B-9 Oceanic sink and source of anthropogenic carbon dioxide in the Pacific (Abstract of the Final Report)

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1. Introduction

The prognostic model for the prediction of climate change should include responses of the land biosphere and ocean, which are the major natural sinks of CO_2 in the global carbon cycles. The ocean is estimated as a sink for anthropogenic CO_2 about 2 Gt/y in 1980's and its sink capacity is predicted to gradually increase with the increasing atmospheric CO_2 concentration during the 21st century. To predict future oceanic sink accurately, the understanding of the present oceanic sink and source distributions, seasonal variability and its secular trend are needed. These are the most useful information for the improvement of the ocean diagnostic model. The improvement of the diagnostic ocean model for the present ocean contributes the improvement of prognostic ocean model predicting future change of oceanic sink of CO_2.

From the observation about the ocean surface CO_2 partial pressure (pCO_2), the present distribution and seasonal change of the CO_2 exchange of the present ocean are evaluated. However, the global coverage of the observation is necessary for the accurate estimation of the present global sink. The international coordination of the observation and the data integration are essential for the global coverage and these issues are now been discussed under international scientific communities of North Pacific region and also of the world oceans. The measurement of the carbonate species (usually dissolved inorganic carbon and alkalinity) along the hydrographic section of the ocean can give present stock of CO_2 in the water column and the secular change of the stock can give information about the long year average of oceanic sink of CO_2. The global hydrographic section measurement is shared with countries and its data exchange is proceeded by the effort of ocean and CO_2 data centers. In the both cases of surface pCO_2 measurement and CO_2 measurement of hydrographic section, analytical accuracies of the measurement is essential for integration of the data obtained by the different institutions and countries.

In the program, the data integration and analysis of surface pCO_2, hydrographic sections have been conducted for Pacific data set and also the comparison between Pacific and Atlantic under collaboration with European research groups. The national database of oceanic biological parameters such as nutrient and chlorophyll, which help the analysis of CO_2 parameters in the surface and deep ocean, is to be built. The international analytical intercomparison of surface seawater CO_2 partial pressure (pCO_2) measurement was carried out to improve the coherency of the measurements under participation of international contributors and national participating institutes of the research program.

2. Sink and source of CO_2 in the Pacific from the data analysis of surface pCO_2 data set

Analysis of inter-annual change of North Pacific CO_2 sink from the surface pCO_2 data set obtained by CGER-NIES (Center for Global Environmental Research of the National Institute for Environmental Studies) global environmental monitoring program was carried out[1]. A 6 year full set of the surface ocean parameter data set including pCO_2, surface temperature (SST) and surface salinity (SSS) was built up to be able to access from internet. The observation was continued as a Japan-Canada cooperative research program between NIES and IOS (Institute of Ocean Sciences, Canada) from 1995.

Initially, the 6 year climatological pCO_2 as an annual mean for each latitude 4.5° by longitude 4.5° grid, where seasonal observation data sets covering more than 3 years exist. The distribution was mapped and the coverage was east of Japan and high latitude North Pacific. Then each year annual average pCO_2 was calculated where seasonal observation exist within a year. The difference from the annual average and climatology is the anomaly of each year. The largest anomaly for a grid was 29 μatm, which is far smaller value than the seasonal variability in pCO_2 in the oceanic basin. In 1997, the North Pacific ΔpCO_2 (ocean minus atmospheric pCO_2) was lower than climatology over the basin. In 2000, Bering Sea ΔpCO_2 was higher than climatology. However, the anomaly distribution was generally as a mosaic, in which high and low anomalies showed complicate distribution. In contrast, SST and SSS anomaly showed simple and wider distributions.

As the results, basin average inter-annual difference was not detected in the western subarctic Pacific and that in eastern subarctic Pacific was 15 μatm in amplitude (Figure 1, upper panel). In Bering Sea, the inter-annual change was more significant. The low ΔpCO_2 in 1997 corresponded to relatively high SST and high ΔpCO_2 in 2000 to low SST (Figure 1, lower panel). Low ΔpCO_2 in high SST year suggests summer shallowing of the surface mixed layer and enhanced biological productivity. High ΔpCO_2 in low SST suggests extensive winter convection. It may be more significant in inter-annual variability in a smaller oceanic basin like Bering Sea than that in large basins.

