Simulations of annual cycle of phytoplankton production and the utilization of nitrogen in the Yellow Sea

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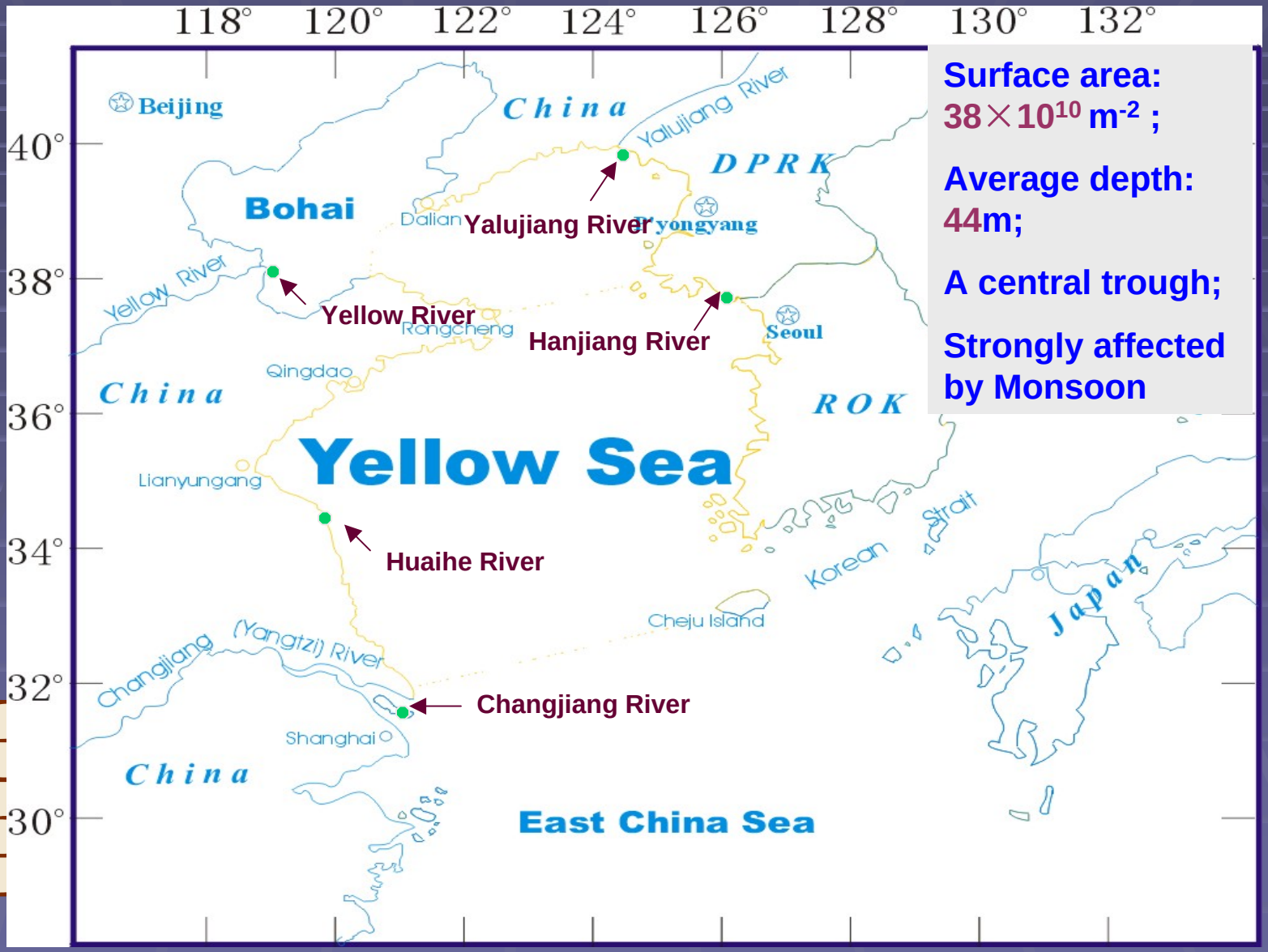
Outline

- Introduction
- Model and Methods
- Results and Discussion
- Conclusion
- Prospect

Geography of the Yellow Sea



Surface area:
38×10^{10} m^{-2} ;

Average depth:
44m;

A central trough;

Strongly affected by Monsoon

The Water Circulation

- The coastal current system
- The warm current system (referred to Lin & Tang, 2002)

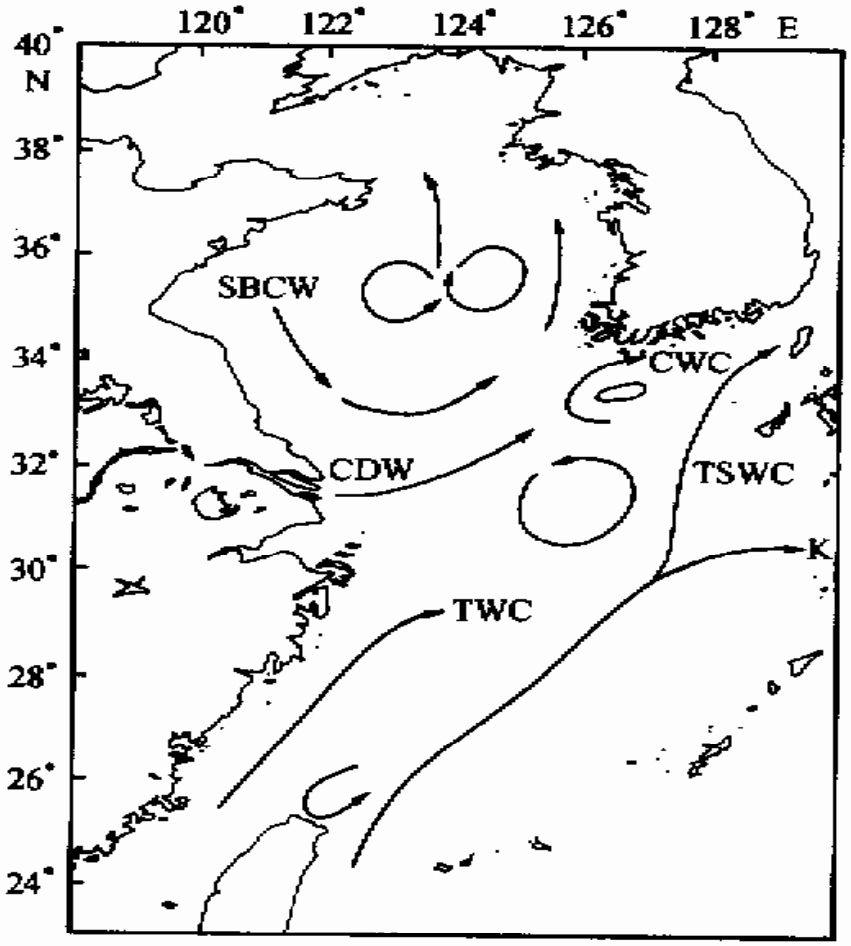


图 8　暖半年黄海、东海表层环流示意图

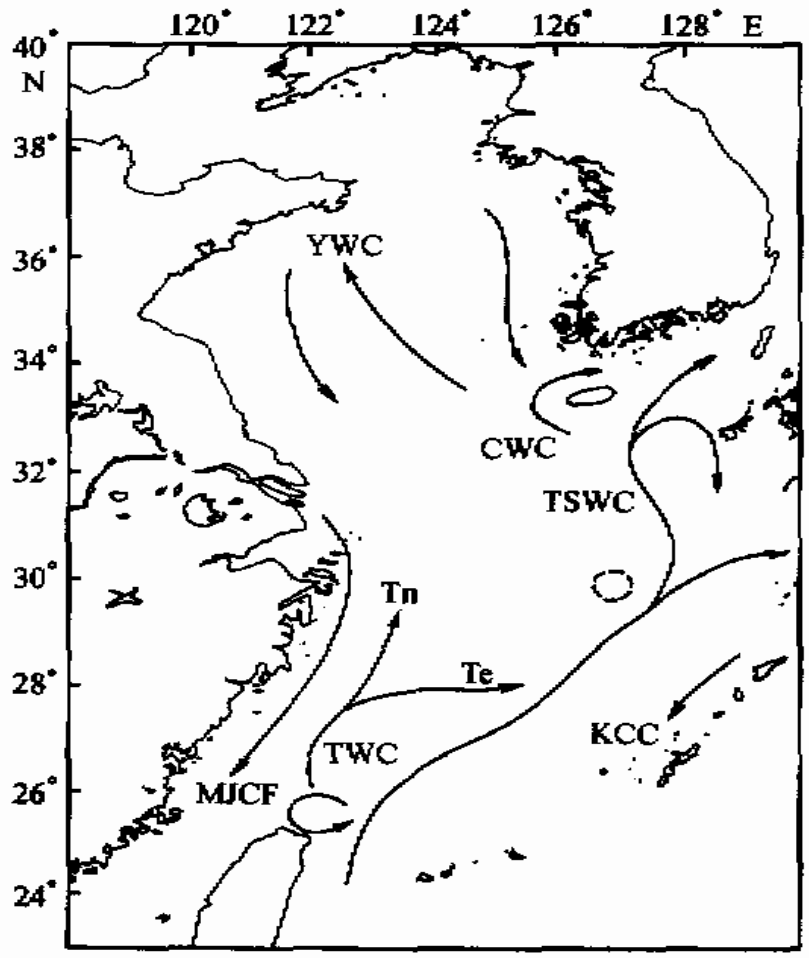
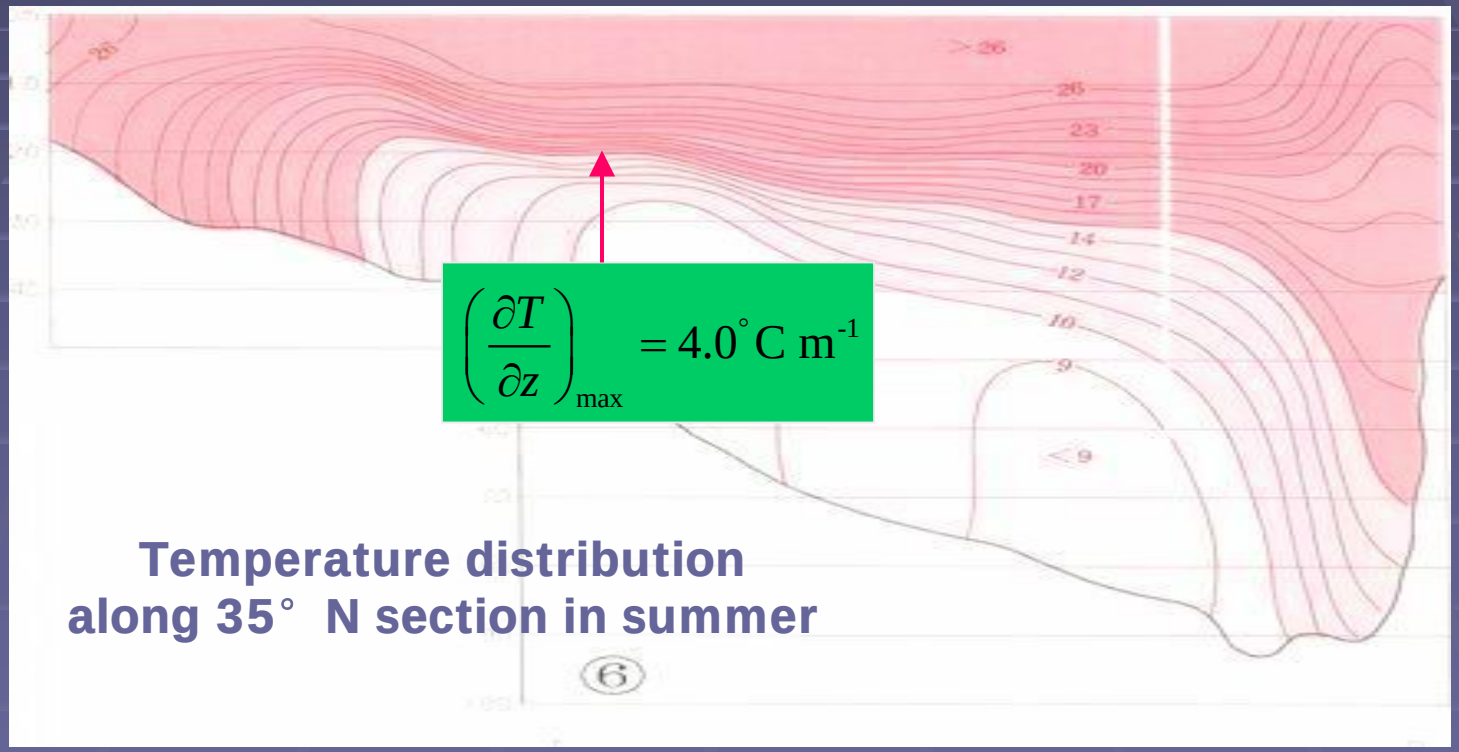


