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Riding over the Kuroshio from the South to the East China Sea: Mixing and transport of DIC

David D. Sheu,[1] Wen-Chen Chou,[2] C. T. Arthur Chen,[1] Ching-Ling Wei,[3]
Hsiu-Ling Hsieh,[1] Wei-Ping Hou,[1,4] and Minhan Dai[5]

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[1] Export of dissolved inorganic carbon (DIC) to adjoining oceans enhances the potential of CO_2 sequestration in marginal seas. By using a series of measured DIC depth profiles and reported flow transports, we estimated that the intermediate outflow (100–600 m) from the South China Sea is capable of transporting 6.5 ± 4.1 Tg (1 Tg = 10^{12}g) of biologically mediated carbon (DIC^{bio}) annually to the East China Sea (ECS) via the northwardly flowing Kuroshio current. The mixing and transport of these DIC-rich waters would raise 3% and 16% of DIC/TA ratio and the Revelle factor of the adjoining seawaters, respectively. Upon upwelling onto the ECS shelf, these DIC-rich waters would counteract the potential of CO_2 uptake of shelf waters that might have been enhanced by the accompanying increase in nutrient inputs, thus complicating assessment of the ECS as a net CO_2 source or sink.

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1. Introduction

[2] The South (SCS) and East (ECS) China Seas are the two largest marginal seas of the Asian continent. Despite water exchanges between the SCS and the West Philippine Sea (WPS) [*Tian et al.*, 2006; *Liang et al.*, 2008] and the upwelling of the Kuroshio waters onto the ECS shelf [*Tang et al.*, 2000] have been studied separately during the past decade, *Chen* [1996, 2008] was amongst the first to recognize that the outflow of subsurface waters from the SCS indeed was the major source of new nutrients to help sustain the high biological productivity observed on the ECS shelf [*Gong et al.*, 2003]. *Chou et al.* [2007b] further showed that not only the nutrients but the dissolved inorganic carbon (DIC) that had been derived from biological production in the SCS interior could also be transported to the West Philippine Sea (WPS) across the Luzon Strait. They further speculated that this very outflow could reach even as far as to the higher-latitude region off northeastern Taiwan via the northwardly flowing Kuroshio Current (KC). Thus, although the SCS separates geographically from the ECS, they are linked inherently by the persistent outflow of subsurface waters from the SCS to the ECS via the KC.

[3] In this study, we apply a series of titration alkalinity (TA) and DIC profiles measured at various depths along two transects (one traces across the Luzon Strait; the other follows the main stream of the Kuroshio current off eastern Taiwan; Figure 1) and at two separate stations in the WPS to derive the amounts of DIC that have been produced from biological activity, here defined as DIC^{bio}, in the SCS interior and Kuroshio subsurface waters. We then multiply these DIC^{bio} concentrations by the known flow transports to estimate the total flux of DIC^{bio} from the SCS to ECS. We also calculate the increments of DIC/TA ratios and the Revelle factors of these waters to show the effect of these DIC^{bio}-rich outflow waters on the overall CO_2 uptake potential of the ECS shelf waters upon upwelling onto the ECS shelf. The linkage between the ECS and SCS revealed by the DIC in this study thus should shed light on a better understanding of the mixing and transport of DIC in these two marginal seas in particular, and the role of marginal seas in the global oceanic CO_2 uptake in general.

2. Material and Methods

[4] Discrete water samples at various depths from stations along the transects A and B (Figure 1) were collected onboard *R/V Ocean Researcher I* (cruise ORI-796), *R/V Ocean Researcher III* (cruise ORIII-1153), and *R/V Fishery Research I* (cruise FRI-950522) using 20L Go-Flo bottles mounted onto a Rosette sampling assembly during a joint hydrographic survey between May 20 and June 03, 2006 (cf. http://www.ncor.ntu.edu.tw/odbs/2006JHS/). Depth distributions of temperature and salinity were recorded with a SeaBird model SBE9/11 conductivity-temperature-depth (CTD) recorder. Seawater analyses for pH, TA and DIC followed *Chou et al.* [2007a, 2007b], and their precisions were better than ±0.005 pH units, ±2μmol kg^{-1}, and ±2.5 μmol kg^{-1}, respectively. Seawater references provided by A. G. Dickson at the Scripps Institution of Oceanography were used for calibration and accuracy assessments. Differences between the certified values (Batch #75; 2005.98 ± 0.25 and 2210.09 ± 0.68 μmole kg^{-1} for DIC and TA,

