Incorporating Respiration into the Ocean Carbon Budget: Lifting the Lid off Pandora's Box

Peter J. le B. Williams,
School of Ocean Sciences,
University of Wales, Bangor,
UK

JGOFS's two primary goals:

1. To determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean and to evaluate the related exchanges with the atmosphere, sea floor and continental boundaries;
2. To develop a capability to predict on a global scale the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular those related to climate change.

Structure of Talk

To look at the implications of observations on heterotrophic processes - principally respiration on:

A) the carbon budget in the upper water column, making the points :

1) that it is poorly constrained by the methods in the JGOFS recommended protocols

2) closing of the budget can be achieved with respiration measurements

B) the assessment of export production, which can be determined from :

1) photosynthesis and respiration balance in the euphotic zone

2) integration of vertical profiles of heterotrophy

The Starting Point

from:

Productivity of the Ocean: Present and Past .

Berger et al. 1989.

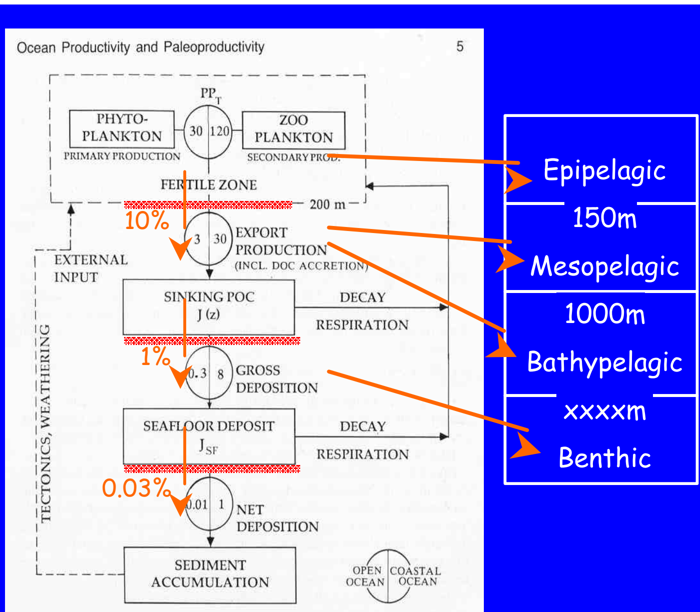
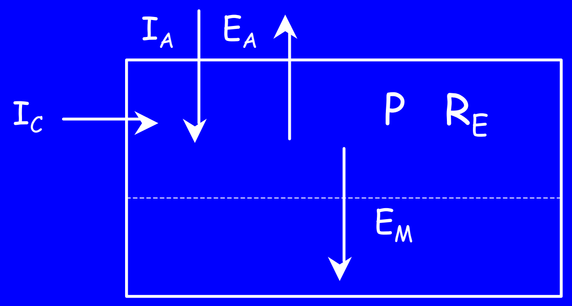


Fig. 2—Sketch of transfer of particulate organic carbon in the ocean, from primary production to burial in the sediment, showing the main elements of the "biological pump." Numbers are fluxes in g C $m^{-2}y^{-1}$; to the left in each circle a typical open ocean value; to the right a typical coastal ocean value.

A) Mass Balance for Oceanic Epipelagic



Euphotic zone Net Community Production (NCP)
$NCP = P - R_E$

ef-ratio $= E_M/P$

I_C = coastal input; I_A = atmospheric input; E_A = export to atmosphere; E_M = export to mesopelagic; P = photosynthesis; R_E = euphotic zone respiration

Equalities:

$0 = P + I_C + I_A - (E_A + E_M + R_E)$; $0 \simeq P - (E_M + R_E)$

as $P >> E_m$, the budget cannot be closed without a measurement or estimate of R_E

A) Closing the Epipelagic Carbon Budget

1) from JGOFS Core Measurements

2) from in vitro and in situ O_2 flux measurements

1) Closing the Epipelagic Budget from JGOFS Measurements

$$0 = P - (R_E + E_M)$$

Net ^{14}C uptake measurements - Production (P)

^{3}H-thymidine uptake

⇒ Bacterial carbon demand

⇒ Bacterial respiration (R_E)

Sediment traps & ^{234}Th - (E_M)

^{15}N uptake - new production - (E_M)

Net Biological Carbon Balance from JGOFS Measurements

Net organic production = $P - R_E$

= P (~30-90% underestimate)

- R_E (~500-2000% uncertainty)

Note as the Errors are SYSTEMATIC, no amount of sampling will eradicate them.

There is no future to this approach.

2) Closing the Epipelagic Budget from in vitro O_2 flux measurements

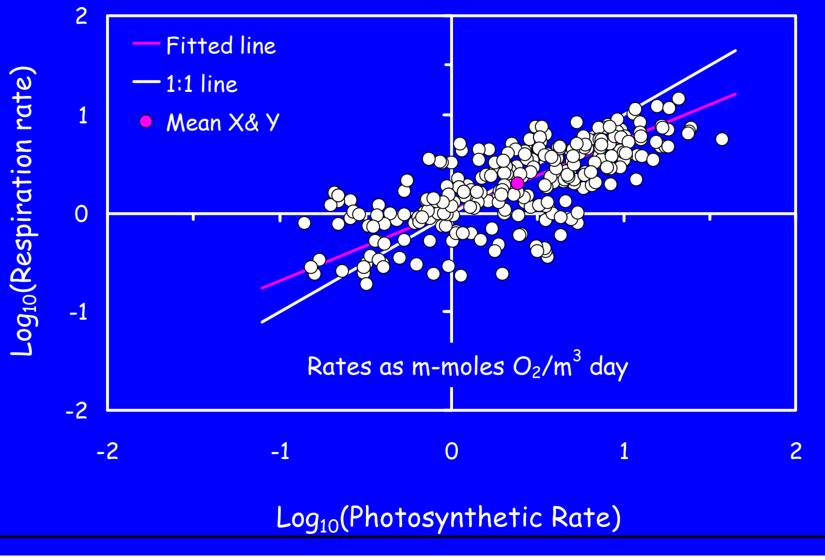
~ 1500 paired O_2-derived photosynthesis and respiration measurement, some 50-100 profiles