图 10　冷半年黄海、东海表层环流示意图

Character of YS hydrography

- Tidal Mixing
- Seasonal Thermo stratification---

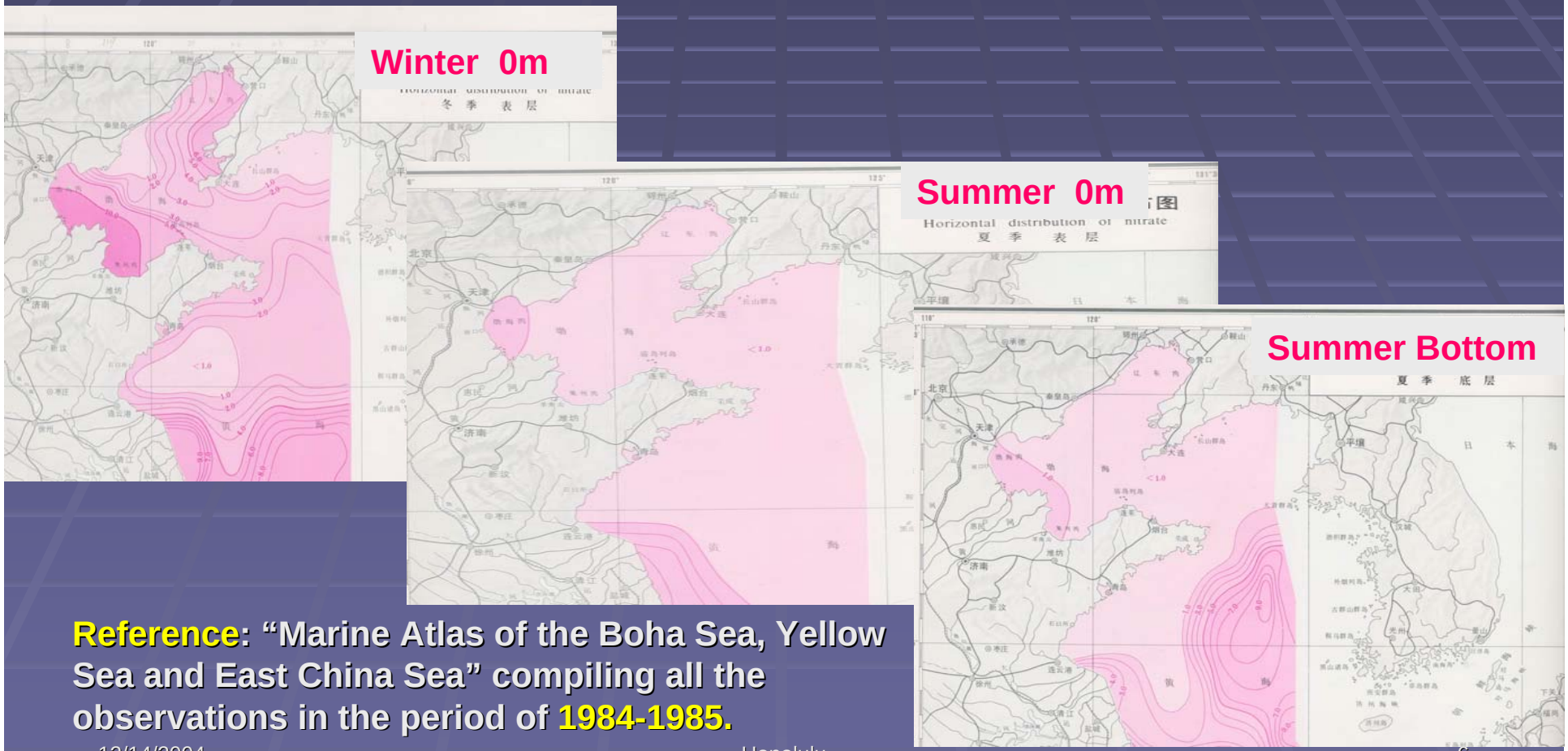
Yellow Sea Cold Water Mass (YSCWM) and Tidal Front



Nitrate Distribution in YS

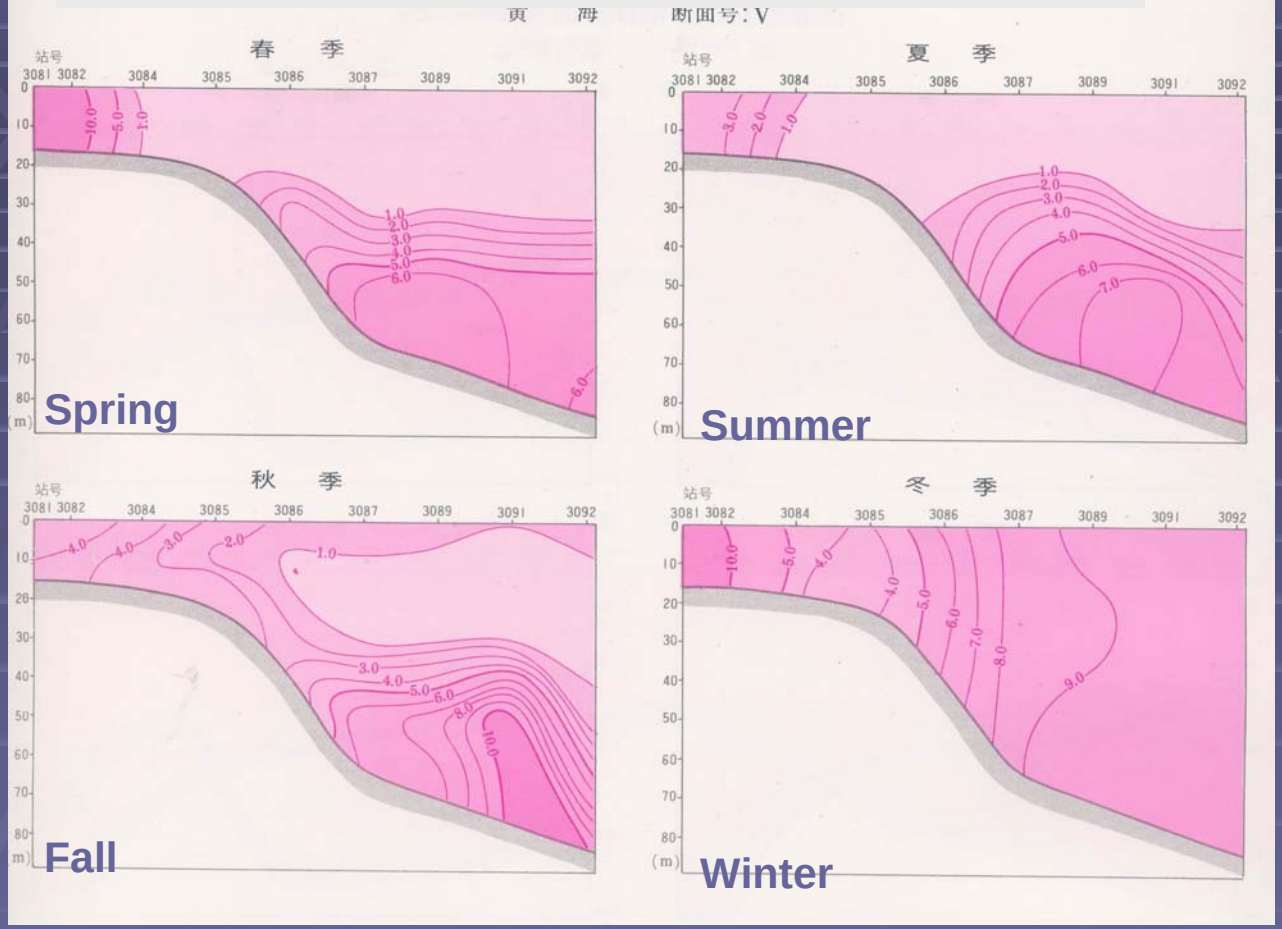
- Spatially

the high concentrations locate near the coasts and the deep trough.



Reference: "Marine Atlas of the Boha Sea, Yellow Sea and East China Sea" compiling all the observations in the period of 1984-1985.

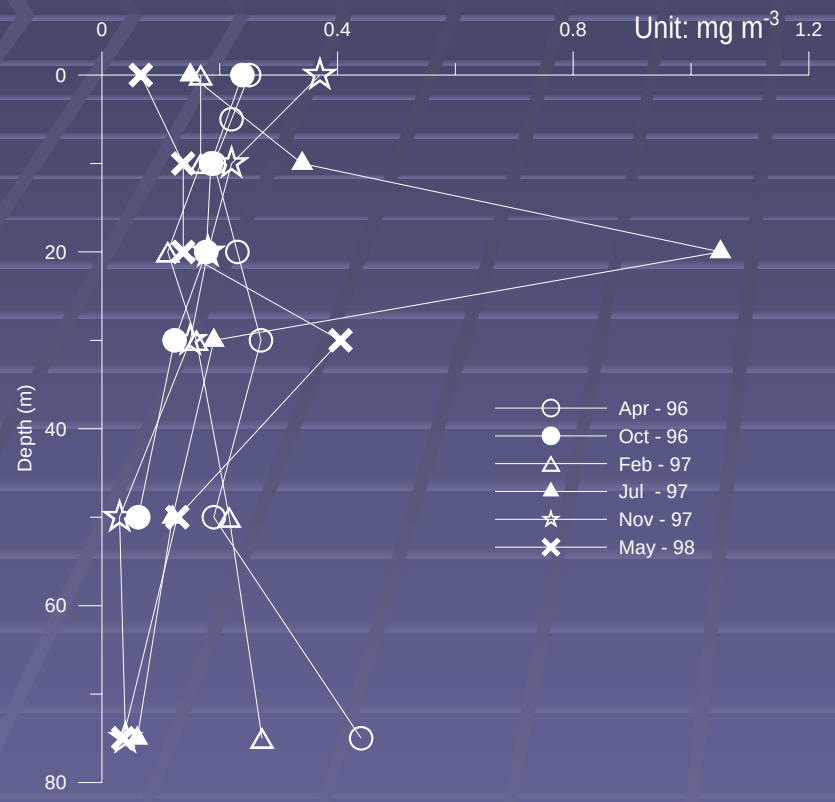
Vertical distribution of Nitrate (mmol N m^{-3}) along 36° N



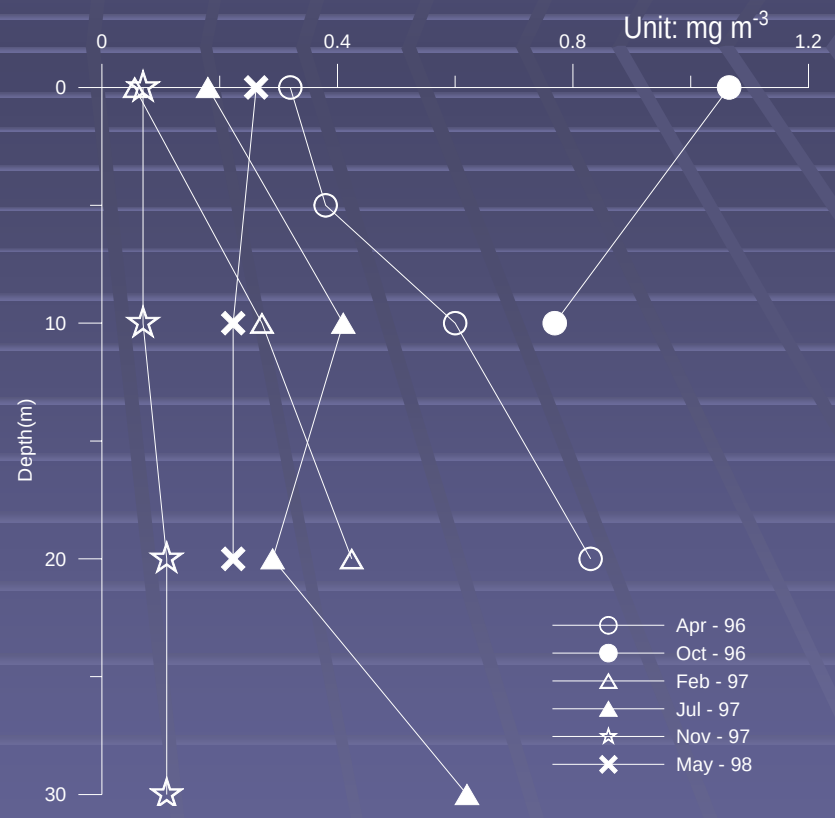
- **Temporally** during the stratified period, nutrients are depleted in the surface waters and enriched in the deep water .
- **Below** the thermocline , the nutrient concentrations linearly increased with time.

Reference: "Marine Atlas of the Boha Sea, Yellow Sea and East China Sea" compiling all the observations in the period of **1984-1985.**

Observed vertical profiles of chl *a* concentrations(mg m^{-3})

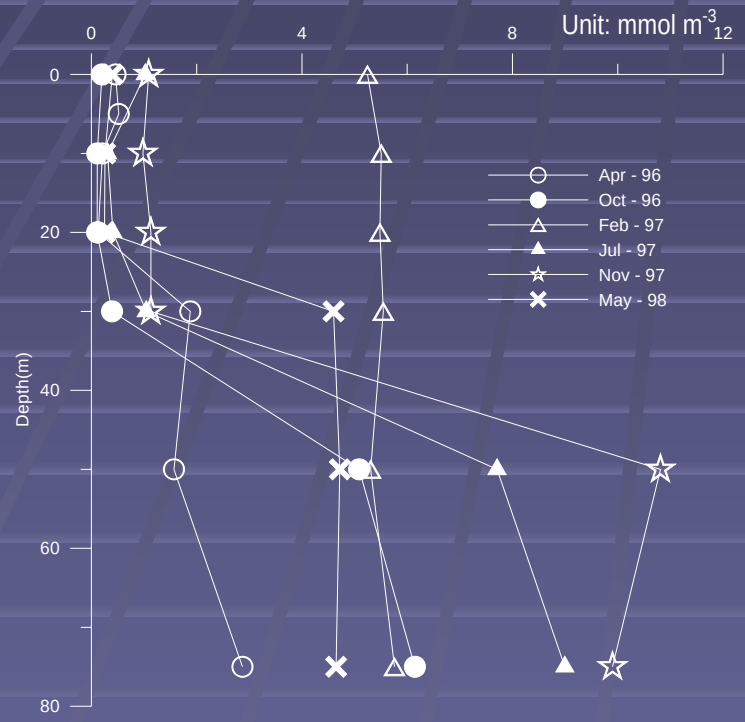


the stratified station
(124° E, 35° N; left)

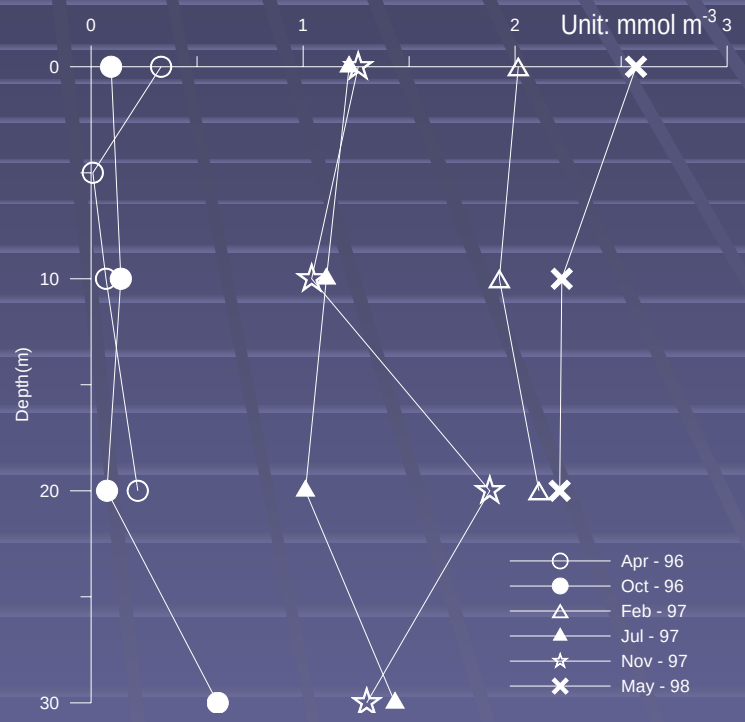


the coastal station
(122.25° E, 34° N; right)

Observed vertical profiles of nitrate concentrations(mmol N m^{-3})



the stratified station
(124° E, 35° N; left)



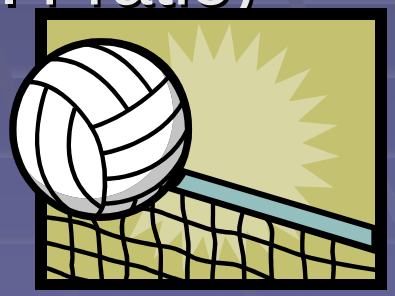
the coastal station
(122.25° E, 34° N; right)

meso-scale physical processes

nutrient transport

primary production

The goal is to analyze the dynamics of phytoplankton bloom and reproduce a complete annual cycle of the production and the corresponding utilization of nitrogen (i.e. f-ratio) under the hydrodynamics environment.