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[1] Institute of Marine Geology and Chemistry, National Sun Yat-Sen University, Kaohsiung, Taiwan.

[2] Institute of Marine Environmental Chemistry and Ecology, National Taiwan Ocean University, Keelung, Taiwan.

[3] Institute of Oceanography, National Taiwan University, Taipei, Taiwan.

[4] Carbon Chemistry Laboratory, National Center for Ocean Research, National Sun Yat-Sen University, Kaohsiung, Taiwan.

[5] State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen, China.

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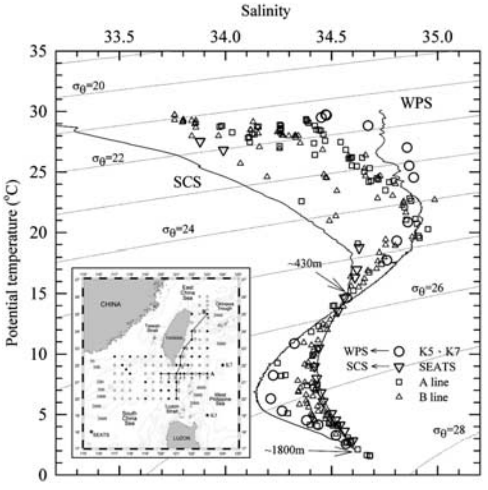

Figure 1. A plot of potential temperature versus salinity for all water samples collected along transects A and B (see the inset; contours are in meters). The marked contrast between SCS (station SEATS) and WPS (stations K5 and K7) proper waters are also shown. Sampling locations along transects A and B are marked in the inset.

respectively) and our measurements were less than 2 and 3 μmol kg^{-1} for DIC and TA, respectively.

3. Results and Discussion

3.1. Depth Distributions of Temperature, pH, DIC, TA, DIC/TA, and Revelle Factor

[5] Figure 1 shows the θ-S diagram of all discrete water samples analyzed in this study, in which the characteristic relationship between potential temperature and salinity of the WPS and SCS proper waters [*Gong et al.*, 1992] is also depicted. Note that values of seawater samples from stations K5 and K7 are averaged to better represent the WPS proper water, whereas the SCS proper water is taken from the well-documented θ-S relationship of seawaters collected at the SEATS site, northern SCS [*Chou et al.*, 2007a]. As can be seen, all water samples collected in this study are mixtures of SCS with WPS waters to varying extents.

[6] Depth profiles of potential temperature, pH, DIC, TA, DIC/TA ratio and Revelle factor at each station along transects A and B are depicted in Figure 2. DIC increases, whereas pH decreases progressively with depth. Moreover, all samples measured in this study have intermediate values between the typical SCS and WPS waters at the same depth in the upper 600 m water column, except those collected from station A3, where DIC is remarkably high but pH is noticeably low, suggesting that an upward advection must have occurred and the process is capable of bringing the lower pH and DIC-rich deeper waters to the shallow depths. Also shown is that WPS waters (stations K5 and K7) have the lowest DIC/TA ratios and Revelle factors among all water samples measured.