c.f. ~ 250,000 ^{14}C productivity measurements

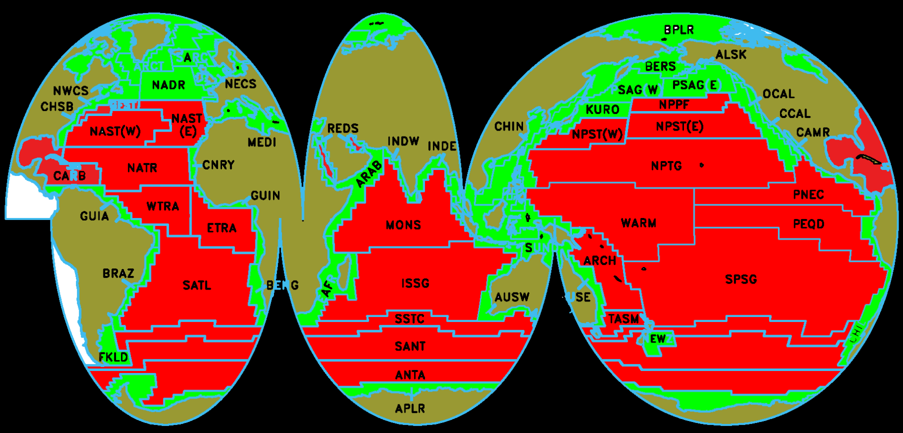
The O_2 flux data base is small, biased being neither wholly systematic nor wholly random and so non-ideal

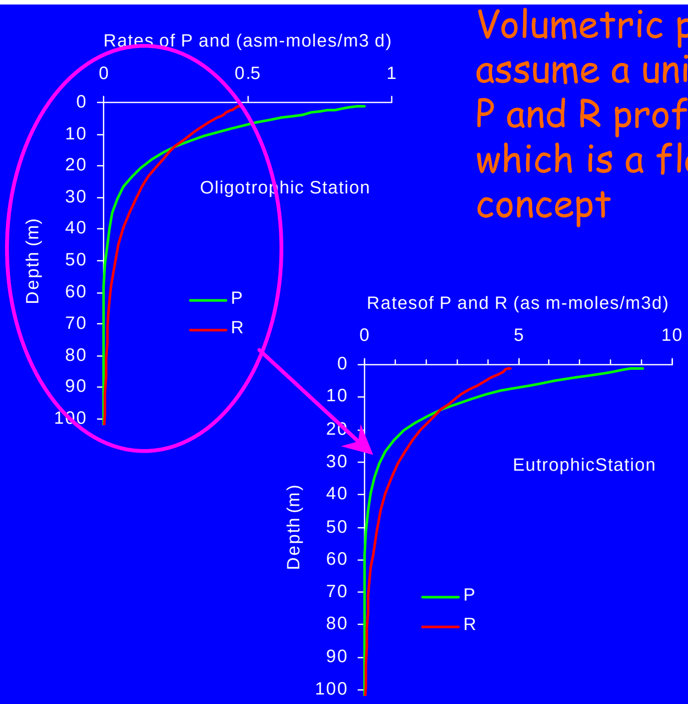
Rather than mapping it has been analysed by seeking statistical trends between P and R and to used these to make global projections

Epipelagic Carbon Balance: Regression Analysis of Volumetric Rates of P and R (ex. Del Giorgio et al, 1997, Duarte & Agusti, 1998)



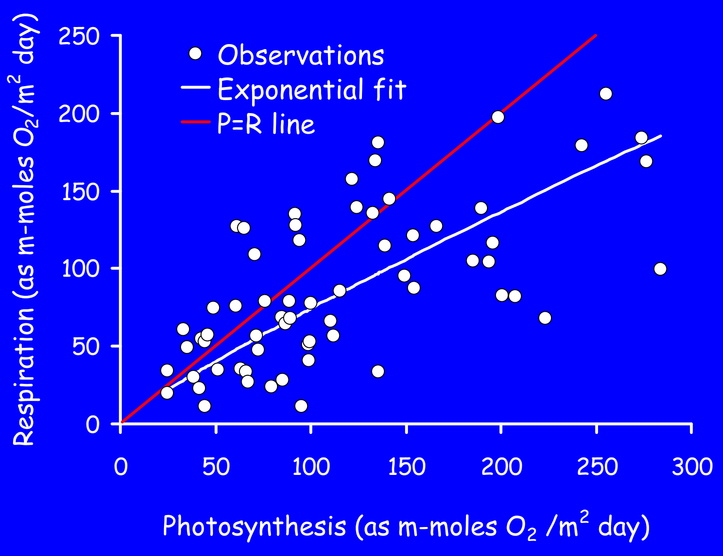
Epipelagic Carbon Balance: Projected Distribution of Areas of Positive (green) and Negative (Red) Carbon Balance Duarti & Agusti et al (1998)



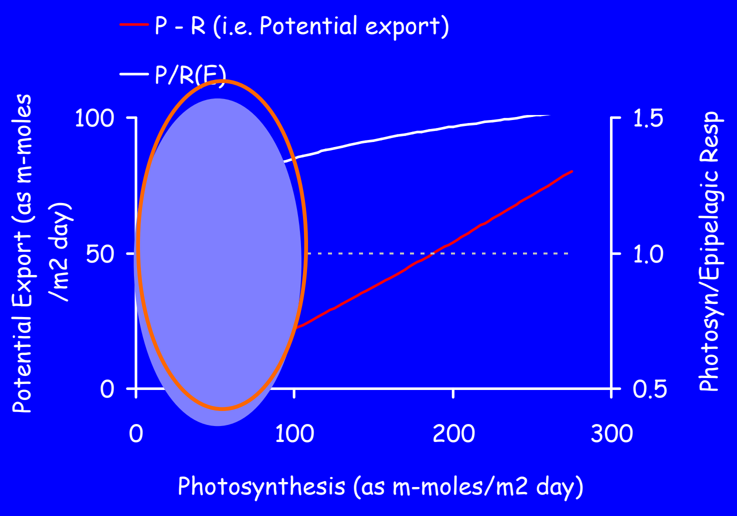


Volumetric plots assume a universal P and R profiles - which is a flawed concept

Epipelagic Carbon Balance: Analysis of Depth Integrated Rates (Williams, 1998)

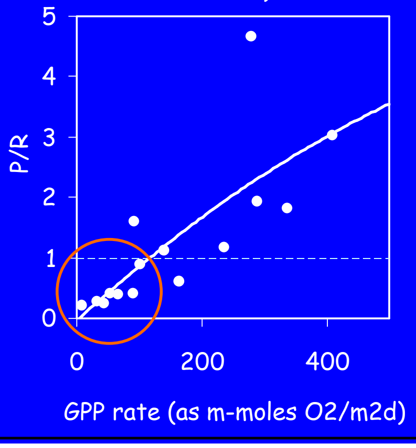


Epipelagic Carbon Balance: Previous Figure Rearranged as P-R (NCP) and P/R versus P

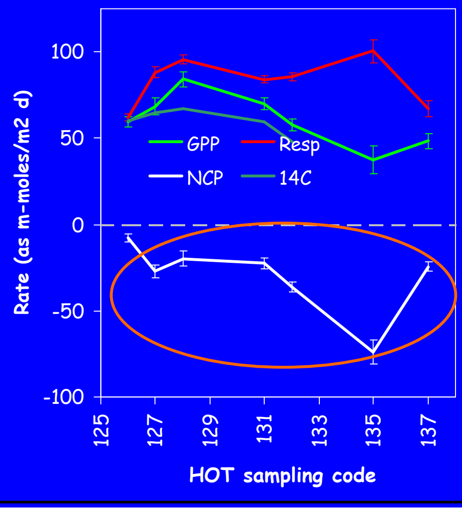


Epipelagic Carbon Balance: we're not out of the woods yet!

