Coastal Ocean:
Biogeochemistry & physical-biogeochemistry coupling I

Minhan Dai (mdai@xmu.edu.cn)
Xiamen University, China

近海海洋环境科学国家重点实验室(厦门大学)
Take-home message: coastal oceanography

• Oceanography is to understand the variability of the ocean in time and space. Such variability is particularly large in coastal ocean where atmosphere, land and ocean interplay with prominent anthropogenic forcing:
  – Considering different domains (upwelling, plume, eddy, fronts etc.) is a must
  – Time-scale matters
• A multidisciplinary and multi-time-scale approach must be taken to study coastal oceanography, which needs
  – Physical-biogeochemical coupling
  – Time-series observation
  – Observation-model integration
• Adoption of approaches/concepts established for open ocean should be justified
Biogeochemical tool box for coastal ocean researches

- Multi-boundaries: mass-balance approach: from sources to sinks
  - Simple box model
  - End-member mixing model
- Diversity-heterogeneity: comparison or Analog
  - Ex: Redfield ratio
Outline

- **Why coastal ocean**
- Basics of the coastal ocean
- Coastal ocean in changing
- Physical - biogeochemistry coupling: a case study
- Coastal ocean carbon cycling
- Outlook
WHY COASTAL OCEAN?

THE GLOBAL COASTAL OCEAN
  - Interesting and important interdisciplinary marine system
  - Natural laboratory for fundamental coupled physical-biogeochemical-sedimentation processes
  - Contribution to global ocean dynamics generally?

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

COASTAL ZONE CHANGES
  - Local and global forcings
  - Natural and anthropogenic origins
  - Sensitive to climate change
  - Increasing human coastal populations and impact

Modified from Robinson & Brink, 2005
STATISTICS

• ~ 7-8% of ocean surface area, <0.5% of volume
  – ~ 30% of oceanic primary production, ~20 new production; ~95% of total biomass in ocean; ~90% of the world’s fish catch
  – ~ 80% of organic carbon burial
  – ~ 90% of sedimentary mineralization; >50% of sedimentary denitrification; ~50% N2O emission
  – ~ 50% of CaCO3 deposition
  – .......

• ~ 40% of the value of the world's ecosystem services and natural capital

• ~ 40% of the world population lives within 100 km of the coastline

• Important also for shipping, oil and gas production, and recreation

• Many pollutants found here
Shelf area = 7 % of ocean surface
Shelf = 20% of Ocean NPP; supports 90% of Marine Fisheries Production

\[ \text{g C m}^2 \text{yr}^{-1} \quad \text{(Field et al. 1998)} \]
Outline

• Why coastal ocean
• Basics of the coastal ocean
• Coastal ocean in changing
• Physical - biogeochemistry coupling: a case study
• Coastal ocean carbon cycling
• Outlook
Coastal Ocean Systems

Useful refs:

• Robinson and Brink (eds.), *THE SEA*, Vols 13 & 14, 2005

Global Coastal Ocean and its Subregions - 1

PRESENTLY NON-UNIFORM TERMINOLOGY
• the coastal ocean, coastal zone, coastal margin, continental shelf, continental margin, shelf sea
• terms used (often without definition) interchangeably by different scientists
• Obfuscates the inter-comparison of quantitative estimates of processes

PROPOSED DEFINITION: the coastal ocean - that area, extending offshore from the surf zone and from estuarine mouths, that includes at least the continental shelf and slope, and that also includes waters extending uninterruptedly farther offshore that are (based on temperature or salinity properties only) of shelf or inshore origin

Robinson & Brink (eds.), 2005, The Sea, V14
Global Coastal Ocean and its Subregions - 2

THE CLASSIFICATION OF SUB-REGIONS VIA GEOGRAPHY, GEOMORPHOLOGY AND DYNAMICAL PROCESSES

- 4 panregions - eastern and western boundaries, polar, semi-enclosed seas/islands;
- 5 physical processes - boundary layers, tides, wind and buoyancy forcing, boundary currents;
- 6 offshore zones - near shore, freshwater influence, well mixed, tidal fronts, thermally stratified, shelf-edge;
- 7 biogeochemical processes - subtropical shelf pumps, temperate shelf: biology or physics dominant, upwelling: biology or physics dominant, coral reefs, polar ice pump;
- 7 ecosystem types (permanent and intermittent polar ice, mid-latitude and topographically forced coastal, upwelling, wet and dry tropical.

