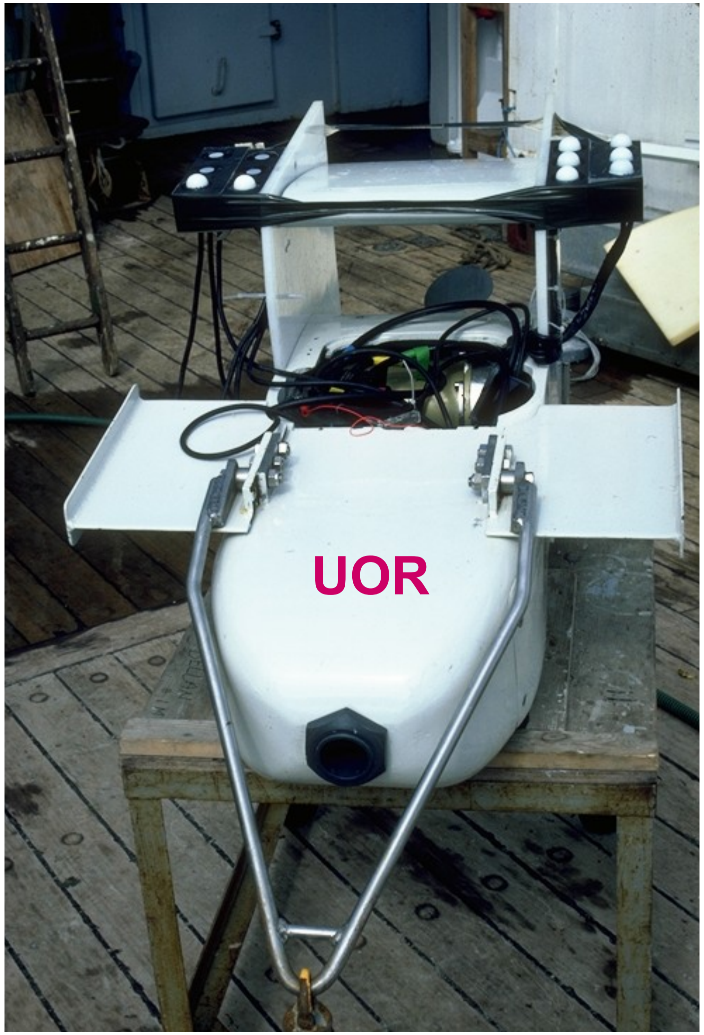
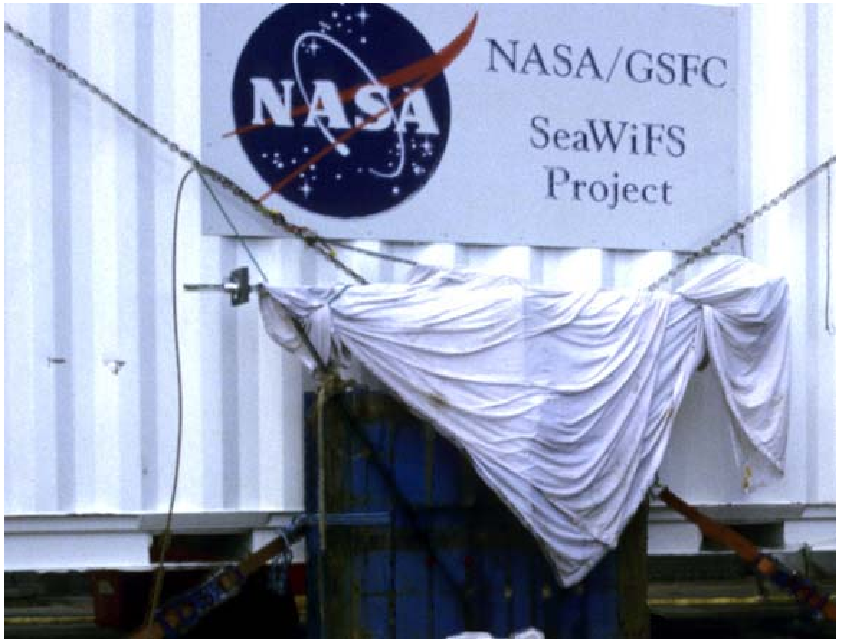




Jim Aiken

Oceanographer 1970 – 2008

Does the Subsurface Chlorophyll Maximum Represent a Violation of Aiken's Second Law of Oceanography?

Patrick M. Holligan
School of Ocean & Earth Science, University of Southampton

Aiken's 2nd Law:
'If you can't see it from space it's not important'

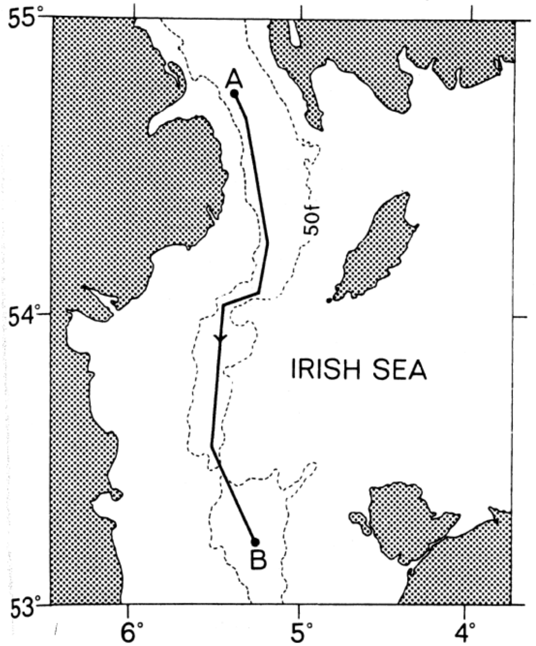
But: .. 'ocean colour satellite sensors receive radiances from one optical depth' …

PART I: Learning the trade
(hydrography and fluorometers)

PART II: Chemical interludes
(nitrogen cycling and fluxes)

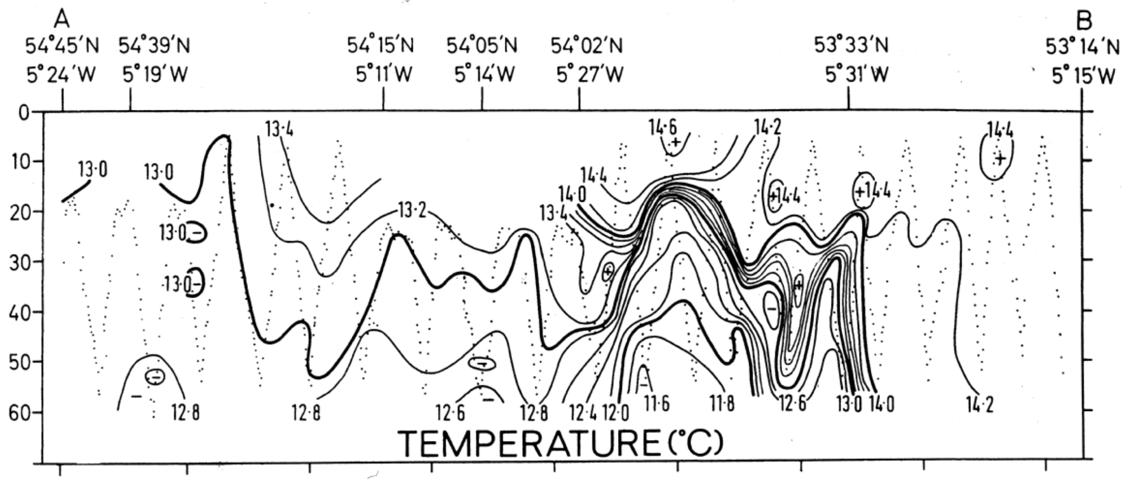
PART III: Trying to keep up with the youngsters
(fluorescence revisited)

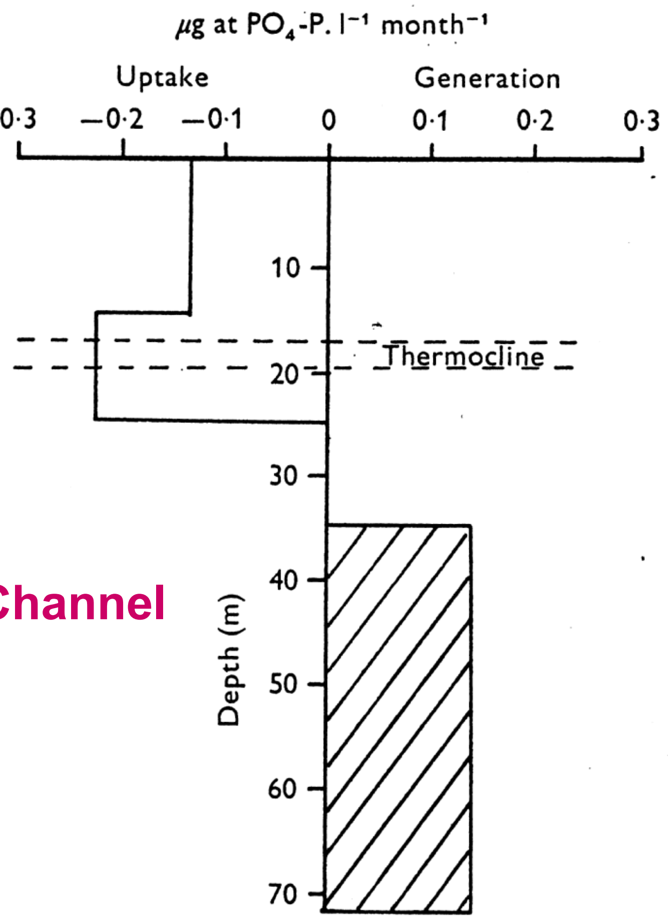
PART I



UOR Tow
30-31 August, 1971

From Bruce & Aiken (1975) Marine Biol. 32, 85-97

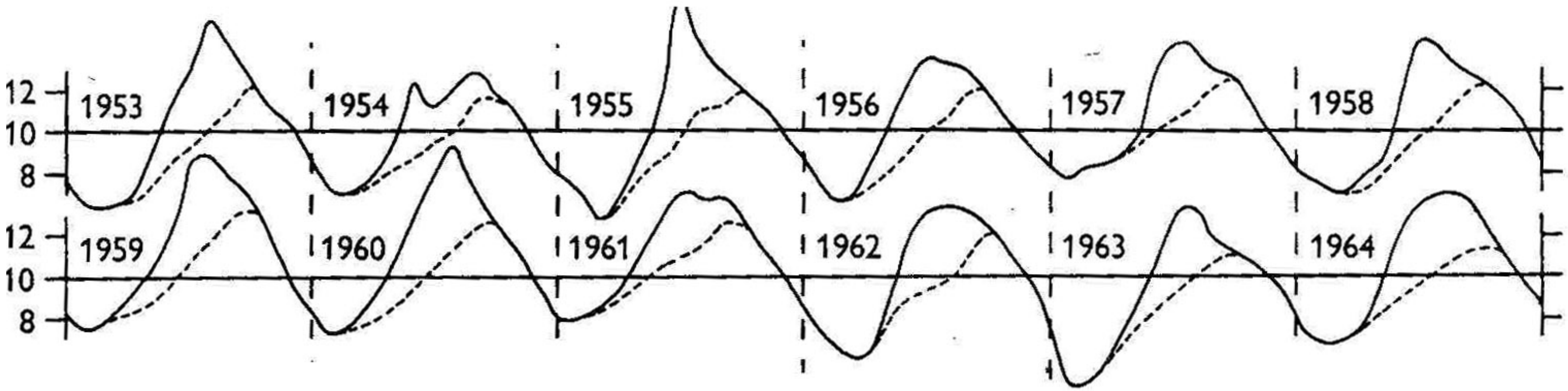




Station E1
W English Channel

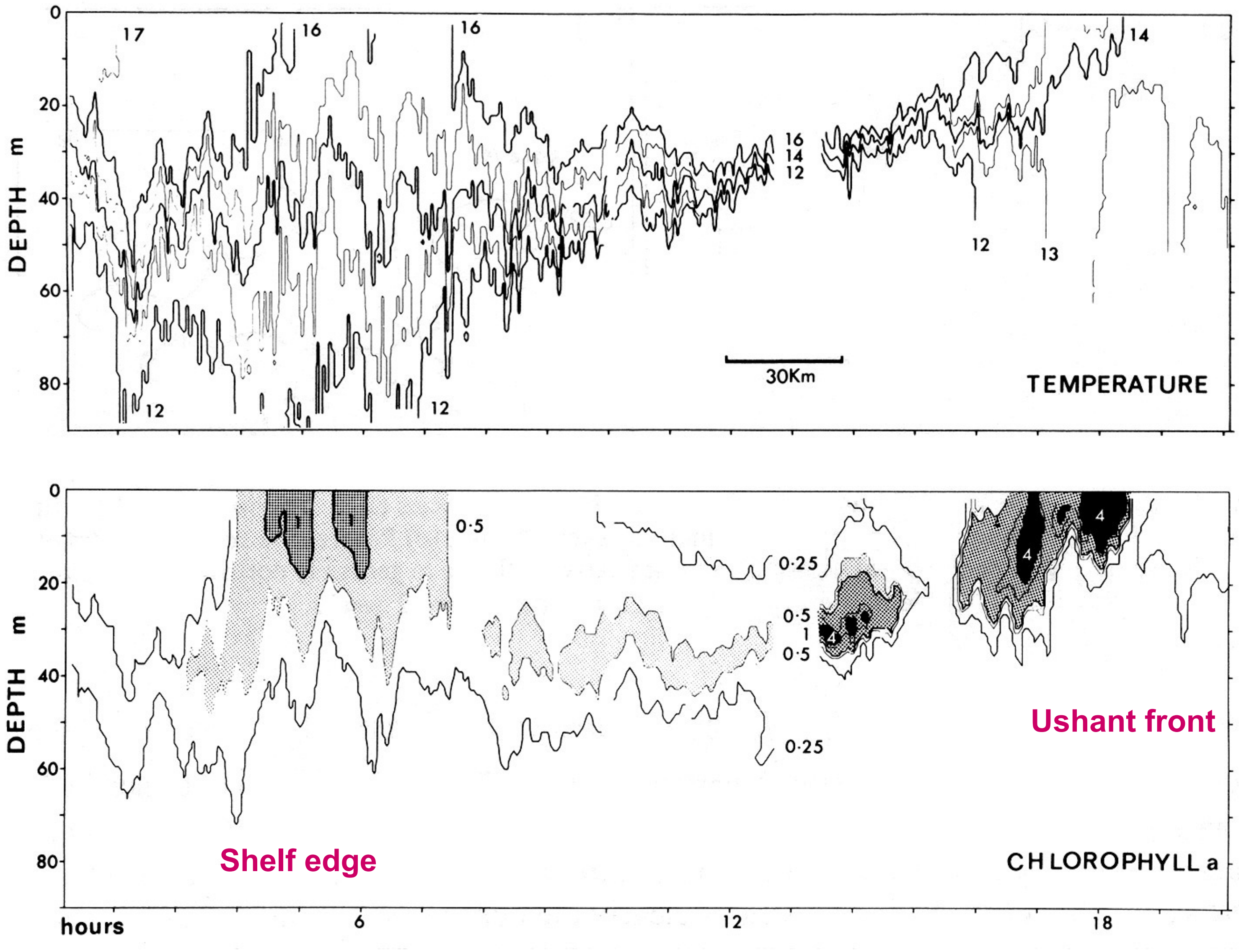
The mean regeneration of inorganic phosphate in the bottom mixed layer and its utilization in and above the thermocline for the months June, July and August.

