2010 PICES Annual Meeting, October 25, 2010, Portland, Oregon

Coastal Ocean Carbon Cycling- Current Understanding and Challenges

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Take home messages

•Coastal ocean links the land and the open ocean, an important missing component in global climate change models, yet …

•Coastal ocean CO_2 fluxes estimations have converged during the past 5 years, which should not be away from a moderate sink at a global scale

•Challenges remains at regional scales in accounting CO_2 fluxes both temporally and spatially

•Mechanistic understanding is to be improved for better modeling the coastal carbon cycling and to improve our predictive capability under future climate change forcing.

Outline

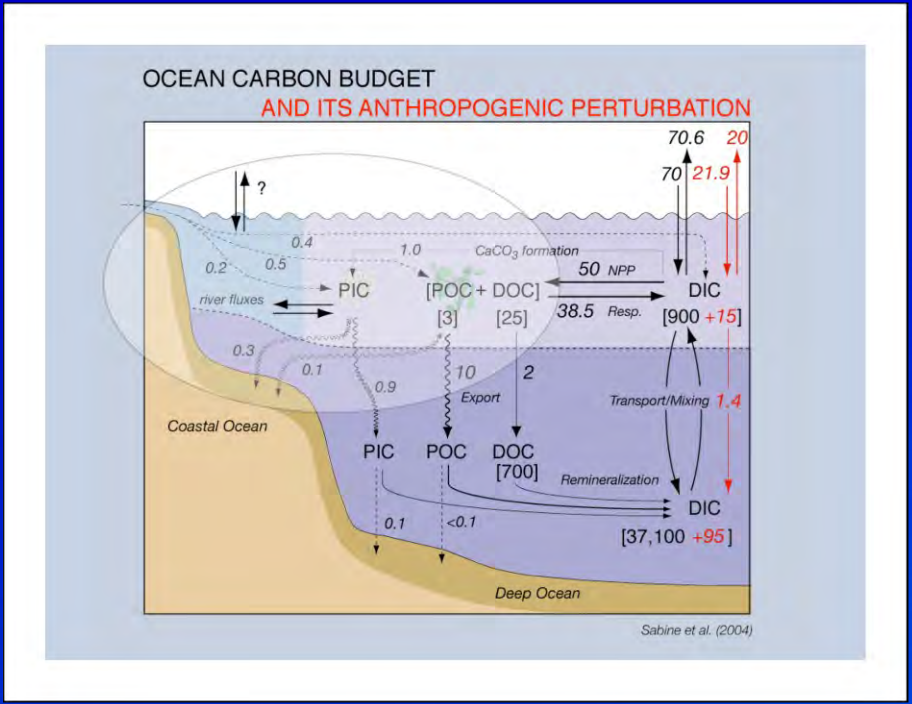
- Why coastal carbon?
- Coastal Carbon budget – an update
- Variability in time and space
- Major Challenges: river-margin-ocean carbon connection
- Outlook

Context

- Carbon cycling is out of natural balance. The human perturbation of the carbon cycle continues to grow strongly.
- The efficiency of the natural sinks has being declining over the last 60 years, a trend not fully captured by climate models.
- CO2 is a green house gas, which surely has a warming effect
- Uncertainties remain in accounting carbon sources and sinks
- Climate response to carbon is complex. Uncertainties are big because CO2 & other GHG are NOT the only forcing to climate change

Le Quéré et al. 2009, Nature-geoscience; Canadell et al. 2007, PNAS; Raupach et al. 2008, Biogeosciences

WHY COASTAL OCEAN & CARBON?



- **Unique physical-biogeochemical system**
- **Carbon is a unique element to examine direct or indirect changes of the system**

THE GLOBAL COASTAL OCEAN:

- **Interesting and important interdisciplinary marine system**
- **Natural laboratory for fundamental coupled physical-biogeochemical-sedimentation processes**

COASTAL OCEAN INTERACTIONS

- **Link together the land, the open sea, the atmosphere and the underlying sediments-boundary for open ocean and land systems**
- **Impact global processes disproportionately to relative volume**
- **Difficult to be included in the GCM**

Modified from Robinson & Brink, 2005

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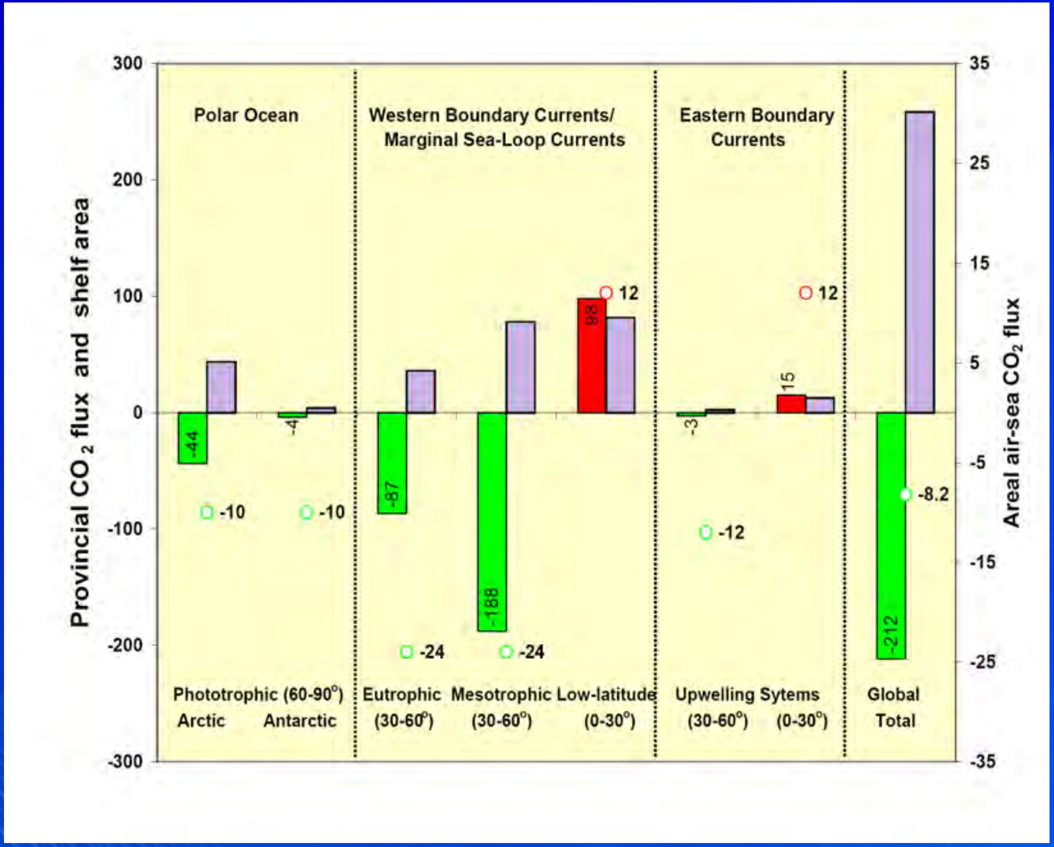
Province-based estimation of CO_2 fluxes



Cai, Dai, and Wang, 2006, GRL

0.221 Pg C/yr
0.76 molC/m²/yr
25.83*10⁶ km²

Open Ocean: ~2pg/yr (–0.35 molC/m²/yr, Takahashi et al. 2009)

361×10⁶ km²

Chen & Borges, 2009: 0.33-0.36 Pg C yr^{-1}

(–0.92 $molC/m^2/yr$, $30*10^6 km^2$)

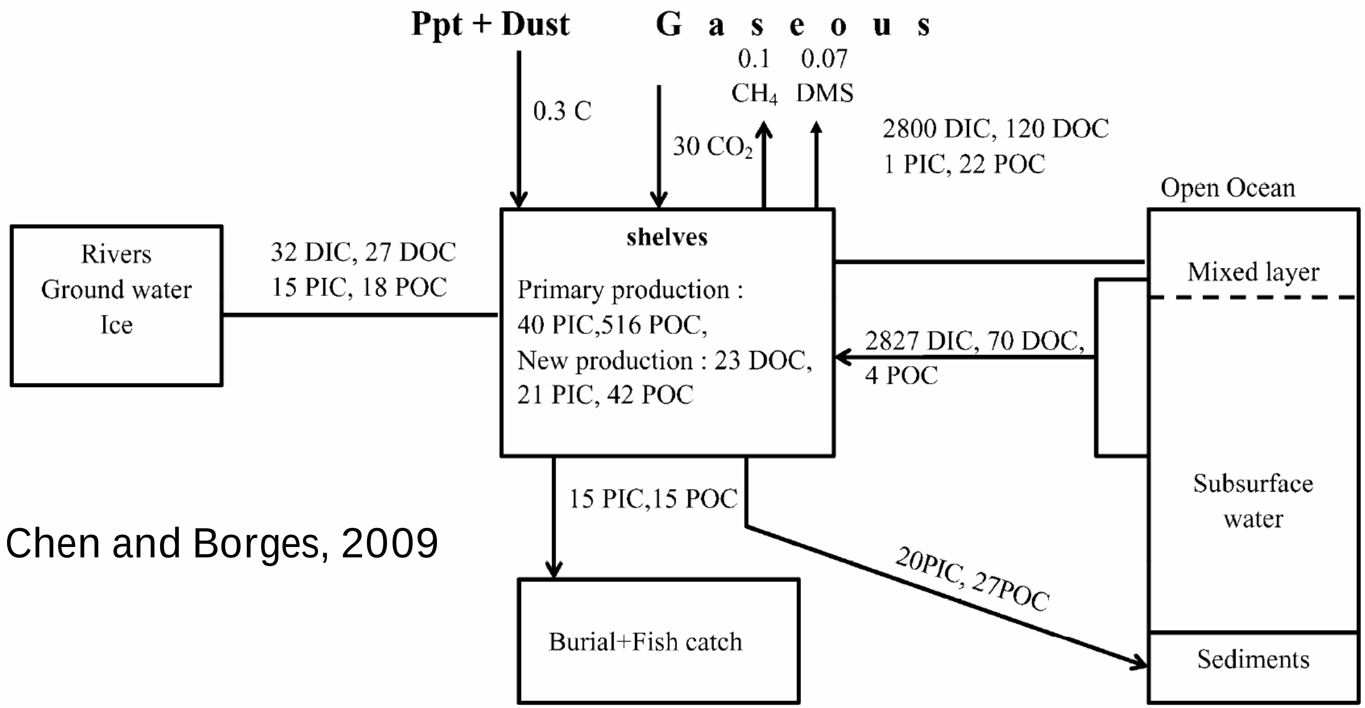


Fig. 3

Chen & Borges, 2009, DSR

Laruelle et al. 2010:
–0.211 ± 0.364 pg C/yr

(–0.71 ± 1.23 molC/m²/yr)

24.7*10⁶ km²

Table 2. Air-Water CO_2 Fluxes per Surface Area and Scaled Globally for Different Types of Continental Shelves Along Three Climatic Zones[a]

