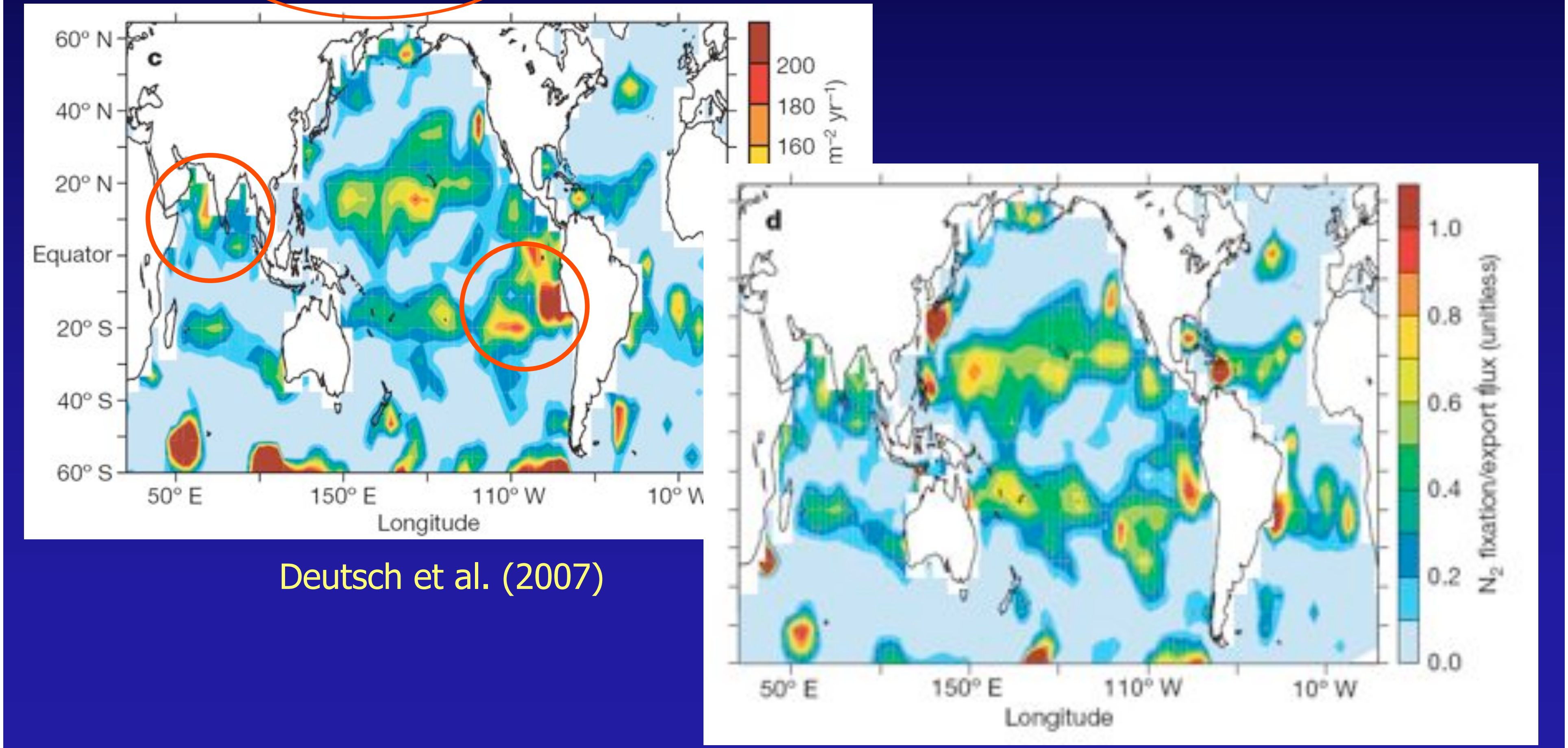
$$\lambda_{graz} = f\left(\frac{d\mu}{dt}\right) \sim f\left(\frac{dNO_3}{dt}\right)$$

$$\longleftrightarrow$$

$$\lambda_{sink} = \left(\frac{dNO_3}{dt}\right)\left(\frac{C}{N}\right) - \lambda_{graz}$$