The observation from

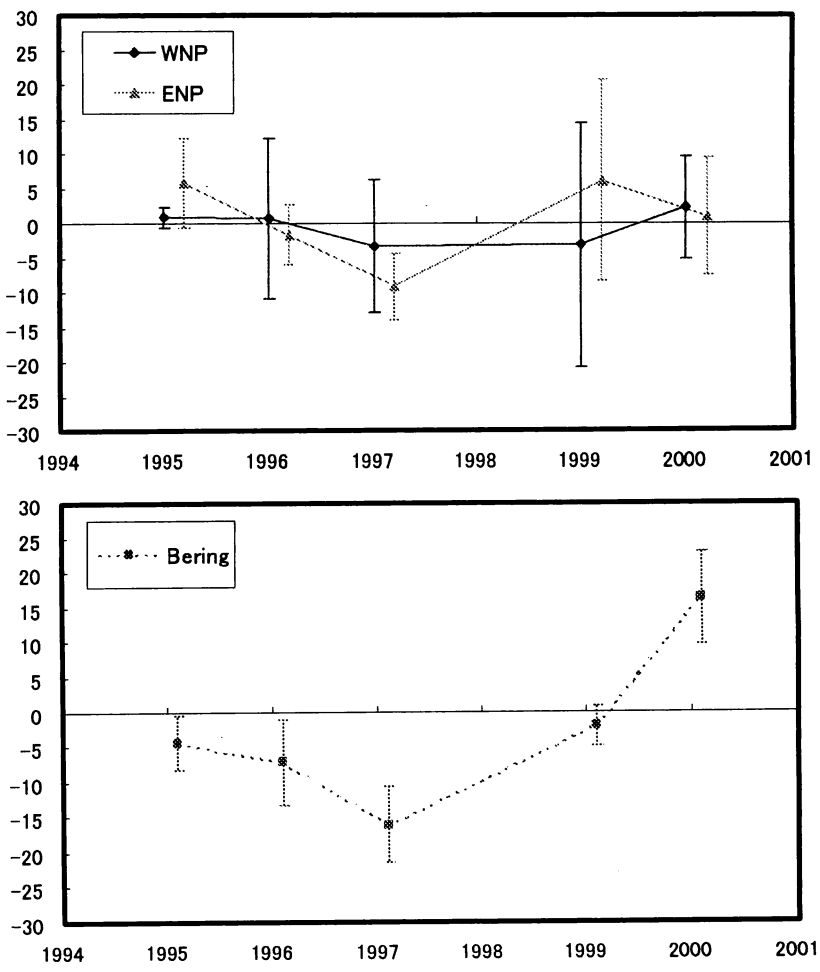

Figure 1. Inter-annual variability in the annual average of ocean surface ΔpCO_2 for western North Pacific, Eastern North Pacific and Bering Sea, analyzed from 1995-2001 observational data. The variation was expressed as difference from climatological annual mean of ΔpCO_2 in μatm unit.

1995-2001 includes intensive El Nino in 1997. However, its effect in the high latitude North Pacific pCO_2 was not apparent. It is completely different from that in the equatorial Pacific, where the change of equatorial upwelling in accordance with El Nino shows straight forward effect to the surface pCO_2.

The effect of temperature, biological processes and air-sea CO_2 exchange as drivers of the seasonality of the surface water pCO_2 were studied for year 2000 in the subarctic North Pacific Ocean, using data from automated pCO_2 measurements onboard the cargo ship M/S Alligator Hope. In addition to underway surface water and atmospheric pCO_2, sea surface temperature and salinity, nitrate concentrations from discrete sampling, were used to calculate the effect of biological processes and temperature to the surface water pCO_2. The effect of air-sea exchange of CO_2 was estimated using wind speeds from the NCEP/NCAR reanalysis and mixed layer depths from Levitus WOA 1994. Data were divided into 4°Lat x 5 °Lon degree grids as well as in six domains to study regional variability. Harmonic functions based on the observed data were used to calculate monthly means for each domain. From the monthly data we investigated the seasonal amplitude for pCO_2, nitrate, salinity and temperature in each grid and

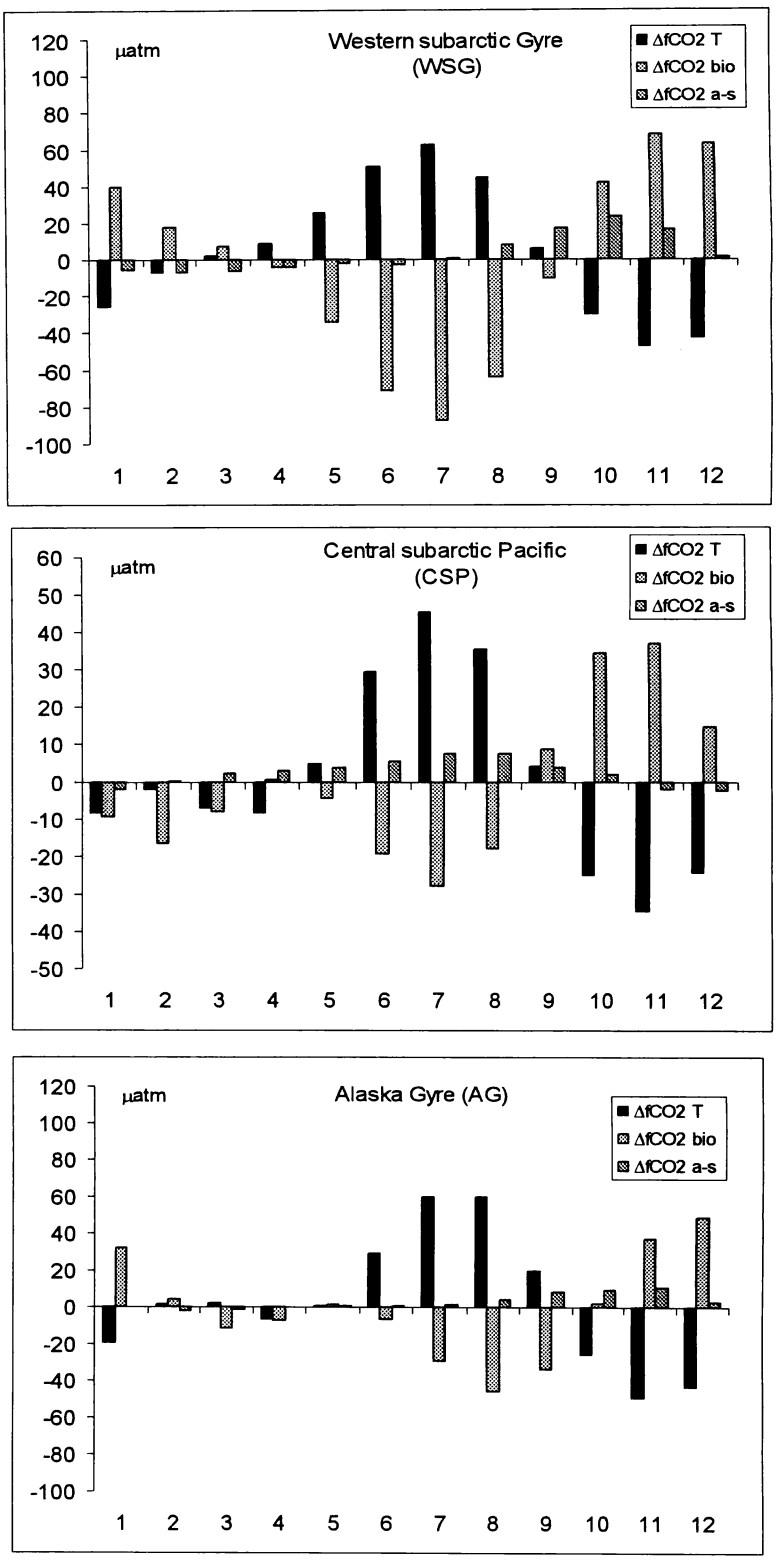

Figure 2. Monthly effect of temperature (ΔfCO_2T), biology (ΔfCO_2bio) and air-sea CO_2 exchange ($\Delta fCO_2air\text{-}sea$) (µatm) on the surface water fCO_2 in each domain of the North Pacific, the western subarctic gyre (WSG), the central subarctic Pacific (CSP), and the Alaska Gyre (AG), bars for each month are representing temperature, biology and air-sea exchange terms from left. A positive value means that an increase of fCO_2sw has occurred relative the previous month and a negative denotes a decrease of fCO_2 from the surface water. A positive $\Delta fCO_2air\text{-}sea$ indicates an oceanic uptake of atmospheric CO_2.