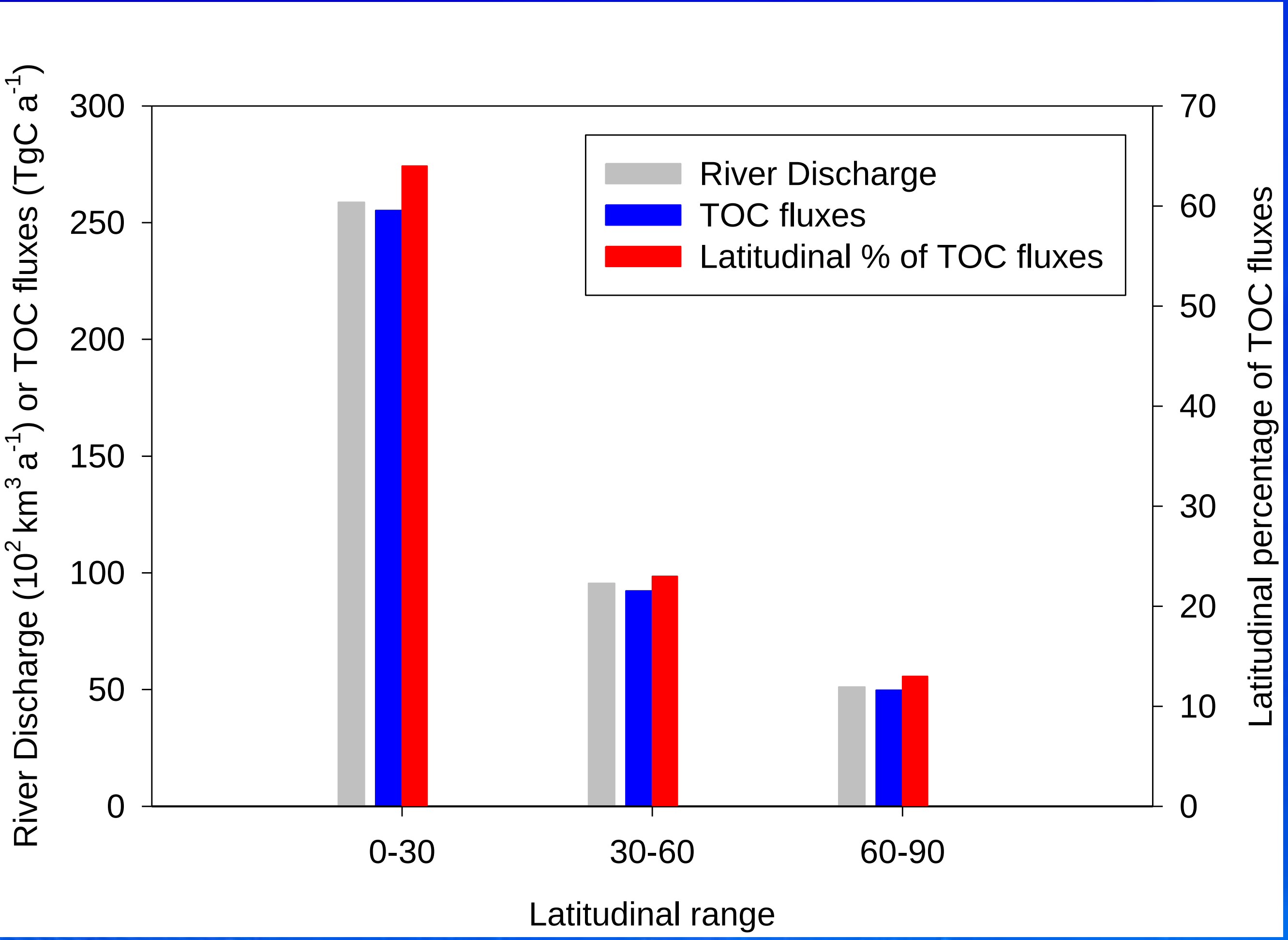
	Surface Area (10^6 km^2)	Air-Water CO_2 Flux (molC m^{-2} yr^{-1})	Air-Water CO_2 Flux (PgC yr^{-1})
Polar (>60°)			
Enclosed	0.189	−0.8 ± 1.1	−0.002 ± 0.003
Open Shelf	5.477	−3.3 ± 1.7	−0.216 ± 0.111
Upwelling Pacific	0.086	3.2 ± 2.4	0.003 ± 0.002
Sub-total	5.752	−3.1 ± 1.7	−0.214 ± 0.116
Temperate (30°–60°)			
Enclosed	1.410	−0.8 ± 1.1	−0.014 ± 0.019
Open Shelf	7.170	−1.0 ± 1.0	−0.086 ± 0.087
Upwelling Pacific	0.293	3.2 ± 2.4	0.011 ± 0.008
Upwelling Atlantic	0.086	−1.6 ± 1.0	−0.002 ± 0.001
Upwelling Indian	0.123	0.9 ± 1.2[b]	0.001 ± 0.002
Sub-total	9.082	−0.8 ± 1.1	−0.090 ± 0.117
Tropical (0–30°)			
Enclosed	0.231	−0.8 ± 1.1	−0.002 ± 0.003
Open Shelf	7.909	0.9 ± 1.0	0.083 ± 0.097
Upwelling Pacific	0.515	3.2 ± 2.4	0.020 ± 0.015
Upwelling Atlantic	0.715	−1.6 ± 1.0	−0.014 ± 0.009
Upwelling Indian	0.520	0.9 ± 1.2[b]	0.006 ± 0.008
Sub-total	9.890	0.8 ± 1.1	0.093 ± 0.131
Total	24.724	−0.7 ± 1.2	−0.211 ± 0.364

Laruelle et al., Geophys. Res. Lett., 37, L15607, doi:10.1029/2010GL043691.

Remaining Questions?

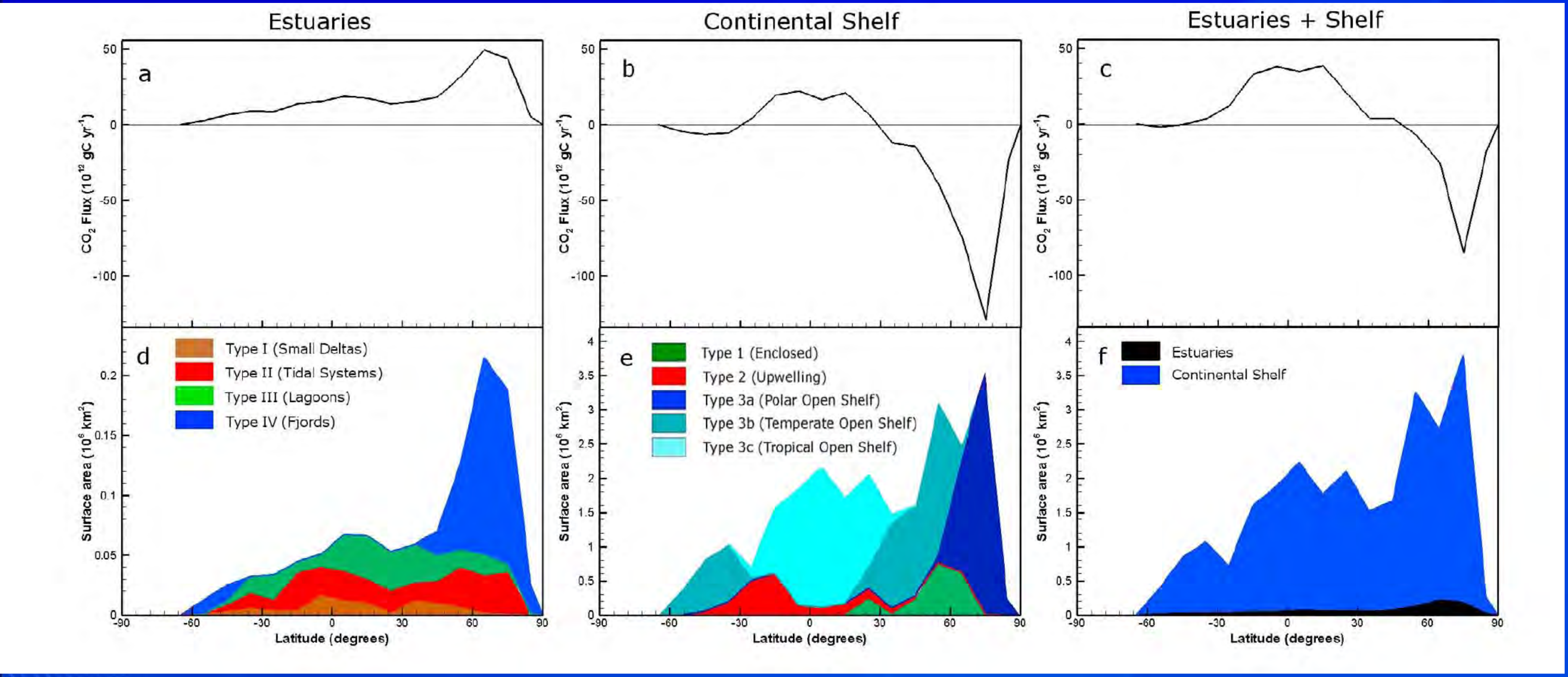
- Latitudinal trend? & upscaling?
- Uncertainties
- Regional variability in space & time
-

TOC influxes & latitudinal pattern? (Cai & Dai, 2004)



Dai et al., unpublished

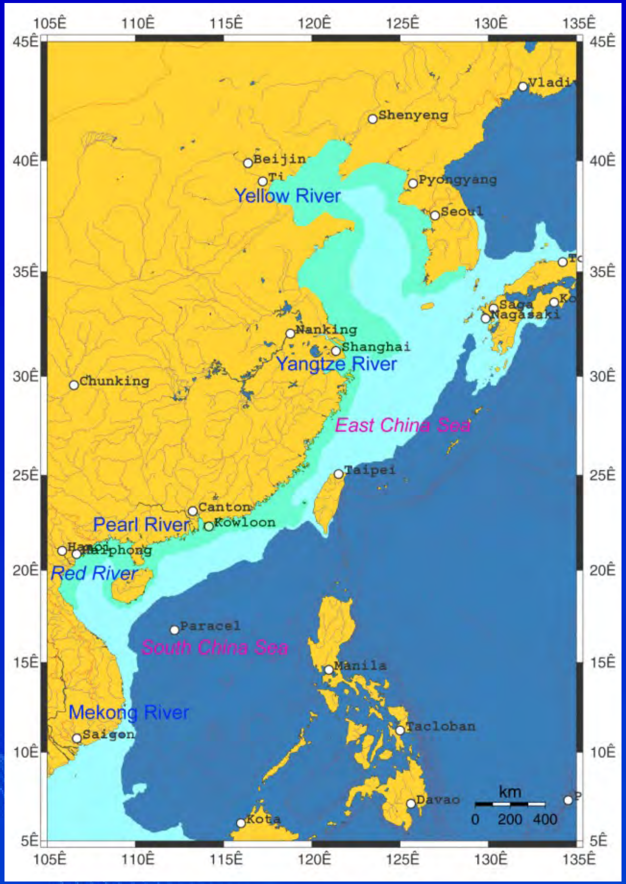
Latitudinal distribution ?

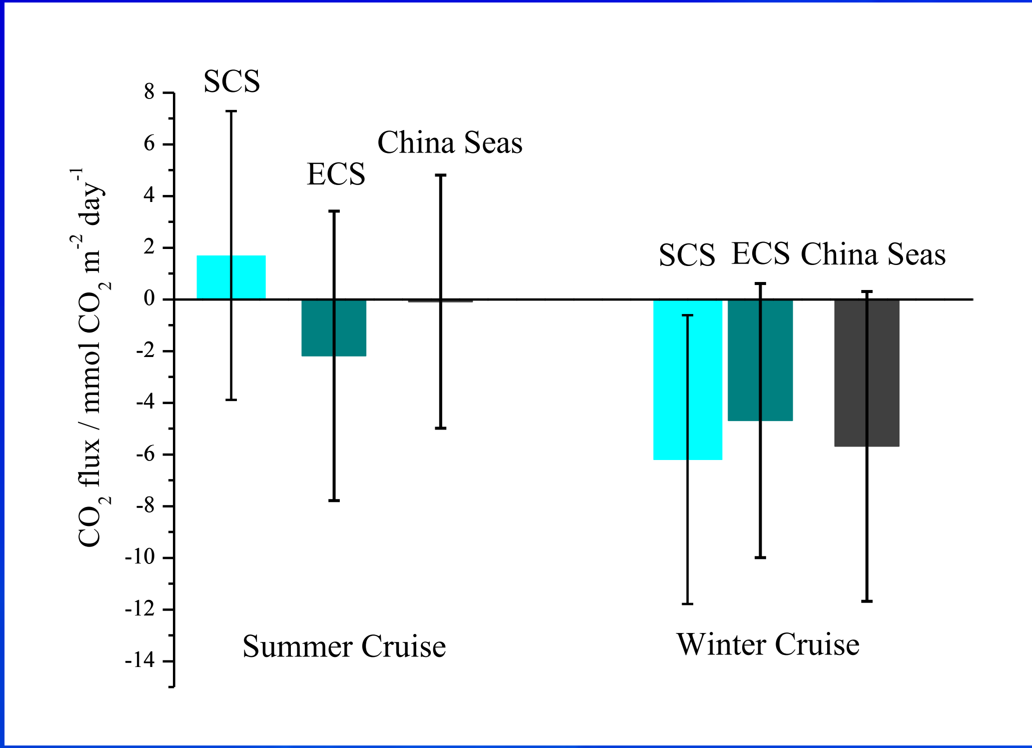


Latitudinal distribution of the air-water CO_2 fluxes (in 10^{12} g C yr^{-1}) and surface areas (in 10^6 km^2) in estuaries and continental shelf seas and the global coastal ocean. A positive value represents a source of CO_2 to the atmosphere.