From Pingree & Pennycuick (1975) JMBA 55, 261-274.
'Transfer of heat, freshwater and nutrients through the seasonal thermocline'.



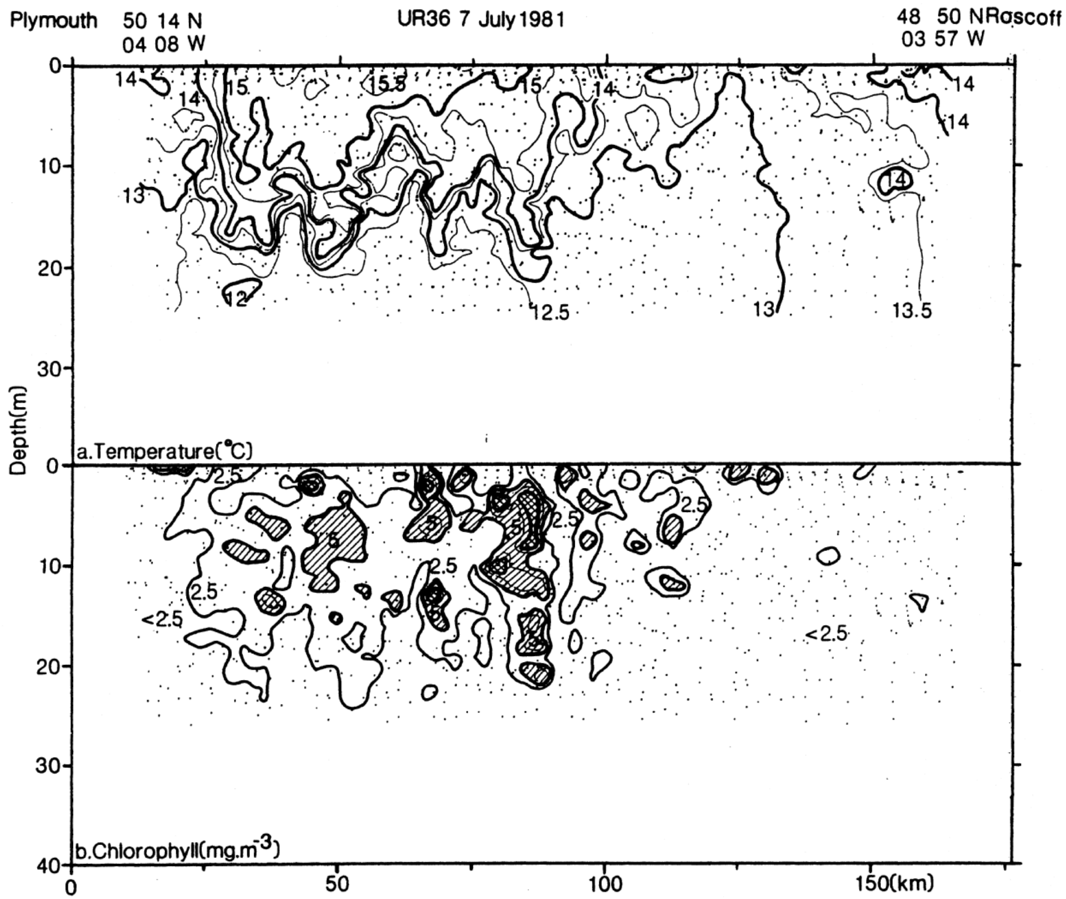
Surface and bottom temperatures (^oC) at station E1
1953-1964

(from Maddock & Swann (1977) J. mar. biol. Ass. UK **57**, 317)



From Pingree *et al*. (1982). Contin. Shelf Res. 1, 99-116

Celtic Sea and Armorican current structure and the vertical distributions of temperature and chlorophyll.



UOR Tow
Plymouth to Roscoff

7 July, 1981

From Robinson, Aiken & Hunt (1986) JMBA 66, 201-218.
‘Synoptic surveys of the western English Channel. The relationships between plankton and hydrography’.

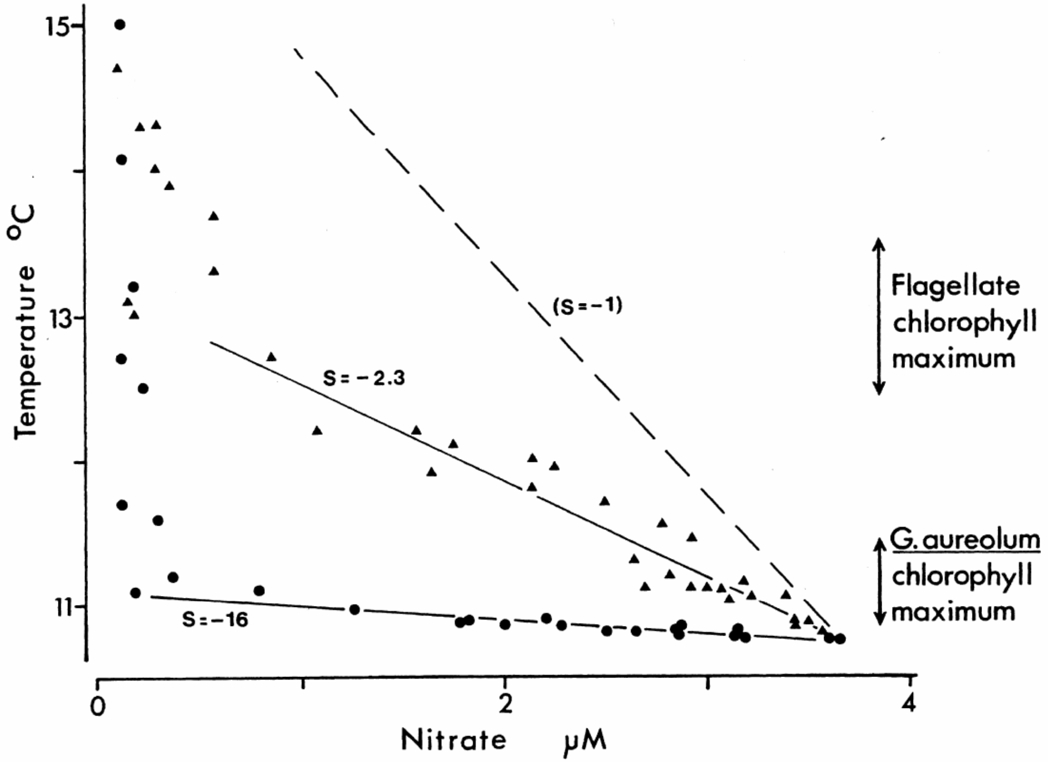
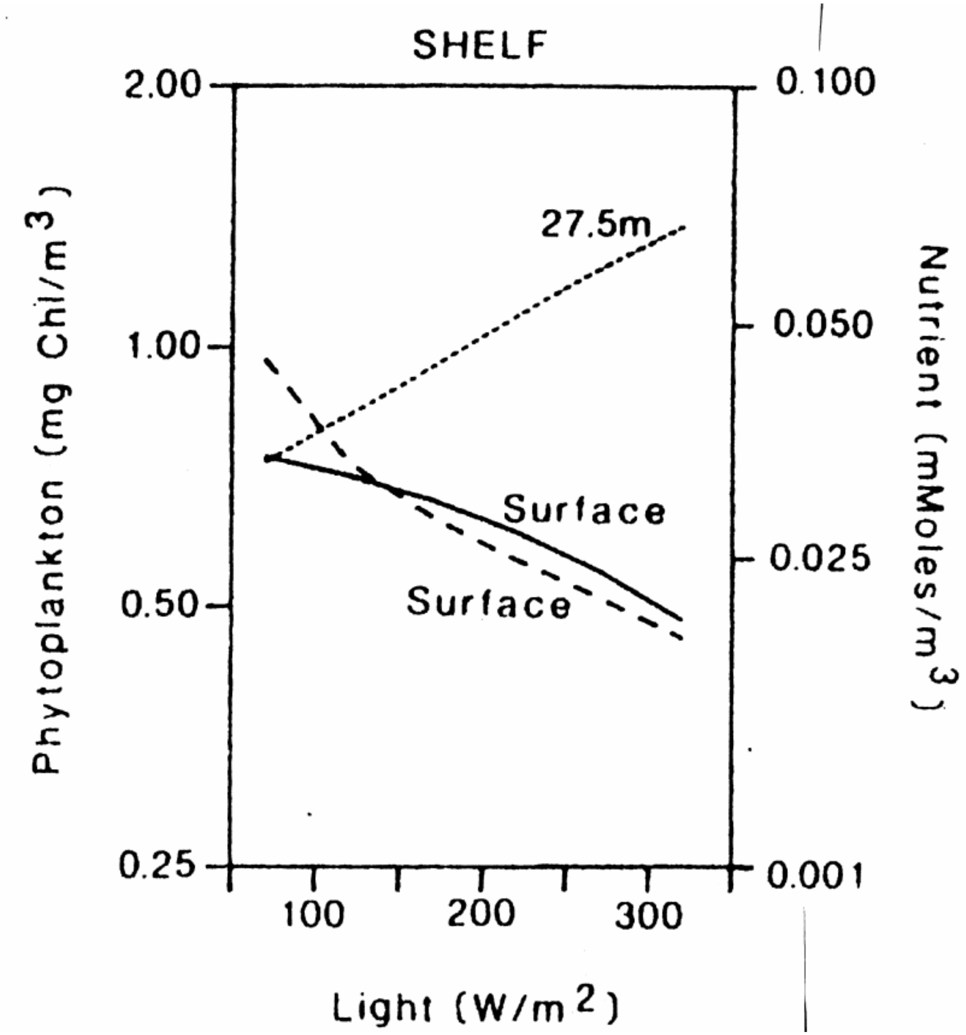


Fig. 4. Temperature-nitrate plots for chlorophyll profiles dominated by *Gyrodinium aureolum* (●) and by small flagellates (▲) at Station E5 on 27 and 28 Jul, 1981. Maximum chlorophyll concentrations were ~2 and 20 mg m^{-3} (Fig. 1A, B). Lines show relative gradients of changes in temperature to changes in nitrate (S). Dashed line (S = −1); expected distribution of nitrate if there was no uptake in the thermocline (i.e. changes in nitrate universely proportional to those in temperature)

From Holligan *et al*. (1984) Mar. Ecol. Prog. Ser. 17, 201-213.