all parameters showed largest amplitude in the western part of the North Pacific. Our results from studying the six domains show that there were two major drivers of the pCO_2 change, temperature and biological processes (Figure 2 for 3 regions in the North Pacific). The air-sea CO_2 flux only played a minor role except in the near coastal domains. A slight difference between the major controls were observed in the two gyres, the Western Subarctic Gyre (WSG) and the Alaska Gyre (AG) where the WSG was mainly controlled by biological effects, while temperature controlled the overall CO_2 seasonality in the AG. The seasonal pCO_2 amplitude was about 100 and 45 µatm in the WSG and AG, respectively. In both gyres CO_2 air-sea exchange was of minor importance to the changes in pCO_2. The seasonal amplitude of surface water pCO_2 was twice as large in the WSG compared to the AG. Surface water pCO_2 showed maximum values in winter and minima in late summer, reflecting the effect of biological production in summer and the addition of nitrate and CO_2 caused by vertical mixing in winter. Biological, production caused a maximum drawdown of CO_2 of 95 µatm in July observed in the WG, twice as high as the corresponding value for the AG which was observed one month later.

We investigated seasonality and interannual variability of the surface water pCO_2 (pCO2sw) and sea-air CO_2 fluxes in the upwelling region of the southern Bering Sea (53 °N to 55 °N, 174 °E to 194 °E). Data of surface water and atmospheric pCO_2, sea surface temperature and salinity were based on automated measurements onboard cargo ships for 6-years (1995 to 2001). We observed a significant interannual trend towards more CO_2 supersaturated surface water relative to the atmosphere. From linear regression of seasonally detrended data we obtained an annual pCO_2sw increase of 6.5 ±1.4 µatm yr-1 and 11 ±1.9 µatm yr^{-1} in the basin and shelf slope, respectively. This was higher than the observed pCO_2air increase. Sea surface temperature and salinity showed a trend towards cooler and more saline conditions. We estimated large interannual variability of net annual oceanic CO_2 outgassing, with low CO_2 outgassing in years before 1998 (<1 mol m^{-2} yr^{-1}), increasing to a maximum of 4.5 mol m^{-2} yr^{-1} in 2000. Highest net CO_2 outgassing was observed in the relatively cold years of 1999 and 2000, whereas the exceedingly warm year

Table 1. The sea-air CO_2 fluxes (mol C m^{-2} yr^{-1}) for each year and the total CO_2 outgassing (g C yr^{-1}), based on the total area of $2.9 \cdot 10^{11}$ m^2 for the southern Bering Sea (here 53 °N to 55 °N, 174 °E to 194 °E). A positive sea-air CO_2 flux denotes oceanic CO_2 outgassing to the atmosphere.

Year	Sea-air CO_2 flux (mol C m^{-2} yr^{-1})	Total CO_2 outgassing (10^{12} mol C yr^{-1})	Total CO_2 outgassing (10^{12} g C yr^{-1})
1995	2.6	0.7	9.0
1996	2.0	0.6	6.8
1997	1.7	0.5	6.1
1998	7.4	2.1	25
1999	5.5	1.6	19
2000	9.1	2.6	32
Average	4.7 ± 3.1	1.4 ± 0.9	16 ± 11
Sum	28	8.2	98

1997 showed four times lower CO_2 flux to the atmosphere (Table 1). Interestingly, we found close coupling between the net CO_2 outgassing and biological production, years with less net CO_2 outgassing coincided with high biological CO_2 drawdown, especially evident in 1997.

3. Estimation for long term CO_2 sink of the Pacific from the data analysis of intermediate and deep seawater

Temporal and spatial variations of carbon dioxide and its related biogeochemical parameters in the Pacific were reassessed using the time-series data and cross-sectional data sets since the 1990s. We estimated the rate of increase of oceanic anthropogenic carbon inventory with CFC11 dating technique. The western North Pacific subtropical region exhibited a maximum in the rate of increase of the anthropogenic carbon inventory of more than 8g C m^{-2} $year^{-1}$ during 1988 – 1998, which was equivalent to 34 % of the total uptake rate in the entire North Pacific. The total uptake rate of anthropogenic carbon in the whole North Pacific and South Pacific increase with time and were 0.54 and 0.78 Pg C $year^{-1}$ during 1988 – 1999 (Figure 3). This indicates that the Pacific ocean absorbs about 60 % of the whole oceanic uptake of anthropogenic carbon.

