Universidade Vigo

Regional variability in nutrient supply and the synthesis and remineralization of organic matter in the oligotrophic ocean

PhD thesis
October 9, 2015

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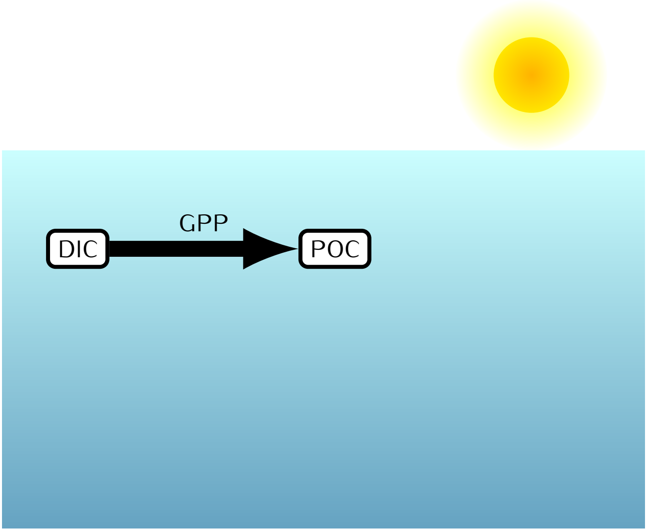
Emilio Marañón Sainz

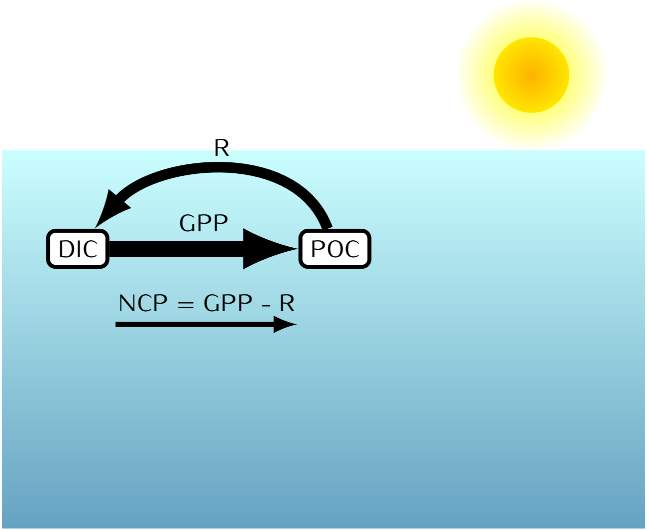
Background

The biological carbon pump



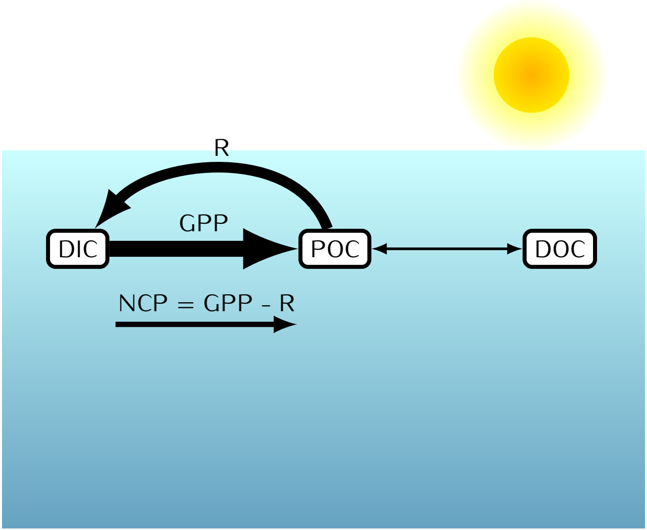
GPP: Gross primary production

The biological carbon pump



NCP: Net community production

The biological carbon pump



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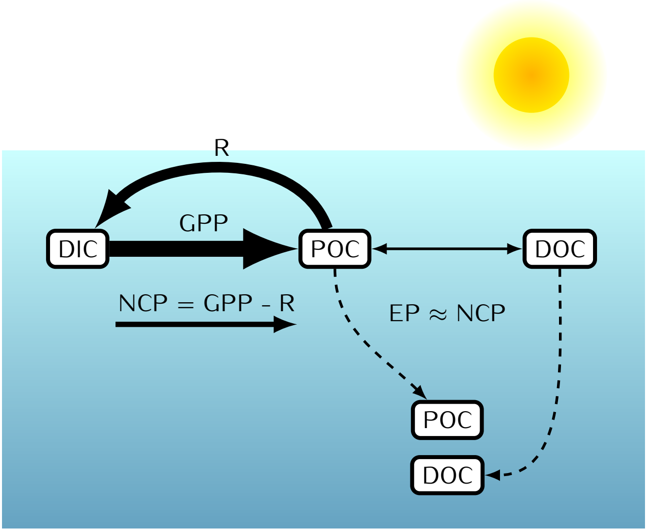
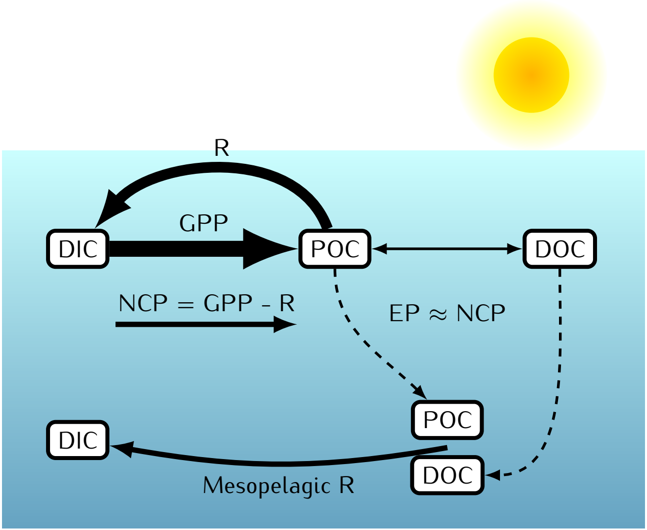


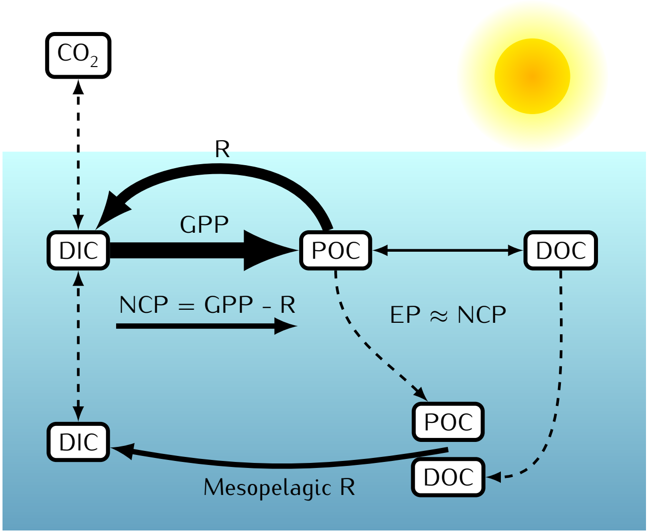
EP: Export production

The biological carbon pump



Mesopelagic respiration

The biological carbon pump



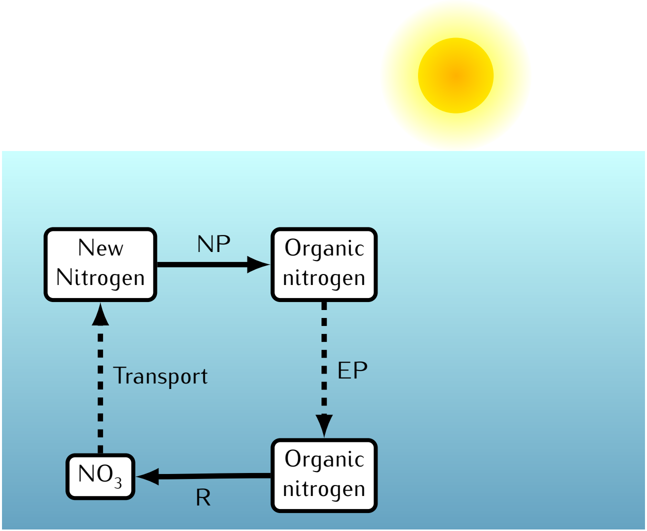
Atmospheric CO_2 exchange

Redfield Ratios

$$106\,CO_2 + 16\,HNO_3 + H_3PO_4 + 78\,H_2O \rightleftharpoons (C_{106}H_{175}O_{42}N_{16}P) + 150\,O_2$$

