

Carbon and Nutrient Budgets on the East China Sea Continental Shelf

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Abstract

The western part of the Kuroshio Intermediate Water originates from the nutrient-rich South China Sea intermediate water which upwells onto the East China Sea (ECS) continental shelf and contributes a large amount of nutrients to the ECS. This contribution is far more than the inputs from the Yangtze and the Yellow Rivers.

Mass balance calculations reveal that ECS gains 1608×10^9 mol organic carbon per year, which translates to a new production rate of phytoplankton as $49 \text{ mg C/m}^2/\text{day}$. The offshore transport of particulate carbon is 2101×10^9 mol/yr of which 485×10^9 mol/yr is organic. This value is only 11 % of the offshore dissolved organic carbon transport, estimated at 4359×10^9 mol/yr.

Key words:

East China Sea, South China Sea, Kuroshio, nutrients, carbon, budget, new production

Introduction

Land-derived carbon and nutrients enter the continental shelves in dissolved and particulate forms. The organic carbon may be respired on the shelf thus forms a potential natural source of atmospheric carbon dioxide (Smith and Mackenzie, 1987). However, how much is actually respired is unknown as much of this carbon is highly inert and mixes with seawater conservatively. On the other hand, enhanced anthropogenic inputs of nutrients, particularly nitrate and phosphate, to the continental shelf may drive the biological pump harder and result in increased biomass production and therefore constitute a new additional sink for atmospheric carbon (Walsh et al., 1985). As a result, it is as yet not possible to state definitively whether coastal seas are sources or sinks of carbon dioxide (Kempe, 1995). Since 1988 we have undertaken intensive studies of the carbon and nutrient cycles of the East

China Sea (ECS). The followings will be the summary of the carbon and nutrient budgets averaged over the ECS shelf.

The Yellow and East China Seas have a total area of $1.15 \times 10^6 \text{ km}^2$ of which about $0.9 \times 10^6 \text{ km}^2$ is the continental shelf, one of the largest in the world. It is also one of the most productive areas of the world oceans. Two of the largest rivers in the world, the Yangtze River (Changjiang) and the Yellow River (Huanghe), empty into the shelf with large nutrient inputs. East of the shelf is the Okinawa Trough, which is along the flow path of the mightiest current in the North Pacific, namely the Kuroshio.

The Kuroshio flows northeastward along the eastern margin of the continental shelf. Since the Kuroshio originates from the subtropical and tropical regions with low nutrient contents near surface, if only near-surface Kuroshio water moves onto the shelf the water would not contribute much to the high productivity of the ECS. Chen et al. (1990, 1995) and Ito et al. (1994), however, have shown that even the North Pacific Intermediate Water (NPIW) contributes up to 30% in the upwelling and cross-shelf mixing. Chen (1996) estimated Kuroshio's contribution of nutrients to the shelf in the dry and raining seasons separately, and reported that the Kuroshio Intermediate Water is the major source of nutrients to the ECS continental shelf. Further, Chen and Huang (1996) found that the western part of the Kuroshio Intermediate Water originates from the nutrient-rich South China Sea (SCS) intermediate water. This water fills the western part of the Okinawa Trough and feeds the upwelling onto the shelf (Chen and Wang, 1996). Armed with these new information we will redo the nutrient budget by taking into consideration the flow through the Taiwan Strait and the denitrification, both neglected in the previous work. The nutrient and carbon budgets will follow.

Method

The Kuroshio surface water (SW), Kuroshio Tropical Water (TW), Kuroshio Intermediate Water (IW) and the Shelf Surface Water (SSW) make up the major water masses near the shelf break (Chen et al., 1995). Although the major currents are parallel to the isobath, the SSW has a net transport offshore because of the net precipitation and the fresh water discharge from rivers, while SW, TW and IW have net onshore transports. In addition, there is an input through the Taiwan Strait (TSW). The river input, precipitation, and evaporation also contribute to the water budget (Fig. 1).

The water balance for the shelf at a steady state is:

$$Q_{Ri} + Q_P + Q_{TSW} + Q_{SW} + Q_{TW} + Q_{IW} = Q_E + Q_{SSW} \dots \dots \dots (1)$$

where Q is the water flux, subscripts Ri, P, TSW, SW, TW, IW, E and SSW denote river input, precipitation, Taiwan Strait Water, Kuroshio Surface Water, Kuroshio Tropical Water, Kuroshio Intermediate Water, evaporation and Shelf Surface Water, respectively.