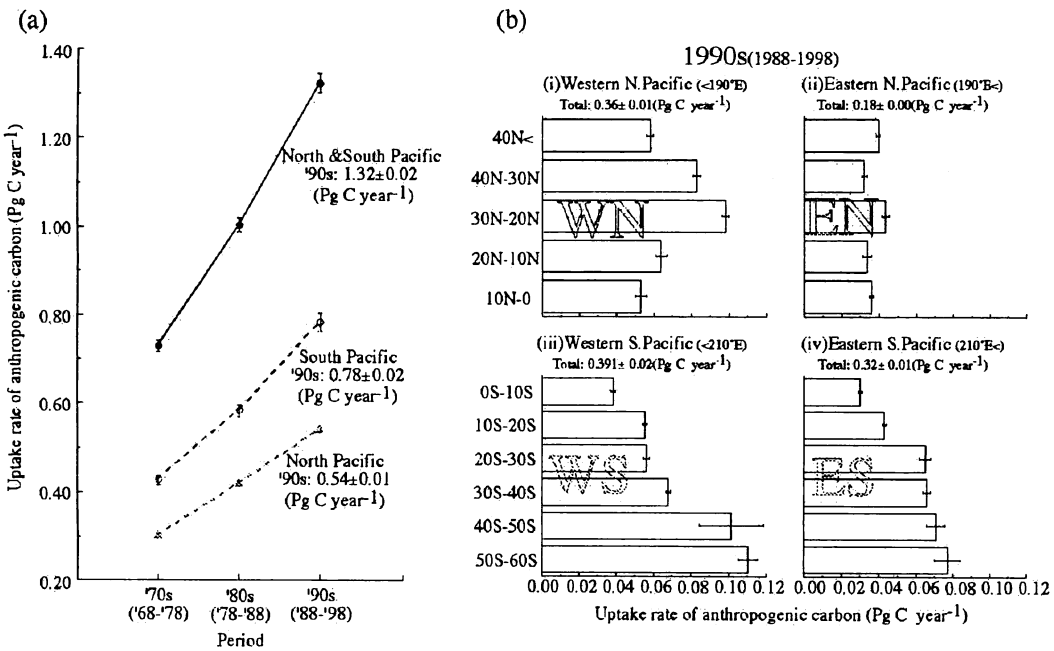

Figure 3. Estimated uptake rate of anthropogenic carbon in the North and South Pacific.

DIC in the surface seawater have been determined by the Japanese ocean time series program at station KNOT (155°E, 44°N) from 1998 to 2004. Applying the equation of the Fourier sine expansion, we estimated the increase rate of DIC in surface seawater at 1.0 μmol kg^{-1} $year^{-1}$. This value closely approximated the expected value under the equilibration between air and sea at KNOT. Increase rate of DIC from subsurface to 1000 m layer suggest that both anthropogenic (Uanth) and non-anthropogenic increase (Unon) are occurred in the western North Pacific. We estimated the increase rates of DIC using the isopycnal data in 1992 and 2000 along the 165°E north-south transect. Increase rates of DIC were several times larger than the predicted values estimated only from the influence of anthropogenic carbon (Figure 4), especially in mid to high latitude areas. The distribution of DIC increase rates in the transect showed similar patterns with that of AOU. This suggests the possibility that the change of water circulation significantly influences the carbon cycle in the ocean.

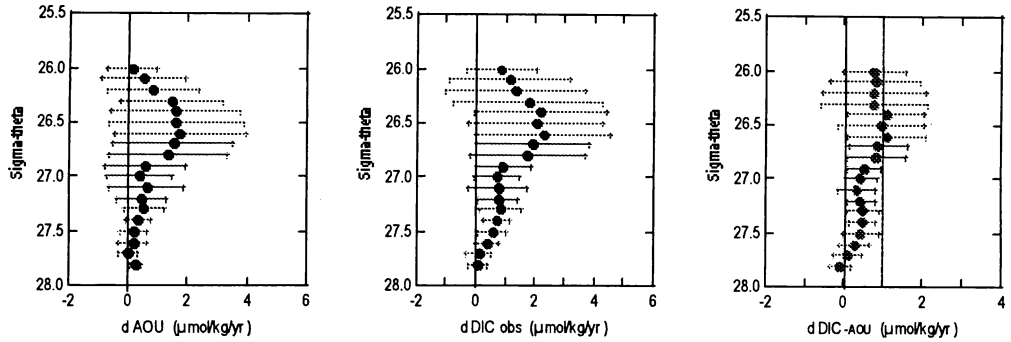

Figure 4. Increase rate of AOU and DIC on the isopycnal surface averaged through the 165E north – south transect.

For equatorial Pacific region, we have analyzed the decadal trends of

(1) total inorganic carbon normalized at a constant salinity (S=35) ($NTCO_2$) and CO_2 concentration (xCO_2) in surface layer of the western equatorial Pacific warm pool, and

(2) preformed $NTCO_2$ (=$NTCO_2$ – AOU*117/170) in the thermocline of the equatorial Pacific between 160°E and 160°W

on the basis of the data collected during 46 cruises conducted between 1990 and 2003. An intrinsic trends of xCO_2^{sea} and $NTCO_2$ in the warm pool was analyzed for the data taken in the surface water with $21.5 < \sigma t < 21.8$ to eliminate the influence of equatorial divergence and the influence of N_2 fixation that was often seen in a shallow mixed layer above a developed barrier layer. The increasing rate of xCO_2^{sea} in the warm pool was +1.2 ± 0.7 ppm yr^{-1} between 1992 and 2003, which is similar to the increasing rate of xCO_2^{air} (Figure 5). It is also consistent with the increasing rate of $NTCO_2$ of +1.0 ± 0.4 μmol kg^{-1} yr^{-1} in the warm pool during the same period. In the thermocline, the preformed $NTCO_2$ (=$NTCO_2$ – AOU*117/170) is showing an increasing trend of +1.0 ± 0.3 μmol kg^{-1} yr^{-1} between 1992

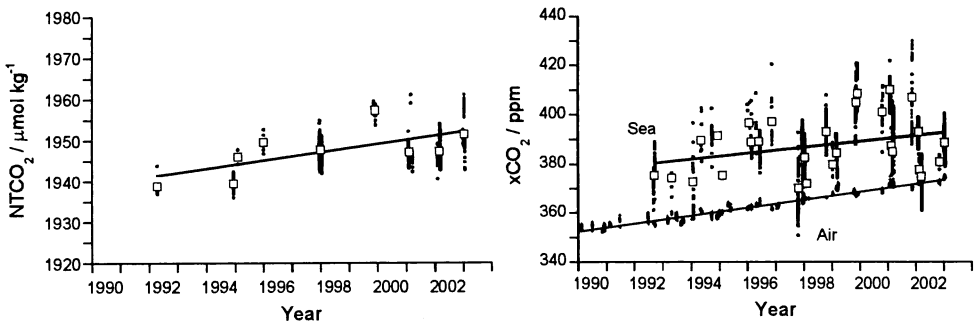

Figure 5. Decadal trend of (a) $NTCO_2$ and xCO_2 in the equatorial Pacific warm pool where $\sigma t = 21.5 - 21.8\sigma$.

