Variation of sea surface $p\mathrm{CO_2}$ and controlling processes in cold seasons in the northern Yellow Sea, China

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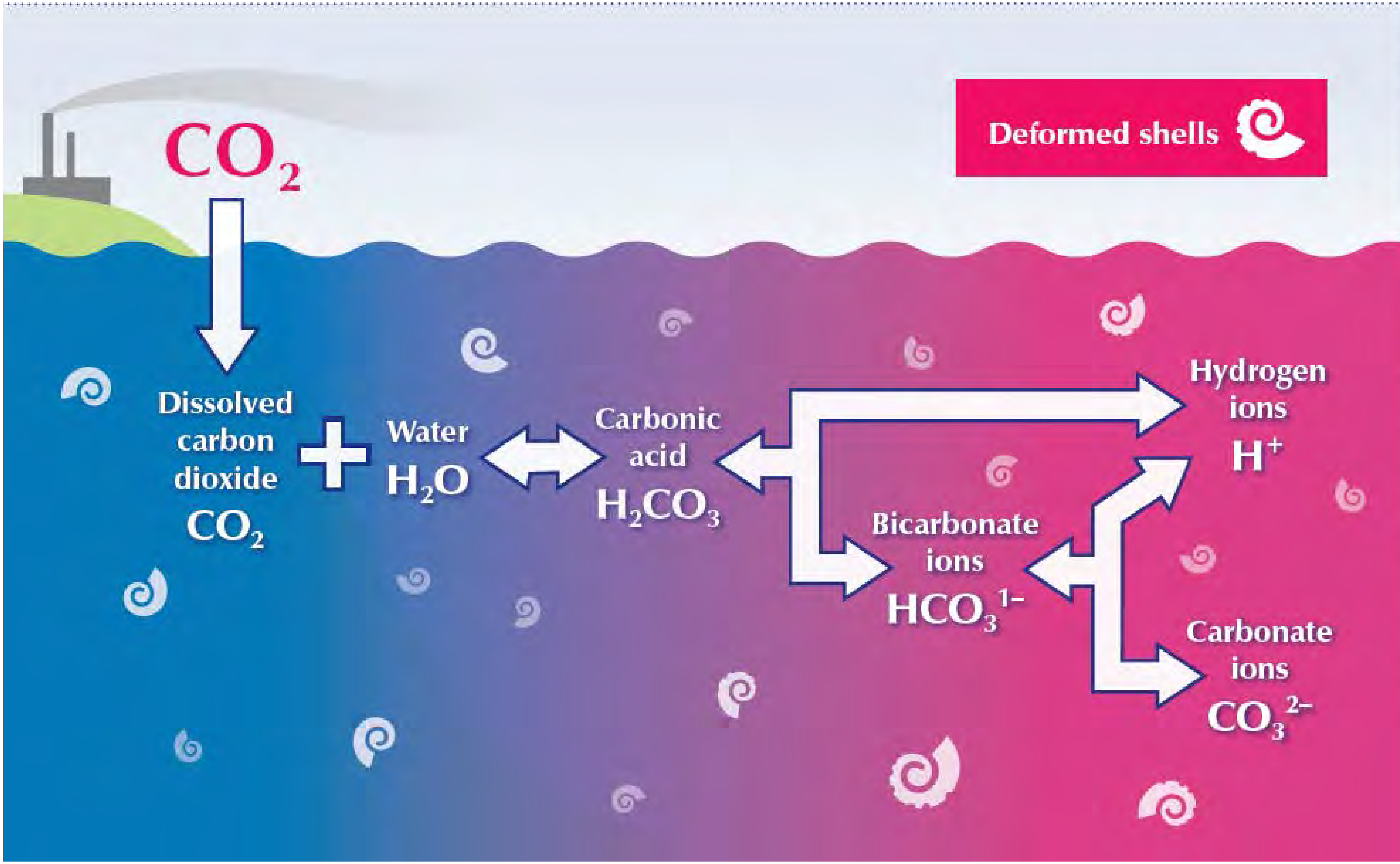
OUTLINE

- Background
- Monthly *p*CO_2 at A4HDYD station(YD Station)
- mmonthly *p*CO_2 in NYS
- Summary

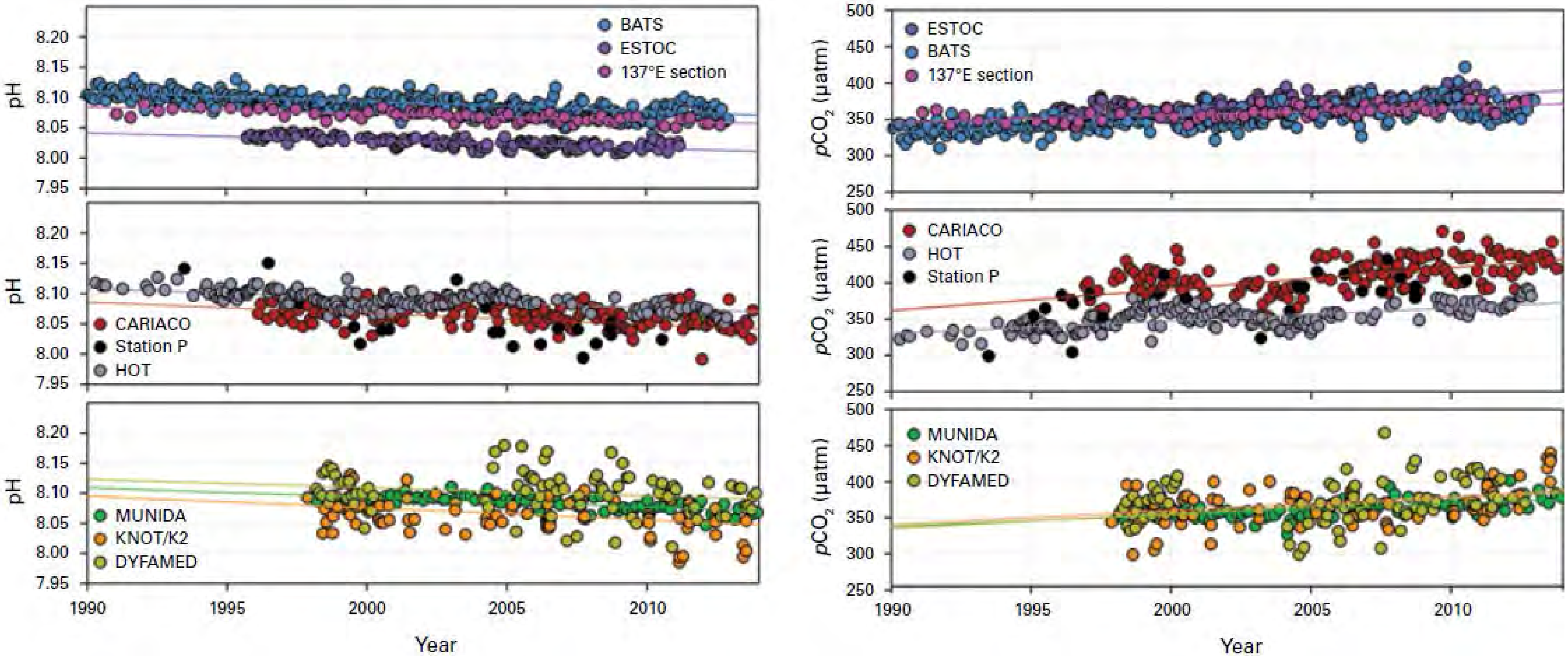
Ocean Acidification: Global Warming's Twin

The burning of fossil fuels result in increased CO_2 in the atmosphere being taken up by the ocean resulting in it becoming more acidic.



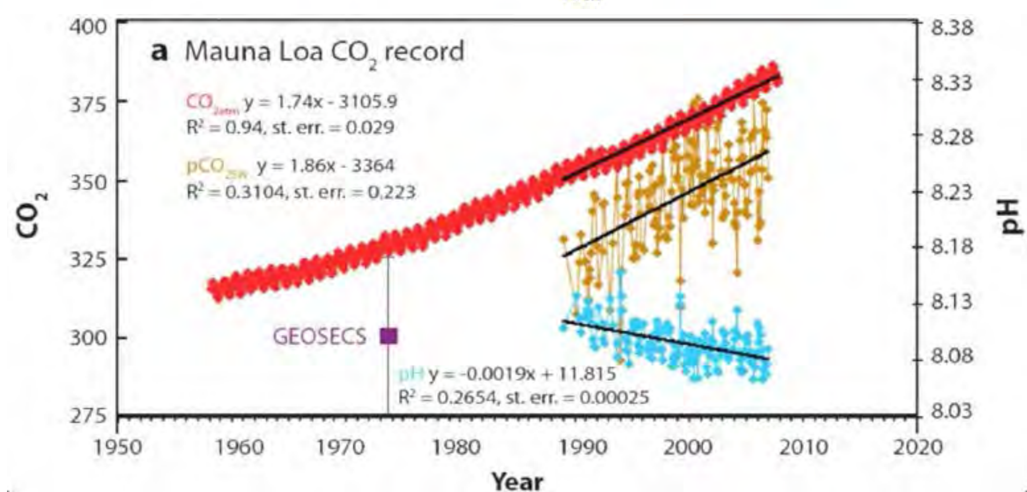
Source: Laffoley et.al. 2010. Ocean Acidification: Questions Answered.

Changes in surface oceanic pCO_2 (in matm) and pH from time series stations



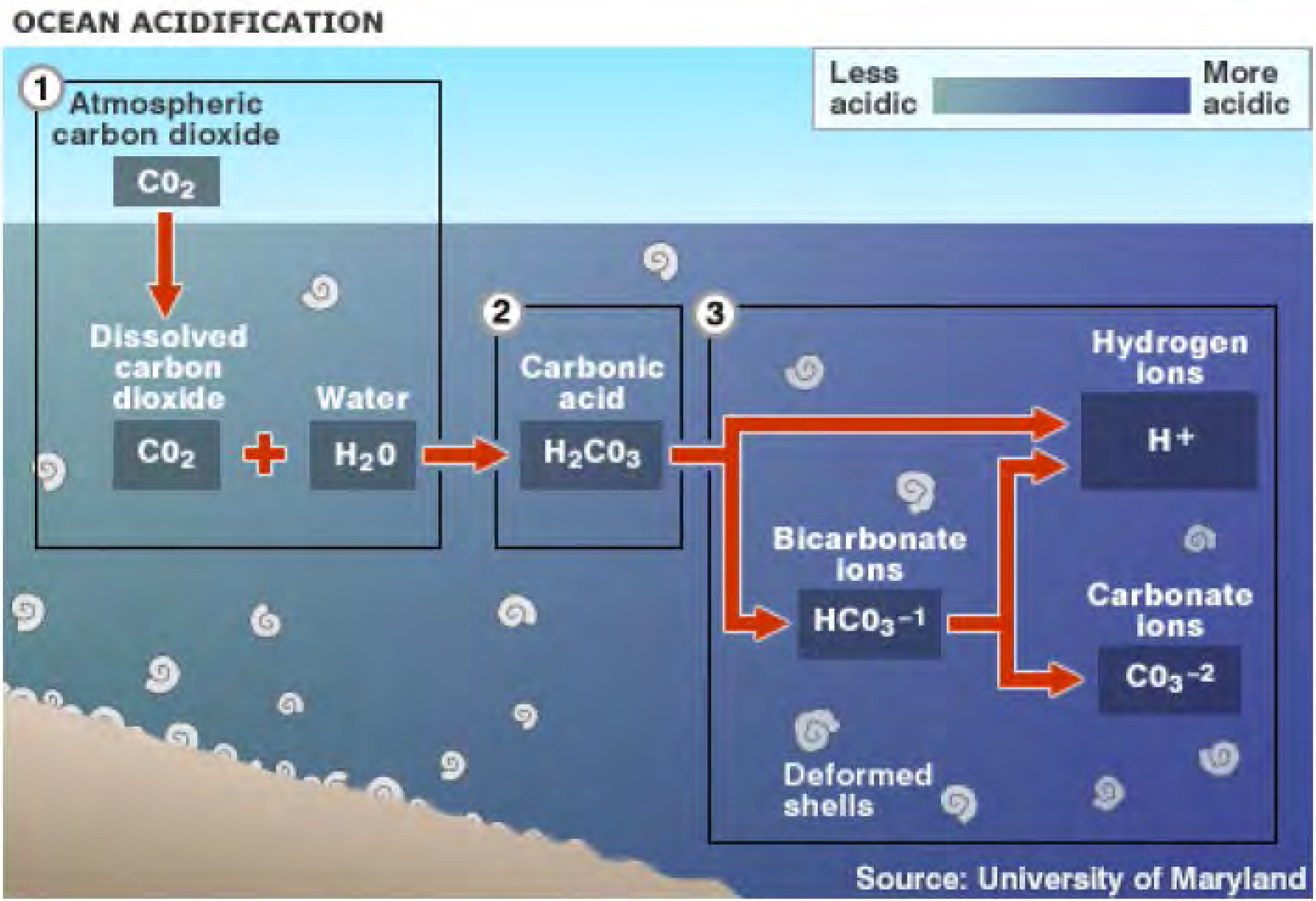
WMO GREENHOUSE GAS BULLETIN, 2014

Ocean acidification is happening now



Doney et al. 2009

OA = carbonate chemistry perturbation



Why coastal ocean CO_2?