Photosynthesis, respiration and nitrogen supply of plankton populations in stratified, frontal and tidally mixed waters

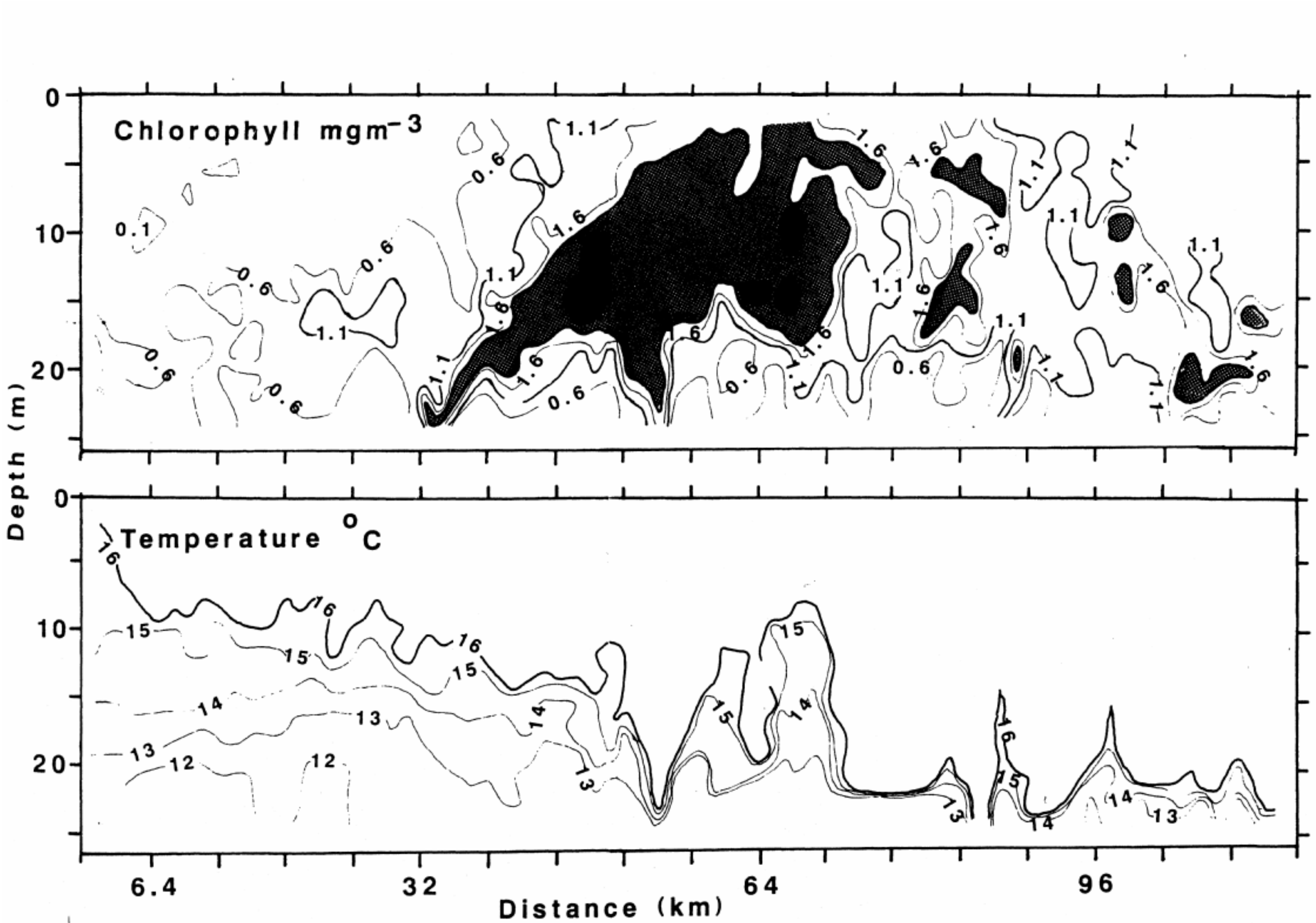
Western English Channel 1981



The dependence of phytoplankton (dashed lines) and nutrient (solid lines) concentrations after 100 days on light incident at the surface.

From Taylor, Harris & Aiken (1986). Marine Interfaces Ecohydrodynamics (ed JCJ Nihoul), pp 313-330. The interaction of physical and biological processes in a model of the vertical distribution of phytoplankton under stratification.

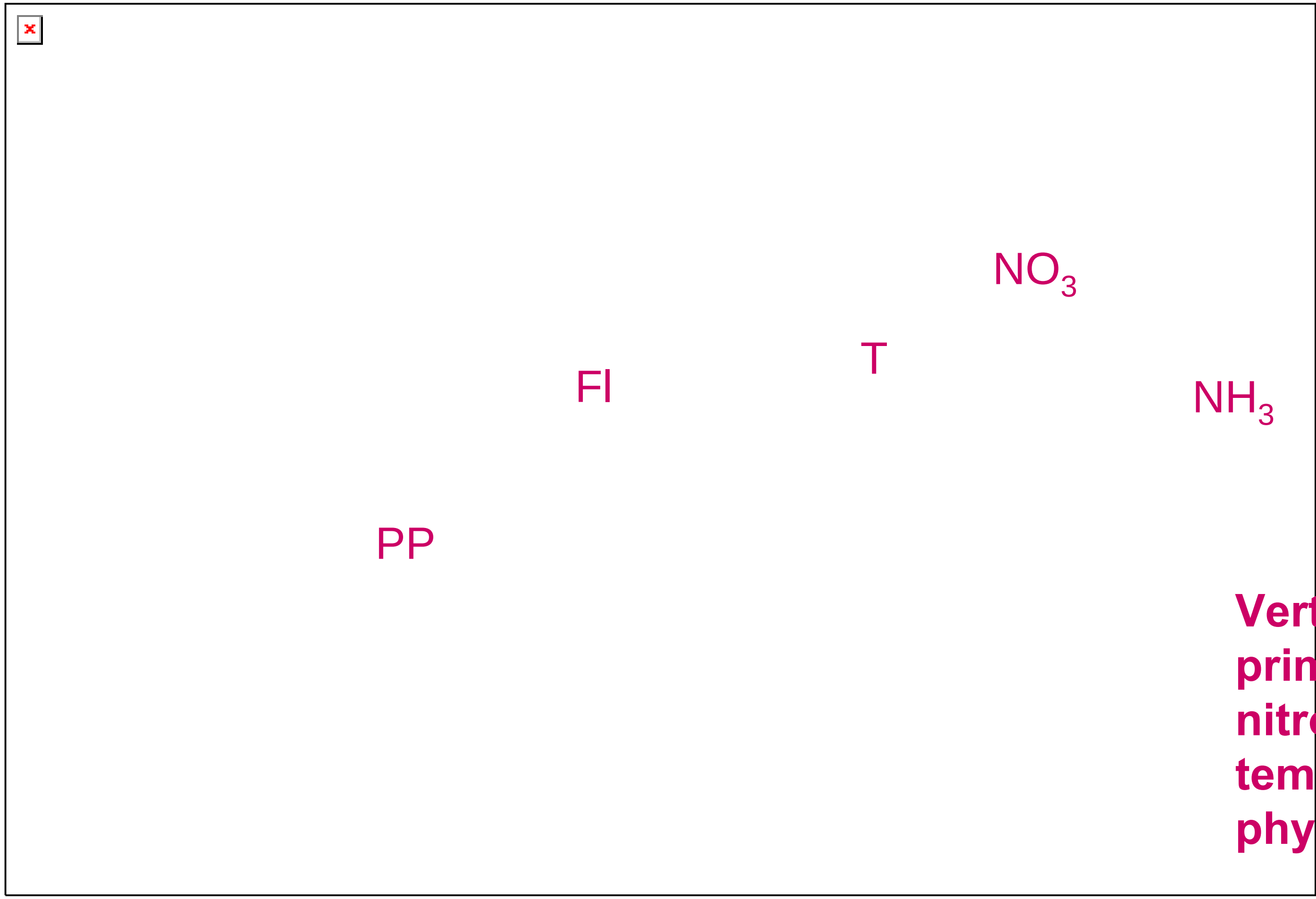
PART II



Undulating Oceanographic Recorder Tow 22. Intermediate shading >2.1 <5.1 mg chlorophyll m^{-3}, heavy shading >5.1 mg m^{-3}.

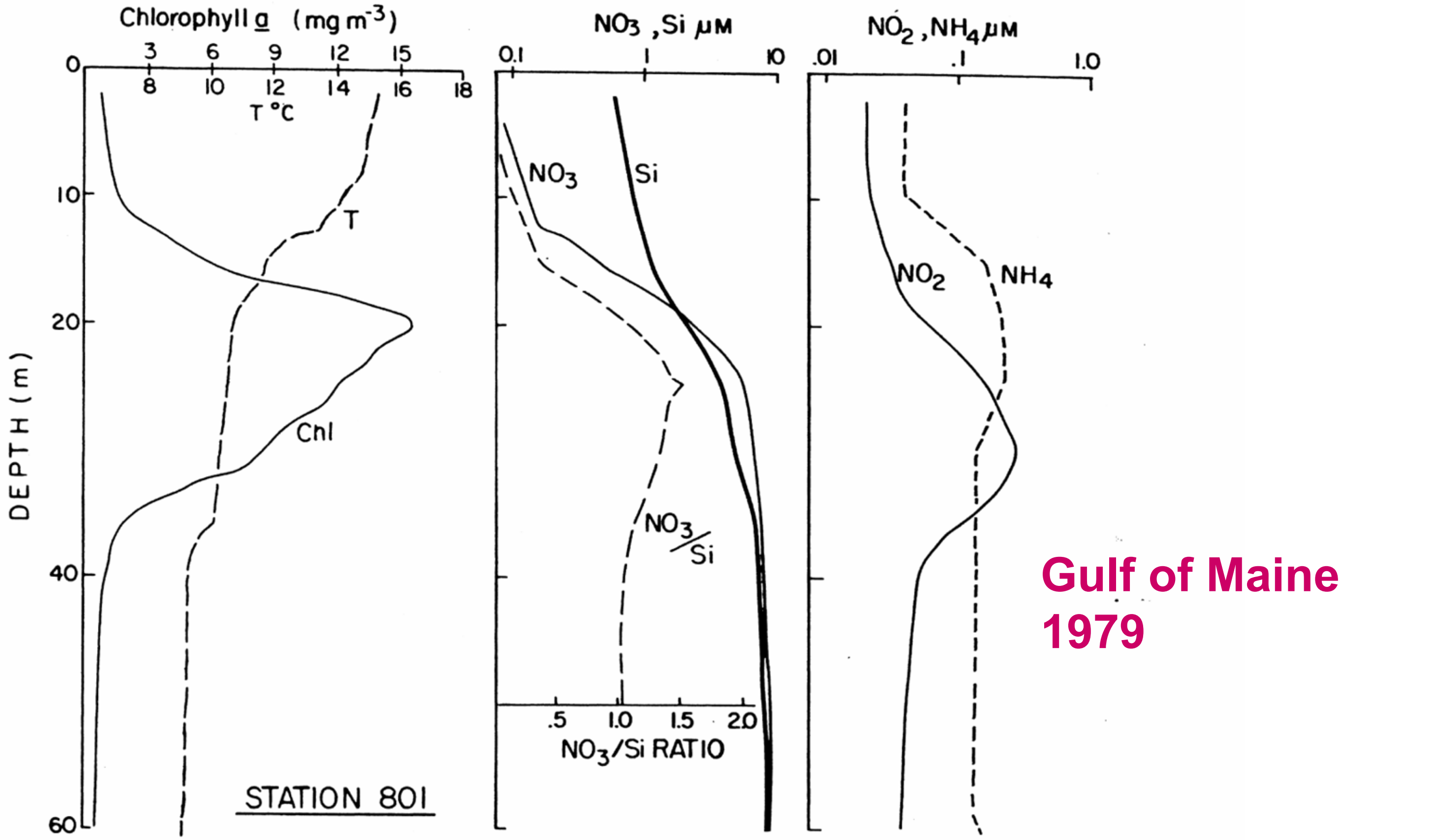
UOR Tow
SE North Sea
July 1987

From Owens, Woodward, Aiken, Bellan & Rees (1990).
Neth. J. Sea Res. 25, 143-154.
Primary production and nitrogen assimilation in the North Sea during July 1987.



Vertical profiles of primary production, nitrogen assimilation, temperature and chlorophyll fluorescence.

From Owens, Woodward, Aiken, Bellan & Rees (1990).
Neth. J. Sea Res. 25, 143-154.
Primary production and nitrogen assimilation in the North Sea during July 1987.



Vertical profiles at station 801 (see Fig. 1A). Note that the nutrient concentrations are plotted on logarithmic scales.

Gulf of Maine
1979

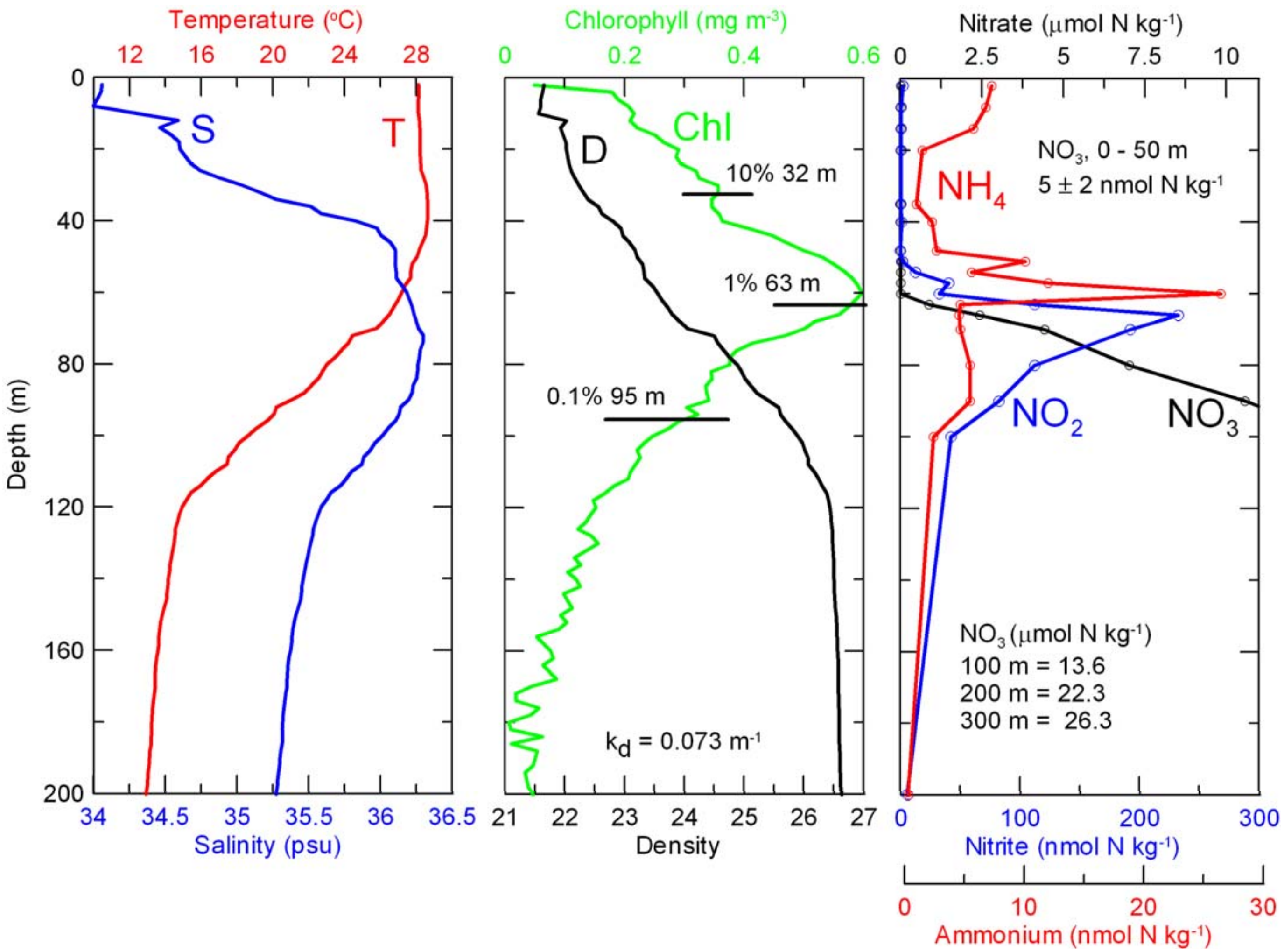
From Holligan, Balch & Yentsch (1984) J. Mar. Res. 42, 1051-1073.