P/R ratios of Depth Profiles along an Atlantic Transect (data provided by Carol Robinson)



HOTS Aloha time series study
Williams, Karl & Morris



Summary

Epipelagic Carbon Balance

1. The JGOFS protocols do not allow us to close the oceanic carbon budget - even for the extensively studied epipelagic zone
2. This can by done from in vitro ? O_2 measurements, with a measure of success
3. BUT, there is a debate whether oligotrophic areas are net heterotrophic, which is far from finished
4. The data set of in vitro ? O_2 measurements is presently too small to allow us to make much further headway into this problem

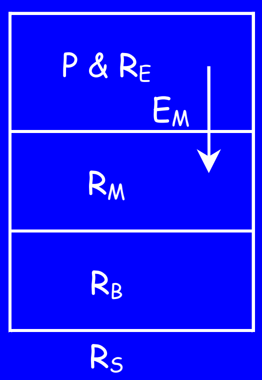
B) Estimation of ef- (new, export, f-) ratio

Eppley (1989) summarised 4 approaches:

1) ^{15}N tracer uptake incubations
2) Seasonal changes in O_2 or nutrient stocks
3) Upper water sediment traps
4) ^{234}Th particle export estimations

There are potentially two further approaches - based on measurements of heterotrophic rates

Water Column Mass Balances



Epipelagic (0-150m)

Mesopelagic (150-1000m)

Bathypelagic (1000-4000m)

Mass balances:

$0 = P - (R_E + E_M)$

$0 = E_M - (R_M + R_B + R_S)$

Export ratios (ef-ratio):

ef-ratio = E_M/P

ef-ratio = $(P-R_E)/P$

ef-ratio = $(R_M+R_B+R_S)/(\Sigma R_E)$

ef-ratio ≈ $R_M/(R_M+R_E)$

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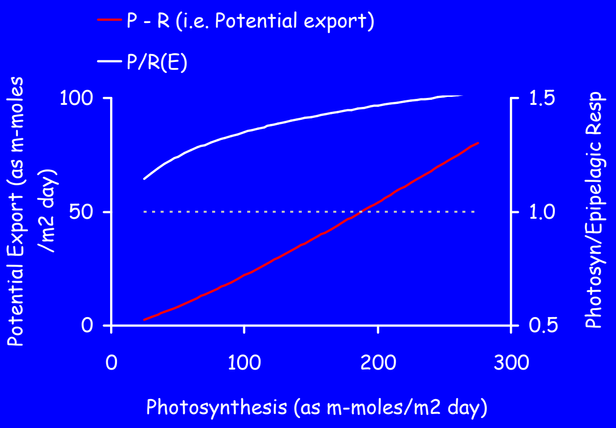
Thus, we can add further approaches:

5) Epipelagic organic balance
6) Depth-integrated heterotrophy

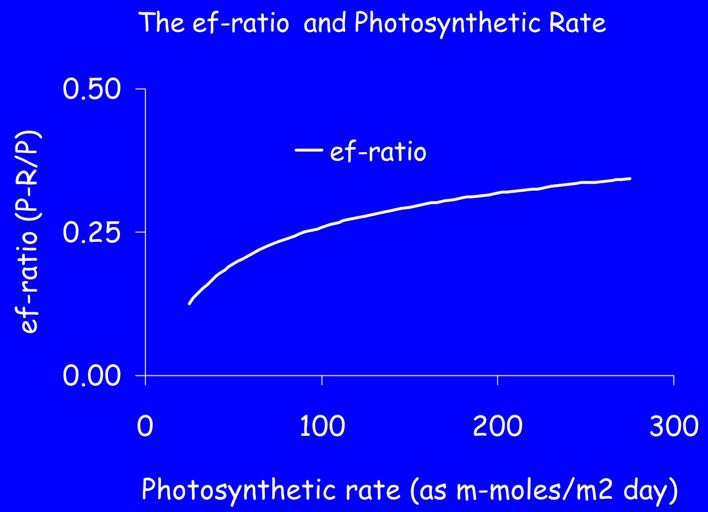
As the latter approaches uses a homogeneous sets of measurement, they are not so susceptible to systematic errors

Estimation of ef-ratio
1) Projections from Epipelagic Organic Balance

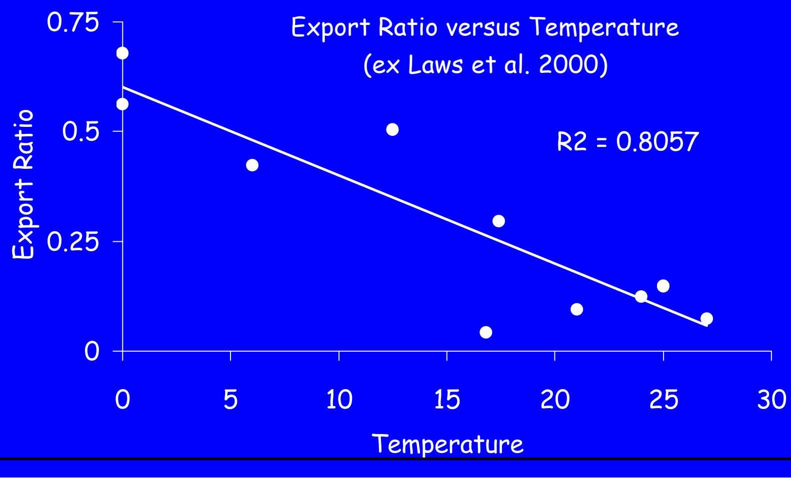
We can take the previous graph and rearrange the of observations of P and R to calculate net community production (NCP) i.e. potential export versus P relations' ·



Estimation of ef-ratio
The Depth Integrated-Areal P and R Data Set, Reworked as P-R/P (i.e. ef-ratio)