- 8% of the surface area of the global ocean
- 15-30% of the oceanic primary production
- 80-85% of the organic matter burial, primarily near large river deltas
- 90% of the sedimentary mineralization
- 50% of the deposition of calcium carbonate

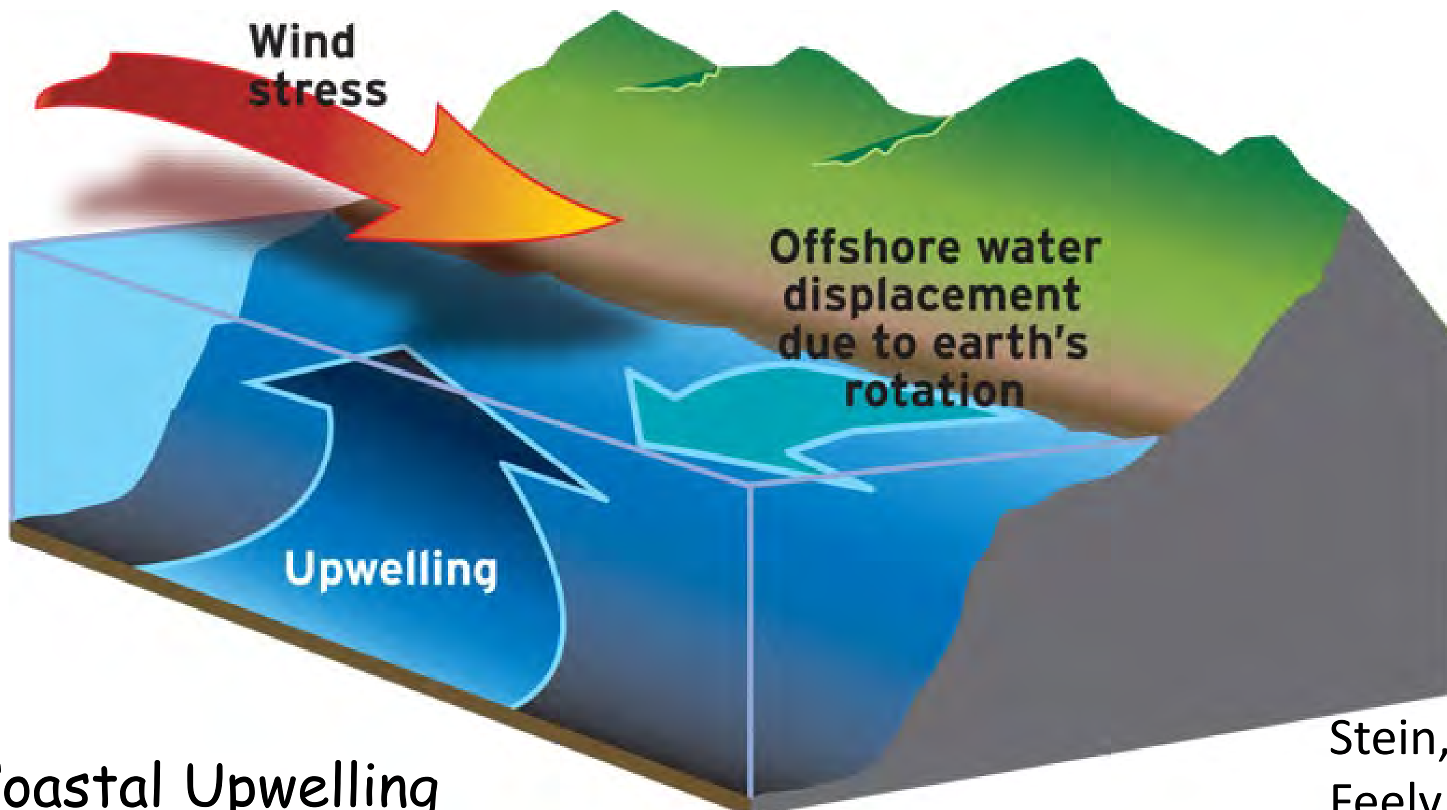
coastal oceans are disproportionately important in ocean carbon cycle

Cai，2008

Distinct temporal/spatial variability:

coastal waters

- Local Oceanography: coastal upwelling
- Metabolism Processes
- Regional Environ. Changes: eutrophication

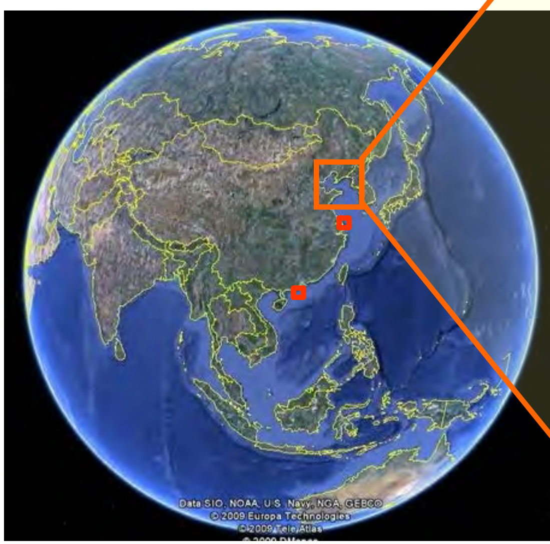


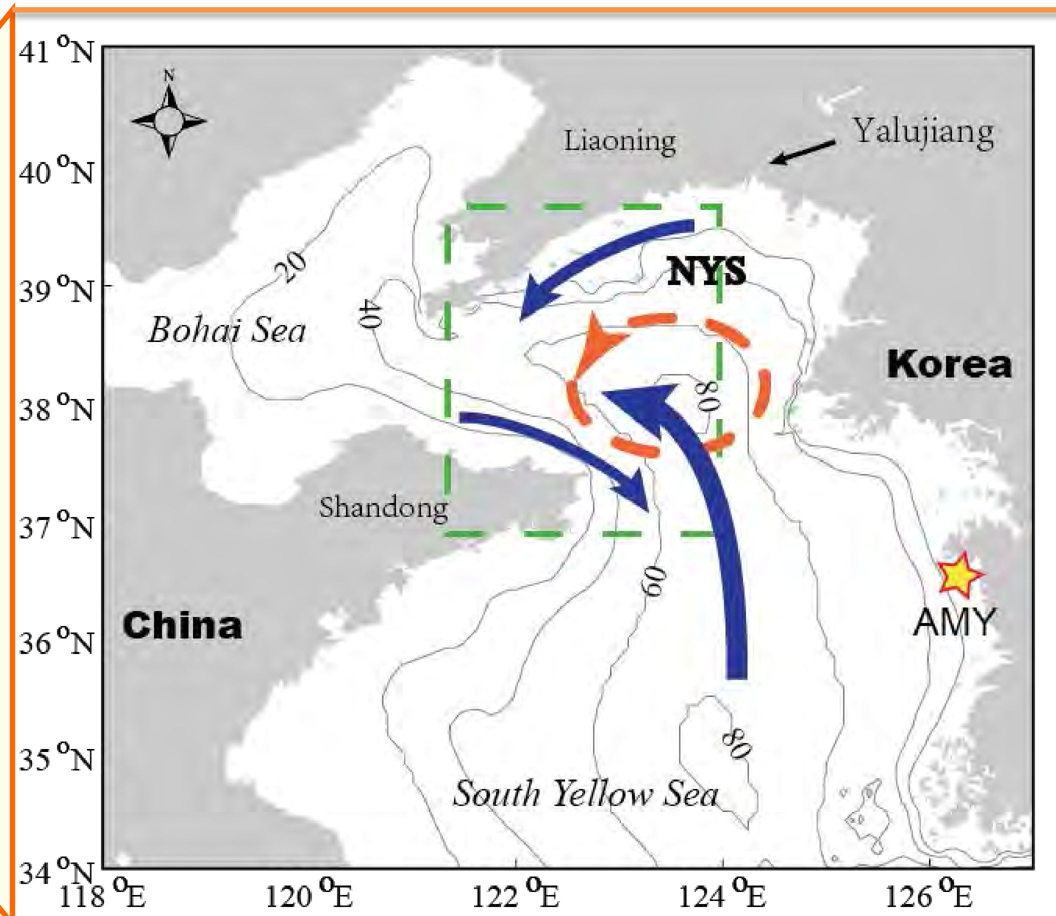
Coastal Upwelling

Stein, 2009; Feely 2009

North Yellow Sea

Study Area





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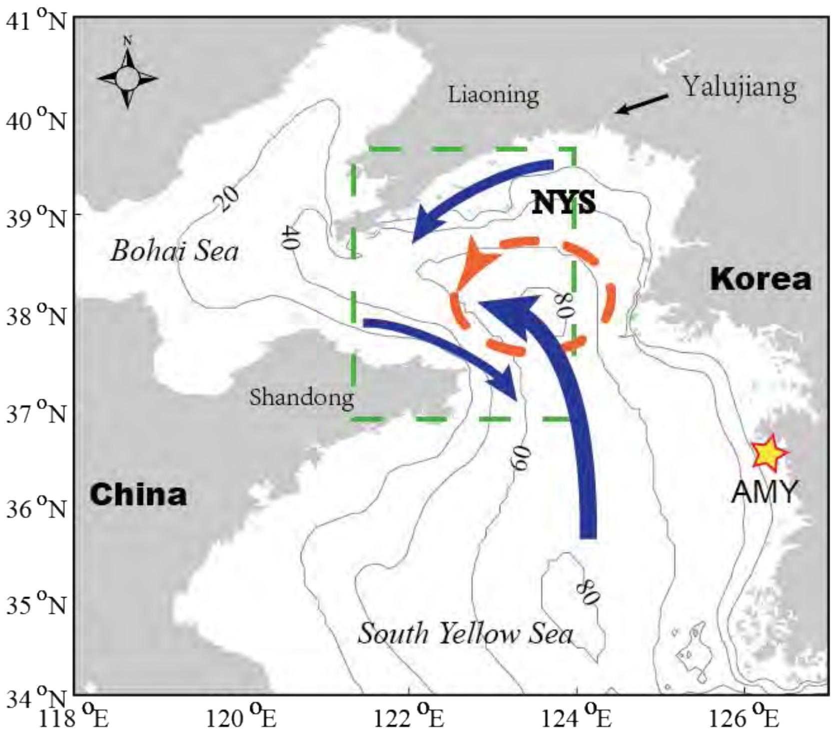
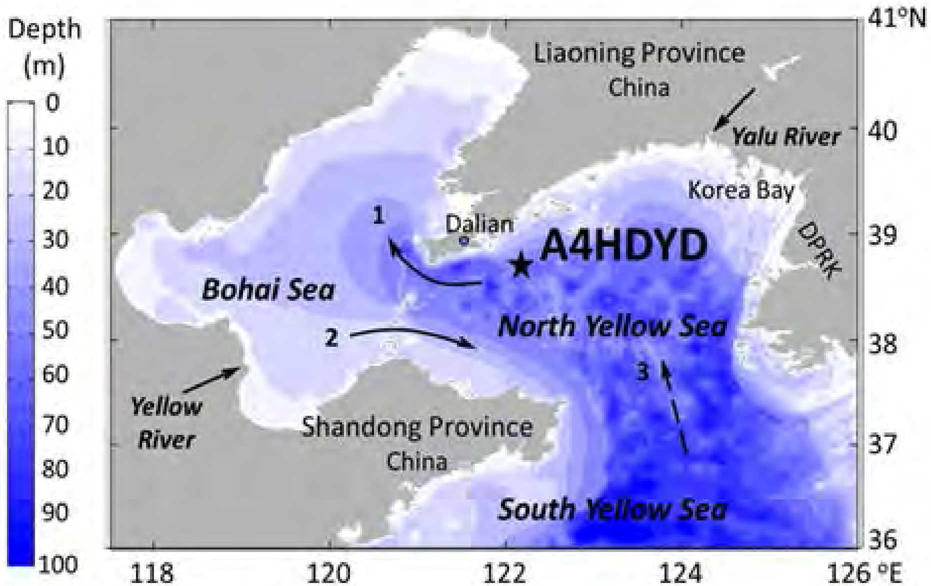