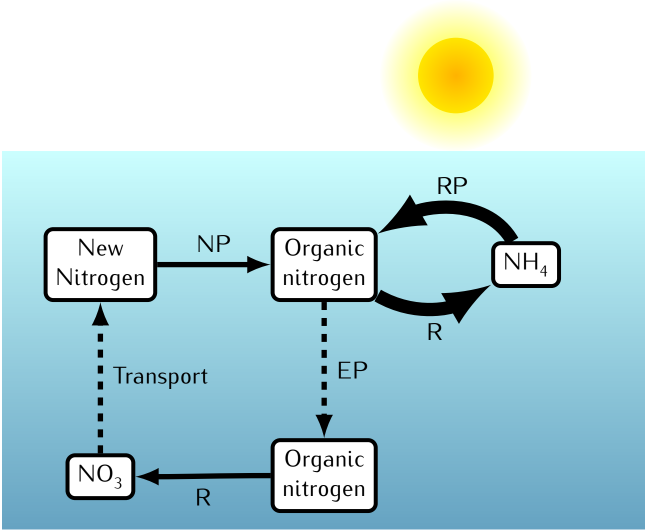
$-O_2$:C	=	1.41
C:N	=	6.6
N:P	=	16

The biological carbon pump



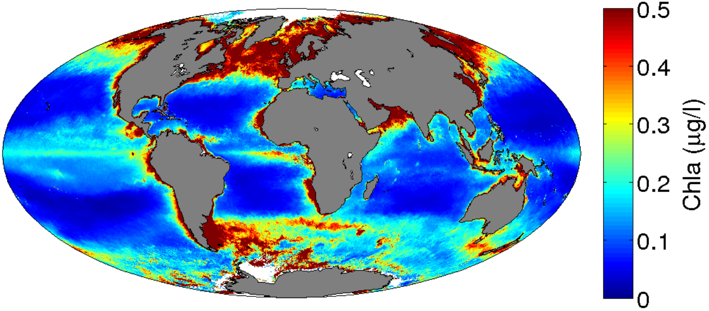
NP: new production

The biological carbon pump



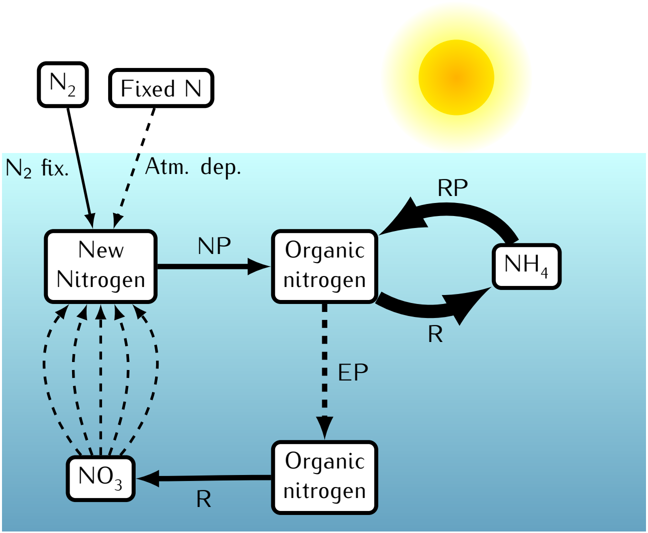
RP: regenerated production

The oligotrophic ocean



- Subtropical gyres
- Low nutrient, low chlorophyll, low biomass
- Occupy 60% of the ocean surface
- Responsible for ≈ 30% of marine carbon export (Emerson et al., 1997)
- Dynamic and heterogeneous

New nutrient supply in the oligotrophic ocean



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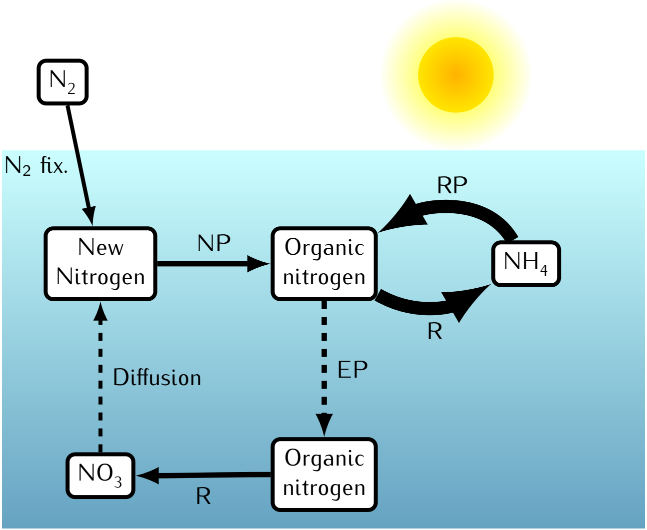

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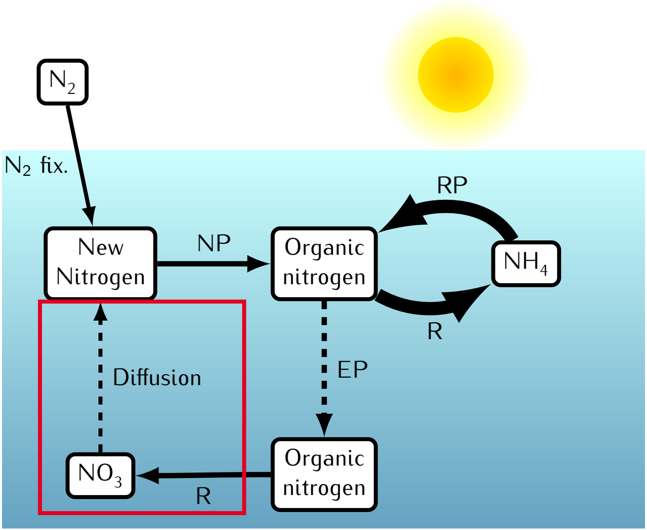
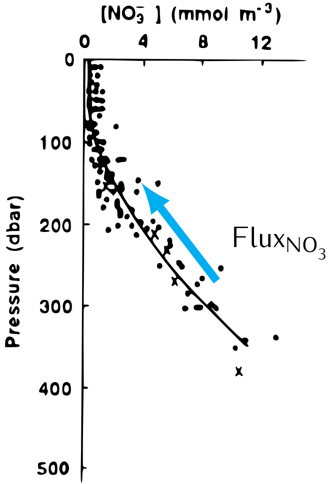




(Lewis et al., 1986)

NO_3 turbulent diffusion

$$Flux_{NO_3} = -K \frac{\partial [NO_3]}{\partial z}$$

K : turbulent diffusivity

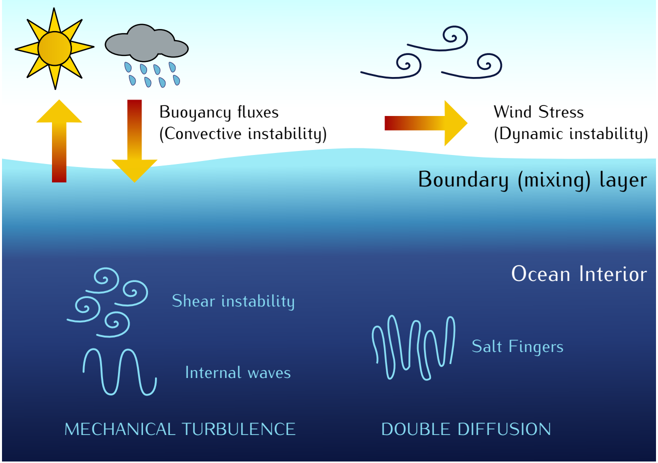
NO_3 turbulent diffusion

$$\mathrm{Flux}_{NO_3} = -K \frac{\partial [NO_3]}{\partial z}$$

K : turbulent diffusivity

- Determined by microstructure measurements or empirical parameterizations
- Driven by different processes

Turbulence-generating mechanisms



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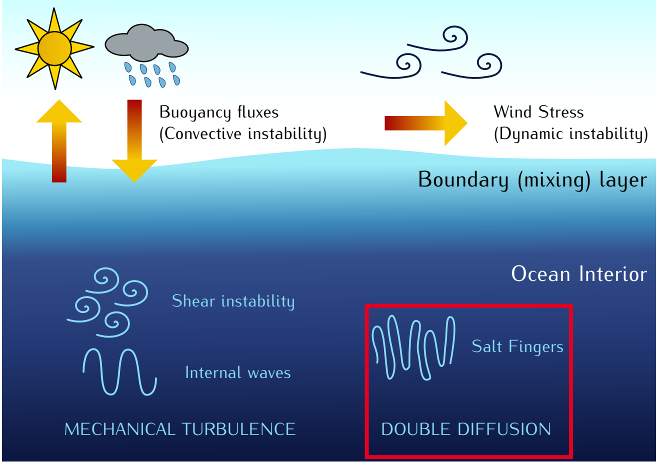
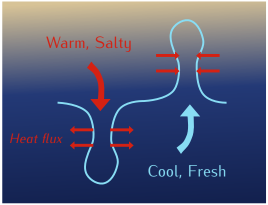
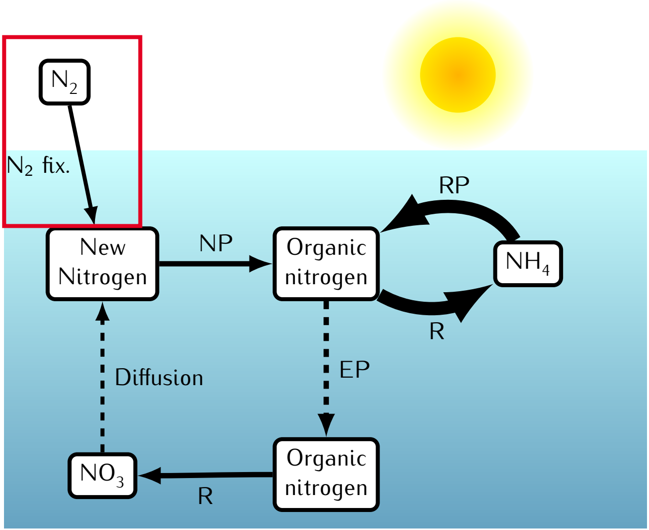