COMMON SCIENTIFIC VERNACULAR NECESSARY FOR COLLABORATIVE INTERDISCIPLINARY RESEARCH AND INTERNATIONAL COOPERATION

Robinson & Brink (eds.), 2005, The Sea, V14
West Boudaries

Relatively narrow shelf

Robinson & Brink (eds.), 2005, The Sea, V14
Eastern Boundaries

Upwelling
steep topography

Robinson & Brink (eds.), 2005, The Sea, V14
Polar Boundaries

Wide shelf
Abundant rivers

Robinson & Brink (eds.), 2005, The Sea, V14
Semi-Enclosed Seas and Islands

Three types:

i) nearly-enclosed with limited exchanges with the open ocean (e.g. Sea of Okhotsk, Bohai Sea, Japan Sea)

ii) Partially-enclosed with moderate exchanges along 1 or 2 boundaries (e.g. Yellow Sea)

iii) Peripheral seas extending along continental margins and having strong interactions (e.g. Outer SE China Sea, shelf seas around Australia)
Semi-Enclosed Seas, Islands and Australia

- Overview on 4 regions: (1) European semi-enclosed seas, (2) Arabian Peninsula and Northern Indian Ocean marginal seas, (3) East Asian (or Western North Pacific) marginal seas, (4) Australia-New Zealand shelf seas
- Contain complex and diverse ecosystems involving rich natural resources and concentrated human activities –provide vital habitat for many commercial and endangered species
- Food web structures, affected by internal and external factors associated with natural and anthropogenic changes, may undergo strong nonlinear changes within existing state or abruptly switch to another state with almost no warning of impending changes
- Must assess types of structural changes possibly introduced by human-induced interventions in the next decades, to what extent they might be controlled, and implementation of possible strategies for sustainable use of their resources through process-oriented model explorations and data assimilation
Estuary distribution

• Estuaries are found around the global coastal zone, wherever rivers (large or small) enter the sea.

• There are thousands of geographical features that fit the criteria.

• Estuaries cover an area of $\sim 10^6$ km$^2$
  – This is $\sim 0.3\%$ of the world ocean.
  – This is $\sim 4\%$ of the world continental shelf.
Estuaries can be grouped into classes, according to their circulation properties and the associated steady state salinity distribution.

The most important estuary types are:

1. salt wedge estuary
2. highly stratified estuary
3. slightly stratified estuary
4. vertically mixed estuary
5. inverse estuary
6. intermittent estuary
(Conservative) Mixing Diagrams

Concentration of conservative contaminant discharged at head (using freshness as tracer)

\[
c_x = \left( \frac{S_o - S_x}{S_o} \right) \frac{\dot{m}}{Q_f}
\]

\[
c_x = a - bS_x
\]

\[
a = \frac{\dot{m}}{Q_f} = c_{\text{max}}
\]

aka C-S (or T-S, etc.) diagram, or property-salinity diagram
Outstanding Qs

• How to accurately estimate the surface area of global coastal ocean (eg., estuary)?
CHARACTERISTICS

• Topography
  – shallow depth: stretched air-sea-benthic interaction
  – complex shorelines
  – greater tidal influence and sea-level changes
  – shaping largely coastal circulation

• Terrestrial inputs:
  – stronger stratification
  – productive and diverse ecosystems
  – high gradient in everything (physical, biological, and chemical)
  – large temporal variability

• Link to open ocean
  – dynamic exchange with open ocean
• When northerly winds along northern hemisphere coasts drive water away from coast, so deep water upwells to replace it.
• Southerly winds produce downwelling.
• Everything opposite in southern hemisphere.

