Climate Variability Studies in the Ocean

Topic 1.

- Long-term variations of vertical profiles of nutrients in the western North Pacific

Topic 2.

- Biogeochemical processes related to ocean carbon cycling: biogenic particle – metal interaction.

Background

Climate Changes and Oceans

1. Oceanic response to climate change
2. Effects to carbon cycling in the ocean
3. Ecological effects due to climate changes

Why is the western North Pacific Ocean important ecologically and climatologically?

Two major currents (Kuroshio and Oyashio) exist in the western North Pacific.
Kuroshio: a western boundary current, warm and salty
Oyashio: a subarctic current cold and less salty

An important fishery exists in the western North Pacific.

Fishing catches are affected by ecological variation due to climate change.

Increase of green-house gases in the atmosphere

⇓

Climate change ⇒ Oceanic change ⇒ Change of nutrient supply into the euphotic layer

Current systems

Upwelling

Eddy formation

⇐ Feedback

Feedback to atmosphere

⇑

⇒Change of primary Production ⇒ Change of export fluxes ⇒ Effect to carbon cycling

⇒ Change of fish mass ⇒ Change of fish catch

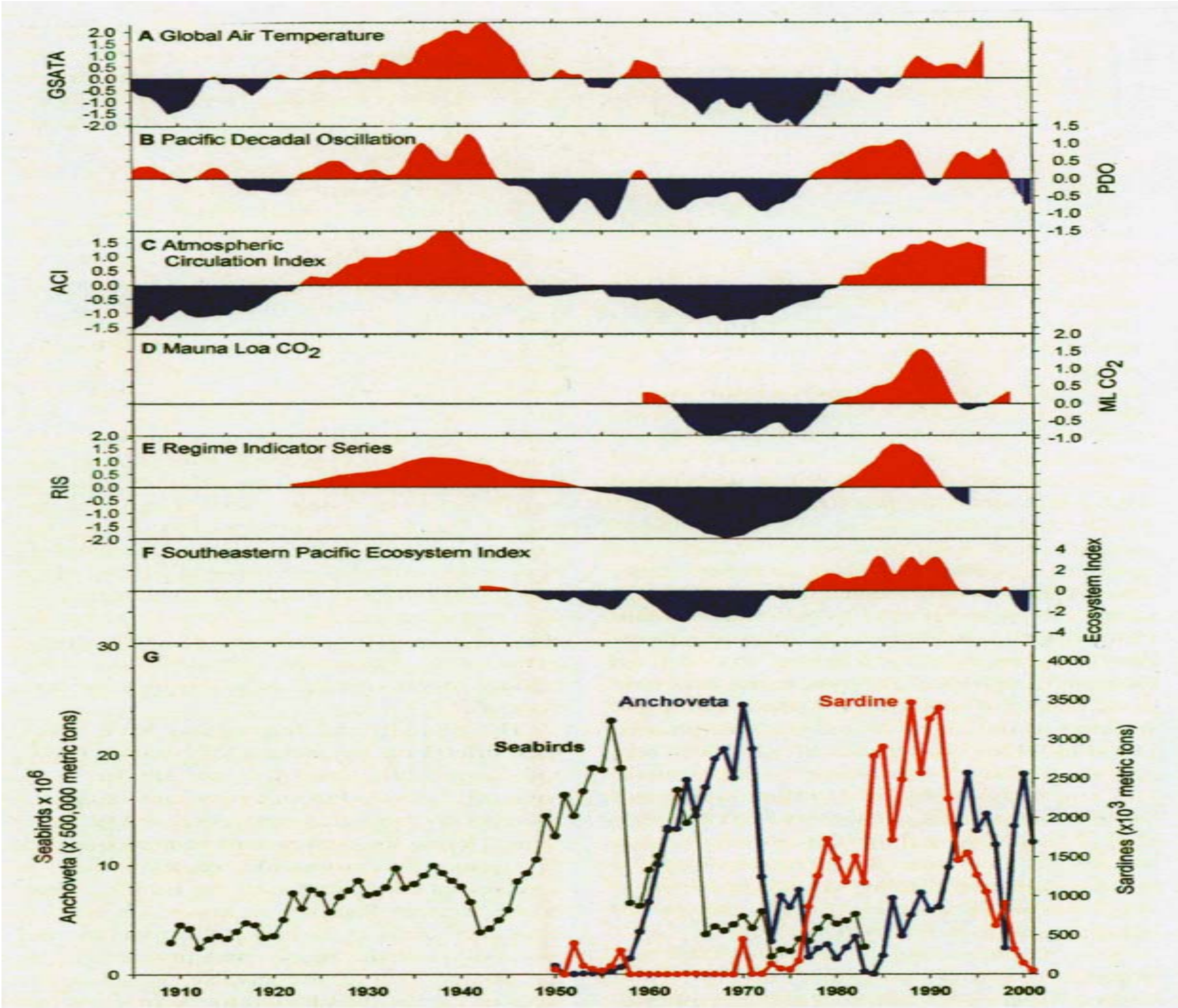

Fig. 1. Anomalies of (A) global air temperature, with the long-term increase removed (8); (B) the Pacific decadal oscillation (PDO) index (°C), derived from principal component analysis of North Pacific SST (10); (C) the atmospheric circulation index (ACl), which describes the relative dominance of zonal or meridional atmospheric transport in the Atlantic-Eurasian region (9); (D) atmospheric CO^2 measured at Mauna Loa (parts per million) with the long-term anthropogenic increase removed (7); (E) the regime indicator series (RIS) that integrates global sardine and anchovy fluctuations (5); and (F) a southeastern tropical Pacific ecosystem index based (19) on (G) seabird abundance and anchoveta and sardine landings from Peru. All series have been smoothed with a 3-year running mean.

A typical example of Ecological regime shift

☛*Chavez et al., Science 299, 217 (2003)*

Long-term variations of vertical profiles of nutrients in the western North Pacific

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- **Objective**
- Physical characteristics of the Kuroshio re-circulation and effect of distributions of nutrients

- Short history
- There were few studies on temporal variations of nutrients
- concentrations in seawater until 1990.
- Major research works were published in the last few years.
- ♦analysis of variation of nutrient concentrations along isopicnal
- surface
- ♦seasonal variation of nutrient concentrations in surface mixed layer

Do vertical profiles of nutrients in water columns vary temporally?

Time-series observation

Station HOT Subtropical Pacific Ocean

BATS Atlantic Ocean

⇒JMA Observation line P9 along 137°E

Start from 1970 winter and summer

Our knowledge

1. Seasonal change
2. Inter-annual change
3. Decadal change

Trends in BATS time series data

Trends in BATS time series data

	Interannual	seasonal
DIC	+	+
Alkalinity	-	-
$\delta^{13}C$	+	+
pCO_2	+	+

NAO North Atlantic Oscillation
Pressure difference between the Atlantic high and low
(Azores) (Ireland)
NAO + $\Rightarrow$ stronger pressure gradient
$\Rightarrow$ Positive SST anomalies (subtropics)
Negative SST anomalies (subpolar gyre)

Detrend

	Internannual	Correlation with NAO
SST anomalies	+	+
DIC	+	+
$\delta^{13}C$	+	-
pCO_2	-	-

Positive NAO $\Rightarrow$ deep convection
$\Rightarrow$ Positive DIC anomaly
Negative δ13C anomaly
$\rightarrow$ NCP increase $\rightarrow$ DIC decrease
Remove light carbon

☛*Gruber et al., Science, 298, 2374 (2002)*

N/P ratios in nutrients

- The variation of N/P ratios of inorganic nutrients

  Example : ALOHA
- *N/P ratios of inorganic nutrients in the western North Pacific*

  Do N/P ratios vary spatially and temporally?

  What are factors controlling N/P ratios?

  How about relationships between N/P ratio in water column and Redfield ratio?

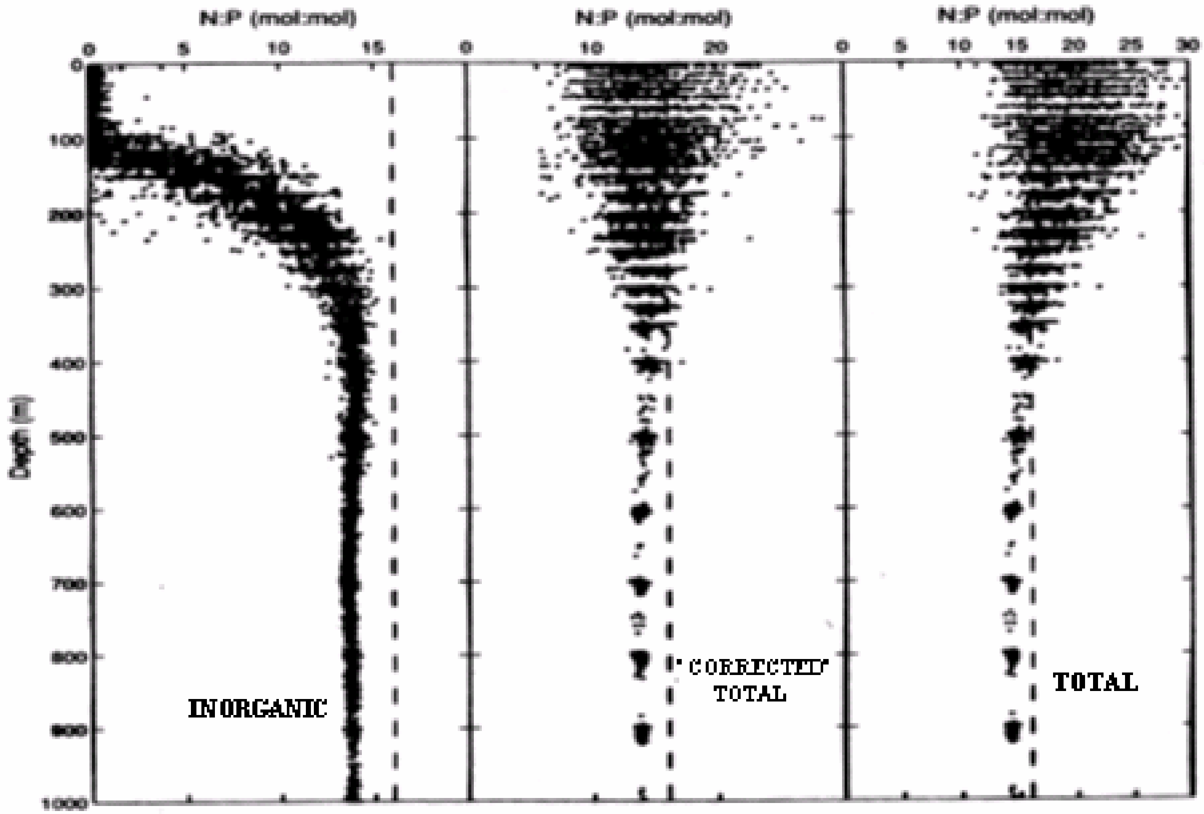
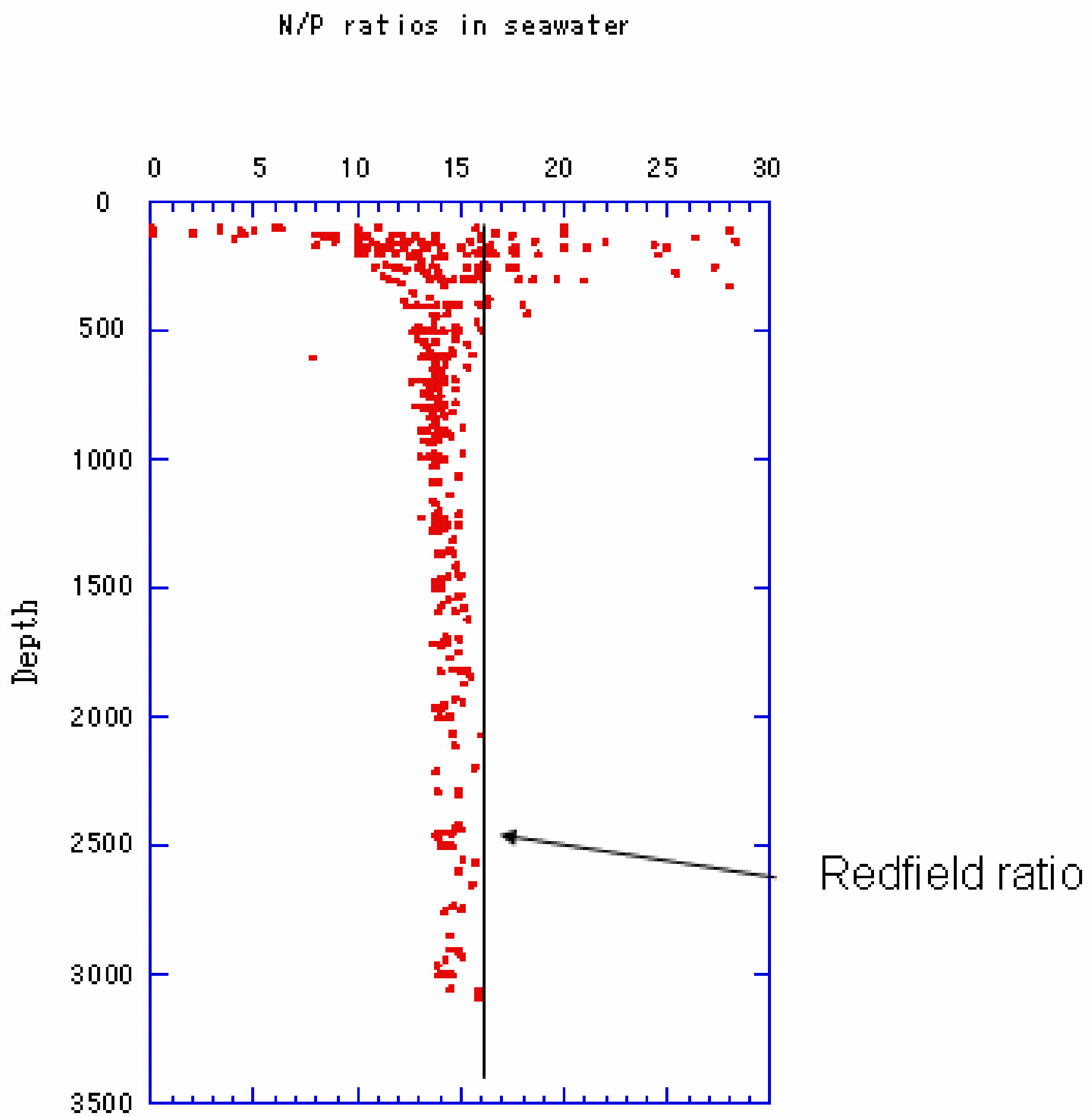