Laruelle et al., Geophys. Res. Lett., 37, L15607, doi:10.1029/2010GL043691.

Latitudinal distribution？





- “Normal” pattern in summer 2009

No latitudinal trend in winter 2009

Outline

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- Variability in time and space
- Major Challenges: river-margin-ocean carbon connection
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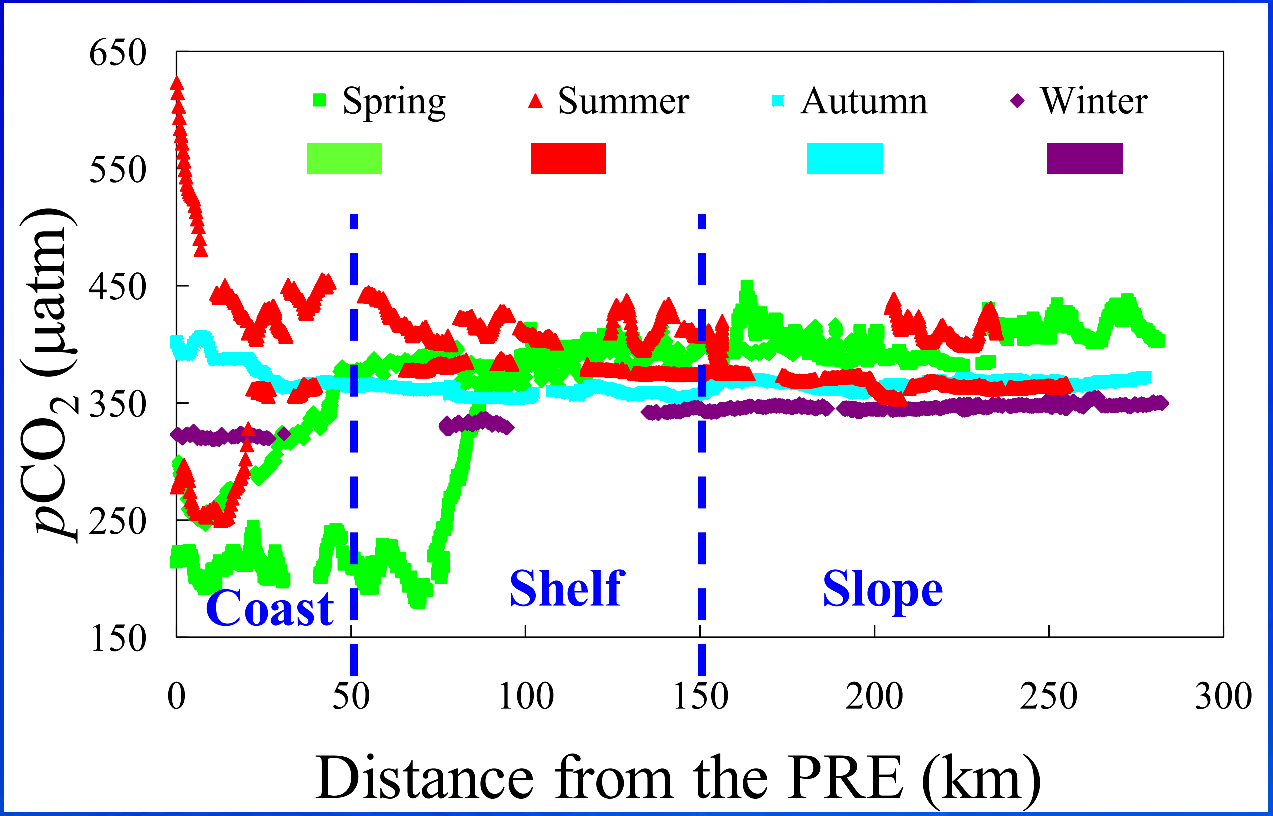
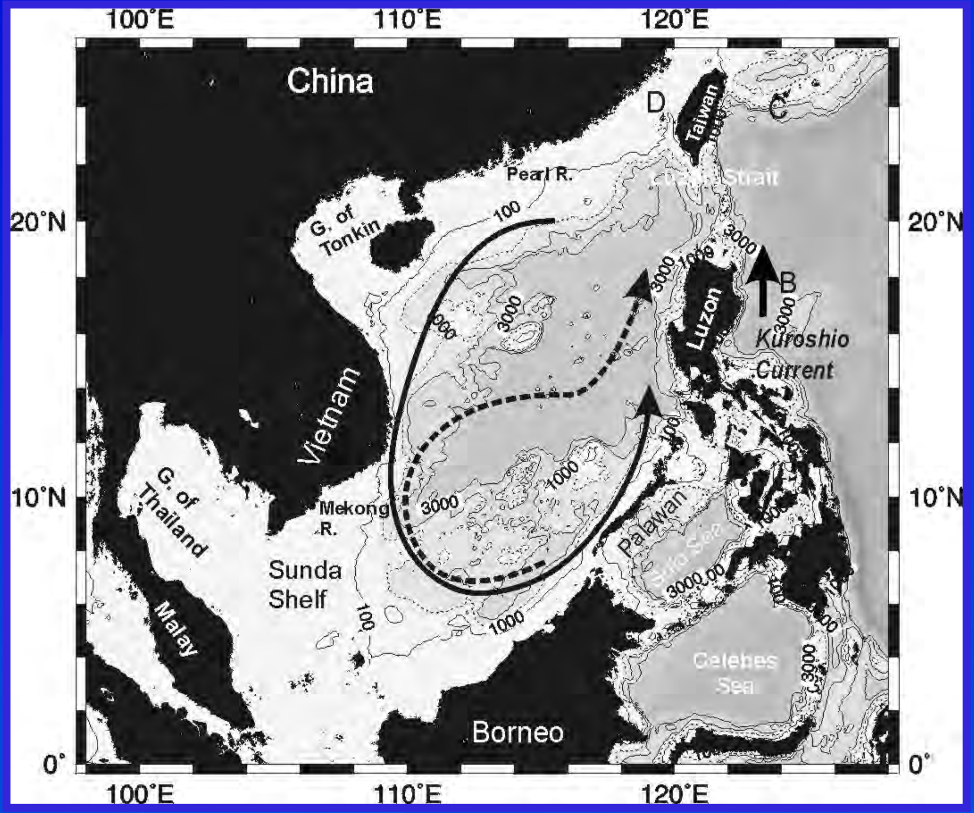
Coastal carbon variability in time and space – fluxes and controls



Zhai et al., Mar Chem 2005; Dai et al., Cont Shelf Res 2008; Guo et al. 2009, JGR

South China Sea (SCS)

- The world's largest subtropical-tropic marginal sea (3.6×10^6 km^2)
- Max depth: >5000 m, average=1350 m
- Basin oligotrophic
  - P: < 10 nM
  - N: ~10 nM
- Large rivers (Pearl, Mekong, Red Rivers)



monsoons, typhoons, strong internal waves and ENSO

Variability:
time scale/spatial domains

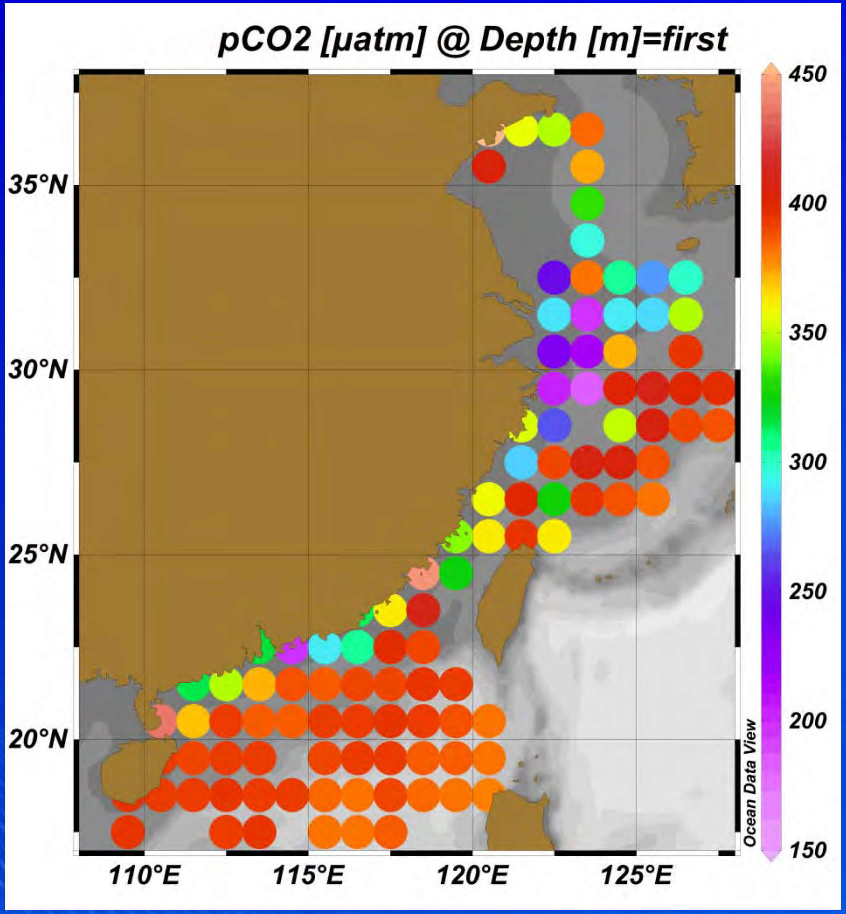
Spatial domains

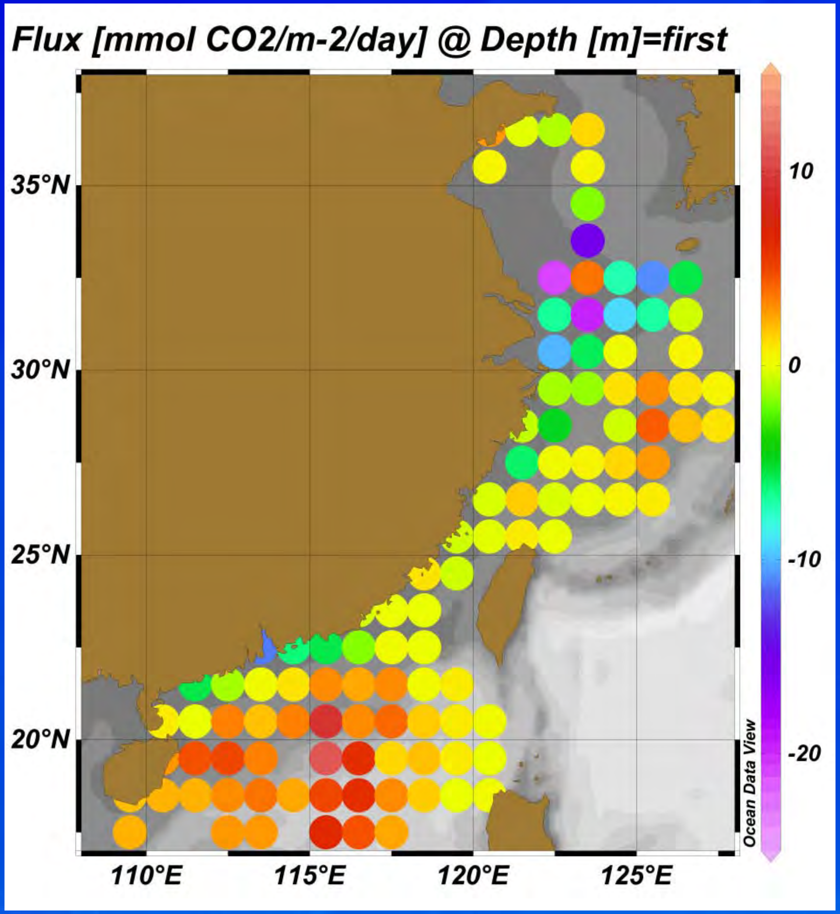
- Upwelling
- Plumes/Bloom
- Eddies
- Coral reef

