

北南海 CO₂ 海氣交換

曾鈞懋 助理教授

國立臺灣大學海洋研究所

大陸邊緣海在全球暖化及氣候變遷下調節大氣 CO₂ 循環上的角色，近年為科學家們所重視。南海是個橫跨亞熱帶-熱帶之西太平洋邊緣的貧營養海域，其水溫終年 24 °C 以上，海水層化明顯，混合層 (<50 m) 及營養鹽躍層 (<70 m) 深度都較淺，因此大氣外力作用很容易造成不同時間尺度之水文和生地化過程作用的變化，譬如季風交替造成南海營養鹽及生地化循環明顯的季節性變化；高頻率的颱風經過 (約每年 6 個) 和大量的亞洲沙塵沉降造成間歇性突發的異常；聖嬰現象造成大尺度年際間的變化等，因此南海之 CO₂ 海氣交換及季節、年際變化之評估，是瞭解近熱帶海域調節大氣 CO₂ 角色的重要研究課題。

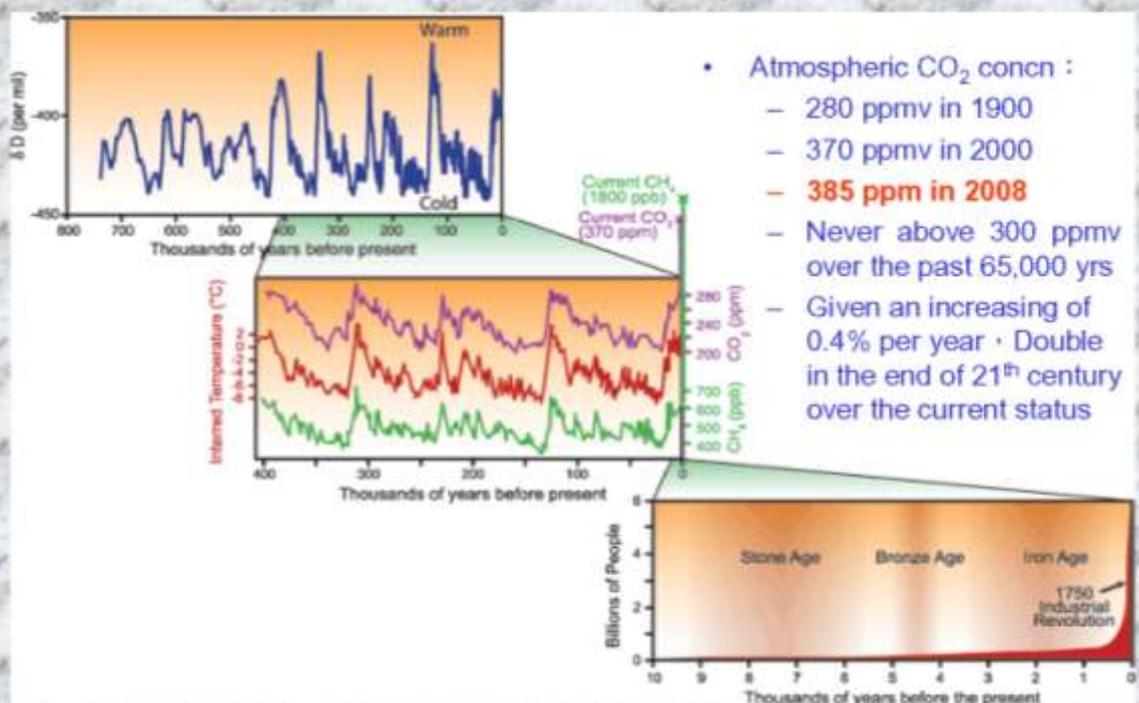
根據過往自 1999~2003 年在北南海的 SEATS (South East Asian Time-series Study) 測站 (18° N, 116° E) 的研究結果顯示，發現表面海水之 fCO₂ 呈現夏高 (400 μatm)、冬低 (340 μatm) 的季節性變化，主要受到海水溫度季節變化之影響 (冬、夏季溫差 ~6 °C)；其氣體交換通量在四~十月間 (春、夏、秋) 由海洋表面釋出到大氣，海洋扮演一個 CO₂ 的源 (Source)，其它月份則呈方向相反的交換現象，是個匯 (sink)，最終通量淨值達平衡近似零。不過，從 1999~2007 較長的資料顯示，整體平均 CO₂ 氣體交換通量由平衡轉為源 (~0.2 mol C m⁻² y⁻¹)，這和大尺度年際的氣候異常，例如聖嬰現象及海水增溫的發生有關。根據 1990 到 2004 年的模式結果，整個南海海盆平均是個 CO₂ 的弱源 (0.33 mol C m⁻² y⁻¹)，其中聖嬰現象會造成比正常年有較多的 CO₂ 從海洋溢散到大氣，有較大源的異常。自 1999~2003，NCO₂ 和 fCO₂ 有年際增加的趨勢，分別為 2 μmol kg⁻¹ yr⁻¹ (~0.1% yr⁻¹) 和 4