Sarmiento & Gruber, 2006, Ocean Biogeochemical Dynamics
Coastal Upwelling Off Hong Kong

Wind Stress (direct northeastward)

Coastal Upwelling Jet

Surface Ekman Layer

Bottom Ekman Layer

From Gan JP
Coastline affecting the circulation: i.e., upwelling jet

\[
\frac{V^2}{R} - fV = -\frac{1}{\rho_0} \frac{\partial p}{\partial n}
\]

From Gan JP
River/estuarine plumes

(from Q. Zheng)
Sarmiento & Gruber, 2006, Ocean Biogeochemical Dynamics
Transport from shelf to basin

— Dynamics? DOC? DIC?

Density driven

Wind driven

Continental shelf pump (ECS) — thermodynamic
(Tsunogai & Watanabe, 1999)

Winter monsoon

Wind driven — dynamic
(胡敦欣, 1999)
Coastal Ocean Primary Production

- Production is highest in continental margins and shallow seas, because
- Food webs are relatively short as compared to open ocean
Sarmiento & Gruber, 2006, Ocean Biogeochemical Dynamics
Sarmiento & Gruber, 2006, Ocean Biogeochemical Dynamics
Gradient in $S$, pCO$_2$ and DO off Changjiang Estuary

Chen et al., CSR, 2008, 28, 1476

Fig. 3. (a) Salinity, (b) air-water pCO$_2$, and (c) dissolved oxygen along the transect surveyed in the Changjiang (Yangtze River) Estuary in August–September 2003. Data for the Huangpujiang (HPJ) are not included.
Outline

• Why coastal ocean
• Basics of the coastal ocean
• Coastal ocean in changing
• Physical - biogeochemistry coupling: a case study
• Coastal ocean carbon cycling
• Outlook
Coastal Ocean in Changing

- Drivers
  - Anthropogenic
  - Climate changes

- Response in the coastal ocean
Coastal population = 2.2 billion (40% of total) (Burke et al., 2001)

Global Population: 1 b (1804); 2 b (1927); 3 b (1960) (UN, 1998)
## Inorganic Nutrient Loading

<table>
<thead>
<tr>
<th>Period</th>
<th>DIP, $10^9$ mols yr$^{-1}$</th>
<th>DIN, $10^9$ mols yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Natural</td>
<td>Anthro</td>
</tr>
<tr>
<td>1890s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Galloway &amp;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cowling 2002)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1970s</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>(Meybeck 1982)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990s</td>
<td>21</td>
<td>53</td>
</tr>
<tr>
<td>(Smith et al.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upwelling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Chen et al.,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>in press)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
River – ocean fluxes of nitrogen and phosphorus

Parameterization:
Population density + runoff

N and P inputs have trebled from the 1970s to the 1990s

Double in 2020
(Tilman et al 2001)

Figure 4. Calculated dissolved inorganic phosphorus (DIP) for the global coastline based on a population–runoff equation. Clusters are identified by the letter in the legend boxes; order is changed by the color-coded ranking in terms of the two variables. (a) DIP yield in kmol per km² per year. The global mean is about 600. (b) DIP load in 10⁸ mol per year.

The global N fluxes (tot N) have increased more than 3 times
Regionally the fluxes have increased more than 10 times
Agriculture and urbanization are the two major N sources

Green et al. 2003
River – ocean fluxes of nitrogen and phosphorus

Coupling of DIN and DIP inputs

Figure 2. Model II regression line for log dissolved inorganic nitrogen (DIN) versus log dissolved inorganic phosphorus (DIP). Note that slope does not differ significantly from 1. Gray triangles represent Land–Ocean Interactions in the Coastal Zone data; open squares represent data from Meybeck and Ragu (1997). Five large river basins are identified: (1) Amazon, (2) Congo, (3) Rio de la Plata, (4) Amur, and (5) Changjiang.