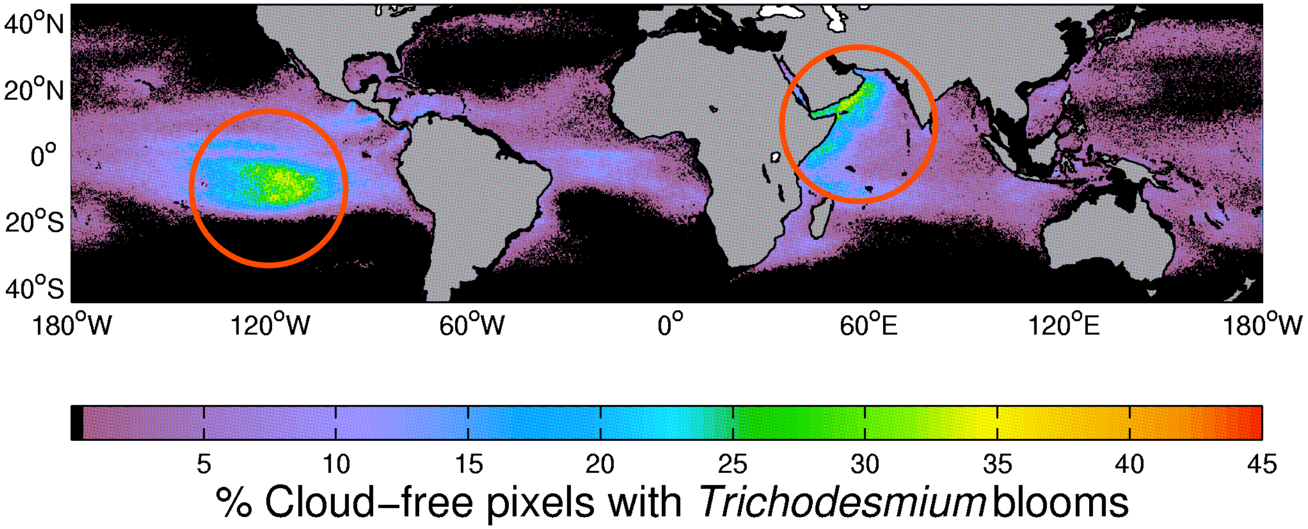
Export – N_2 fixation (1)

- What about other sources of nutrients?
  - N_2 fixation, atmospheric deposition, rivers



Deutsch et al. (2007)

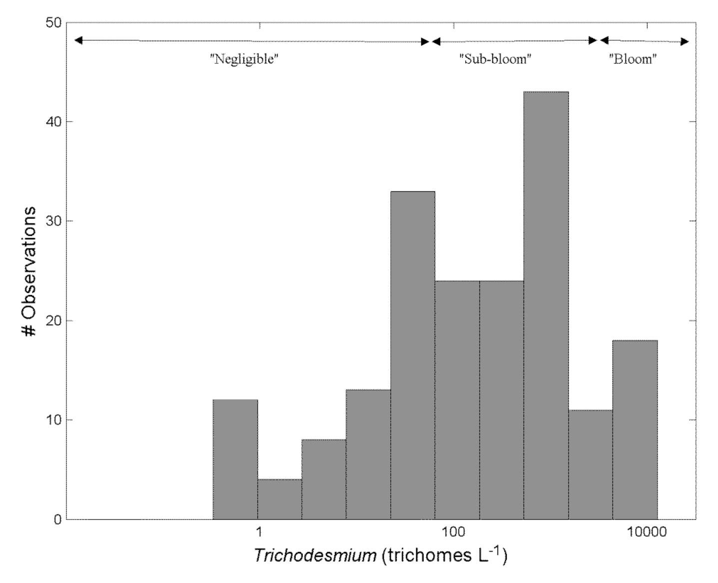
Export – N_2 fixation (2)



Westberry and Siegel (2006)

- Can apply areal rates and produce dynamic, global N_2 fixation estimates from satellite

Export – N_2 fixation (3)



Westberry and Siegel (2006)