Time scale

- Diurnal (!?)
- Seasonal (!)
- Inter-annual (?)
- Decadal (?)
- Longer time scale

pCO$_2$ and fluxes in China Seas in Summer 2009





pCO$_2$ (150 -450 μatm) fluxes

Variability:
importance of time scale/spatial domains

Spatial domains

- Upwelling
- Plumes/Bloom
- Eddies
- Coral reef

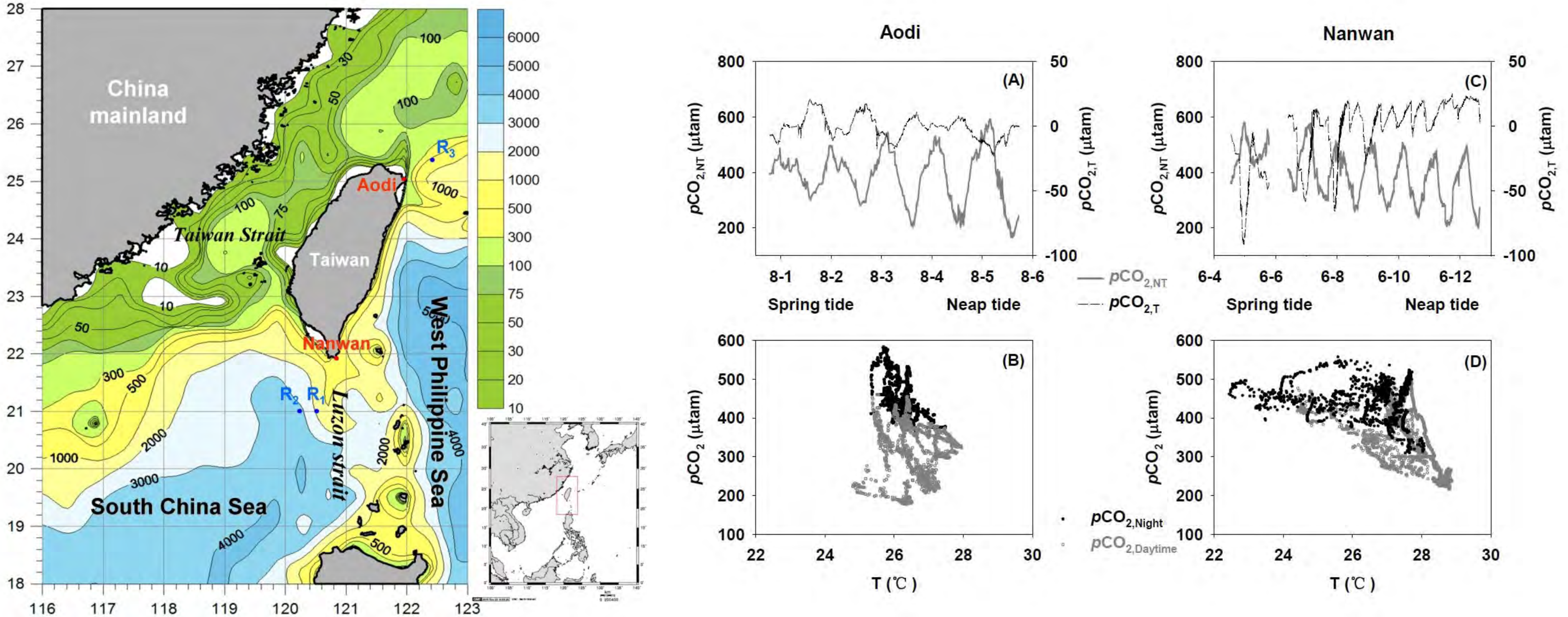
Time scale

- Diurnal (!?)
- Seasonal (!)
- Inter-annual (?)
- Decadal (?)
- Longer time scale

Diurnal Variations: Significant uncertainties may be derived solely by ΔpCO_2 potentially caused at different sampling time (Dai et al., 2009, L&O)

	Area km^2	pCO_2 diel variation	Flux variation mmol C m^{-2} d^{-1}	Flux mmol C m^{-2} d^{-1}
Open areas of coastal ocean	3.36×10^8	~10-16 µatm	~±0.48-0.77	-3.0 (Chen & Borges 2009)
Shelf (ie TS)	2.60×10^7	40 µatm	±1.76	-1.9 (Cai et al., 2006)
Coral reefs	2.8×10^5	200~600 µatm	±9.61-28.82	4.14 (Borges et al., 2005)

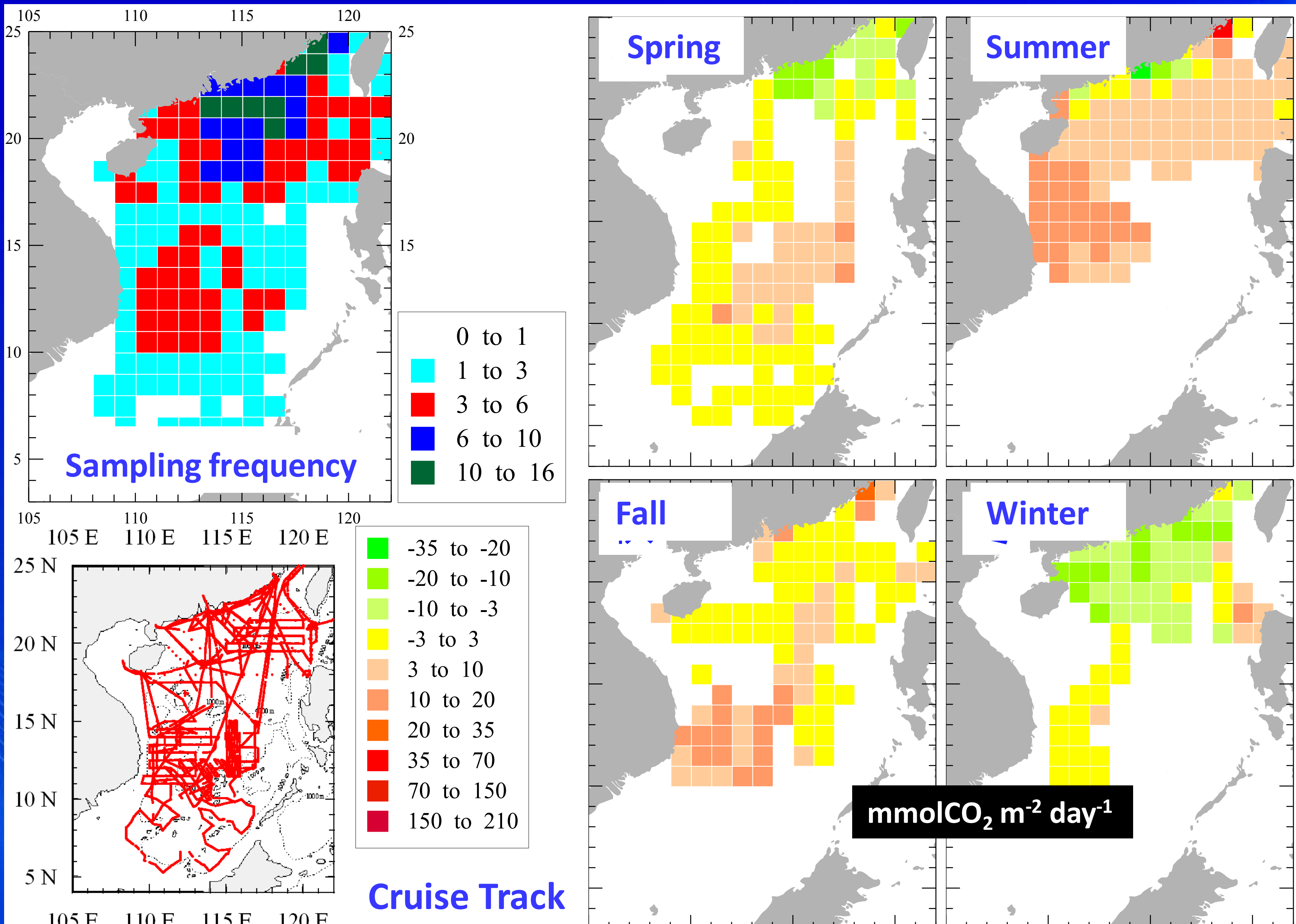
Intra-Seasonal Changes



pCO_2 normalized to the observed mean temperature (*p*$CO_{2,NT}$, see equation 4 in the text) and *p*CO_2 offset caused by temperature variations (*p*$CO_{2,T}$, see equation 5 in the text). B&D): *p*CO_2 observed in daytime (*p*$CO_{2,Daytime}$) and at night (*p*$CO_{2,Night}$) with temperature. The offshore subsurface water at Nanwan was characterized by low temperature and high *p*CO_2 in penal D.

Jiang et al., submitted to L&O

Air-Sea CO_2 fluxes in South China Sea (Since 2000)



Seasonality in SCS

- Spring: equilibrium/weak source/weak sink
- Summer: weak source/source (compounded by river plumes)
- Fall: equilibrium/weak source/weak sink
- Winter: sink
- Annually: equilibrium/weak source/weak sink

  →Large uncertainty in winter and near shore and wind speed

Summary

- Time Scale: time scale matters in the constraint of source and sink terms
  - Better knowledge in the seasonality
  - Intra-seasonal observations lacking
  - Diurnal variation critical for sampling strategy
  - Inter-annual to be constrained
- Spatial: heterogeneous in space-key domain must be considered for regional extrapolation
  - Nearshore still challenging
  - Plume-upwelling with large variations
  - Meso-scale eddies difficult
  - Internal waves unknown