The significance of subsurface chlorophyll, nitrite and ammonia maxima in relation to nitrogen for phytoplankton growth in stratified waters of the Gulf of Maine.

Vertical distributions (0-200m) of water properties at a station in the NECC

(Note changes in scale for the different forms of inorganic N)

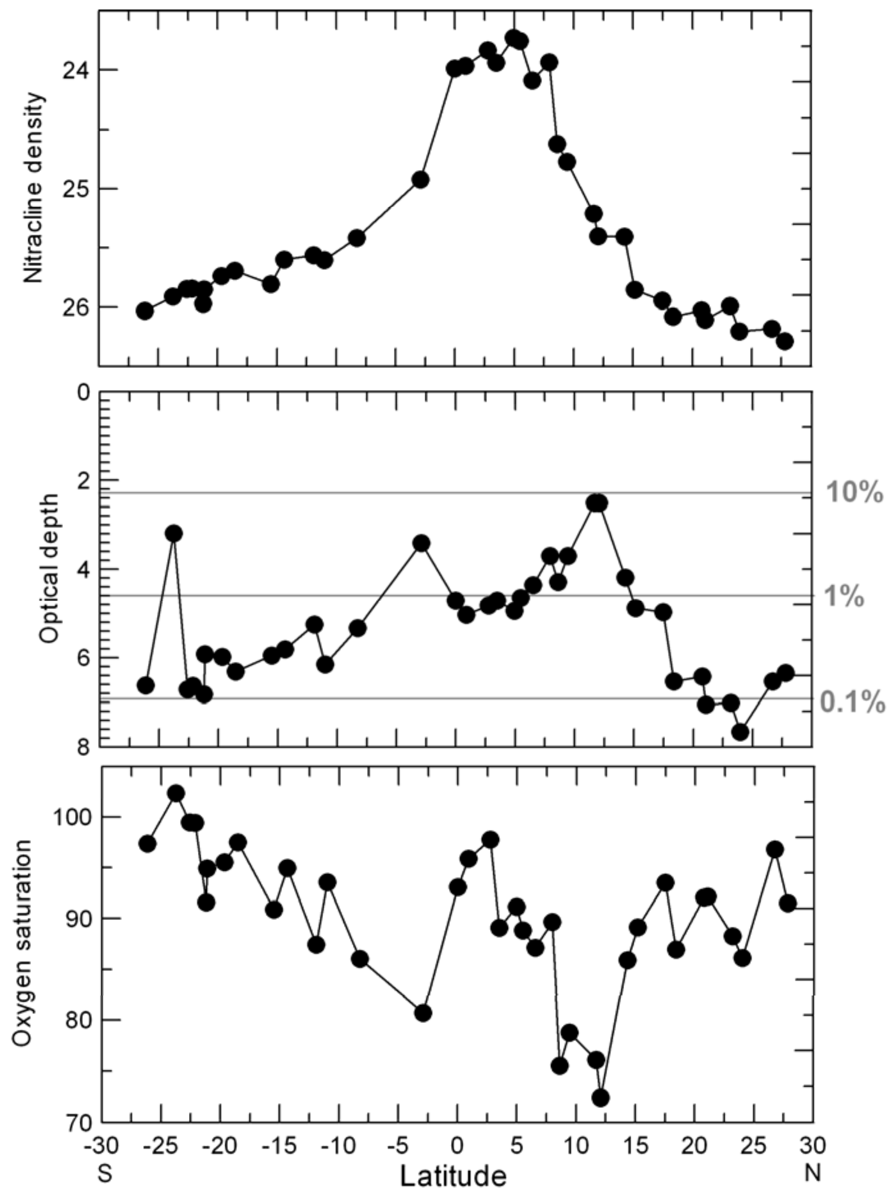
AMT-17, CTD30: 5.46°N, 27.61°W, November 2005

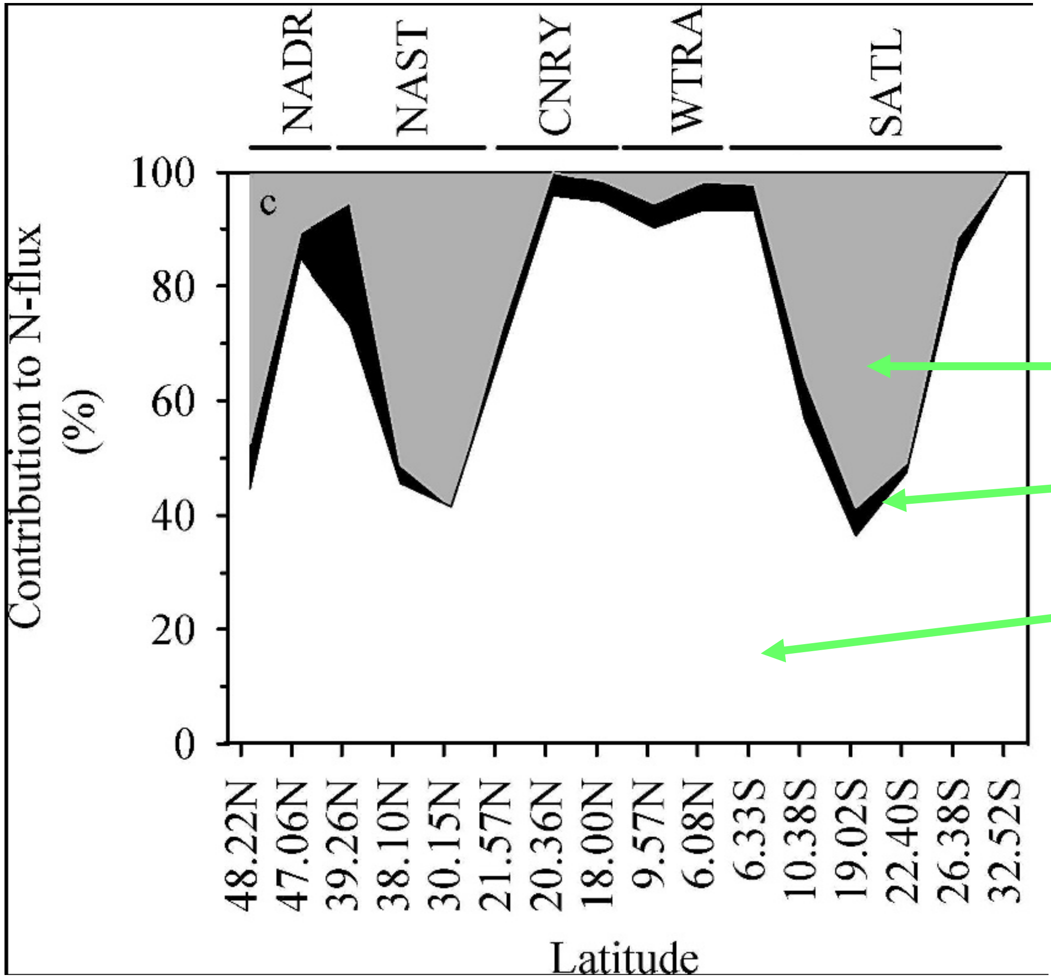


AMT 17. Water properties at the nitracline

(1 µM NO_3)

UK to South Africa
Oct – Nov 2005





AMT 13, Sept-Oct 2003

% contribution to total N flux at 1% of surface PAR:

NO_2 oxidation

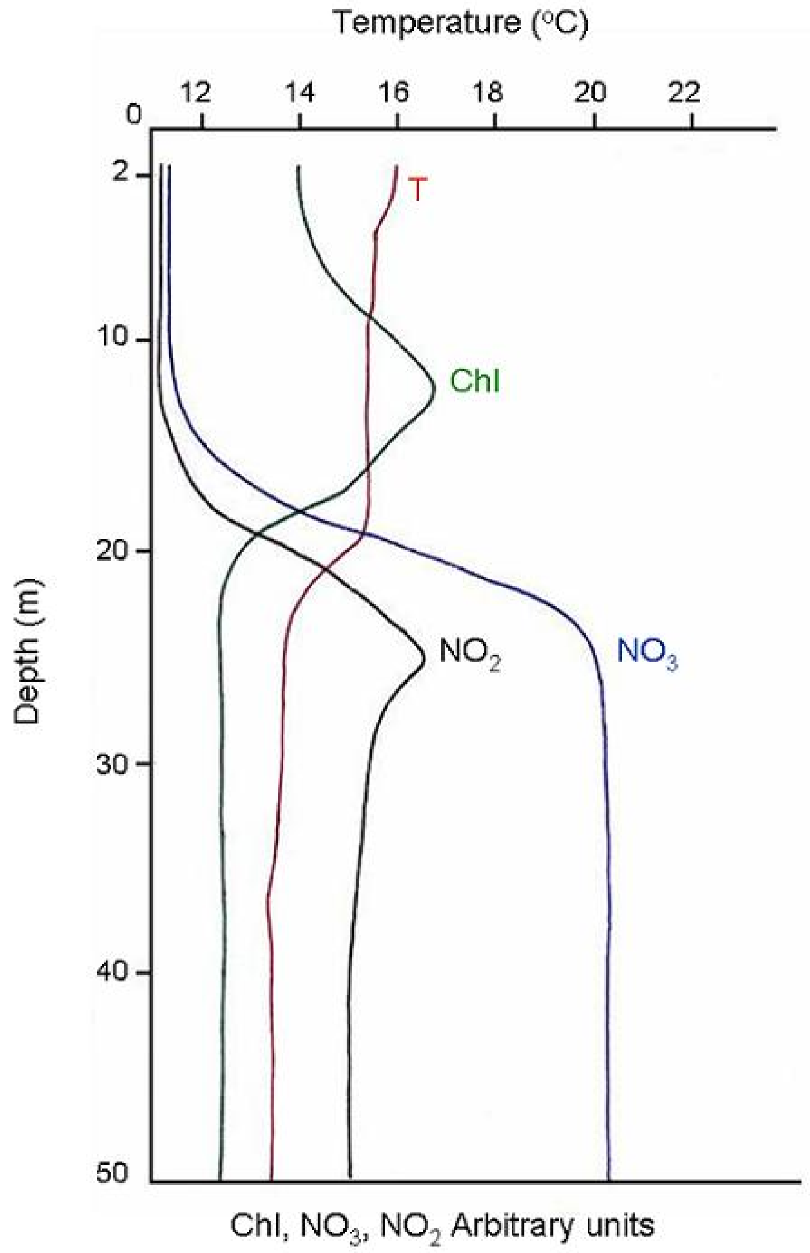
NH_4^+ oxidation

NH_4^+ regeneration

Turnover rates for NO2 variable but rapid

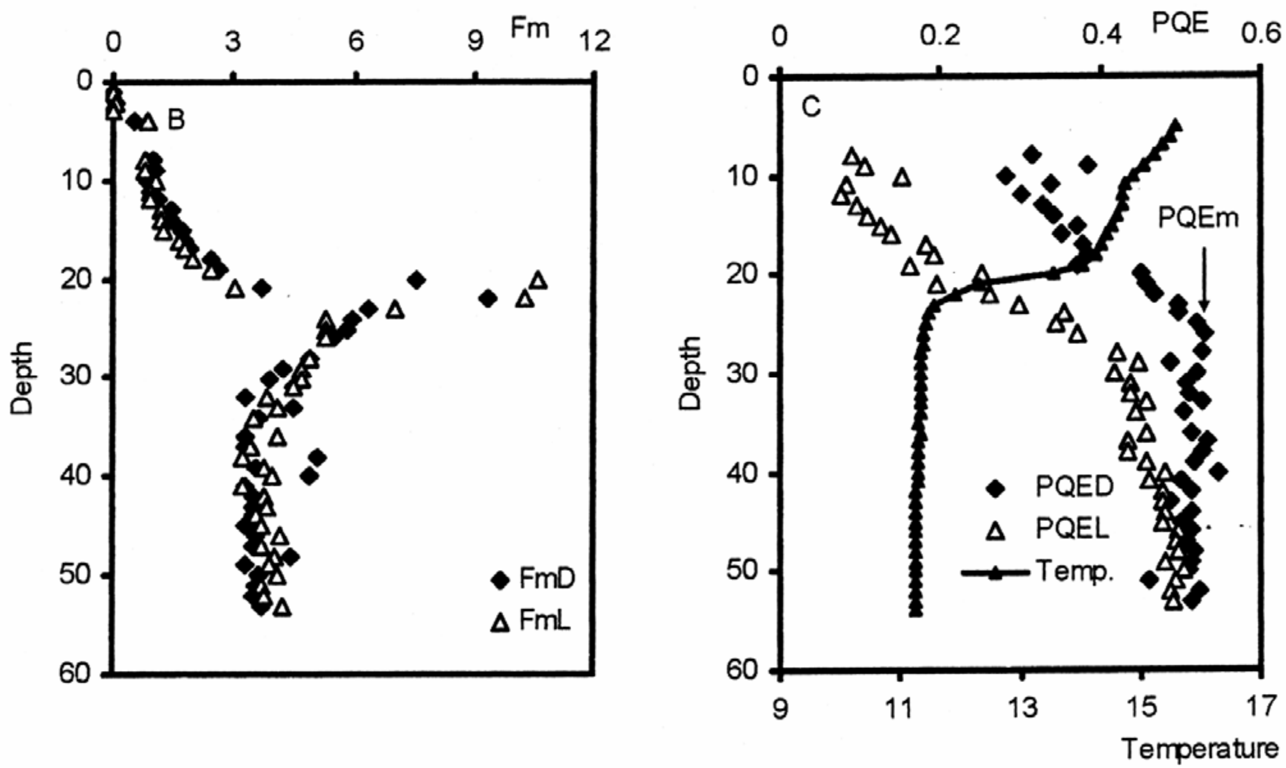
From Clark, Rees & Joint (2008)
Limnol. Oceanogr. 53, 52-62
Ammonium regeneration and nitrification rates in the oligotrophic Atlantic Ocean: Implication for new production estimates.

cf Lomas & Lipschulz (2006)
Limnol. Oceanogr. 51, 2453-2467
Forming the primary nitrite maximum: Nitrifiers or phytoplankton?