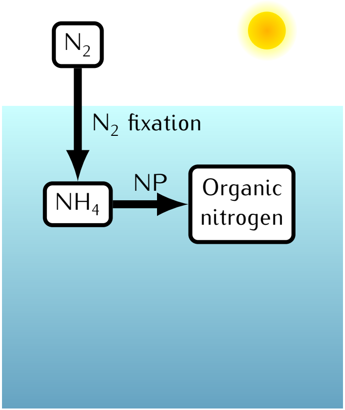
Salt fingers diffusion



- Common in subtropical oceans
- More efficient mixing than mechanical turbulence
- Theoretical models and parameterizations predict a 6-fold increase in nitrate fluxes (Hamilton et al., 1989, Dietze et al., 2004)

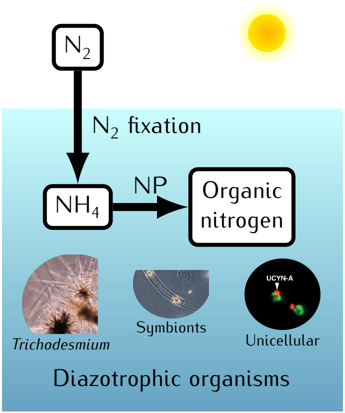
New nutrient supply in the oligotrophic ocean





N_2 fixation

- Transformation of N_2 into bioavailable nitrogen, and biomass



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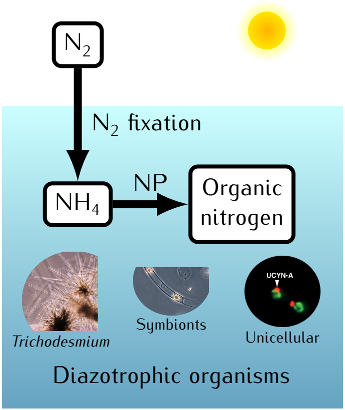
- Transformation of N_2 into bioavailable nitrogen, and biomass
- Carried out by a restricted group of (cyano)bacteria

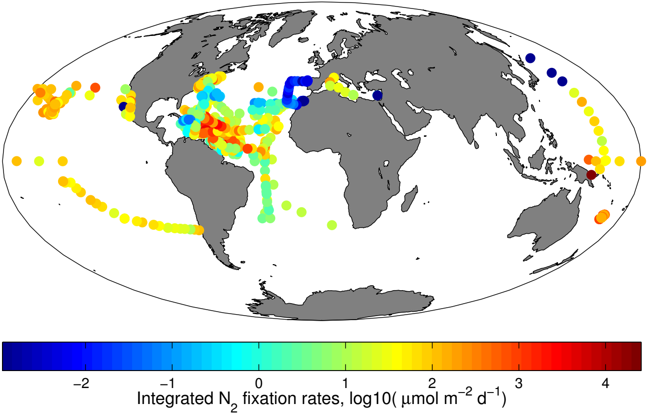


N_2 fixation

- Transformation of N_2 into bioavailable nitrogen, and biomass
- Carried out by a restricted group of (cyano)bacteria
- Controls: temperature, phosphorus (P), N:P, iron(Fe), . . .

New nitrogen supply in the oligotrophic ocean

N_2 fixation vs. NO_3 diffusion



(Luo et al., 2012)

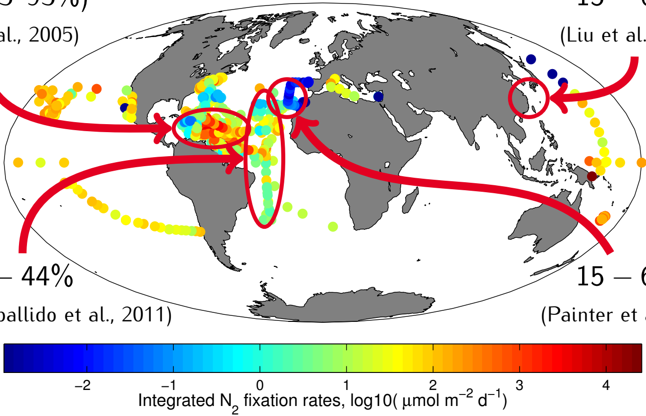
N_2 fixation vs. NO_3 diffusion

$\sim$ 50% (13–95%)
(Capone et al., 2005)

15 – 60%
(Liu et al., 2013)

2 – 44%
(Mouriño-Carballido et al., 2011)

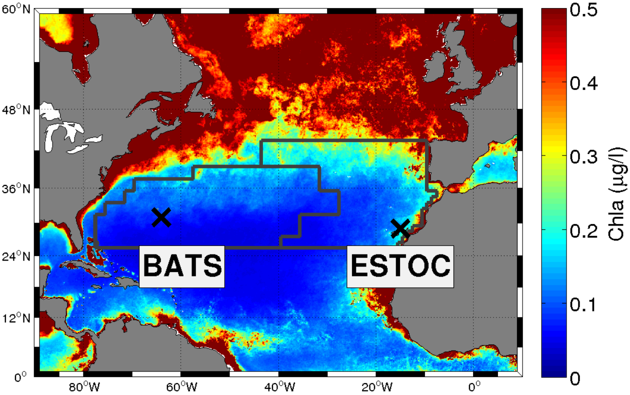
15 – 60%
(Painter et al., 2013)



(Luo et al., 2012)

These studies overlooked the contribution of salt fingers

Hetereogeneity of the oligotrophic ocean



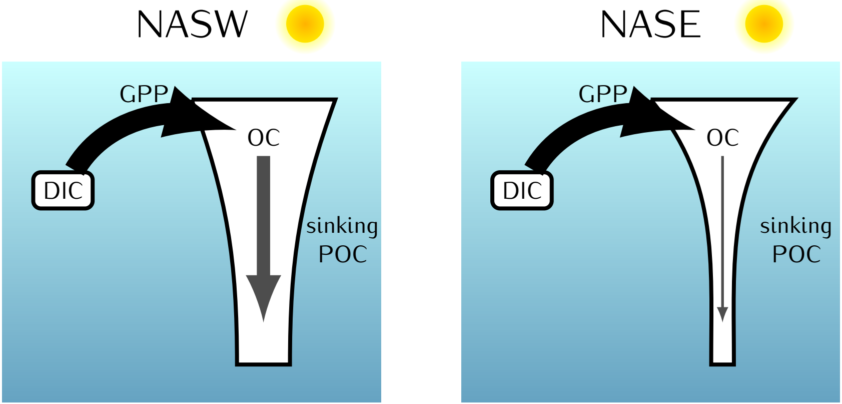
BATS (NASW)

(Bermuda Time-series Study)

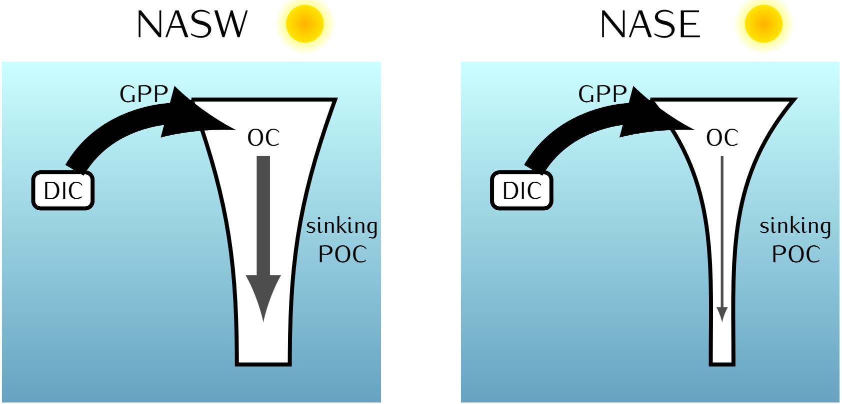
ESTOC (NASE)

(European Station for Time series in the Ocean, Canary Islands)

Hetereogeneity of the oligotrophic ocean

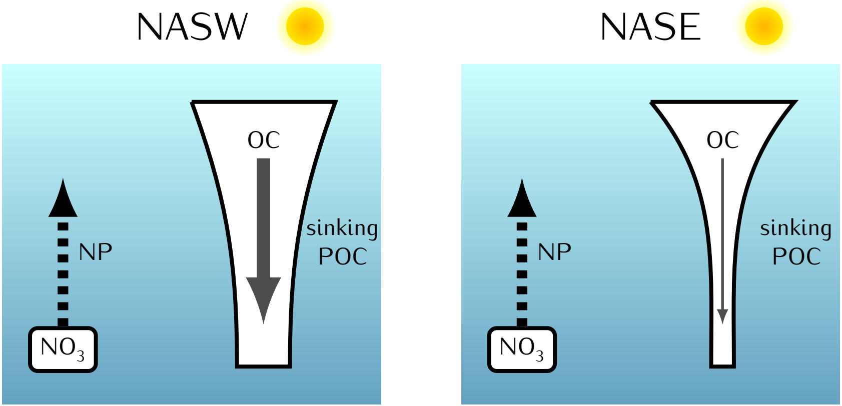


Despite similar biomass and primary productivity, export of organic matter is 3–4–fold higher at NASW (Neuer et al., 2002, Helmke et al., 2010)



WHY?