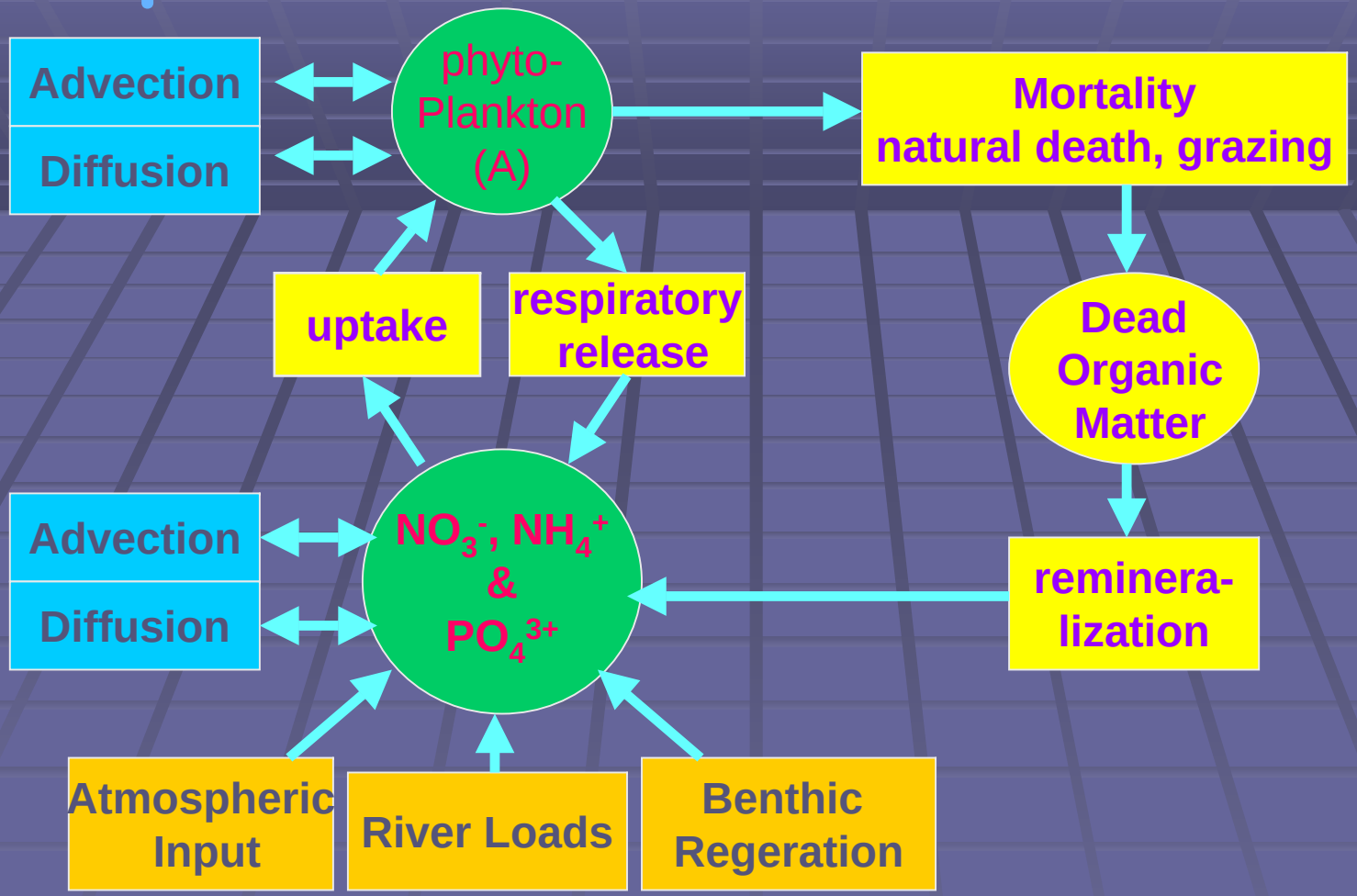
Model and Methods (1+1+1)

- **HAMSOM:** a 3-D baroclinic hydrodynamic model
- **Nutrient Dynamic Model:**

  Phytoplankton Biomass (A, mg m^{-3}) +

  Nutrient Concentration(NO3, NH4, PO4, mmol m^{-3})
- ***f-ratio*** = New Production / Primary Production

Concept Model



$$f = NP/PP \quad = UPTA\,(NO3)/UPTA\,[NO3 + NH4]$$

Explanation of f ratio

- The byproduct of this nutrients dynamics model is the assessment of local and seasonal *f*-ratios with *f* = *UPTA* (*NO*3)/*UPTA* [*NO*3 + *NH*4] (Harrison, 1990) under the definition of *f*-ratio given by Eppley and Peterson (1979), as *f* = NP / PP. Theoretically new production (NP) is the portion of primary production, supported by newly available nitrogen (N) forms, such as NO_3^- and N_2, whereas regenerated production (RP) is supported by nutrients recycled (e.g.NH_4^+ and urea) within the euphotic zone.
- In the coastal environment, ammonium and urea may be significantly enriched due to the river discharge and in such cases they should be included in new N (and thus new production).
- Does the traditional definition of *f*-ratio by Harrison in the coastal zone underestimate the new production?
- In answering this question Yang S.R. *et al*. (1999) assessed that the ammonium supplied from three major external sources (i.e. atmosphere, river and oceanic dumping) is only over 7% of total annual ammonium requirement by phytoplankton in the Yellow Sea and he suggested that the concept of new production (nitrate-based) is applicable to the Yellow Sea.

Forcing:

- **Physical Model :**

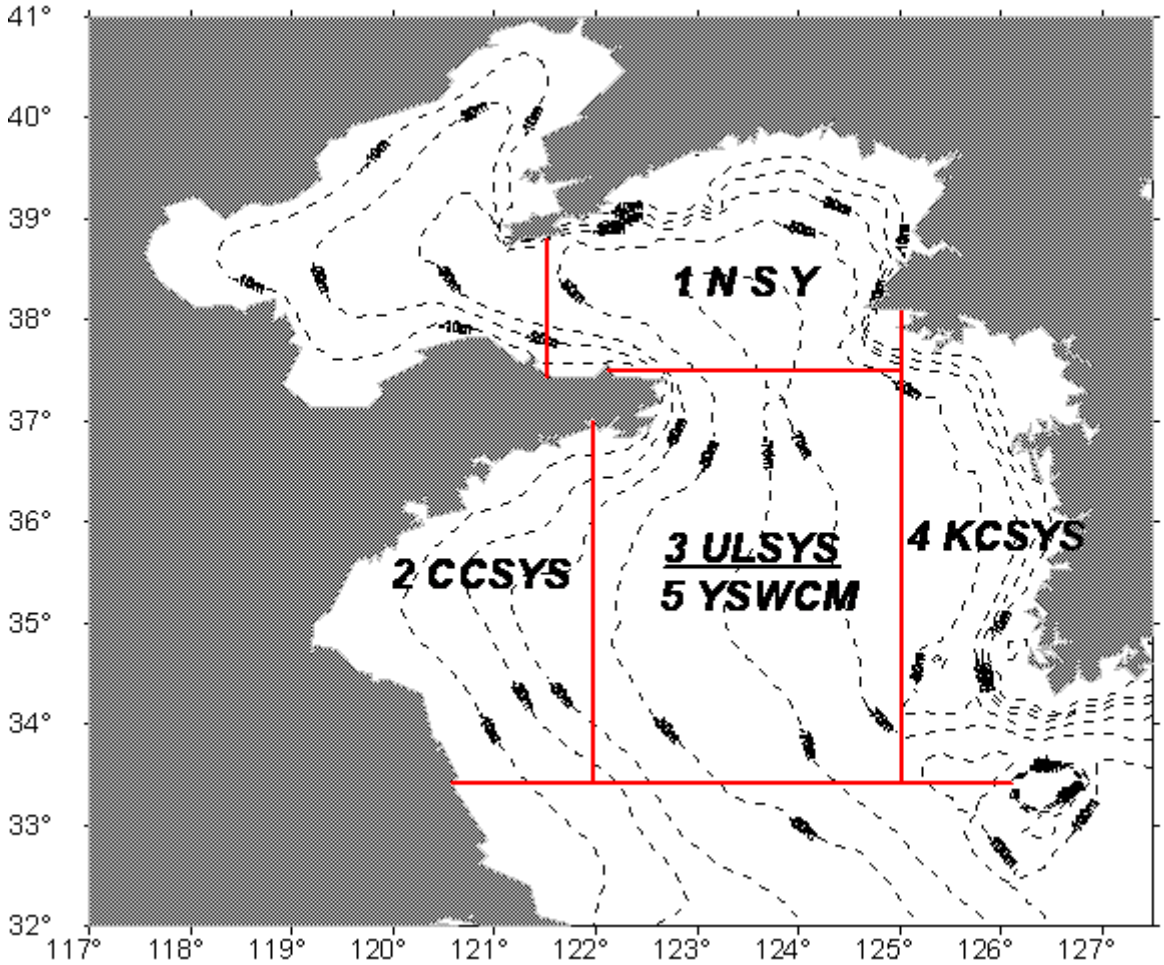
  Levitus' data for monthly mean temperature, salinity and wind speed, 5 tidal components (*M2, S2, N2, O1, K1*);

- **Biological Model:**

  Water Temperature and Solar Radiation (the monthly Cloud Condition and Water Transparency).

Reference: "Marine Atlas of the Boha Sea, Yellow Sea and East China Sea" compiling all the observations in the period of 1949 -1987.

Model Configuration



The division of YS into 5 sub- regions

3D coupled model

Resolution:

5′ ×5′ horizontally,

9 vertical levels(5,10,15,…m)

Time Step: 900s

Initial conditions:

The field data in Feb, 1997 for the project(1996-1998) "China-Korea Joint Research on the Seawater Circulation Dynamics in the Yellow Sea "

Boundary conditions:

The external sources of DIN and DIP in Table 1.

No-gradient condition at the open ocean boundary of 33.5° N.

Table 1. Boundary input of nutrients ($\times 10^9$ mol/ a)

Source		Nutrient fluxes ($\times 10^9$ mol yr^{-1})			Reference
		NO_3^-	NH_4^+	PO_4^{3-}	Tang and Su (2000)
River	Yalujiang	11.7	0.303	0.0015	Zhang, 1997,1998
	Huaihe	1.25	0.362	0.018	Liu, 1999
	Han	1.1	1.4	0.2	Hong, 1995
Wet deposition	The eastern part	4.4	12.2	0.11	Chung, 1998
	The western part	3.5	7.8	0.31	Zhang, 1994,1999
Dry deposition		4.5	17	0.47	Liu, 1999
Sediments		185	-1.81	0.035	Liu, 1999
Total		211.45	37.255	1.145	

Table 2. Parameters for th[illegible]nd conversion factors

Param	Comparison with the references	Symbol	Value	Unit
Maxin	1.0 in the western subarctic Pacific (off Japan) by Yoshimori *et al*. (1995)	r_p	1.0	day^{-1}
Percer	0.1 in the North Sea, by Moll (1998); 0.138 in the Bohai Sea, by Zhao *et al*. (2002)	r_B	0.13	
Percer	0.05 by Moll (1998) and Zhao *et al*. (2002)	r_{PR}	0.05	
Phytop	0.05 by Moll (1998) and Zhao *et al*. (2002); 0.1 by Yoshimori (1995)	r_M	0.11	day^{-1}
Percer	0.2 of remineralized fecal material,	p_M	0.5	
the wa	0.2 of remineralized dead phyto-plankton, 0.2 of reminearalized dead zooplankton in the water column by Moll (1998)			
Tempe	0.069 by Moll (1998)	r	0.08	$(^\circ C)^{-1}$
Nitrate	1.0 at Georges Bank by Franks and Chen (1996) and in the Bohai Sea by Gao *et al*. (1998)	K_n	1.0	$mmolN\ m^{-3}$
Ammo		K_a	0.5	$mmolN\ m^{-3}$
Phospi	0.5 by Fasham *et al*. (1990)	K_p	0.1	$mmolP\ m^{-3}$
Ammo	0.06 by Moll (1998), 0.068by Zhao *et al*. (2002)	ψ	1.5	$(mmolN\ m^{-3})^{-1}$
N/C ra	1.5 by Wroblewski (1977)	g_n	12.1	$mmolN(gC)^{-1}$
P/C ra	12.277 by Zhao *et al*. (2002)	g_p	1.0	$mmolP(gC)^{-1}$
C/Chl	1.0012 by Zhao *et al*. (2002)	g_C	50.0	$gC(gChl\ a)^{-1}$
Optim	50.0 by Moll (1998), 38.306 by Zhao *et al*. (2002)	I_o	150	Wm^{-2}
	150 by Zhao *et al*. (2002)			

