The role of continental margins in the global carbon cycle

K.-K. Liu
Inst. of Hydrological & Oceanic Sciences
National Central University, Taiwan

Contributors
L. P. Atkinson, R. A. Jahnke,
R. Quiñones, L. Talaue-McManus
Changing Atm Composition due to human activities -- from background to contemporary level
Global Carbon Cycle: 1990s (IPCC, 2007)

How does ocean take up anthropogenic CO₂?


Reservoir sizes in GtC
Fluxes and Rates in GtC yr⁻¹

Atmosphere: 597 + 165
Land use change: 1.6 GtC
GPP: 119.6 GtC
Weathering: 120 GtC
Respiration: 2.6 GtC
Weathering: 0.2 GtC

2.2 GtC yr⁻¹
2.6 GtC yr⁻¹
1.6 GtC yr⁻¹

+3.2 GtC yr⁻¹
6.4 GtC yr⁻¹

+3.2 PgC/y
6.4 PgC/y

Global Carbon Cycle: 1990s (IPCC, 2007)


Reservoir sizes in GtC
Fluxes and Rates in GtC yr⁻¹

Atmosphere: 597 + 165
Land use change: 1.6 GtC
GPP: 119.6 GtC
Weathering: 120 GtC
Respiration: 2.6 GtC
Weathering: 0.2 GtC

2.2 GtC yr⁻¹
2.6 GtC yr⁻¹
1.6 GtC yr⁻¹

+3.2 GtC yr⁻¹
6.4 GtC yr⁻¹

+3.2 PgC/y
6.4 PgC/y

Global Carbon Cycle: 1990s (IPCC, 2007)


Reservoir sizes in GtC
Fluxes and Rates in GtC yr⁻¹

Atmosphere: 597 + 165
Land use change: 1.6 GtC
GPP: 119.6 GtC
Weathering: 120 GtC
Respiration: 2.6 GtC
Weathering: 0.2 GtC

2.2 GtC yr⁻¹
2.6 GtC yr⁻¹
1.6 GtC yr⁻¹

+3.2 GtC yr⁻¹
6.4 GtC yr⁻¹

+3.2 PgC/y
6.4 PgC/y

Global Carbon Cycle: 1990s (IPCC, 2007)


Reservoir sizes in GtC
Fluxes and Rates in GtC yr⁻¹

Atmosphere: 597 + 165
Land use change: 1.6 GtC
GPP: 119.6 GtC
Weathering: 120 GtC
Respiration: 2.6 GtC
Weathering: 0.2 GtC

2.2 GtC yr⁻¹
2.6 GtC yr⁻¹
1.6 GtC yr⁻¹

+3.2 GtC yr⁻¹
6.4 GtC yr⁻¹

+3.2 PgC/y
6.4 PgC/y

Global Carbon Cycle: 1990s (IPCC, 2007)


Reservoir sizes in GtC
Fluxes and Rates in GtC yr⁻¹

Atmosphere: 597 + 165
Land use change: 1.6 GtC
GPP: 119.6 GtC
Weathering: 120 GtC
Respiration: 2.6 GtC
Weathering: 0.2 GtC

2.2 GtC yr⁻¹
2.6 GtC yr⁻¹
1.6 GtC yr⁻¹

+3.2 GtC yr⁻¹
6.4 GtC yr⁻¹

+3.2 PgC/y
6.4 PgC/y

Global Carbon Cycle: 1990s (IPCC, 2007)


Reservoir sizes in GtC
Fluxes and Rates in GtC yr⁻¹

Atmosphere: 597 + 165
Land use change: 1.6 GtC
GPP: 119.6 GtC
Weathering: 120 GtC
Respiration: 2.6 GtC
Weathering: 0.2 GtC

2.2 GtC yr⁻¹
2.6 GtC yr⁻¹
1.6 GtC yr⁻¹

+3.2 GtC yr⁻¹
6.4 GtC yr⁻¹

+3.2 PgC/y
6.4 PgC/y

Global Carbon Cycle: 1990s (IPCC, 2007)