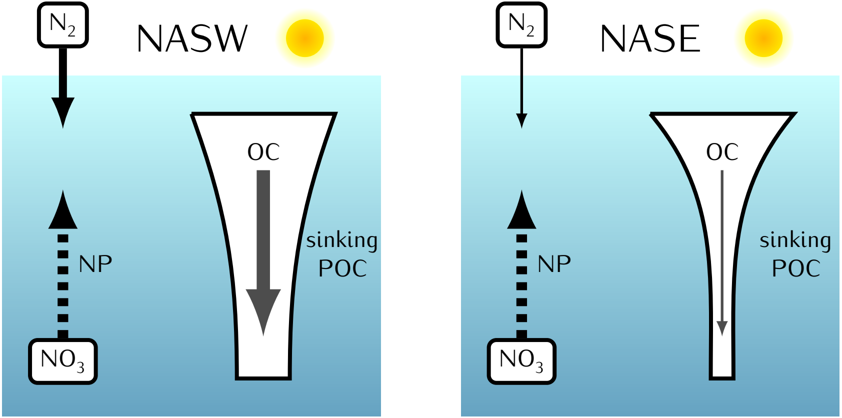
Why?



NITRATE SUPPLY?

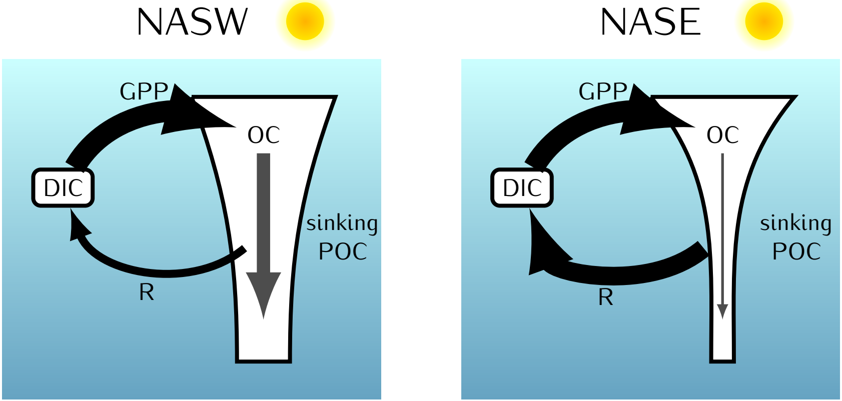
NASE receives ~75% of the nitrate at NASW (Cianca et al., 2007)

Why?



N_2 FIXATION?

Why?



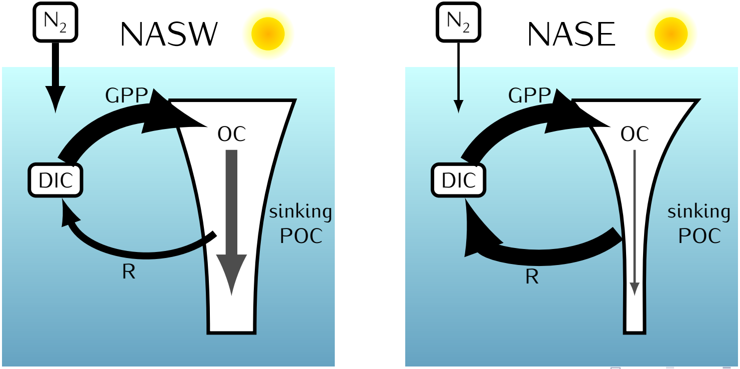
RESPIRATION?

Hypothesis and objectives

Hypothesis

Hypothesis I

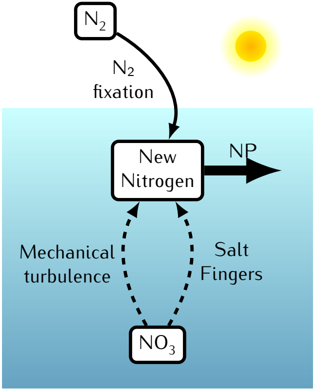
Differences in remineralization and N_2 fixation explain the dissimilarities in the fluxes of sinking organic carbon reported between NASW and NASE



Hypothesis

Hypothesis II

Nitrate diffusion mediated by salt fingers represents a significant source of new nitrogen in large areas of the oligotrophic ocean



Objectives

Objectives

- To compute NCP and shallow (100–250 m) remineralization at BATS and ESTOC
- To compute mesopelagic (150–700 m) respiration at ESTOC
- To investigate the role of N_2 fixation and its interactions with atmospheric N deposition and preferential P remineralization in NASW and NASE
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Results

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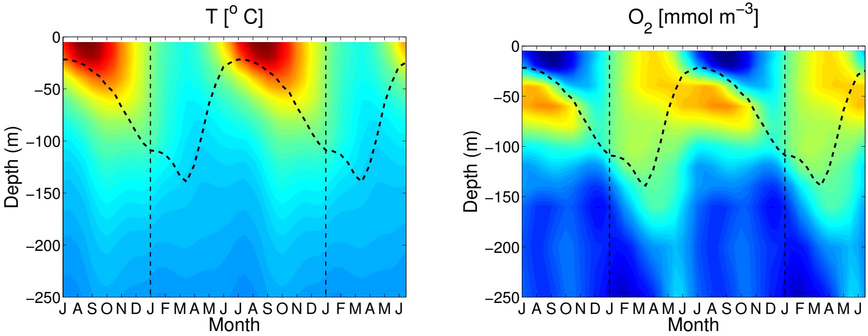
How? A tracer conservation model

BATS



How? A tracer conservation model

$$C = T, O_2, \text{DIC}, NO_3$$

$$\frac{\partial C}{\partial t} = \boxed{\underbrace{-u\frac{\partial C}{\partial x} - v\frac{\partial C}{\partial y}}_{\text{Lateral Advection}} \underbrace{-w\frac{\partial C}{\partial z}}_{\text{V. Ekman advection}} \underbrace{+\frac{\partial}{\partial z}\left(K\frac{\partial C}{\partial z}\right)}_{\text{V. Diffusion}}} \underbrace{+J_c}_{\text{Sources-Sinks}}$$

Main physical procesess simulated on seasonal scales

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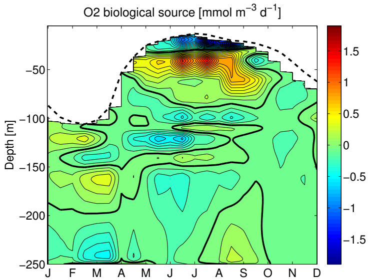
Main physical procesess simulated on seasonal scales

Biological rates (J_C) computed diagnostically from seasonal cycles of biological tracers ($\partial C/\partial t$) (MLD–250 m).

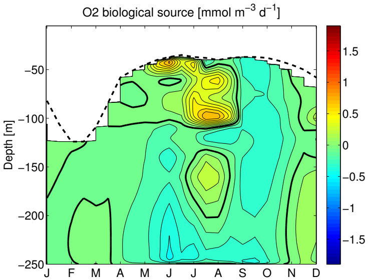
J_C = Seasonal Change – Physical transport

Biological source term, J_C: oxygen

BATS



ESTOC



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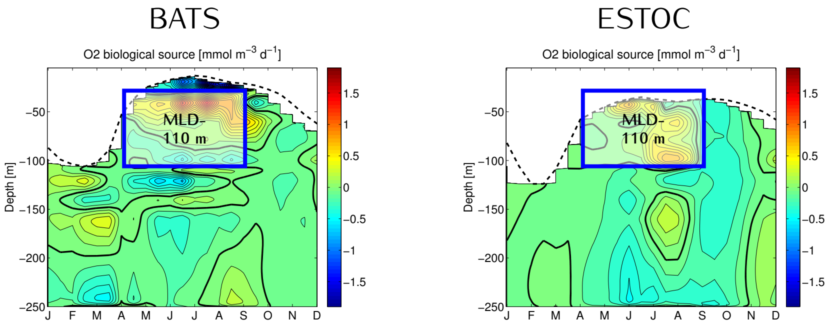

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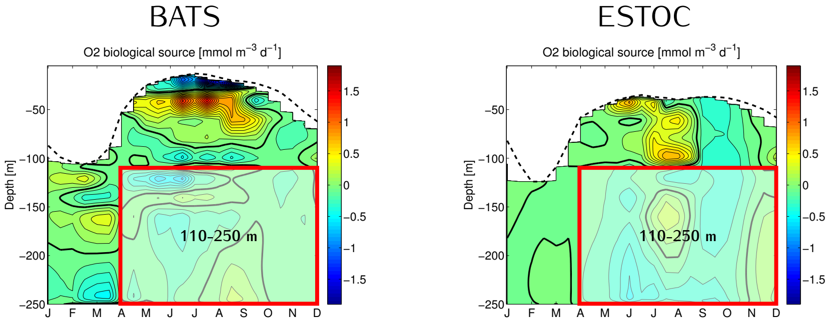
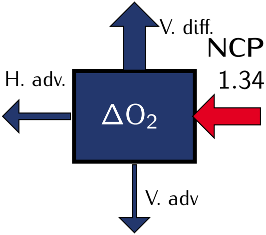


Net community production (NCP) rates (mol m^{-2})

BATS



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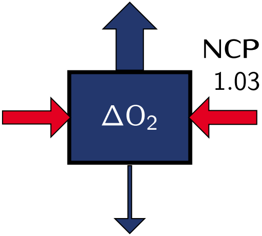