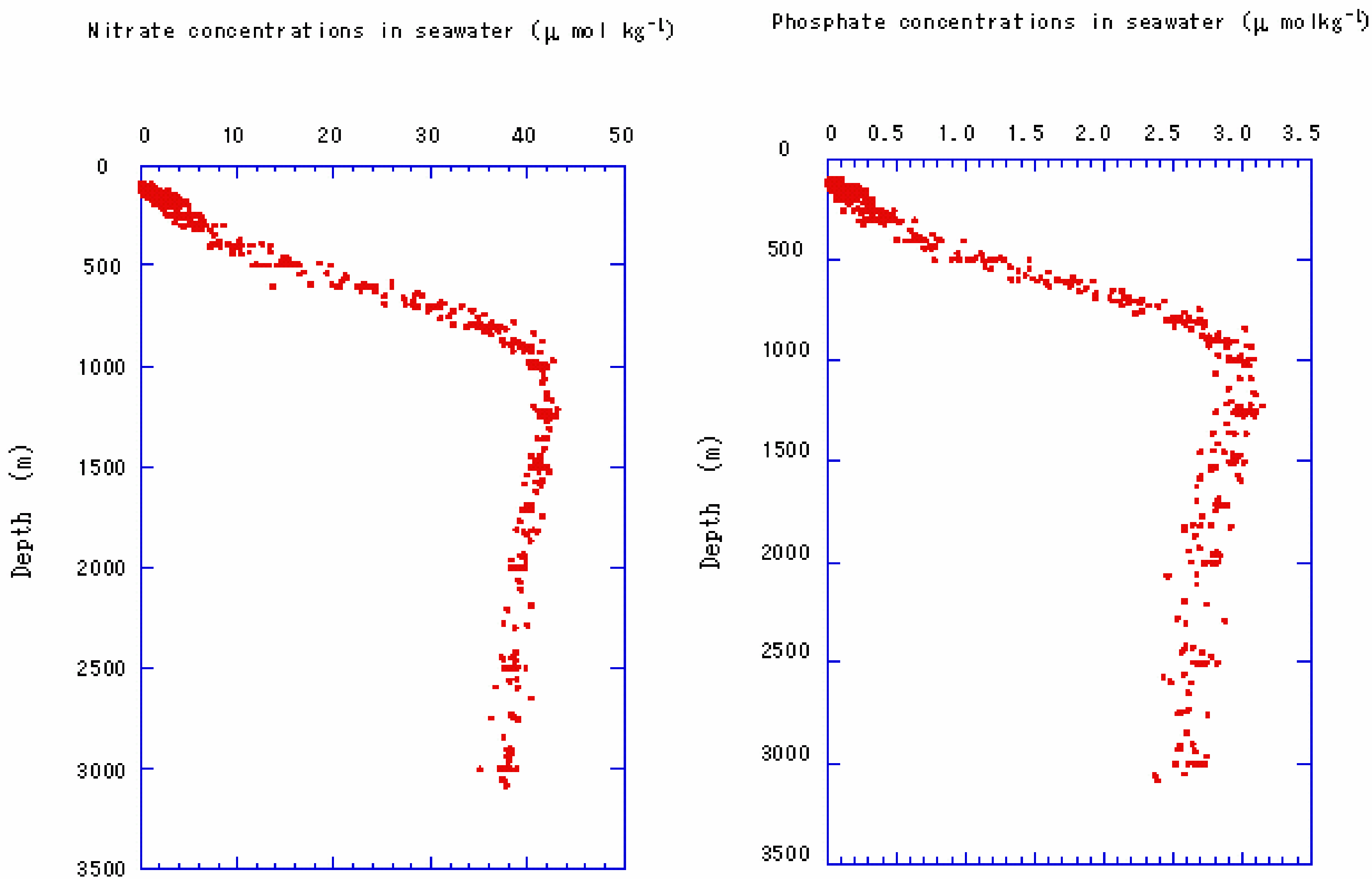
Figure 22 Nitrogen-to-phosphorus (N:P) ratios versus water depth for samples collected at Sta. ALOHA During the period October 1988 to December 1997. (Left) Molar N:P ratios for dissolved inorganic pools calculated as nitrate plus nitrite (N+N):soluble reactive phosphorus (SRP). (Center) Molar N:P ratios for the "corrected" total dissolved matter pools (see text for details). (Right) Molar N:P ratios for total dissolved matter pools, including both inorganic and organic compounds, calculated as total dissolved nitrogen (TDN):total dissolved phosphorus (TDP). As a point for reference, the vertical dashed line in each graph is the Redfield molar ratio of 16N:1P. Redrawn from Karl et al. (2001b).

Karl et al., Deep-Sea Res. II, 48, 1529 (2001)

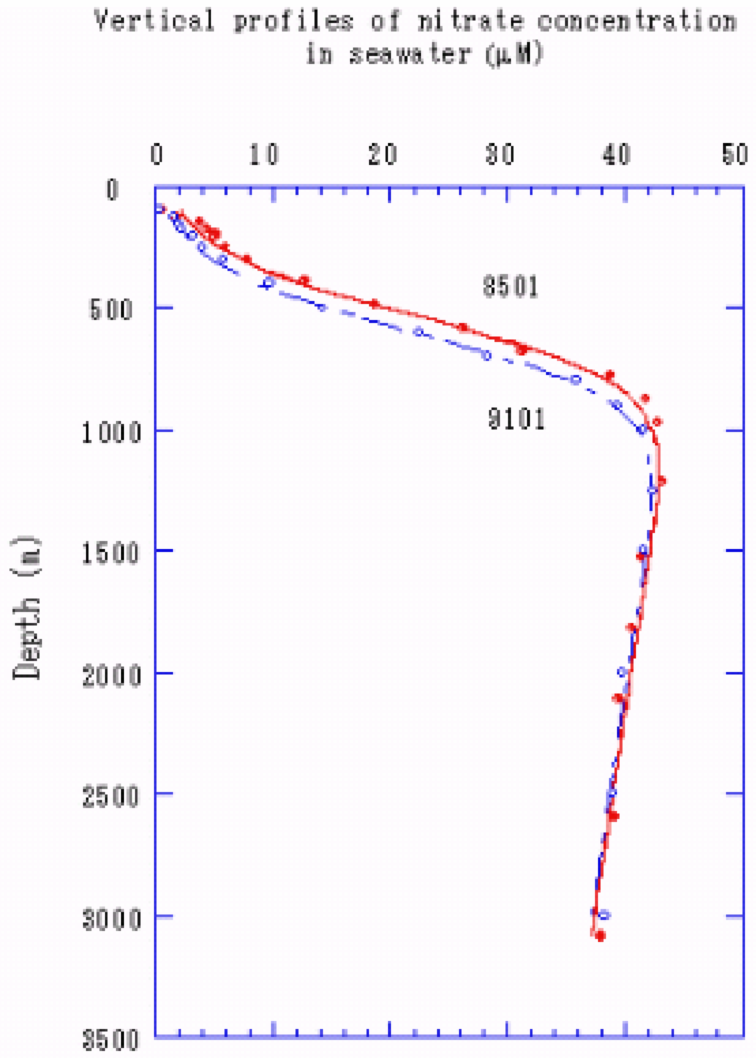
A composite of N/P Ratios in water column

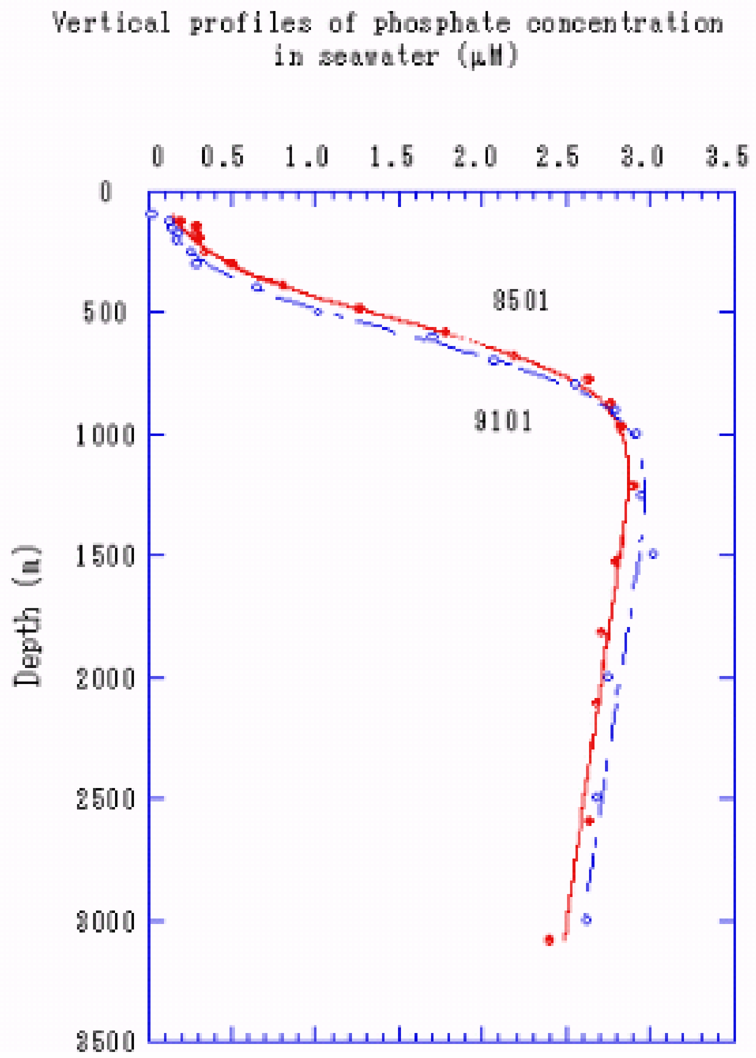
Location: 25°N 137°E





A composite of nutrient concentrations in water column in the site of 25°N 137°E during the period 1980 to 1992.