Reservoir sizes in GtC
Fluxes and Rates in GtC yr⁻¹

Atmosphere: 597 + 165
Land use change: 1.6 GtC
GPP: 119.6 GtC
Weathering: 120 GtC
Respiration: 2.6 GtC
Weathering: 0.2 GtC

2.2 GtC yr⁻¹
2.6 GtC yr⁻¹
1.6 GtC yr⁻¹

+3.2 GtC yr⁻¹
6.4 GtC yr⁻¹

+3.2 PgC/y
6.4 PgC/y
Net trans-boundary C-fluxes (PgC/y): pre-industrial

Net trans-boundary C-fluxes (PgC/y):

- Atm
- Surf Oc
- Deep Oc
- Crust

Fluxes (PgC/y):
- Land: 0.2
- Atmosphere: 0.6
- Surf Oc: 0.2
- Deep Oc: 0.8
- Crust: 0.6
Net trans-boundary C-fluxes (PgC/yr): 1990s

<table>
<thead>
<tr>
<th></th>
<th>Atm</th>
<th>Land (+1.0)</th>
<th>Surf Oc (0.6)</th>
<th>Deep Oc (+1.6)</th>
<th>Crust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atm</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Land</td>
<td>2.6</td>
<td>0.8</td>
<td>1.6</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Surf Oc</td>
<td>2.2 (3.2)</td>
<td>(+0.6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep Oc</td>
<td></td>
<td></td>
<td>1.6</td>
<td>(+1.6)</td>
<td></td>
</tr>
<tr>
<td>Crust</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2 PgC/yr (Takahashi et al., 1999)
JGOFS/WOCE: Global air-sea CO₂ flux

Net air-sea flux = 2.2 Pg/yr
(Takahashi et al, 1999)
Continental margins should be a source of $CO_2$. Are they?
$P_{CO_2}$ in the ECS
(Tsunogai et al., 1999)

-35 gC m$^{-2}$ yr$^{-1}$
Air-to-sea $CO_2$ flux in the North Sea (Thomas et al., Science 2005)

-17 gC m$^{-2}$ yr$^{-1}$
Estimation of air-sea CO$_2$ fluxes in global continental margins
(Cai et al., 2006, GRL)

Net sink: 0.2 PgC/yr
JGOFS/WOCE:
Global air-sea CO₂ flux

Net air-sea flux = 2.2 Pg/yr
(Takahashi et al, 1999)
Assessment of carbon and nutrient fluxes in global continental margins
Continental Margin Task Team (CMTT)

JGOFS
IMBER
(Integrated Marine Biogeochemistry & Ecosystem Research)

LOICZ
(LAND-OCEAN Interaction in the Coastal Zone)
What is a continental margin?

- Coastal zone (LOICZ) + slope (boundary current)
Global bathymetry
Global continental margins

- Occupy 12% of global ocean in area
- Produce 20% of global ocean NPP, 22% of global export production
Estimation of air-sea $CO_2$ fluxes in global continental margins

Net sink: 0.3 PgC/yr (Jahnke 2008)
How do continental margins function as a net sink of atm. CO$_2$?
Global C-cycle w/CM
1990s Scenario

Net = 0.3 Pg/yr


Crust (PgC/yr)
(1990s with margins)
Issues

• How do continental margins take up anthropogenic CO$_2$?
• What is the fate of terrigenous carbon discharged to margins?
• Does the carbon taken up by continental margins enter the deep ocean?
• Why do Eastern Boundary Current systems not release CO$_2$ to the atm?
• How does the new estimate reconcile with global ocean CO$_2$ uptake?
How do Continental margins take up anthropogenic $CO_2$?
SeaWiFS
Chl-a in the East China Sea (Summer)
ECS: High biological uptake of CO$_2$ in summer
## Estimated Global Riverine loads of nutrients (Gmol/yr)