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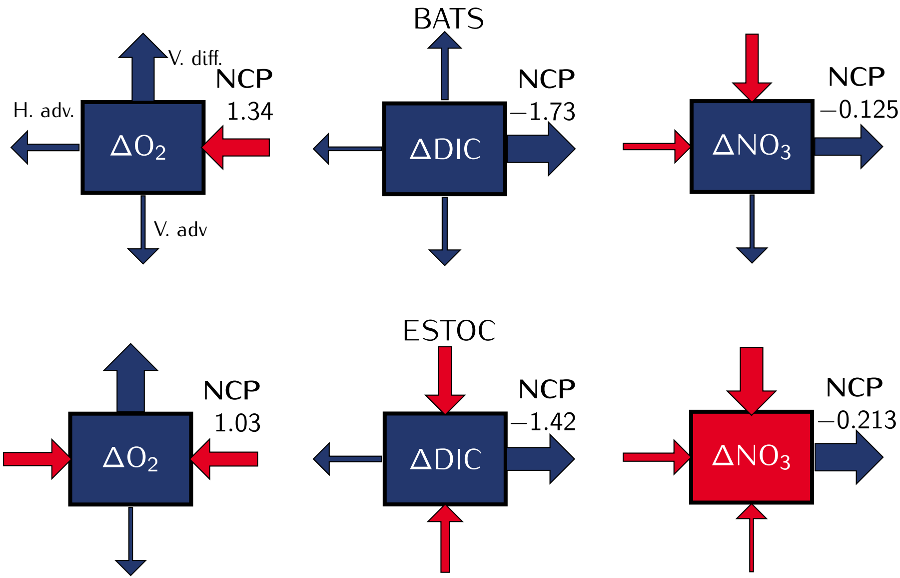
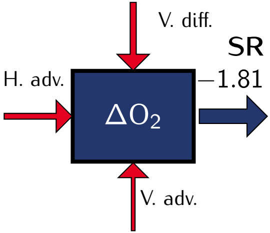
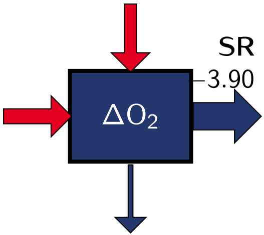


Shallow remineralization (SR) rates (mol m^{-2})

BATS



ESTOC



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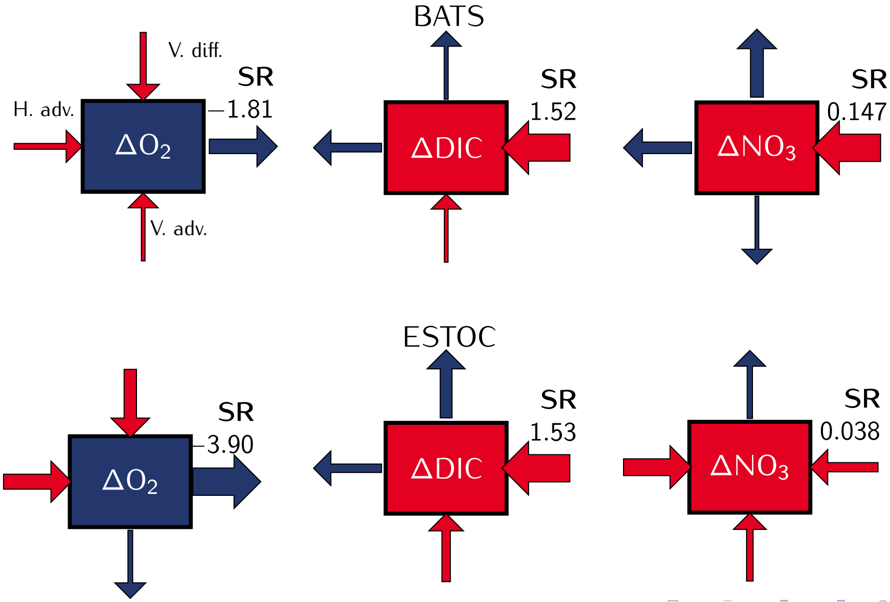

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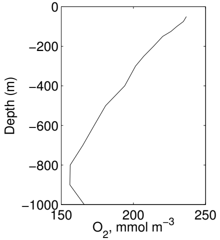
Different approach due to weak seasonal variations in the mesopelagic (Cianca et al., 2013):

- Annually averaged tracers profiles (WOA09)
- Annually averaged physics
- Steady state assumption

Biological source term, J_C: oxygen

WOA09 initial profile



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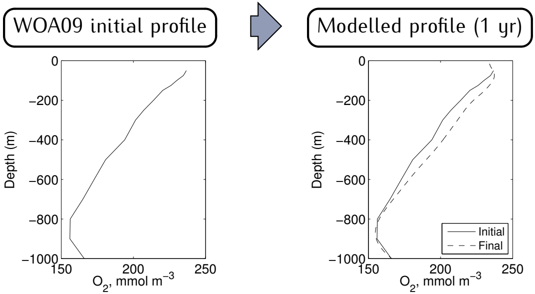
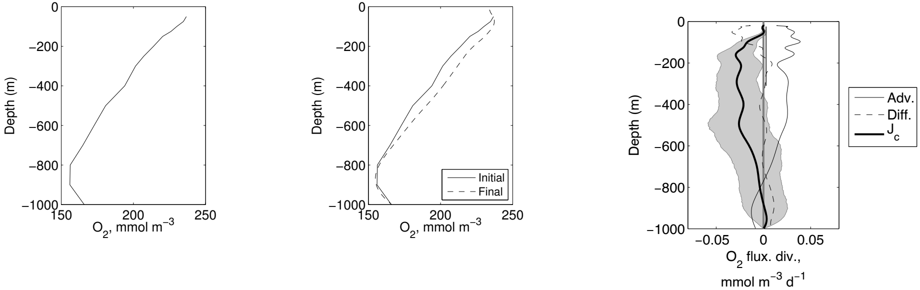


Biological source term, J_C: oxygen

WOA09 initial profile → Modelled profile (1 yr) → $J_C(z) = -\frac{C_{obs}(z) - C_{mod}(z)}{365\ \mathrm{d}}$



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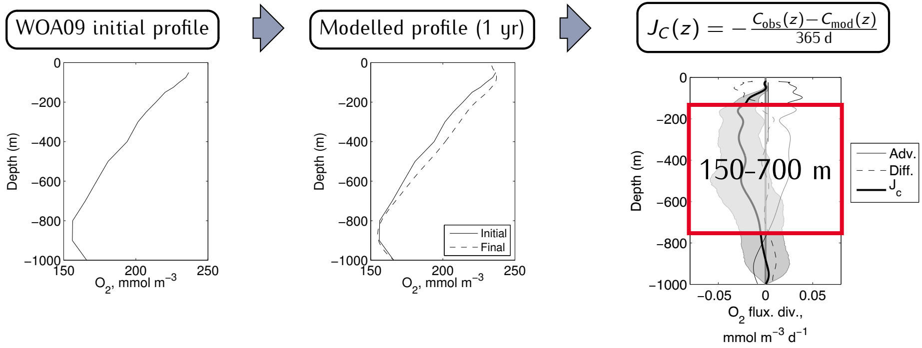
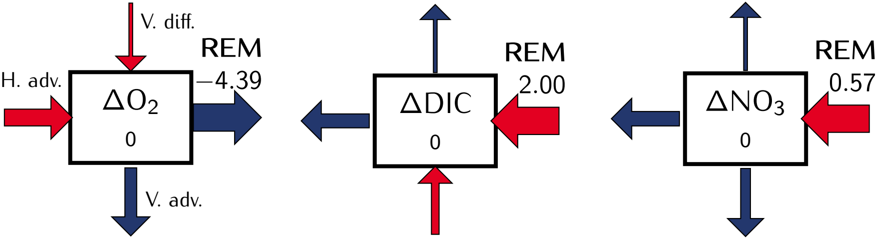
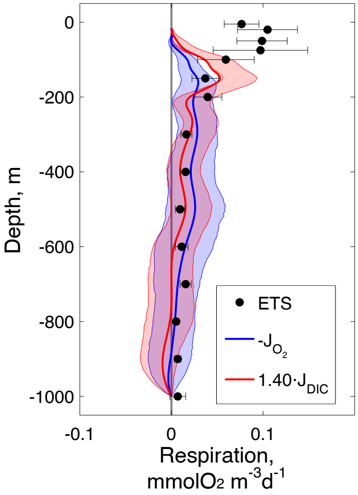


Mesopelagic respiration (MR) rates $(\text{mol m}^{-2}\,\text{y}^{-1})$



Model vs. observations



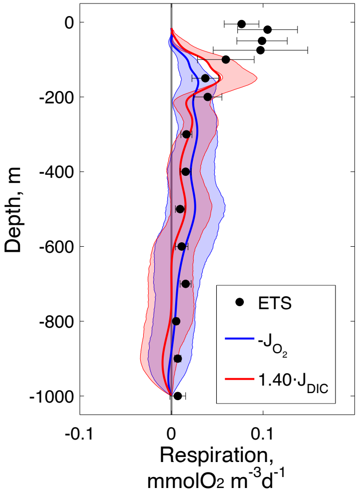
Model:

$4.39\ \text{molO}_2\ \text{m}^{-2}\ \text{y}^{-1}$

ETS:

$3.61\ \text{molO}_2\ \text{m}^{-2}\ \text{y}^{-1}$

Model vs. observations

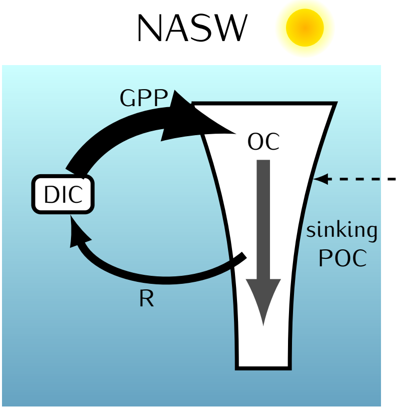


Model:
$4.39\ \mathrm{molO_2\ m^{-2}\ y^{-1}}$

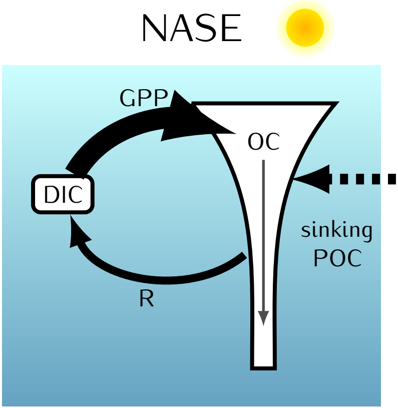
ETS:
$3.61\ \mathrm{molO_2\ m^{-2}\ y^{-1}}$

Similar to BATS mesopelagic respiration ($5\ \mathrm{molO_2\ m^{-2}\ y^{-1}}$) (Jenkins and Goldman, 1985)

NASW



NASE



Objectives

Objectives

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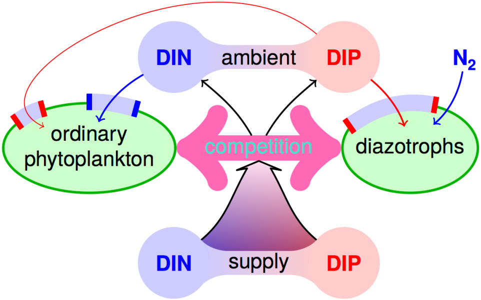
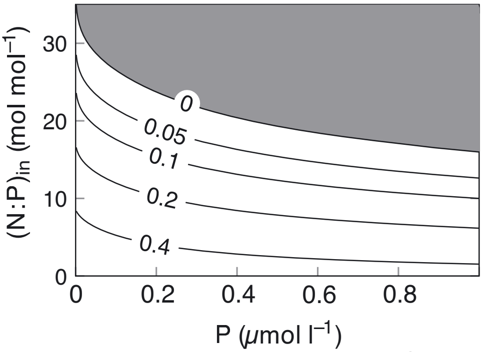
How? An Optimality-based model



Optimality-based model for phytoplankton growth and diazotrophy (Pahlow et al., 2013)

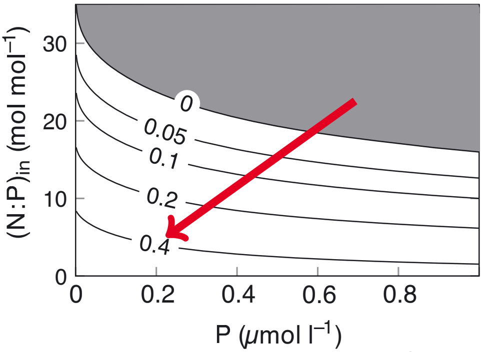
Diazotrophs:phytoplankton biomass



(Pahlow et al., 2013)

How? An Optimality-based model

Diazotrophs:phytoplankton biomass

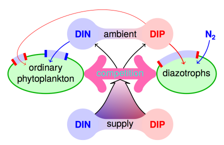


(Pahlow et al., 2013)

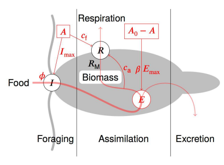
Fixation favoured by low N:P supply ratios and low nutrient availability

How? An Optimality-based model

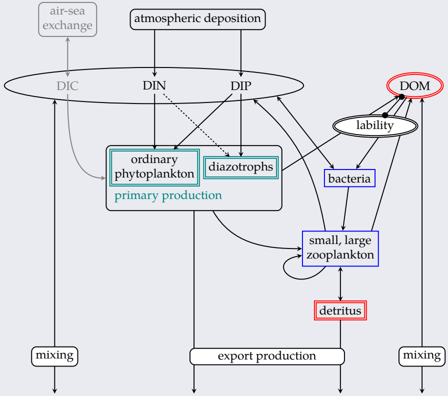
Optimal phytoplankton growth and diazotrophy model (Pahlow et al., 2013)



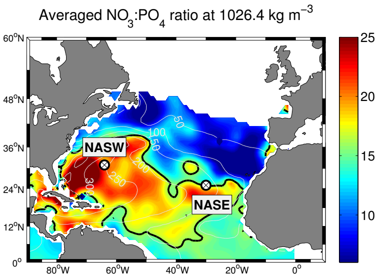
Optimal zooplankton current feeding model (Pahlow and Prowe, 2010)



Ecosystem model

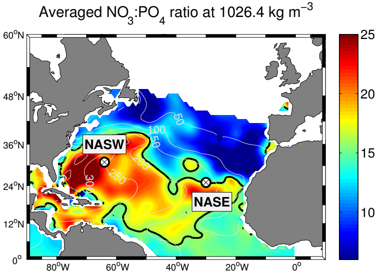


How? An Optimality-based model



12-year (1988-2000) 1-D physical forcing

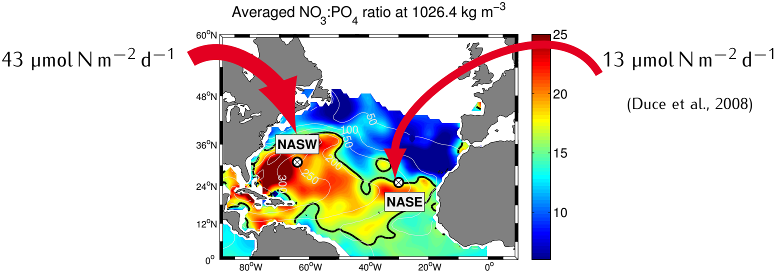
How? An Optimality-based model



High N:P>16 in the North Atlantic, influenced by:

- Diazotrophy (Gruber and Sarmiento, 1997)
- Atmospheric N deposition (Zamora et al., 2010)
- Preferential P remineralization (Monteiro and Follows, 2012, Letscher and Moore, 2015)

How? An Optimality-based model



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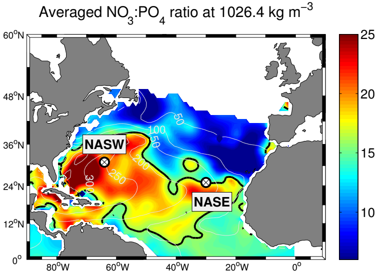

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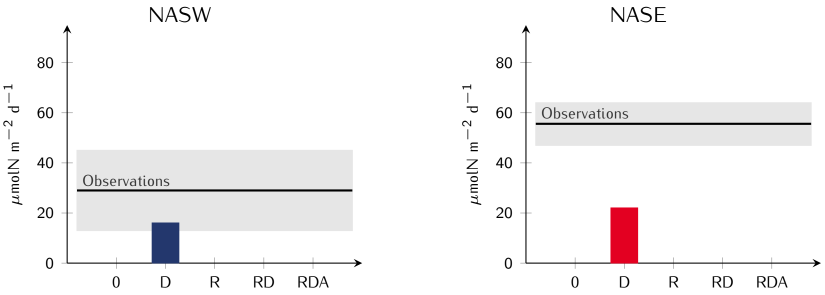
Model treatments

R: Preferential remineralization of phosphorus	}	P source
D: Diazotrophy A: Atmospheric deposition	}	N sources