Validation

Data comparison with observations

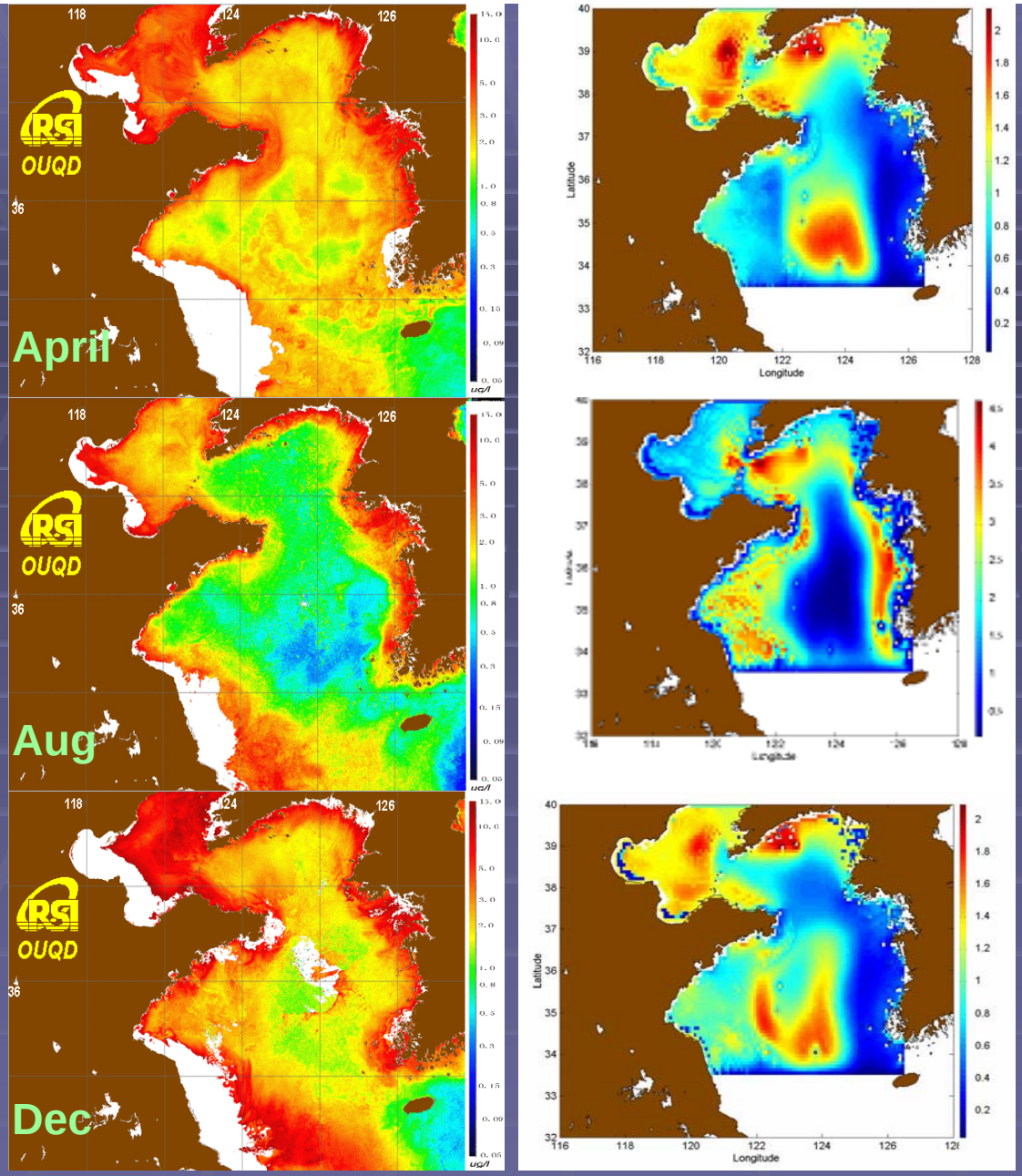
Results and Discussion

Focus

① **Annual Cycle of Nutrients and Phytoplankton**

② **Dynamics of Phytoplankton Blooms**

③ **New Productivity —the net capability of absorbing CO2 from the atmosphere.**



surface chl *a* concentrations (mg m^{-3})

for the monthly averaged SeaWiFS data (left) and simulations (right)

RESULT 1- chl *a*

The model reproduce the phenomena:

1) the North Yellow Sea ranks among the major regions with high primary production;

2) the high algal bloom show once in coastal regions in summer and twice in the central part a year;

3) the high biomass occurs at the front area in summer.

RESULT 2

Data comparison of the observed and simulated regionally annual-averaged concentrations of nutrients

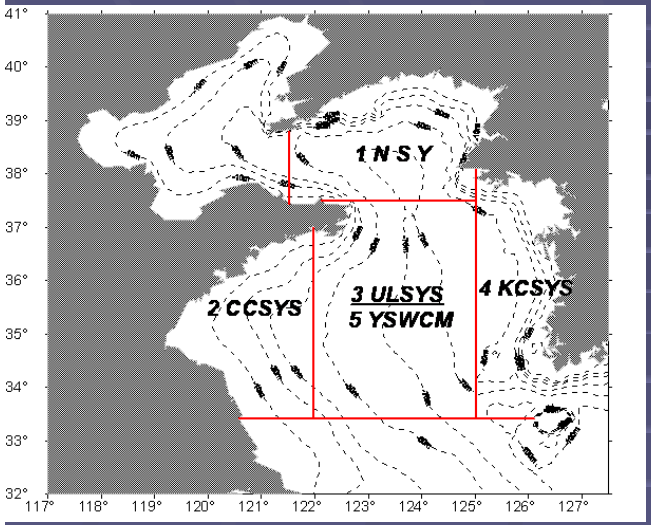
Yearly averaged value ($mmol\ m^{-3}$)		NYS	CCSYS	ULSYS	KCSYS	YSCWM
DIN	simulated	2.85	2.65	3.79	4.44	5.69
	observed	2.08	2.10	2.48	3.73	7.34
DIP	simulated	0.30	0.23	0.3	0.37	0.37
	observed	0.34	0.20	0.21	0.33	0.60

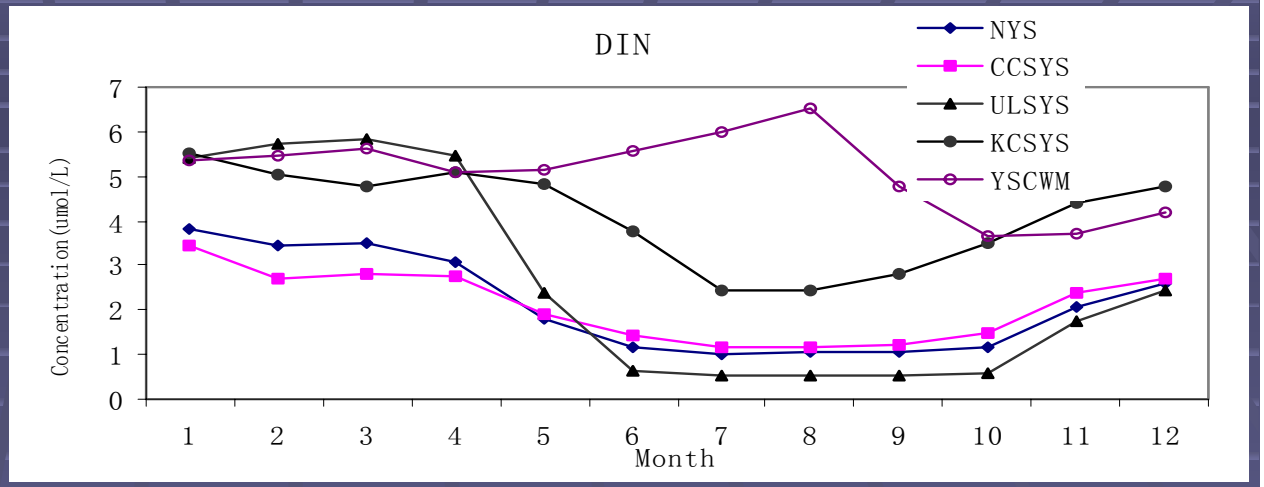
- **The observed and simulated value agrees well**
- **Except the central part of the Yellow Sea:**

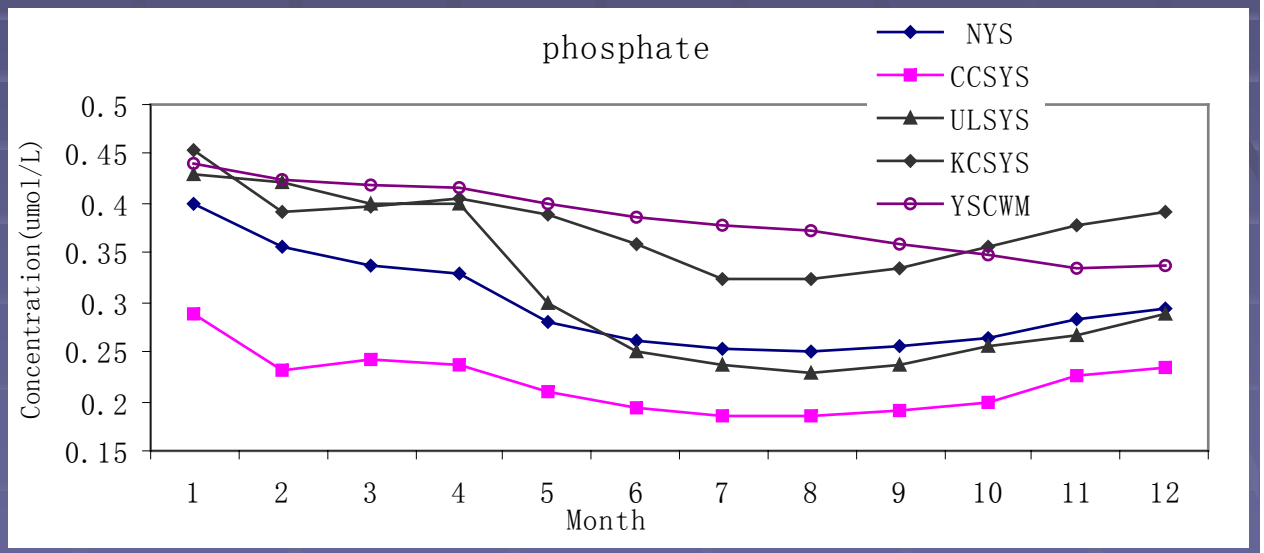
  the results above the CWM is higher than the observation and vice versa.

- **It suggests that the real seasonal stratification, which depends on weak vertical mixing to maintain, plays a more important role in the vertical distribution than the model does.**

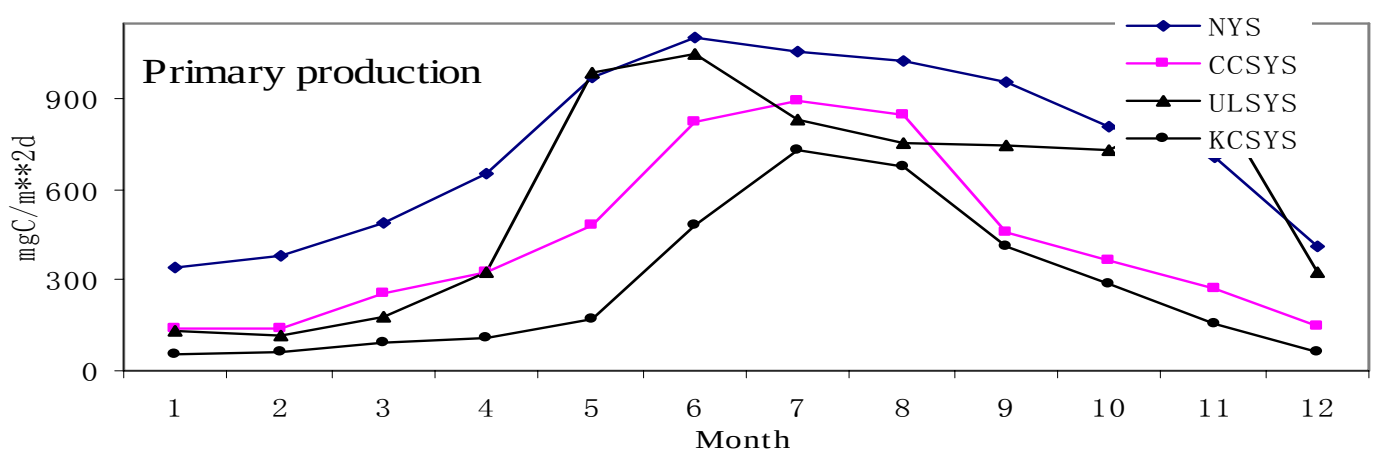
RESULT 3 Annual cycle of nutrients

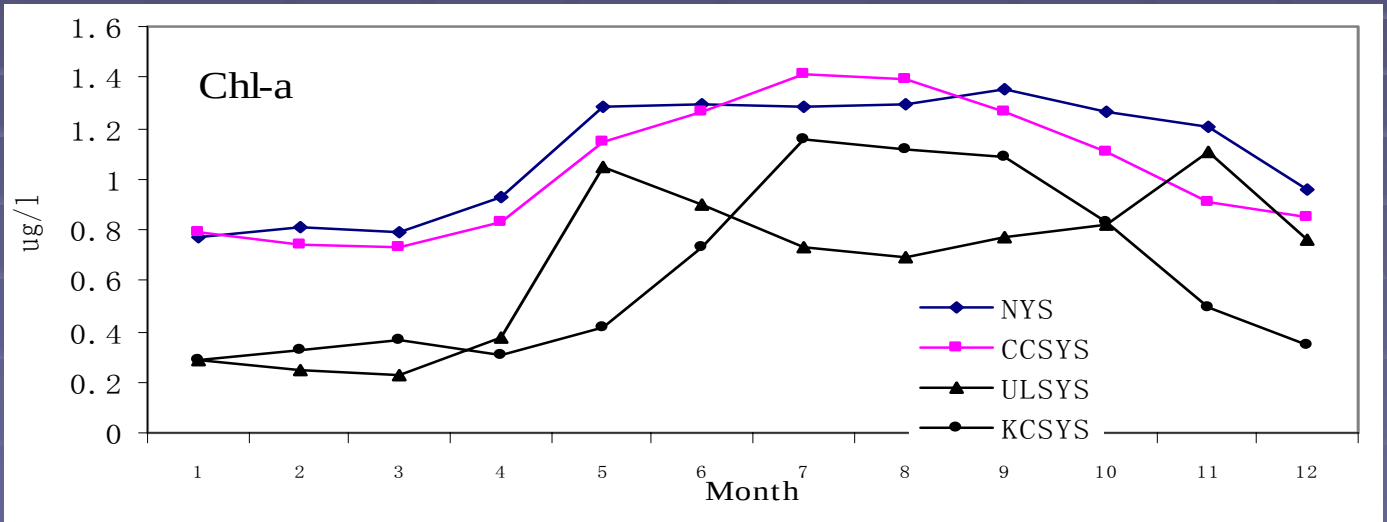






RESULT 3 Annual cycle of Primary Production





RESULT 4 ---Nitrate (mmol N m^{-3})