<table>
<thead>
<tr>
<th>Species</th>
<th>1970(^a)</th>
<th>1990 LOICZ(^b)</th>
<th>1990 NEWS(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Natural</td>
<td>Anthro</td>
<td>Total</td>
</tr>
<tr>
<td>DIN</td>
<td>321</td>
<td>500(^*)</td>
<td>821</td>
</tr>
<tr>
<td>DON</td>
<td>714</td>
<td>714</td>
<td>1428</td>
</tr>
<tr>
<td>PN</td>
<td>1500</td>
<td></td>
<td>1500</td>
</tr>
<tr>
<td>TN</td>
<td>2536</td>
<td>500</td>
<td>3036</td>
</tr>
<tr>
<td>DIP</td>
<td>13</td>
<td>13</td>
<td>26</td>
</tr>
<tr>
<td>DOP</td>
<td>19</td>
<td>19</td>
<td>39</td>
</tr>
<tr>
<td>PIP</td>
<td>387</td>
<td></td>
<td>387</td>
</tr>
<tr>
<td>POP</td>
<td>258</td>
<td></td>
<td>258</td>
</tr>
<tr>
<td>TP</td>
<td>677</td>
<td>32</td>
<td>710</td>
</tr>
</tbody>
</table>

\(^*\)No distinction between organic or inorganic forms was specified.

\(^**\)No distinction between organic or inorganic forms or between natural or anthropogenic origins was specified.
Continental margins as a nutrient pump

(Walsh, 1991)
SCS as a nutrient pump
Extra nutrient source: N-fixation in continental margins

Baltic Sea sediment core results (Struck et al., 2000)
Nutrient dynamics in the Baltic Sea

<table>
<thead>
<tr>
<th>Code</th>
<th>Sea Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>BA</td>
<td>Baltic Sea</td>
</tr>
<tr>
<td>BB</td>
<td>Bay of Bengal</td>
</tr>
<tr>
<td>BL</td>
<td>Black Sea</td>
</tr>
<tr>
<td>EC</td>
<td>East China Sea</td>
</tr>
<tr>
<td>GM</td>
<td>Gulf of Mexico</td>
</tr>
<tr>
<td>GS</td>
<td>Gulf of St Lawrence</td>
</tr>
<tr>
<td>GT</td>
<td>Gulf of Thailand</td>
</tr>
<tr>
<td>HB</td>
<td>Hudson Bay</td>
</tr>
<tr>
<td>KA</td>
<td>Kara Sea</td>
</tr>
<tr>
<td>LS</td>
<td>Laptev Sea</td>
</tr>
<tr>
<td>NA</td>
<td>Northern Adriatic Sea</td>
</tr>
<tr>
<td>NS</td>
<td>North Sea</td>
</tr>
<tr>
<td>SO</td>
<td>Sea of Okhotsk</td>
</tr>
</tbody>
</table>

Nutrient dynamics in the Baltic Sea
P-cycling in continental shelf

Diagram showing the cycling of different forms of phosphorus (P) in the continental shelf environment. Key stages include:

- *DIP* (from sediment to water column)
- *DOP* (from ocean interior to sediment)
- Fe-P (iron-phosphorus complex)
- Ca-P (calcium-phosphorus complex)
- POP (particulate organic phosphorus)

Processes include:

- Dry & wet deposition
- Upwelling
- From Land to Column
- Oxidic Sed
- Anoxic Sed

The diagram illustrates the movement and transformation of phosphorus across different environments and compartments.
ECS: CO$_2$ uptake in winter due to low SST

- SST superimposed by depth-averaged surface circulation in December

Winter

satellite SST and modeled flow field in winter

1 m/s

Yellow River
Shandong
Korea
Shikoku
Kyushu
Taiwan

23-25 Mar 2008
Mitzpe Ramon
How does the C get out of the shelf?

What is the fate of terrigenous C?