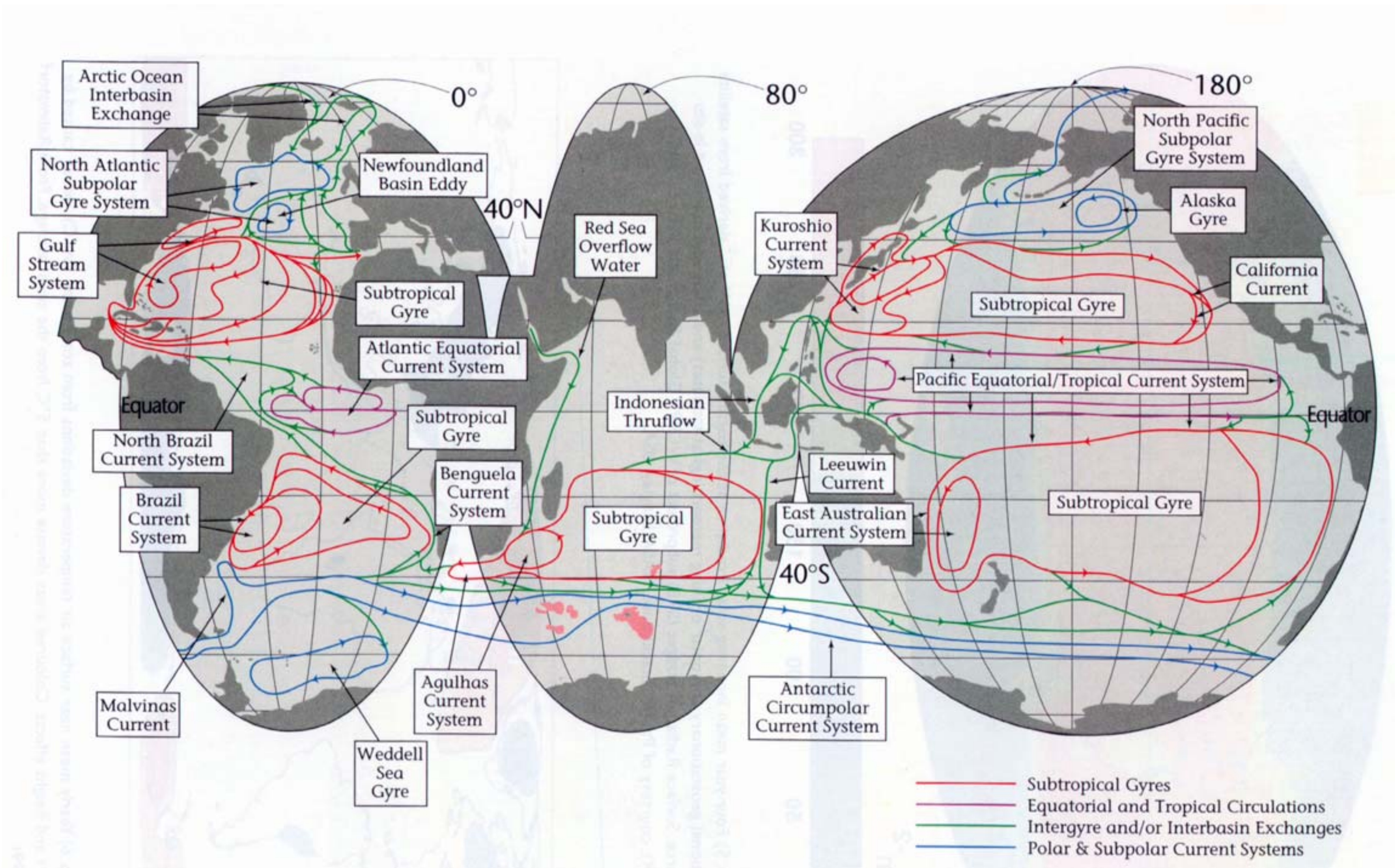
The profile pattern shifts vertically in depth from 100 to 500 m

The phosphate concentrations systematically shift in deep waters.

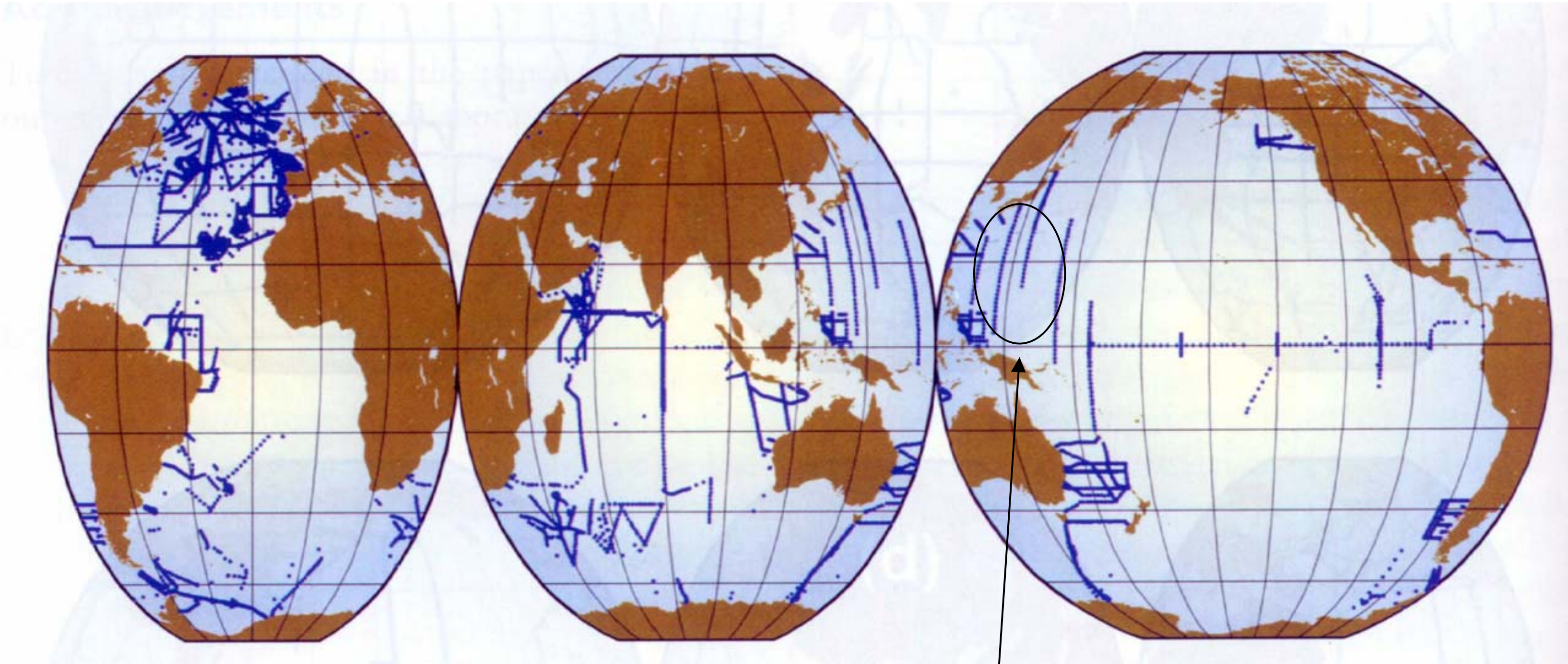
Oceanographic characteristics of the western North Pacific

- 1. Kuroshio current (a typical western boundary current)
- 2. Kuroshio recirculation area
  →The western North Pacific subtropical mode water (NPSMW)
  →The North Pacific Intermediate Water (NPIW)
- 3. The North Equatorial current
  → Tropical Water (TW)
- 4. The Equatorial current system

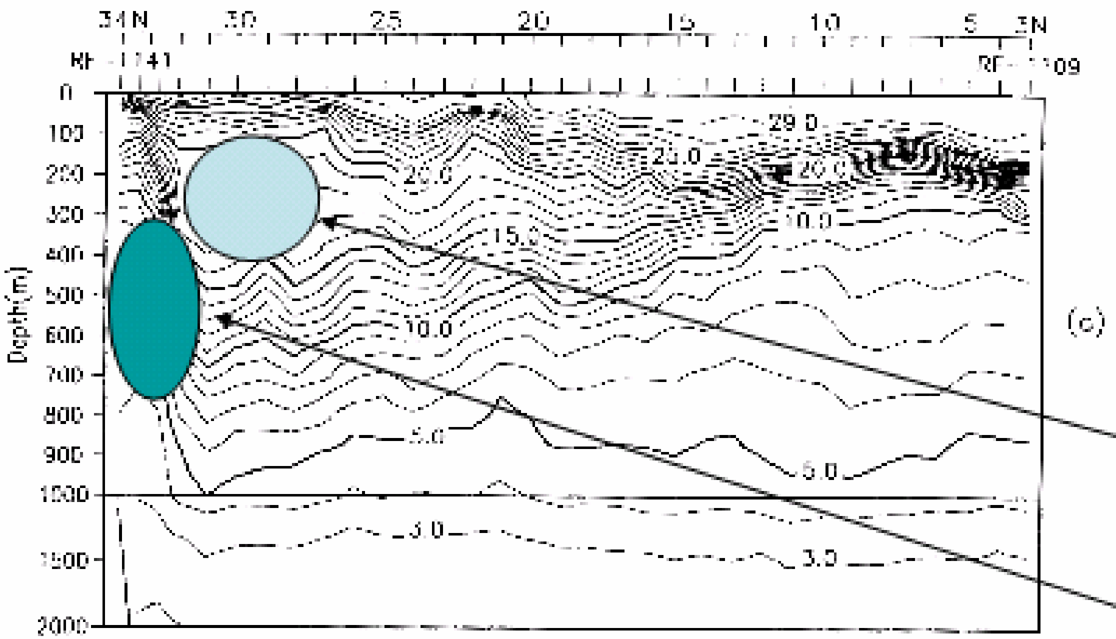
Surface current system in the world ocean



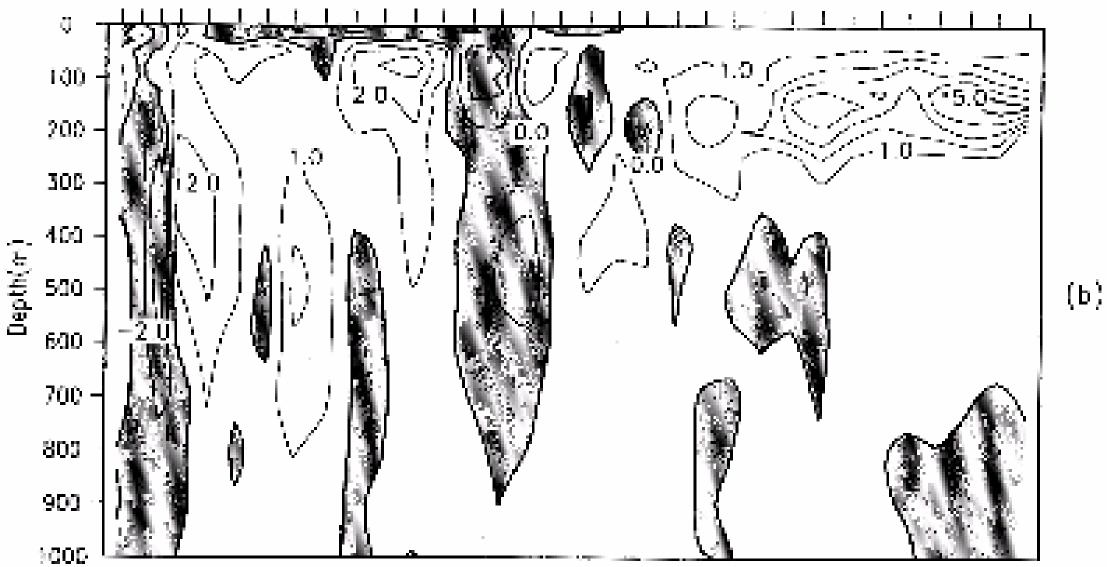
Oceanographic observation



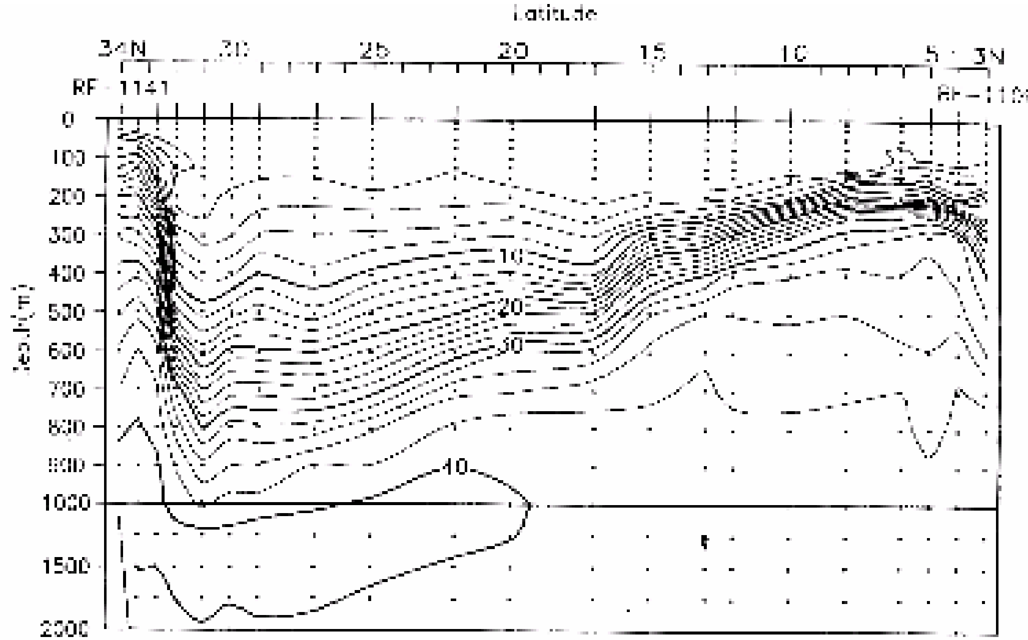
JMA observation lines



Cross section of water temperature along 137°E in the western North Pacific

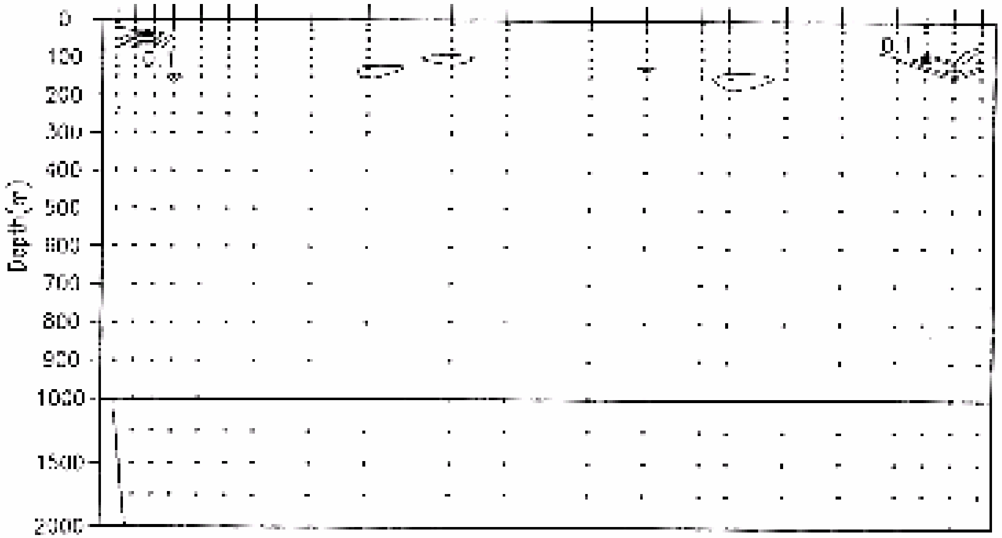


Cross section of water temperature anomaly along 137°E in the western North Pacific