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- Why coastal carbon?
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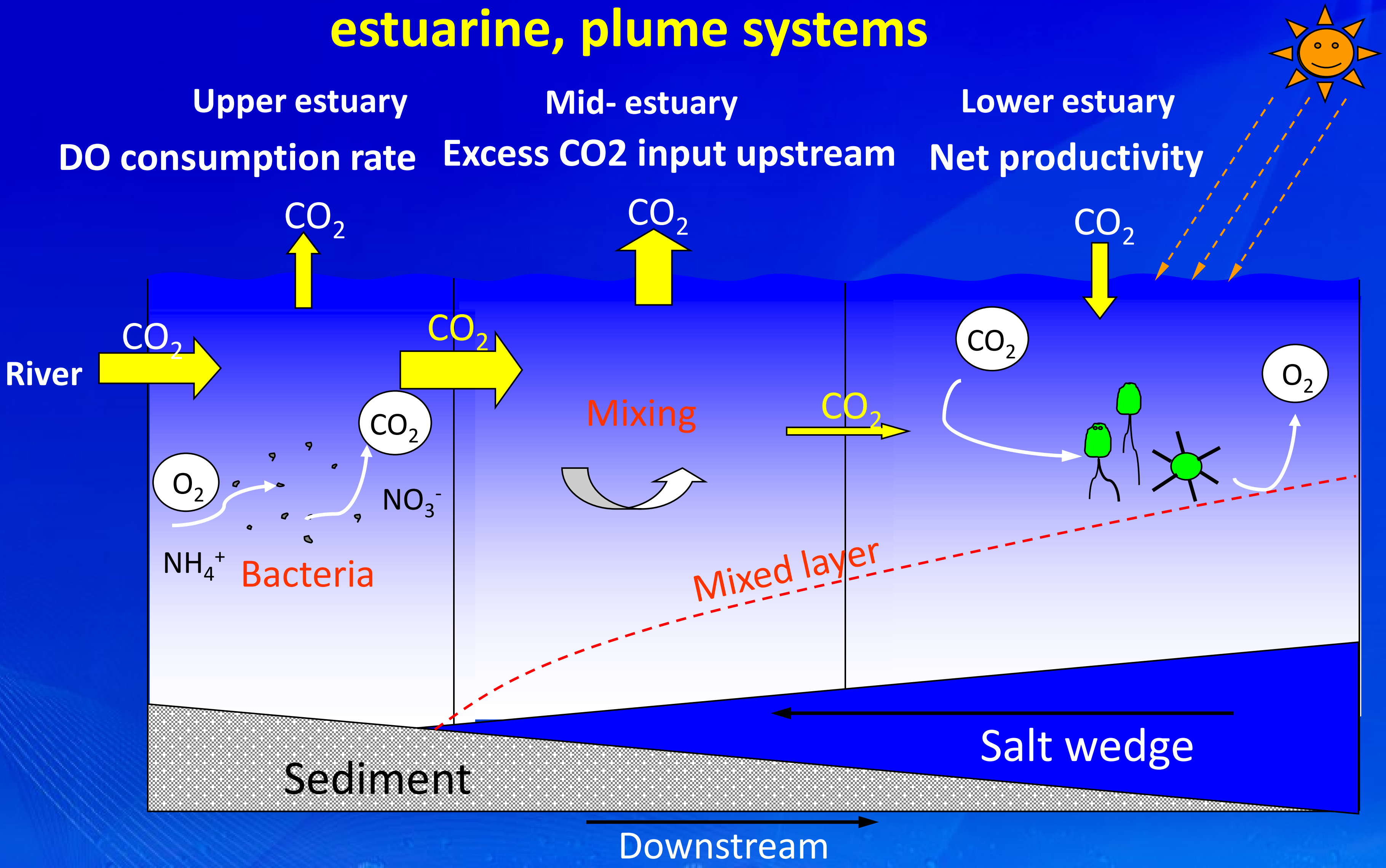
- Major Challenges: river-margin-ocean carbon connection
  - Fate of riverine carbon and metabolism of the coastal ocean
  - Carbon export from the marginal sea
- Outlook

Conceptual model of CO_2 fluxes and controls in estuarine, plume systems

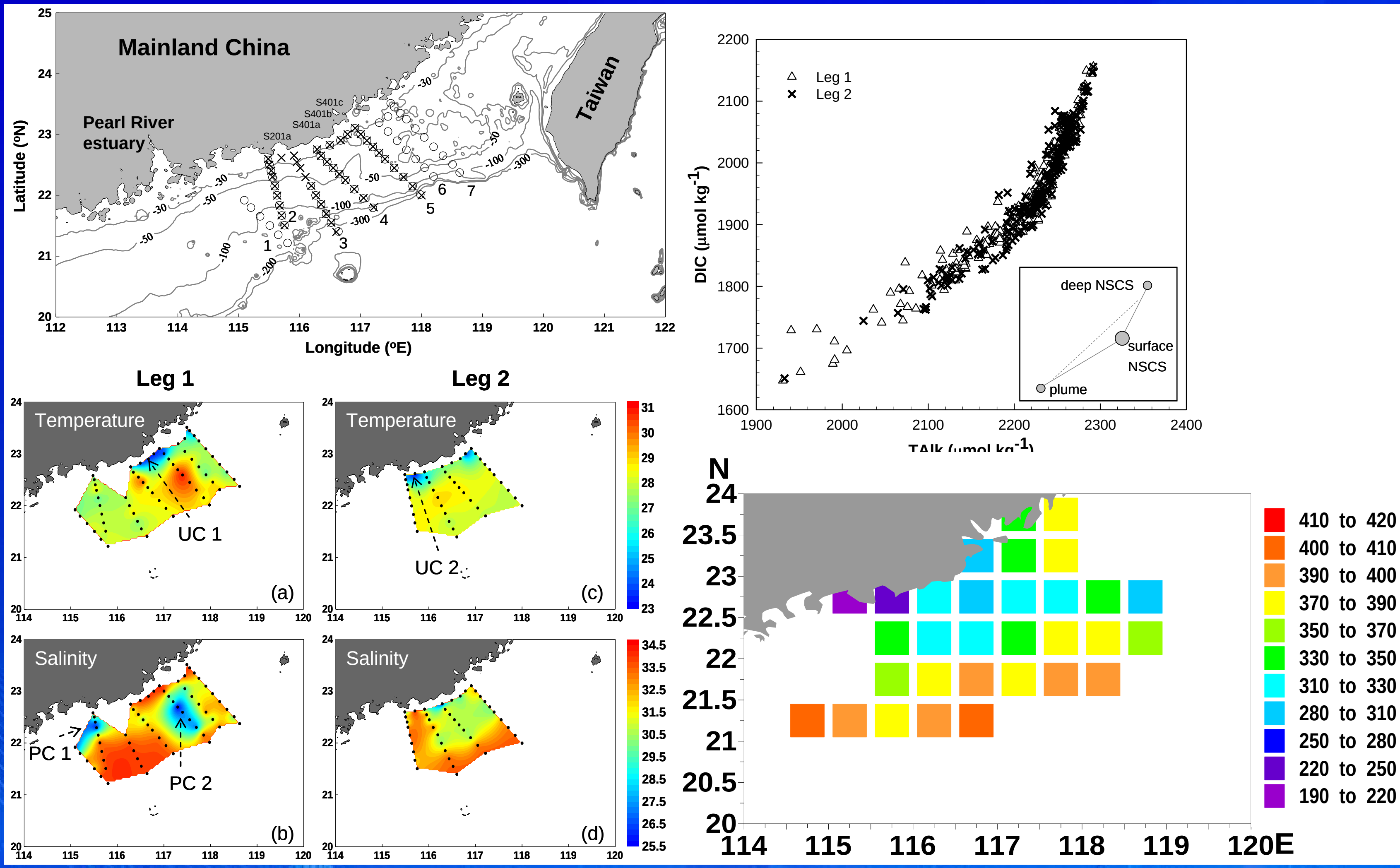


Guo et al., 2009, JGR-Biogeosciences

- **Known:**
  - Inner estuaries are generally degassing CO2
  - Lower estuaries uptake CO2
  - Typically heterotrophic in lower estuary/plume

- **Unknown:**
  - Impact of riverine inputs of DIC/TA, OC on the shelf air-sea CO2 exchange (quantitatively) and ecosystem metabolism
  - Plume variability and its impact on the CO2 sinks on the shelf
  - Plume & upwelling interaction and their modulation on CO2

3 end-member mixing in the NSCS shelf

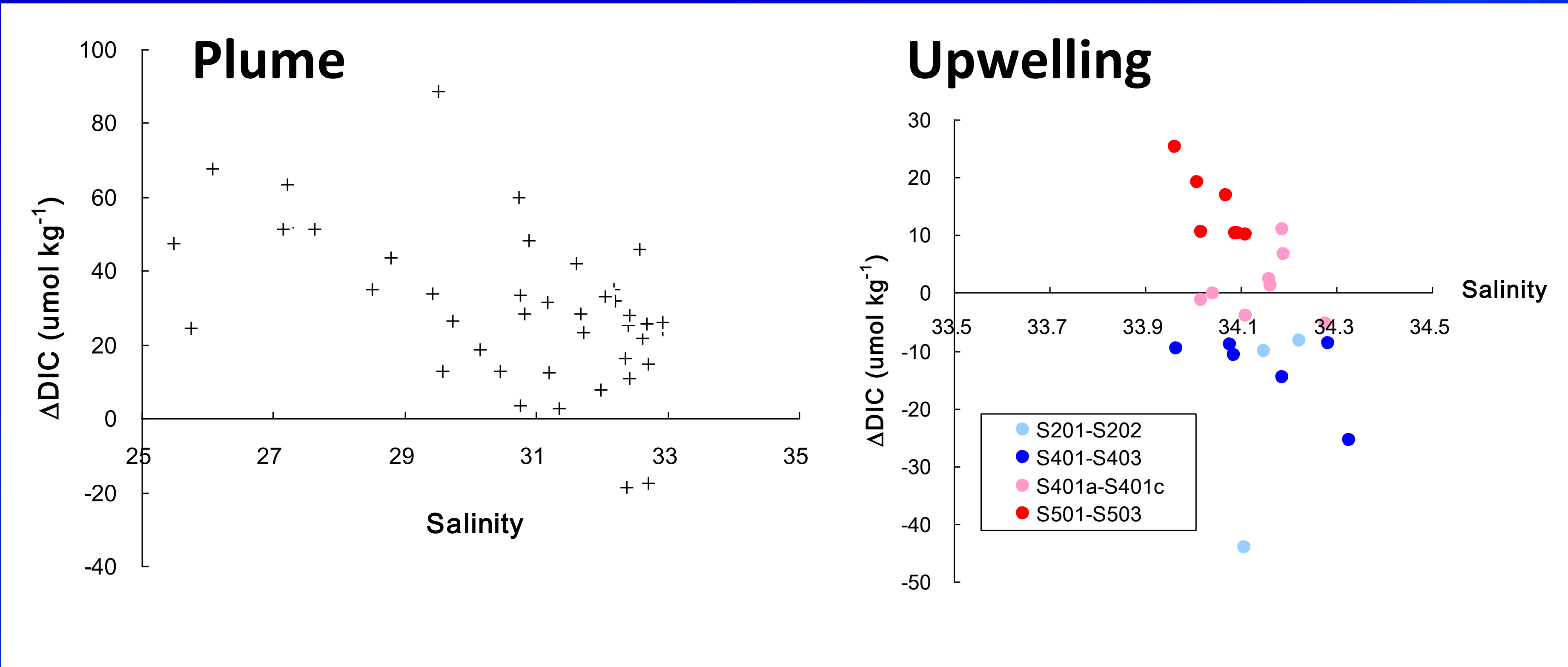


Based on SCOPE cruise in summer 2008

Major Features

- A strong plume followed by the flooding upstream in the Pearl River Estuary
- Upwelling near the coast
- Carbon and nutrient dynamics affected by both plumes and upwelling via physical and biogeochemical interactions