~7 TgC/y

12~36 TgC/y

23-25 Mar 2008
Mitzpe Ramon
2nd Kaplan Workshop:
Environmental Geochemistry
Global C-cycle w/CM: 1990s scenario

Crust (PgC/yr) (1990s with margins)

Atmosphere (+3.2)

Land (+2.6-1.6)

Margins (+0.05)

Surface layer of ocean interior (+0.55)

Intermediate & deep ocean (+1.6)

Biota


6.4 (Fossil fuel burning)

1.6 (Deforestation)

0.4

2.6

0.2

0.5

0.4

1.7

0.05

9

0.35

2

0.1

0.45

2

0.15

0.2

0.15

0.2
Physical processes operating in continental margins

- Wind mixing, Ekman spiral
- Coastal jet
- Tides
- River discharge, estuarine circulation
- Anthropogenic activities
- Watershed processes
- Damming
- Air-sea exchange
- Eddy
- Boundary current
- Surface waves
- Coastal upwelling, downwelling
- Shelf-break upwelling
- Internal waves, tides
- Sediment ballasting, discharge
- Sediment resuspension, deposit
- Sediment burial
- Turbulence
IMBER-LOICZ
Continental Margins Processes
East China Sea: TOC in sediments
Contents of terrigenous & marine organic carbon off SW Taiwan

Kao et al., 2006, CSR

TOCmar burial = 2.3% PP
Delivery & burial efficiency of POC wrt PP in margins: SW Taiwan vs OMEX-I

Efficient burial of POC due to ballast effect of sediments
Fate of C in East China Sea

- Along shore transport
- Coastal upwelling induced bloom
- Algal bloom
- Offshore current
- Warm surface water
- Cold subsurface water
- Sinking of organic particles
- Burial
- Export of organic carbon
- DIC
- Upwelling of nutrients
- CO₂
- 1200 Gmol
- 900 Gmol
- 630 Gmol
- 730 Gmol
- 750 Gmol
Shelf pump in the North Sea (Thomas et al., 2005)

-17 gC m\(^{-2}\) yr\(^{-1}\)

- Efficient bio-pump
- Over-consumption of C due to preferential recycling of nutrients
- Rapid shelf-interior exchange
Does CO2 taken up by margins enter deep ocean?

Increase of DIC (μM) from margin injection (Yool & Fasham, GBC, 2001)
pCO2 in Kuroshio after exchange with ECS shelf

![Graph showing pCO2 in Kuroshio water south of Japan](image.png)
JGOFS/WOCE:
Global air-sea CO₂ flux

Net flux (10^12 grams C/yr in each 4 x 5° area)
Why do EBCs not release much $\text{CO}_2$?

![Graph showing CO2 flux for different regions](graph.png)
Why don’t EBCs release (a lot of) CO₂?

Iron-enrichment?
How does the new estimate reconcile with global ocean CO$_2$ uptake?


\[ \text{Net} = 0.3 \, \text{Pg/yr} \]
\[ \text{Net} = 1.3 \, \text{Pg/yr} \]

2.2 PgC/yr (Takahashi et al., 1999)
Potential surfactant effect
(Tsai & Liu, JGR, 2003)

- Net uptake reduction: ca 20%
- Strong dependence on wind product used for calculation
JGOFS/WOCE: Global air-sea CO$_2$ flux

Net air-sea flux = 1.2-1.4 Pg/yr
(Takahashi et al, DSR-II, in prep)

- Wind field was overestimated.
- Southern ocean sinks were overestimated.

Net flux (10$^{12}$ grams C/yr in each 4 x 5° area)
Summary

• Continental shelf pump, which is facilitated by active bio-uptake and effective margin-interior exchange driven by boundary current systems, may account for 14% of global anthropogenic CO$_2$ uptake.

• Riverine nutrients from anthropogenic sources may contribute significantly to biological CO$_2$ uptake with preferential recycling of N & P.

• Sediments serve as effective carrier & ballasts for OC transports in continental margins.
More Questions

• How did carbon fluxes in continental margins change in the past?
• How will they change in the future?
How did carbon fluxes in continental margins change in the past?

- Pre-industrial: CO2 source of 0.2 PgC/yr
- Now: CO2 sink of 0.3 PgC/yr
- How could it change so much?