Synthesis of data sets from 165 rivers by Smith et al. (2003)
Anthropogenically enhanced fluxes of water and carbon from the Mississippi River (40% ↑ /50yrs)

Raymond et al., 2008, Nature,
Outstanding Qs

• Why coastal ocean is so productive? Nutrient source?
The amount of nutrients supplied by Kuroshio across the shelf break region through upwelling and frontal exchanges is about 5 times more than supplied from the inner shelf.

Chen and Wang, 1999 (JGR)
Oguz and Su, 2006 (The Sea, V. 14A, p106)
From C-T A Chen: N budget for the continental shelves of the North Atlantic Ocean (10^9 mol y^{-1}; modified from Galloway et al., 1996). Numbers in parentheses are from Seitzinger (2000).
Shelf Ecosystem Response:

- Eutrophication & HAB
- Hypoxic zones, denitrification & competing microbial pathways, and greenhouse gases
- Additional jeopardy from aquaculture & damming
Ecosystem response to historical overfishing + heavy nutrient load

- Loss of suspension feeders & seagrasses
- Add nutrients → **Microbialization of the coastal ocean**

(Jackson et al. 2001)
East China Sea off Changjiang

**HAB frequency**

Data from Yan Weijin et al., 2003

Variation in the percentage of diatom species to the overall species in the Changjiang River estuary and adjacent coastal waters during the last 20 years

<table>
<thead>
<tr>
<th>Time</th>
<th>Location</th>
<th>Percent diatom (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>30°00'–32°10'N, 121°21'–124°00'E</td>
<td>85</td>
<td>Wang (2002a)</td>
</tr>
<tr>
<td>1985.8–1986.10</td>
<td>30°20'–32°00'N, 121°10'–124°00'E</td>
<td>80</td>
<td>Guo and Yang (1992)</td>
</tr>
<tr>
<td>1990.8–9</td>
<td>31°10'–31°55'N, 121°00'–122°15'E</td>
<td>63</td>
<td>Shen et al. (1995)</td>
</tr>
<tr>
<td>1996.9</td>
<td>31°00'–31°30'N, 121°30'–122°34'E</td>
<td>56</td>
<td>Xu et al. (1999)</td>
</tr>
<tr>
<td>1998.5,10; 1999.2–3.8; 2000.3</td>
<td>30°00'–32°10'N, 121°21'–124°00'E</td>
<td>64</td>
<td>Wang (2002a)</td>
</tr>
</tbody>
</table>

Zhou et al., CSR, 2008, 28
“Dead zones,” or hypoxic areas – major global problem
(UNEP, March 2004)
Gulf of Mexican “dead Zone”

http://www.ncat.org

(Goolsby & Battaglin, 2000)

2001: 8000 sq mi
Changjiang Estuary/East China Sea

1980: 1000 km²
1999: 13,700 km²

Li & Zhang, 2002
Tong & Zhang, 2007, IMBER Newsletter, 2007

Characteristic of dissolved oxygen observed off the Changjiang Estuary in 3 months in 2006
Three Gorges Dam?

Reduction in sediment loading (by 55%) Si/N (from 1.5 to 0.4) and PP (by 86%)

2004 vs 1998
Qs about Dams

- Three Gorges Dam: Reduced freshwater outflow by 10% would reduce upwelling rate by 10%, thus reducing fisheries production in East China Sea. Damming has greater effects on deltaic processes than on fisheries production which is mostly subsidized by upwelling (Chen, 2000)?

- Dam would also change the river discharge pattern and the ecosystem downstream?
Lastly, Water Levels Dropping in Some Major Rivers as Global Climate Changes? Its impact on coastal ocean?

