Methane distributions and sea-to-air fluxes in the South China Sea and the West Philippines Sea

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Introduction

Methane (CH_4), an atmospheric trace gas, has a global warming potential in a 100-year time frame (GWP_{100}) that is 34 times that of carbon dioxide (CO_2). CH_4 is the most abundant hydrocarbon in the atmosphere and plays an important role in atmospheric chemistry. The South China Sea (SCS) is the largest marginal sea in the world and is connected with the West Philippines Sea (WPS) via the Luzon Strait, which is around 2200 m in depth and is the deepest sill that connects the SCS with any adjacent body of water. This work elucidates the spatial and vertical distributions of CH_4 in the water column of the SCS and WPS, as well as its sea-to-air fluxes, and further discusses differences between these seas and the factors that influence those distribution and fluxes.

Materials and Methods

Samples from the SCS were taken during six cruises on board R/V Ocean Researchers I and III (Fig. 1a); samples from the WPS were collected during three cruises (Fig. 1b). Fluxes of CH_4 across the air-water interface were estimated using $F=k(Cw-\alpha Ca)$ where k (cm h^{-1}) is the gas exchange coefficient, as described by Wanninkhof (2014). Wind speeds at 10 m above from the surface were obtained from the NASA QuikSCAT satellite platform. The seawater fluxes from the SCS to the WPS were calculated as described by Chen *et al.* (2001).

Results and Discussion

- The surface CH_4 concentration that was measured during the wet seasons in the WPS was 3.0±1.2 nM (saturation 155%) and in the SCS was 4.5±3.6 nM (saturation 230%); the sea-to-air CH_4 fluxes in wet season in the SCS was 8.6±12.7 μmol m^{-2} d^{-1} and in the WPS was 4.9±4.9 μmol m^{-2} d^{-1} (Table 1).
- The maximum CH_4 and chlorophyll *a* concentrations were found in the subsurface waters (Figs. 2a and 2b) in the WPS. Although the formation of CH_4 in the surface water layer may relate to the biological activity, no significant correlation between CH_4 and chlorophyll *a* concentrations in the surface 200 m layer was identified herein (Fig. 4). This result not only shows that the formation of CH_4 may not be directly associated with the photosynthetic process or phytoplankton biomass but it also reveals that other processes, such as the physical mixing of different water masses, or CH_4 inputs from seeps or sediments, may affect the distribution of CH_4 in the WPS.
- Since little biogenic CH_4 is produced outside of the euphotic zone, CH_4 concentrations generally decline to undersaturated levels with increasing depth beyond the euphotic zone and remain constant below 1,000 m (Figs. 2a and 3b). Some high CH_4 concentrations were measured in the mid-depths of the SCS (Fig. 3b).
- According to Chen *et al.* (2001), in the wet season, surface and intermediate waters are net-exported from the SCS to the WPS but deep water is net-imported. The net export of surface and intermediate waters carry 1.5×10^6 mol d^{-1} and 0.53×10^6 mol d^{-1} CH_4 from the SCS to the WPS in the wet season while the deep water from the WPS imports 0.15×10^6 mol d^{-1} CH_4 to the SCS (Table 2).

Conclusions

The SCS influences the surface and intermediate waters in the WPS. This study has established that the SCS emits CH_4 to the atmosphere and also exports CH_4 to the WPS, and the sea-to-air flux is larger than the horizontal flux in the wet season. However, the CH_4 distribution and flux during the dry season could not be determined because data are not available.