The salt balance is:

$$Q_{Ri} \cdot S_{Ri} + Q_{TSW} \cdot S_{TSW} + Q_{SW} \cdot S_{SW} + Q_{TW} \cdot S_{TW} + Q_{IW} \cdot S_{IW} = Q_{SSW} \cdot S_{SSW} \dots \dots \dots (2)$$

where S is salinity, subscripts denote the same waters as for eq. (1)

As an example, the percentages of SSW, SW, TW and IW at a cross-section off the northeast corner of Taiwan in September and December, 1988 and in December, 1989 have been calculated, and can roughly represent the raining season and the dry season respectively, assumed to be constant during the six months (Chen et al., 1990, 1995). Chen et al. (1995) estimated that 70% of the water near the shelf break northeast of Taiwan come from Kuroshio with SW contributing 30% out of the 70%; TW contributing 25% and IW contributing 15%. Other data along the ECS shelf break suggest a smaller contribution from IW (Chen et al., 1996a). Thus for the Kuroshio waters that move onto the shelf the fluxes are assumed to be in the following proportions, i.e. in the raining season (May through October) $Q_{SW} \approx Q_{TW} \approx 3 Q_{IW}$. $Q_{TSW} \approx 7884 \text{ km}^3 / 6 \text{ months}$, $Q_P - Q_E \approx 420 \text{ km}^3 / 6 \text{ months}$ (Oberhuber, 1988; Zhang et al., 1991; Fang, 1992; Wang and Chen, 1992; Zhang and Yao, 1992; Yanagi, 1994) and $Q_{Ri} \approx 813 \text{ km}^3 / 6 \text{ months}$ (Chen, 1992; Kim, 1992). The salinities for the water masses are also assumed to be constant during the raining season.

Water Column Budgets

With the above information and solving for eqs. (1) and (2), $Q_{SSW} = 31895 \text{ km}^3$, $Q_{SW} = 9762 \text{ km}^3$, $Q_{TW} = 9762 \text{ km}^3$ and $Q_{IW} = 3254 \text{ km}^3$ for the six-month wet season. Q_{SSW} includes the outflow through the Tsushima Strait (Table 1).

Chen et al. (1990, 1995) calculated the mixing ratios of SSW, SW, TW and IW at 2 cross-sections northeast of Taiwan in the dry season. Kuroshio water made up 90% of the shelf water with SW contributing 63% out of the 90%; TW contributed 20% and IW contributed 7%. Assuming the fluxes of each component were in the same proportion, they were as follows: (November

-- April): $Q_{SW} \doteq 8 Q_{IW}$, $Q_{TW} \doteq 3 Q_{IW}$, $Q_{TSW} \doteq 3154 \text{ km}^3 / 6 \text{ months}$, $Q_{Ri} \doteq 404 \text{ km}^3 / 6 \text{ months}$ and $Q_P - Q_E \doteq -280 \text{ km}^3 / 6 \text{ months}$ (Oberhuber, 1988; Zhang et al., 1991; Chen, 1992; Fang, 1992; Kim, 1992; Zhang and Yao, 1992; Yanagi, 1994). The salinities are from Chen, 1996. The resulting $Q_{SSW} = 7730 \text{ km}^3$, $Q_{SW} = 2968 \text{ km}^3$, $Q_{TW} = 1113 \text{ km}^3$ and $Q_{IW} = 371 \text{ km}^3$ for six months (Table 1). The upwelling is much reduced because of the much smaller fresh-water influx (Chen, 1996). The annual water fluxes are given in Fig. 1.

Since the Kuroshio Surface Water is very low in nutrient contents ($\text{NO}_3 \leq 0.1 \mu\text{mol/kg}$, $\text{PO}_4 \leq 0.02 \mu\text{mol/kg}$, $\text{SiO}_2 \leq 1 \mu\text{mol/kg}$), the onshore fluxes of nutrients due to SW are small: Q_{NO_3} in summer and in winter are roughly 0.98 and $0.30 \times 10^9 \text{ mol}$, respectively; Q_{PO_4} is 0.20 and $0.06 \times 10^9 \text{ mol}$, respectively; Q_{SiO_2} is roughly 9.8 and $3.0 \times 10^9 \text{ mol}$, respectively, all for six months (Table 2). The Kuroshio Tropical Water has smaller water fluxes than the Kuroshio Surface Water but since the nutrient concentrations are much higher ($\text{NO}_3 \sim 4 \mu\text{mol/kg}$, $\text{PO}_4 \sim 0.3 \mu\text{mol/kg}$, $\text{SiO}_2 \sim 4 \mu\text{mol/kg}$), the nutrient fluxes due to TW are larger than that due to SW (Table 2): Q_{NO_3} in the summer and in the winter are roughly 39.0 and $4.4 \times 10^9 \text{ mol}$ for six months, respectively; Q_{PO_4} are roughly 2.9 and $0.3 \times 10^9 \text{ mol}$ for six months, respectively; Q_{SiO_2} are roughly 39.0 and $4.4 \times 10^9 \text{ mol}$ for six months, respectively.