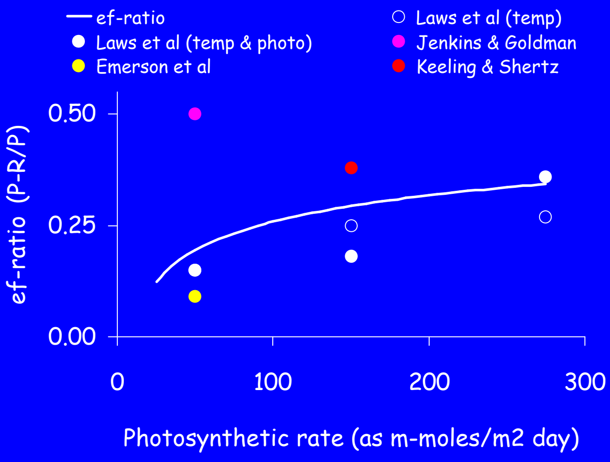
Estimation of ef-ratio
Laws et al (2002) Analysis of ^{15}N and sediment trap-determined ef-ratios



Estimation of ef-ratio
In situ Net (New) Production: Geochemical Gas Exchange Studies

	Annual NCP (as moles O_2/m^2) or (as T-moles O_2)	Annual GPP (same units)	Export Fraction (as %)	Approach
Jenkins & Goldman (1985) Atlantic - Sargasso Sea	+5	10	~ 50	$O_2/^3He/^3H$ distributions
Emerson *et al.* (1995) Pacific - HOTS site	+1.4	15	9	O_2/N_2 distributions
Keeling & Shertz (1992) Global Estimate	~ +1660	4200	38	Atmospheric O_2/N_2 budgets

Combining the Three Data Sets



Estimation of ef-ratio
2) Export Ratio Derived from Mesopelagic and Bathypelagic Metabolisms

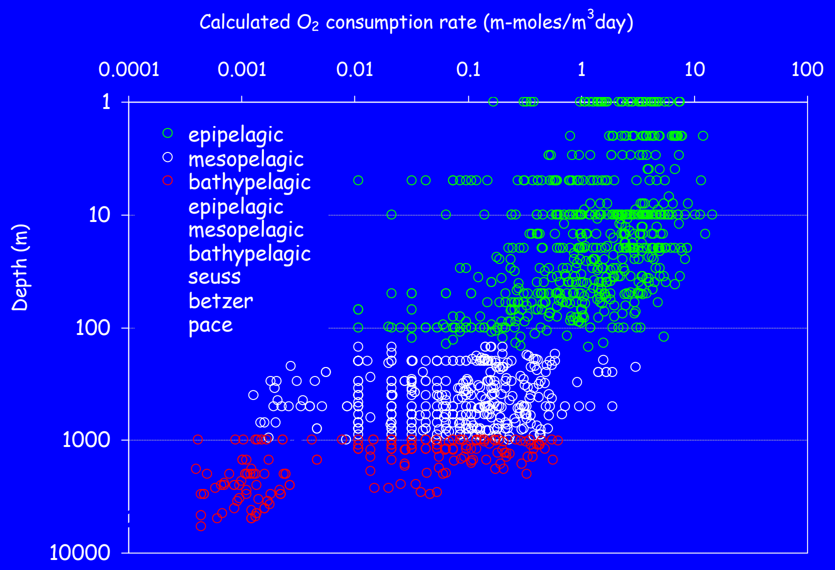
$$\text{ef-ratio} = (R_M+R_B+R_S)/(R_E+R_M+R_B+R_S)$$

Analyse 4 data sets:

1) a large compilation of volumetric ΔO_2 and ETS observations
2) a consistent set of ETS data from the Mediterranean (Lefèvre)
3) a set of ^{3}H-thymidine observations for the N. Central Pacific gyre (Chou & Azam)

[[4) a set of ^{3}H-thymidine observations from the Pacific from areas of varying productivities (Nagata et al.)]]

Estimation of ef-ratio
a) Compilation of 1200 ETS and ? O_2 Observations



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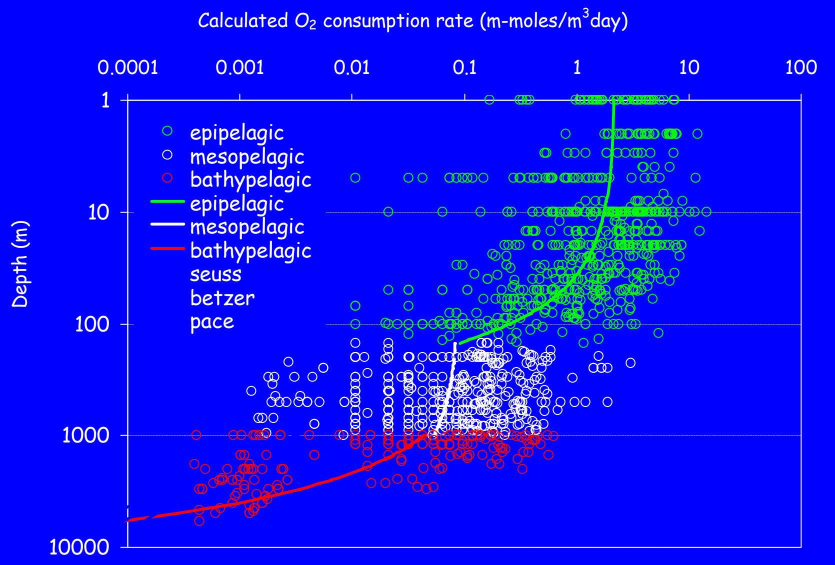