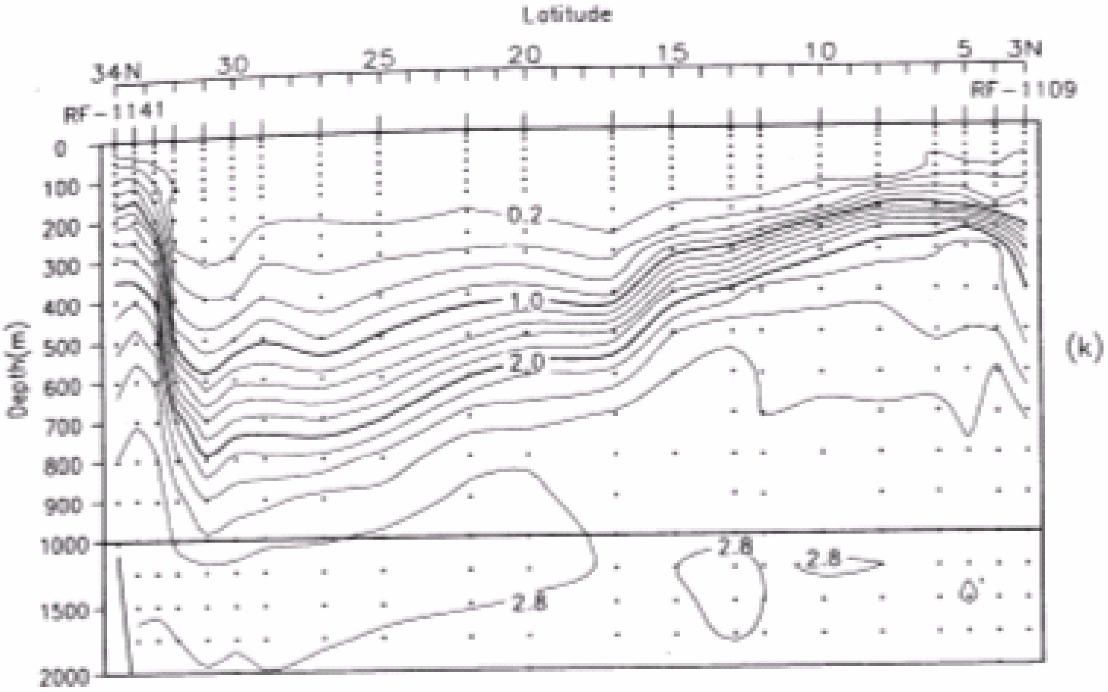
(i)

Cross section of nitrate concentrations along 137°E in the western North Pacific

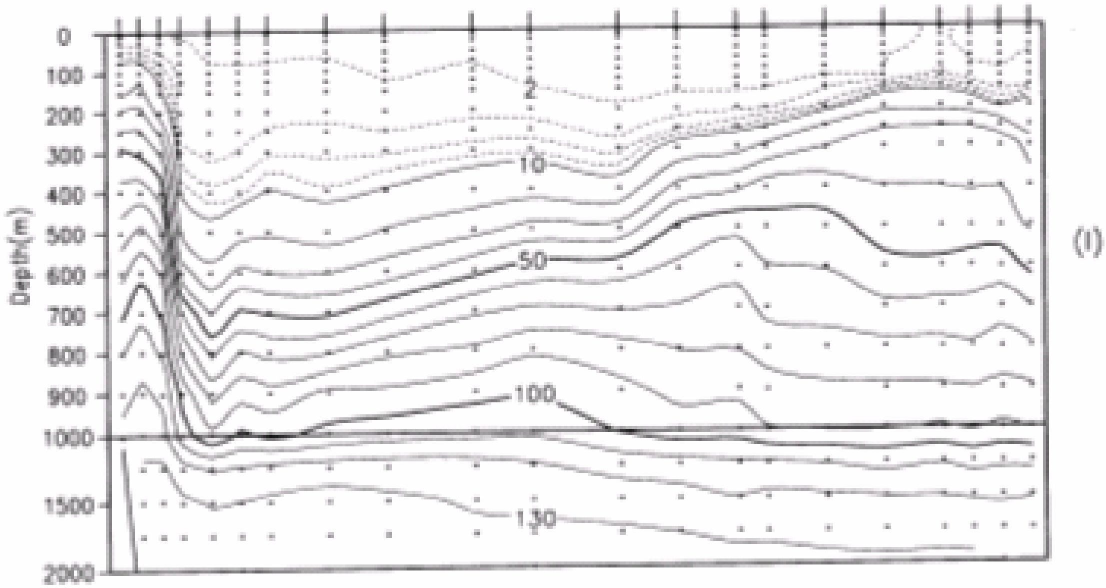


(j)

Cross section of nitrite concentrations along 137°E in the western North Pacific



Cross section of phosphate concentrations along 137°E in the western North Pacific



Cross section of silicate concentrations along 137°E in the western North Pacific

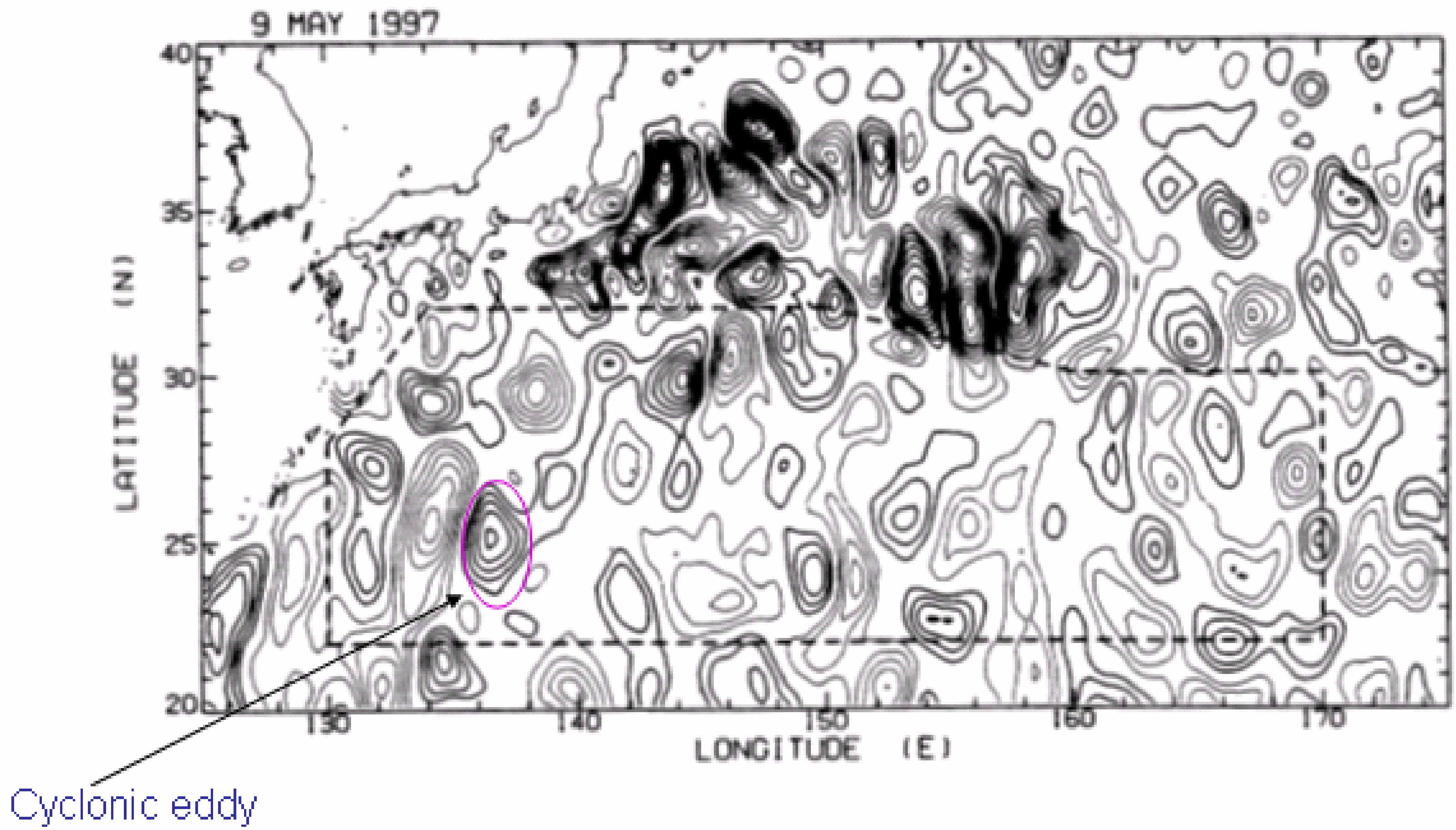


Fig. 2. Example of the filtered map of the sea surface height (SSH) anomaly fields (May 9, 1997). Contour interval is 5 cm. Thick and thin lines represent positive and negative SSH anomalies, respectively. Thick broken line shows study domain where mesoscale eddies are traced in SSH anomaly maps.

Another characteristics of the western North Pacific

→ Presence of meso-scale cyclonic and anti-cyclonic eddies

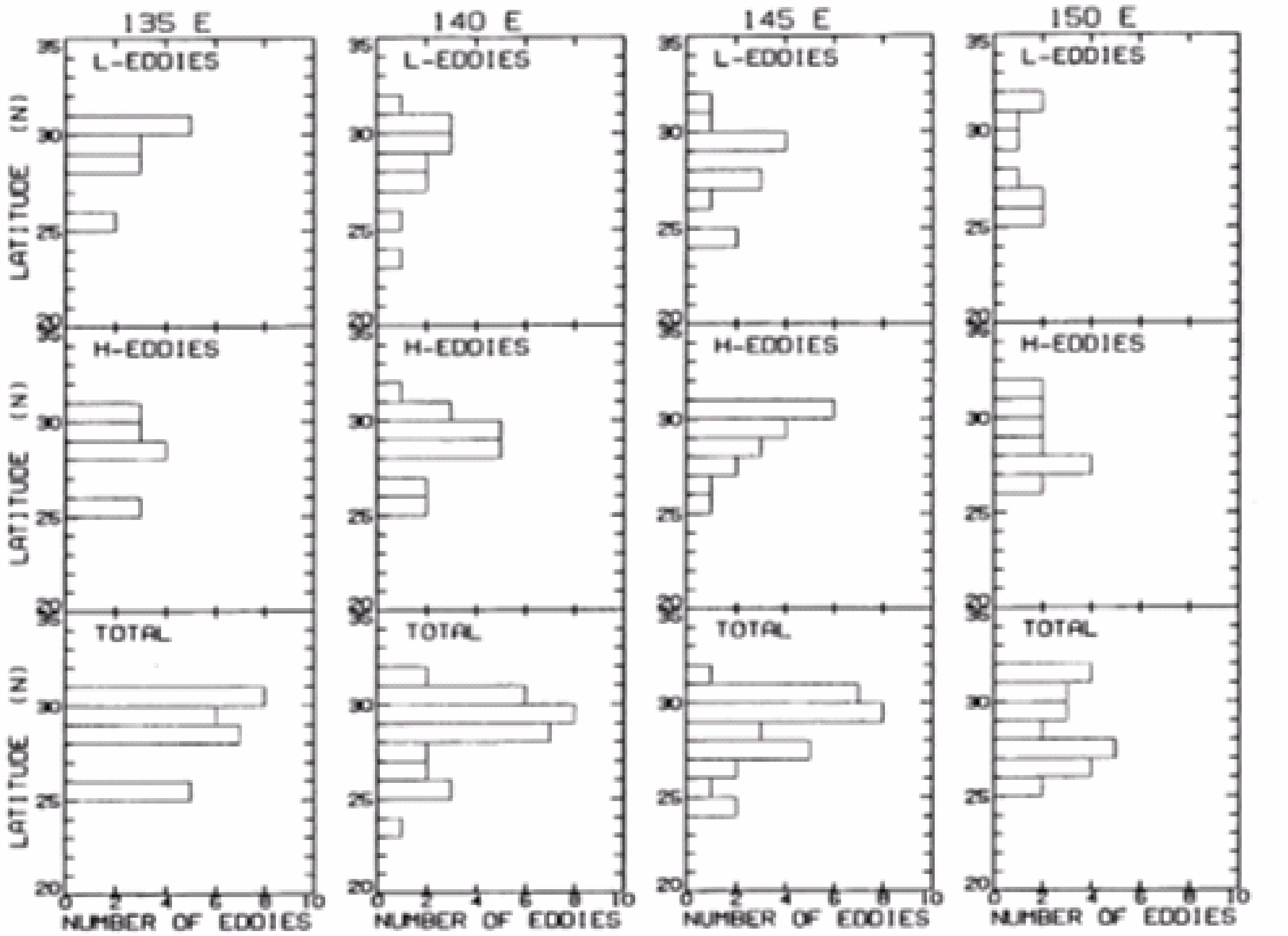


Fig. 5. Histogram of eddies which passed across the meridians of 135°, 140°, 145°, and 150°E. Histograms of cyclonic (upper panel), anti-cyclonic (middle) and both types of eddies (lower).