3.2. Estimates of DIC^{bio}, DIC^{pre}, and DIC Export: From SCS to ECS

[7] It has been well documented that the water exchange across the Luzon Strait (LS) exhibits a ‘‘sandwich-like’’ flow pattern [*Tian et al.*, 2006; *Liang et al.*, 2008], i.e., an inflow from the WPS in the upper and deeper layers but an outflow from the SCS in the intermediate layer. In order to quantify the amount of DIC that is carried out by the intermediate water outflow from the SCS to the WPS, we adopt the terms DIC^{pre}, DIC^{meas}, and DIC^{bio} defined and applied previously by *Chou et al.* [2007b], in which DIC^{pre} denotes the initial value of DIC that enters the SCS from the WPS, whereas DIC^{meas} represents the measured DIC value that flows out from the SCS to the WPS. The difference (DIC^{bio}) between DIC^{meas} and DIC^{pre} thus signifies the additional DIC derived from biological production in the

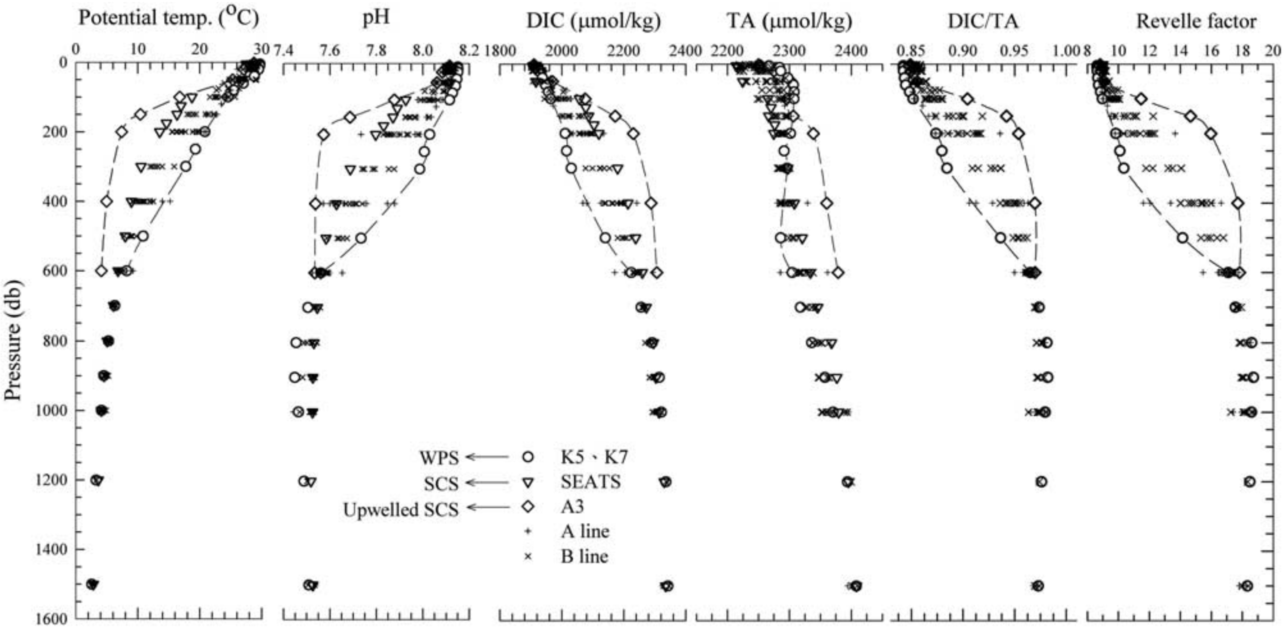

Figure 2. Depth distributions of potential temperature, pH, DIC, TA, DIC/TA ratio, and the calculated Revelle factor of seawater samples collected along transects A and B.