Can add N_2 fixation from non-bloom populations also

→ 42 TgN yr^{-1} from blooms + 20 TgN yr^{-1} non-blooms

(cf, ~ 80 TgN yr^{-1}, Capone et al. (1997)
~ 110 TgN yr^{-1}, Gruber & Sarmiento (1997)
~ 140 TgN yr^{-1}, Deutsch et al. (2007))

Export – END

- CbPM provides critical pieces of information for diagnosing export from satellite (μ, C, NPP)

- Can estimate time varying fields of export from mixing and sinking (haven’t solved the whole problem yet)

- Can account for export due to N_2 fixation from satellite (thought to be significant)

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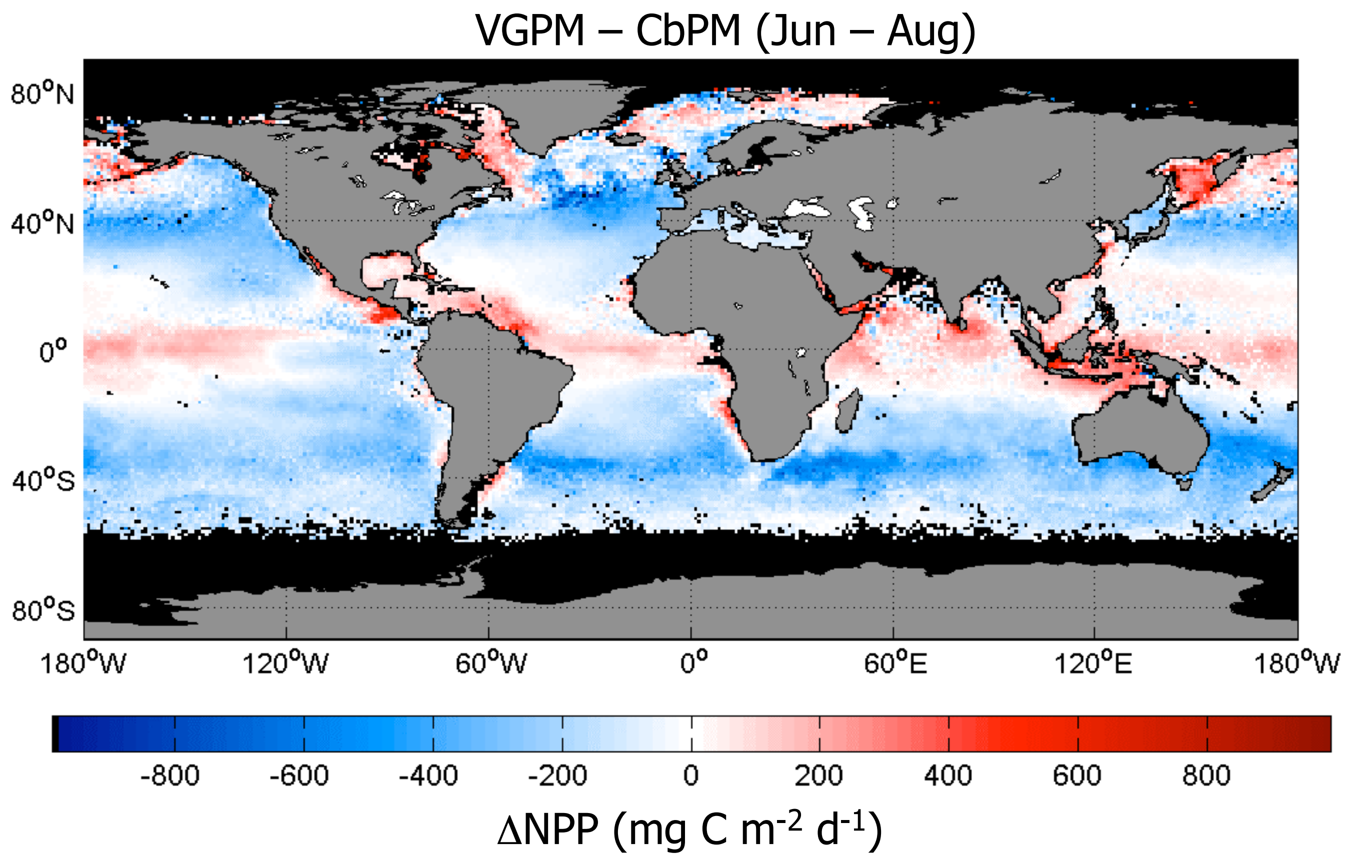
EXTRA