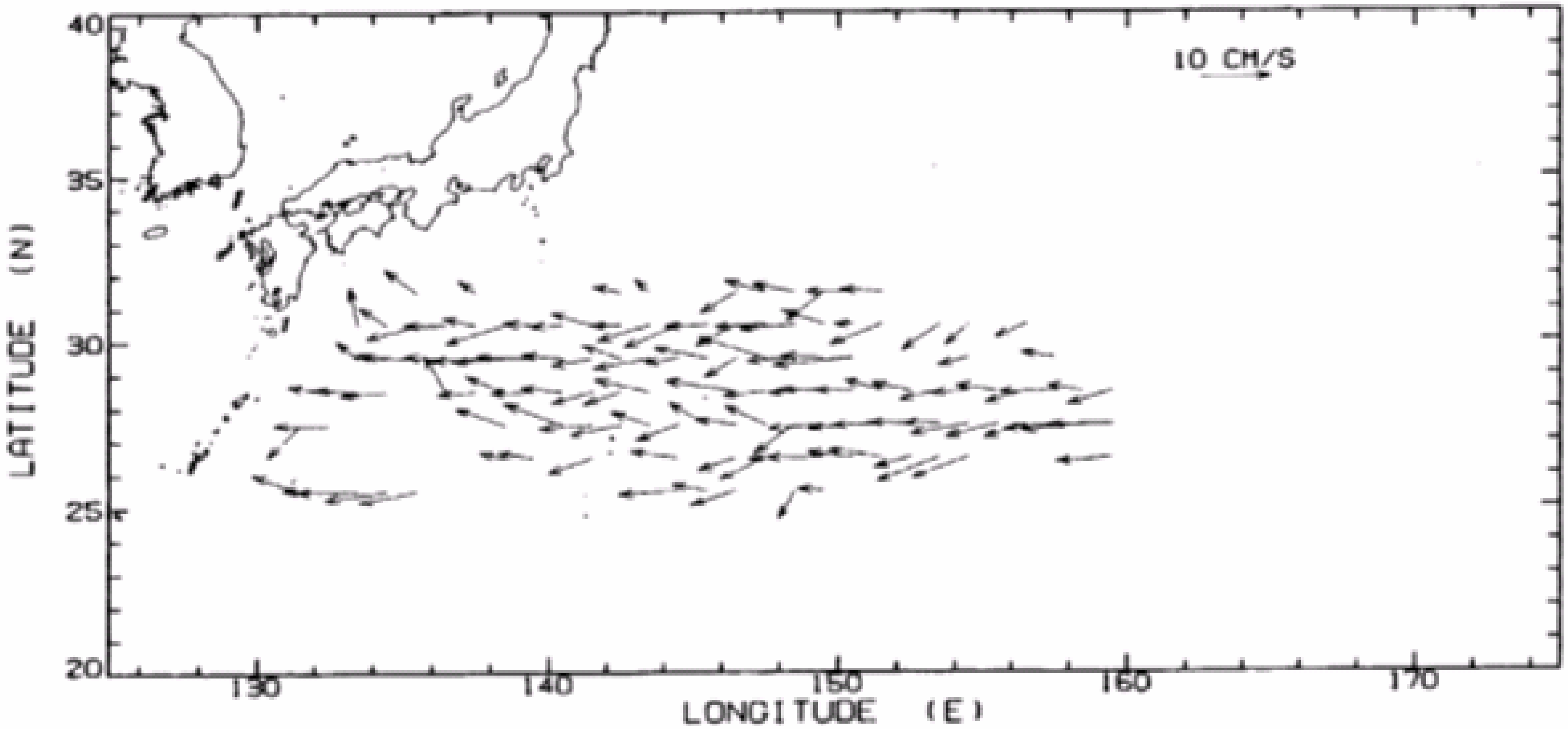


Fig. 6. Propagation velocity vectors of mesoscale eddies averaged in box of 1°× 1°. Both cyclonic eddies are treated together in the calculation.

Summary of Meso-scale eddies in the western North Pacific

Ebuchi and Hanawa, (2001) Trajectory of mesoscale eddies in the Kuroshio recirculation region.
J. Oceanogr., 57, 471-480.
Uehara et al., (2003) A role of eddies in formation and transport of North Pacific subtropical mode water.
Geophy. Res. Lett., 30, 1705.

Characteristics of meso-scale eddy

Spatial scale	250 km
Temporal scale	80 days
Typical maximum surface velocity	15-20 cm s-1
SSH anomaly	15 cm
Advection velocity to southwest	7 cm s-1

Eddies with a strong nonlinear nature can trap a substantial amount of water parcels within them.
(greater than 30-40% of volume）

Oceanic cycle of nutrients

- (Comparison with inorganic carbon in the ocean)
- 1.Solubility pump (Air-Sea exchange) very small
- 2.Biological pump
  - particle export significant
  - DOC transport relatively small
- 3.Carbonate pump none
- 4.Other process N_2fixation
  - nitrification
  - denitrification
- Residence time of phosphorus
  - Very long 10000-17000y

Dose vertical profiles of nutrients vary？

We examine the temporal variation of vertical profiles of nitrate and phosphate in 25°N 137°.

To use about 20 years dataset of nutrients observed by JMA.

A result

⇒The temporal variation of nutrients systematically occurs at all of depth.

Causes of variation 1. Chemical analysis

offset --- no offset due to chemical analysis because of lack of surface nutrients in the subtropical North Pacific,

slope --- inability to estimate the past data because of no standard materials

2. Natural variation

○Systematic variation of nutrient concentrations in deep waters

○Systematic variation of depths where the same nutrient concentrations occurred

To separate these two variations ⇒ Hirose's simple model

Concept of model

⇓ Aeolian input

NA(IN) | ⇒ | ⇒NA(OUT)

Advection

ko

N(inorg) → N(org)

←

ki

→ N(part)

⇑ ⇓

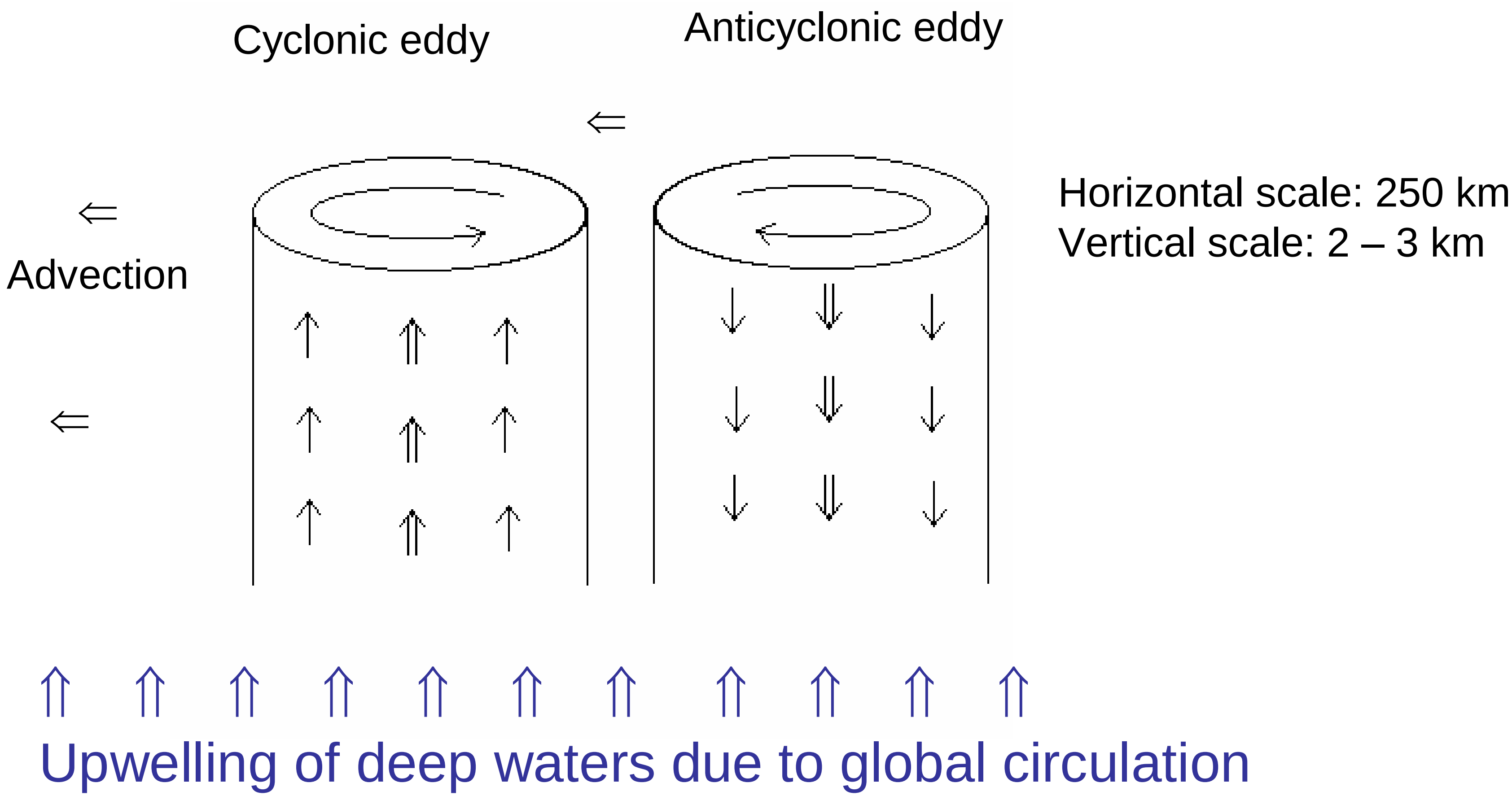
Upwelling w F_e Export flux

← Decomposition

N(inorg) k_{rm}

Remineralization

Movement of meso-scale eddies in the western North Pacific



Scheme of model

- The differential equation governing the vertical distribution of nutrients Ni(z) in the steady state is expressed as follows:

$$\frac{d}{dz}(wNi(z)) - Si(z) = 0 \qquad (1)$$

where z denotes depth and Si(z) is a biogeochemical term reflecting sources and sinks of nutrients. Si(z) is constructed from the consumption of the nutrients, Pi(z), and the regeneration of nutrients (or remineralization), Qi(z); Si(z) = Qi(z) - Pi(z). The upwelling velocity, w, is assumed to be constant.

☛*Hirose and Kamiya, J. Oceanogr., 59, 149 (2003)*

Consumption scheme of nutrients

- We adopted a first-order kinetics for the consumption of nutrients to simplify the biological process. The differential consumption rate is given as
- $Pi(z) = \frac{d}{dz} (kp(z)Ni(z))$. (2)
- The depth-dependent consumption rate of nutrients due to the biological process, kp(z), is represented as an exponential function of depth.
- $kp(z) = ko/\lambda p \exp(-\lambda p\, z)$ (3)
- where ko (unit: yr-1)and λp (unit: m-1) respectively stand for the consumption rate constant in the surface layer (100 m depth).