Station A1 off Plymouth
Early October, 1980

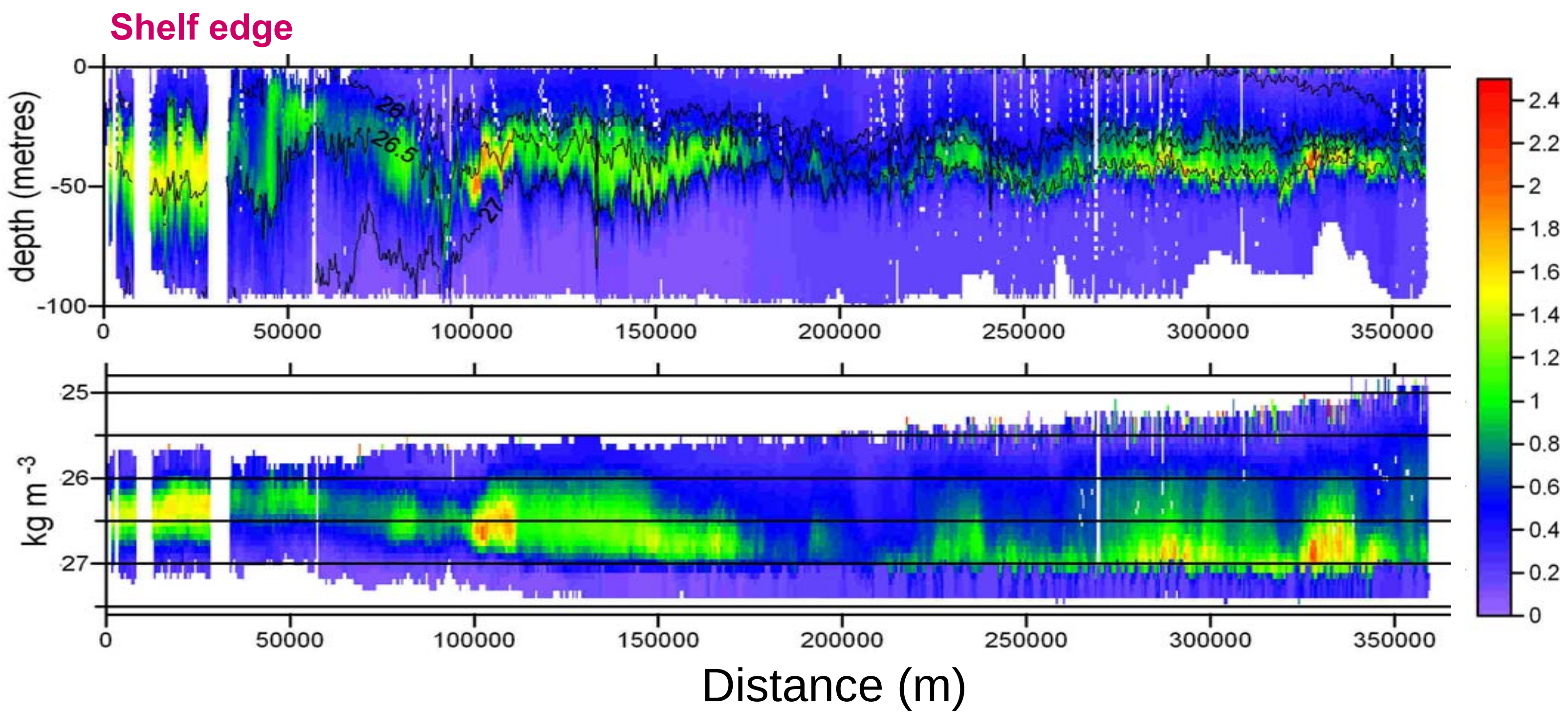
PART III



FRRF data from station E1, June 2001.

From Aiken *et al*. (2004). JMBA 84, 301-313.

The annual cycle of phytoplankton photosynthetic quantum efficiency, pigment composition and optical properties in the western English Channel.



Chlorophyll distribution as a function of a) depth (m) and b) density (σ_t) along a transect across the Celtic Sea

RRS James Clark Ross, August 2003

Celtic Sea 2003

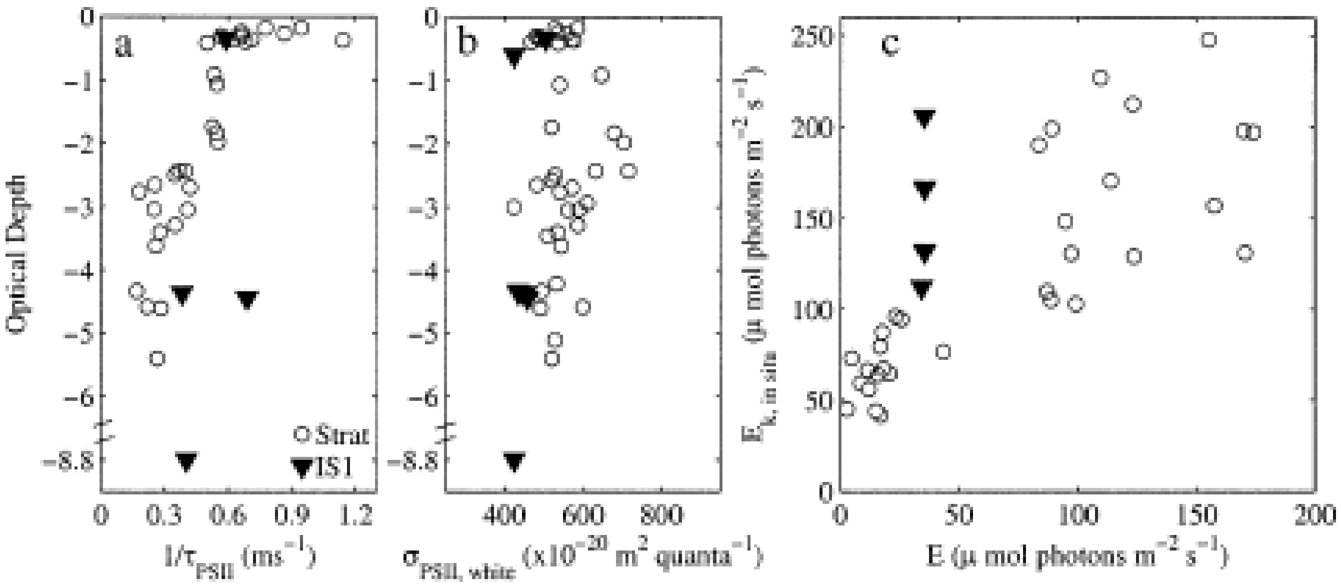
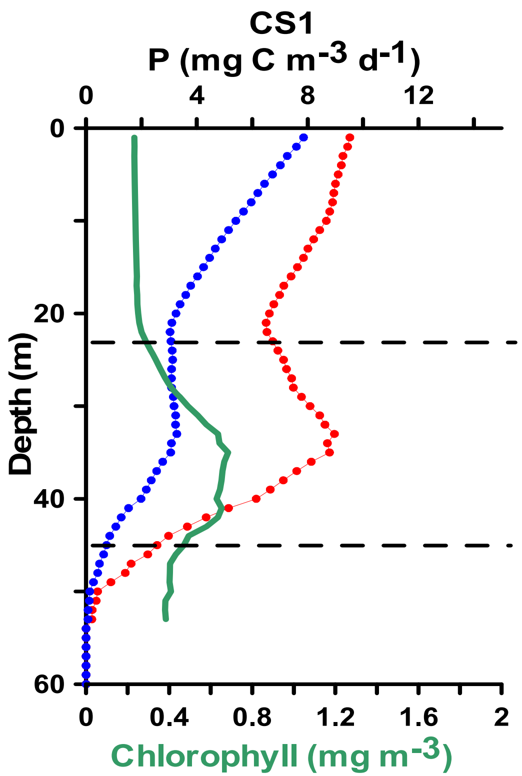


Fig. 7. Relation of photosynthetic parameters to optical depth (OD) and estimated mean 24-h irradiance. (a) $1/\tau_{PSII}$ versus OD (significant correlation observed for stratified sites, $r^2 = 0.725$ (0.761 for log-transformed $1/\tau_{PSII}$), $n = 31$, $p < 0.001$). (b) σ_{PSII} versus OD, no significant relation found. (c) $E_{k\,in\,situ}$ from ^{14}C P versus E data as a function of estimated mean daily irradiance. (For stratified stations, $r^2 = 0.702$, $n = 31$, $p < 0.001$).

From Moore *et al*. (2006). Limnol. Oceanogr. 51, 936-949.
Phytoplankton acclimation and photoadaptation in response to environmental gradients in a shelf sea.

Estimates of daily *in situ* Primary Production (PP)

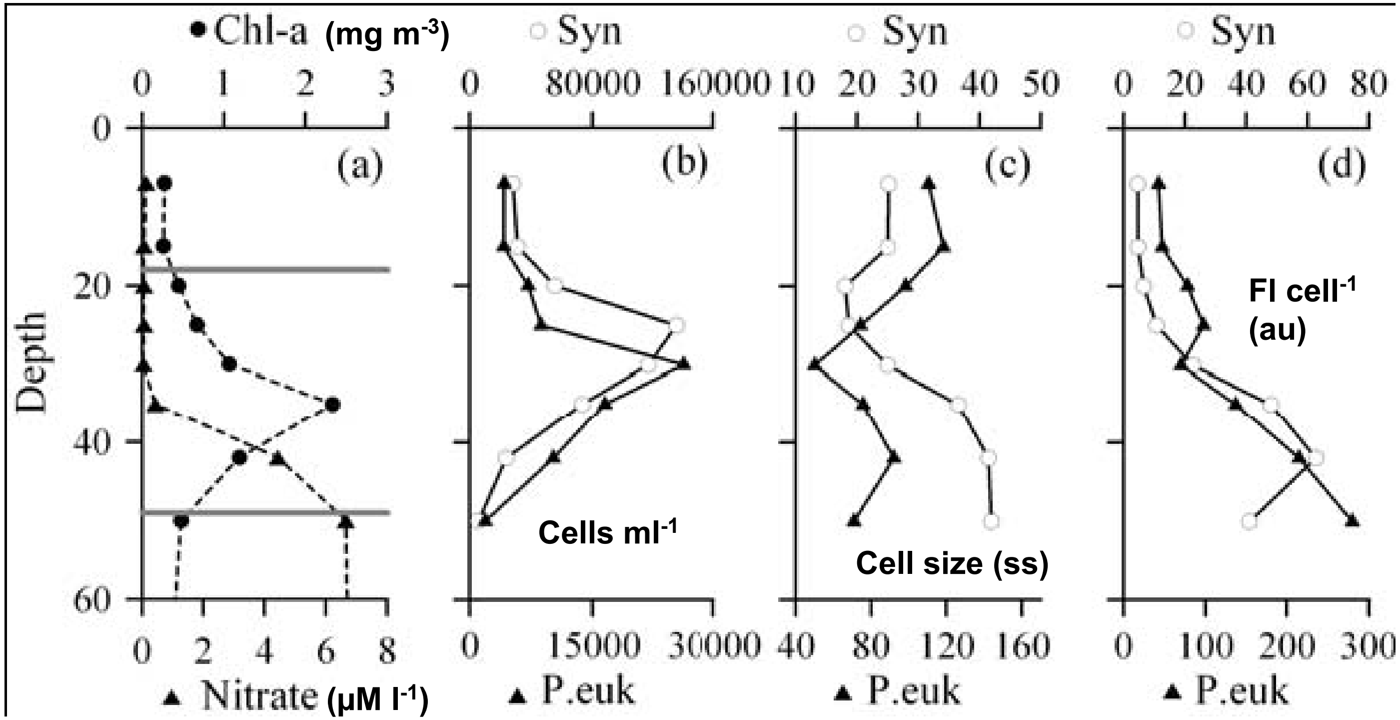


Station CS1, Celtic Sea
August 2003

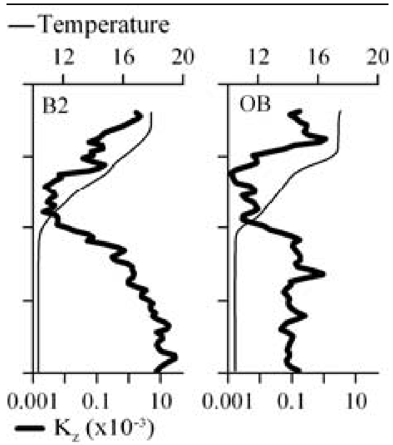
(courtesy of A. Hickman)

Cloudy day (Mean 188.1 μE m^{-2} s^{-1})
Sunny day (Mean 625.1 μE m^{-2} s^{-1})

		CLOUDY	SUNNY
TOTAL PP	(mg C m^{-2} d^{-1})	174	343
SURFACE PP	"	116	184
THERM PP	"	58	159



Vertical eddy diffusivity



Observations on picoplankton within the seasonal thermocline at station JB1 in the Celtic Sea, July 2005.