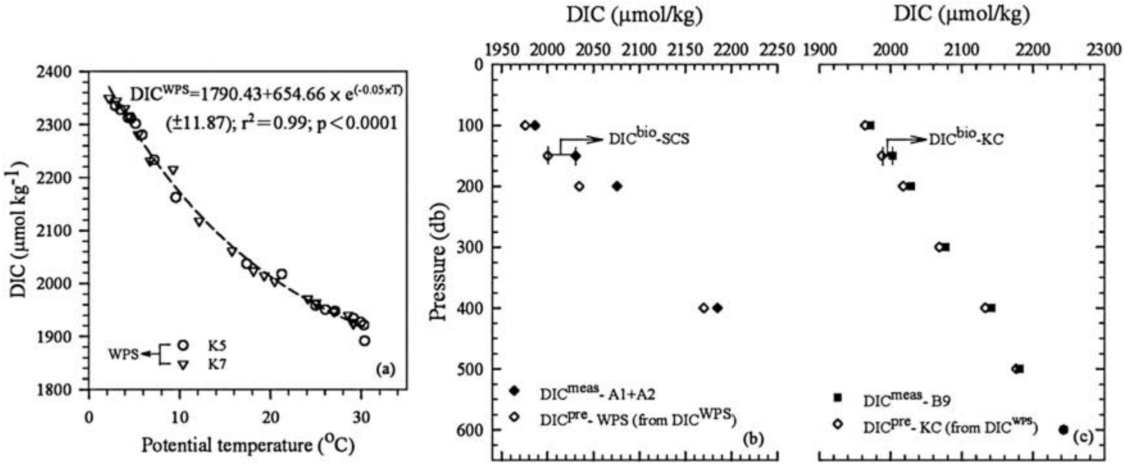

Figure 3. Plots of (a) DIC versus potential temperatures of waters collected at stations K5 and K7 from the WPS, and depth distributions of measured and preformed DIC (b) at stations A1 and A2 ($DIC^{meas} - A1 + A2$) and (c) at station B9 ($DIC^{meas} - B9$), respectively. See text in section 3.2 for the definitions and calculations of DIC^{meas}, DIC^{pre}, and DIC^{bio}.

interior of the SCS and can be calculated by subtracting the DIC^{pre} from DIC^{meas} of a given water sample at a specific site, i.e.,

$$DIC^{bio} = DIC^{meas} - DIC^{pre}.$$

[8] In the following estimation, we utilize DIC values measured at stations K5 and K7 as well as A1 and A2 for representing DIC^{pre} and DIC^{meas}, respectively. To derive the preformed DIC value ($DIC^{pre}_{(WPS)}$) of the WPS proper waters, we first construct the relationship (DIC^{wps}) between DIC and potential temperature measured at station K5 and K7 (Figure 3a). We then substitute the measured temperature of the subsurface waters at stations A1 and A2 into this relationship by means of which the physical effects, e.g., upwelling and vertical mixing occurring in the interior of the SCS, on the DIC increase can largely be eliminated and thus can better represent the DIC values entering the SCS. The difference, denoted as $DIC^{bio}_{(SCS)}$, between $DIC^{pre}_{(WPS)}$ and $DIC^{meas}{}_{(A1+A2)}$ (Figure 3b) thus represents the amount of DIC added from the biological production in the interior of the SCS and exported readily across the Luzon Strait to the WPS. Accordingly, the average concentration of $DIC^{bio}_{(SCS)}$ for the SCS subsurface water outflow between 100 m and 600 m water depths can be calculated to be 25 ± 14 μmol kg^{-1}. This value is essentially the same as the DIC^{bio} (24.6 ± 11.5 μmol kg^{-1}) estimated previously by *Chou et al.* [2007b]. By multiplying this $DIC^{bio}_{(SCS)}$ value (25 ± 14 μmol kg^{-1}) with the reported annual outflow of 1.9 ± 0.4 Sv for the SCS subsurface waters [*Tian et al.*, 2006; *Liang et al.*, 2008], the SCS subsurface outflow would transport 18.4 ± 11 Tg (1Tg = 10^{12}g) of carbon in the form of DIC^{bio} annually from the SCS to the WPS. It should be noted, however, that the above $DIC^{bio}_{(SCS)}$ estimate emphasized biological contribution and was relied solely upon the difference between $DIC^{pre}_{(WPS)}$ and $DIC^{meas}{}_{(A1+A2)}$; other processes, that might cause changes of DIC in the SCS interior during the circulation of the WPS seawaters through the SCS (cf. the North Sea case of *Thomas et al.* [2004, 2005]), were not considered in this study.