Export scheme of nutrients

- The regeneration of nutrients in the water column, from the biological decomposition of sinking particles, is related to the export flux of particulate matter, Fi(z). We assume that the change of the export flux at depth corresponds to the input of nutrients remineralized in the water column as a result of decomposition by bacterial activity. The differential regeneration of nutrients in the water column is given as follows:
- $$Qi(z) = \frac{d}{dz} Fi(z) \quad (4)$$
- The particle export flux is represented as an exponential function of depth (Shaffer, 1989):
- $$Fi(z) = Fio \exp(-\lambda f\, z) \quad (5)$$
- where Fio (unit: mol m-2yr-1) and λf (unit: m-1) denote the export flux of N and P in the surface and the particle flux decay constant, respectively.

Basic equation of vertical profile of nutrients in the Kuroshio recirculation region

- Substituting eq. 2-5 in eq. 1, we obtain a following differential equation:

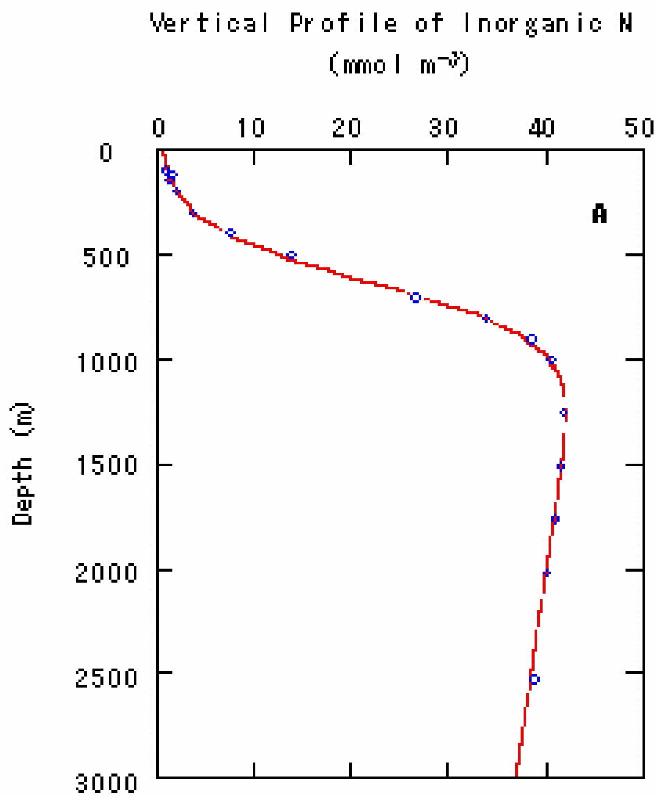
- $\frac{d}{dz}(w(z)Ni(z)) + \frac{d}{dz}(ko/\lambda p \exp(-\lambda p\, z)\, Ni(z))$
- $- \frac{d}{dz}(Fio \exp(-\lambda f\, z)) = 0 .$ (6)

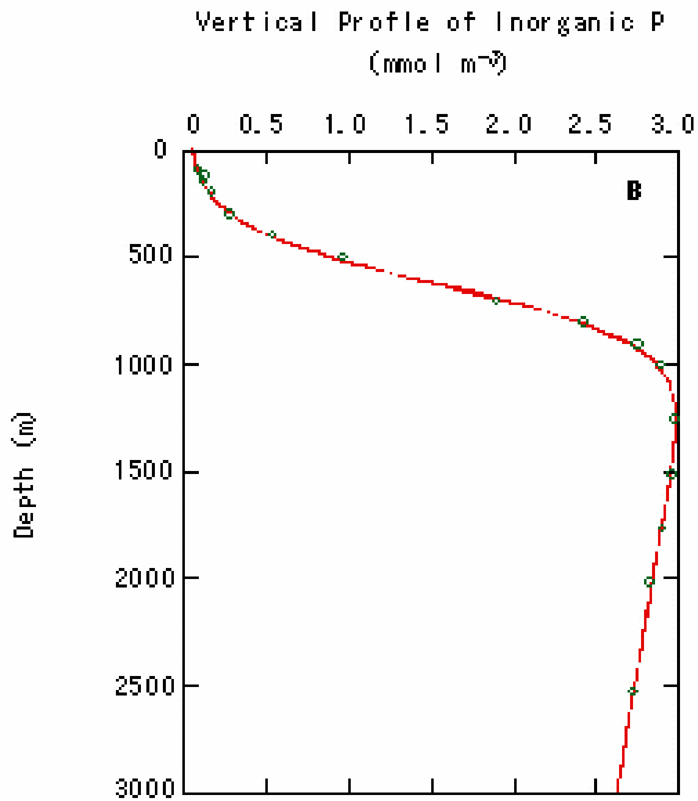
- This differential equation (eq. 6) can be solved under the conditions that concentrations of inorganic N and P in surface waters are negligible. Finally we have a simple equation as a result of integration:

- $Ni(z) = A \exp(\lambda p - \lambda f)z / \{1 + B \exp(\lambda p z)\}$ (7)

- where A and B are constant at each station; $A = Fio\lambda p/ko$ (unit: mol m-3) and $B = w\, \lambda p/ko$ (non-dimensional parameter). Equation 7 has been applied to fit the vertical distribution of inorganic N and P in the western North Pacific using adjustable parameters, A, B, λp and λf.

Application of the model to WOCE P9 data





June-July, 1994

Open circle: observed values

Solid curve: fitting curve with the model (Eq. 7)

- *Relationship between adjustable parameters*
- Information obtained from model fitting with the observed vertical profile.
- → A, B, λp, λf

  (We used a constant λf value in all of the western North Pacific sites.)

  $\lambda f = 8 \times 10^{-5}\ m^{-1}$
- $F_{i,o}/w = A/B$ $F_{i,o}$: export flux at 100 m depth
- $w = B \lambda p^{-1} k_o$ w: upwelling velocity

- $(F_{N,o}/F_{P,o})(k_{o,P}/k_{o,N}) = A_N/A_P$
- $(k_{o,P}/k_{o,N}) = B_N/B_P$ $k_{o,P}$: consumption rate constant

Implication of parameters obtained by a simple model

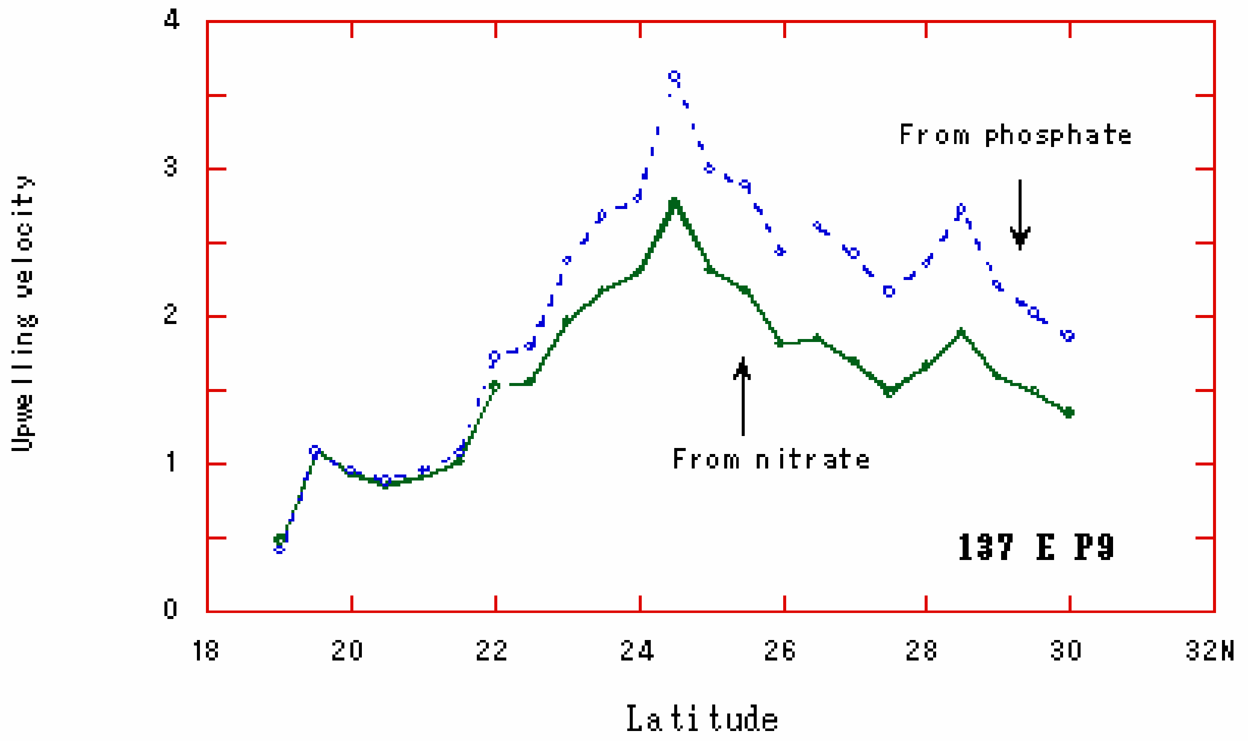
w/k ≒ w (k ∽ 1) upwelling velocity

F/w : to be a linear relationship with maximum concentration of nutrients.

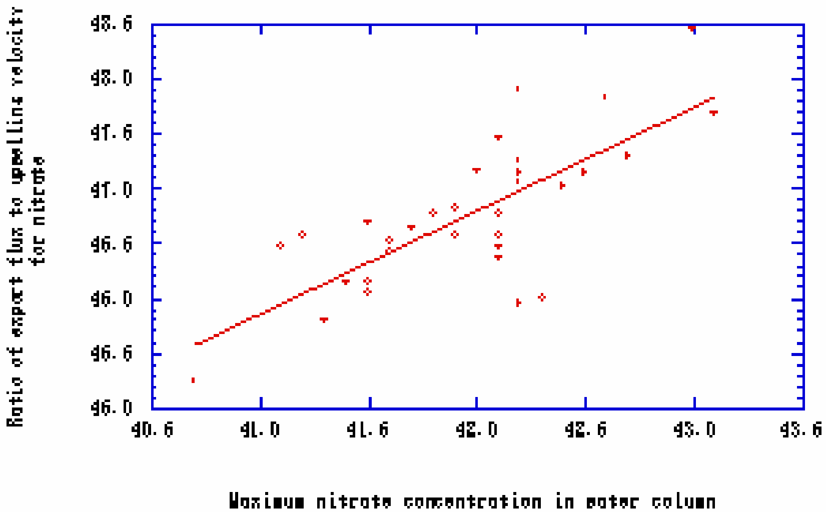
To correspond to the variation of nutrient inventory

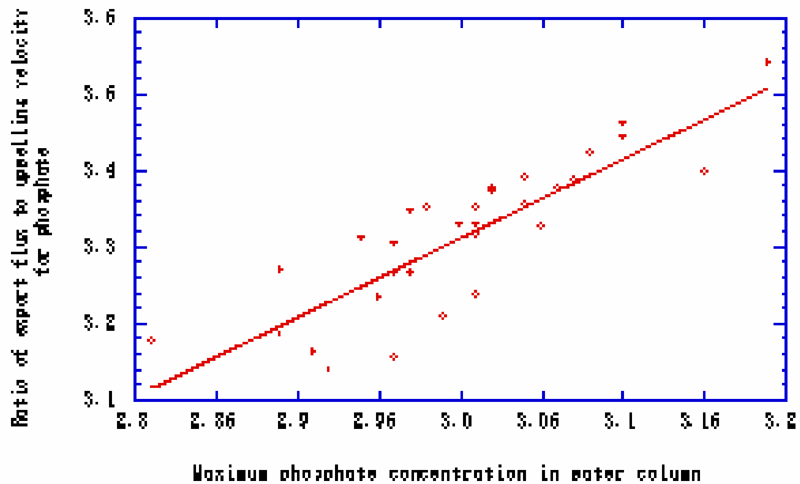
koP/koN >1 : To preferentially consume phosphate.

<1 : To preferentially consume nitrate.



A peak of upwelling velocities may be corresponding to cyclonic eddy.