Modeled N_2 fixation

Preferential P remineralization + Diazotrophy + Atmos. N deposition

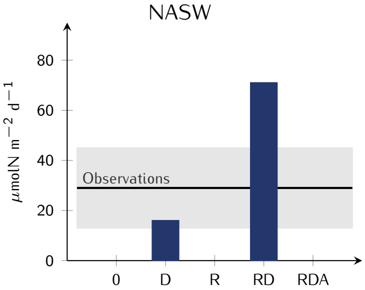
RDA

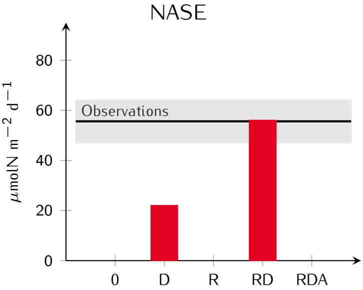


Modeled N_2 fixation

Preferential P remineralization + Diazotrophy + Atmos. N deposition

RDA

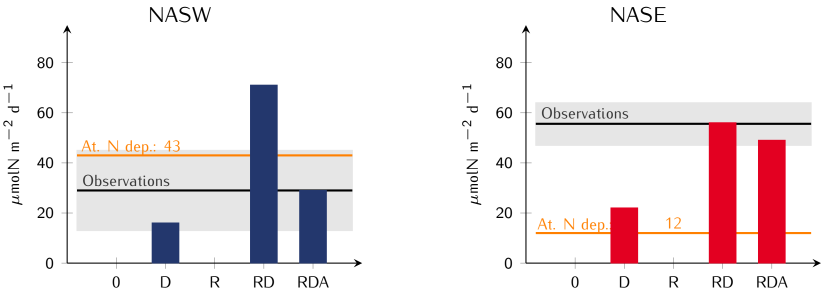




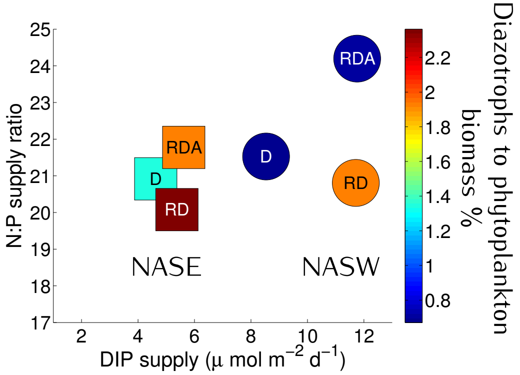
Modeled N_2 fixation

Preferential P remineralization + Diazotrophy + Atmos. N deposition

RDA



The role of diazotrophy

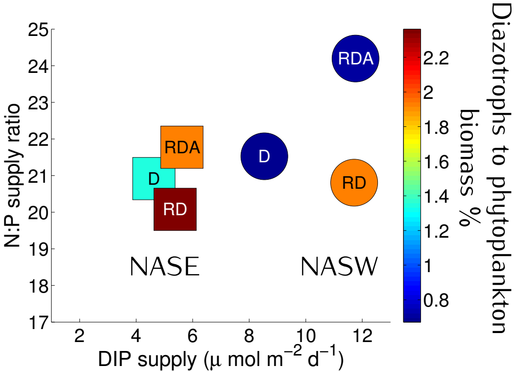


R: Preferential remineralization of phosphorus

D: Diazotrophy

A: Atmospheric deposition

The role of diazotrophy



More important role of diazotrophy in NASE

R: Preferential remineralization of phosphorus

D: Diazotrophy

A: Atmospheric deposition

Objectives

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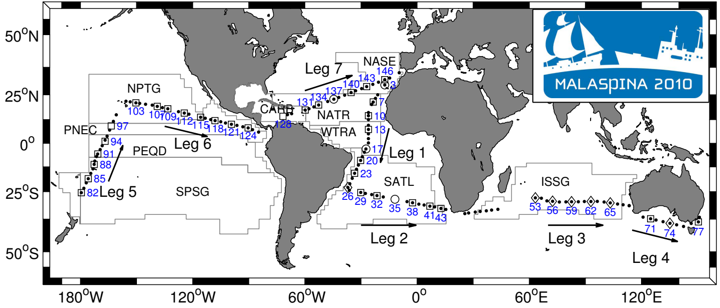
Malaspina 2010 expedition (December 2010 – July 2011)



45 stations
- Turbulence ⟵ MSS profiler; K-profile parameterization (7 stations)
- Nutrient profiles
- N_2 fixation ⟵ $^{15}N_2$ uptake bubble injection technique (Montoya et al., 1996)

132 stations ⟵ *Trichodesmium* and other diazotrophs abundance

How?

Microstructure turbulence profiler (MSS)

Microstructure shear sensor → ε Disipation rate of turbulent kinetic energy

Microstructure temperature sensor → χ Disipation rate of thermal variance

Vertical Diffusivity, K_z

ε
Dissipation rate of turbulent kinetic energy

Osborn (1980)

$$K_\varepsilon = \Gamma \frac{\varepsilon}{N^2}$$

Mechanical turbulence

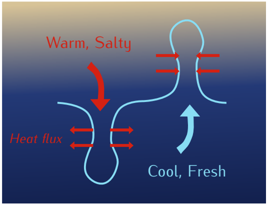
$$K_\varepsilon = 0.2 \frac{\varepsilon}{N^2}$$

χ
Dissipation rate of thermal variance

Osborn and Cox (1972)

$$K_\chi = 0.5 \frac{\chi}{(\partial T / \partial z)^2}$$

Diffusion by salt fingers



$\Gamma > 0.2$

ε
Disipation rate of turbulent kinetic energy

Osborn (1980)

$$K_\varepsilon = 0.2\frac{\varepsilon}{N^2}$$

χ
Disipation rate of thermal variance

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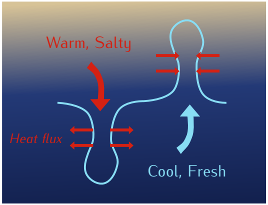
$$K_\chi = 0.5\frac{\chi}{(\partial T/\partial z)^2}$$

M. turbulence + Salt Fingers

$\langle K \rangle^{t+sf}$

(St Laurent and Schmitt, 1999)

Diffusion by salt fingers



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M. turbulence
+
Salt Fingers

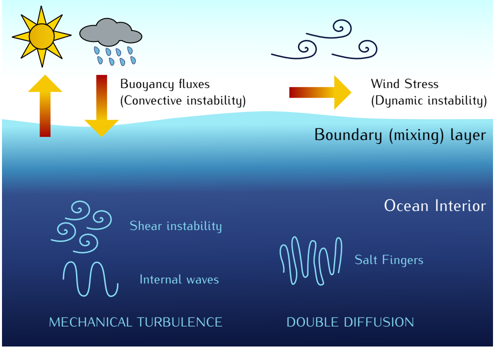
$\langle K \rangle^{t+sf}$

(St Laurent and Schmitt, 1999)

Parameterized K_z estimates

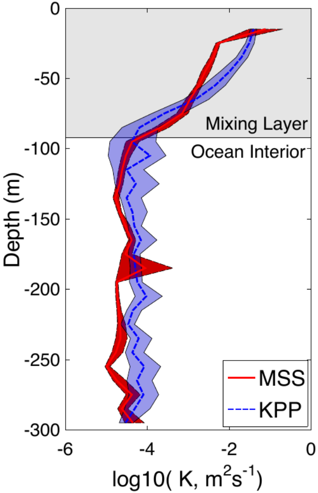
KPP, Large et al. (1994)

CTD + LADCP + METEO →



→ K_z

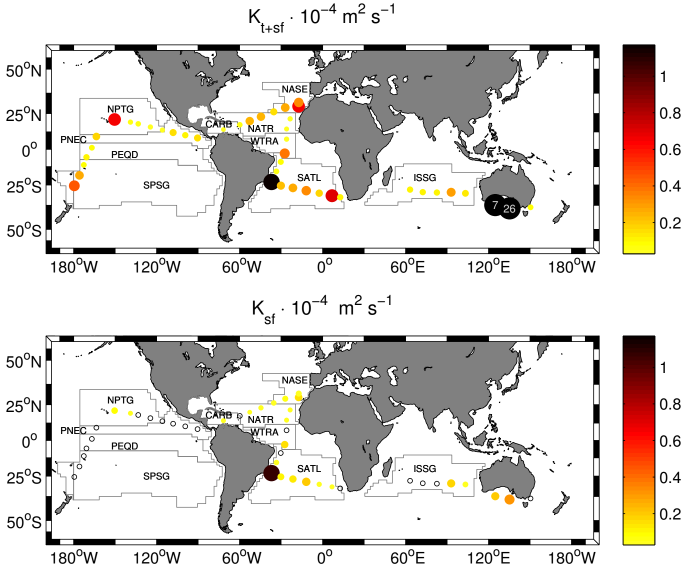
Validation of the KPP with MSS data



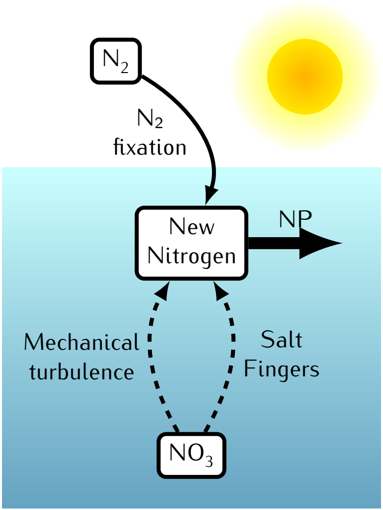
Diffusivity patterns and salt fingers contribution

Turbulence + salt fingers

Salt fingers



NO_3 diffusion (turbulence + salt fingers) vs. N_2 fixation



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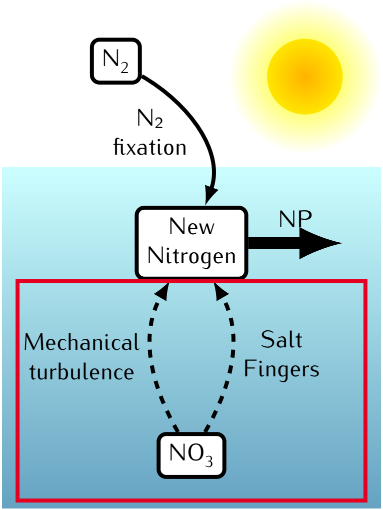
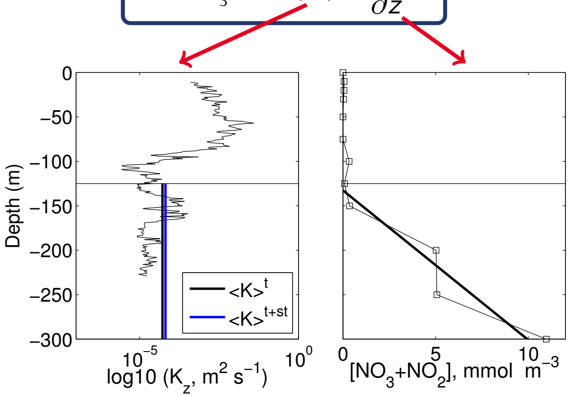