This map shows the change in runoff inferred from streamflow records worldwide between 1948 and 2004, with bluish colors indicating more streamflow and reddish colors less. In many heavily populated regions in the tropics and midlatitudes, rivers are discharging reduced amounts into the oceans. In parts of the United States and Europe, however, there is an upward trend in runoff. The white land areas indicate inland-draining basins or regions for which there are insufficient data to determine the runoff trends. (Graphic courtesy Journal of Climate, modified by UCAR.)
SUMMARY & FUTURE CHANGES?

- **Forcings:**
  - atmospheric CO2 rise
  - Temperature rise
  - Anthropogenic (nutrient ↑, dams)

- **Potential responses**
  - chemical weathering ↑
  - CaCO3 dissolution ↑
  - Primary production ↑
  - Retention of Si→diatom ↓ →R ↑
  - **Retention of P →N/P ↑** → need more external P to sustain the new production on shelves
  - Retention of POC →R ↓
  - Better waste treatment →DOC ↓

Com�plex response of coastal seas to river/estuarine changes
Application of a stoichiometric approach: oxygen depletion & biogeochemical coupling of oxygen, carbon, and nitrogen in the Pearl River Estuary

• Oxygen depletion in coastal systems
• The Pearl River Estuary-facts: low DO / high $pCO_2$
• Coupled biogeochemical processes
• The significance of nitrification
• Implications

Refs:
Dai, M.H., et al., 2006, Oxygen depletion in the upper reach of the Pearl River estuary during a very drought winter, Marine Chemistry, 102, 159-169.
Zhai, W., et al., 2005. High partial pressure of CO2 and its maintaining mechanism in a subtropical estuary, the Pearl River estuary, China, Marine Chemistry, 93: 21-32
Guo, X. et al., 2009, CO2 flux and seasonal variability in a large subtropical estuarine system, the Pearl River Estuary, China, 2009, Journal of Geophysical Research - Biogeosciences, in press
Pearl River
13th largest world river
2nd to Changjiang River

The case of upstream Pearl Estuary
Surface DO in the upper reach Pearl River estuary
DO in Guangzhou section
1990-2005

Zhang et al., 1999 and this study
DO and $p\text{CO}_2$ distribution

- DO $\approx 0.35$-2.2 mg L$^{-1}$ at low salinity area
- DO mirrored $p\text{CO}_2$, highest $p\text{CO}_2$ $\approx$ 7000-7460 $\mu$atm ($S < 3.3$)
• Mostly well mixed
• DO depletion in the whole water column
## Persistent oxygen depletion at Humen Vicinity and upstream

<table>
<thead>
<tr>
<th>Dates</th>
<th>Locations</th>
<th>DO mg/L</th>
<th>Salinity</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jul 2000</td>
<td>Humen Vicinity</td>
<td>1-3</td>
<td>0-2</td>
<td>Upstream not investigated</td>
</tr>
<tr>
<td>May 2001</td>
<td>Humen Vicinity</td>
<td>0.5-3</td>
<td>0-2</td>
<td>Upstream not investigated</td>
</tr>
<tr>
<td>Nov 2002</td>
<td>Humen Vicinity</td>
<td>0.5-3</td>
<td>0-2</td>
<td>Upstream not investigated</td>
</tr>
<tr>
<td>Feb 2004</td>
<td>Humen Vicinity</td>
<td>0.2-3</td>
<td>1.0-4.0</td>
<td>Upstream included</td>
</tr>
<tr>
<td>Jan 2005</td>
<td>Humen Vicinity</td>
<td>0.2-2.3</td>
<td>1.0-4.0</td>
<td>Upstream included</td>
</tr>
<tr>
<td>Aug 2005</td>
<td>Humen Vicinity</td>
<td>&lt;0.5-2.0</td>
<td>0-2</td>
<td>Upstream included</td>
</tr>
</tbody>
</table>
What’s unique?