The Kuroshio Intermediate Water contributes the least to the upwelled water but has the highest nutrient concentrations ($\text{NO}_3 \sim 25 \mu\text{mol/kg}$, $\text{PO}_4 \sim 1.7 \mu\text{mol/kg}$, $\text{SiO}_2 \sim 60 \mu\text{mol/kg}$), thus contributing the most to the nutrient fluxes (Table 2). The summer and winter fluxes are respectively: $Q_{\text{NO}_3} = 81.4$ and $9.3 \times 10^9 \text{ mol}$; $Q_{\text{PO}_4} = 5.5$ and $0.6 \times 10^9 \text{ mol}$; $Q_{\text{SiO}_2} = 195$ and $22.3 \times 10^9 \text{ mol}$, all for six months. Altogether, the annual contributions by the Kuroshio are as follows: $Q_{SW+TW+IW} = 27230 \text{ km}^3/\text{yr}$ or 0.86 Sverdrups; $Q_{\text{NO}_3} = 135 \times 10^9 \text{ mol/yr}$; $Q_{\text{PO}_4} = 9.6 \times 10^9 \text{ mol/yr}$; $Q_{\text{SiO}_2} = 274 \times 10^9 \text{ mol/yr}$. The Taiwan Strait Water is relatively rich in nutrients, on the same order as the Kuroshio Tropical Water (Wang, 1991). The summer and winter contributions of TSW to ECS in terms of nutrients are: $31.5 \times 10^9 \text{ mol}$, and $12.6 \times 10^9 \text{ mol}$ nitrate, respectively; 2.4×10^9 and $0.9 \times 10^9 \text{ mol}$ phosphate, respectively; and $31.5 \times$

10^9 mol and 12.6×10^9 mol silicate, respectively (Table 2). These values compare with the river fluxes of 40×10^9 mol/yr for NO_3 and NH_4 together; 0.32×10^9 mol/yr for PO_4 and 119×10^9 mol/yr for SiO_2 (Huang et al., 1983; Gan et al., 1983).

Budgets Including Offshore Transport of Suspended Sediments

It is also possible to use the simple box model to calculate the offshore transport of organic matter in the suspended sediments from the East China Sea shelf (Fig. 2):

$$Q_{\text{Ri}} \cdot N_{\text{Ri}} + Q_{\text{Re}} \cdot N_{\text{Re}} + Q_{\text{TSW}} \cdot N_{\text{TSW}} + Q_{\text{SW}} \cdot N_{\text{SW}} + Q_{\text{TW}} \cdot N_{\text{TW}} + Q_{\text{IW}} \cdot N_{\text{IW}} + Q_{\text{P}} \cdot N_{\text{P}} = Q_{\text{SSW}} \cdot N_{\text{SSW}} + Q_{\text{AS}} + Q_{\text{B}} \cdot N_{\text{B}} + Q_{\text{SS}} \cdot N_{\text{SS}} \dots (3)$$

where N denotes nutrients, Re denotes the release from sediments, AS denotes the air-sea exchange, B denotes the nutrients buried, and SS denotes suspended sediments transported offshore. By rearranging eq (3), we can obtain the net offshore sediment transport as:

$$Q_{\text{SS}} \cdot N_{\text{SS}} = Q_{\text{Ri}} \cdot N_{\text{Ri}} + Q_{\text{Re}} \cdot N_{\text{Re}} + Q_{\text{TSW}} \cdot N_{\text{TSW}} + Q_{\text{SW}} \cdot N_{\text{SW}} + Q_{\text{TW}} \cdot N_{\text{TW}} + Q_{\text{IW}} \cdot N_{\text{IW}} + Q_{\text{P}} \cdot N_{\text{P}} - Q_{\text{SSW}} \cdot N_{\text{SSW}} - Q_{\text{AS}} - Q_{\text{B}} \cdot N_{\text{B}} \dots (4)$$

where N_{Ri} is taken as $33 \mu\text{mol/kg}$ for NO_3 and NH_4 together, $0.26 \mu\text{mol/kg}$ for PO_4 and $98 \mu\text{mol/kg}$ for SiO_2 (Huang, et al., 1983; Gan et al., 1983); Q_{P} is roughly $1400 \text{ km}^3/\text{yr}$ (Kim, 1992), N_{P} comes from rain and dust and is roughly 30×10^9 mol/yr for nitrate and ammonia together and 1.5×10^9 mol/yr for dissolvable phosphate and silicate (Tsunogai et al., 1985; Hong et al., 1996), N_{SSW} is 0.1, 0.02 and $2 \mu\text{mol/kg}$ for NO_3 , PO_4 and SiO_2 respectively (Chen et al., 1991, 1995; M.P. Chen et al., 1992).