and 2004 (Figure 6). It is in good agreement with the increasing rate of $NTCO_2$ in the surface layer of the equatorial Pacific and indicates the anthropogenic CO_2 accumulation in the thermocline. On the basis of the data of total alkalinity, it is thought that the water in the thermocline of the equatorial Pacific has its origin in the surface layer of the subtropical gyre. These results suggest the importance of the anthropogenic CO_2 uptake in the high-latitude of the subtropics, its transport to the equatorial zone through the meridional overturning, and its transport from the Pacific to the Indian Ocean through the Indonesian Through Flow.

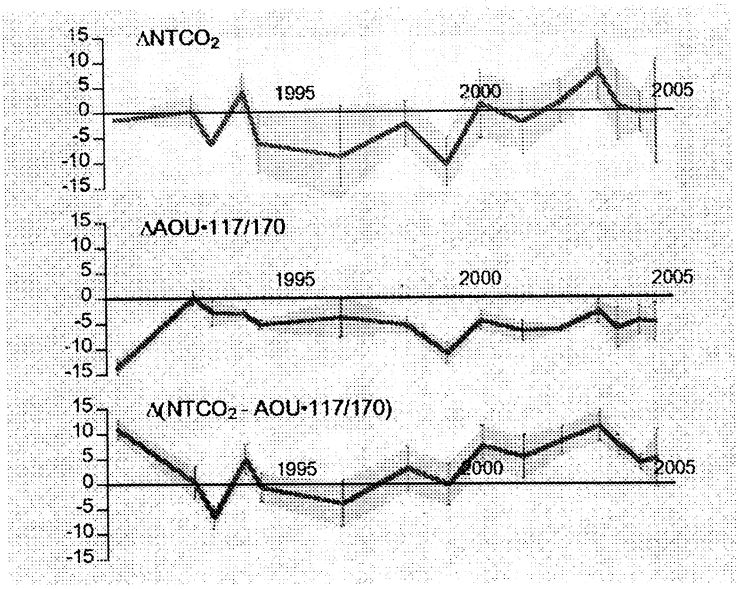

Figure 6. Mean anomaly of $NTCO_2$, AOU, and $prefNTCO_2$,relative to those in 1992 in the thermocline ($\sigma\theta$ 24.5- 25.8) of the equatorial Pacific between 160°E and 160°W

Time series analysis of biochemical parameter in sea water also showed decadal scale change. AOU in the North Pacific intermediate water increased 20 – 80 μ mol/kg from 1984 to 2000 (Figure 7) suggesting slow dawn of water circulation in the North Pacific. Time series analysis of phytoplankton pigment and zooplankton biomass showed decrease of production and size of phytoplankton in this 30 years in North Pacific. Zooplankton biomass also decreased in this decade. This change of phytoplankton species may affect not only carbon system in the ocean but also the budget of other biogenic gas related to global warming. Estimation of time series of DMS concentration of surface layer in whole North Pacific showed increase of the flux of DMS from ocean to atmosphere (Figure 8).