- Surface & whole water column low DO
- Persistent: year-round
- Related to organic pollutant discharge (& ammonia) + other DO consumption processes (thus DO, C & N coupling)
Major DO/pCO2 related processes in estuaries

- **Primary production:**
  \[ \text{CO}_2 + \text{H}_2\text{O} + \text{light} = \text{CH}_2\text{O} + \text{O}_2 \]

- **Respiration:**
  \[ \text{CH}_2\text{O} + \text{O}_2 = \text{CO}_2 + \text{H}_2\text{O} \]

- **Nitrification**

- **Other processes:**
  - Denitrification
  - Calcification/dissolution:
  \[ \text{Ca}^{2+} + 2\text{HCO}_3^- = \text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \]
Aerobic respiration

\[(\text{CH}_2\text{O})_{106}(\text{NH}_3)_{16}\text{H}_3\text{PO}_4 + 138 \text{ O}_2 + 18 \text{ HCO}_3^- \rightarrow 124 \text{ CO}_2 + 140 \text{ H}_2\text{O} + 16 \text{ NO}_3^- + \text{HPO}_4^{2-}\]

\[\Delta\text{CO}_2/(−\Delta\text{O}_2) = 124/138 = 0.899\]

Excess CO\(_2\)\(=\)[CO\(_2^*\)]\(-K_H^{\text{CO}_2}\times p\text{CO}_2^{\text{air}}\)

Oxygen depletion = \([O_2]_{\text{eq}} − [O_2]\)
Waste discharge

Sewage treatment rate: 9.0% in 1990, 35% in 2003

High density of population: 53 M, 70/km²
• Removal behavior
• Higher DOC end-member in dry season
• OM sources?
DO consumption: respiration

- Most $\Delta$CO$_2$/($-$ΔO$_2$) ~0.62-0.9
  → aerobic respiration

**Stoichiometric approach 1:**

$$(\text{CH}_2\text{O})_{106}(\text{NH}_3)_{16}\text{H}_3\text{PO}_4 + 138 \text{O}_2 + 18 \text{HCO}_3^- \rightarrow 124 \text{CO}_2 + 140 \text{H}_2\text{O} + 16 \text{NO}_3^- + \text{HPO}_4^{2-}$$

$\Delta$CO$_2$/($-$ΔO$_2$) = 124/138 = 0.899

Dai et al., 2006, Mar Chem
Significance of nitrification
Feb., 2004

High NH4

Peak Nitrate

- Implying nitrification

Dai et al., 2006, Mar Chem
• The max. NH$_4^+$ > 600 μmol L$^{-1}$,

• NH$_4^+$ dominate nitrogen species

• peaks of nitrate at S~2-5

• Removal of ammonia while nitrite remains relatively constant in low salinity zone→ nitrification.

• Contrast between Lingdingyang and Huangmaohai

Dai et al., 2008, Biogeosciences
Nitrification vs nitrifier abundance

Dai et al., 2008, Biogeosciences
Ammonia oxidation rate (μmol L⁻¹ d⁻¹)

Nitrite oxidation rate (μmol L⁻¹ d⁻¹)

pH

Nitrite (μmol L⁻¹)

Temperature (℃)

DO (mg L⁻¹)

(a) Mar. 2006

y = 1.7236x - 11.98

R² = 0.7579

(b) All cruises

y = 0.3338x - 2.1225

R² = 0.5202

(c) Upstream Guangzhou

y = 0.0523x - 0.6274

R² = 0.9999

(bottom) All cruises

y = 0.8421x - 13.69

R² = 0.9919

Dai et al., 2008, Biogeosciences
DO consumption: nitrification

$\Delta CO_2/(-\Delta O_2) = 1.9/1.89 \sim 1$

Stoichiometric approach 2:

$NH_4^+ + 1.89 O_2 + 1.98 HCO_3^- \rightarrow 0.984 NO_3^- + 0.016 C_5H_7O_2N + 1.90 CO_2 + 2.93 H_2O$