Courtesy of Anna Hickman.

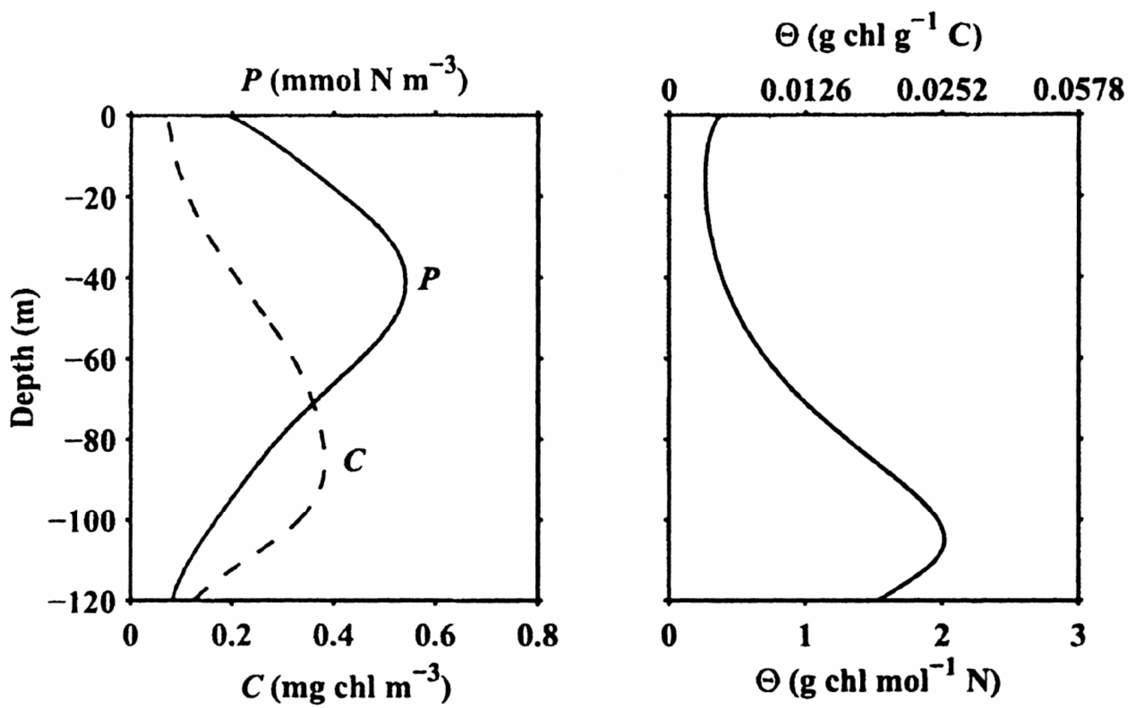


Fig. 12. Model-predicted profiles of phytoplankton *P*, chlorophyll *C*, and the chlorophyll : phytoplankton nitrogen ratio Φ. To compare the simulated values of the chlorophyll : biomass ratio Φ (g Chl mol^{-1} N) with observed ratios, we converted Φ to g Chl (g $C)^{-1}$ by dividing by the Redfield ratio C : N = 106 : 16 and by the molar weight of carbon (upper axis in right panel).

From Fennel & Boss (2003). Limnol. Oceanogr. 48, 1521-1534.

Subsurface maxima of phytoplankton and chlorophyll: Steady-state solutions from a simple model.

Estimates of NO_3-N fluxes across the seasonal thermocline (mid-summer) in the Celtic Sea

a) Based on direct measurements of energy dissipation
(Rippeth *et al*. (2006) unpublished)

2-4 (-37) mMol N m^{-2} d^{-1}

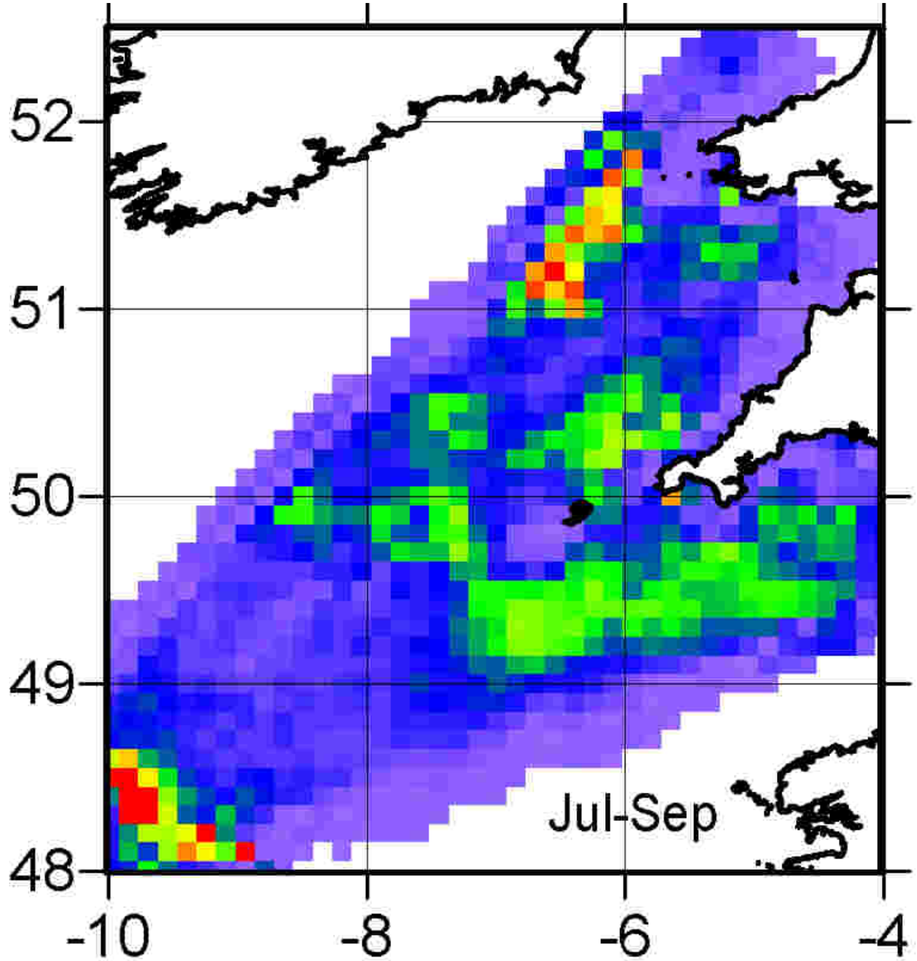
High values due to local physical forcing

b) Based on seasonal heat flux calculations
(Holligan *et al*. (1984) Mar. Ecol. Prog. Ser. **17**, 201)

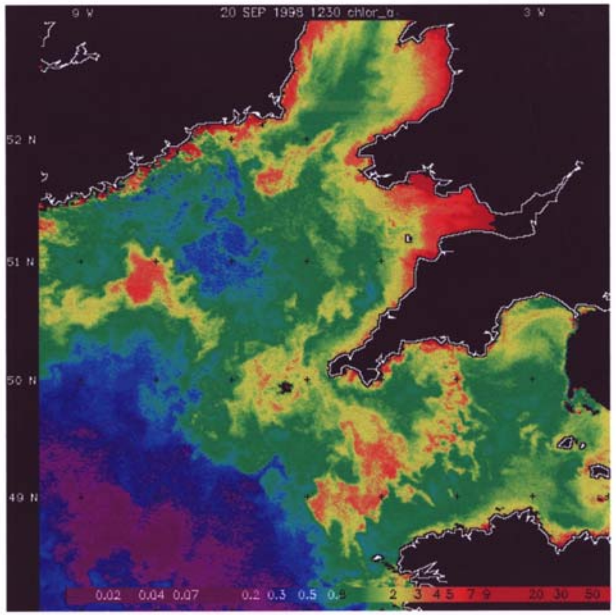
2-3 (-29) mMol N m^{-2} d^{-1}

High values due to biological forcing

Note that, over a period of ~ 3 months, values of 2-4 mMol N m^{-2} d^{-1} are equivalent to NO_3 assimilation during the spring bloom.



Distribution of fishing boats, mid to late summer. (J. Sharples)



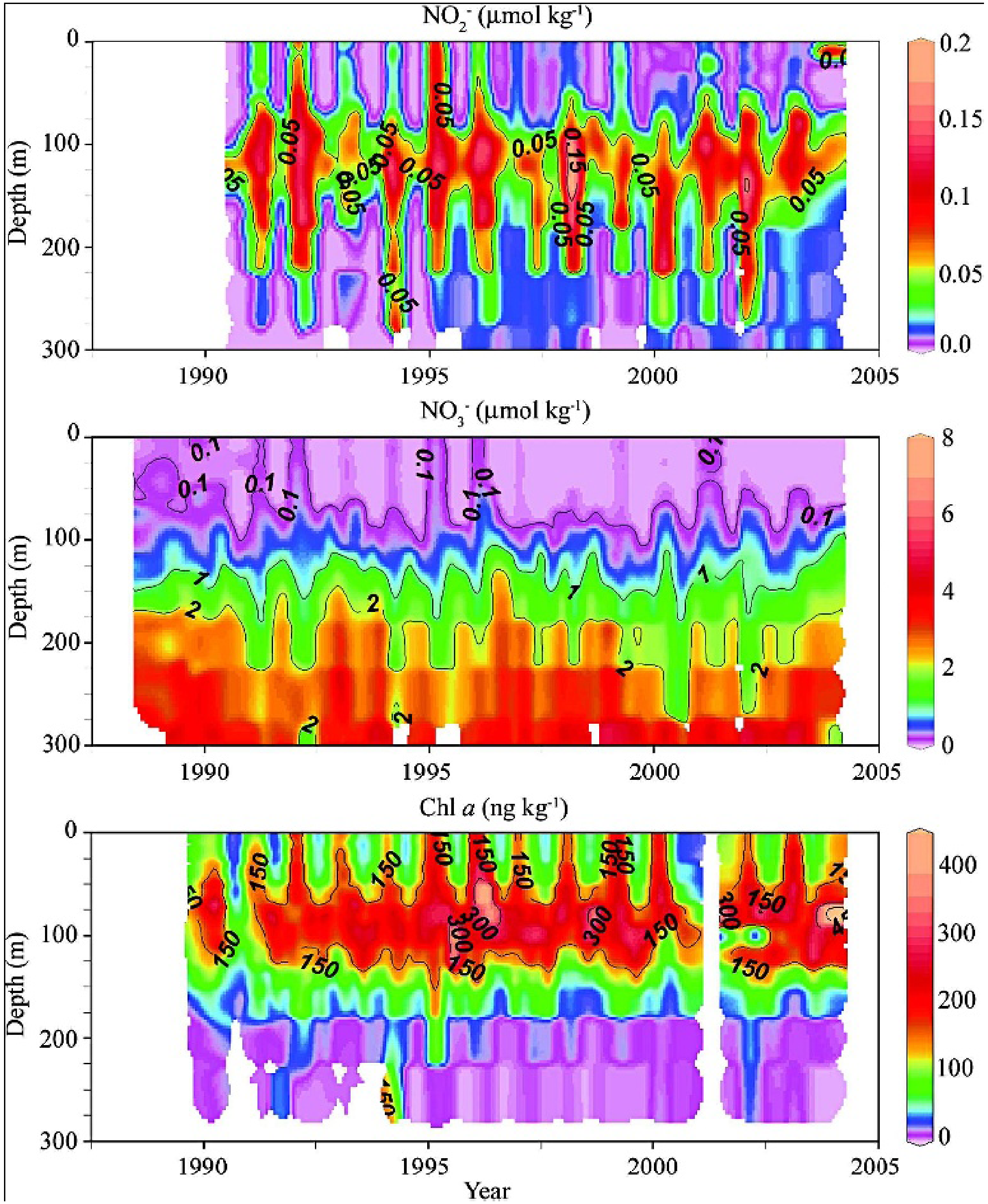
SeaWIFS surface chlorophyll, 20th September 1998.