[9] Moreover, the preformed values of DIC ($DIC^{pre}_{(KC)}$) of the Kuroshio subsurface waters can also be evaluated using the same relationship (i.e., DIC^{wps}; Figure 3a) formulated above for the SCS outflow waters. However, unlike the $DIC^{bio}_{(SCS)}$ derived previously, which represents the net increase of DIC after the WPS waters circulate through the SCS, the difference ($DIC^{bio}_{(KC)}$) between $DIC^{pre}_{(KC)}$ and $DIC^{meas}_{(B9)}$ (Figure 3c) represents not only the amount of DIC^{bio} that has been obtained from the remineralization within the Kuroshio subsurface waters, but also that contributed in part from the $DIC^{bio}_{(SCS)}$ of the SCS intermediate outflow. This is because that the Kuroshio current is known to make its journey through the region in the eastern Luzon Strait, encounters and subsequently mixes vigorously with the outflow waters from the SCS, before it continues flowing northwardly along the eastern coast off Taiwan to the higher latitude region. An average concentration of $DIC^{bio}_{(KC)}$ of 8 ± 5 μmol kg^{-1} is obtained. This value is about only 32 ± 27% of the $DIC^{bio}_{(SCS)}$ (25 ± 14 μmol kg^{-1}) derived previously for the SCS intermediate outflow, further confirming a considerable dilution of the SCS intermediate waters by the immense transport of the oligotrophic Kuroshio waters. Furthermore, since station B9 (Figure 1) is located in the region where KC bifurcates into an eastward mainstream and a northwestward branch current that subsequently intrudes onto the ECS shelf [*Tang et al.*, 2000], the flux of DIC^{bio} onto the ECS shelf can be calculated to be 6.5 ± 4.1 Tg C a^{-1} by multiplying the $DIC^{bio}_{(KC)}$ (8 ± 5 μmol kg^{-1}) between 100 m and 600 m at station B9 and the summer volume transport of the northwest Kuroshio branch current of ~2.11 Sv reported by *Liu et al.* [2000]. This flux counts about 22 ± 14% to 50 ± 32% of the total CO_2 uptake rate (13–30 Tg C a^{-1}) in the ECS [*Wang et al.*, 2000]. It is worth pointing out that some of the ~2.11 Sv KC flow into the ECS may only stay a short time inside ECS or even bypass it, thus will have a less effect on the ECS CO_2 system. Results of all these estimates are depicted in Figure 4. It should be noted, though, that since DIC^{bio} estimated in the present study are derived exclusively from DIC depth profiles in summer-

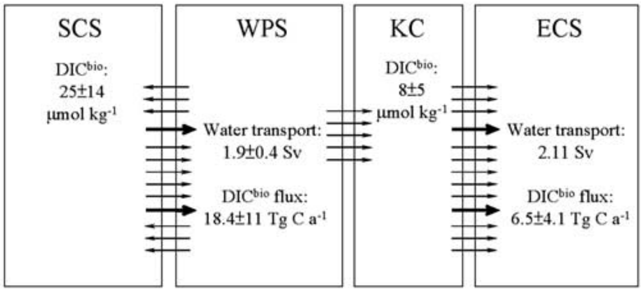

Figure 4. A sketch diagram showing the reported water transports and fluxes of DIC^{bio} estimated in the SCS-KC-ECS region.

time, seasonal variability in monsoonal winds and subsequent changes in upwelling intensity and flow patterns in the region that may differ significantly from present estimates are not considered.