CbPM (5) - ∫NPP Patterns

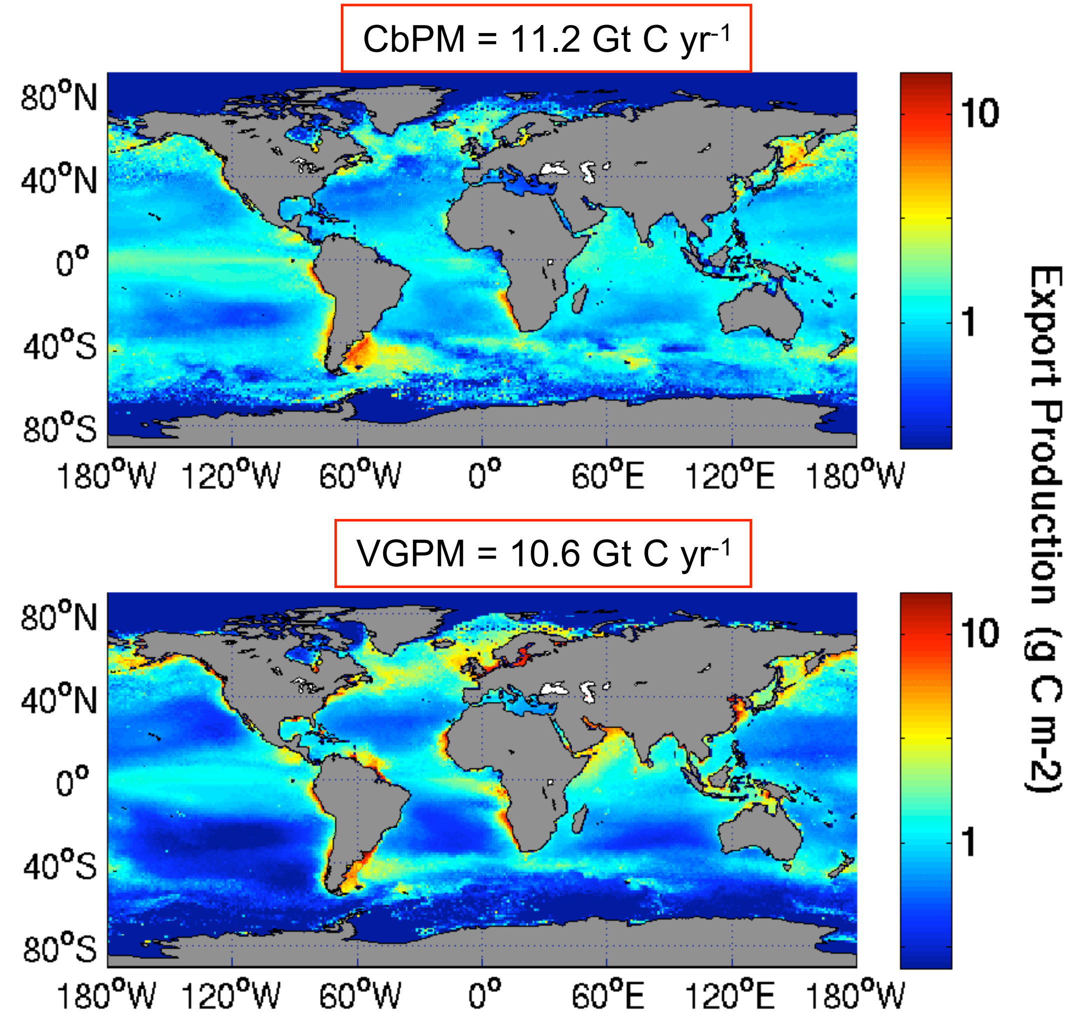
Spatial (and temporal) patterns of NPP are different compared to Chl-based model (VGPM, Behrenfeld & Falkowski, 1997)