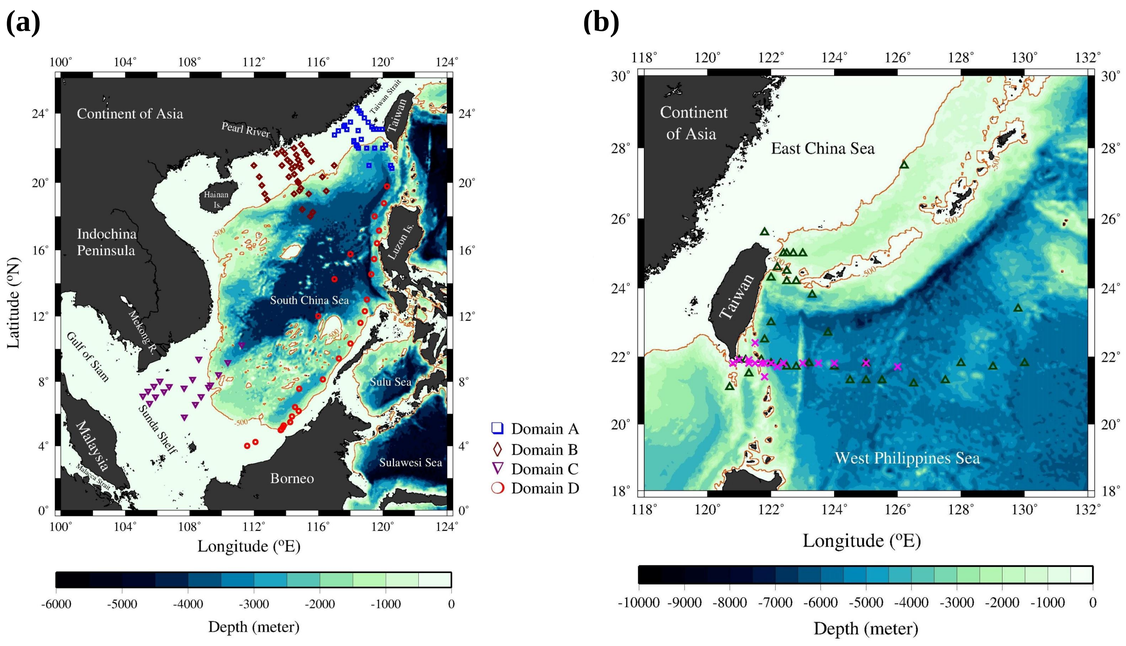

Fig. 1. Study area and station locations:

(a). South China Sea stations. □:Domain A, ORIII-896 (Aug. 2003) and ORIII-983 (Jul. 2004); ◇: Domain B, ORI-695 (Sep. 2003), ORIII-1081 (Jul. 2005) and ORI-802 (Jul. 2006)-Stn.SCS1; ▽: Domain C, ORI-802 (Jul. 2006); ○: Domain D, ORI-837 (Jul. 2007));

(b). West Philippines Sea stations. △: surface sampling stations, ORI-725 (Aug. 2004), ORI-837 (Jul. 2007) -Stn.A-D;1-5 and unpublished data from C. T. A. Chen; ×: discrete sampling stations, ORI-725 (Aug. 2004) and ORIII-1149 (May 2006))

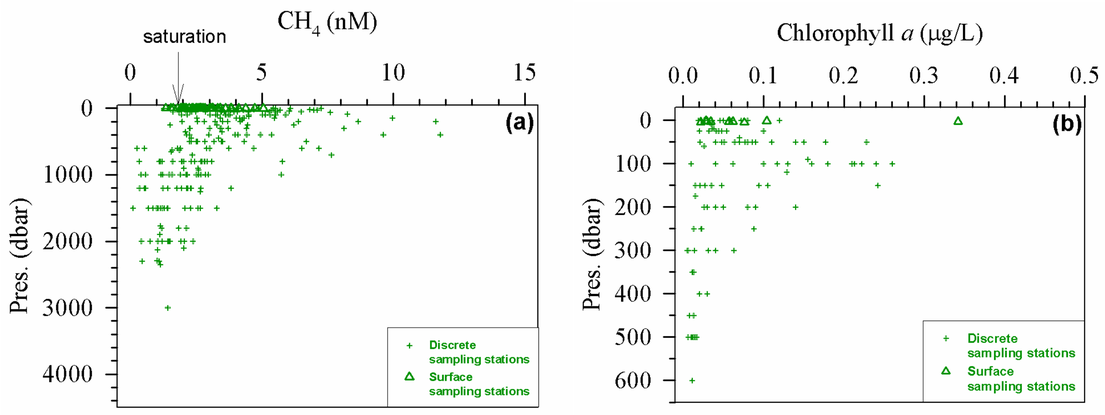

Fig. 2. Vertical distributions of (a) CH_4 (nM) and (b) chlorophyll *a* (μg L^{-1}) in the West Philippines Sea, obtained at 43 stations during three cruises from August 2004 to July 2007.