Zhai et al., 2013; Qiao et al., 1998; Miao et al., 1991; Chen, 2009)

- Exchange water with Bohai Sea;
- relatively low salinity (31.5-32.5) compared with open oceans;
- nearly year-round weak counter clockwise gyre;
- summertime characterized by a pronounced stratification in the deeper region;
- Cold water mass, typically 5-11℃;
- Wintertime circulation is characterized by the Yellow Sea Warm Current (YSWC)

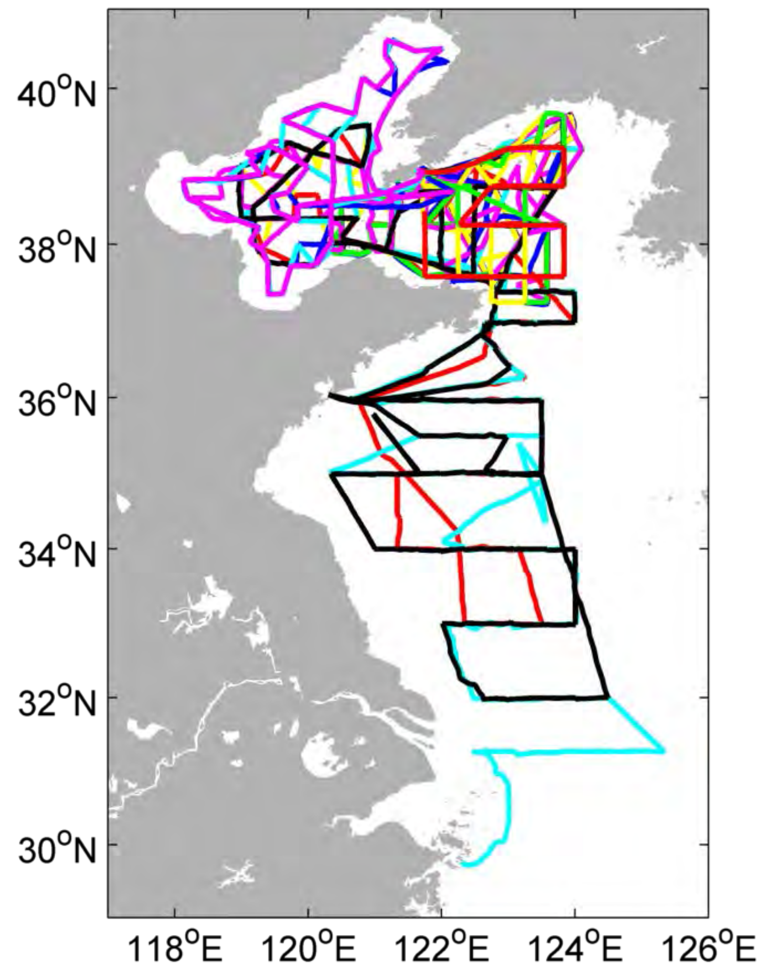
Monthly pCO_2 at A4HDYD station



The study area. The black star denotes the A4HDYD station, while DPRK denotes the Democratic People's Republic of Korea. Black arrows denote the Bohai Sea inflow current (1), the Bohai Sea outflow current (2), and the YS Warm Current (3), which were modified from *Chen* (2009).

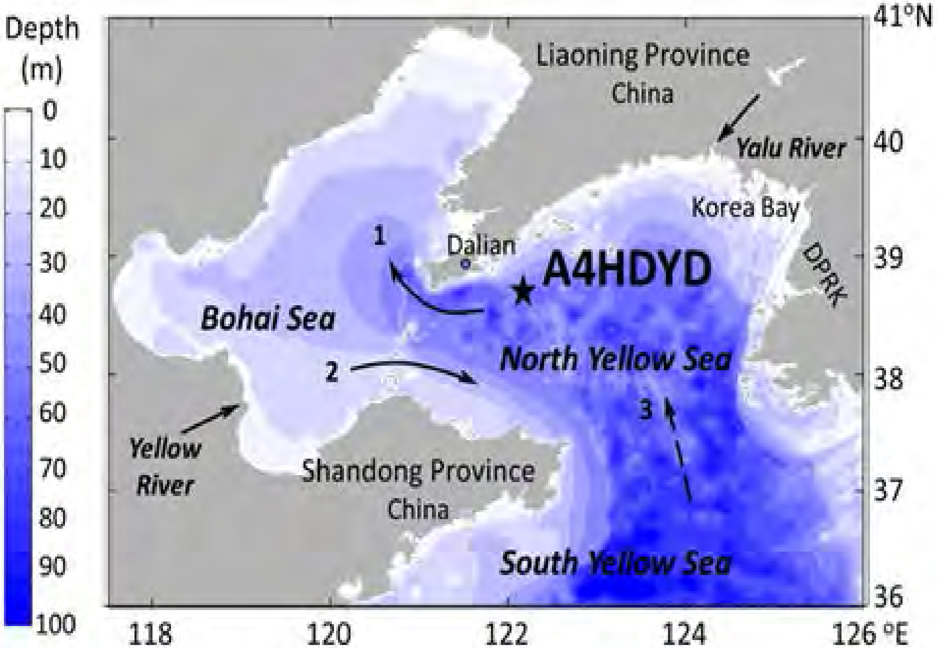
The A4HDYD station was surveyed 21 times on board R/V YiXing from March 2011 to November 2013 covering all the seasons

Underway pCO_2 in the NYS



~30 cruises in Bohai and/or Yellow Sea from 2009 to 2015

Monthly pCO_2 at A4HDYD station



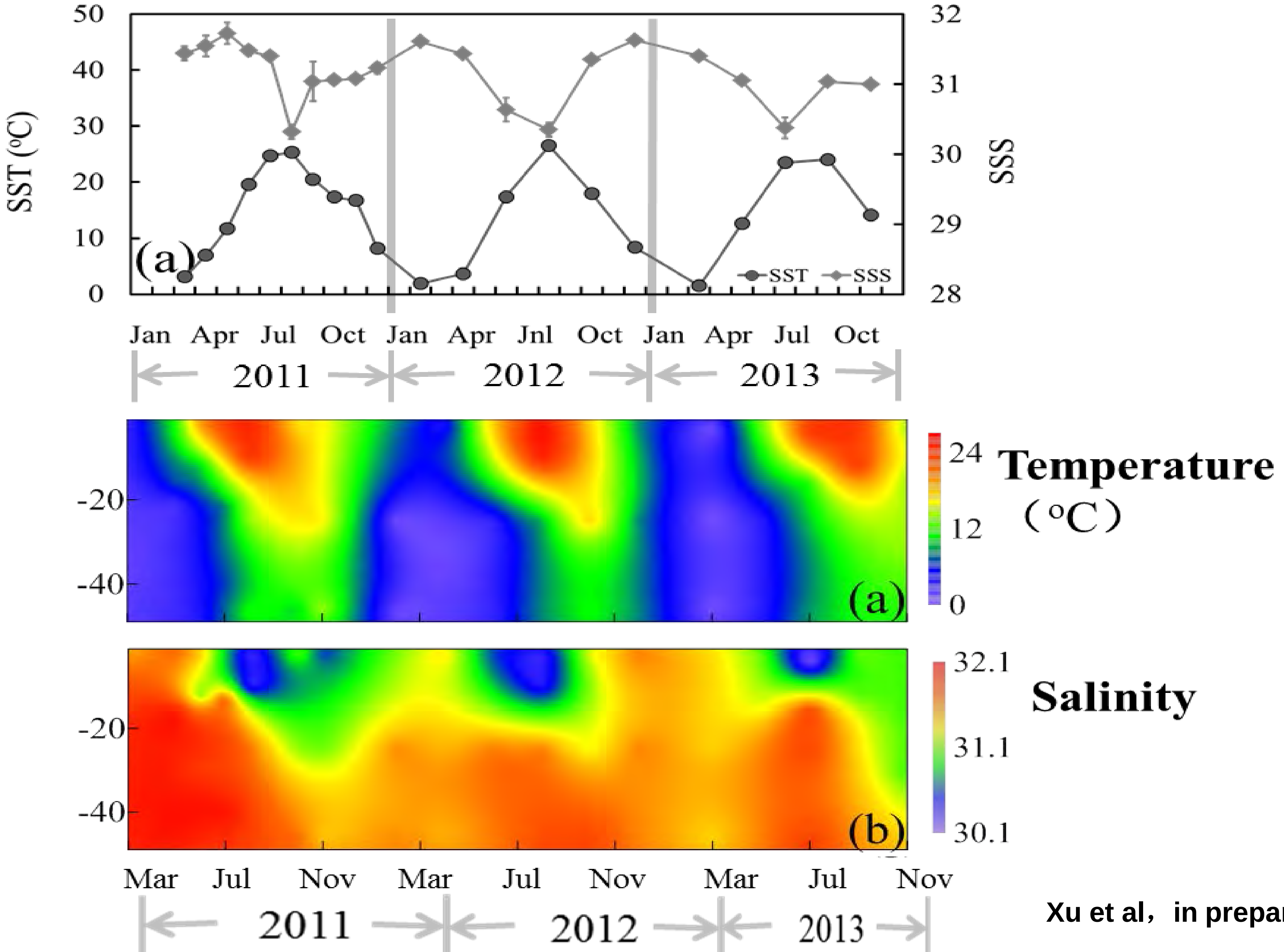
38° 40′N, 122° 10′E

Depth of 50 m

at 5 h intervals for 25 h

	Surveying time	Sampling depth(m)
1	28-29 March 2011	2,25,44
2	27-28 April 2011	2
3	15-16 May 2011	2,16,21,42
4	22-23 June 2011	2,12,30,48
5	27-28 July 2011	2,13,22,40
6	26-27 August 2011	2,10,25,47
7	26-27 September 2011	2
8	23-24 October 2011	2,25,46
9	3-4 November 2011	2,25,46
10	19-20 December 2011	2
11	27-28 February 2012	2,25,45
12	6-7 April 2012	2,25,45
13	8-9 June 2012	2,25,45
14	16-17 August 2012	2,10,25,47
15	19-20 October 2012	2.5,25,47
16	12-13 December 2012	2,25,47
17	14-15 March 2013	2,24,46
18	29-30 May 2013	2,15,25,46
19	30-31 July 2013	2,15,25,47
20	5-6 September 2013	2,10,25,49
21	12-13 November 2013	2,15,30,48

Hydrological Settings at A4HDYD station



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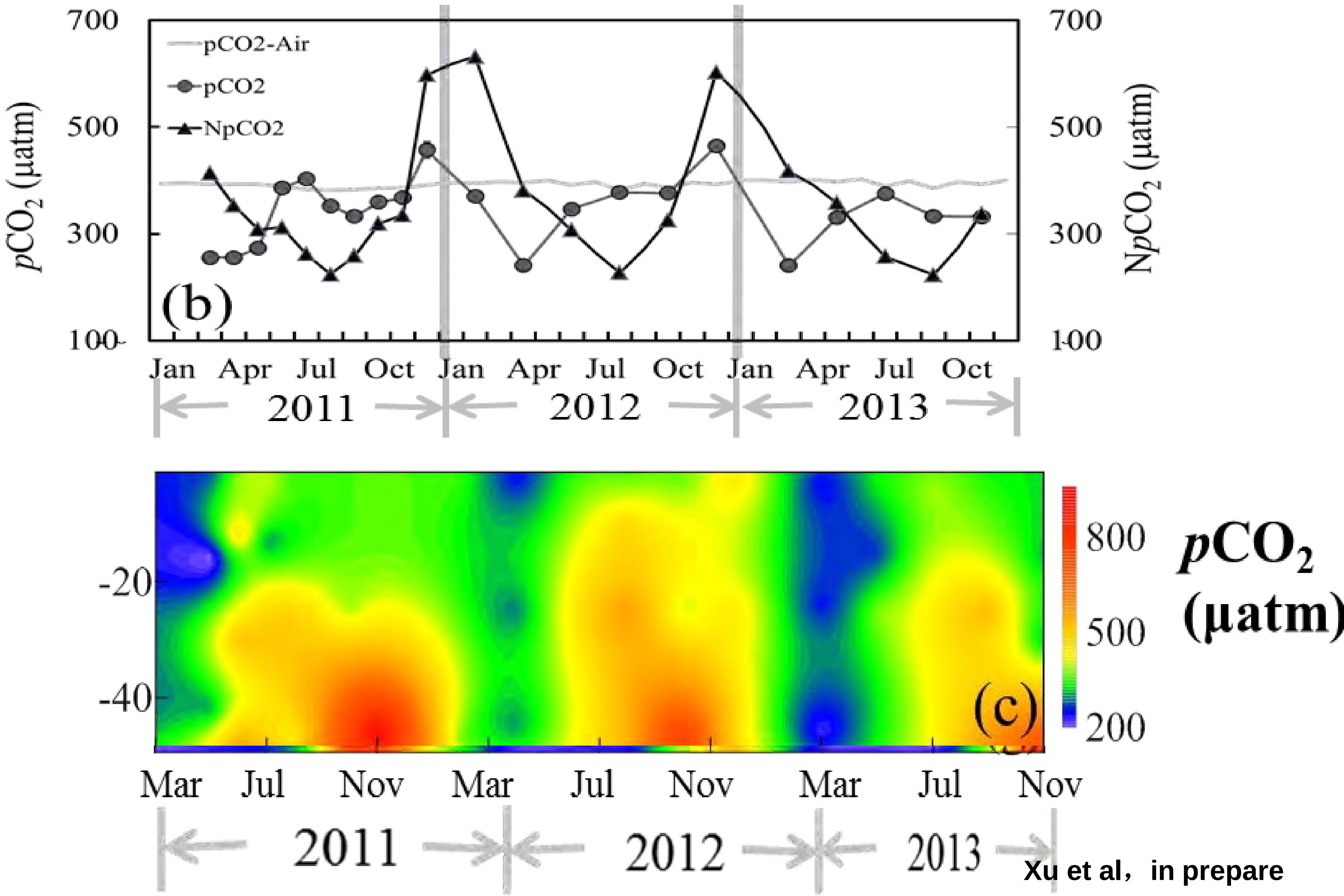
pCO_2 at the A4HDYD station



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Mean values of SST, SSS , DIC , TAlk, ΔpCO_2 , wind speed, and air–sea CO_2 fluxes at A4HDYD station in each month of an annual cycle.