$\mu\text{mol kg}^{-1} \text{ yr}^{-1}$ ($\sim 0.1\% \text{ yr}^{-1}$)，這也反應了全球大氣二氧化碳之增加及年際間氣候環境的變遷有關。另外，夏天因颱風作用造成海域生產力偶發性增高，此生物幫浦對 CO_2 海氣交換通量的改變及生物攝取及傳輸至深海的過程回應，是將來值得研究的議題。

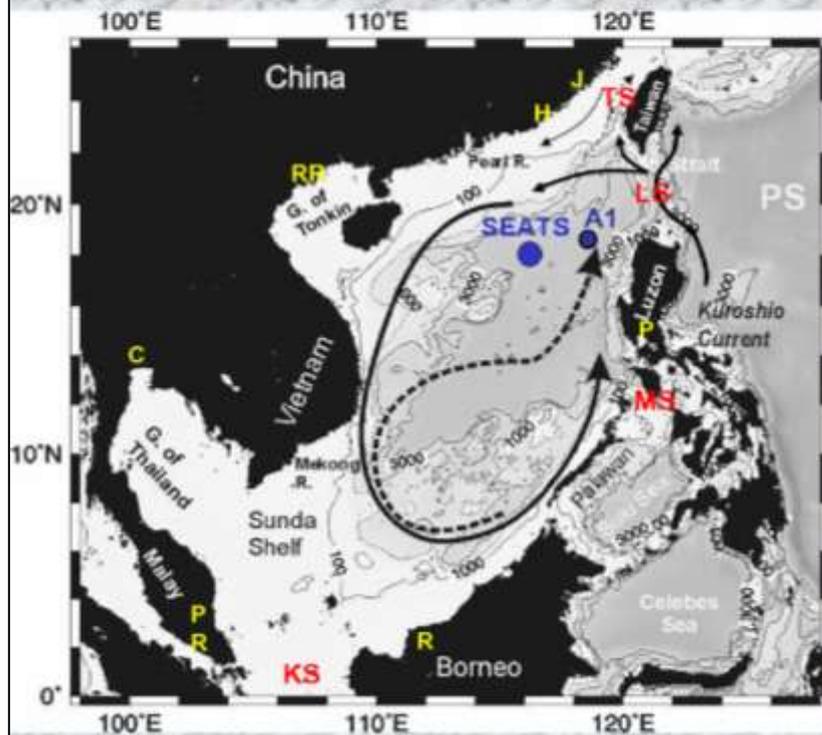
Talk outline

- Introduction & Overview
- Annual & inter-annual variability of *Ocean CO₂*
- Physical and biogeochemical processes affecting variability
- Magnitude and variability of Air-sea exchange CO₂ flux relative to global scales
- Increasing magnitudes of TCO₂ and *fCO₂*
- Future study (e.g., El-Niño, Typhoon)

“Why Study the CO₂??” – Global Warming & Climate Change



Environmental Forcing



Physical

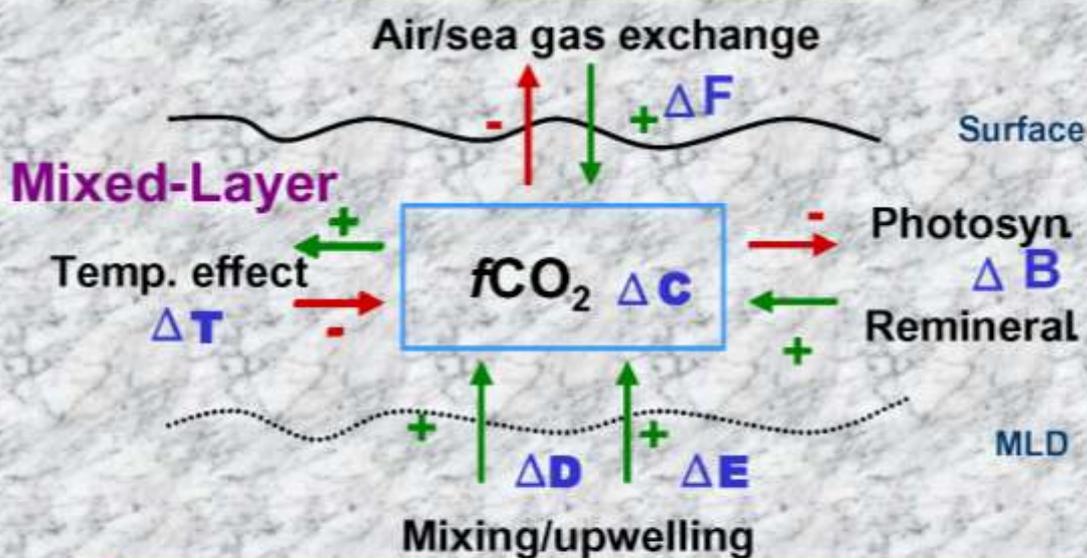
- Seasonal circulation
- Kuroshio intrusion
- Coastal diluted waters
- Internal tides/waves
- Upwelling