Phosphorus Budget

We will start with phosphorus as it does not involve degassing at the air-sea interface thus the Q_{AS} term is zero in eq. 3. The sum of the offshore transport and the net annual burial rates is 13.9×10^9 mol/yr, most of which is probably in the organic form. We can not separate the net burial from the offshore transport directly, thus have to obtain the former value from the

sediment organic carbon data. The sedimentation rate on the $0.9 \times 10^6 \text{ km}^2$ shelf is roughly $0.3 \pm 0.12 \text{ g/cm}^2/\text{yr}$ (DeMaster et al., 1985; Yanagi, 1994; Lin et al., 1995; Hong et al., 1995), making the total deposit as $2.7 \pm 1.1 \times 10^{15} \text{ g/yr}$. Taking the organic carbon content as $0.45 \pm 0.1 \%$ gives the burial rate as $900 \pm 450 \times 10^9 \text{ mol org C/yr}$. Taking the organic phosphorus content as 106 times smaller in terms of molar ratio makes the total organic P burial rate as $8.5 \times 10^9 \text{ mol/yr}$. As a result, the offshore organic P transport rate is $5.4 \times 10^9 \text{ mol/yr}$ (Fig. 2).

It is clear from looking at the fluxes in Fig. 2 that the rivers play only a very minor role as they contribute only 2.2% of the input. The major contributors of phosphorus, in the inorganic form, are the Kuroshio Tropical and Intermediate Waters and the Taiwan Strait Water. Most of the incoming inorganic P is converted to the organic form which is either deposited on the shelf or is transported offshore as particulates. Note even if there is any man-made eutrophication or increased biomass production due to the increased anthropogenic input of phosphorus, the increase is probably very small. On the other hand, enhanced or damped upwelling due to changes in climatic forcing would make a large difference in the biological pump.

Nitrogen Budget

We now proceed with the nitrogen budget which is more complicated because denitrification converts nitrate to N_2O and N_2 which degas at the air-sea interface. On the other hand, nitrogen fixation by planktons utilizes N_2 . As a first step we calculated the sum of offshore transport, net burial, and the net nitrogen release from the surface ECS as $245 \times 10^9 \text{ mol/yr}$ based on eq. (3). Li (1990) reported the average organic nitrogen content in the ECS sediments as 0.058 %, which is similar to the value of 0.06 % if the organic carbon content is taken as $0.4 \pm 0.1 \%$ (Huang et al., 1983; DeMaster et al., 1985; Yanagi, 1994; Hong et al., 1995) and when a Redfield C/N ratio of 8.2 is used to convert C to N (Chen et al., 1996b). As a result, the N burial rate is $112 \times 10^9 \text{ mol/yr}$, leaving the sum of the offshore transport and the net degassing as $133 \times 10^9 \text{ mol/yr}$. Assuming that the N/P ratio of the offshore transport portion as 16 and using the offshore P transport as $5.4 \times 10^9 \text{ mol/yr}$ obtained above, the offshore N transport is $86 \times 10^9 \text{ mol/yr}$. Thus the degassing of N_2O and N_2 comes to $47 \times 10^9 \text{ mol/yr}$, most of it is N_2 as the evasion rate of N_2O is only $0.9 \times 10^9 \text{ mol/yr}$ ($2.79 \mu\text{mol/m}^2/\text{day}$; S. Tsunogai, personal communication, 1995). Note

DON fluxes are ignored as there is no data but the influx is probably close to the outflux.

The nitrogen budgets are given in Fig. 3. The riverine input is still smaller than the contribution from the incoming water masses but the difference is not as dramatic as that for phosphorus. Not much nitrogen leaves ECS with the outflowing seawater. Instead, the largest sinks are the net burial on shelf, the offshore transport in the form of sediments, and in the form of degassing as N_2 .