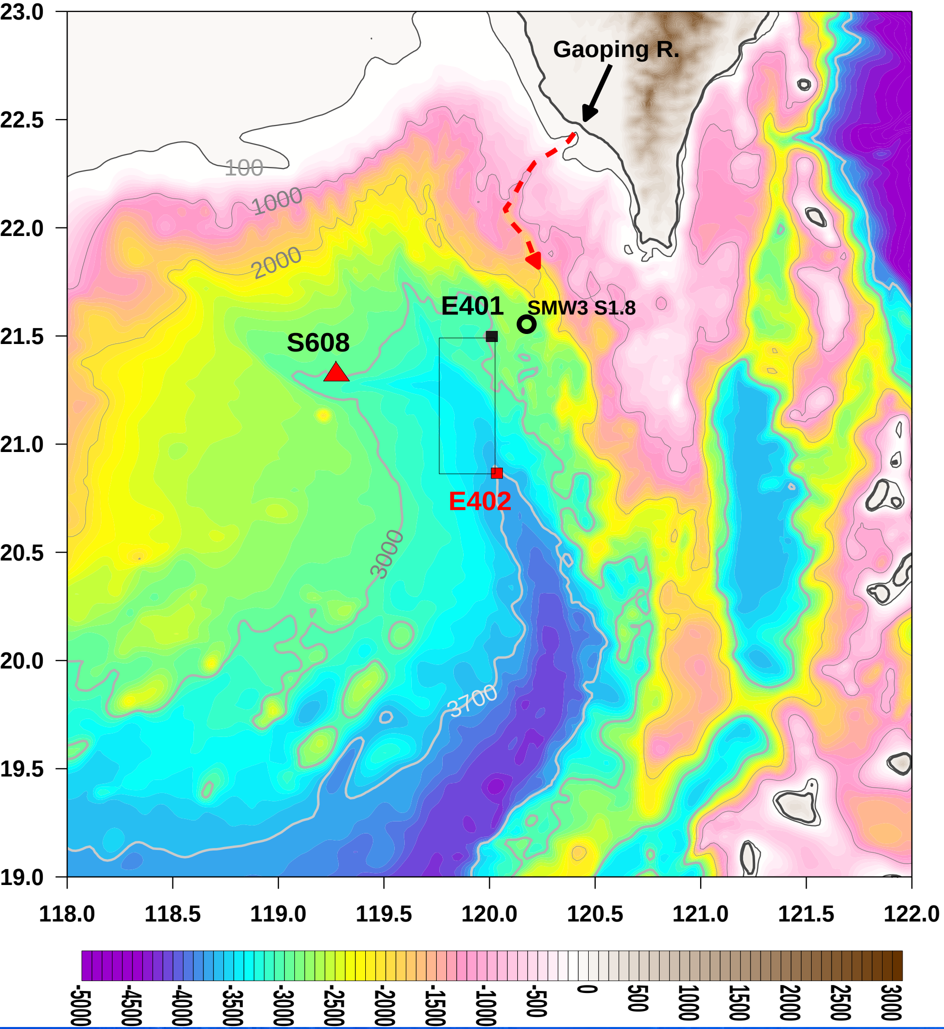
Contrasting NCP in plumes and upwelling zones

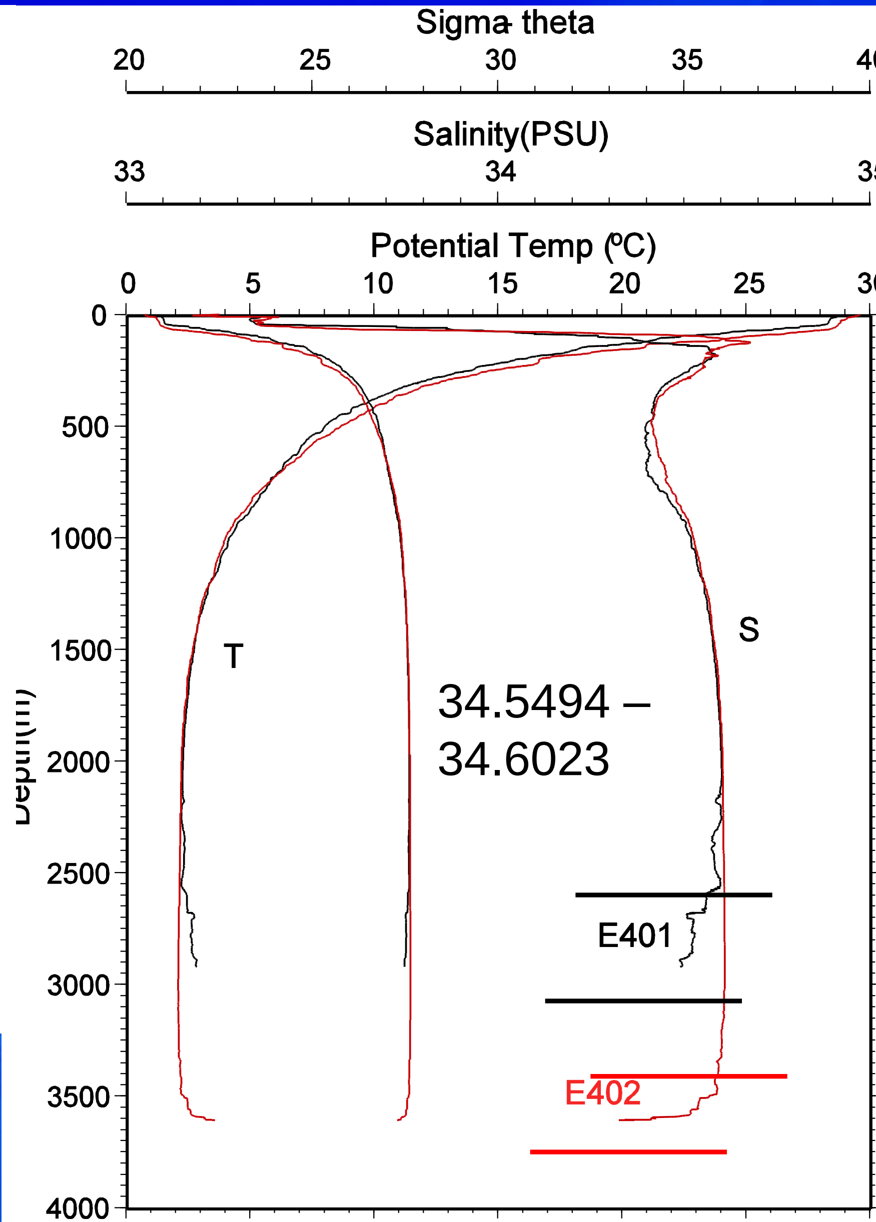


- average ΔDIC = 30 umol kg^{-1}
- NCP ~ 33 mmol C m^{-2} d^{-1}

- average ΔDIC ≈ 0 umol kg^{-1}
- nearshore, DIC release to uptake gradually

Direct injection of carbon and fresh water into the deep ocean induced by Typhoon Morakot, summer 2009





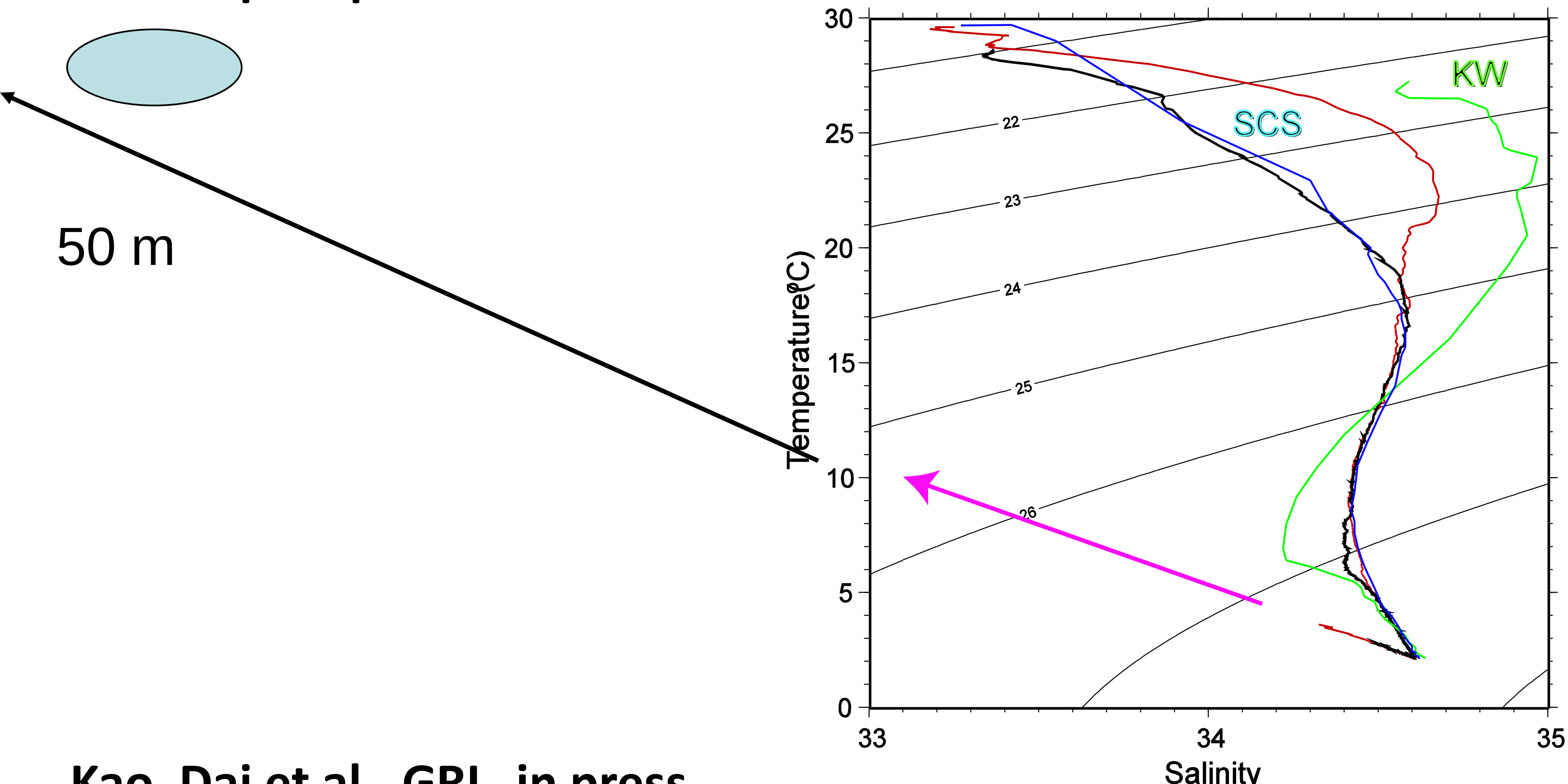
Kao, Dai et al., GRL, in press

turbid water mass was 600 km^3

~ 10 % precipitation

Carbon injection?

Under increasing Typhoon intensity?



Kao, Dai et al., GRL, in press

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- Coastal Carbon budget – an update
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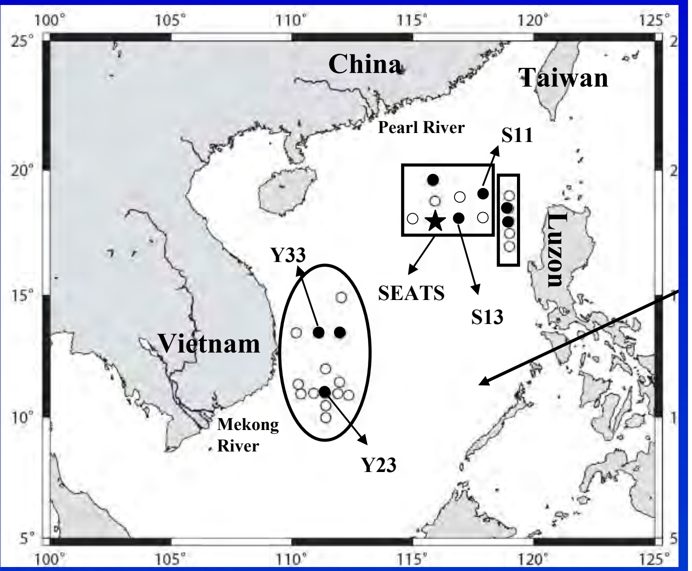
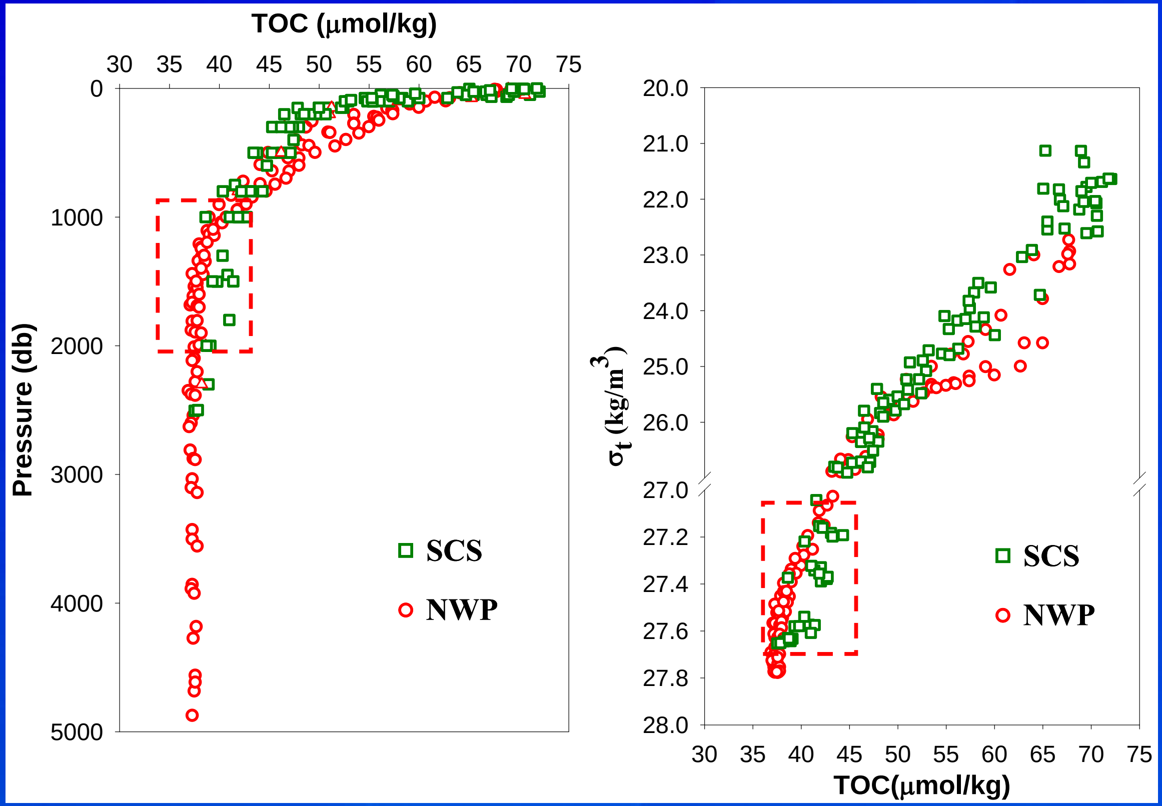
- **Major Challenges: river-margin-ocean carbon connection**
  - Fate of riverine carbon and metabolism of the coastal ocean
  - **Carbon export from the marginal sea**
- Outlook