Month	Surveying time	SST (° C)	SSS	DIC (μmol kg^{-1})	TAlk (μmol kg^{-1})	△pCO_2 (μatm)	Winds (m s^{-1})	Air-sea CO_2 flux (mmol C m^{-2} d^{-1})
February	2012/2/27	1.93±0.05	31.61±0.01	2109±14	2231±12	-24±7	7.8±1.0	-3.2±0.8
March	2011/3/29 2013/3/14	2.32±1.16	31.42±0.02	2070±10	2257±27	-147±15	6.7±0.8	-14.8±5.3
April	2011/4/28 2012/4/6	5.30±2.31	31.49±0.08	2053±6	2257±14	-147±13	5.1±0.1	-8.1±0.6
May	2011/5/15 2013/5/29	12.20±0.64	31.39±0.48	2030±14	2269±50	-94±36	3.7±0.4	-2.7±1.5
June	2011/6/22 2012/6/8	18.48±1.52	31.06±0.60	2020±28	2225±3	-24±30	4.3±1.3	-1.3±1.7
July	2011/7/28 2013/7/31	24.14±0.86	30.89±0.73	1948±19	2207±30	3±24	4.5±0.6	0.0±0.9
August	2011/8/26 2012/8/16	25.93±0.86	30.33±0.02	1909±28	2180±24	-29±17	4.8±1.6	-0.6±0.3
Septembe r	2011/9/26 2013/9/5	22.30±2.50	31.04±0.00	1965±13	2226±4	-52±1	6.0±1.1	-3.8±1.3
October	2011/10/23 2012/10/19	17.65±0.45	31.21±0.21	2010±5	2235±0	-18±11	6.1±1.1	-1.3±0.3
November	2011/11/3 2013/11/12	15.45±1.82	31.04±0.06	2032±1	2240±6	-40±29	7.8±0.6	-5.2±4.5
December	2011/12/19 2012/12/12	8.30±0.11	31.43±0.28	2153±64	2298±71	68±4	7.8±0.0	8.8±0.5

-0.89±0.62mol C m^{-2} yr^{-1}

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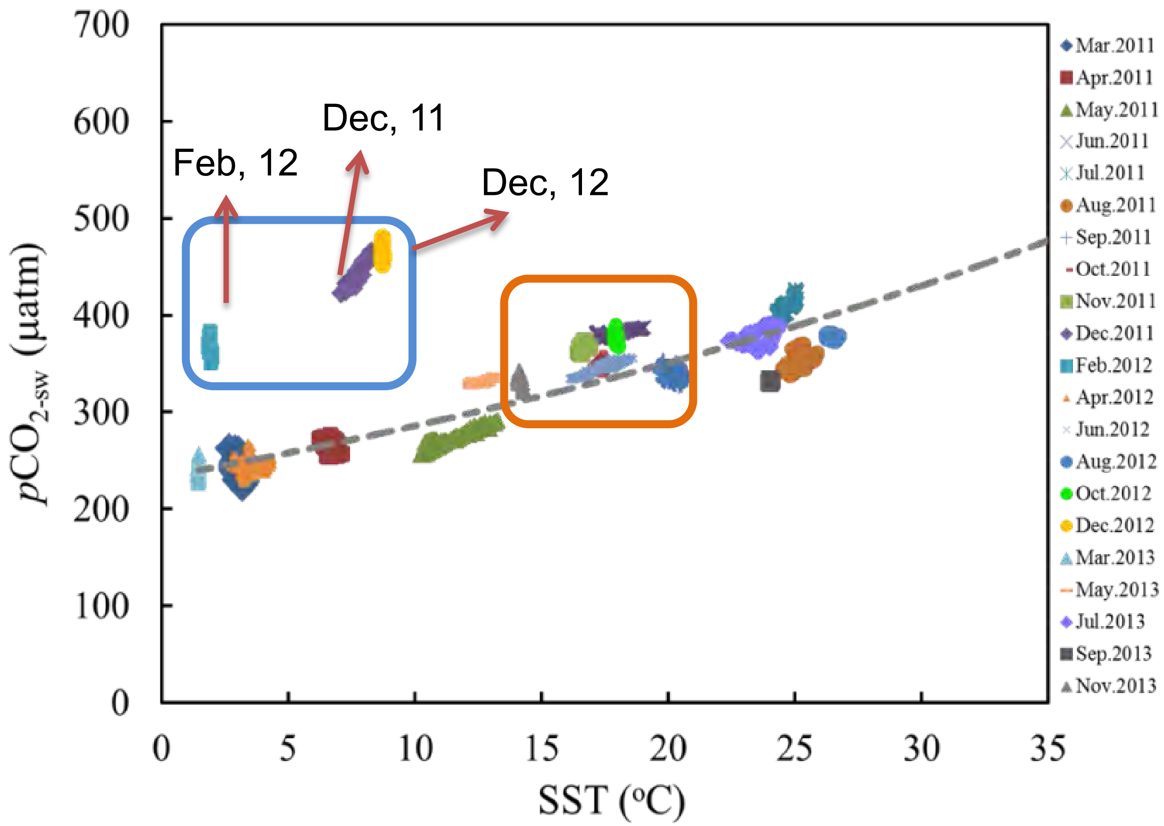
Effect of temperature on monthly variation of pCO_2



Generally, pCO_2 increases by 0.0423 °C^{-1} (Takahashi et al.1993)

the temperature effect on seawater pCO_2 was weakened by other processes

Dashed lines represent function of $pCO_{2,i+1}$=$pCO_{2,i} \times e^{0.0205(T_{i+1}-T_i)}$. This indicated that temperature had an important influence on pCO_2 monthly cycle.

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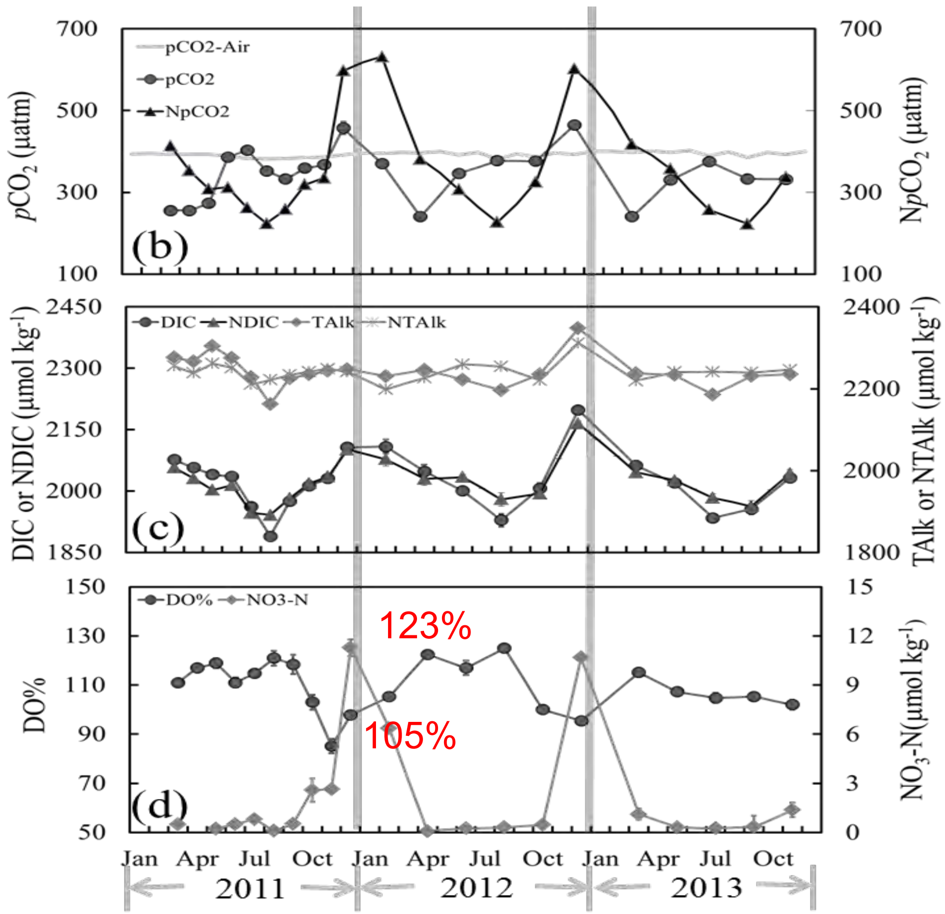
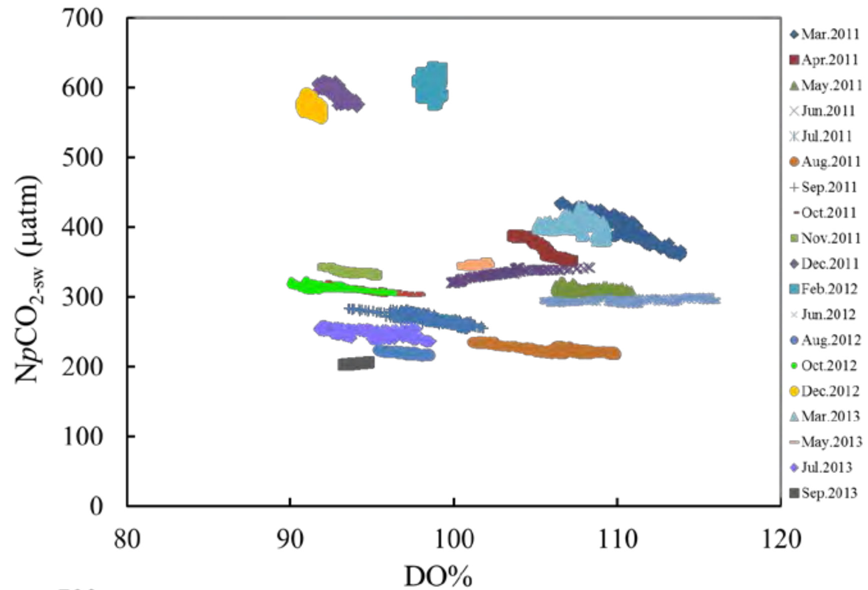
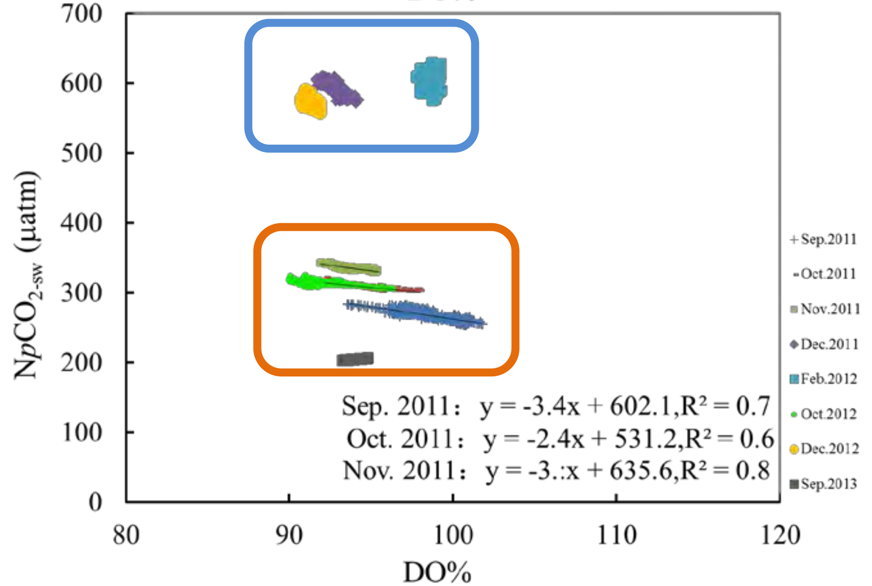
Biological effect on surface pCO_2