Image courtesy of the Remote Sensing Group, Plymouth Marine Laboratory

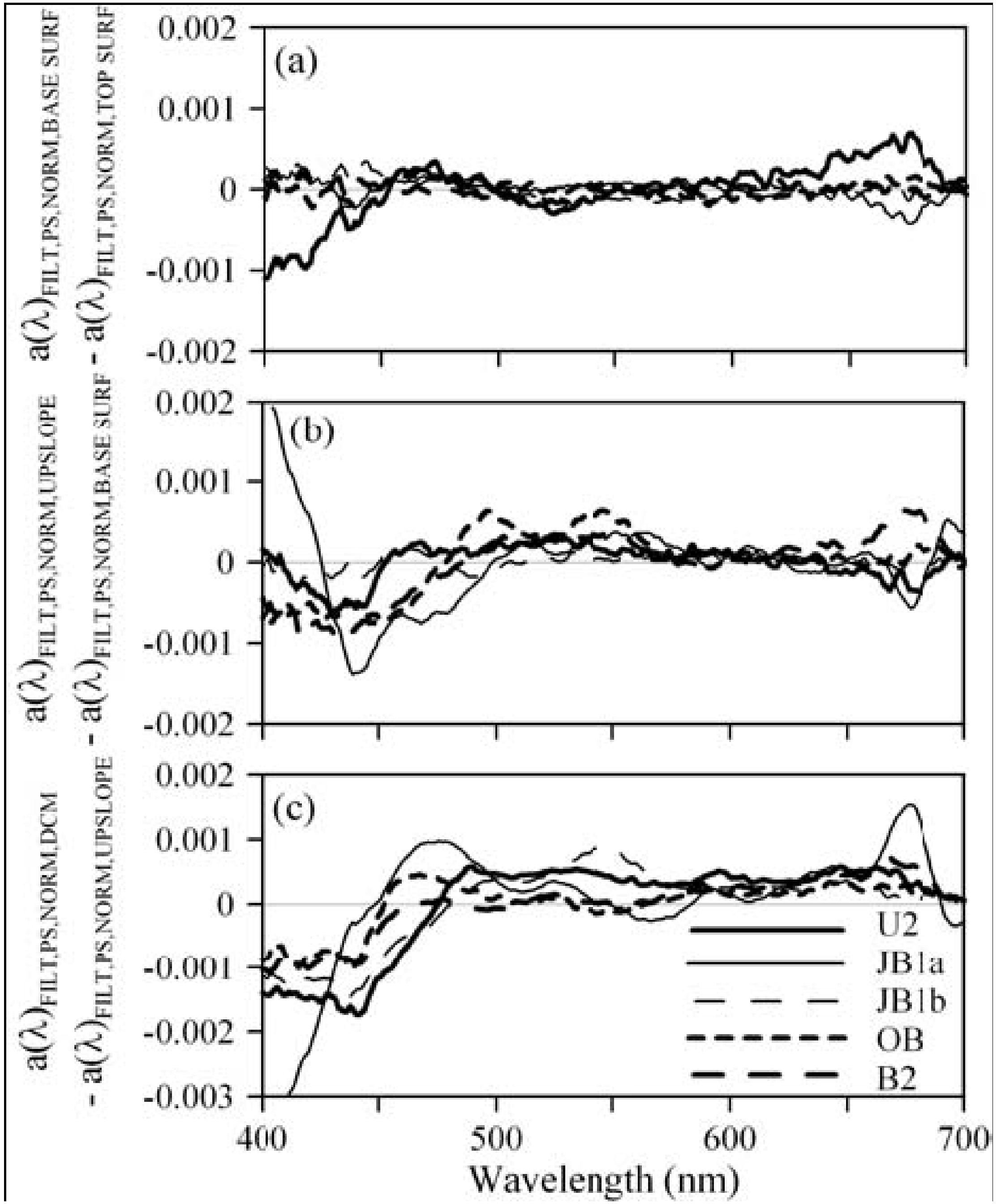
CONCLUSION

Perhaps Aiken's 2nd law should be:

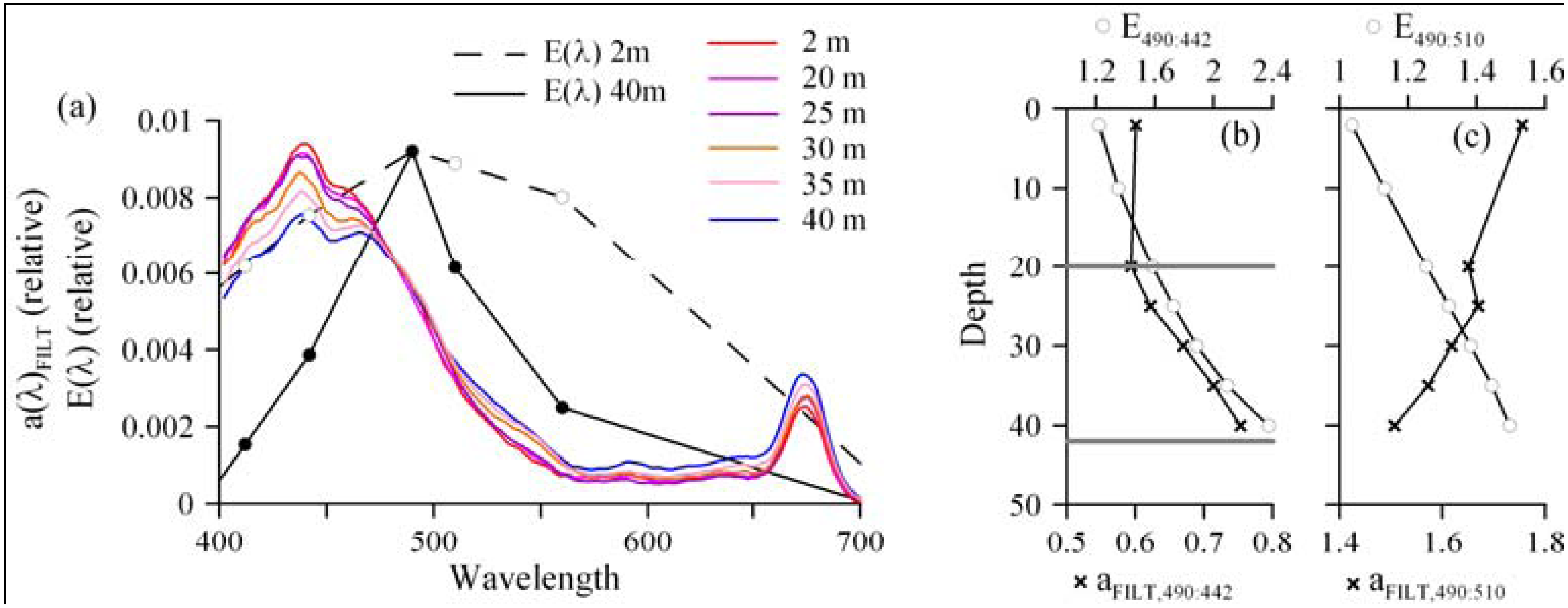
'If you can see it from space it's important'!



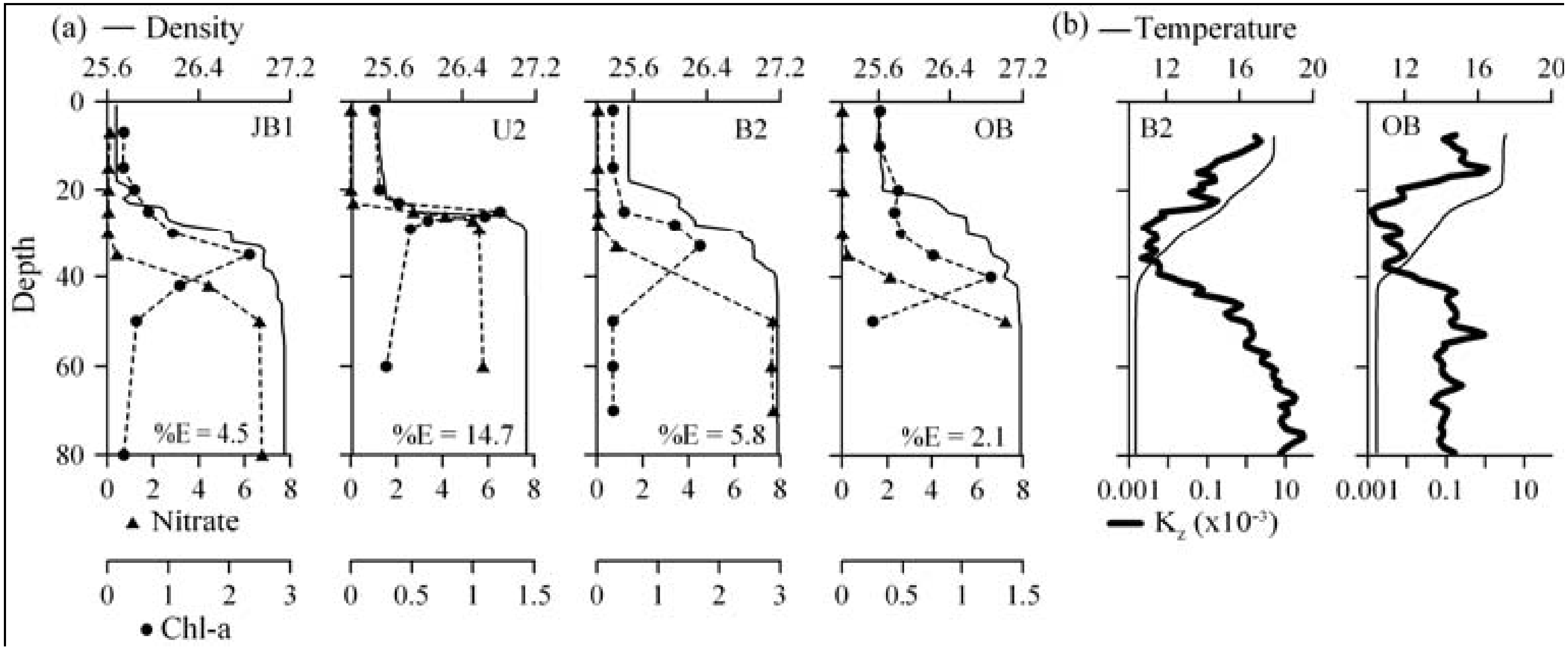
NO$_2^-$ (µmol kg^{-1})
NO$_3^-$ (µmol kg^{-1})
Chl *a* (ng kg^{-1})
Depth (m)
Year



(a)
(b)
(c)
0.002
0.001
0
-0.001
-0.002
-0.003
400
500
600
700
Wavelength (nm)
a(λ)FILT,PS,NORM,BASE SURF - a(λ)FILT,PS,NORM,TOP SURF
a(λ)FILT,PS,NORM,UPSLOPE - a(λ)FILT,PS,NORM,BASE SURF
a(λ)FILT,PS,NORM,DCM - a(λ)FILT,PS,NORM,UPSLOPE
U2
JB1a
JB1b
OB
B2

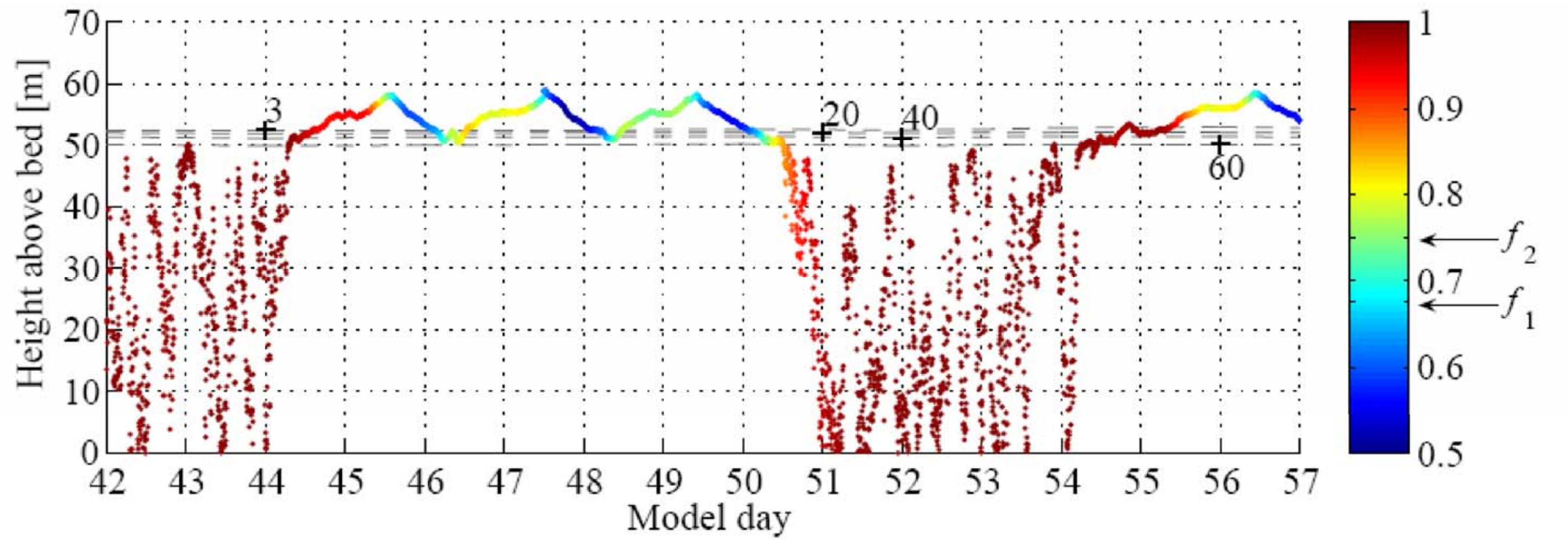


(a)
E(λ) 2m
E(λ) 40m
2 m
20 m
25 m
30 m
35 m
40 m
$a(\lambda)_{FILT}$ (relative)
E(λ) (relative)
Wavelength
(b)
(c)
$E_{490:442}$
$E_{490:510}$
Depth
$a_{FILT,490:442}$
$a_{FILT,490:510}$



(a) — Density
25.6
26.4
27.2
JB1
U2
B2
OB
Depth
%E = 4.5
%E = 14.7
%E = 5.8
%E = 2.1
▲ Nitrate
● Chl-a
(b) —Temperature
12
16
20
B2
OB
0.001
0.1
10
K_z (x10^{-3})