NO_3 diffusion (turbulence + salt fingers)

$$\mathrm{Flux}_{NO_3} = -\langle K \rangle \frac{\partial [NO_3]}{\partial z}$$



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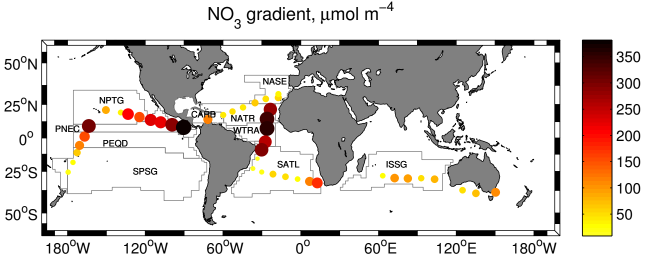
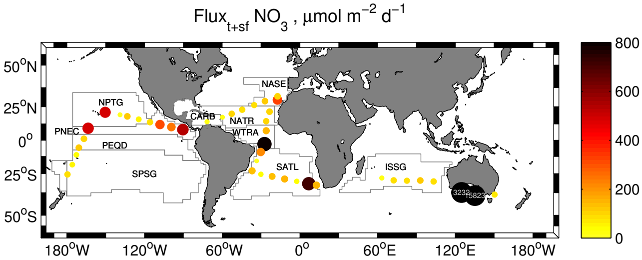
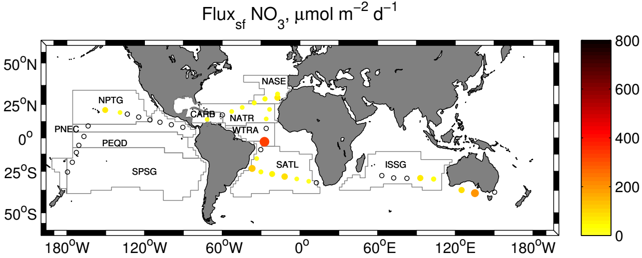


NO_3 diffusion (turbulence + salt fingers)

Turbulence
+
salt fingers



Salt fingers



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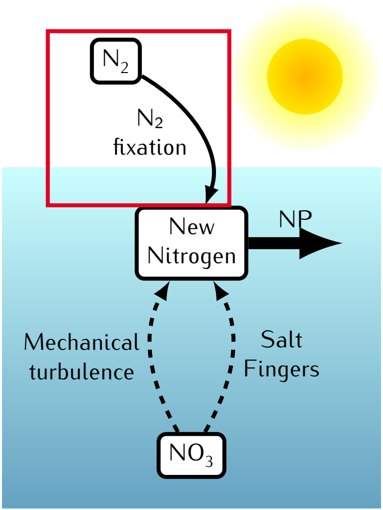
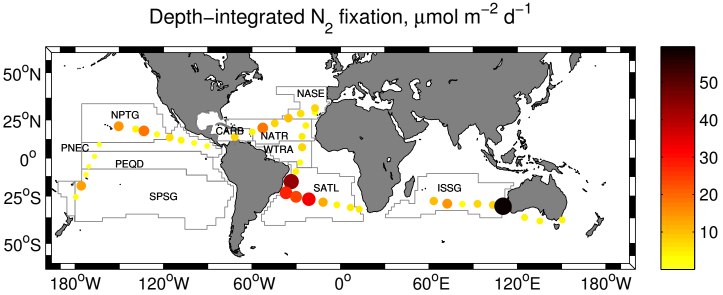


Biological N_2 fixation



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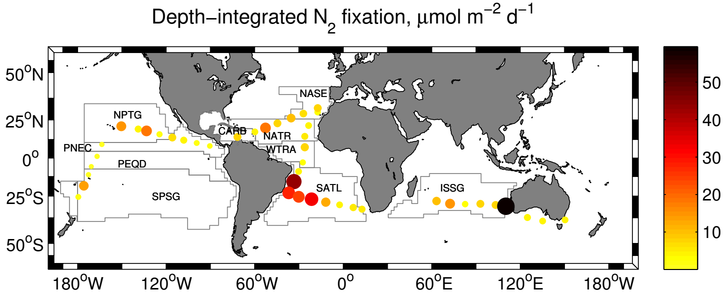
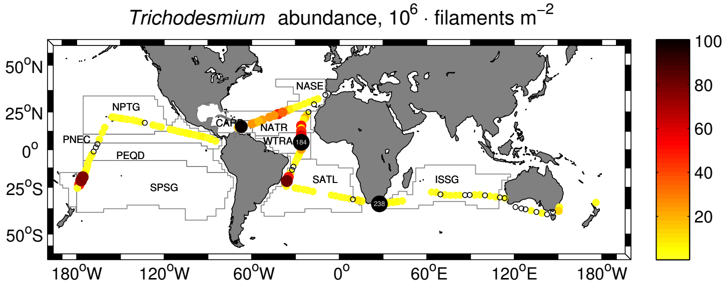
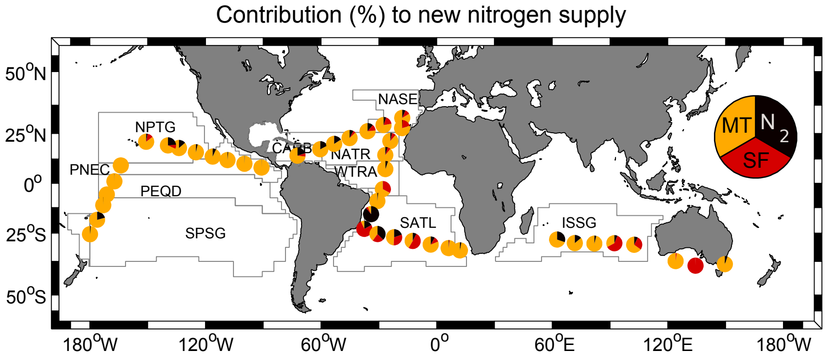




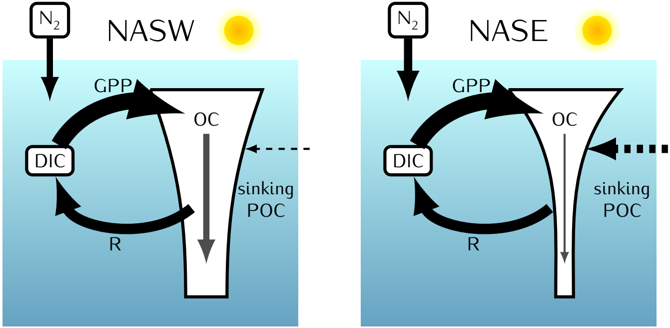
NO_3 diffusion (turbulence + salt fingers) vs. N_2 fixation



Conclusions

Conclusions I

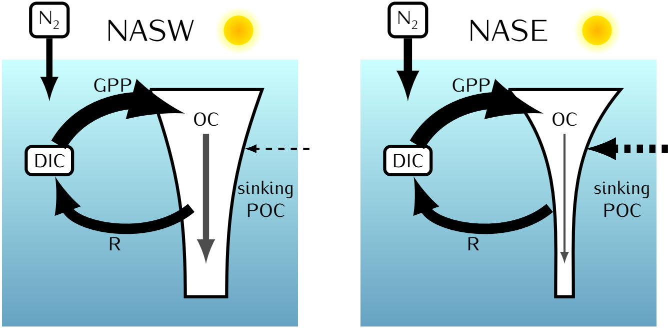
- No significant differences in respiration
- More important role of diazotrophy in NASE
- More important role of horizontal transport in NASE



Conclusions

Hypothesis I

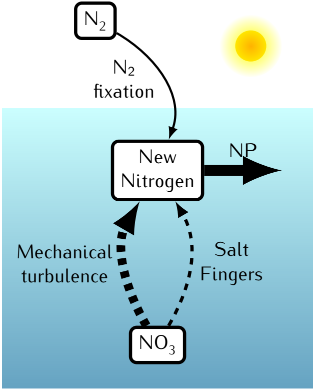
Differences in remineralization and N_2 fixation explain the dissimilarities in the fluxes of sinking organic carbon reported between NASW and NASE



Conclusions

Conclusions II

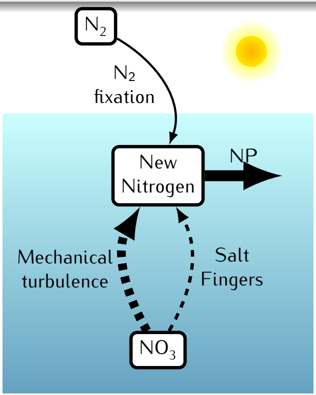
- Nitrate diffusion dominated over N_2 fixation
- The contribution of salt fingers was similar to N_2 fixation (ca. 20%)



Conclusions

Hypothesis II

Nitrate diffusion mediated by salt fingers represents a significant source of new nitrogen in large areas of the oligotrophic ocean



Many thanks for your attention!