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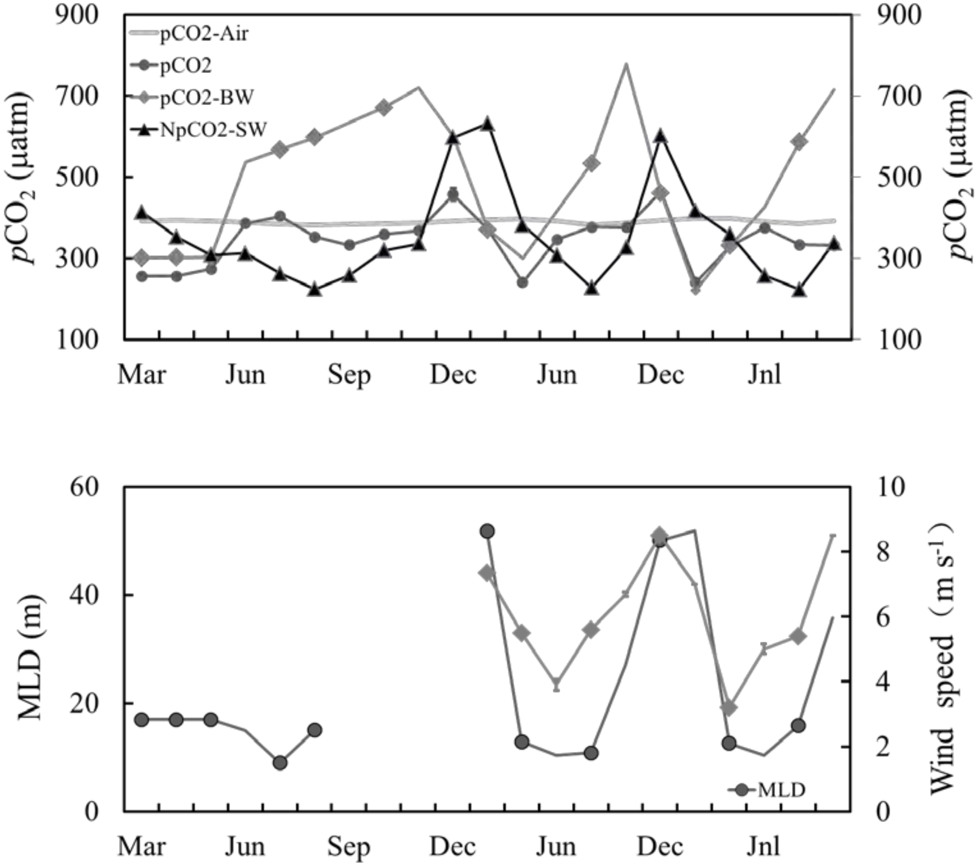
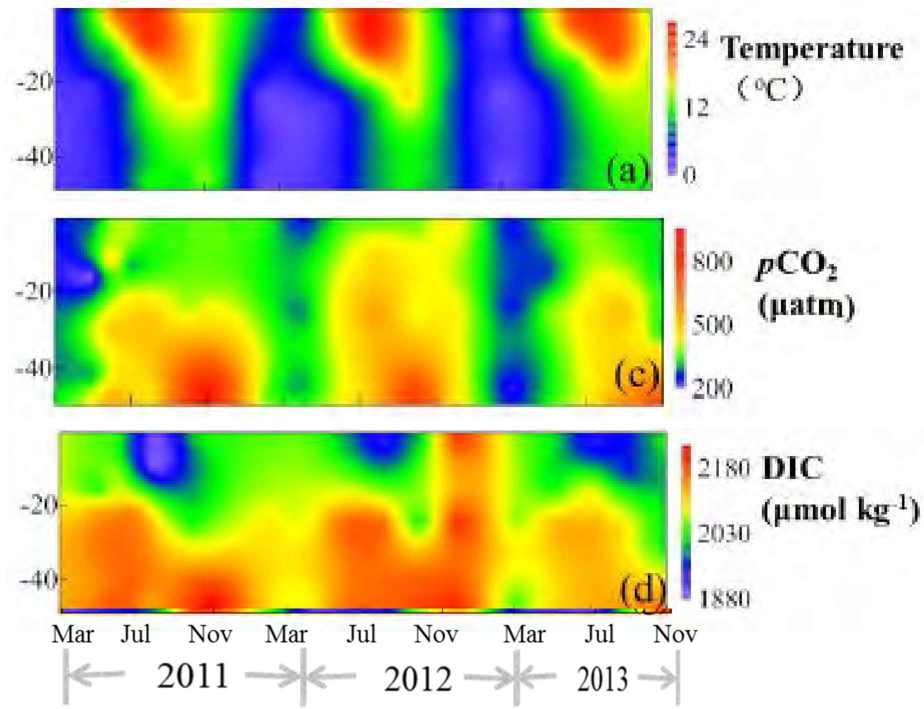
Vertical mixing





Time series at the A4HDYD station: sea surface pCO_2, bottom-water pCO_2 (pCO_{2BW}), NpCO_2, atmospheric pCO_2 ($pCO_{2(air)}$), wind speed and the mixed layer depth.

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Processes influencing surface pCO_2

The variation of pCO_2 was a combined result of various processes: changes in temperature ($d_{SST}pCO_2$), salinity variation ($d_{SSS}pCO_2$), biological activity ($d_{Bio}pCO_2$) (an increase of CO_2 by respiration and a decrease during phytoplankton production), the CO_2 increase induced by vertical mixing of CO_2-rich waters from below ($d_{Mix}pCO_2$), air–sea CO_2 exchange ($d_{As}pCO_2$), and a residual term ($d_{Res}pCO_2$) required to close the budget.

$$dp\mathrm{CO_2} = d_{\mathrm{SST}}\,p\mathrm{CO_2} + d_{\mathrm{SSS}}\,p\mathrm{CO_2} + d_{\mathrm{Bio}}\,p\mathrm{CO_2} + d_{\mathrm{Mix}}\,p\mathrm{CO_2} + d_{\mathrm{As}}\,p\mathrm{CO_2} + d_{\mathrm{Res}}\,p\mathrm{CO_2}$$

$$d_{\mathrm{SST}}\,p\mathrm{CO_{2,i}} = p\mathrm{CO_{2,i}} \times \exp^{0.0423(T_{i+1}-T_i)} - p\mathrm{CO_{2,i}}$$

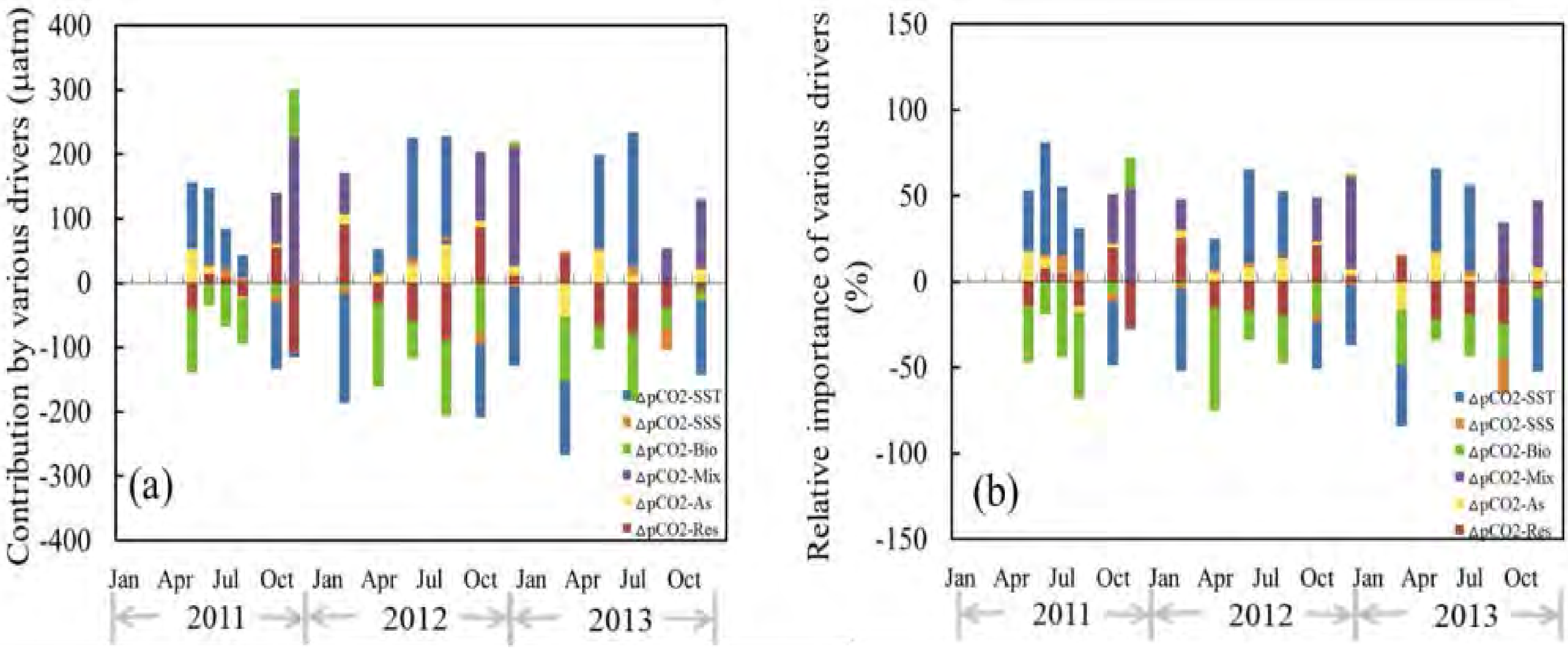
$$d_{\mathrm{SSS}}\,p\mathrm{CO_{2,i}} = p\left(DIC_i, TAlk_i, SSS_{i,}SST_i\right) - p\left(DIC_i \times \frac{SSS_{i+1}}{SSS_i}, TAlk_i \times \frac{SSS_{i+1}}{SSS_i}, SSS_{i+1,}SST_i\right)$$

$$d_{Bio}\,pCO_{2,i} = p(DIC_i + d_{Bio}\,DIC_i, TAlk_i + d_{Bio}\,TAlk_i, SSS_{i,}SST_i) - p(DIC_i, TAlk_i, SSS_{i,}SST_i)($$

$$d_{Mix}\,pCO_{2,i} = p(DIC_i + d_{Mix}\,DIC_i, TAlk_i + d_{Mix}\,TAlk_i, SSS_{i,}SST_i) - p(DIC_i, TAlk_i, SSS_{i,}SST_i)$$

$$d_{\mathrm{AS}}\,p\mathrm{CO_{2,i}} = p(DIC_i + d_{\mathrm{AS}}\,DIC_{\mathrm{i}}, TAlk_i, SSS_{i,}SST_i) - p(DIC_i, TAlk_i, SSS_{i,}SST_i)$$

Processes influencing surface pCO_2



Contribution (a) and relative importance (b). (a) and (b) of various processes (temperature, salinity biological effect, vertical mixing, air–sea exchange, and a residual term) to the pCO_2 at the A4HDYD station.