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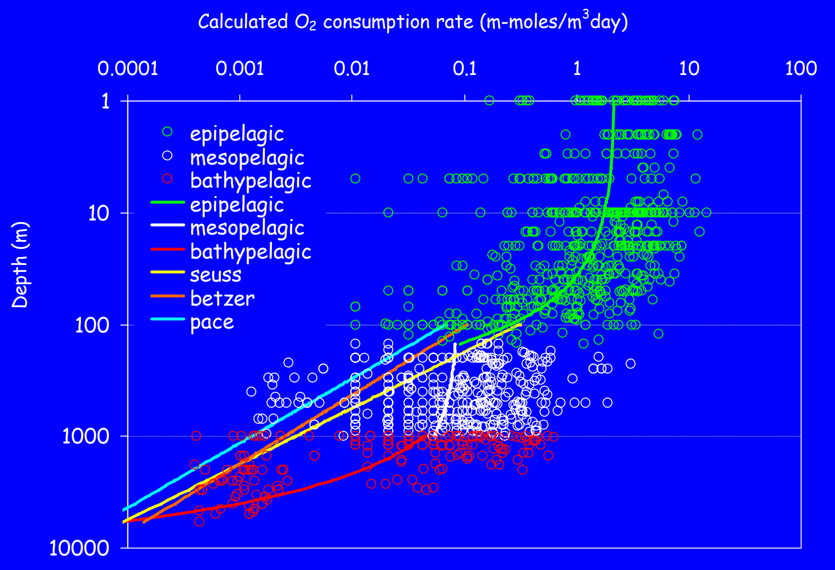
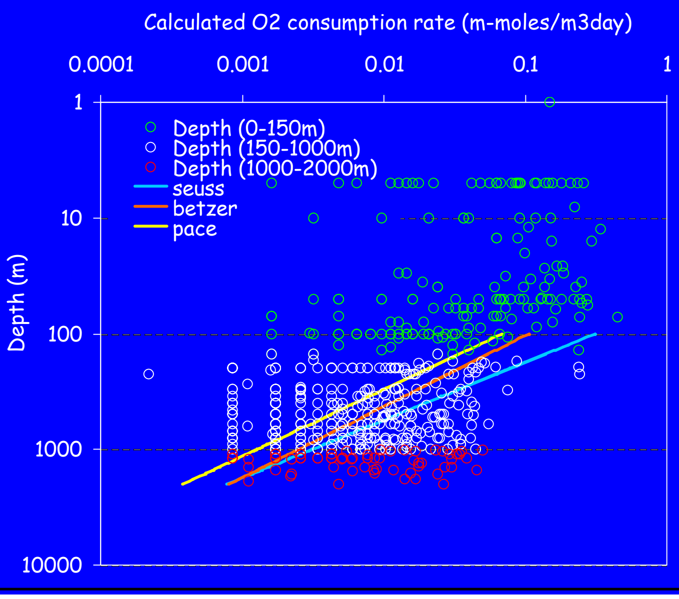
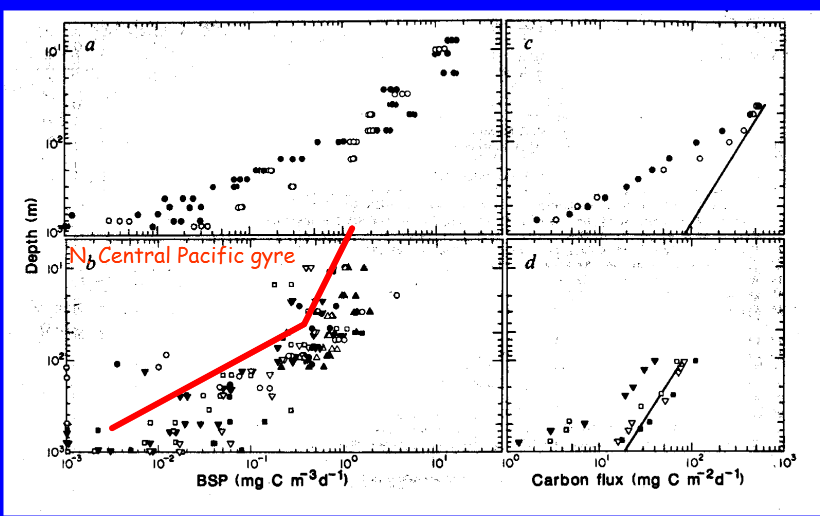


Estimation of ef-ratio
b) Mediterranean ETS Data (Lefèvre)



Estimation of ef-ratio
c) Bacterial Carbon Demand Profiles (Chou & Azam)



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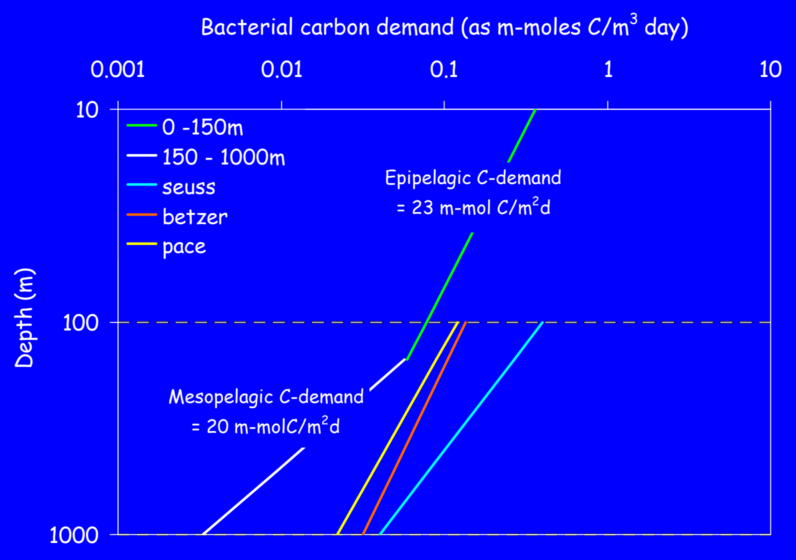
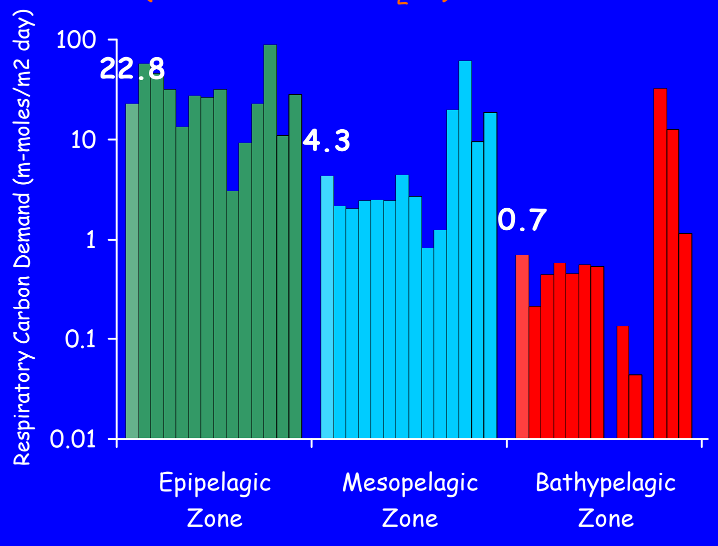
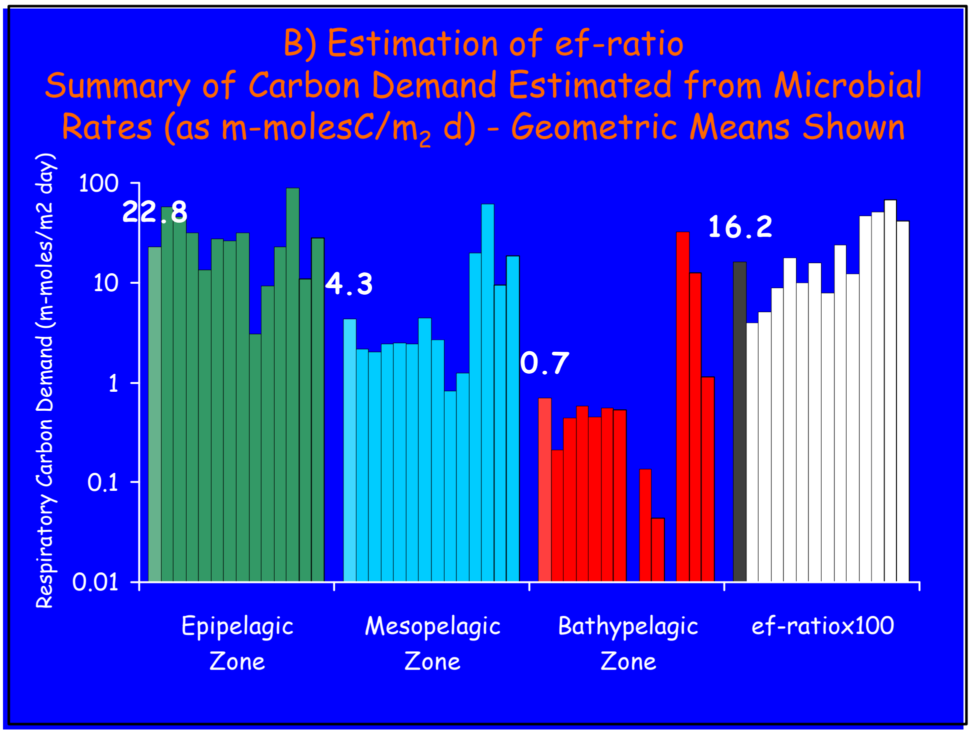