(Ver et al., 1999)
Demand & riverine supply of nutrients in margins

<table>
<thead>
<tr>
<th>Fluxes</th>
<th>OC (PgC/y)</th>
<th>OC (Tmol/y)</th>
<th>N (Tmol/y)</th>
<th>P (Tmol/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Margin uptake of anth CO2</td>
<td>0.5</td>
<td>42</td>
<td>6.3</td>
<td>0.39</td>
</tr>
<tr>
<td>Riverine Diss. Inorg. Nutrients</td>
<td>1.77</td>
<td>0.078</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Riverine Total Nutrients</td>
<td>4.7</td>
<td></td>
<td></td>
<td>0.77</td>
</tr>
</tbody>
</table>

Riverine fluxes from Global NEWS model (Seitzinger et al., 2005)
Heterotroph ≠ CO2 release
How will carbon fluxes in continental margins change in the future?

ΔfCO$_2$ (μatm): $-69 \pm 57 (-258\sim67)$

June 19~26, ‘03

12 ± 34 (-126~105)

Aug. 13~23, ‘03

(CM Tseng, unpublished data)
Three Gorge Dam (三峽大壩)
Possible damming effect on the ECS
(Gong et al., 2006, GRL)

After 1st stage of water storage in the 3-Gorges Dam
Continental Shelf pump is losing capacity in the North Sea (Thomas per. Comm.)

2005: pCO2sw - pCO2air

2005-2001
Carbon and Nutrient Fluxes in Continental Margins: A Global Synthesis
Chapter 4
Indian Ocean Margins

1.1 Overview

S.M.A. Nayar

The North Indian Ocean is characterized by the monsoon climate, which is distinguished by the seasonal reversal of winds that are driven by thermal differences between the land and sea. During winter (January-February), the prevailing winds are from the north, while during summer (June-September), they are from the south.

The monsoon winds drive surface currents in opposite directions during the two monsoon seasons. However, surface circulation in the region is not dictated entirely by local winds. The North-Eastern Arabian Sea is characterized by strong monsoon winds, which drive a northward current during the monsoon season and a southward current during the pre-monsoon season. This results in a complex system of currents in the Indian Ocean, which is influenced by the monsoon winds and regional climate patterns.

The Indian Ocean is characterized by a strong influence of the monsoon winds, which drive surface currents in opposite directions during the two monsoon seasons. However, surface circulation in the region is not dictated entirely by local winds. The North-Eastern Arabian Sea is characterized by strong monsoon winds, which drive a northward current during the monsoon season and a southward current during the pre-monsoon season. This results in a complex system of currents in the Indian Ocean, which is influenced by the monsoon winds and regional climate patterns.

1.1.2 Surface Currents

The monsoon winds drive surface currents in opposite directions during the two monsoon seasons. However, surface circulation in the region is not dictated entirely by local winds. The North-Eastern Arabian Sea is characterized by strong monsoon winds, which drive a northward current during the monsoon season and a southward current during the pre-monsoon season. This results in a complex system of currents in the Indian Ocean, which is influenced by the monsoon winds and regional climate patterns.
Conclusions

• Continental margins occupy 12% of total area of the global ocean, which has an estimated annual increase of 2.2 Pg C in carbon inventory. Of the annual increase, 40% enters the ocean via continental margins.

• Aside from the 0.6 PgC discharged from rivers, 20% of the oceanic uptake of atmospheric CO2 by air-sea exchange occurs in continental margins.
Conclusions

• The efficient CO2 uptake in continental margins is partially attributed to the rich supply of nutrients, which nourish active biological production and CO2 uptake. The stratified water column enhanced by freshwater input in continental margins help export of carbon to the deep ocean. Sediments serve as effective carriers, protectors and preservers of organic carbon.

• The continental shelf pump is prone to human perturbation and becoming less efficient due to saturation of the buffering capacity of the seawater. This may be one of the most critical sources of uncertainty in predicting the future trend of atmospheric CO2 level.
Thank you!
Ill-defined continental margin systems

• Estuaries & marshes

Net sink:
0.05 PgC/yr (Borges et al., 2005, GRL)
0.2 PgC/yr (Cai et al., 2006, GRL)
Models for CMs with predicting power are badly needed.