Carbon Budget

At this point we look at the carbon budget. The method is similar but the air-sea exchange of molecular CO_2 must be taken into account. This can not be done easily recognizing that there are large spatial and temporal variations in ΔpCO_2 (pCO_2 (air) — pCO_2 (seawater)) and in wind speed which affects the transfer coefficient. We have plotted the pCO_2 of surface waters in Fig. 4 for the summer condition in 1992 based on the pH and alkalinity data of Chen et al., (1996a). On the Kuroshio side the surface water is more or less at equilibrium with the atmosphere but nearshore the pCO_2 is all under-saturated. The same is true in winter (Tsunogai, 1996). A rough estimate gives an influx of CO_2 as 3×10^{12} mol/yr based on the average transfer coefficient of Liss and Merlivat, (1986) and Wanninkhof (1992). The aerosol deposit is taken as 11×10^9 mol/yr (Buat-Menard et al., 1989). The outgassing includes 3×10^9 mol/yr CH_4 (Tsurushima et al., 1996; Chen, C.T.A., S.L. Wang and J.M. Chang, 1996, unpublished data) and 2×10^9 mol/yr DMS (Uzuka et al., 1994).

The major rivers bring in carbon in the form of dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), particulate inorganic carbon (PIC) and particulate organic carbon (POC). A mass-balance calculation based on eq. 3 gives the sum of net burial and offshore transport of particulate carbon as 5741×10^9 mol/yr of which $900 \pm 450 \times 10^9$ mol org C per year or 41 ± 23 mg org C/m²/day is buried. The average inorganic carbon content in the sediments is 10.15 % $CaCO_3$ which translates to an inorganic carbon burial rate as 2740×10^9 mol/yr. Thus the offshore particulate carbon transport rate is 2101×10^9 mol/yr. If this material has the same composition as the material on the slope then the weight is 0.808×10^9 tons/yr.

The particulate organic carbon to inorganic carbon molar ratio in the slope region and the Okinawa Trough is roughly 0.3 (Wang, 1991). Consequently

the offshore particulate organic carbon transport rate is 485×10^9 mol/yr. Dividing this value by 106 gives the particulate organic P transport rate as 4.6×10^9 mol/yr, in good agreement with the estimate of 5.4×10^9 mol/yr obtained earlier.

Much of the land-derived organic carbon in dissolved and particulate form is highly inert and mixes with seawater conservatively. Should this carbon partially or totally respire on the shelf it would form a potential natural source of atmospheric carbon dioxide (Kempe, 1995). The rivers around ECS indeed transport 1000×10^9 mol/yr organic carbon onto the shelf of which 170×10^9 mol/yr is in the form of DOC. This is a relatively small number compared with the amount (3321×10^9 mol/yr) carried by the seawater masses entering ECS. The DOC outflow, however, is 4359×10^9 mol/yr which is 868×10^9 mol/yr higher than the total input. Thus this much new DOC is produced on the shelf each year.

On the other hand, the riverine input of POC (830×10^9 mol/yr) is larger than the sum of the incoming seawater fluxes (211×10^9 mol/yr). The outflowing shelf water exports 396×10^9 mol/yr POC and the downslope transport amounts to 485×10^9 mol/yr. So ECS actually receives more POC than it exports. When the net burial of POC (900×10^9 mol/yr) is taken into account, the ECS shelf waters produce 740×10^9 mol/yr POC for export out of the water column. Overall ECS gets 4532×10^9 mol/yr organic carbon from outside sources and exports 5240×10^9 mol/yr organic carbon excluding the 900×10^9 mol/yr buried. So ECS currently is a net exporter of organic carbon and is a net sink of atmospheric CO_2 .

The net conversion of inorganic carbon to organic carbon is of course by the new primary production which amounts to 1608×10^9 mol/yr, or 49 mg org C/m²/day which is 13 % of the average primary production rate (Zhang, 1991). Note the new production rate obtained from the phosphorus budget is 54 mg C/m²/day. Chen (1996) estimated the new production rate at 73 ± 22 mg C/m²/day.

Conclusions

It is as yet not possible to measure the degassing rate of nitrogen directly because of the small air-to-sea differences in the N_2 partial pressures. This

study estimated the rate as 46×10^9 mol/yr for the East China Sea Shelf based on mass balance calculations.

It is also not yet possible to measure directly the offshore transport of particulate matter because of large spatial and temporal variabilities. Again mass-balance calculations reveals an offshore flux of particulate organic phosphorus as 5.4×10^9 mol/yr. Independent calculations give an offshore flux of particulate organic and inorganic carbon at 485 and 1616×10^9 mol/yr, respectively.

