River-dominated Ocean Margins (RiOMar): Linkages with Global Climate Change

Brent McKee
Center for River-Ocean Studies (CeROS)
Tulane University
Many ways to characterize margins (in red)

**Tectonics:** Active vs. Passive  
**Geomorphology:** Narrow vs. Wide  
**Biogeochemistry:** Recycling vs. Exporting
“Major Rivers”: rivers whose input fluxes have a significant impact on the ocean (freshwater, sediments, dissolved or particulate materials)
Rivers: the active interface between land and oceans (the 2 largest global sinks for atmospheric CO₂)

~87% of Earth’s land surface is connected to the ocean by rivers
World’s 10 Largest Rivers transport ~ 40% of freshwater and particulate materials that reach the ocean
## Top 25 Major World Rivers

> 50% of freshwater and particulate flux

<table>
<thead>
<tr>
<th>RIVER</th>
<th>Sediment* Discharge 10^6 t yr⁻¹</th>
<th>Sediment* Discharge Rank</th>
<th>Water* Discharge 10^9 m³ y⁻¹</th>
<th>Water* Discharge Rank</th>
<th>Drainage Basin Area 10^6 km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amazon</td>
<td>1150</td>
<td>1</td>
<td>6300</td>
<td>1</td>
<td>6.15</td>
</tr>
<tr>
<td>Zaire</td>
<td>43</td>
<td>22</td>
<td>1250</td>
<td>2</td>
<td>3.82</td>
</tr>
<tr>
<td>Orinoco</td>
<td>150</td>
<td>11</td>
<td>1200</td>
<td>3</td>
<td>0.99</td>
</tr>
<tr>
<td>Ganges-Brahmaputra</td>
<td>1050</td>
<td>3</td>
<td>970</td>
<td>4</td>
<td>1.48</td>
</tr>
<tr>
<td>Yangtze (Changjiang)</td>
<td>480</td>
<td>4</td>
<td>900</td>
<td>5</td>
<td>1.94</td>
</tr>
<tr>
<td>* Yenisey</td>
<td>5</td>
<td>6</td>
<td>630</td>
<td>6</td>
<td>2.58</td>
</tr>
<tr>
<td>Mississippi</td>
<td>210</td>
<td>7</td>
<td>530</td>
<td>7</td>
<td>3.27</td>
</tr>
<tr>
<td>* Lena</td>
<td>11</td>
<td>8</td>
<td>510</td>
<td>8</td>
<td>2.49</td>
</tr>
<tr>
<td>Mekong</td>
<td>160</td>
<td>9</td>
<td>470</td>
<td>9</td>
<td>0.79</td>
</tr>
<tr>
<td>Parana/Uruguay</td>
<td>100</td>
<td>14</td>
<td>470</td>
<td>10</td>
<td>2.83</td>
</tr>
<tr>
<td>* St. Lawrence</td>
<td>3</td>
<td>11</td>
<td>450</td>
<td>12</td>
<td>0.43</td>
</tr>
<tr>
<td>Irrawaddy</td>
<td>260</td>
<td>5</td>
<td>430</td>
<td>12</td>
<td>0.43</td>
</tr>
<tr>
<td>* Ob</td>
<td>16</td>
<td>13</td>
<td>400</td>
<td>13</td>
<td>2.99</td>
</tr>
<tr>
<td>Amur</td>
<td>52</td>
<td>20</td>
<td>325</td>
<td>14</td>
<td>1.86</td>
</tr>
<tr>
<td>Mackenzie</td>
<td>100</td>
<td>13</td>
<td>310</td>
<td>15</td>
<td>1.81</td>
</tr>
<tr>
<td>Pearl (Xi Jiang)</td>
<td>80</td>
<td>16</td>
<td>300</td>
<td>16</td>
<td>0.44</td>
</tr>
<tr>
<td>Salween</td>
<td>100</td>
<td>15</td>
<td>300</td>
<td>17</td>
<td>0.28</td>
</tr>
<tr>
<td>Columbia</td>
<td>8</td>
<td>18</td>
<td>250</td>
<td>18</td>
<td>0.67</td>
</tr>
<tr>
<td>Indus</td>
<td>50</td>
<td>21</td>
<td>240</td>
<td>19</td>
<td>0.97</td>
</tr>
<tr>
<td>Magdalena</td>
<td>220</td>
<td>6</td>
<td>240</td>
<td>20</td>
<td>0.24</td>
</tr>
<tr>
<td>Zambezi</td>
<td>20</td>
<td>21</td>
<td>220</td>
<td>21</td>
<td>1.2</td>
</tr>
<tr>
<td>Danube</td>
<td>40</td>
<td>24</td>
<td>210</td>
<td>22</td>
<td>0.81</td>
</tr>
<tr>
<td>Yukon</td>
<td>60</td>
<td>19</td>
<td>195</td>
<td>23</td>
<td>0.84</td>
</tr>
<tr>
<td>Niger</td>
<td>40</td>
<td>25</td>
<td>190</td>
<td>24</td>
<td>1.21</td>
</tr>
<tr>
<td>* Purari/Fly</td>
<td>110</td>
<td>12</td>
<td>150</td>
<td>25</td>
<td>0.09</td>
</tr>
<tr>
<td>* Yellow (Huang He)</td>
<td>1100</td>
<td>2</td>
<td>49</td>
<td>2</td>
<td>0.77</td>
</tr>
<tr>
<td>* Godavari</td>
<td>170</td>
<td>8</td>
<td>92</td>
<td>8</td>
<td>0.31</td>
</tr>
<tr>
<td>Red (Hunghe)</td>
<td>160</td>
<td>10</td>
<td>120</td>
<td>10</td>
<td>0.12</td>
</tr>
<tr>
<td>Copper</td>
<td>70</td>
<td>17</td>
<td>39</td>
<td>17</td>
<td>0.06</td>
</tr>
<tr>
<td>Choshui</td>
<td>66</td>
<td>18</td>
<td></td>
<td></td>
<td>0.003</td>
</tr>
<tr>
<td>Liao He</td>
<td>41</td>
<td>23</td>
<td>6</td>
<td>6</td>
<td>0.17</td>
</tr>
</tbody>
</table>