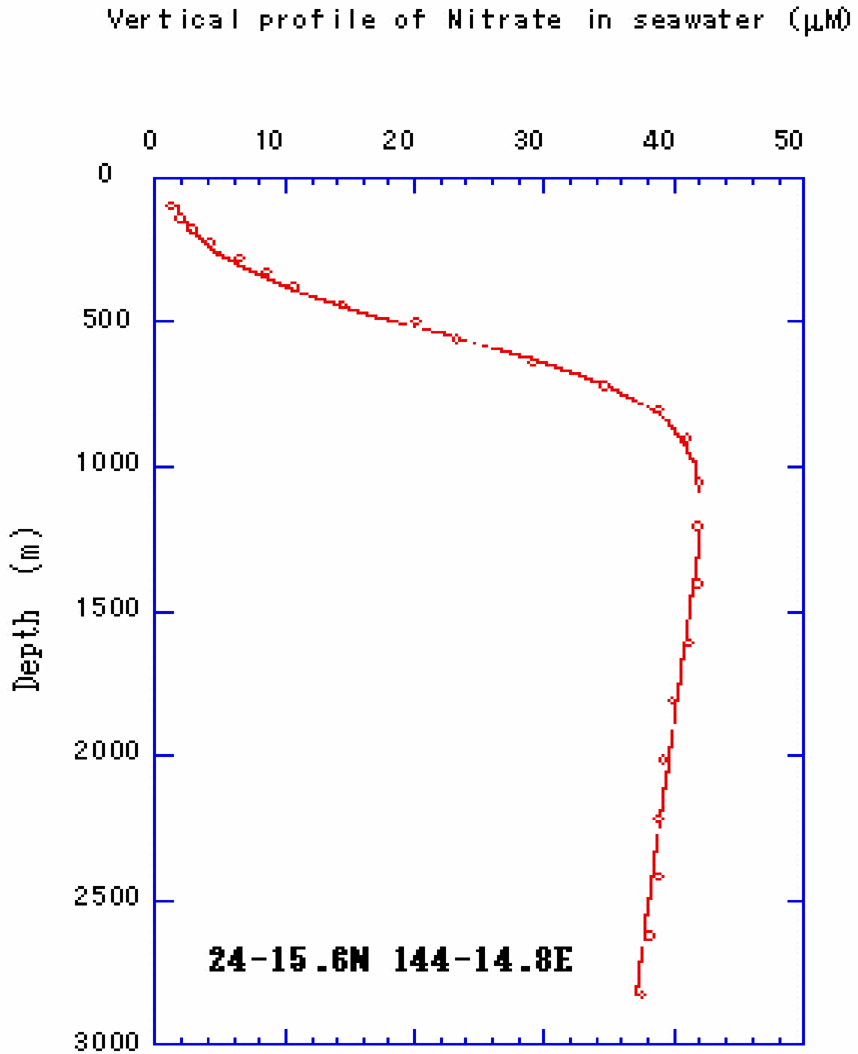


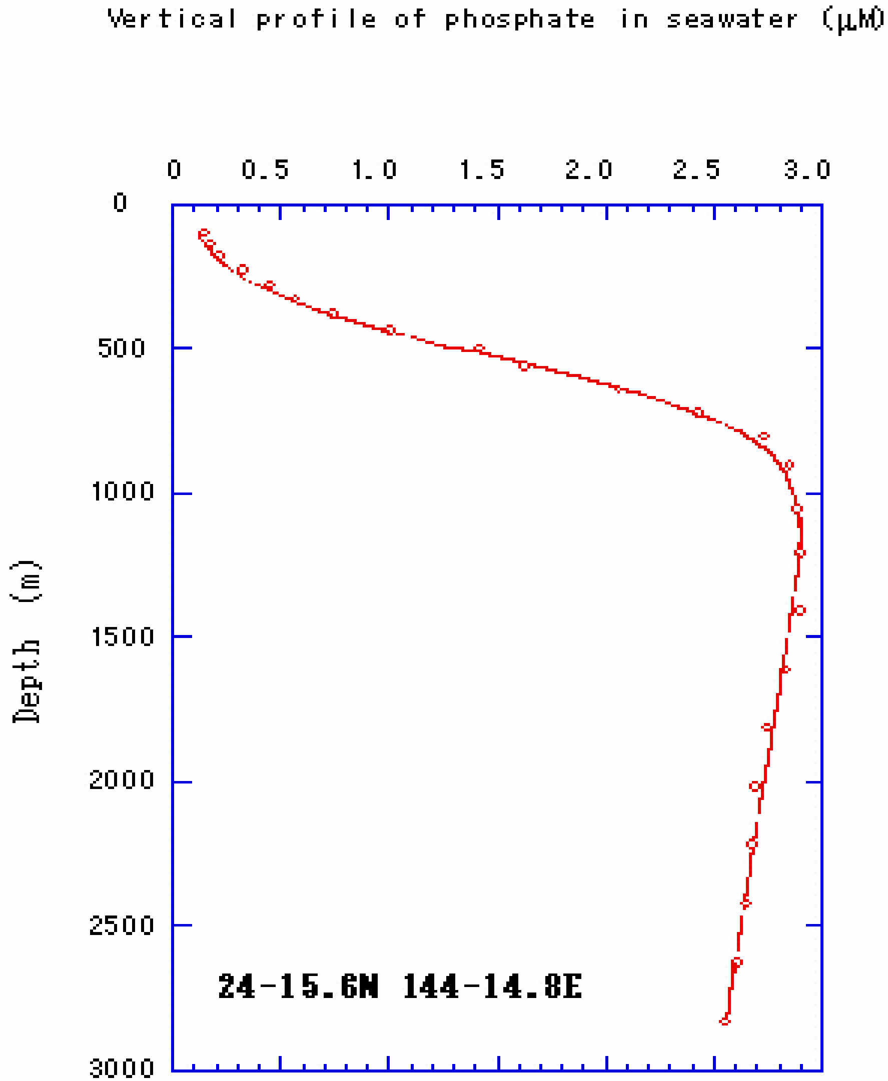


The value of Fi,o is linearly related to a maximum concentration of the nutrient in deep water.

This value reflects offset of nutrient concentrations in deep water.

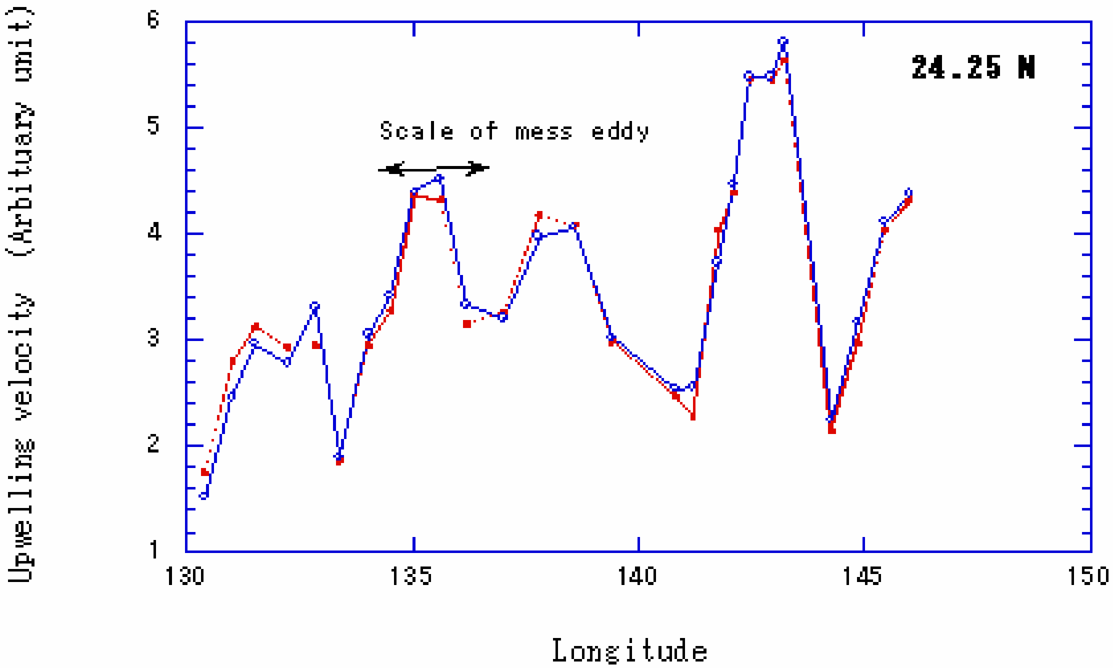
Application of the model to WOCE P3 data



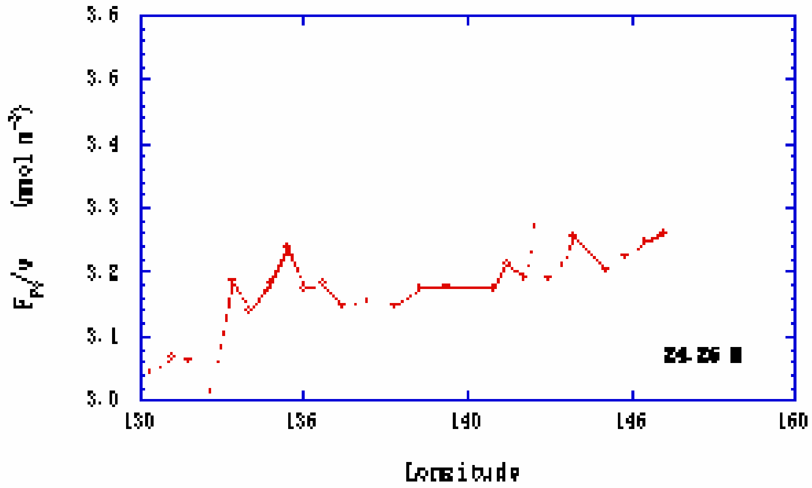


May, 1985

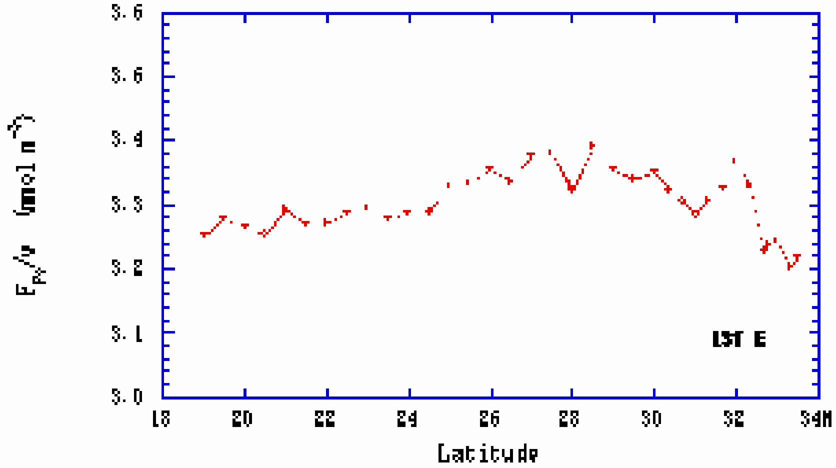
Open circle: observed values
Solid curve: fitting curve with the model (Eq. 7)



A peak of upwelling is corresponding to a cyclonic eddy.



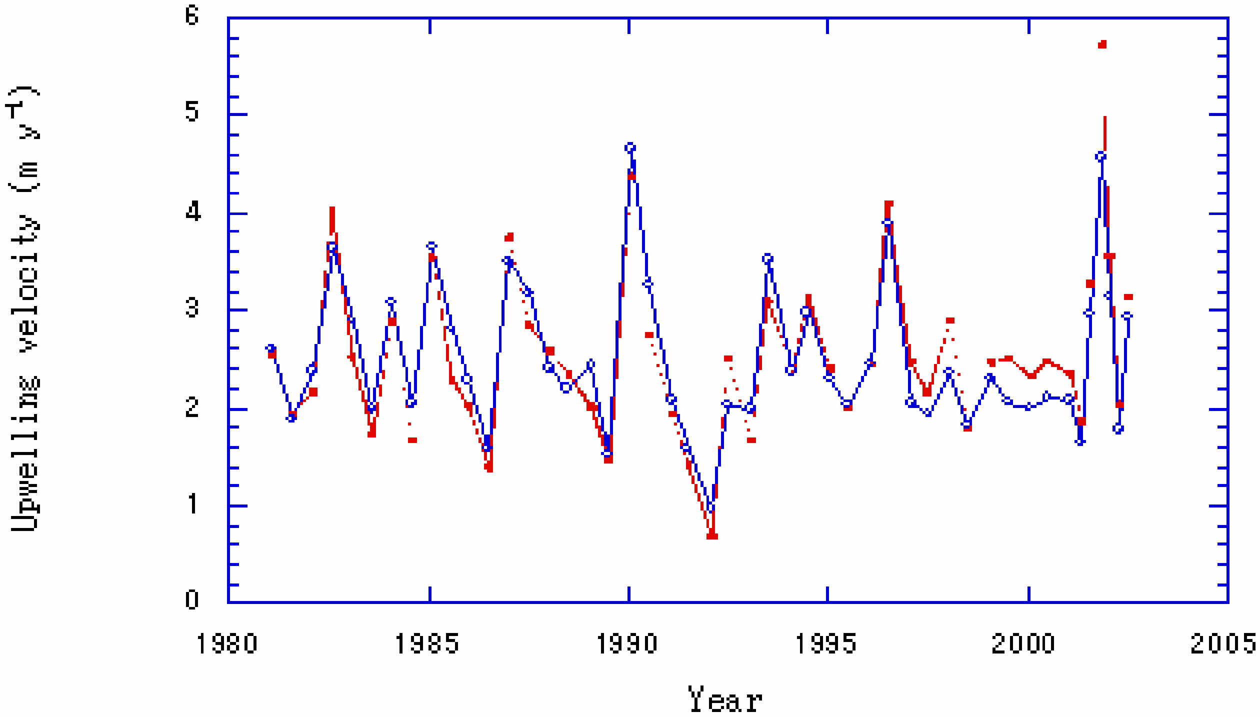
Longitudinal distribution of F/w values
P3 data