Excess TOC in the intermediate water of the SCS and its export





- Gradient in DOC below 1000 m (contrast to NP)
- Deep DOC: 39.2±0.5 mmol/kg， ~ 1000 m DOC at NP (38.7±0.7 mmol/kg)
- Excess TOC 3.2±1.1 mmol/kg

Dai et al., 2009, G3

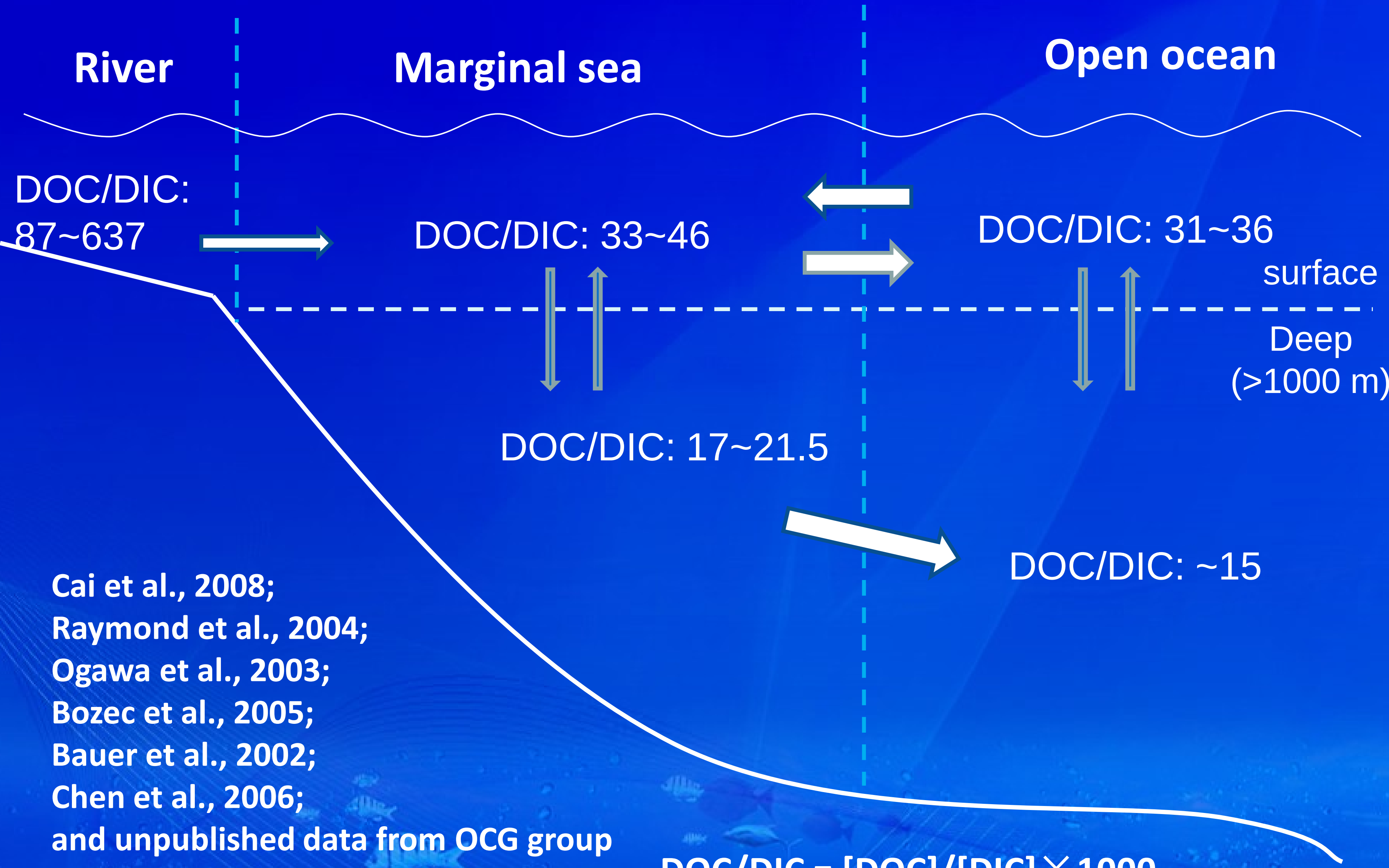
Excess TOC export

- SCS intermediate water outflow (2.5±1.5 Sv) acted as a source of TOC, transporting 3.1±2.1 Tg organic carbon to the North Pacific interior annually. (river influx~2 Tg/y)

- According to short water residence time of SCS basin, the exported organic carbon is likely from the recently-fixed organic carbon within the marginal sea

Dai et al., 2009, G3

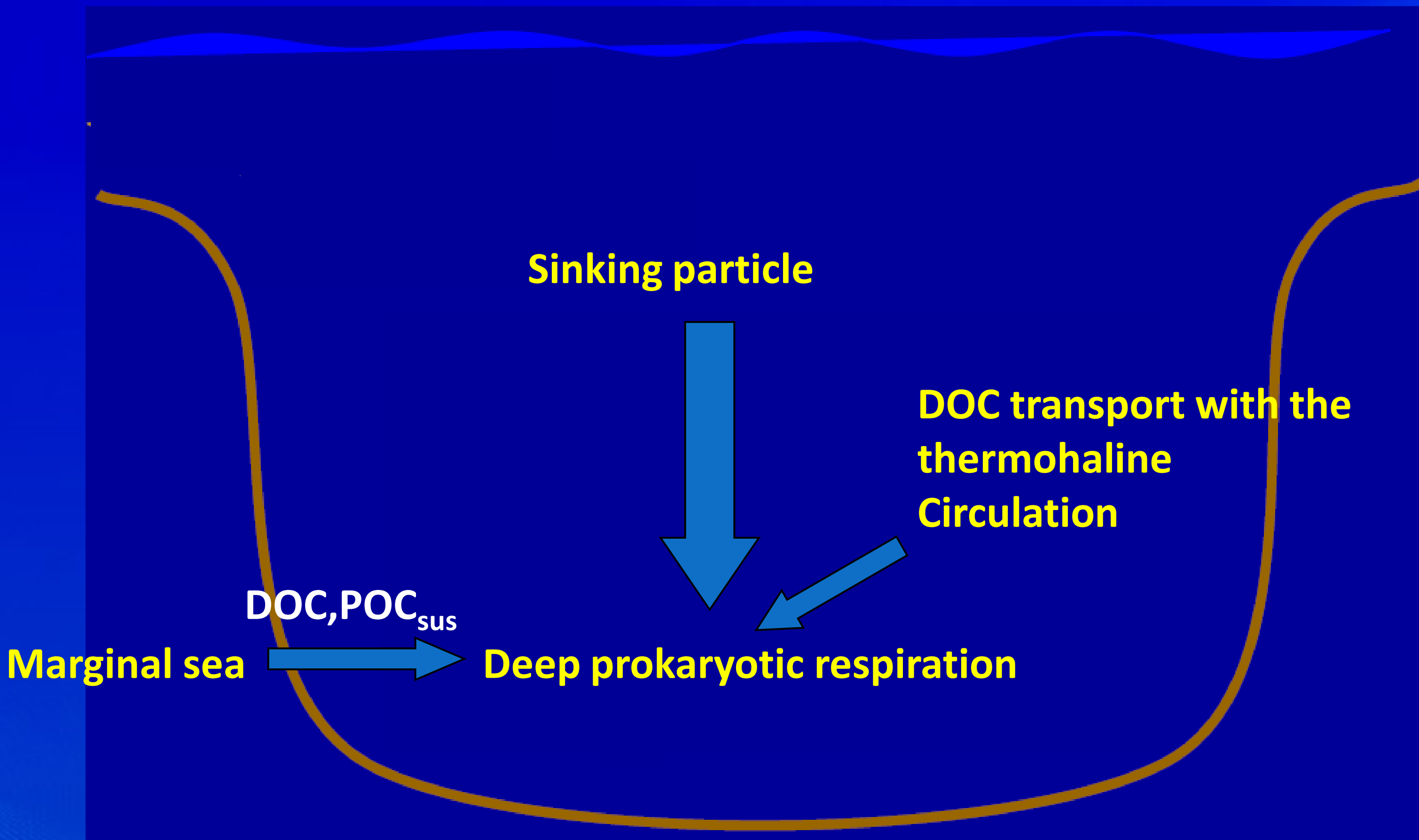
Global river-marginal seas-ocean



Cai et al., 2008;
Raymond et al., 2004;
Ogawa et al., 2003;
Bozec et al., 2005;
Bauer et al., 2002;
Chen et al., 2006;
and unpublished data from OCG group

DOC/DIC = [DOC]/[DIC] × 1000

Dark ocean fertilization



Microbial life in the deep ocean is likely dependent on the laterally advected organic carbon from the marginal seas.

Baltar et al., 2009

Summary

- DOC: dissolved organic carbon
  - 700 pg ~ atmospheric CO2 pool
  - Essential food source to microbial
- Higher production in marginal sea: **export may serve as a CO2 pump**
- Fresh and "good" food source: **export may sustain and even determine (to some extend) the microbial activities in the ocean interior**.
- **Unknown:**
  - fate of this excess TOC and its transformation processes during transportation.
  - How significant is this exported TOC and its contribution to the deep organic carbon reservoir at a global scale?
  - The export from different marginal seas differ depending on the topography, circulation and riverine DOM composition
  - Future change? (e.g. with nutrient riverine fluxes ↑)

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- **Outlook: Coastal Ocean Acidification and feedbacks**

How about the coastal ocean?

We do not even know if there occurs acidification in the coastal ocean (very likely though) where most of the calcifiers live!