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Table 1. Water Fluxes (km^3) for the East China Sea Shelf

	Summer	Winter	Ref.
Ri	813	404	Chen (1992); Kim (1992)
$Q_P - Q_E$	420	-280	Oberhuber (1988)
SW	9762	2968	this work
TW	9762	1113	this work
IW	3254	371	this work
TSW	7884	3154	Zhang et al. (1991); Wang and Chen (1992)
SSW	31895	7730	this work

Table 2. The Nutrient Fluxes (10^9 mol) for the East China Sea Shelf

	NO_3		PO_4		SiO_2	
	Summer	Winter	Summer	Winter	Summer	Winter
SW	0.98	0.30	0.20	0.06	9.8	3.0
TW	39.0	4.4	2.9	0.33	39.0	4.4
IW	81.4	9.3	5.5	0.63	195	22.3
Subtotal	135		9.6		274	
TSW	31.5	12.6	2.4	0.94	31.5	12.6
Total seawater in flux	179		12.9		318	
SSW	3.2	0.8	0.64	0.15	6.3	1.5
Ri	40		0.32		119	
dissolvable form in rain and dust	30		1.5		1.5	

Table 3. Where goes organic carbon produced by the primary production
($\times 10^9$ mol/yr)

in:

primary production	11997
net POC influx	645
total in	12642

out:

denitrification	118
Mn reduction	18
Fe reduction	234
sulfate reduction	658
CH ₄ reduction	6
POC deposit on shelf	900
POC transported offshore	485
net DOC export	868
total out	3287
aerobic regeneration	9355

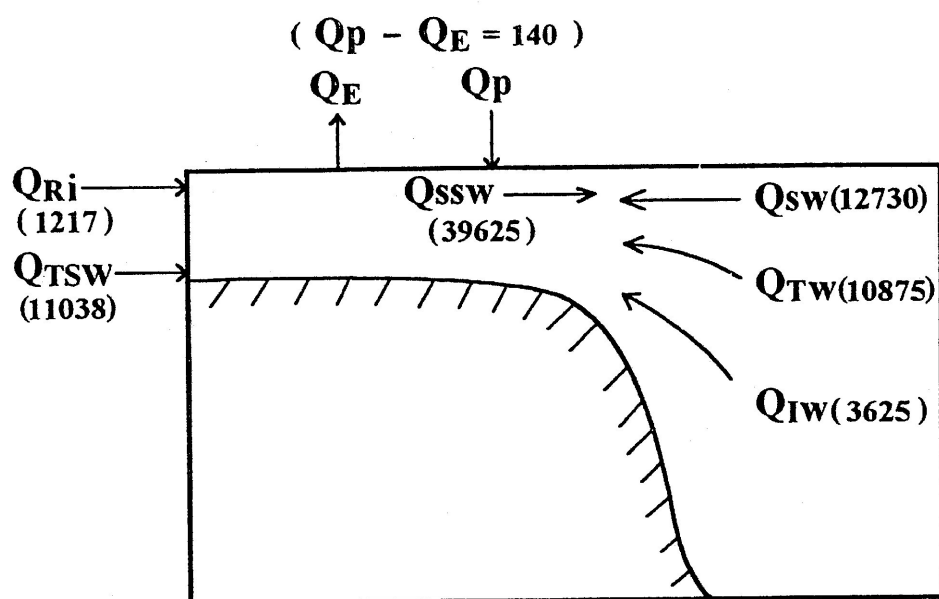


Fig. 1. Schematic diagram for the annual water budget (numbers in km^3).

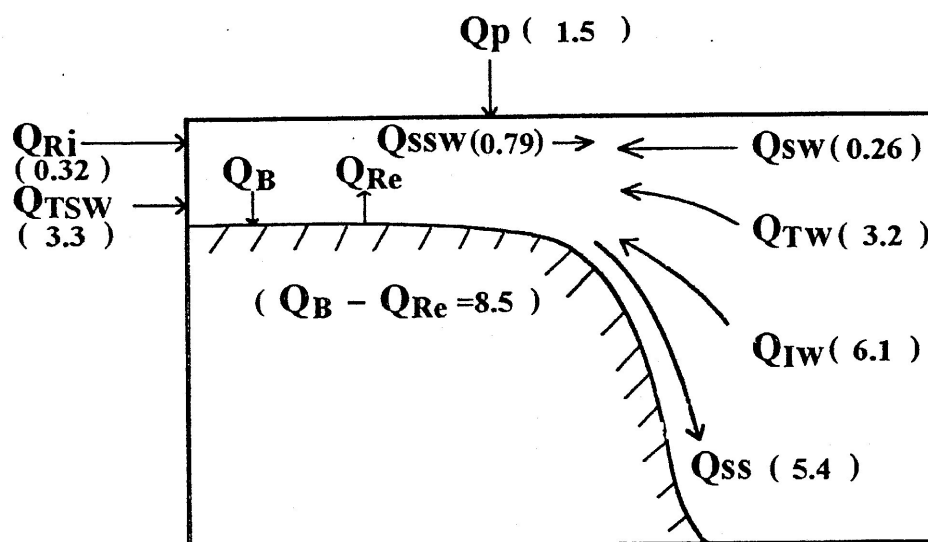


Fig. 2. Schematic diagram for the annual phosphate budget (numbers in 10^9 mol/yr).