Onset and peak of blooms can be delayed (~1-2 months)

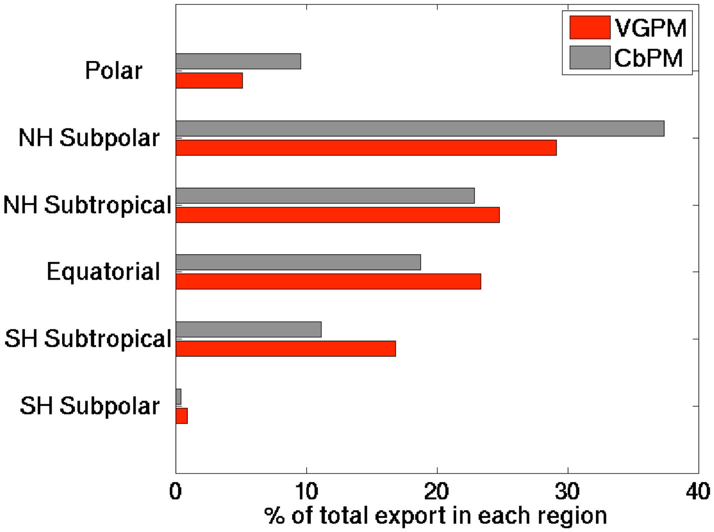
NPP to Export – empirical (1)

- Annual particle export predicted from Laws et al. (2000)



CbPM = 11.2 Gt C yr^{-1}

VGPM = 10.6 Gt C yr^{-1}



Zonal regions as in Yoder et al. (1993)

Export – empirical (2)

Total Export (Gt C yr^{-1})

	VGPM	CBPM
Oligotrophic	1.9 (18%)	3.1 (28%)
Mesotrophic	3.6 (34%)	4.4 (39%)
Eutrophic	5.1 (48%)	3.7 (33%)
Total	10.6	11.2

Fraction of total export

> 60°N	46%	22%
30°N - 60°N	22%	19%
0° - 30°N	10%	11%
0° - 30°S	8%	12%
30°S - 60°S	6%	14%
> 60°S	8%	23%

NPP to Export – mechanistic (2)