SeaWiFS Chl-a (mg/m³)
Flow field (Lee et al., 2004)
SEEP (Shelf Edge Exchange Processes)

- Not very efficient lateral export of POC
Net Trans-boundary Carbon Fluxes
(Pg C/y), incl. continental margins
East China Sea Studies

“Atm. Inverse Model” predicted oceanic $CO_2$ uptake $\ll 2$ PgC/yr

- Oceanic $CO_2$ uptake = 0.3-0.8 Pg C/yr via air-sea exchange (Tans, Fung and Takahashi, Science, 1990)
1986: Negative results came out of SEEP. (Rowe et al., 1986)

TOC = 7.9% (Berner, 1992) (Pg/yr)

Do continental shelves export organic matter?


*Oceanographic Sciences Division, Department of Applied Science, Brookhaven National Laboratory, Upton, New York 11973, USA
†Northeast Fisheries Center, NMFS/NOAA Woods Hole, Massachusetts 02543, USA
‡Northeast Fisheries Center, NMFS/NOAA Sandy Hook, New Jersey 07732, USA
§University of Maryland, Center for Environmental Studies, Cambridge, Maryland 21613, USA
Earth System Model (IPCC, 2007)

Changes in the Atmosphere:
- Composition
- Circulation

Changes in the Hydrological Cycle

Volcanic Activity

Atmosphere

Atmosphere-Biosphere Interaction

Clouds

Human Influences

Atmosphere

N₂, O₂, Ar, H₂O, CO₂, CH₄, N₂O, O₃, etc.

Aerosols

Terrestrial Radiation

Heat Exchange

Wind Stress

Precipitation Evaporation

Ice-Ocean Coupling

Hydrosphere: Ocean

Changes in the Cryosphere:
- Snow
- Frozen Ground
- Sea Ice
- Ice Sheets
- Glaciers

Land Surface

Biosphere

Land-Atmosphere Interaction

Changes in/on the Land Surface:
- Orography
- Land Use
- Vegetation
- Ecosystems

Changes in the Ocean:
- Circulation
- Sea Level
- Biogeochemistry

23-25 Mar 2008
Mitzpe Ramon

2nd Kaplan Workshop:
Environmental Geochemistry
Increasing loads of OC and N in Baltic Sea sediment study (Struck et al., 2000).
Global C-cycle w/CM

(Pg C or PgC/yr)

Global Carbon Cycle Model

- Atmosphere (+3.2)
- Net = 0.3 Pg/yr
- Net = 1.3 Pg/yr

- Land (+2.6-1.6)
- Microbial activity (+0.05)
- Surface layer of ocean interior (+0.55)
- Intermediate & deep ocean (+1.6)

- Crust (1990s with margins)
- Marine
- Terrigenous
- Anthropogenic

Net = 1.3 Pg/yr

Net = 0.3 Pg/yr
Figure 9. Export production of particulate organic matter (POM) [mol C m$^{-2}$ yr$^{-1}$] for the global model.
benthic O\textsubscript{2} Flux [mol O\textsubscript{2} m\textsuperscript{-2} yr\textsuperscript{-1}]
Differences between Arabian Sea & Bay of Bengal

Arabian Sea

Nitrate (μM)

Nitrite (μM)

Depth (m)

W. Naqvi
3. Feedbacks to the Earth System

4. Responses of Society

2. Sensitivity to Global Change

1. Interactions between Biogeochemical Cycles and Marine Food Webs
Continental margins as a nutrient pump

(Walsh, 1991)

(Liu et al., 2007)
Land-Ocean: LOICZ

- Vulnerability of coastal systems & hazards to human societies
- Implications of global change & land & sea use on coastal development
- Anthropogenic influences on the river catchment & coastal zone interaction
- Fate & transformation of materials in coastal & shelf waters
- Towards coastal system sustainability by managing land-ocean interactions

44% of the world’s population live within 150 km of a coastline