$DCO_2/(-DO_2) = 1.9/1.89 \sim 1$
Stoichiometric approach 3:

\[ \text{NH}_4^+ + 1.89 \text{O}_2 + 1.98 \text{HCO}_3^- \rightarrow 0.984 \text{NO}_3^- + 0.016 \text{C}_5\text{H}_7\text{O}_2\text{N} + 1.90 \text{CO}_2 + 2.93 \text{H}_2\text{O} \]

\( \Delta \text{HCO}_3^-/(\Delta \text{NH}_4^-) = 1.98 \sim 2 \)

\( \frac{V_{\text{DIC consume}}}{V_{\text{ammonia oxidation}}} = \frac{2.78}{1.36} = 2.04 \sim 2 \)

(Based upon an incubation experiment in Aug., 2005. Sample taken from Station Changzhou, upper Pearl Esturay)
Contrasting Region

• Yamen: no coupling
# Nitrification vs. DO consumption

<table>
<thead>
<tr>
<th>Sta</th>
<th>Time</th>
<th>BOD (mmolk g(^{-1})h(^{-1}))</th>
<th>DO via nitrification (mmolkg(^{-1})h(^{-1}))</th>
<th>Nitrification/BOD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sta 1</td>
<td>Jan., 2005</td>
<td>1.94(^*)</td>
<td>0.44</td>
<td>22.4</td>
</tr>
<tr>
<td></td>
<td>Jan., 2005</td>
<td>3.13(^*)</td>
<td>0.33</td>
<td>10.5</td>
</tr>
<tr>
<td>Sta 2</td>
<td>Aug., 2005</td>
<td>7.53(^*)</td>
<td>2.50</td>
<td>33.2</td>
</tr>
<tr>
<td></td>
<td>Mar., 2006</td>
<td>2.67(^*)</td>
<td>0.72</td>
<td>26.8</td>
</tr>
</tbody>
</table>
Summary

- Low DO (down to < 10%) persistently occurred to the upstream Pearl Estuary. $pCO_2$ overall mirrors Oxygen in polluted regions.
- Low DO is largely related to the respiration of organic pollutants.
- Additional DO consumption due to nitrification
- Close biogeochemical coupling between oxygen, carbon and nitrogen in polluted regions with high sewage discharge and high dissolved organic carbon concentration
Open Questions

- DO/CO₂/nitrification coupled within polluted regions while decoupled in “clean” environments
- Complex mixing and biogeochemical processes? Others?
- Sediment consumption of DO?
- Applicability of stoichiometry in the estuarine environment?
- Environmental protection in similar estuarine environment? Best approach?
Outline

- Why coastal ocean
- Basics of the coastal ocean
- Coastal ocean in changing
- Physical-biogeochemistry coupling: a case study
  - Rapid buildup of excess N and N/P ratios induced by mesoscale eddies in the upper layer in the WSCS
- Coastal ocean carbon cycling
- Outlook
Eddies make up much of the variability in the ocean in time and space.
Eddies make up much the variability in the ocean in time and space.
Small scale variability in the Ross Sea

Hales, B., Sweeney, C. and T. Takahashi: “...resolution as fine as 15km misses 2/3 of the total variability in well-resolved fields...”
Eddy is everywhere!

• From open ocean to coastal regions

• Most looked eddies:
  – Oligotrophic regions
    • Hawaii
    • Bermuda (Gulf Stream)….
  – Slope/Shelf/Coastal regions-interaction with plumes/near shore upwellings
Eddies

Red, green, and turquoise patches to the west of British Columbia/Alaska indicate high concentrations of chlorophyll. Eddies in the Pacific Ocean formed by outflow currents from rivers along the coast that are rich in nutrients from the springtime snowmelt running off the mountains. Stimulate the phytoplankton blooms within the eddies.