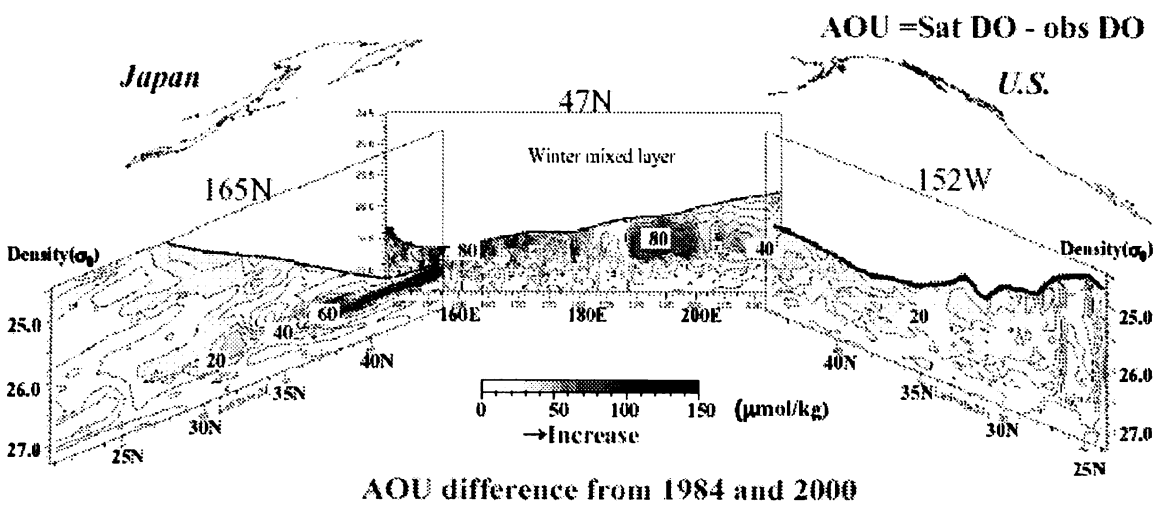

Figure 7. Distribution of AOU difference from 1984 and 2000 in North Pacific

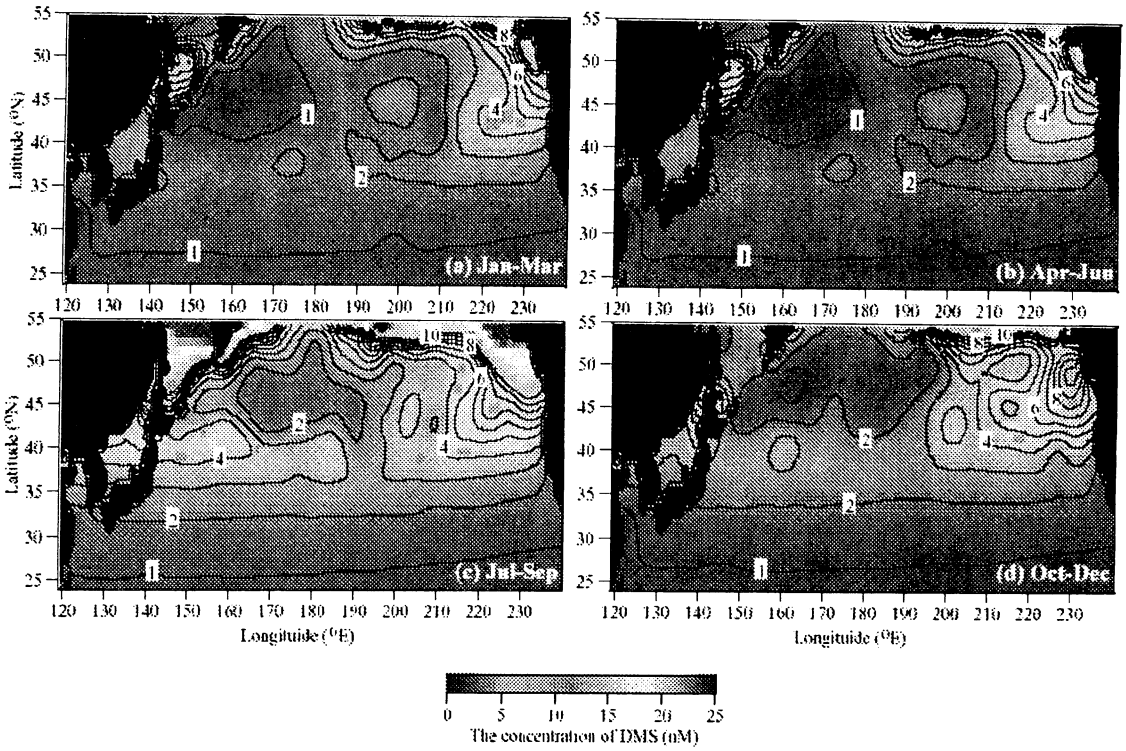

Figure 8. Seasonal variation of estimated DMS in North Pacific.

4. Data integration of marine biological data relating to ocean carbon cycle study

Nutrient and chlorophyll datasets are useful for ocean carbon cycle studies relating to surface biological productivity and also the decomposition processes in the water column. In this study, the compilation and quality control of nutrient and chlorophyll data from fishery research vessels belong to Fishery Research Agency were carried out for the building up of the public available database. The data-access home page has been opened to public from National Research Institute of Fisheries Science since February 2004. The data opened in the home page are useful to analyze biological productivity relating to CO_2 uptake of ocean in vicinity of Japan.

In this study, we had a trial to detect the regime shift in 1998, by using the database, first. As a result, we succeed to detect the significant signal of the regime sift. Secondly, we analyzed the database to draw long-term change in phosphate concentration in the subarctic North Pacific Ocean (Oyashio region) during 1960-2002 and to elucidate its effect on carbon cycle in the sea. As a result, periodic cycles with same phase were observed in the upper mixed layer and the intermediate layer (Figure 9). In addition, a decreasing long-term trend was observed for phosphate concentration in the upper mixed layer, whereas an increasing trend in the intermediate layer (Figure 9). On the other hand, in the Kuroshio region, a deceasing long-term trend was also observed for phosphate concentration in the upper mixed layer. We think that other new theory is required to explain the periodic change and long-term trend, and hence to analyze the effect of nutrient on the carbon cycle in the sea.

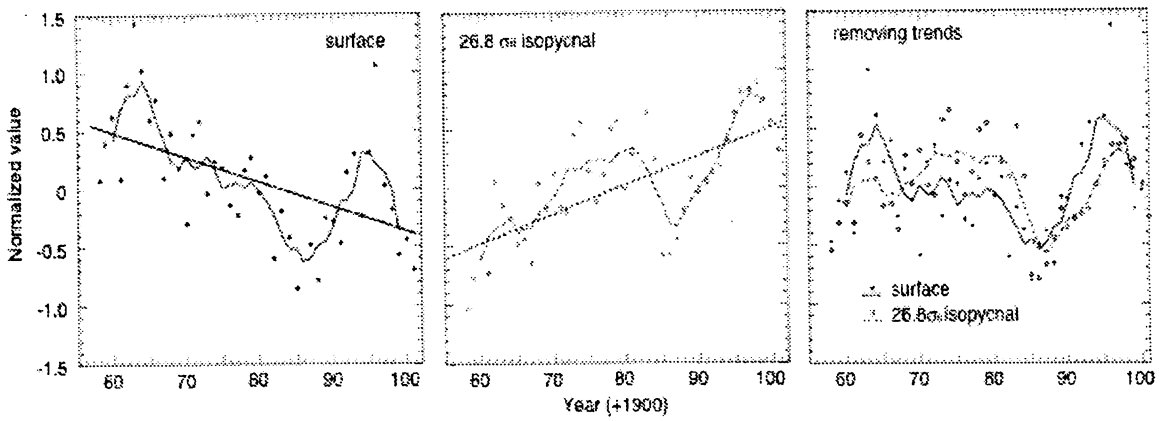

Figure 9. Long-term change in phosphate concentrations in the upper mixed layer (left) and intermediate layer (middle) in the Oyashio region. Long-term after eliminating the long-term trends were shown on the right.