B) Estimation of ef-ratio
Summary of Carbon Demand Estimated from Microbial Rates (as m-molesC/m_2 d) - Geometric Means Shown

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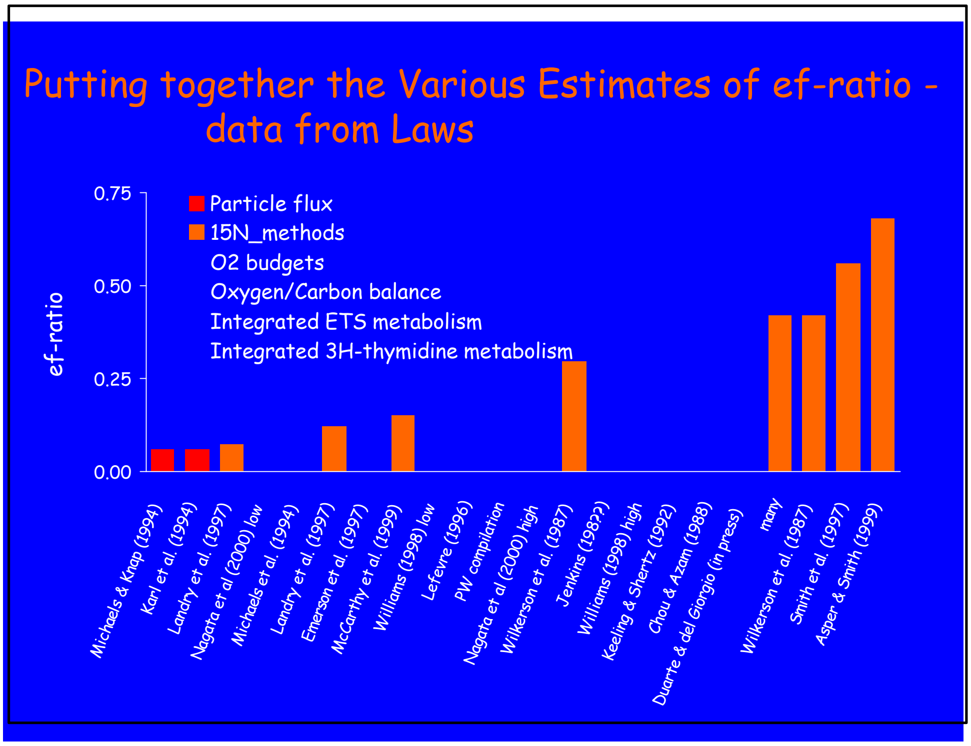
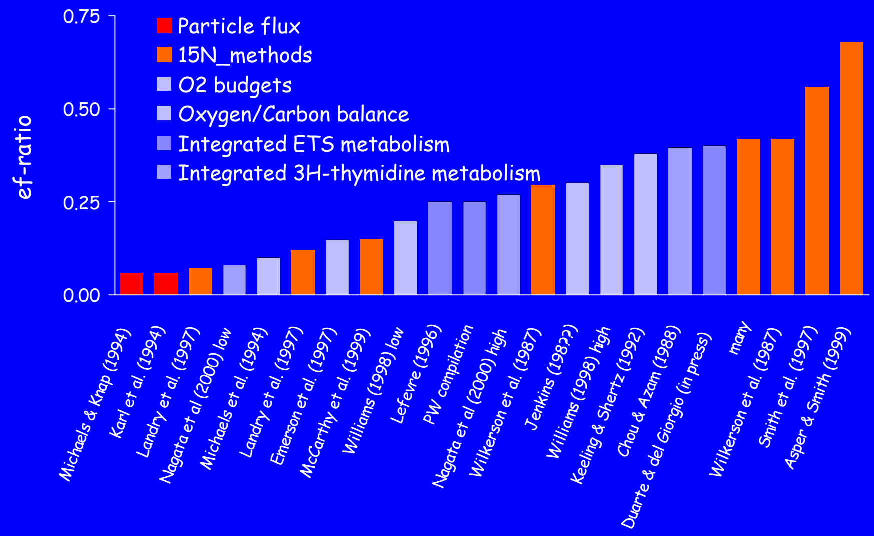
Respiratory Carbon Demand (m-moles/m2 day)
100
10
1
0.1
0.01
22.8
4.3
0.7
16.2
Epipelagic Zone
Mesopelagic Zone
Bathypelagic Zone
ef-ratiox100