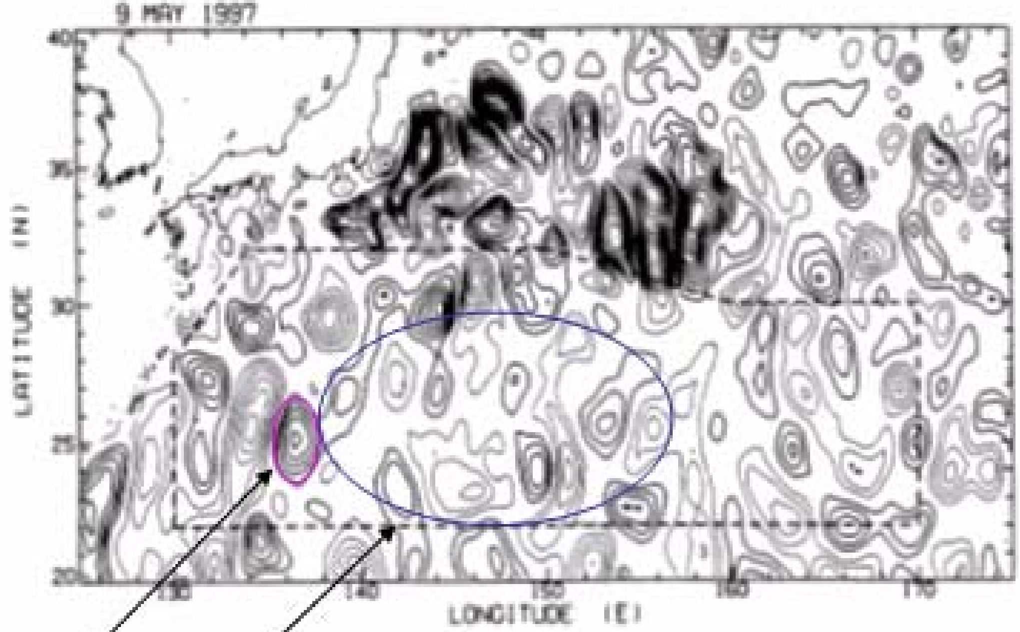
Latitudinal distribution of F/w values
P9 data

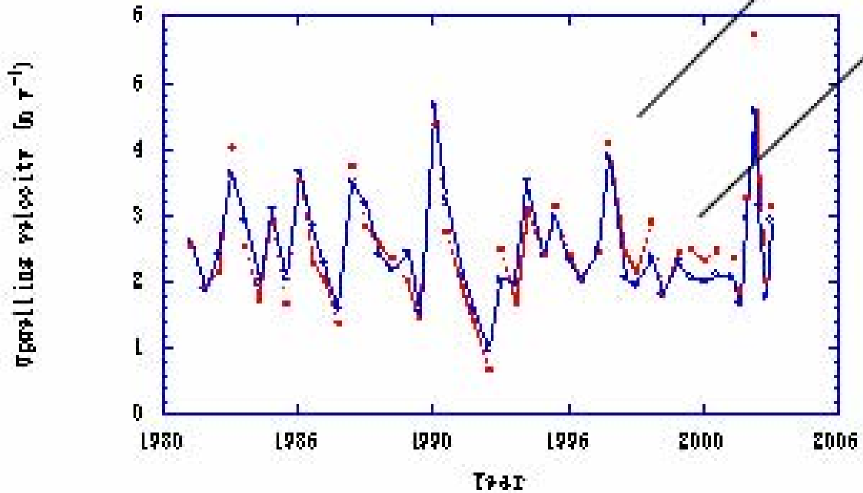
Temporal variations of the vertical profiles of nutrients

- 25°N 137°E time-series data (winter, summer) started from 1970 by JMA.
- We used data from 1980.
- Temporal variations of the vertical profiles of nutrients reflect the values of upwelling velocity and F/w.
- The variation of upwelling velocity corresponds to passage of cyclonic and/or anticyclonic eddies.



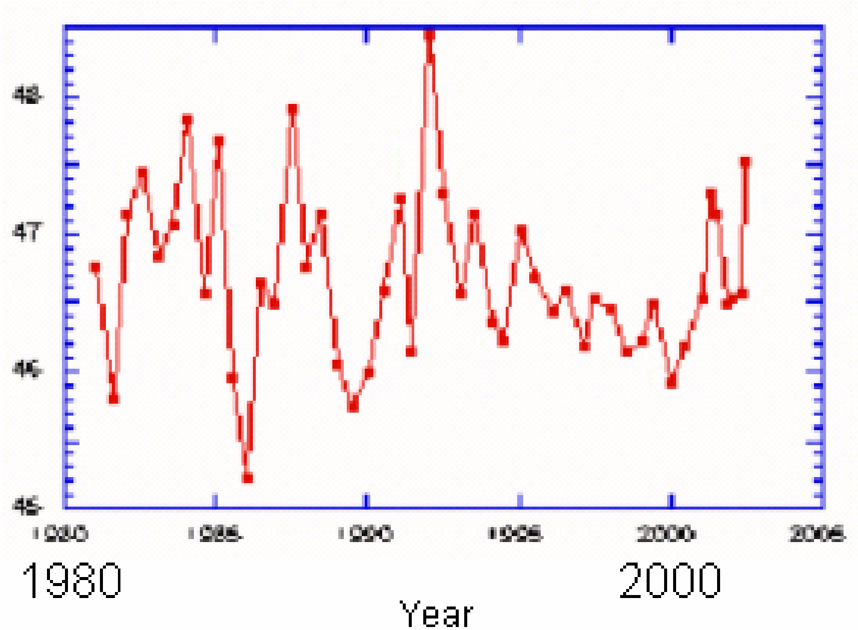
Temporal variations of upwelling velocity in the station (25°N, 137°E) in the western North Pacific



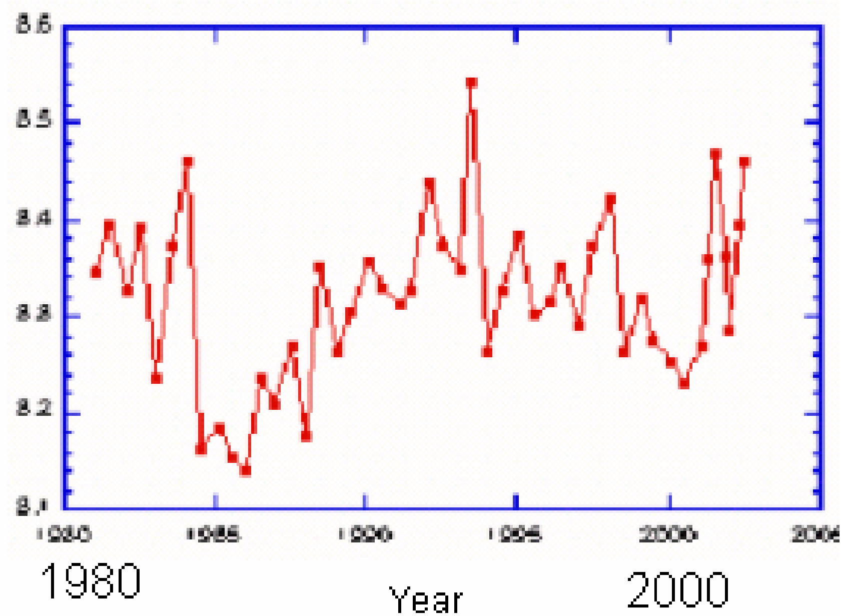


The temporal variation of upwelling velocity corresponds to movement of eddies.

Nitrate



Phosphate



Width of variation: ±3.5% (nitrate) ±7% (phosphate)

Temporal variations of the F/w values of nitrate and phosphate in the station (25°N, 137°E) of the western North Pacific

2.Analysis of time-series data of nitrate and phosphate in 25°N 137°E

◇The upwelling velocity varies according to path-through meso-scale eddies (cyclonic and anti-cyclonic).

◇We observe a marked change of nutrient profiles in 1990-92 in the station of 25°N 137°E. There is no marked eddy during the period from 1992 to 2000.

◇Nitrate was preferentially consumed by phytoplankton in the 1980s, whereas phosphate was consumed by phytoplankton in the 1990s

◆The value of F/w corresponding to inventory for phosphate shows decadal variation.

3.Change spatial variation of nutrients in P3 to temporal variation

A number of anticyclonic and cyclonic eddies are generated in the vicinity of the Kroshio Extension.

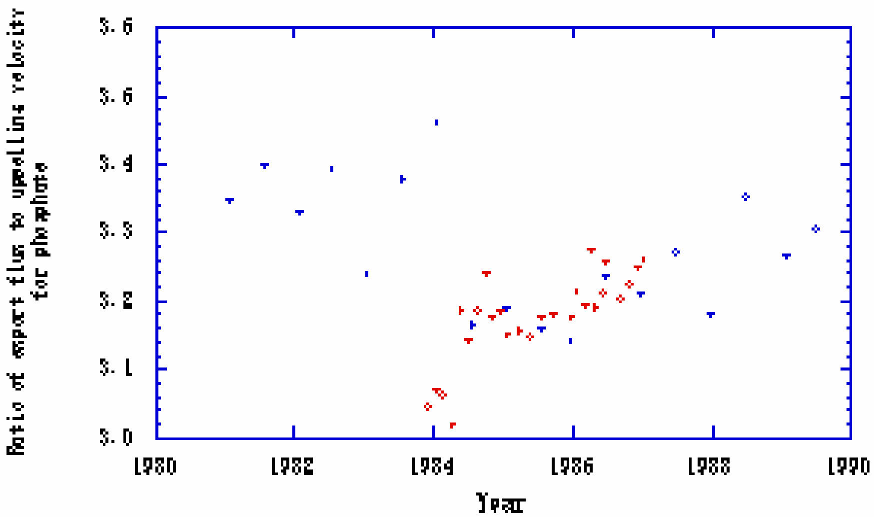
Eddies move westward in the western North Pacific
We assume a southwestward advection rate of 500 km y^{-1}.

Results

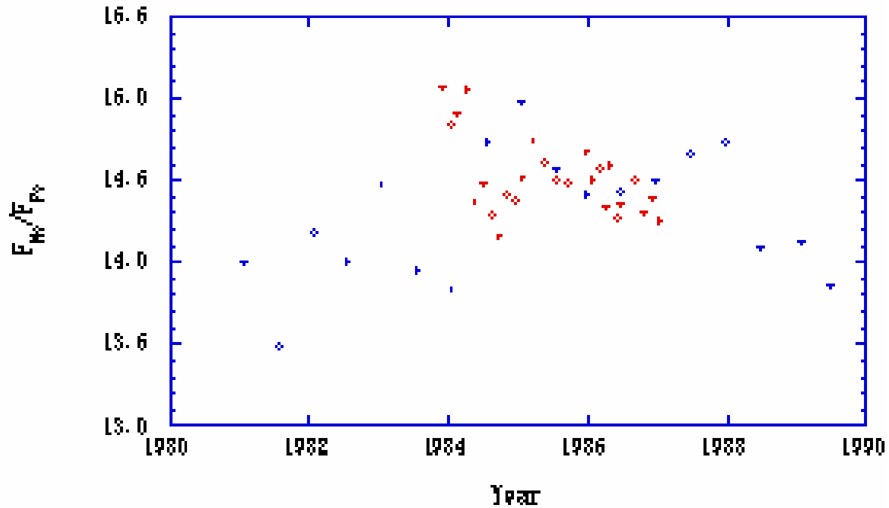
Low phosphate in deep water around 1985 was observed by two independent observations (US and JMA).

The N/P ratios in deep water around 1985 determined by JMA agreed with US observations.

⇒Phosphate and nitrate in deep waters may show decadal variation at an order of several percent.



Temporal variations of F/w values



Temporal variations of N/P ratios
In export flux

Blue: data by JMA
Red: P3 data

Concluding remarks

- Nutrient concentrations in deep waters show decadal variations.
- The width of variation of phosphate concentrations in deep water is about 7%.
- The width of variation of nitrate concentrations in deep water is about 3.5 %.
- This variation is due to a natural variability in the western North Pacific.
- The variations of vertical profiles of nutrients are related to the formation and southwest motion of meso-scale eddies, which are produced in the Kuroshio extension region.

One possible ecological effect due to the climate change

- Cyclonic eddies steadily support a significant amount of biomass because nutrients continuously supply to the euphotic layer in eddies.
- Movement of eddies can transport a significant amount of biomass at the scale of basin.
- The variation of the formation of cyclonic eddies and their movement affects ecology of marine organisms.
- The climate change affects the formation of cyclonic eddies and their movement.
- *The climate change affects marine ecosystems.*