5. Standardization and improvement of analytical method for the integration of ocean CO_2 data set

The global data integration of oceanic carbon dioxide data needs the quality assurance of the participating data sets. It has been developed the standard material for dissolved inorganic carbon and alkalinity, which is greatly contributing the quality improvement of water column CO_2 measurements by the worldwide use. However, the standard material for surface partial pressure of CO_2 is difficult to prepare. The intercomparison experiment with gathering analytical systems is the possible best way to check the accuracy of the measurement. A pCO_2 inter-comparison is carried out using an large indoor seawater pool of National Research Institute of Fishery Engineering in March 2003 under CO_2 Advisory Panel of IOC/SCOR (Intergovernmental Oceanographic Commission/ Scientific Committee on Oceanic Research). Three domestic and eight overseas institutes participated the campaign bringing their pCO_2 systems. Data discussion was done in the International Workshop on Ocean Surface pCO_2, Data Integration and Database Development was held in Tsukuba, January 2004. From the discussion by the experiment participants, several causes of error were confirmed. Temperature change is one of largest sources of error. It is recommended to minimize temperature change during traveling of seawater on board ship and also in equilibrator. Accurate temperature sensors to detect change of equilibrator temperature from sea surface temperature are necessary. Decomposition of organic material is source of positive error in pCO_2 measurement. Cleaning of seawater line and equilibrator and also the increasing of water flow rate is recommended to reduce the effect. Resupply air to the equilibrator is the source of negative bias in the high pCO_2 measurement than the atmosphere and the source of positive bias in the low pCO_2 measurement. To minimize the effect of resupply air, it is recommended to minimize the volume of resupply air or to pre-equilibrate the resupply air prior to introduce into the equilibrator. Equilibrator pressure effect is also the cause of error. Equilibrator inside pressure should be designed to be accurately equal to ambient air pressure or appropriate correction of the pressure effect is necessary. The workshop participants covered nearly all the world important principal investigators in the ocean pCO_2 observations and the workshop results were announced through web page of IOCCP (International Ocean Carbon Coordination Project). The knowledge about the possible error in pCO_2 measurement should be beneficial to the improvement of the ocean surface pCO_2

measurement in the world-wide observation programs.

In 2005, a new cargo ship measurement program was launched with corporation of a Japanese cargo ship, M/V Trans Future 5, between Japan and Oceania. In the occasion of new ship building, an oceanic pCO_2 system was installed. It is similar to the system, of which accuracy was ensured by the inter-comparison program. The inter-comparison knowledge was used avoiding various error causes in pCO_2 measurement. The test measurement was successfully done at the first voyage of the ship from Japan to New Zealand via Australia. In Figure 10, preliminary results of ΔpCO_2 (μatm, ocean minus atmosphere) over the cruise route. It was clearly shown the low pCO_2 feature of the Tasmanian Sea, which was suggested by the climatological data set of Takahashi et al. (2002), even though there exists only a few data sets for the oceanic area. The continuation of the measurement will reveal the seasonal and spatial characteristics of pCO_2 in the large area covering Northern, Equatorial and Southern parts in the Western Pacific Ocean.

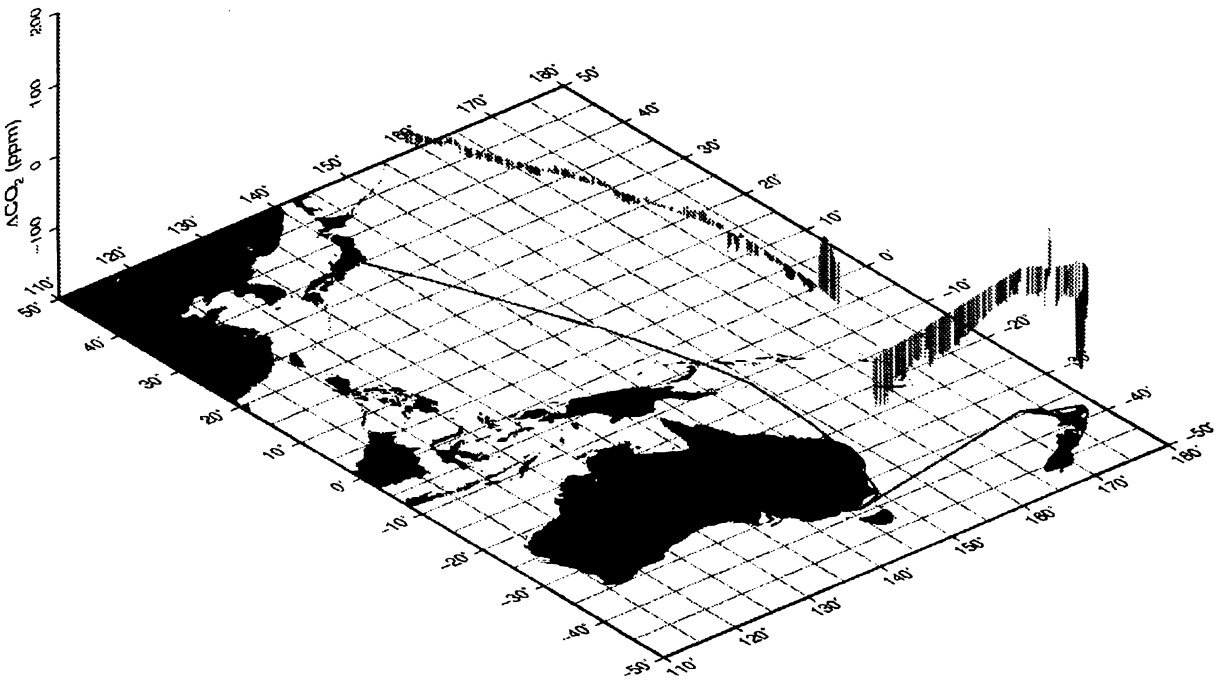

Figure 10. Measurement of ΔpCO_2 at the first voyage of M/V Trans Future 5 from Japan to New Zealand via Australia in 2005 November. Level parallel to the cruise route is equal level of atmospheric and oceanic pCO_2. Bar length denotes ΔpCO_2, upper direction sign denotes oceanic pCO_2 is higher than the atmosphere (oceanic CO_2 source area) and lower direction sign denotes lower oceanic pCO_2 than the atmosphere (oceanic CO_2 sink area).