Putting together the Various Estimates of ef-ratio - data from Laws
ef-ratio
0.75
0.50
0.25
0.00
Particle flux
15N_methods
O2 budgets
Oxygen/Carbon balance
Integrated ETS metabolism
Integrated 3H-thymidine metabolism
Michaels & Knap (1994)
Karl et al. (1994)
Landry et al. (1997)
Nagata et al (2000) low
Michaels et al. (1994)
Landry et al. (1997)
Emerson et al. (1997)
McCarthy et al. (1999)
Williams (1998) low
Lefevre (1996)
PW compilation
Nagata et al (2000) high
Wilkerson et al. (1987)
Jenkins (1982)
Williams (1998) high
Keeling & Shertz (1992)
Chou & Azam (1988)
Duarte & del Giorgio (in press)
many
Wilkerson et al. (1987)
Smith et al. (1997)
Asper & Smith (1999)

Putting together the Various Estimates of ef-ratio - data from Laws & the Present Analysis



Estimation of ef-ratio - Summary

1. Microbial metabolic rate measurements provide an additional approach of determining export ratios
2. The apparently give "sensible" rates
3. Calculations from epipelagic in vitro ? O_2 P and R measurements give ef-ratios ranging from 0.12 to 0.34
4. Separate integrations of epi-, meso- and bathy-pelagic metabolisms give ef-ratios ranging from 0.04 to 0.6
5. These approaches have the disadvantage that the do not give good spatial and temporal averaging - thus are not ideal for compiling global budgets but have the advantage that they give insight into mechanisms

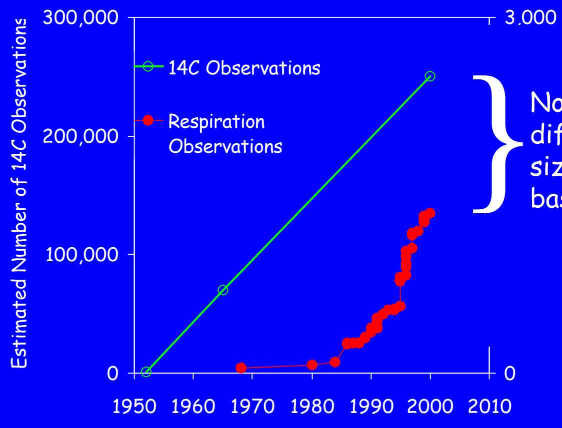
What Next

1) If we want to close the oceanic C-budget then we will need to revise and extend the JGOFS core measurements - to improve our understanding of water column respiration
2) As in some cases, perhaps as much as half in not more of heterotrophic organic utilisation occurs in the mesopelagic region, this zone demands more attention

What are the implications

Extending the Respiration/NCP Data Base Where we Presently are:

Cumulative ^{14}C and ΔO_2 Observations

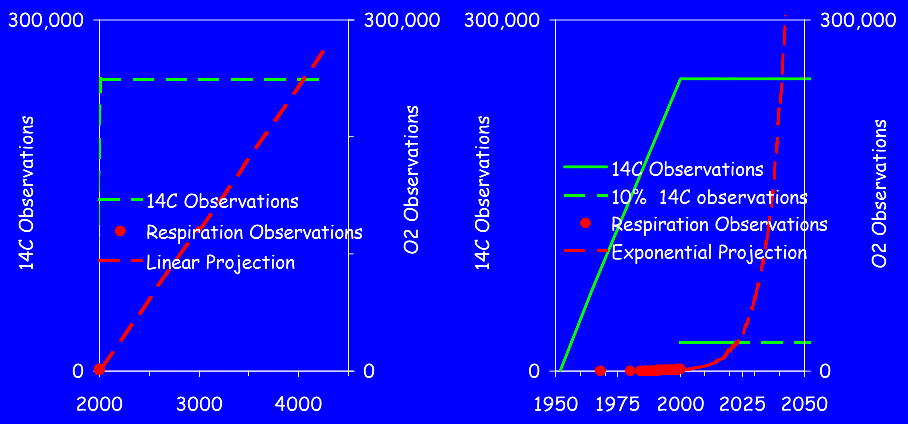


Note 100-fold difference in the sizes of the data bases

Extending the Respiration/NCP Data Base
How Do We Manage the Future:

Maintain Present Effort with O_2 Work

Allow the O_2 Work to Grow Exponentially



We get there in the 4th millennium !

We get there at some not too distant future

Mesopelagic Respiration

^3H thymidine measurements ⇒ massive problems with conversion factors

ΔO_2 ⇒ technically possible but definitely not for the feint-hearted

ETS (electron transport system assay) Þ largely rejected by the US oceanographic community for reasons that are not clear

The data would not be outstandingly expensive nor exceptionally difficult to acquire

Conclusions - A) Upper Water Column C-balance

1) We presently have a poorly developed capacity to close the upper water column carbon budget
2) If we wish to harden up the budget we shall need to attend to the following :
   i) improve the accuracy of primary production measurements by establishing what the ^{14}C technique measures or by looking beyond the ^{14}C technique
   ii) introduce respiration measurements into the routine set of observations

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   i) improve the accuracy of primary production measurements by establishing what the ^{14}C technique measures or by looking beyond the ^{14}C technique
   ii) introduce respiration measurements into the routine set of observations

The radical proposition is that we substitute ? O_2 measurements for the ^{14}C

With the ? O_2 approach you get <u>three</u> (Photo, NCP & Resp) for the price of <u>one</u> - "how can you resist this offer !"

Conclusions -
B) Mesopelagic Metabolism

1) There are strong indications that extensive metabolism is occurring in the twilight and dark zones below the euphotic zone
2) This calls for measurements of heterotrophic processes to be routinely extended into this zone
3) A number of approached (ETS, in vitro ΔO_2, ^3H-thymidine) are available
4) These will provide a better understanding of the export of organic material out of the euphotic zone