In RiOMar Environments, rivers serve to connect all four compartments of the Carbon Cycle: Land, Ocean, Atmosphere, and Sediments.
Do River-Ocean Margins Play an Important Role in the Ocean Carbon Cycle and in Climate Change?

I. What we know and what we need to know about:

a. The Carbon Cycle in RiOMar systems

b. Climate change: Effects on RiOMar systems and possible feedbacks

c. The Human Dimension: impacts (past and future)

II. What is the best approach to answer critical questions?
   Where to focus efforts
   How to examine
River Inputs
Net Atm-Ocean Exchange
Burial
Net Export to Ocean

Carbon Fluxes

Atmosphere

Land
Ocean
Sediments

Carbon Cycle in RiOMar Systems
What is the magnitude of these fluxes?
What controls them?
How will each be affected by global changes (climate and human)?

River Inputs
Net Air-Sea Exchange
Burial
Net Export to Ocean

Carbon Cycle in RiOMar Systems
River Inputs
Riverine C flux same order as net air-to-sea CO$_2$ transfer

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>“Best” Value</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Tg C yr$^{-1}$)</td>
<td>(Tg C yr$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>Dissolved Inorganic Carbon (DIC)</td>
<td>381-410</td>
<td>400</td>
<td>1,2,3</td>
</tr>
<tr>
<td>Total Organic Carbon (TOC)</td>
<td>200-530</td>
<td>550</td>
<td>2,3,4,5</td>
</tr>
<tr>
<td>Particulate Organic Carbon (POC)</td>
<td>138-288</td>
<td>250</td>
<td>4,6,7</td>
</tr>
<tr>
<td>Dissolved Organic Carbon (DOC)</td>
<td>214-360</td>
<td>300</td>
<td>2,4,8,9,10</td>
</tr>
<tr>
<td>Total Riverine Carbon Input to the Ocean</td>
<td>950</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

% anthropogenic?

1 Meybeck, 1993
2 Meybeck and Vörösmarty, 1999
3 Degens et al., 1991
4 Spitzy and Ittekkot, 1991
5 Schlunz and Schneider, 2000
6 Lyons et al., 2002 (and references within)
7 Ittekkot and Laane, 1991
8 Spitzy and Leenheer, 1991
9 Aitkenhead and McDowell, 2000
10 Hedges et al, 1997
11 Stallard, 1998
12 Berner, 1982
13 Hedges and Keil, 1995
14 Berger, 1989
How well is the magnitude of river carbon fluxes known?

- Large number of studies have measured concentrations
  - Concentrations measured---not fluxes
  - Temporal coverage is inadequate (especially seasonal and event scale)
  - Spatial coverage is poor. Some major river systems relatively well studied; others are completely unknown
How well is the magnitude of river carbon fluxes known?