Atmospheric

- Winter and summer monsoons
- Typhoons
- Asian dusts
- ENSO events
- Climate variability

(Shaw & Chao, 1994; Shaw et al., 1996)

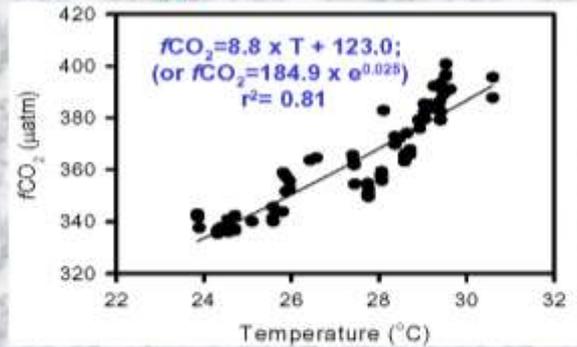
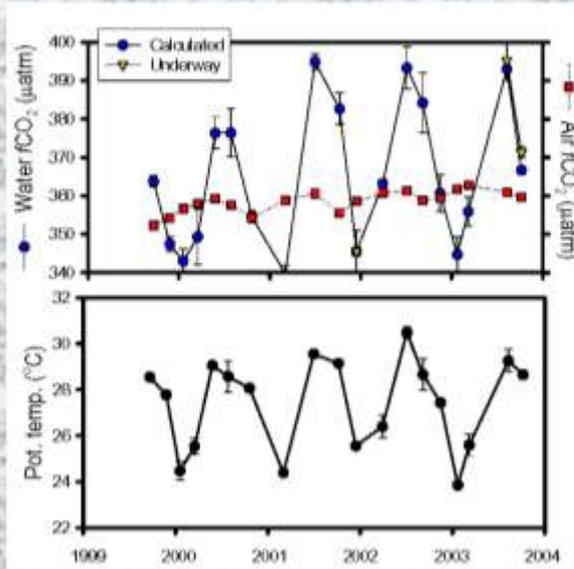
Factors affect the oceanic CO₂ variability in the MLD



$$\Delta C = (\Delta D + \Delta E) + \Delta F + \Delta B + \Delta T$$

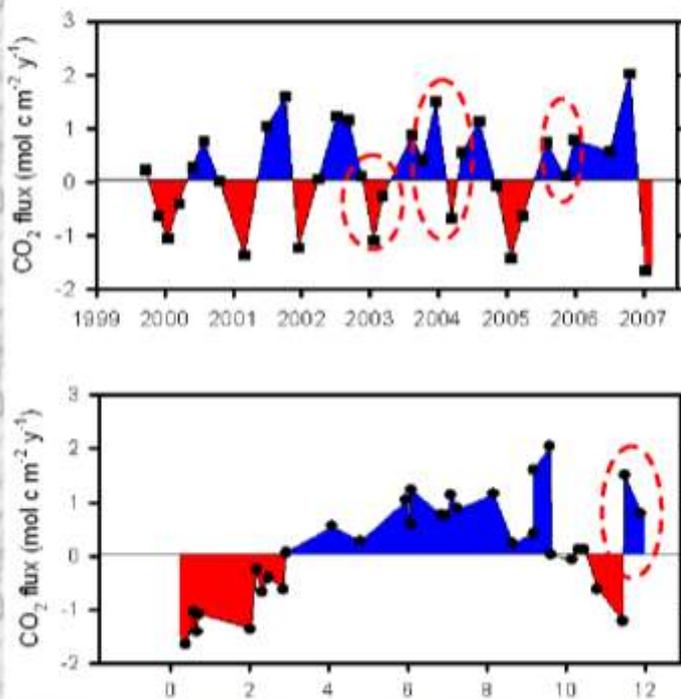
SEATS: Mixed-layer $f\text{CO}_2$

Temperature Effect



- Water $f\text{CO}_2$ varies directly with T and inversely with chl-a – Low $f\text{CO}_2$ in Winter (Solubility+Biological pump).
- $f\text{CO}_2$ water < $f\text{CO}_2$ air in Winter[®] invasion; $f\text{CO}_2$ water > $f\text{CO}_2$ air in Summer[®] evasion