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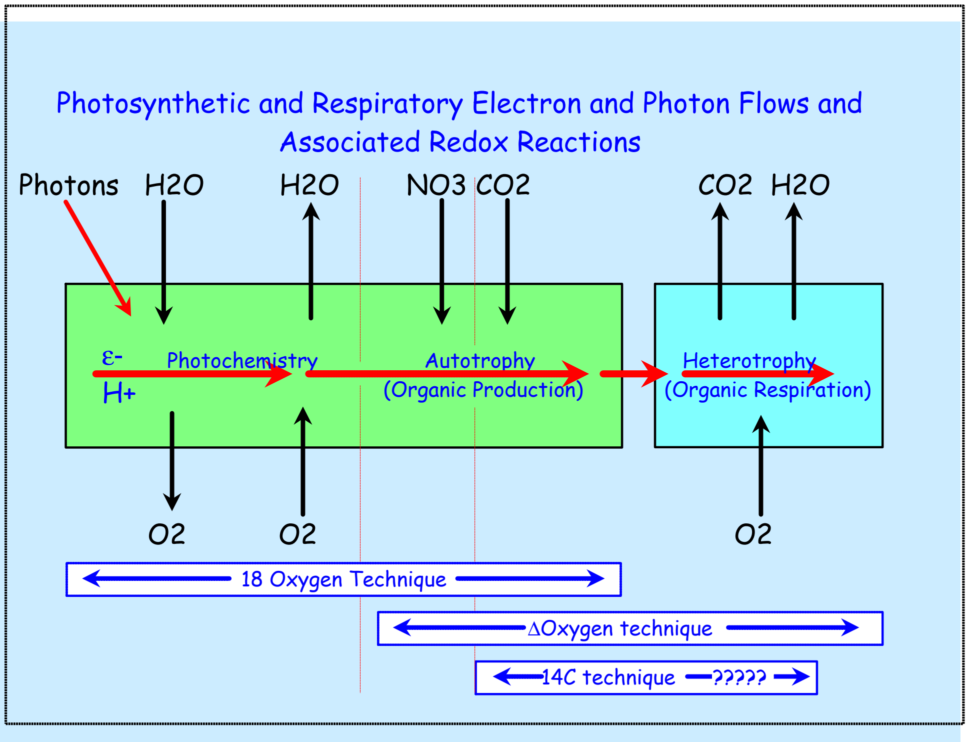
4) These will improve our understanding of the export of organic material out of the euphotic zone

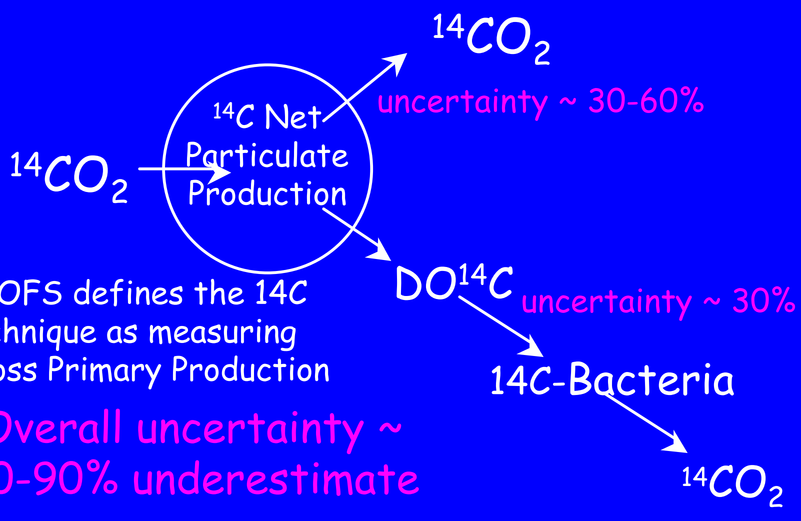
Finally, if we wish to develop a sound understanding of organic carbon balance in the oceans, we will need to overcome our longstanding obsession with the measurement primary production and direct more effort to the measurement of respiration

Thank you !



Photosynthetic and Respiratory Electron and Photon Flows and Associated Redox Reactions
Photons
H2O
H2O
NO3
CO2
CO2
H2O
ε-
H+
Photochemistry
Autotrophy
(Organic Production)
Heterotrophy
(Organic Respiration)
O2
O2
O2
18 Oxygen Technique
ΔOxygen technique
14C technique
?????

^{14}C-determined primary production - fate of fixed carbon



JGOFS defines the 14C technique as measuring Gross Primary Production

Overall uncertainty ~ 60-90% underestimate

Respiration determined from ^{3}H-thymidine measurements

Step 1: 3H thymidine ⇒ bacterial production (BP)

- uncertainty ~ x 2.5 to 10

(Ducklow, 1999; Pomroy & Joint 1999)

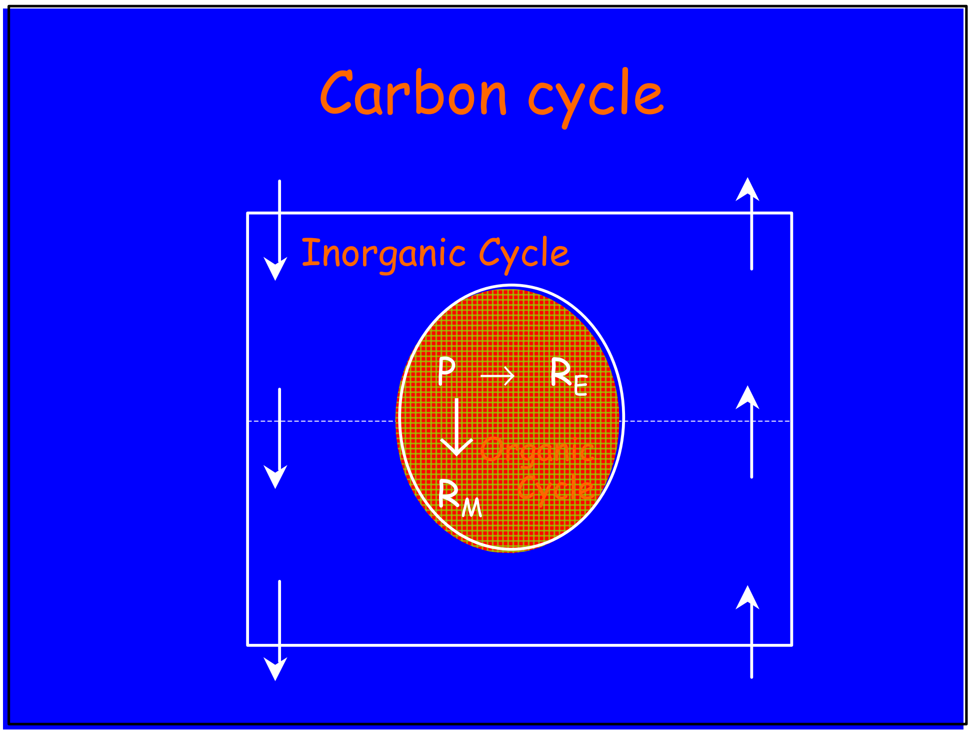
Step 2: Bacterial production (BP) ⇒ bacterial respiration (BR)

$BR=BP(1-y)/y$

y = growth yield; range of estimates 0.15 - 0.25 (optimistic)

- uncertainty ~ x 2 (del Giorgio and Cole, 1999)

Overall uncertainty ~ 5 to 20 fold


Carbon cycle
Inorganic Cycle
P → R_E
R_M
Organic Cycle