Nutrient quota scale :
<f_1 cells swim down
>f_2 cells swim up

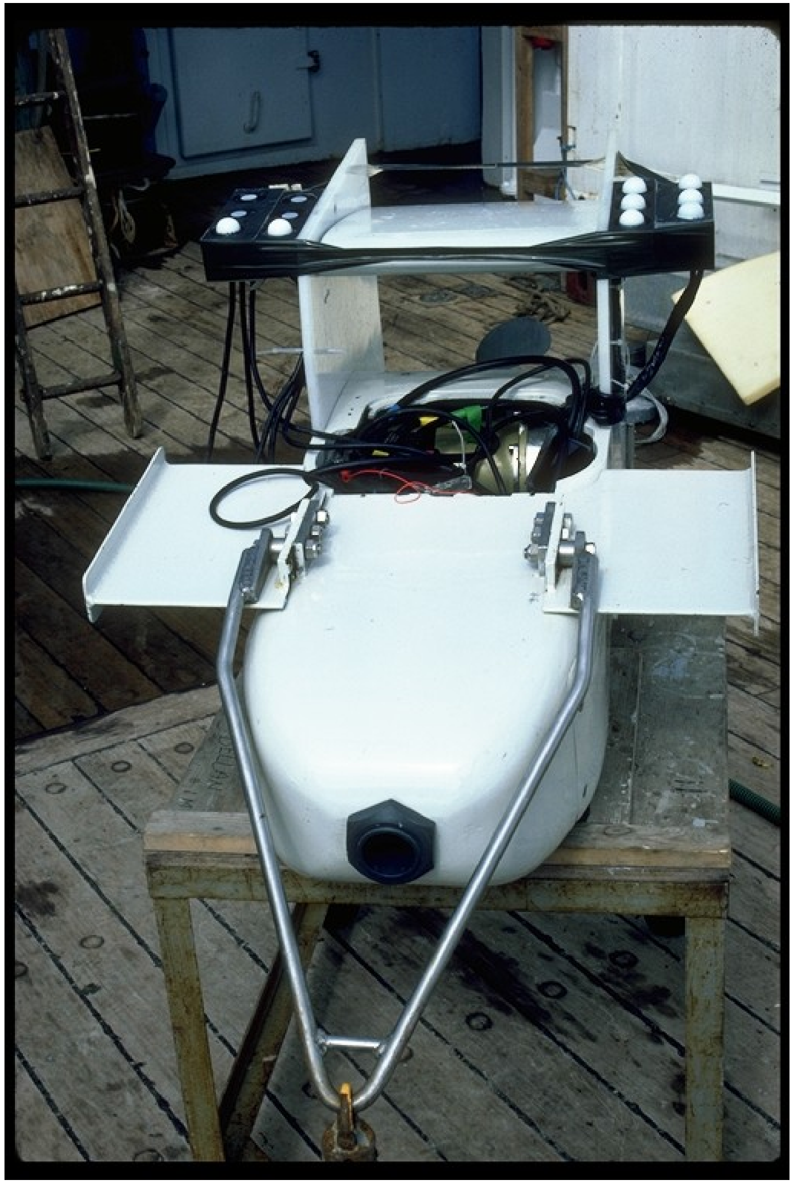


1-D numerical model of vertical migration by a dinoflagellate with a swimming speed of 0.1mm sc-1

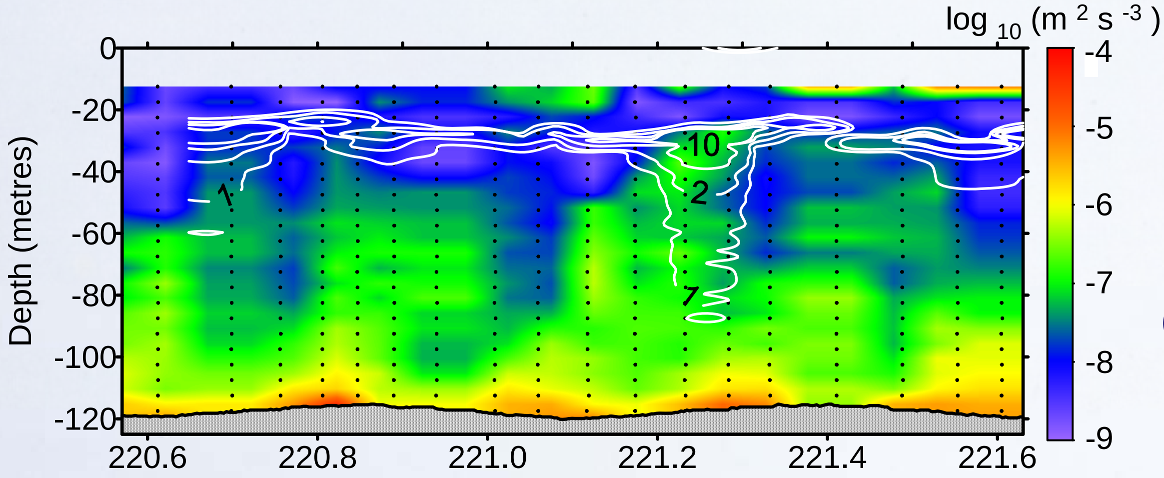
(from Ross & Sharples, J. Mar. Systems in press)


NASA/GSFC


NASA
NASA/GSFC
SeaWiFS
Project

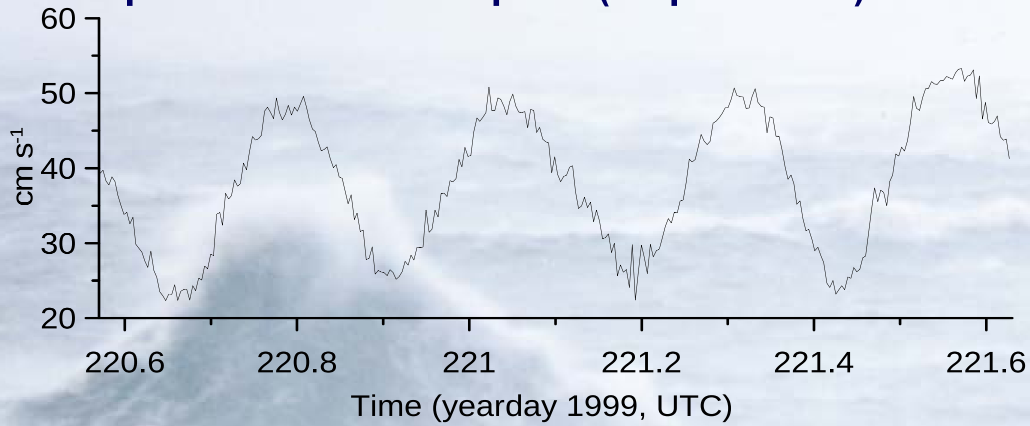


Tidal mixing at the base of the chlorophyll maximum



Chlorophyll (lines) and turbulent dissipation (coloured) over the 25 hour time series.

Depth-mean current speed (ship's ADCP)



RRS *Challenger*

W Channel, Aug 1999

(from Sharples *et al.* (2001)

Limnol. Oceanogr. **46**, 486.)

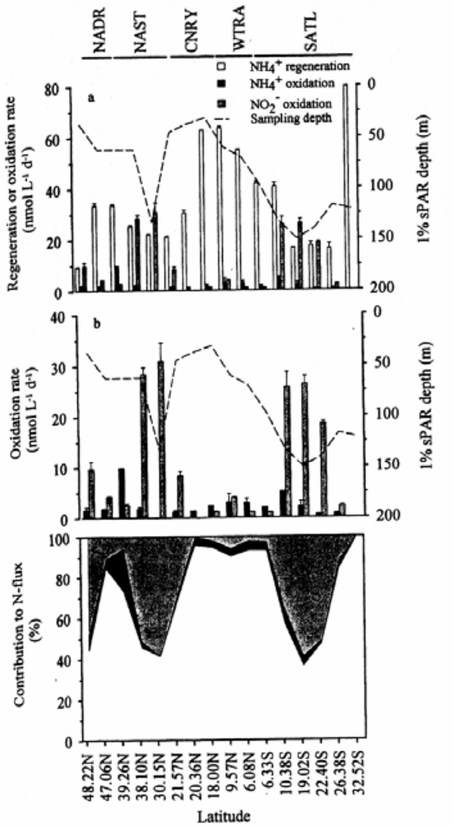


Fig. 5. (a) NH_4^+ regeneration, NH_4^+ oxidation, and NO_2^- oxidation rates (nmol L^{-1} d^{-1}) measured at the 1% sPAR depth. (b) NH_4^+ regeneration rate data omitted to allow for scale expansion. (c) Percentage contribution from NH_4^+ regeneration, NH_4^+ oxidation, and NO_2^- oxidation to total measured N flux.

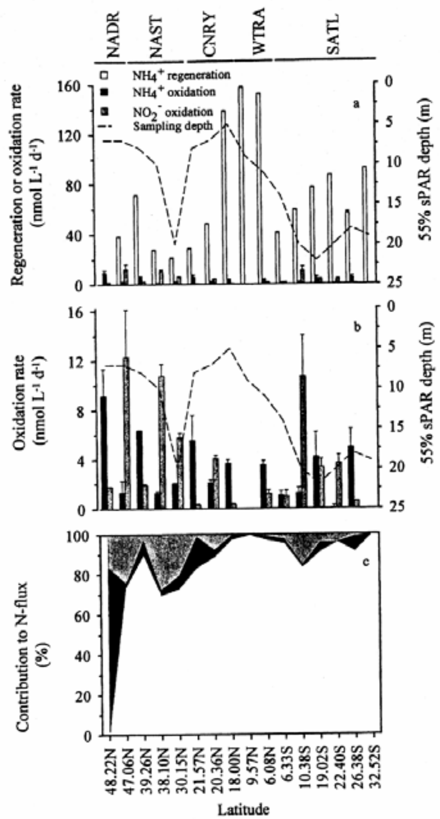
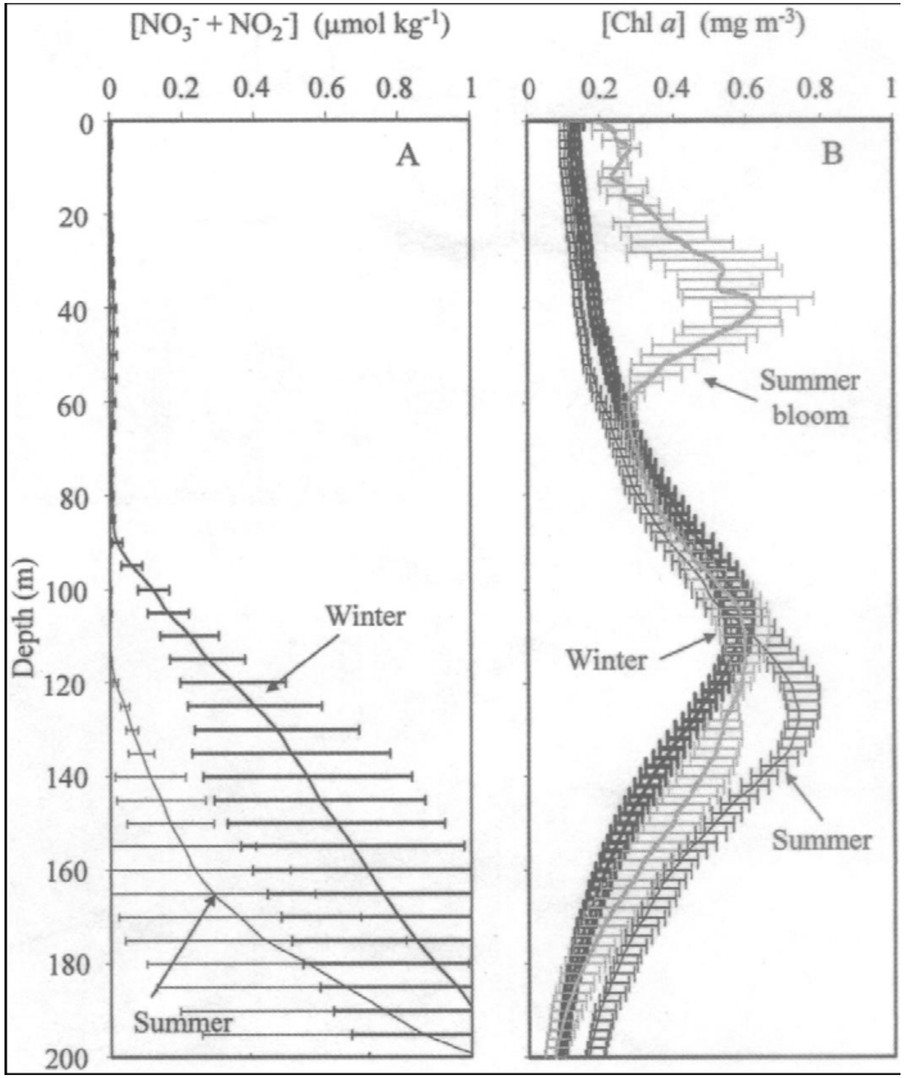


Fig. 6. (a) NH_4^+ regeneration, NH_4^+ oxidation, and NO_2^- oxidation rates (nmol L^{-1} d^{-1}) measured at the 55% sPAR depth. (b) NH_4^+ regeneration rate data to expand the scale. (c) The percentage contribution from NH_4^+ regeneration, NH_4^+ oxidation and NO_2^- oxidation to total measured N flux.

...dency for turnover rates due to NH_4^+ regeneration to

providing a NO_2^- source, could replace at least half of the



From Letelier *et al*. (2004). Limnol. Oceanogr. 49, 508-519
Light driven seasonal patterns of chlorophyll and nitrate in the lower euphotic zone of the North Pacific Subtropical Gyre.

Nitrate assimilation associated with summer deepening of the DCM is equivalent to 34% of the annual sedimentary flux of Nitrogen at 150m.