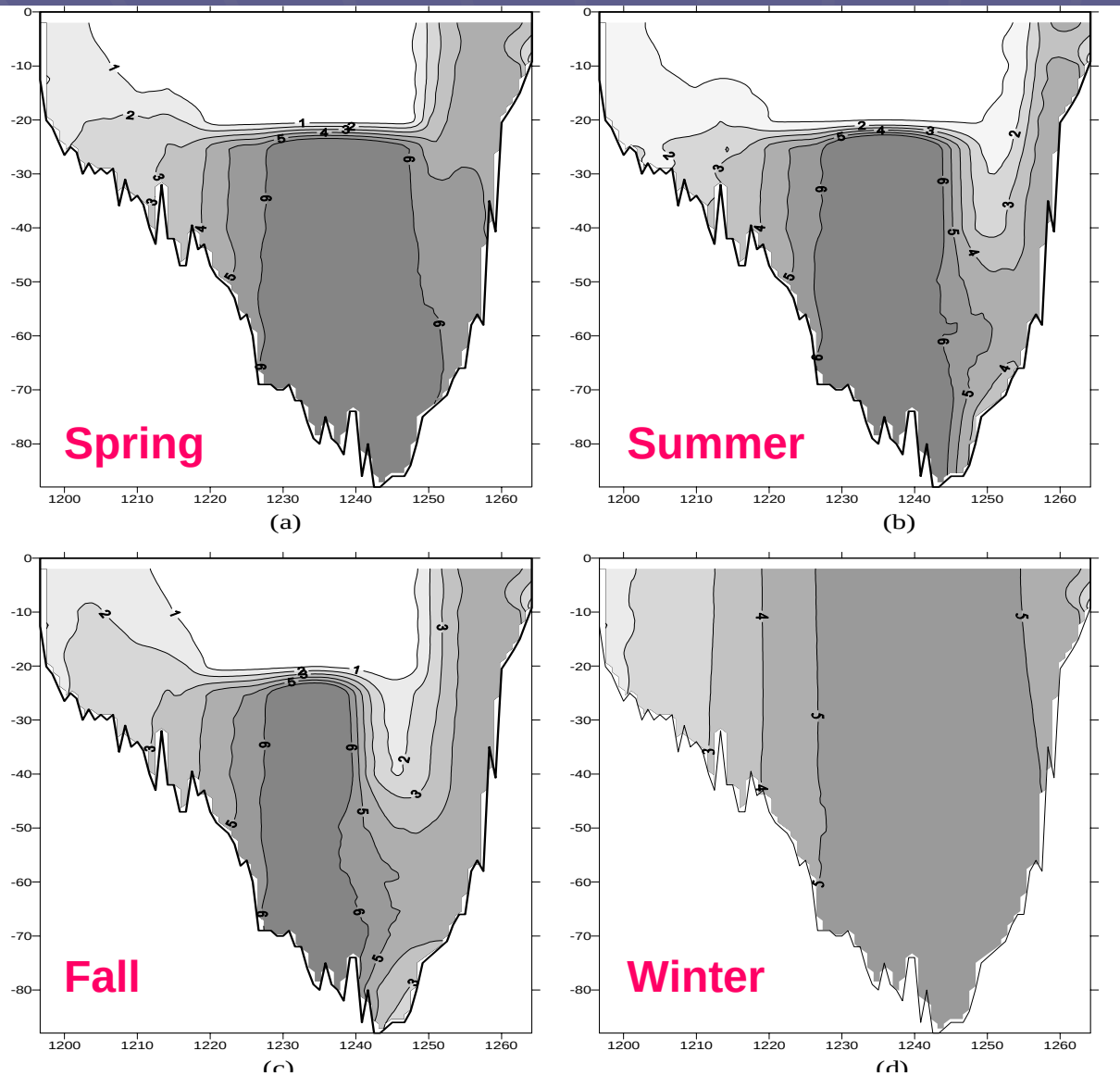


图 6. 硝酸盐 (c)秋季，(d)冬季

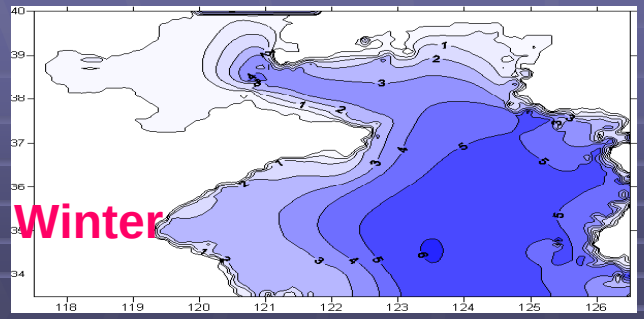
Vertical distribution **along 35° N**

The seasonal nutrient cline accompanies the thermocline;

Below the theromcline the YSCWM performs as a storage pool of nutrients;

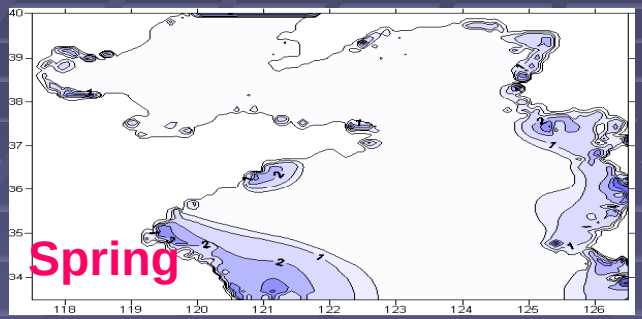
In winter the high concentration is a clue of YS Warm Current.