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Relative contribution of various processes

Surveyed period	SST	SSS	Biological effect	Vertical mixing	Air-sea CO_2 exchange	Residual term	Dominant processes
Feb to Apr 2012	18%	2%	-60%	0%	5%	-15%	Bio
Mar to May 2011	35%	-1%	-32%	0%	18%	-14%	SST+Bio
Mar to May 2013	48%	1%	-12%	0%	17%	-22%	SST
Apr to Jun 2012	55%	3%	-17%	0%	8%	-17%	SST
May to Jun 2011	65%	2%	-19%	0%	6%	8%	SST
May to Jul 2013	50%	3%	-25%	0%	3%	-19%	SST
Jun to Jul 2011	40%	9%	-44%	0%	0%	7%	SST+Bio
Jun to Aug 2012	36%	1%	-28%	2%	14%	-19%	SST+Bio
Jul to Aug 2011	25%	6%	-51%	0%	-3%	-15%	SST+Bio
Jul to Sep 2013	1%	-21%	-20%	33%	0%	-25%	Mix+SST+Bio
Aug to Oct 2011	-38%	-4%	-7%	29%	2%	20%	SST+Mix
Aug to Oct 2012	-28%	-4%	-19%	26%	2%	21%	SST+Bio
Sep to Nov 2013	-43%	0%	-5%	39%	8%	-5%	SST+Mix
Oct to Nov 2011	-2%	0%	18%	54%	0%	-26%	Mix
Oct to Dec 2012	-35%	-2%	2%	53%	4%	4%	SST+Mix
Nov 2011 to Feb 2012	-48%	-3%	-2%	18%	5%	24%	SST
Dec 2012 to Mar 2013	-36%	2%	-32%	0%	-16%	14%	SST+Bio

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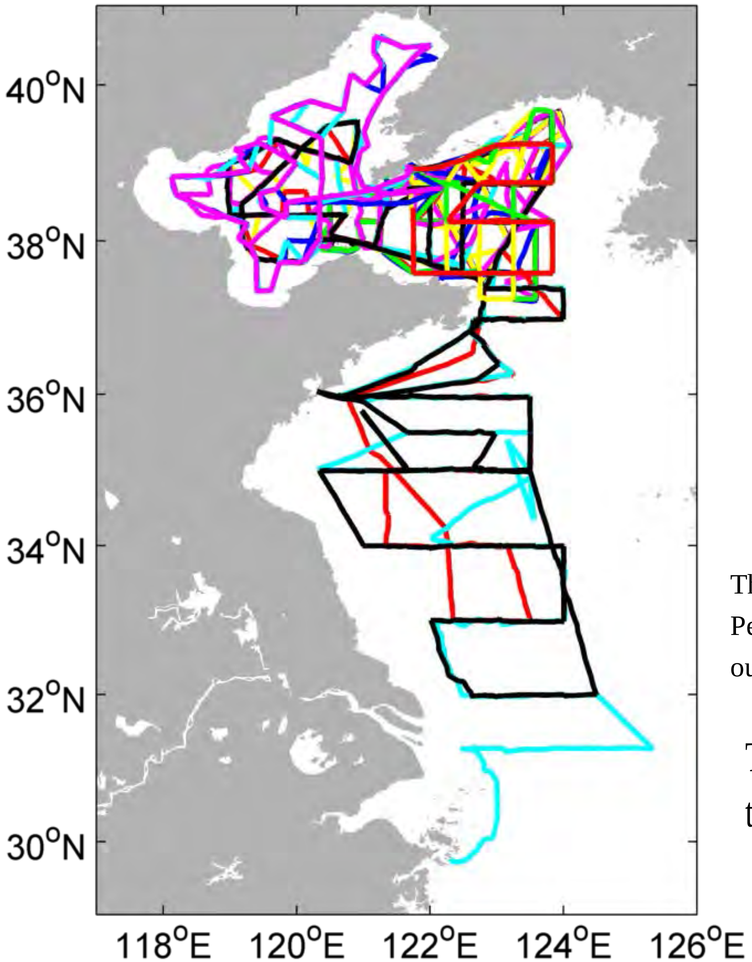
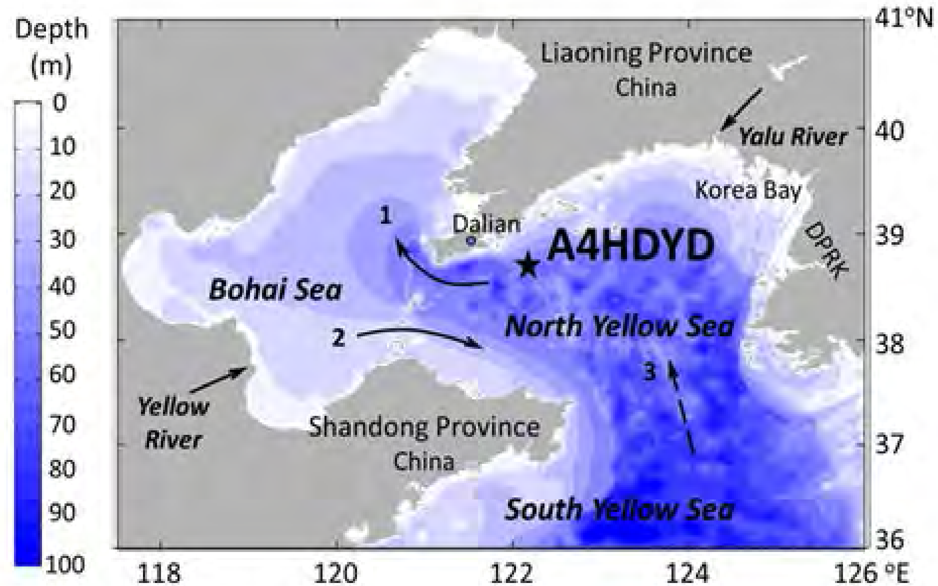
Underway pCO_2 in the NYS



~30 cruises in Bohai and/or Yellow Sea from 2009 to 2015

Monthly pCO_2 at A4HDYD station



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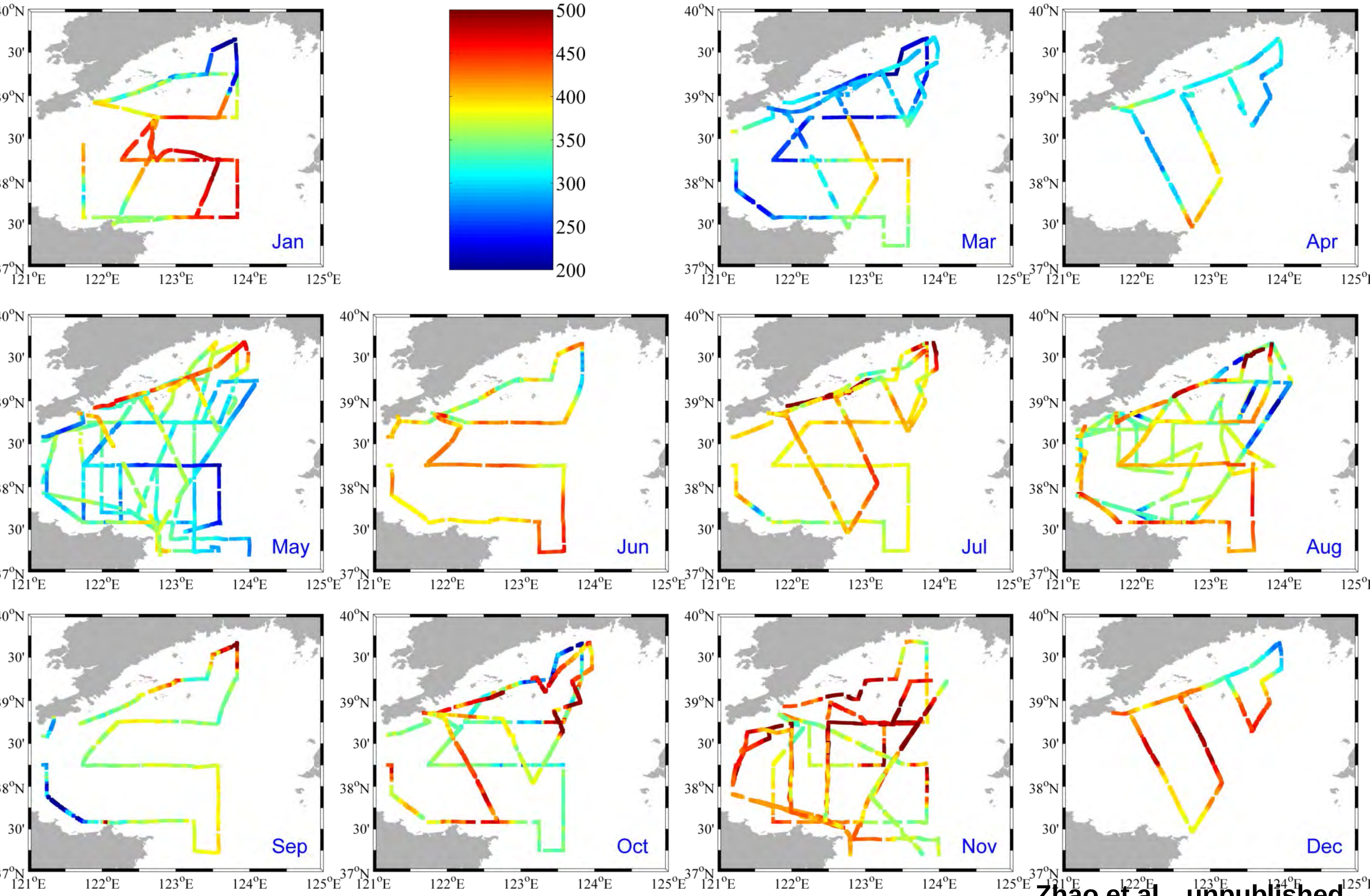
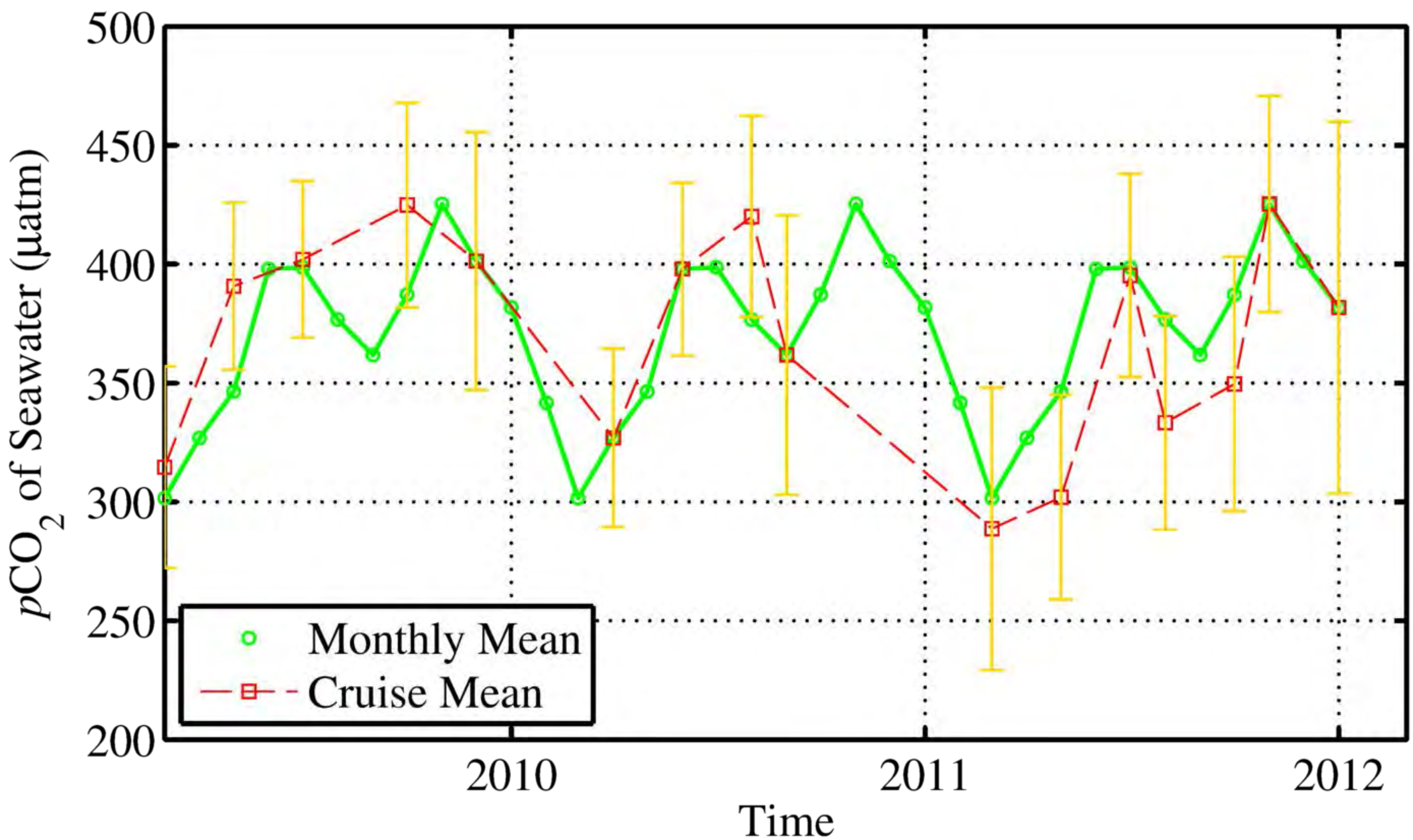
Underway pCO_2 of seawater in the NYS