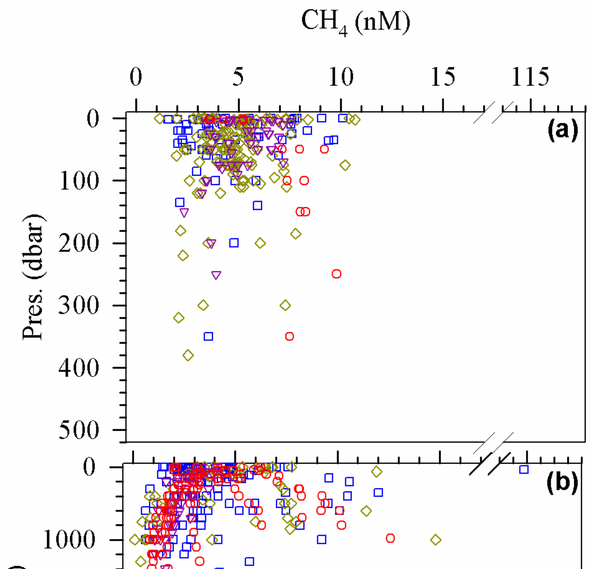

Fig. 3. Vertical distributions of CH_4 (nM) (a) on the continental shelf and upper slope (depth<500m) and (b) in the deep sea (depth>500m) in the South China Sea, obtained at 122 stations during six cruises from August 2003 to July 2007.

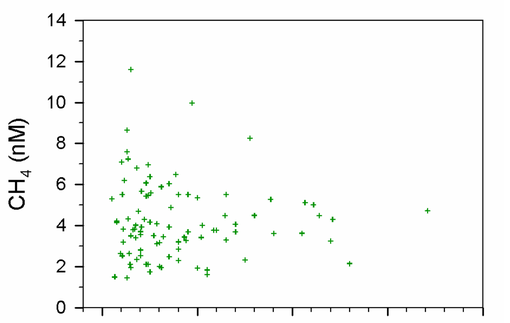

Fig. 4. CH_4 (nM) versus chlorophyll *a* (μg L^{-1}) in the surface 200 m layer in the West Philippines Sea, obtained at 43 stations during three cruises from August 2004 to July 2007.

Table 1. Surface CH_4 concentrations and sea-to-air fluxes in the SCS and the WPS in the wet season

			Latitude (°N)	Longitude (°E)	Sal.	Average Surface CH_4 Concentration (nM)	Wind Speed (m/s)	Sea to Air Flux (μmol m^{-2} d^{-1})	Surveying Cruises/Months
SCS	Domain	A	20-25	117-120	33.86±0.34	4.5±2.3 (n=31)	7.2±1.8	9.9±8.7	ORIII-896 (Aug. 2003) ORIII-983 (Jul. 2004)
		B	17-23	112-117	33.17±1.08	5.2±2.1 (n=42)	7.0±1.3	12.0±7.4	ORI-695 (Sep. 2003) ORIII-1081 (Jul. 2005) ORI-802 (Jul. 2006)-Stn.SCS1
		C	3-12	104-113	33.23±0.19	4.9±1.5 (n=19)	6.2±1.0	8.3±4.1	ORI-802 (Jul. 2006)
		D	4-20	110-120	32.87±1.00	3.4±1.0 (n=30)	6.3±0.9	4.3±3.9	ORI-837 (Jul. 2007)
	Avg.		3-25	104-120	33.28±1.5	4.5±3.6 (n=122)	6.3±0.8	8.6±12.7	ORIII-896 (Aug. 2003) ORI-695 (Sep. 2003) ORIII-983 (Jul. 2004) ORIII-1081 (Jul. 2005) ORI-802 (Jul. 2006) ORI-837 (Jul. 2007)
	Avg. Continental Shelf region (depth<500m)				33.29±0.9	5.1±2.1 (n=72)		11.0±7.4	
	Avg. Deep Sea (depth>500m)				33.54±0.7	3.8±1.6 (n=50)		6.1±6.0	
WPS	Avg		21-26	120.5-130	34.22±0.27	3.0±1.2 (n=68)	7.4±1.3	4.9±4.9	ORI-725 (Aug. 2004) ORIII-1149 (May 2006) ORI-837 (Jul. 2007)-Stn.A-D;1-5, unpublished data from C. T. A. Chen

Table 2. CH_4 concentrations, water flux and CH_4 flux of various water masses in the SCS and WPS

	SCS			WPS		
	Avg. Concentration	Water Flux	CH_4 Flux	Avg. Concentration	Water Flux	CH_4 Flux
	nM	$\times10^6$ t s^{-1}	$\times10^6$ mol d^{-1}	nM	$\times10^6$ t s^{-1}	$\times10^6$ mol d^{-1}
Surface Water Layer (0~350m)	4.8±5.7	-13.9±1.8	-5.78	3.9±1.9	12.8±1.1	4.28
Intermediate water Layer (350~1350m)	3.4±3.0	-1.8±0.4	-0.53			
Deep Water Layer (1350~2200m)				1.5±0.7	1.2±0.2	0.15

Positive and negative numbers represent inflow and outflow, respectively.

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