- “Dissolved” fluxes best quantified; measuring colloidal and particulate fluxes is problematic (> > factor of 3 uncertainty)

- Very poor understanding of riverine organic matter lability

  Estimates range from 35 – 70% of river POC input ----depending on definition and timescale
How well is the magnitude of river carbon fluxes known?

- Great uncertainties in sediment discharge estimates
  - Amazon: ~12 discharge-weighted measurements (Meade, 1996)
  - Irrawaddy: data > 150 years old
  - Orinoco: great uncertainties 150 ± 50
  - Salween: just a guess

- Inherent problem with “endmember” river stations
What is the magnitude of these fluxes?

What controls them?

How will each be affected by global changes (climate and human)?

River Inputs
Atm-Ocean Exchange
Burial
Net Export to Ocean

Carbon Cycle in RiOMar Systems
Riverine Flux to the Ocean: Product of Many Processes

Watershed processes
- Weathering/erosion
- Transport (water and particulates)
- Exchange (surface and groundwater)
- Storage (alluvial/colluvial/floodplain)
- Biogeochemical transformations
- Aggregation/coagulation/settling
- CO₂ evasion
Within the Watershed

Two major terrestrial processes that sequester atmospheric CO$_2$

1) Net Organic C production

- Stored on land or
- Exported via rivers

2) Terrestrial production of excess Alkalinity during chemical weathering

- Can be transported to ocean margin
  - Weathering of silicates sequester atm CO$_2$ longer (millions of years) than the weathering of carbonates (100’s to 1000’s years) because of reverse weathering in margins
Examining River Inputs: Different Perspectives (Measuring fluxes vs. predicting fluxes)

November 1-3, 2001
New Orleans, LA

Hosted by
Tulane

Funded by
NSF
NASA

http://www.tulane.edu/~riomar

www.tulane.edu/~riomar
Predict Changes in Riverine Flux?

Strong Interactions Between Subsystems

Non-linear Responses to Change
DOC Fluxes strongly influenced by drainage intensity (discharge rate per unit area of the watershed), basin slope and the carbon stored in soils.

*Ludwig et al., 1996*
POC Fluxes mainly governed by **drainage intensity** and **sediment yield**

Factors controlling sediment yield:

- **Climate** (rainfall variability and runoff intensity)
- **Geology**
- **Basin relief** (elevation and slope)
- **Land Use** (including vegetation cover)
- **Pleistocene history**
Surface area?

In situ production?

Dilution?
World Average

DOC : POC ~ 1

Range 0.1 – 10.0

<table>
<thead>
<tr>
<th>TSM range (mg/l)</th>
<th>DOC/POC</th>
</tr>
</thead>
<tbody>
<tr>
<td>5–15</td>
<td>10.8</td>
</tr>
<tr>
<td>15–50</td>
<td>5.8</td>
</tr>
<tr>
<td>50–150</td>
<td>3.4</td>
</tr>
<tr>
<td>150–500</td>
<td>2.3</td>
</tr>
<tr>
<td>500–1500</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Ittekkot, 1988
Predicted climate changes that affect RiOMar systems

Temperature: direction and magnitude of change, variability

Precipitation: direction and magnitude of change, variability and form (snow/rain)

Change in phases: ice/water, permafrost

Hydrological cycle: discharge peak and timing
Changes in mean temperature

**Predicted:** more warming over land compared to oceans, and more warming over polar regions

Temperature Change (2020-2030 relative to 1990-2000)

Zweirs et al. 2002
Changes in mean precipitation

**Predicted:** Increase in precipitation over high latitude regions and decrease in tropics and subtropics

Change in annual precipitation pattern due to climate warming. 2070-2100 minus 1960-1990 in CGCM1 (mm/day)

Arora et al. (2003)
Changes in mean and variability of temperature and precipitation

- No general conclusion in regards to what may happen to variability (T and P) within drainage basins in a warmer world

- However, both extreme temperature and precipitation events are expected to increase in frequency
Changes in mean streamflow

The 23 major river basins selected for this study

Streamflow a function of:
- Runoff (precipitation – evaporation)
- Basin Geomorphology (river slope)

Arora et al, 2003
Changes in mean streamflow

Mean annual discharge of 9 out of 23 rivers goes DOWN (most of these are tropical and subtropical rivers)

Arora et al, 2003
Changes in mean streamflow

Mean annual discharge of 6 out of 23 rivers goes UP (most of these are mid-high latitude rivers)

Arora et al, 2003
Changes in streamflow seasonality

Mid-high latitude rivers

Seasonality of streamflow for river basins characterized by snow changes significantly.