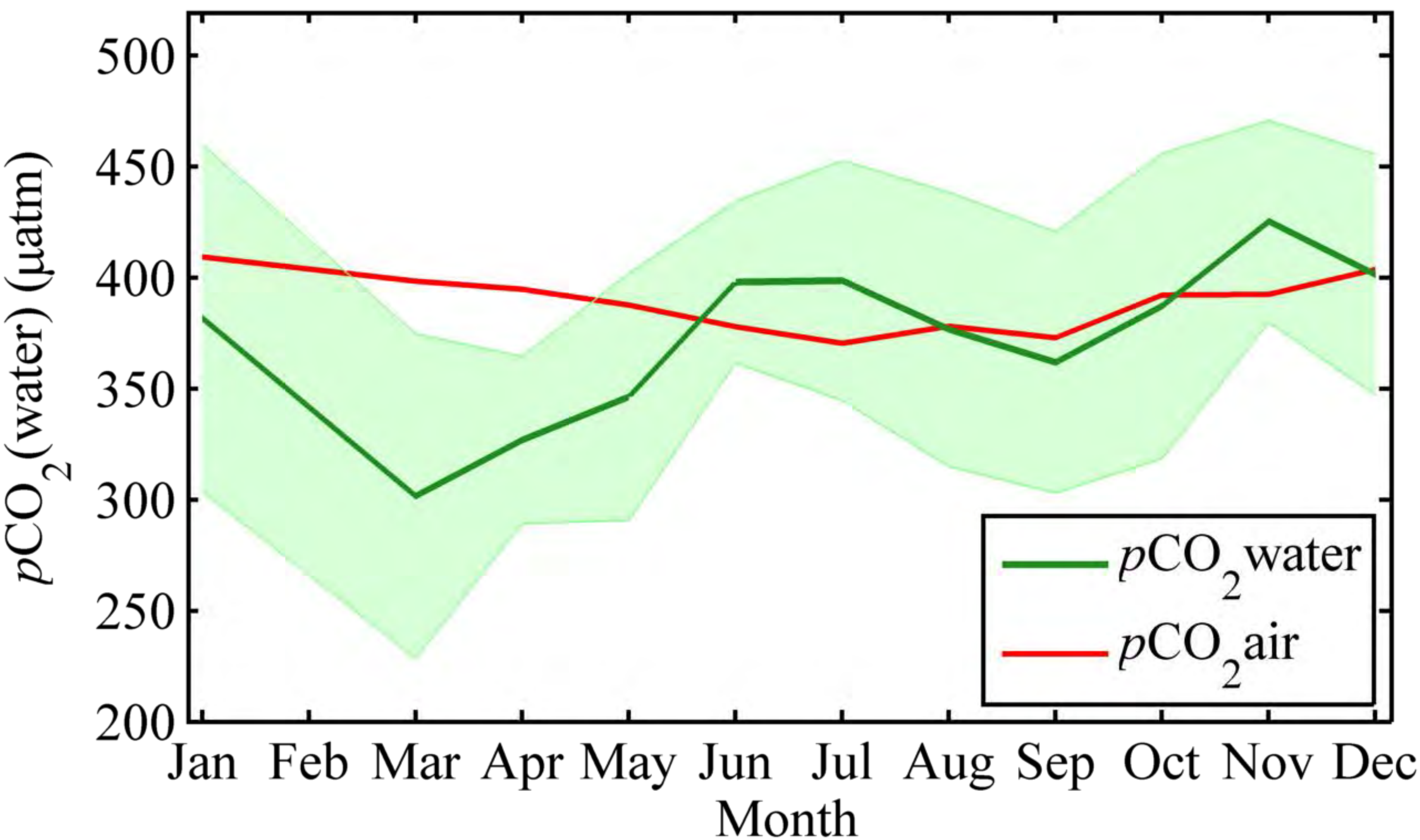
Zhao et al，unpublished

Average of pCO_2 in every Cruise



Zhao et al，unpublished

Monthly Average of $p\mathrm{CO}_2$



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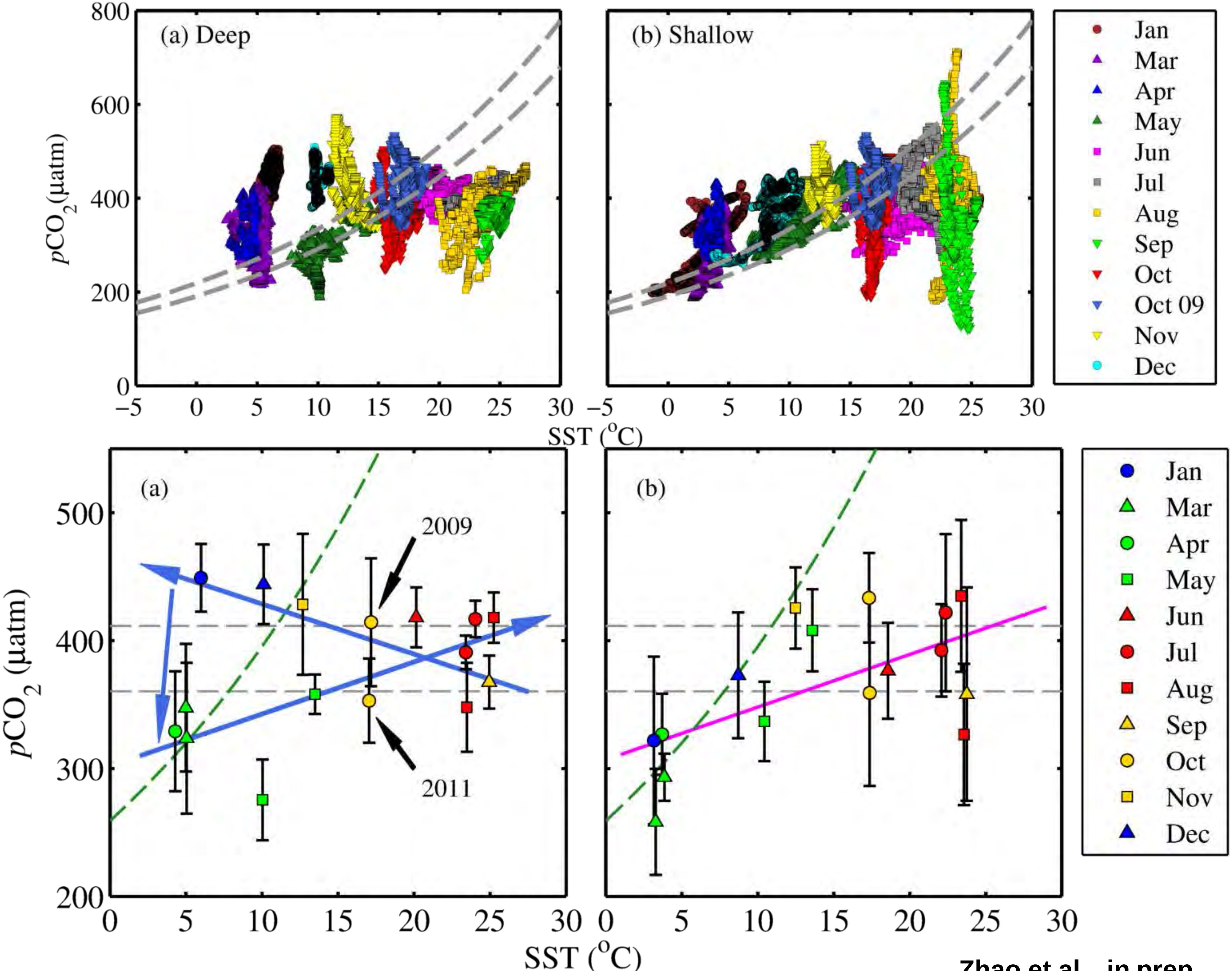

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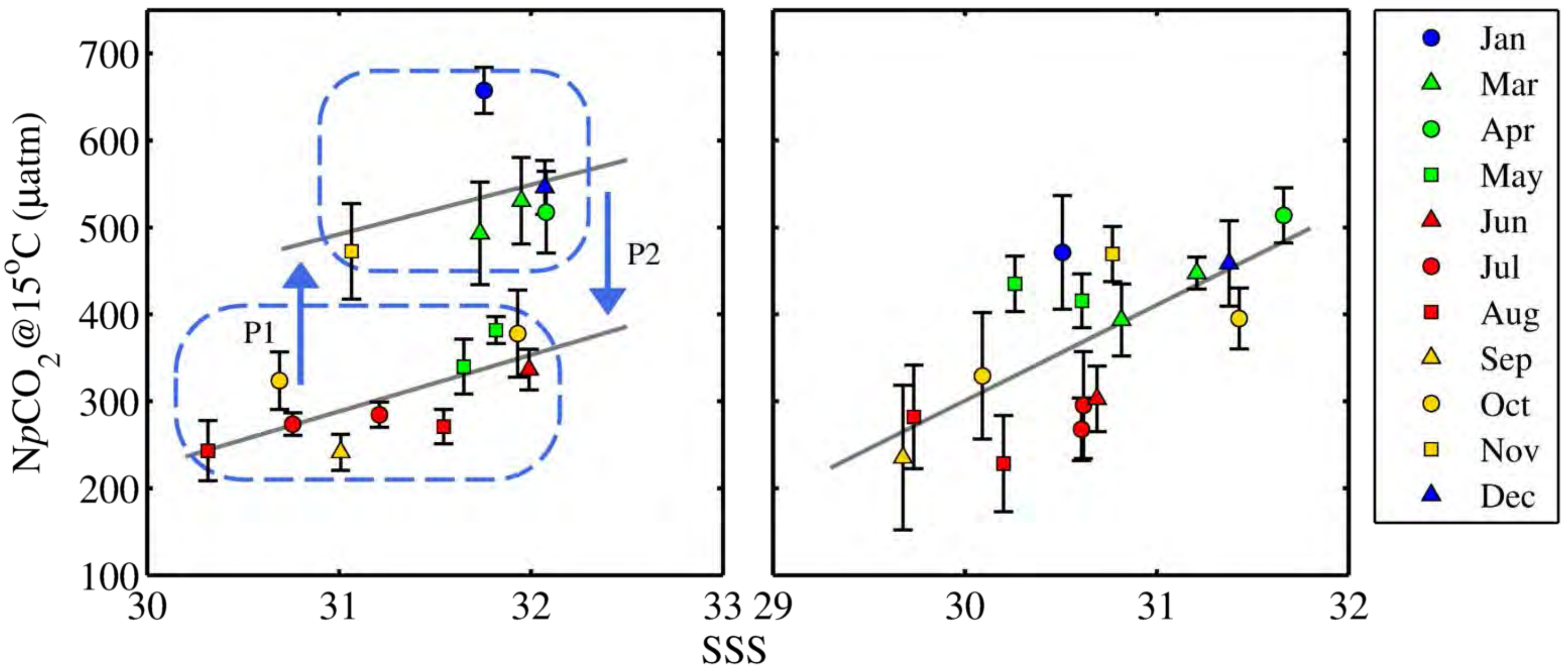

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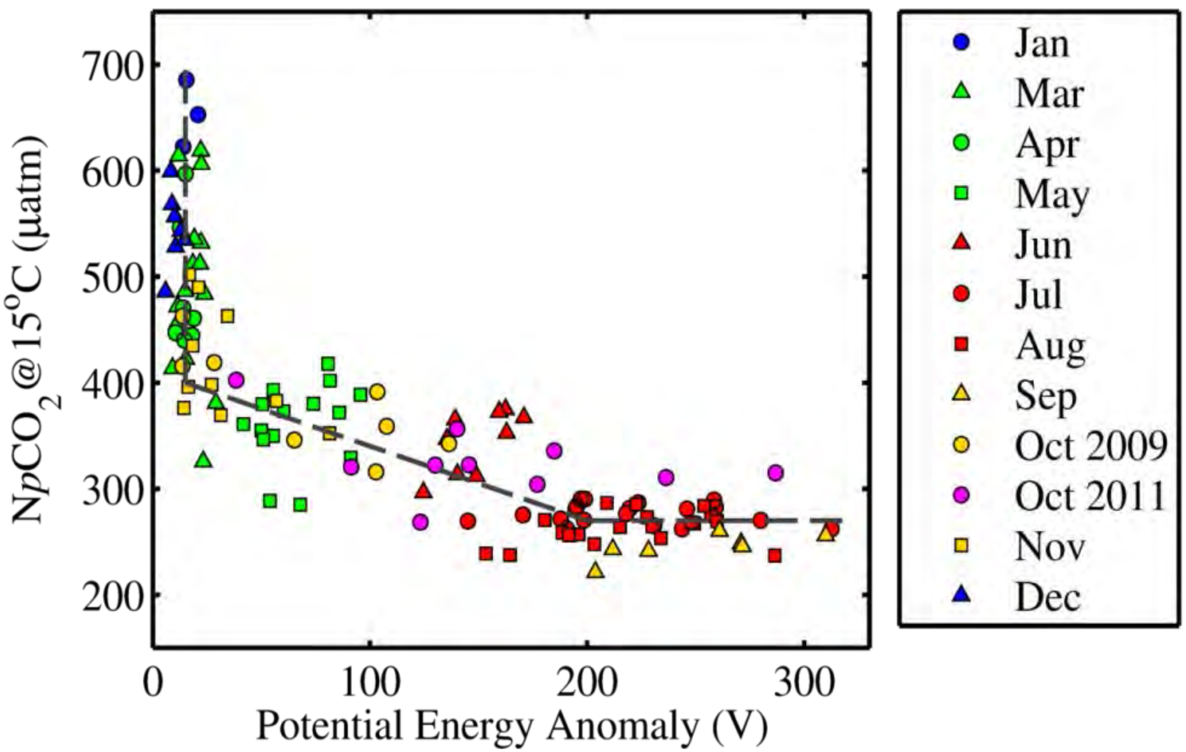