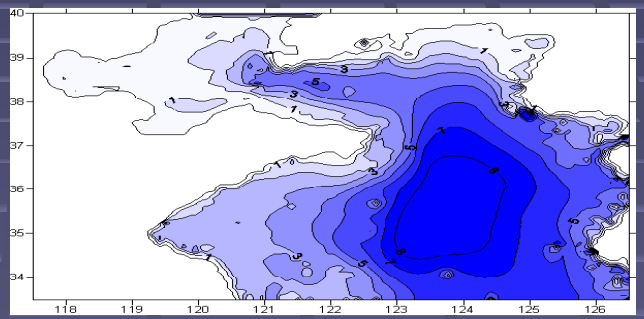
RESULT 5
|
Nitrate

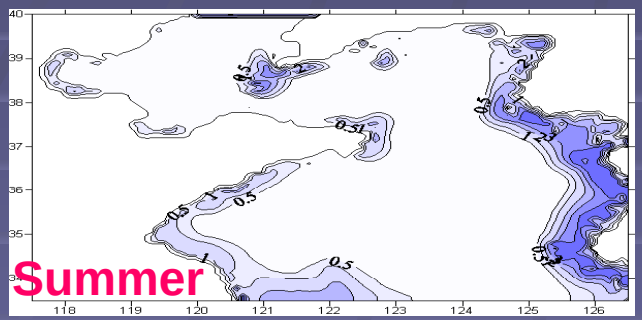


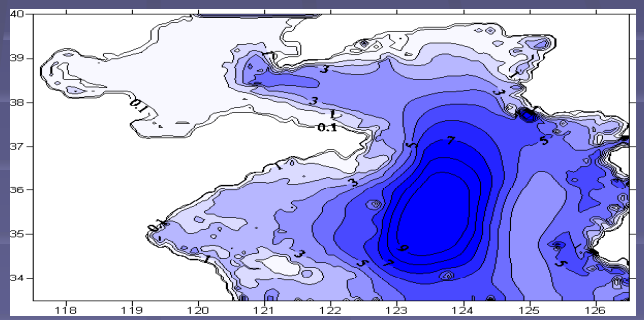
Surface

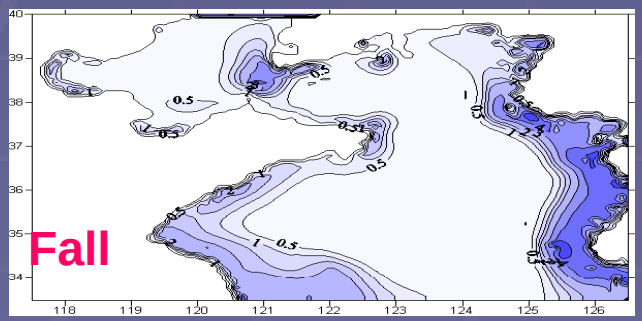
Bottom

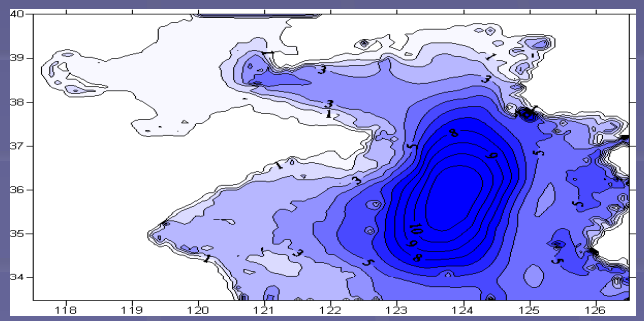








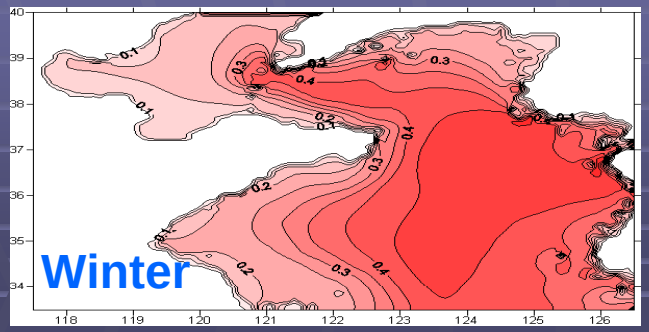


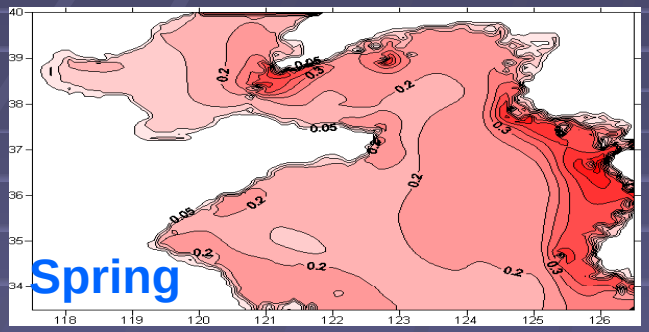


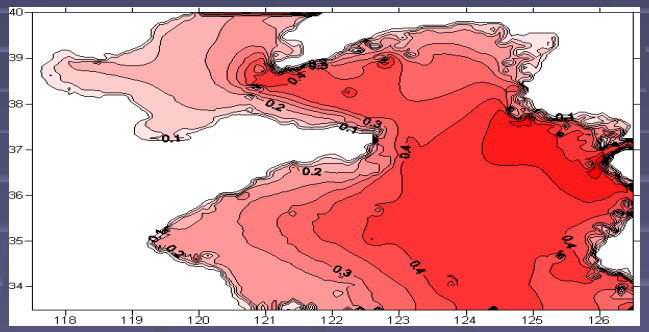
RESULT6 | Phosphate

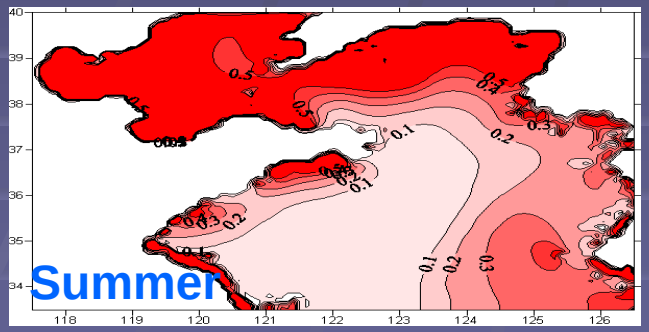
Surface

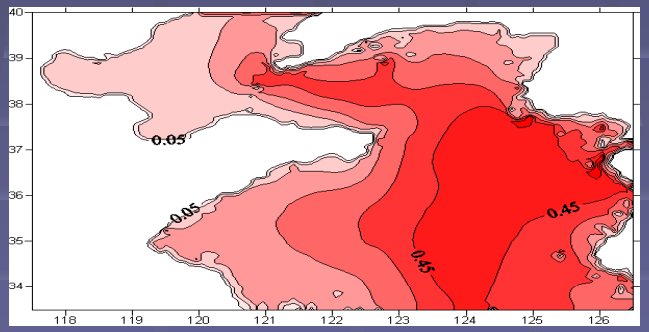
Bottom

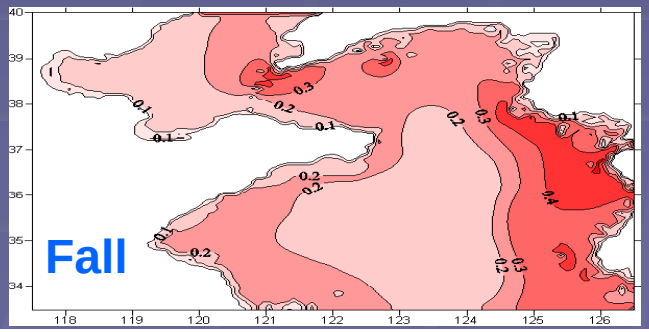


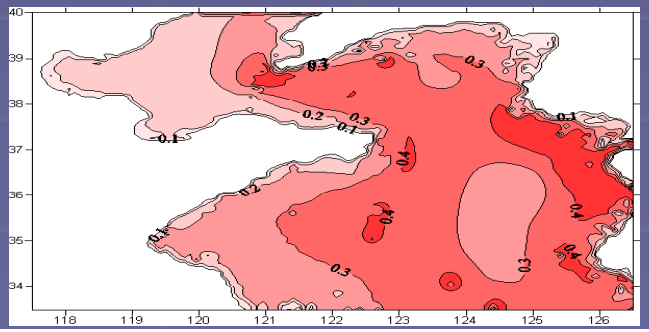






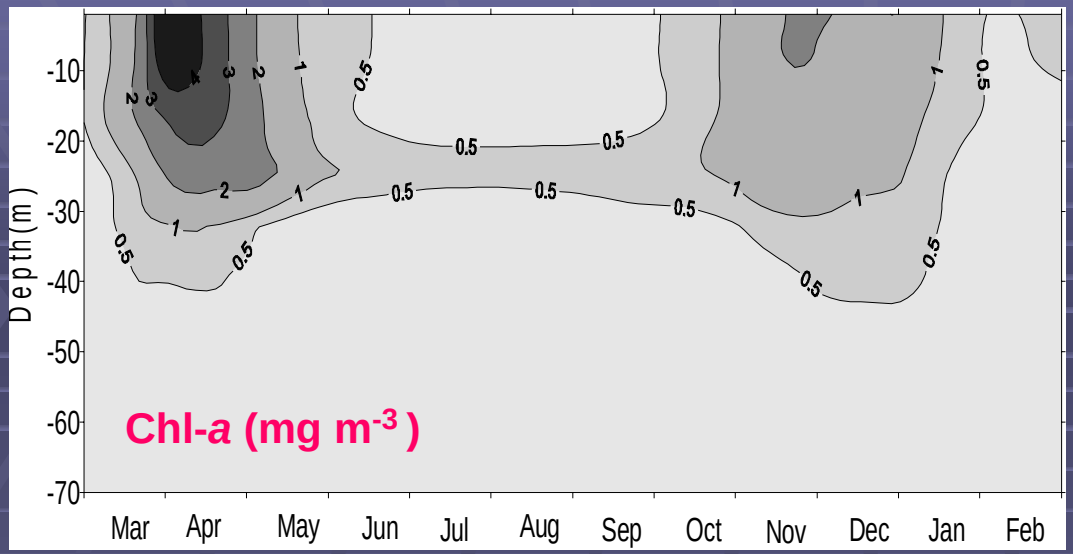


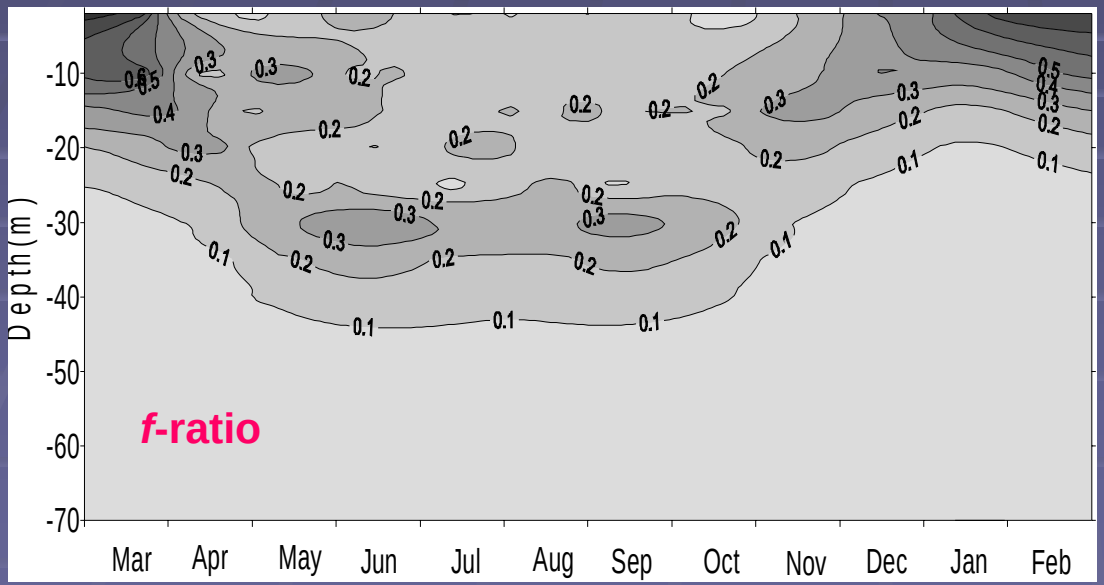




The discharge of Hanjiang River is a major source for phosphate。

RESULT 7



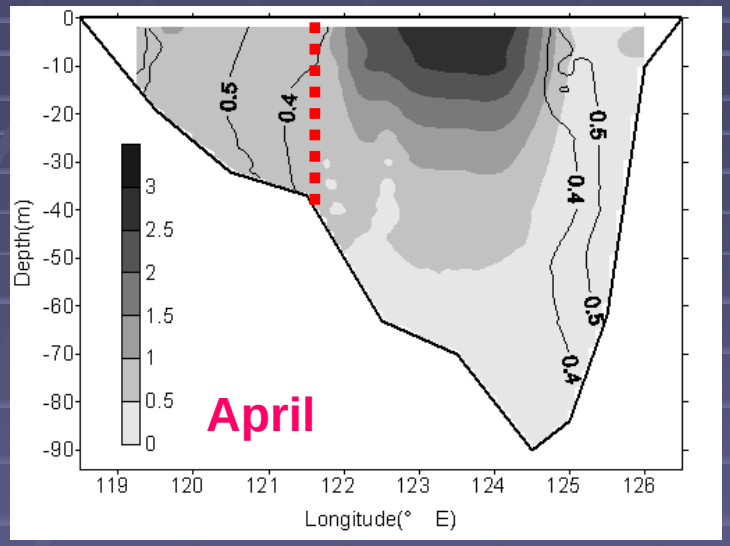


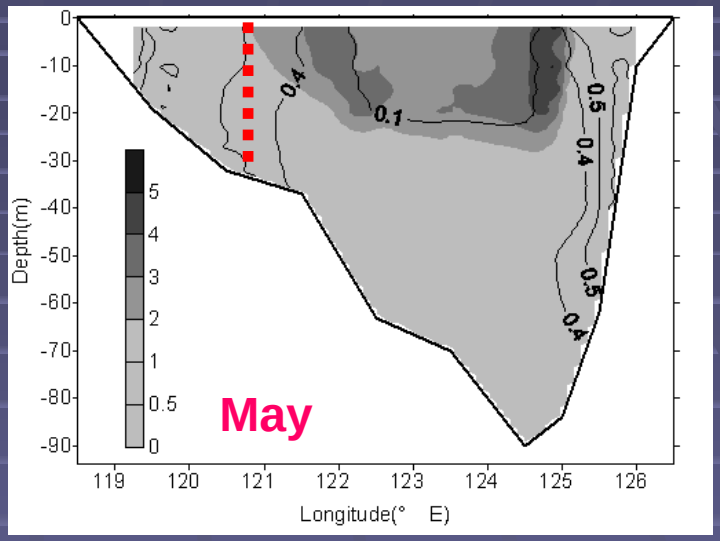
A subsurface max. of chl-*a* shows at the base of thermocline with a high *f*-ratio where high nutrient gradient and moderate light condition locate.

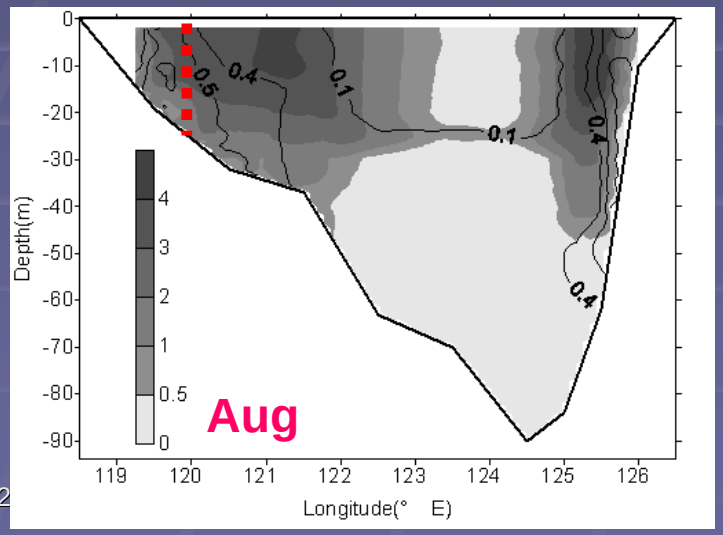
It indicates that the strength of mixing is favorable to support the plant growth by entraining new N from YSCWM and maintain the high content of chl *a*.

RESULT 8---The YS capability of PP and NP

Vertical distribution of chl *a* concentrations (mg m^{-3}, coloured) together with *f*-ratio profiles (contour line), along 35° N

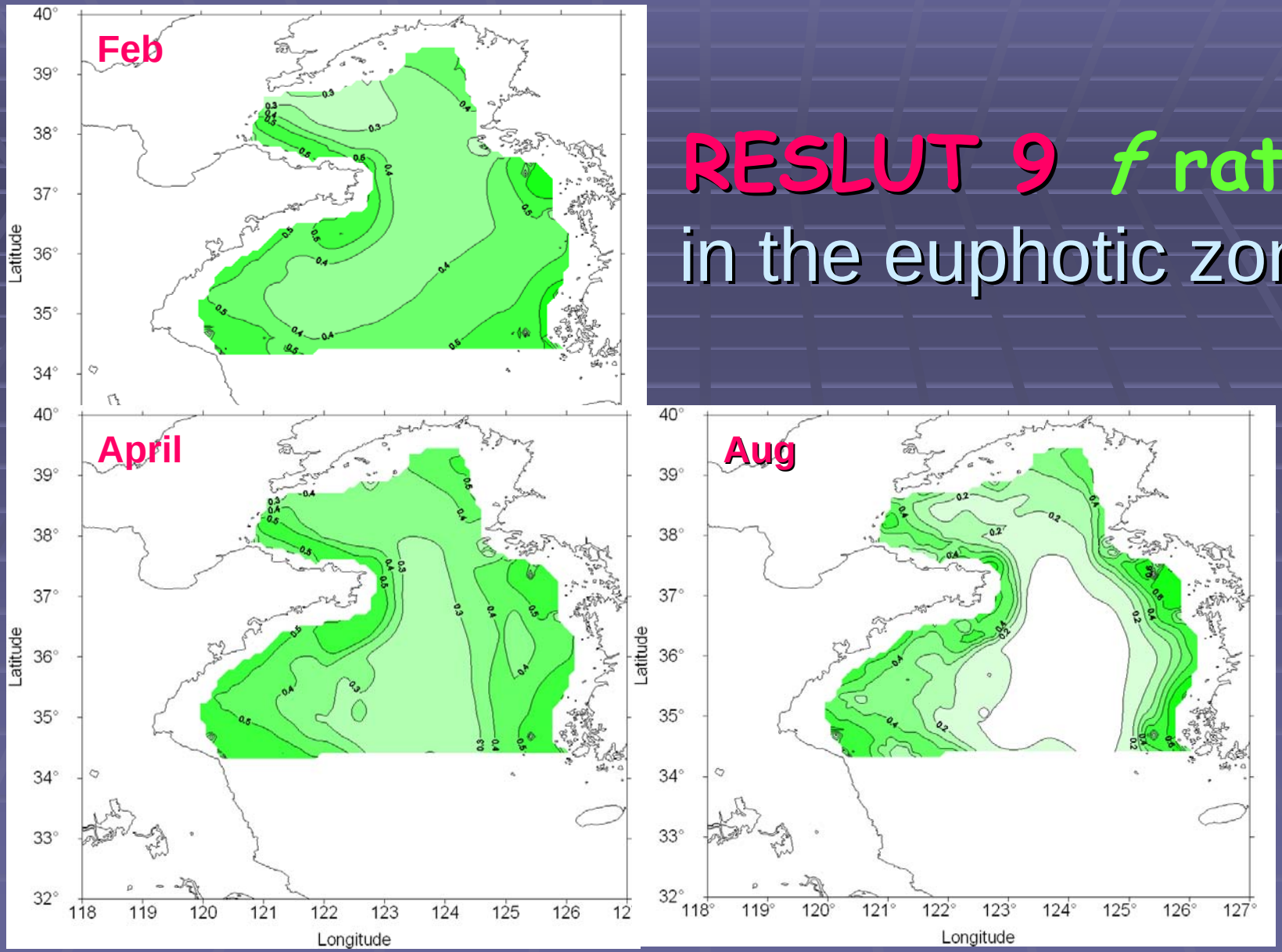






- **The maximum of *f* does not locate at the frontal area.**
- **It suggests that the frontal convergence is the hydrodynamic mechanism of the high chl *a* concentration other than the upwelling, inducing a high new production.**

RESLUT 9 *f* ratio
in the euphotic zone



RESULT 10---NUTRIENT BUDGET

- External sources contribute to 27.2% of N and less than 2% of P for PP;
- Benthic nitrogen fluxes account for 54.6% of NP utilization, responsible for the high *f*-ratios of the coastal water;
- The input of atmospheric deposition is as much as 3-5 times that of river loads;
- The Yalujiang River discharges 49 % of the nitrate, supplied by all the rivers. The Han River supplies the Yellow Sea with 52 % of the ammonia and 47.5 % of the phosphate of the total river loads.