K490MODIS data product for 5 August 2003 at 1-km resolution. K490 is the diffuse attenuation coefficient for light penetration (CDOM + phyto). The eddy core is located at ~15°N, 67°00′W. During CaVortEx I (14–16 Aug), the eddy core had reached 67°50′W, a westward displacement of approximately 50 nautical miles. High-chlorophyll, high-CDOM, near-surface river plume water (green) surrounds the low-chlorophyll, low-CDOM waters of the eddy core (light blue). A filament of plume water spirals within the eddy core.

Corredor et al., 2004, Eos, 85, 20
Implications for nutrient transport and biological productivity

• “eddy pumping” of nutrients upwards from deep to shallow waters by cyclonic eddies

• transport of nutrients and productivity offshore from coastal, frontal or upwelling areas by either cyclonic or anticyclonic eddies
Cyclonic and Anti-cyclonic Eddies

Doming of thermocline in cyclonic rings:

Northern hemisphere:

Primary production increased within cyclonic rings (cold-core, anti-clockwise rotation).

Coriolis force deflects water movement to the right, i.e. away from the center in a cyclonic ring. The spreading surface water is replaced by deep water.

⇒ depth of the thermocline decreases
⇒ nutrient-rich waters closer to (illuminated) surface.
⇒ increased primary production.

Anti-cyclonic rings: vice versa.

Cold core ring: thermocline is pushed up.
Warm core ring: thermocline pushed down.

Sweeney, 2003
Stage of cyclonic eddy

- little effect is expected during intensification,
- significant amounts of nutrients are upwelled. - nutrient injection is likely to be followed by increased pp, pigment and/or other possible biological responses
- After some period of time, the biological response is expected to stimulate increased export. Then, as the eddy begins to decay, the nutrient injection would subside.
- At some time nutrients will be exhausted, productivity decreases, and a high export signal remains due to the longer time scale over which export is averaged by the $^{234}$Th tracer
- Finally, even the thorium signal is expected to disappear as the eddy continues to decay

Sweeney, 2003
Summary

• Ocean is full of meso-scale variability both in time and space
• Variability also occurs between eddies as well as during the different stages of eddies in terms of:
  – Water motion
  – Nutrient enhancement
  – Biological responses (carbon fixation, export, re-minerization…)
• More intra-eddies
  – Sub-eddy changes
• → many opportunities for new findings
Upper Ocean Circulation Features (on a seasonal time scale):

- The Indo-Pacific warm pool
- East Asian monsoon system: N-Easterlies in winters, S-Westerlies in summers

Map showing the circulation patterns in the Pacific and Indian Oceans.
Sampling sites at four different stage with eddy development: “spin up-mature” stage (September 1-8), “mature-degrading” stage (August 15-24, ), “relaxation” stage (August 25-31, ) during the southwest monsoon in 2007 and “no eddy” stage (December, ) during the northeast monsoon in 2006.

Dai et al., in preparation
Geographic locations and depth contours of eddy I and eddy II in the western South China Sea: Sea surface height anomalies (cm, color shading and contours line) and sea current at 25 m from ADCP (panels a, b), vertical profiles of salinity in the upper 150 m (panels c, d). Blue arrows indicate sea current, red dots are sampling sites and crosses represent depth of sampling at each station.

Dai et al., in preparation
Summary

• The transient and elevated N:P stoichiometry observed with eddies spinning up may be explained by the rapid response of nitrogen fixation to eddies.

• $\text{N}_2$ fixation sitting in the oligotrophic euphotic zone is stimulated almost instantaneously as the occurrence of upwelling.
Concluding remarks:

- Oceanography is to understand the variability of the ocean in time and space. Such variability is particularly large in coastal ocean where atmosphere, land and ocean interplay with prominent anthropogenic forcing:
  - Considering different domains (upwelling, plume, eddy, fronts etc.) is a must
  - Time-scale matters
- A multidisciplinary and multi-time-scale approach must be taken to study coastal oceanography, which needs
  - Physical-biogeochemical coupling
  - Time-series observation
  - Observation-model integration
- Adoption of approaches/concepts established for open ocean should be justified
Xiamen University Campus

Thank you!