- Potential Energy Anomaly was used to indicate the degree of stratification in water column
- N*p*CO_2 was negatively correlated with stratification in the transition seasons

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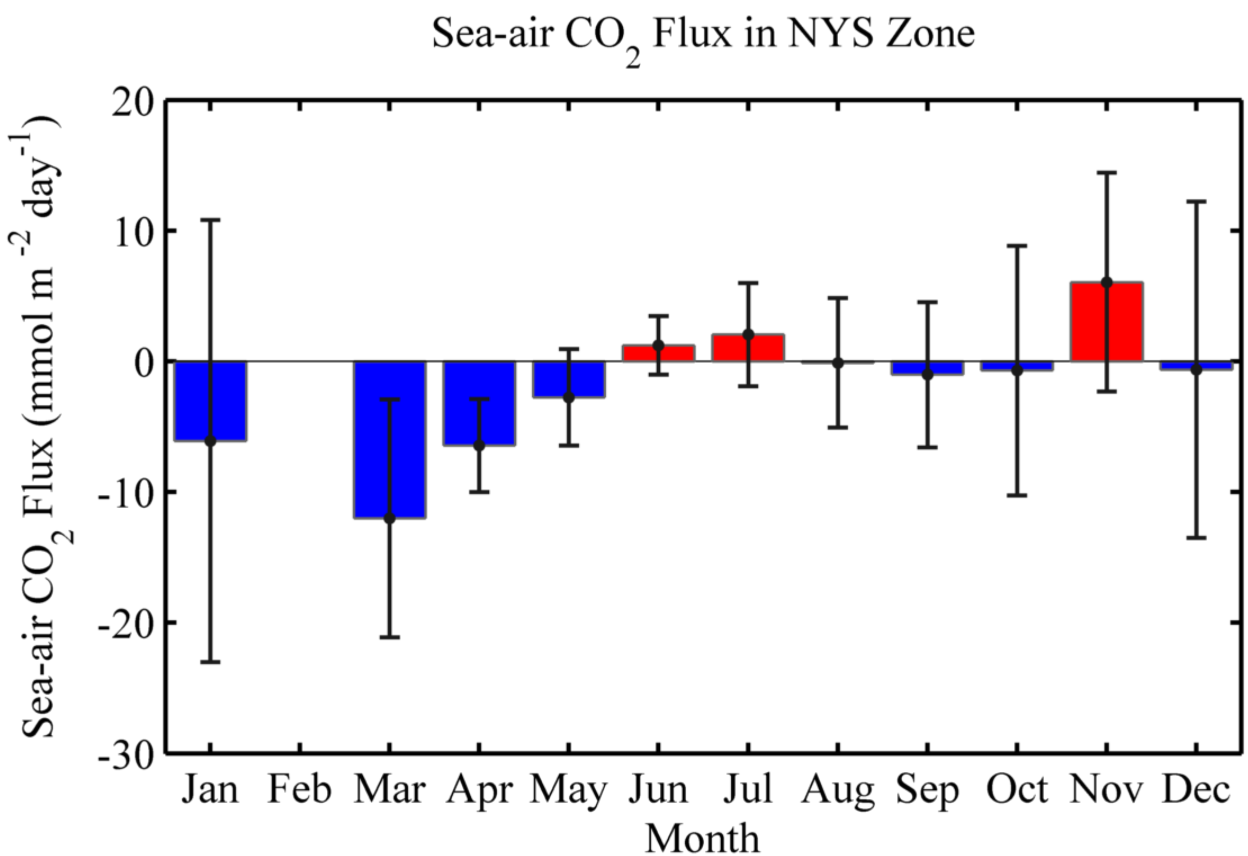
Sea-air CO_2 Fluxes



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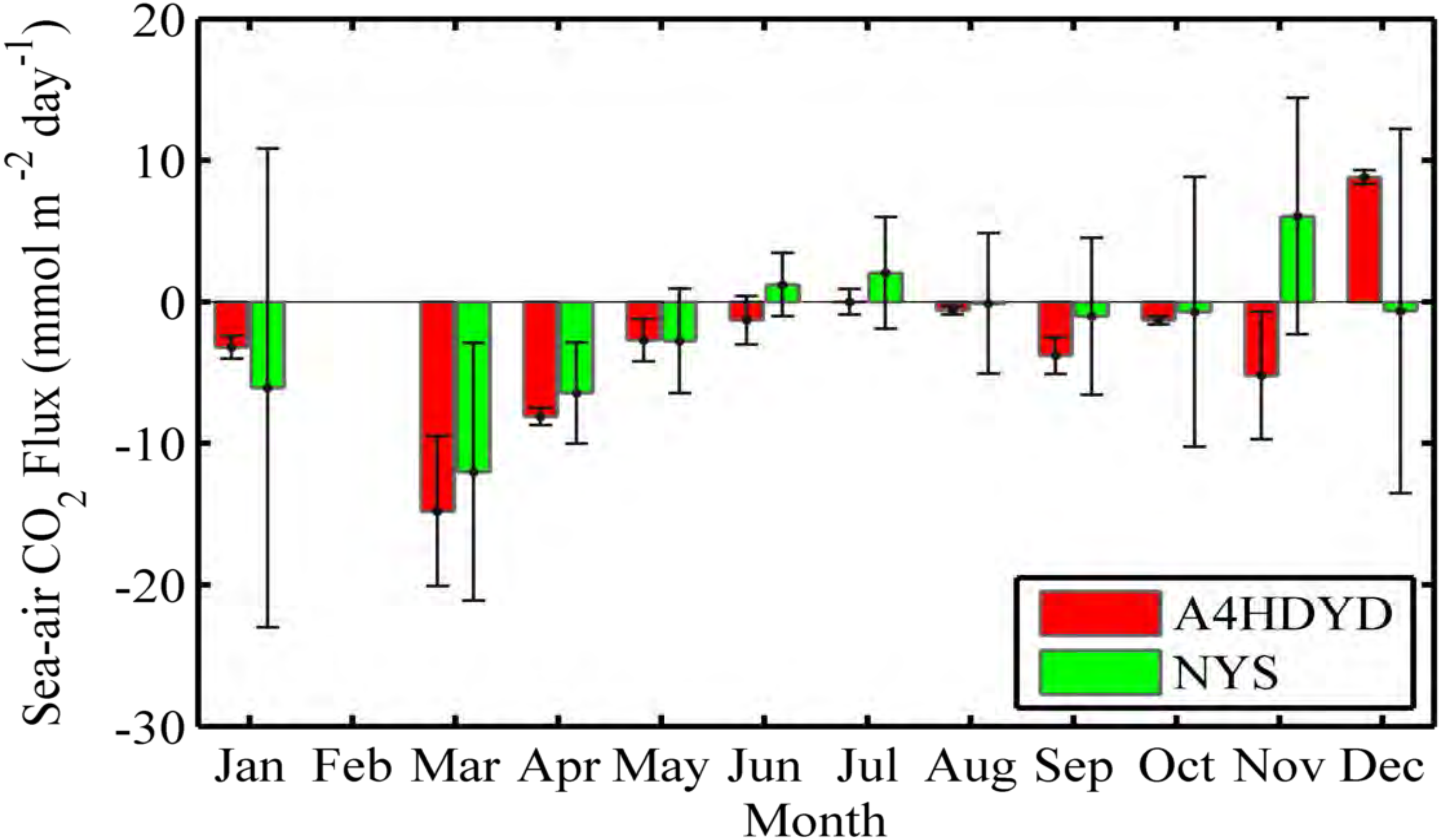
Comparing Sea-air CO_2 Fluxes

Month	Underway		A4HDYD station
	$p$$CO_2$water (μatm)	Flux_WK92 (mmol C/m^2/day)	Air-sea CO_2 flux （mmol C m^{-2} d^{-1}）
Jan	381.7	-6.08	
Feb			-3.2±0.8
Mar	301.6	-12.01	-14.8±5.3
Apr	326.9	-6.44	-8.1±0.6
May	346.3	-2.76	-2.7±1.5
Jun	397.9	1.23	-1.3±1.7
Jul	398.6	2.06	0.0±0.9
Aug	376.7	-0.11	-0.6±0.3
Sep	361.8	-1.02	-3.8±1.3
Oct	387.2	-0.70	-1.3±0.3
Nov	425.3	**6.07**	**-5.2±4.5**
Dec	401.3	**-0.64**	**8.8±0.5**
Total	-0.88±0.84 mol C m^{-2} yr^{-1}		-0.89±0.62mol C m^{-2} yr^{-1}

Comparing Sea-air CO_2 Fluxes



Summary(1)

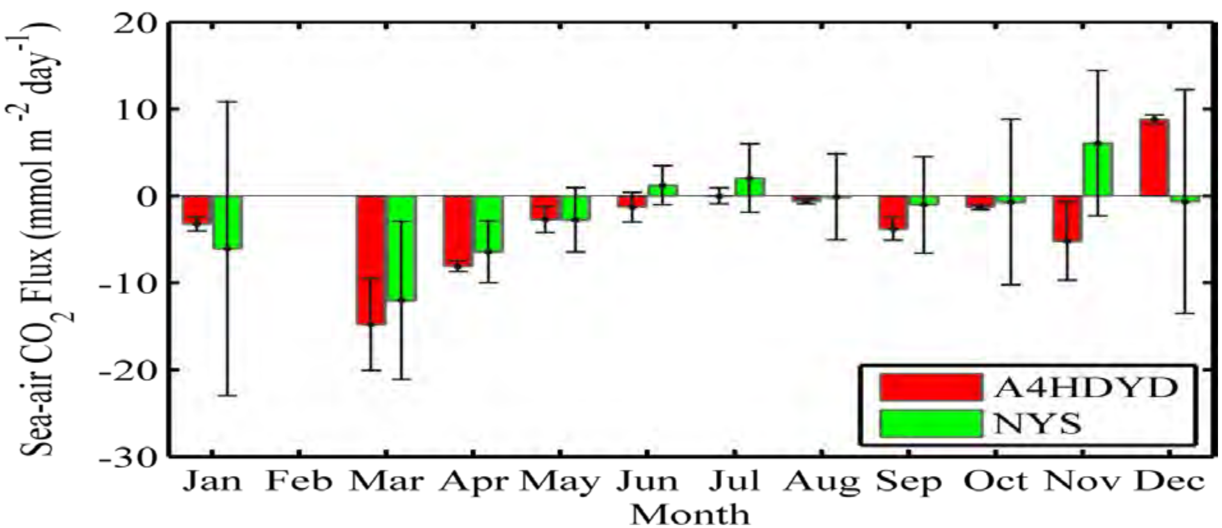
- It was obviously that our findings were different from Xue et al. (2012) with the conclusion that the study area acted as a net CO_2 source with respect to the atmosphere in spring. The biogeochemistry and ecosystems of the continental margins is complicate, leading to the monthly and annual variation of the seawater pCO_2.

	Summer (n=67)[a]	Fall (n=80)	Winter (n=70)	Spring (n=77)
SST	22.30±1.73	18.73±0.44	6.99±1.21	9.25±0.97
SSS	30.91±0.53	31.16±0.43	32.02±0.44	31.85±0.62
ΔpCO_2	93±41	11±17	−1±41	27±31
QuikSCAT winds	3.91±0.33	7.00±0.34	6.93±0.52	5.10±0.49
Air–sea CO_2 flux	3.38±0.48	1.39±0.38	0.24±0.43	1.88±0.31

[a] n is the total number of CTD stations for each cruise, where SST, SSS, and sea surface pCO_2 data were collected.

Summary(2)

- It would result in uncertainties in the flux calculation just based on data collected during one ‘‘snapshot’’ observation to represent a whole season.
- The results may have implications in carbon flux estimation in coastal regimes with dynamic variability. An integrated frame dealing with multiple temporal/spatial scales will improve our understanding to the coastal carbon fluxes and biogeochemistry.



Thank you for your attention!