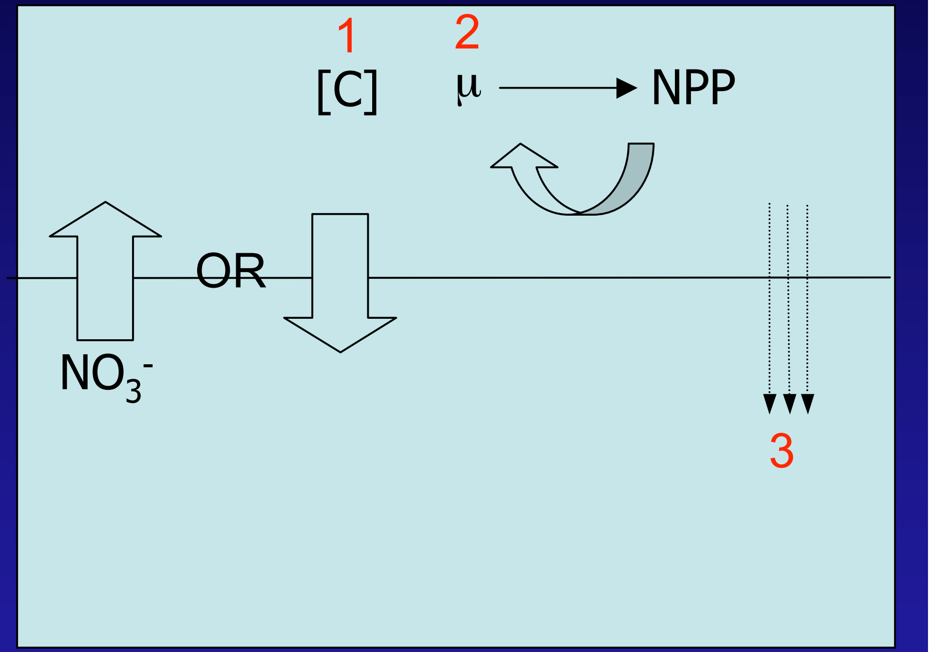
Considerations

1. Are there nutrients IN the mixed layer?

2. Were nutrients entrained into the mixed layer? Drawn down?

4. Was there an increase in biomass? Decrease?

5. Was there an increase in growth rate? Decrease?



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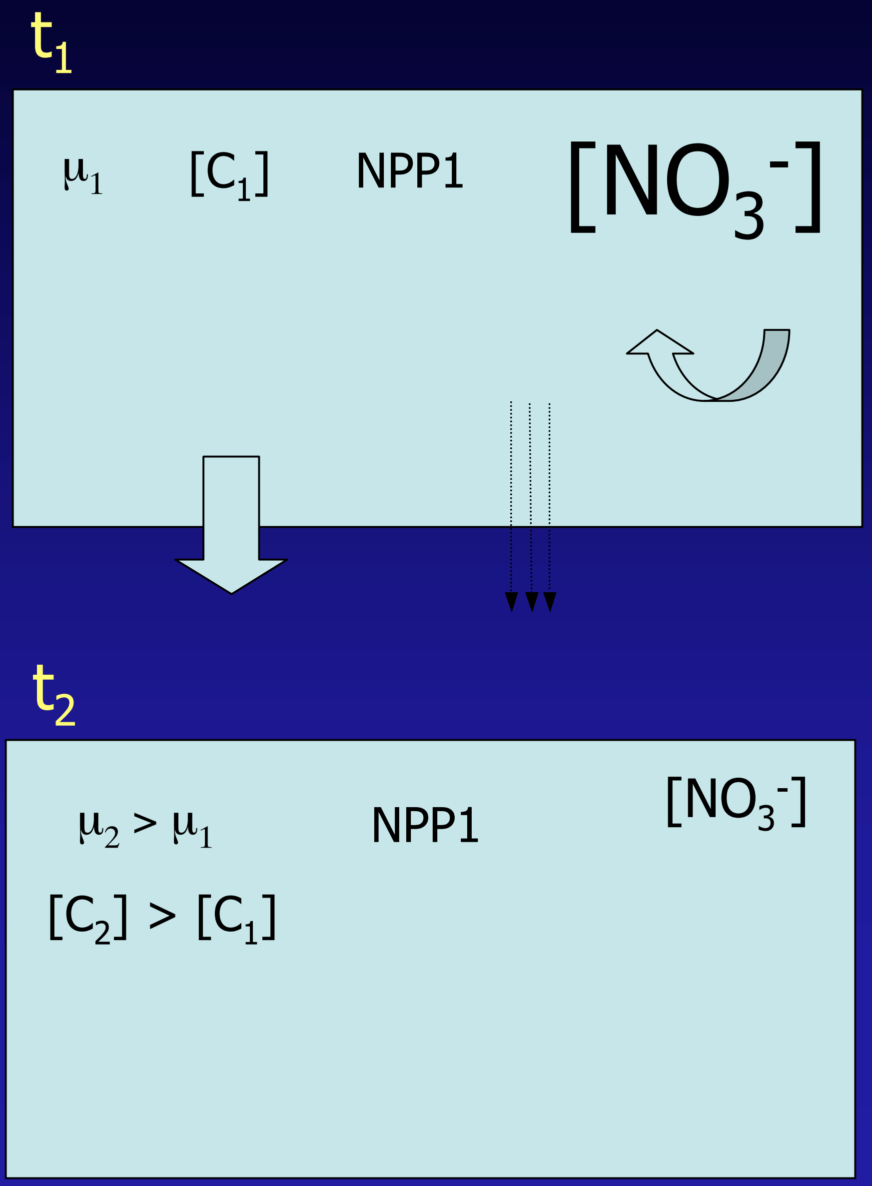

t_1

μ_1 $[C_1]$ NPP1 $[NO_3^-]$

t_2

$\mu_2 > \mu_1$ NPP1 $[NO_3^-]$

$[C_2] > [C_1]$