At the open boundary at 33.5° N, there are 13.2×10^9 mol N and 0.8×10^9 mol P, transported into the East China Sea.

CONCLUSION--- PP & NP

The distributions of the nutrients and the ecological functions are under the control of the mixing mechanism in the Yellow Sea. Two ecological function sub-regions are divided as the seasonally stratified water and permanently well-mixed turbid coastal water (Chung, 1999).

The coastal water system:

Both high primary production (PP) and high new production (NP) in summer.

The limiting factor: light condition

The stratified water system:

Two blooms in the upper 30m waters take place at the beginning of the spring in April and at the end of fall in Nov.

The limiting factor: light condition and T for 1st major bloom;

new nutrients from YSCWM for 2nd minor bloom.

The North of the Yellow Sea has the characteristics of both systems and is the most significant region with the high PP and NP all over the year.

YSCWM is an important storage pool of nutrients for the euphotic zone. The exchange at the sediment-water interface is an important source of nitrate and responsible for the high NP in the Yellow Sea.

Old Hypothesis:

The high production supported by the new nutrient is usually supposed to be a result of upwelling and *f* will be more than 0.5.

Generally the regenerated production plays its dominant role along with the evolution of the thermocline.

New Finding:

The key mechanisms of nutrient supplement in the central part of YS should be the mixing due to strong wind processes , internal waves and variation of thermocline other than upwelling

It was estimated that turbulence in one strong wind process could bring about 15.9 mgC $m^{-2}d^{-1}$ new production to the upper layer and at this rate the nutrients could be replenished in half a month. (Wei, 2002)

Nutrient Utilization

A noticeable feature: phosphate is the major nutrient limiting factor to the euphotic production in the whole area almost in the whole year. The observations (Wang et al, 2003) demonstrate that a bloom is always associated with a high phosphate stock.

It indicates that the control of phosphate stock in the water column will be the most useful measure to maintain the healthy ecosystem environment of the Yellow Sea.

PROSPECT

Evaluation: the first time in YS

To give a complete depiction about the biological role of the physical environment in a year cycle;

To explore the dynamics of phytoplankton production;

To use the definition of "new" and "regenerate" N to estimate regional and seasonal *f* ratio.

The model successfully reproduced the main features of phytoplankton-nutrient variation and the production dynamics.

Future work

- ***To change*** some coefficients in the current model according to the observation and lab experiment
- ***To couple*** Trophodynamics Model with **IBM** of anchovy early life history

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Thank you

The Sunset of the Yellow Sea

Control equations

$$\frac{\partial A}{\partial t} = -\left[u\frac{\partial A}{\partial x} + v\frac{\partial A}{\partial y} + w\frac{\partial A}{\partial z}\right] + \left[\frac{\partial}{\partial x}\left(A_x\frac{\partial A}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_y\frac{\partial A}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_z\frac{\partial A}{\partial z}\right)\right] + PROD - RESP - DEAD,$$

A: the concentration of the chlorophyll-a (mgC · m^{-3}),

PROD: gross primary production, $PROD = r_p \cdot r_T \cdot \min(r_I, r_{NN}, r_{NP}) \cdot A$, r_p : maximum grow rate of the phytoplankton, r_T : temperature dependent factor, $r_T = \exp(0.05(T-10))$, T is temperature, r_I: light limited factor, $r_I = \frac{I}{I_{opt}}\exp(1-\frac{I}{I_{opt}})$, I_{opt} : optimum light intensity, I: averaged light intensity in the transparent layer of the water, $I = I_0 \exp(-k_{ext} z)$, I_0 : radiation intensity at the sea surface, k_{ext} : light vanish parameter, k_{ext}=1.51/S, S : transparency of the sea water, z: water depth; $r_N = N/(N+K_s)$, N: nutrient concentrations including DIN and DIP, K_s : half saturation constant of nutrition;

RESP: respiration consumption, $RESP = r_p \cdot r_T \cdot r_B \cdot A + r_{PR} \cdot PROD$, r_B : percentage of basic respira-tion, r_{PR} : percentage of photorespiration; DEAD: mortality, $DEAD = r_M \cdot A$, r_M: mortality rate.

N represents the concentrations of the nitrate (NO_3 ,mmol · m^{-3}), the ammonium (NH_4 ,mmol · m^{-3}) and phosphate (PO_4 ,mmol · m^{-3}) in the 3 nutrient equations, respectively,

$$\frac{\partial N}{\partial t} = -\left[u\frac{\partial N}{\partial x} + v\frac{\partial N}{\partial y} + w\frac{\partial N}{\partial z}\right] + \left[\frac{\partial}{\partial x}\left(A_x\frac{\partial N}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_y\frac{\partial N}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_z\frac{\partial N}{\partial z}\right)\right]$$
$$-UPTA + RELE + REMA + Air + Bot + Riv$$

UPTA : nutrient uptake, $UPTA = g_P \cdot PROD$; RELE: nutrient release, $RELE = g_P \cdot RESP$;
REMA: nutrient mineralization of the dead organism in water column, $REMA = g_P \cdot p_M \cdot DEAD$;

$$PROD = r_p \cdot r_T \cdot \lim \cdot A, \quad RESP = r_p \cdot r_T \cdot r_B \cdot A + r_{PR} \cdot PROD, \quad \lim = \begin{cases} {}^1\min(r_i, r_{NO3}, r_{NP}) \\ {}^2\min(r_i, r_{NH4}, r_{NP}) \\ {}^3\min(r_i, r_{NN}, r_{NP}) \end{cases},$$

$\lim^{1,2,3}$: nutrient limited functions (NO_3^-、NH_4^+、PO_4^{3-}, respectively);
In the equations of the nitrate and ammonia,

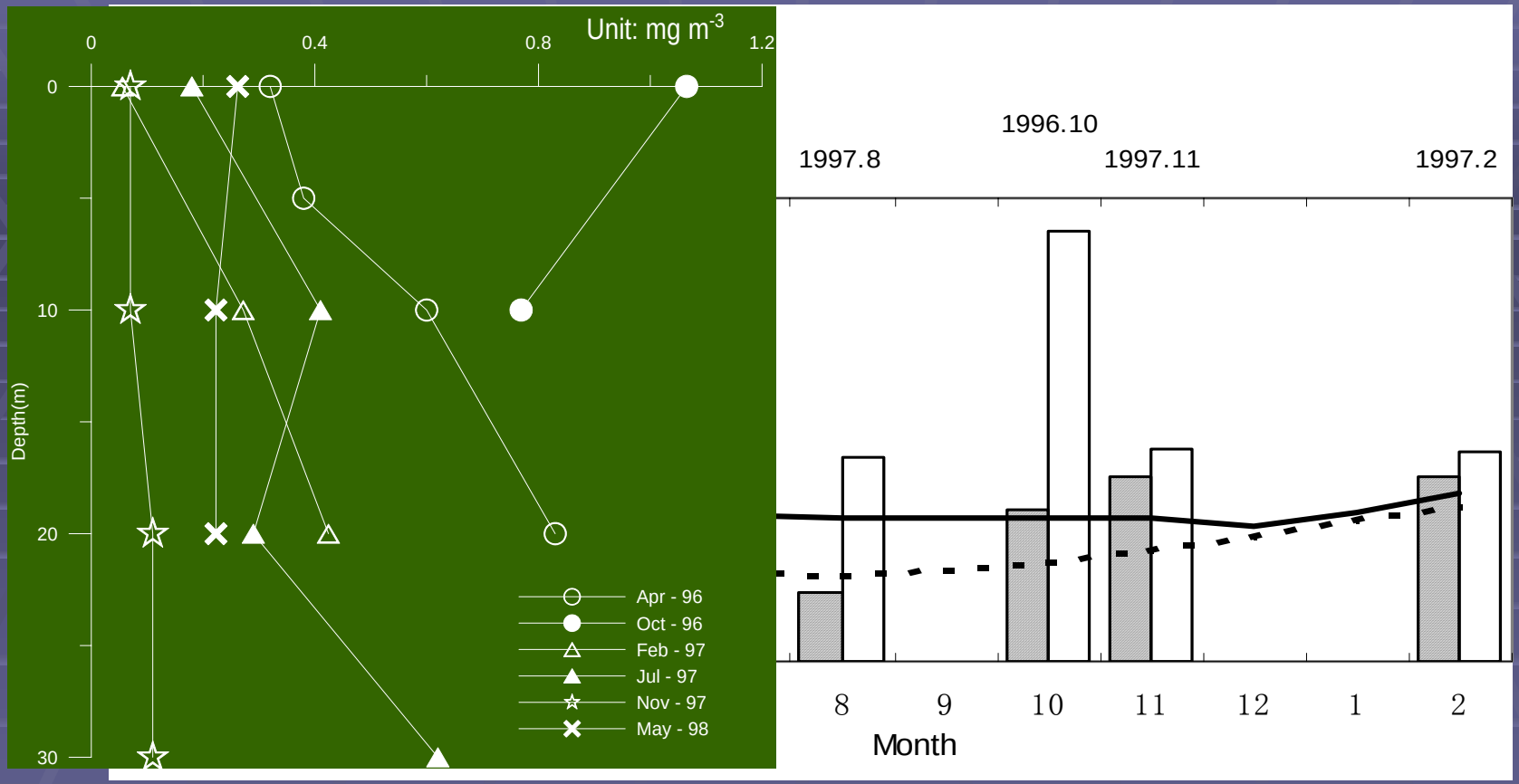
g_p : N/C, $r_{NO3} = \frac{NO_3}{NO_3 + k_{NO_3}} e^{-2.0NH_4}$, $r_{NH4} = \frac{NH_4}{NH_4 + k_{NH_4}}$,

where the equation of the nitrate: RELE＝0，REMA＝0；
In the equation of the phosphate,

g_p :P/C, $r_{NN} = r_{NO3} + r_{NH4}$, $r_{NP} = \frac{PO_4}{PO_4 + k_{PO4}}$,

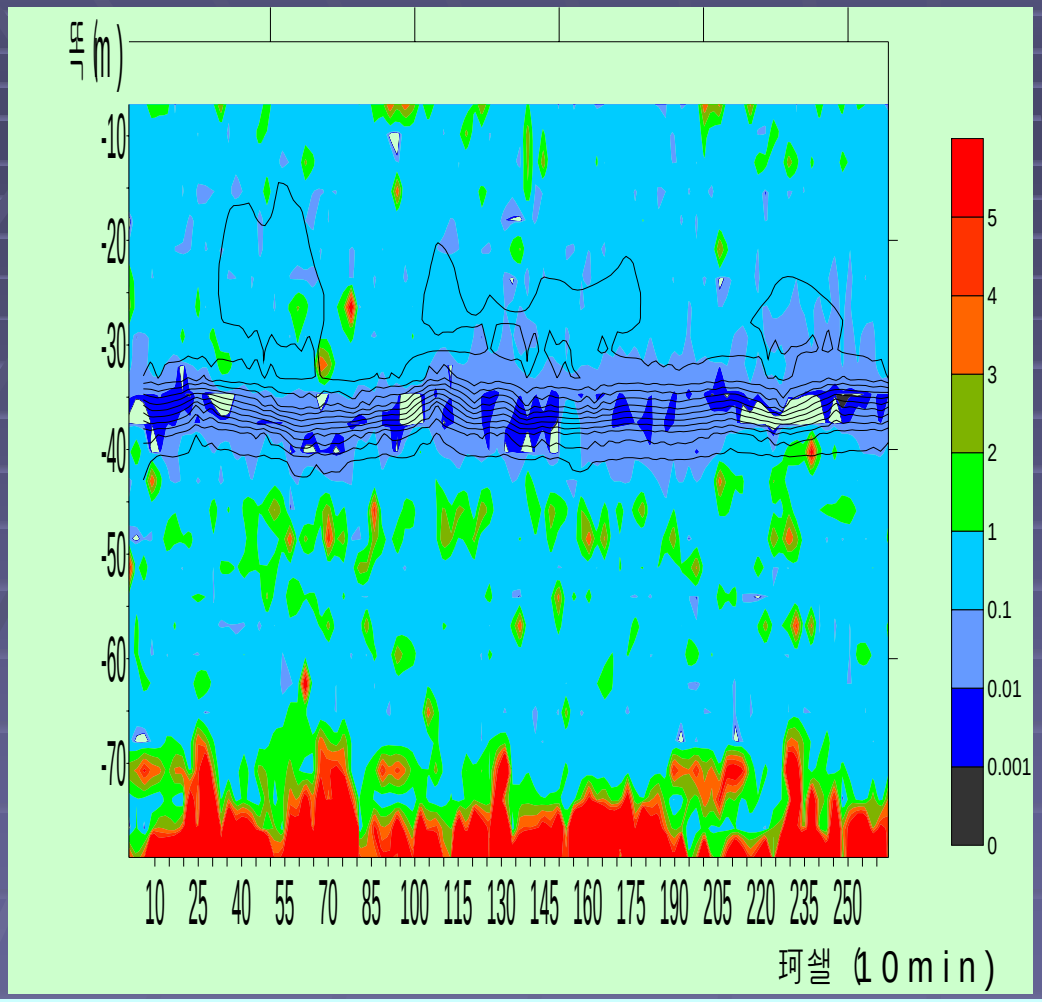
$k_{NO_3}, k_{NH_4}, k_{PO_4}$: nutrient half-saturation constant (Table 1.).

The flux at the boundaries: Air is atmosphere deposition, Bot is the exchange between the sediment and water interface, Riv is river loads.



Annual cycle of phosphate concentrations (mmol P m^{-3}) averaged in the euphotic layers (dashed line) and bottom layers (solid line), compared with the data in the surface water (striped bars) and at the depth of 50m (blank bars) measured by Chung *et al*. (1999).