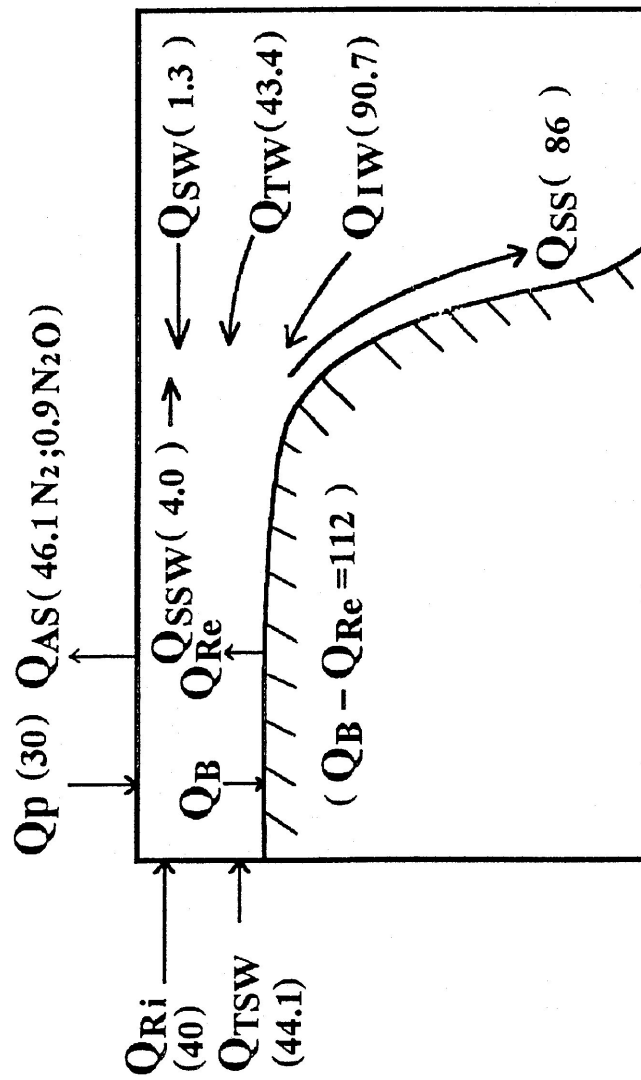


Fig. 3. Schematic diagram for the annual nitrate budget (numbers in 10^9 mol/yr).