SEATS CO_2 Flux (1999~2007)

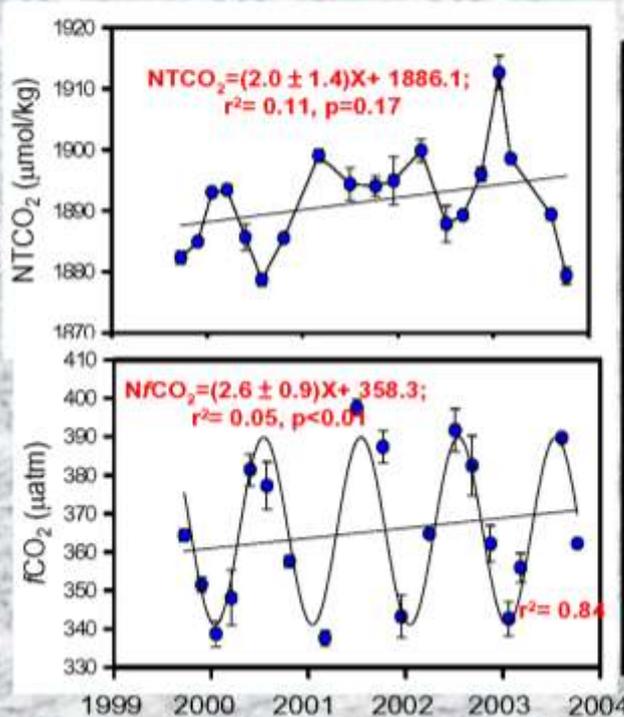


- CO_2 flux varies inter-annually marked in red dashed circle
- Normally CO_2 invasion in Winter; CO_2 evasion in Summer
- However, interannual anomaly may be linked to large-scale climate variability (e.g., ENSO, Pacific Decadal Oscillation etc.)

Net evasion flux:
+ 0.1 ± 0.7

Interannual Trends of CO₂ at SEATS

An increase of M-L *f*CO₂ & NTCO₂



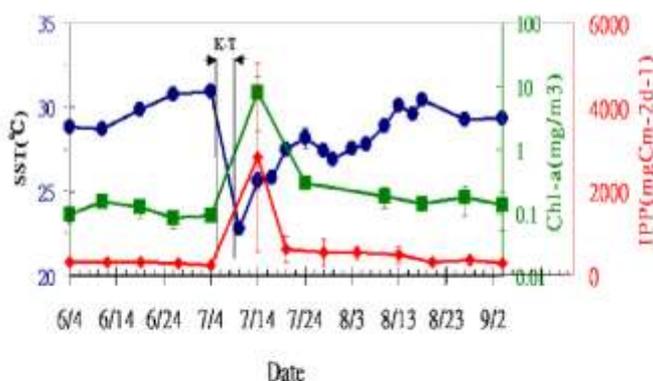
Mixed Layer	NTCO ₂ (µmoles kg ⁻¹ yr ⁻¹)	<i>f</i> CO ₂ (µatm yr ⁻¹)
HOT	+1.0 (0.72~1.37) (1988-1996) (Winn et al., 1994)	
BATS	+1.7 (1988-1993) (Bats et al, 1996) +1.6 ± 5.8 (1988-1998) (Bats et al, 2001) +1.2 ± 0.3 (r ² = 0.37, 1988-2001) (Bats et al, 2002)	+1.4 ± 10.7 (1988-1998) (Bats et al, 2001)
SEATS	2.0 ± 1.4 (1999-2004)	2.6 ± 0.9 (1999-2004)

Tseng et al., 2007

Typhoon: Atmospheric pumping

SEATS : Tropical Cyclone Kai-Tak

At bloom center



[Lin et al. (2003) GRL 30, 1718]

Biomass (chl-a) was elevated by up to 300 times.

Effect of storm-induced changes could be detected for about one month.

Depth-integrated primary production increased from 300 to 2800 mg-C/m²/d. This single event (0.8 Mt-C) could account for ~2-4% of annual new production. [1 Mt = 10¹² g]