3.3. Influence on the CO_2 Uptake of the ECS Shelf Waters

[10] It has been established that the intrusion of the cold, nutrient-rich Kuroshio subsurface waters occurs all year round and is a major nutrient source to sustain a high productivity on the ECS shelf [*Chen*, 1996, 2008]. As shown in Figure 2, SCS upwelled waters (cf. station A3) are characterized by the highest DIC/TA ratios and Revelle factors among all waters measured in this study. As these waters transport northwardly and upwell onto the ECS shelf, they would significantly alter the carbon chemistry and the potential of CO_2 uptake of the surface waters on the ECS shelf. This is because that addition of these DIC^{bio}-rich waters would render a higher DIC/TA ratio and Revelle factor, thereby lower the capacity of CO_2 sequestration of seawaters [*Sarmiento and Gruber*, 2006].

[11] To better illustrate the sequential influence of this outflow en route from the SCS to the northern end of the KC in the region adjacent to northeast Taiwan (i.e., station B9), we first averaged the DIC/TA ratio and the Revelle factor depth profiles at stations (K5 + K7) and all stations along transects A and B, respectively. Next, we integrated them over the depth range between 100–600 m to derive their respective integrated values. By taking appropriate ratios among these values, we then calculated the percent increments (%) of the DIC/TA ratios and the Revelle factors of waters transporting from SCS to WPS, and from WPS to station B9, respectively. The results show that the outflow of SCS subsurface water between 100–600 m would lead to an increase of 2% of the DIC/TA ratio and 10% of the value of Revelle factor of the WPS water. As this outflow, after mixing thoroughly with the WPS water, continues to dispatch to the higher-latitude region off northeast Taiwan along the main stream of the KC, there is another 1% and 5.5% increase in the DIC/TA ratio and the Revelle factor, respectively. As a whole, the cumulative effect of the SCS intermediate water outflow will lead to a total of 3% and 15.5% of DIC/TA ratio and Revelle factor increase, respectively. Thus, despite that the nutrient influx from Kuroshio branch water would enhance the biological productivity on the ECS shelf and were in favor of removal of more CO_2 from the atmosphere, the accompanying increase in DIC concentrations of these waters, once they mixed and surfaced up onto the shelf, would render a counteracting effect on the potential of overall CO_2 uptake in the ECS. To the best of our knowledge this effect has not been considered in the assessment of the ECS, or other shelves, as a source or sink of CO_2 [*Borges et al.*, 2005; *Cai et al.*, 2006], except that *Thomas et al.* [2004, 2005] unraveled recently that the North Sea could indeed be regarded as a bypass pump as the CO_2 that had been taken up by the North Sea seawaters was readily exported to the Atlantic Ocean and might further attenuate the buffer capacity of the inorganic carbon system (increasing Revelle factor) of North Sea and North Atlantic Ocean waters.

4. Conclusion

[12] While contrasted behaviors among individual marginal sea have been recognized and estimates of the net air-sea CO_2 fluxes have been investigated intensively with respect to the potential of CO_2 sequestration, the outflow of the DIC^{bio}-rich waters from the marginal seas to the adjoining open ocean waters that circulate between different marginal seas have been to a large extent ignored. The close link of DIC between the SCS and the ECS demonstrated in the study, and the conclusion that the SCS outflow could reduce the potential of CO_2 uptake in the ECS, therefore should contribute to a better understanding of the role of marginal seas in the global oceanic carbon cycle.

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C. T. A. Chen, W.-P. Hou, H.-L. Hsieh, and D. D. Sheu, Institute of Marine Geology and Chemistry, National Sun Yat-Sen University, 70 Lien-Hai Road, Kaohsiung 804, Taiwan. (ddsheu@mail.nsysu.edu.tw)

W.-C. Chou, Institute of Marine Environmental Chemistry and Ecology, National Taiwan Ocean University, No. 2, Pei-Ning Road, Keelung 202, Taiwan.

M. Dai, State Key Laboratory of Marine Environmental Science, Xiamen University, 422 Siming Nanlu, Xiamen 361005, China.

C.-L. Wei, Institute of Oceanography, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 106, Taiwan.