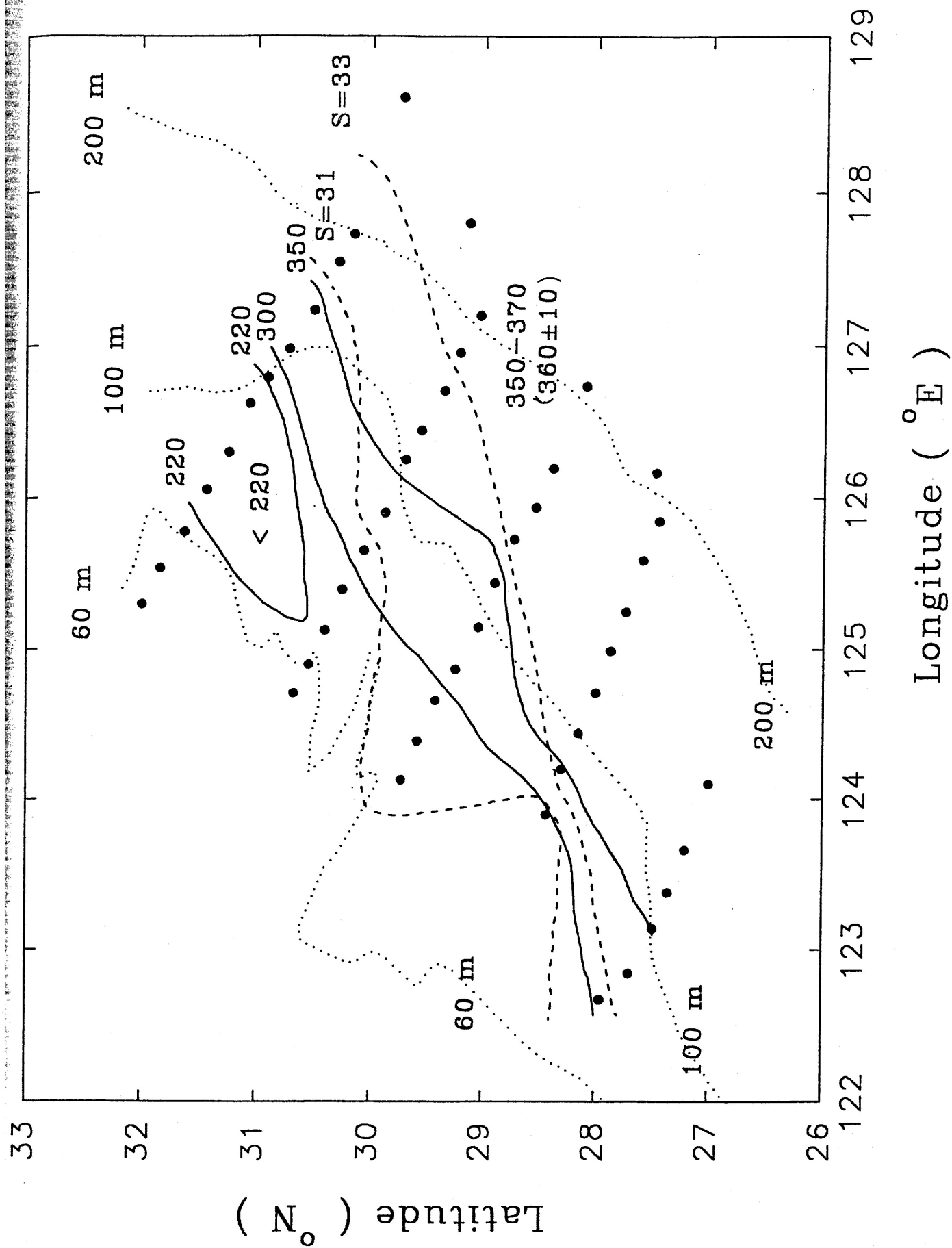


Fig. 4. The $p\text{CO}_2$ of surface waters in the East China Sea in summer, 1982.

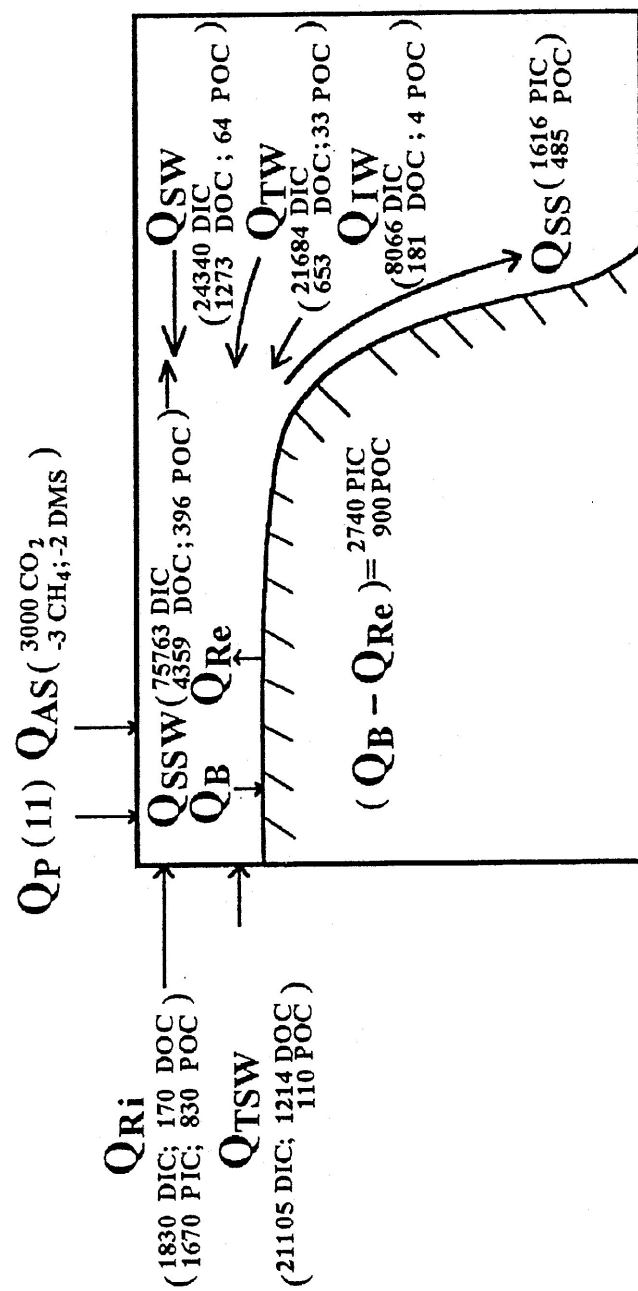


Fig. 5. Schematic diagram for the annual carbon budget (numbers in 10^9 mol/yr).