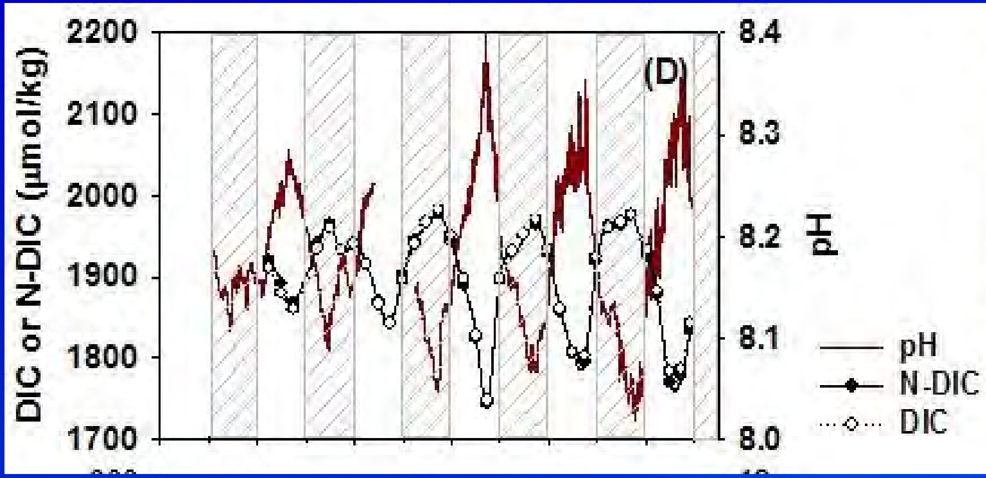
Complications:

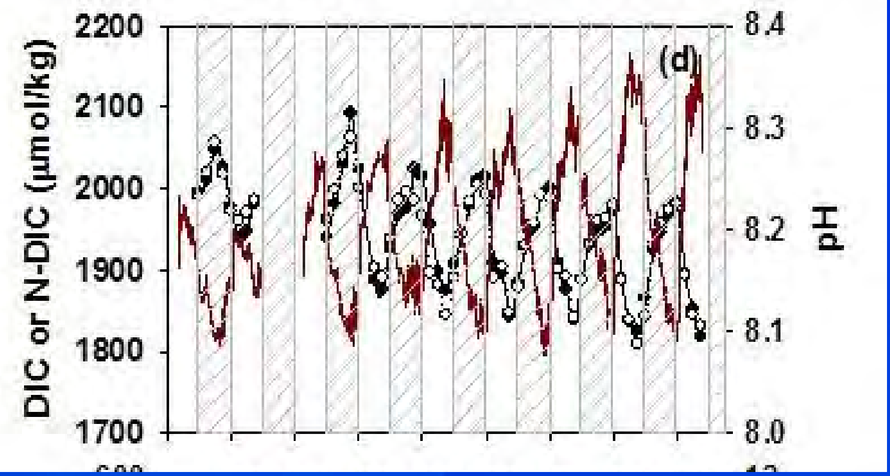
- TALK input from rivers
- Fluctuation of baseline pH

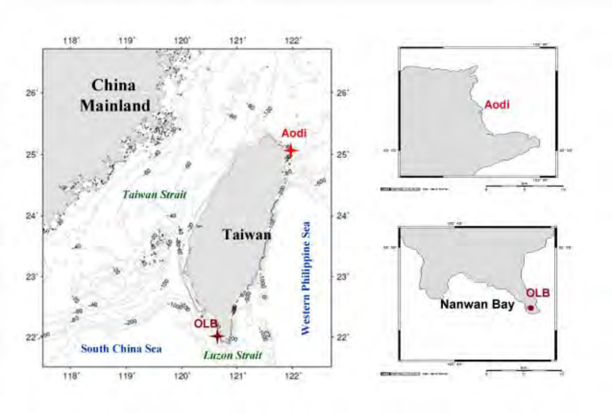
At the same time:

- Intensified upwelling
- More respiration with temp rise

pH variability in coastal systems

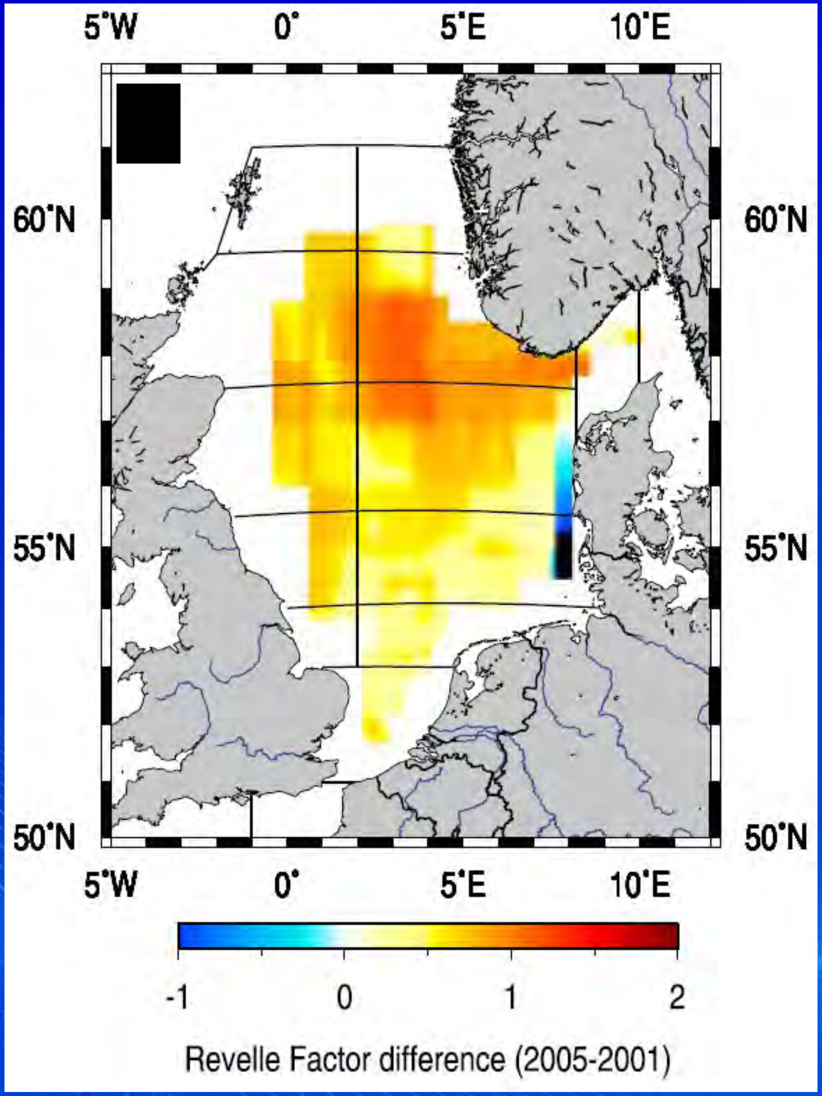






From Jiang ZP

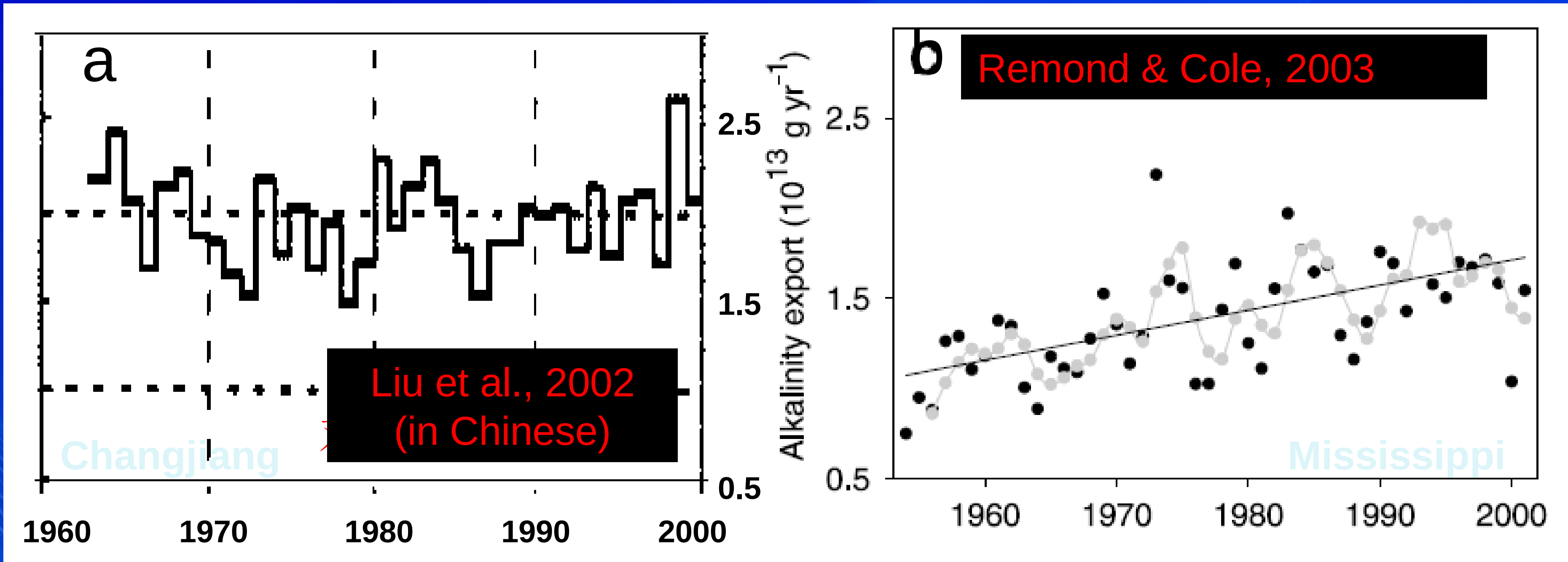
E.g., “Rapid decline of the CO_2 buffering capacity in the North Sea from 2001 to 2005”



Thomas et al. (2007), GBC, 21, GB4001, doi:10.1029/2006GB002825.

- Significant RF increase in the past 5 years
- No significant river input, however

Changjiang – East China Sea
vs.
Mississippi – Gulf of Mexico



Take home messages

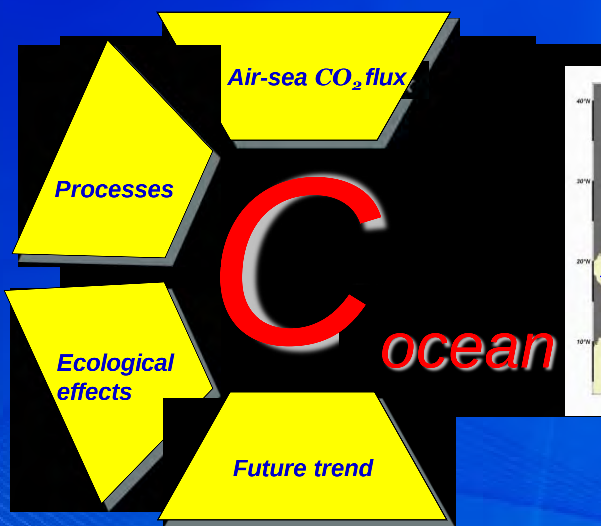
- Coastal ocean links the land and the open ocean, an important missing component in any global climate change model, yet …
- Coastal ocean CO_2 fluxes estimations have converged during the past 5 years, which should not be away from a moderate sink at a global scale
- Challenges remains at regional scales in accounting CO_2 fluxes both temporally and spatially
- Mechanistic understanding is to be improved for better modeling the coastal carbon cycling and to improve our predictive capability under future climate change forcing.

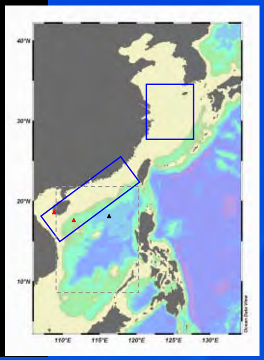
Thank you for your audience!

CHOICE-C: Carbon Cycling in China Seas - budget, controls and ocean acidification

A national program funded by Ministry of Science and Technology through National Basic Research Program of China (973 Program) & a SOLAS endorsed program

Jan 2009-Aug 2013





http://973oceancarbon.xmu.edu.cn