6. Comparison of oceanic sink and source of CO_2 in the Pacific and Atlantic oceans with data integration of observational data sets

Surface seawater pCO_2 and related parameters were measured at high frequency in the North Atlantic ocean between 36 and 52°N onboard the volunteer observing ship M/S Falstaff. Over 90,000 data points are used to produce the seasonal cycles of CO_2 fluxes for 2002/2003. An oceanic CO_2 flux distribution map was produced based on the observational data set for the northern north Atlantic (Figure 11). The CO_2 flux in this region shows a seasonal cycle with close to zero fluxes or outgassing in the summer and fluxes into the ocean during fall and winter in this region. The CO_2 air-sea fluxes are determined using two averaging schemes. In the first, the fluxes are calculated for each location from the measured ΔpCO_2 and gas transfer velocity determined from a relationship with wind speed retrieved at the location of the ship. In the second method the ΔpCO_2 is averaged over

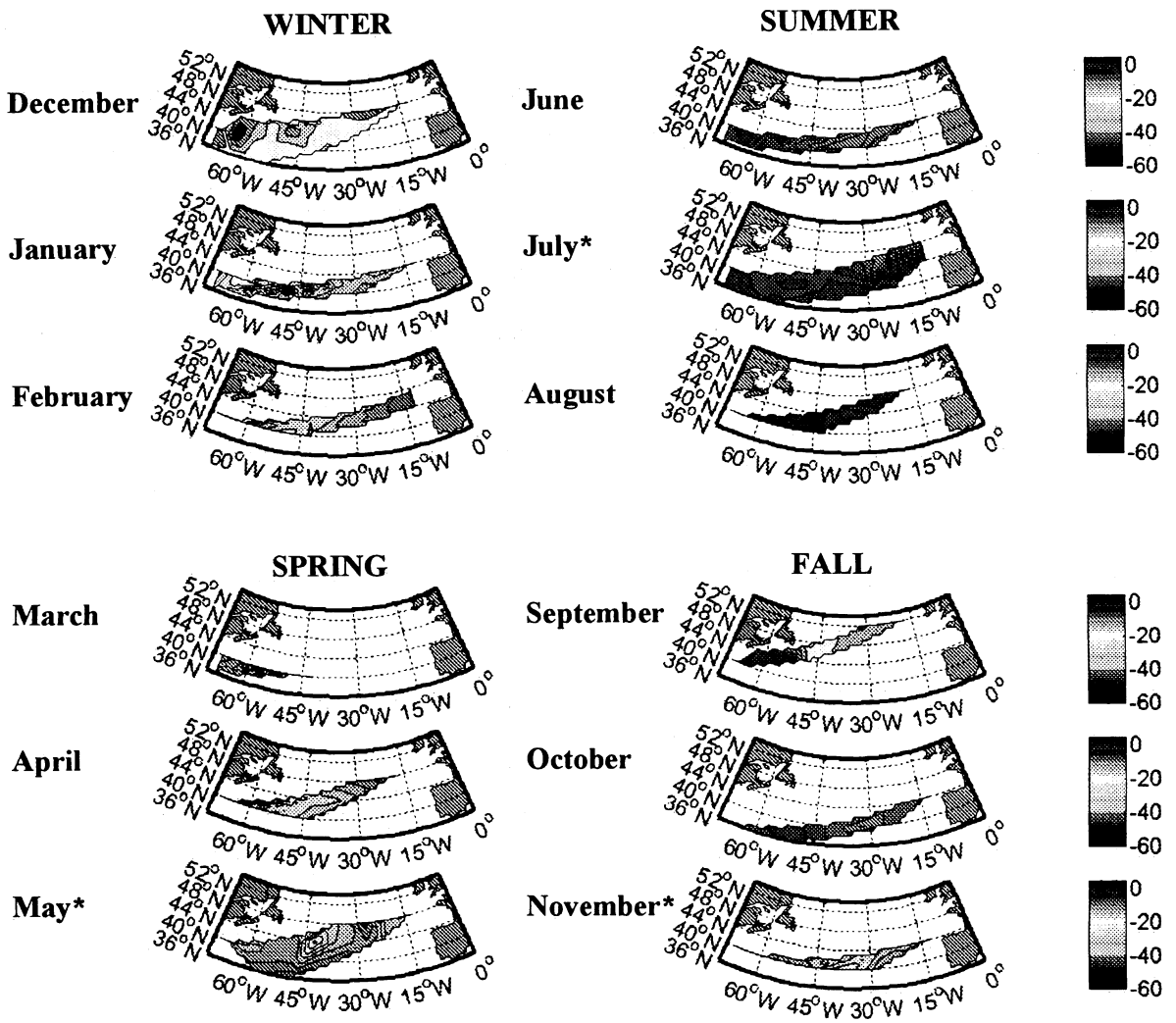

Figure 11. Oceanic CO_2 flux distribution map in the North Atlantic estimated from the observational data from M/S Falstaff (February 2002-February 2003). Green and blue regions indicate strong oceanic sink, and yellow to orange regions weak oceanic sink. Red indicates region closed to zero CO_2 flux.

each 4° by 5° pixel and multiplied by an averaged gas transfer velocity for this pixel. The fluxes determined by the first method are nearly 50 % lower than the averaged fluxes. This bias is mainly caused by the variability in wind speed. The covariance terms estimated in this dataset have a small effect of 1% on the flux calculation. The Falstaff fluxes are compared to the climatology by Takahashi et al. (2002) and the difference is 2-5 % depending on the time-correction scheme. Furthermore we use two wind speed sources to analyze the effect on the CO_2 flux: satellite data (QuikSCAT) and 6-hourly reanalysis data (NCEP/NCAR). The annual CO_2 sink is only 4 % less when using 6-hourly NCEP/NCAR wind speeds compared to the QuikSCAT wind speed data.

Reference

1) T. Takahashi, S. C. Sutherland, C. Sweeney, A. Poisson, N. Metzl, B. Tilbrook, N. Bates, R. Wanninkhof, R. A. Feely, C. Sabine, J. Olafsson, and Y. Nojiri, Global sea-air CO_2 flux based on climatological surface ocean pCO_2, and seasonal biological and temperature effects, *Deep-Sea Res. II*, **49**, 1601-1622 (2002).