DISCUSSION ---Turbulence and Marine Ecosystem



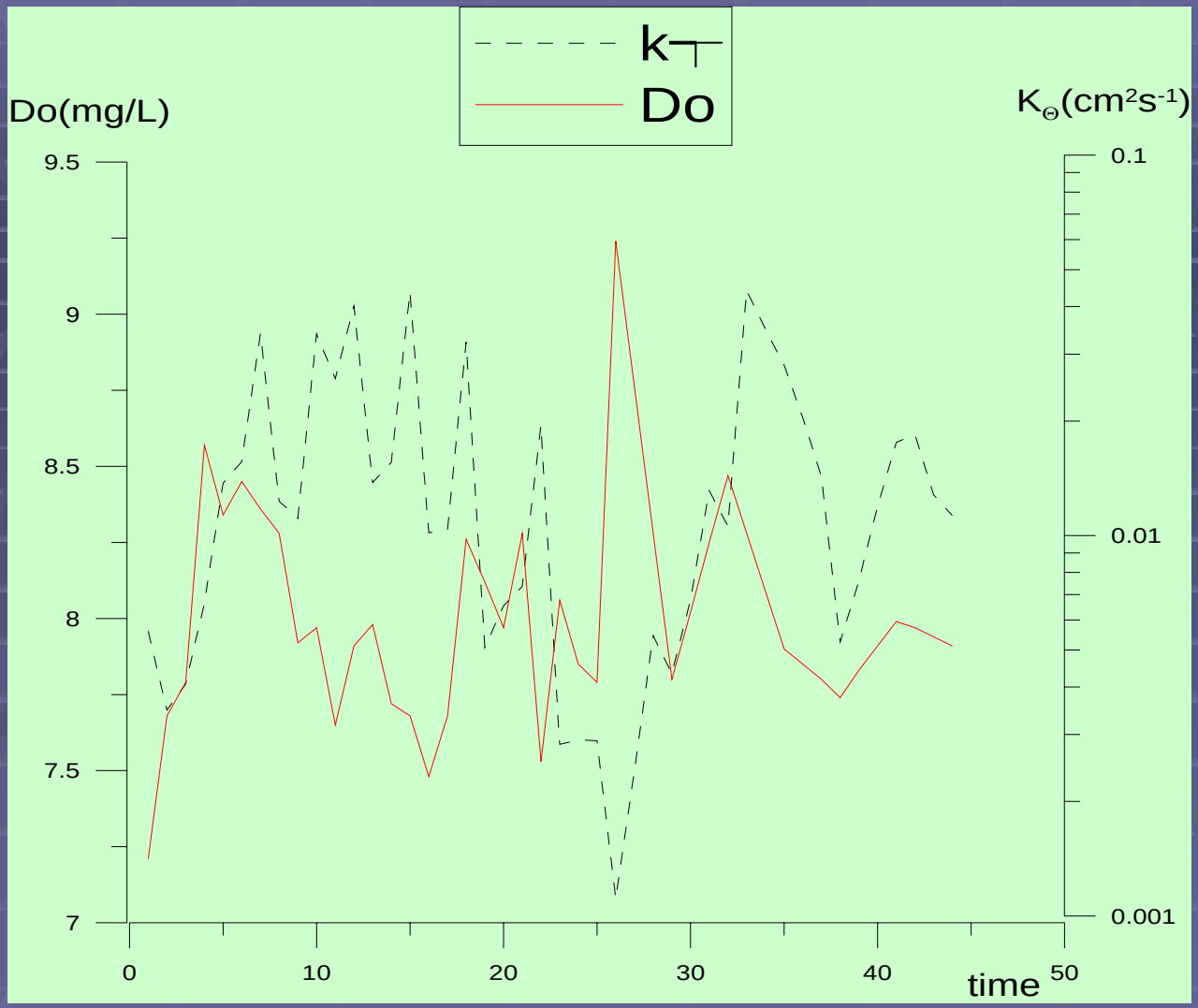
vertical eddy diffusivity at the station of YSCWM (34° 30′ N, 123° 06′ 'E) on October 23-25, 2000 by Wei (2004)

Its maximum near the bottom layer: $5\times10^{-4}m^2s^{-1}$,

the upper and lower mixing layers: $10^{-5}\sim10^{-4}\ m^2s^{-1}$,

near the thermocline: $10^{-7}m^2s^{-1}$

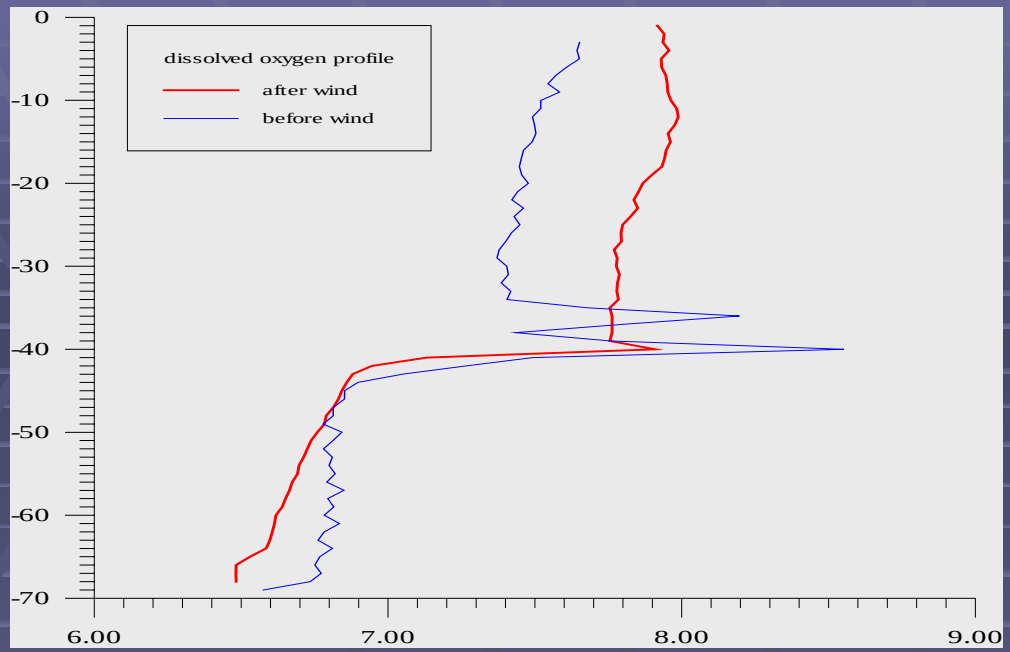
- The presence of thermocline weakened the turbulence mixing of water column;
- Spectral analyses reveal that the significant period is semi-day.
- There is the mass transport across the thermocline by means of turbulence entrainment during the strong tide current.

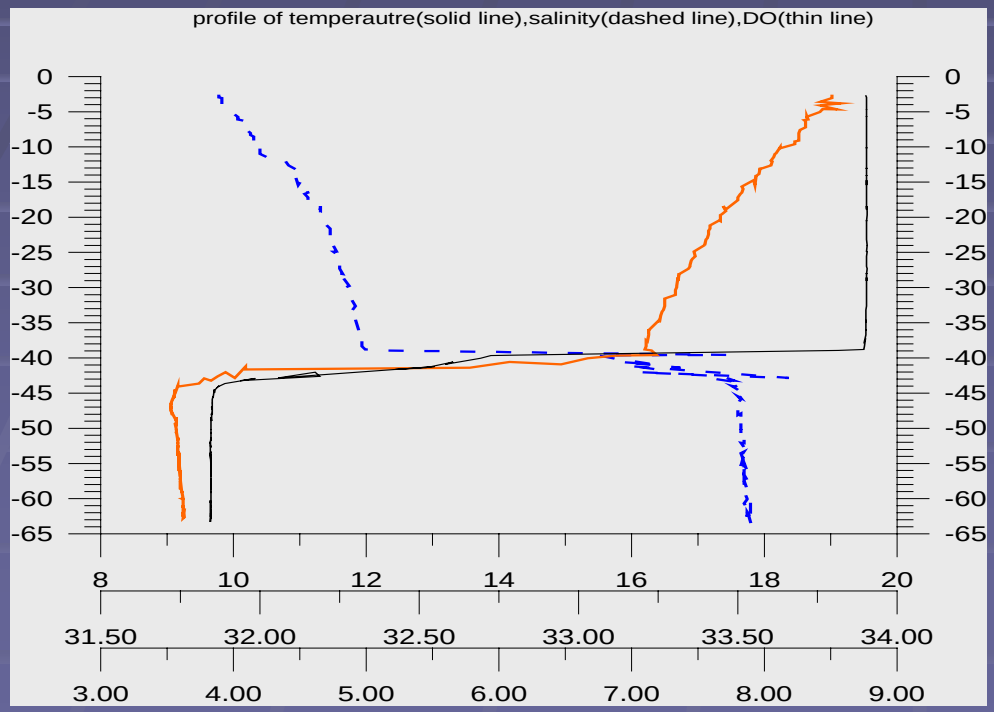


Relationships between

DO and **turbulent coefficient**

- **In the thermo-cline DO was markedly negatively correlated with k_ρ;**
- **DO are mainly controlled by photo-synthesis of phytoplankton.**
- **The conclusion is that the weak mixing in thermo-cline is the main mechanism of the highest DO.**

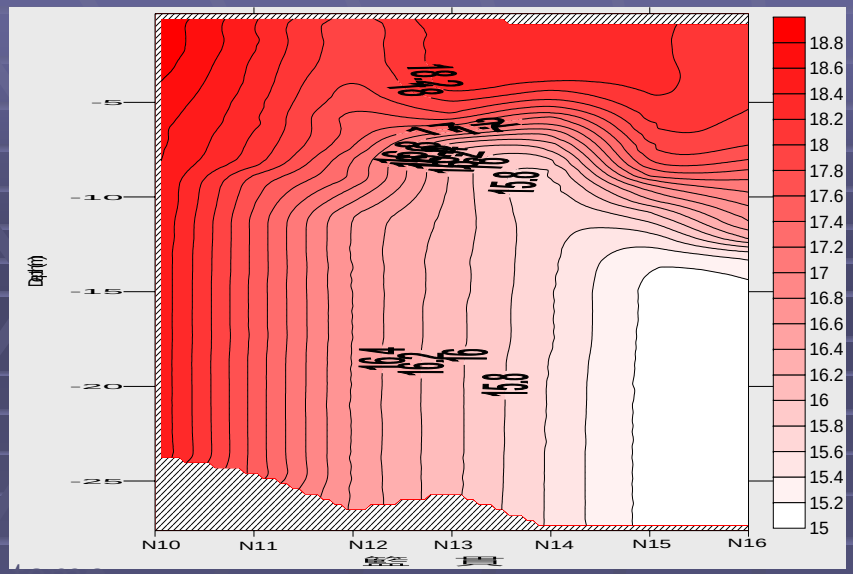


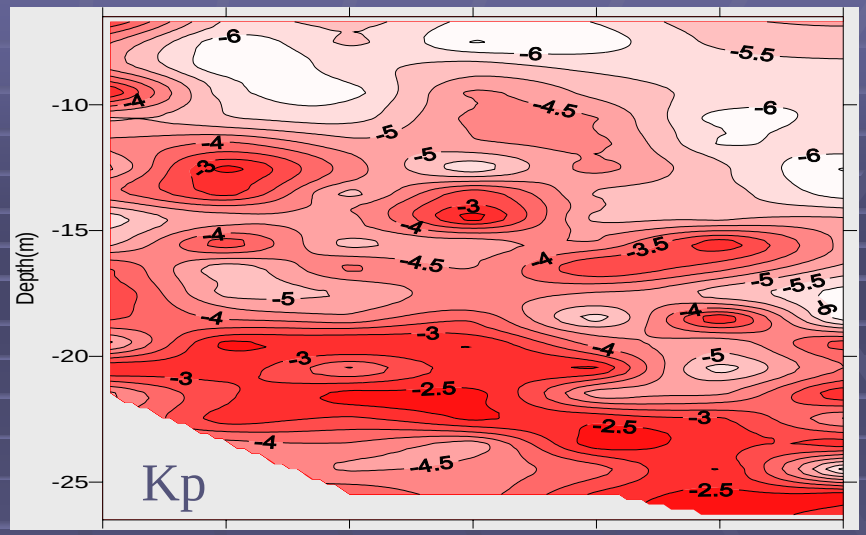


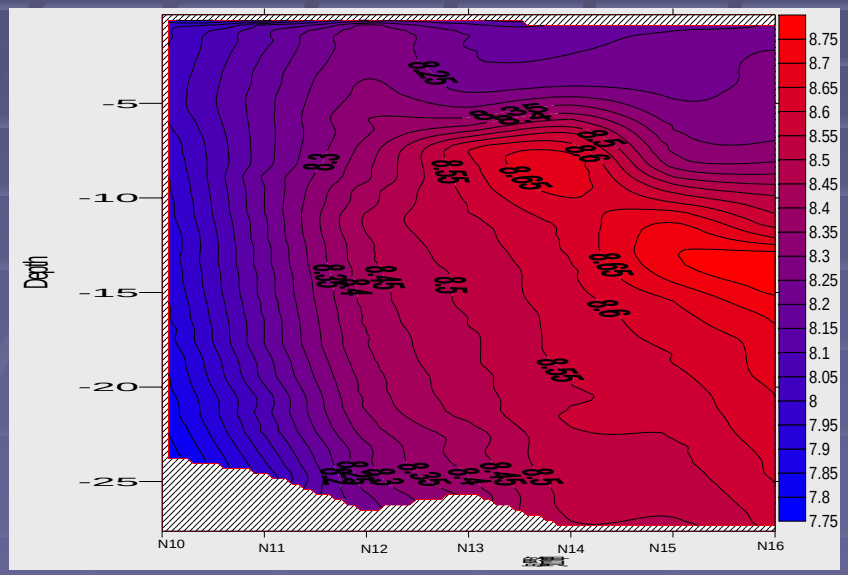
- **Once we had an observation in the strong wind in the central Yellow Sea.**
- **The profile of DO refered to Wei (2002)**

---after wind ---before wind

- **In the strong wind, the highest DO in the thermocline disappeared. After the wind, the highest value generated again, so it also proved our conclusion.**







DO

Another observation in tidal front area in the YS in July 2004.

k_ρ : $10^{-3} \sim 10^{-2}$ m^2s^{-1} in the front and near the bottom; $10^{-6} \sim 10^{-5}$ m^2s^{-1} in the thermocline.

- The highest DO in thermocline only appeared in stratified side.
- The mixing is strong and DO is low in the mixing side of the front.