Arora et al, 2003
Changes in streamflow seasonality

Tropical and low latitude rivers

Seasonality of streamflow for tropical and subtropical rivers doesn’t change considerably, however, for most rivers the amplitude of the annual cycle decreases.

Arora et al, 2003
Implications for delivery of material

- Increase in warming and NPP, and increase in discharge of high-latitude rivers, is expected to increase delivery of DOC

- NPP of tropical and subtropical regions expected to be adversely affected by warming and reduction in rainfall. Delivery of POC and DOC is generally expected to be reduced

- An increase in extreme precipitation events may lead to an increase in sediment load due to erosion but the change in discharge will also play an important role
Two examples of processes that may be altered in response to global change---resulting in river flux changes

1) Terrestrial Sediment Storage

2) Deposition and Diagenesis in lower river
1) Terrestrial Storage

- 80 – 90% of the sediment presently being eroded off the land surface is being stored somewhere between the uplands and the sea (Meade et al., 1990; Milliman and Syvitski, 1992)

- ~1 Pg C potentially stored within river systems annually (estimate range: 0.6 – 1.5 Pg C/y⁻¹) (Stallard, 1995)

- ~4X annual river POC flux ---not in equilibrium

- Primarily in N. Hemisphere

- Storage where?
  - trapping (behind dams)
  - land use changes (rice paddies)
  - storage in channels (slope/flow changes)

- Storage time? When remobilized-----during large floods?
2) Deposition and Diagenesis in the lower river

The “Missing Link”
Any Transformation, Loss or Addition that occurs within the lower river is not reflected in traditional flux estimates.
Net loss of surface suspended particulate material over lower 400 km of Mississippi River

(Dagg et al., 2005)
Preferential settling of larger particulate material

Size fractionated chlorophyll a

Chlorophyll concentration (mg l⁻¹) vs. River km

Downriver Sampling June 2003
(Dagg et al., 2005)
> 15% of Annual Sediment Discharge is Deposited in Lower River during Low Flow Stages
Newly Deposited Sediments Remain on the Riverbed from 1 to 6 months (mean ~ 3 months)

Seasonal Storage
Strong evidence for substantial Remineralization during seasonal storage

Net change in: Phase (particulate to dissolved/colloidal); Reactivity?

Porewater Profiles in Repeat Cores from Lower River (May and November 1999)

Increases in Porewater Concentrations Over 162 Days:
• 2 fold for PO₄
• 5-6 fold for NH₄ and SiO₄
• 15 fold for Mn
• 20 fold of Fe
During rising discharge (higher shear stresses):

- Advection of Porewater Constituents
- Remobilization and Delivery as Mobile or Fluid Mud
On the Adjacent Shelf......

**River Export Flux to the Ocean from River Mouths:**
*Product of Many Processes*

**Water Column processes**
- Net atmosphere-ocean exchange
- Primary production
- Grazing
- Microbial and photochemical transformations
- Transport (water and particulates)
- Sorption – Desorption
- Aggregation/coagulation/settling

**Benthic processes**
- Deposition and Resuspension
- Diagenesis
- Flux across sediment-water interface
- Burial / Storage
- BBL Export
What is the magnitude of these fluxes?
What controls them?
How will each be affected by global changes (climate and human)?
Net Atmosphere-Ocean Exchange


What about RiOMar environments?

High productivity fueled by riverine nutrients and nutrient upwelled nutrients from buoyancy effect (Chen et al. 2003)
What is the magnitude of these fluxes?
What controls them?
How will each be affected by global changes (climate and human)?
Benthic Boundary Layer (BBL) /Seabed Processes:
## Burial

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>“Best” Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Tg C yr⁻¹)</td>
<td>(Tg C yr⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Burial in River-Margin Sediments</td>
<td>98-159</td>
<td>115</td>
<td>5,12,13</td>
</tr>
<tr>
<td>Allochthonous Organic Carbon</td>
<td>43-104</td>
<td>60</td>
<td>5,12</td>
</tr>
<tr>
<td>Autochthonous Organic Carbon</td>
<td>55</td>
<td>55</td>
<td>5,14</td>
</tr>
</tbody>
</table>

### Note:
- **Org. C input ~ 550 Tg C yr⁻¹**
- **Primary Production**
- **Terrestrial: Marine Org. C in RiOMar sediments ~ 1:1**

---

1. Meybeck, 1993
2. Meybeck and Vörösmarty, 1999
3. Degens et al., 1991
4. Spitzy and Ittekkot, 1991
5. Schlunz and Schneider, 2000
6. Lyons et al., 2002 (and references within)
8. Spitzy and Leenheer, 1991
9. Aitkenhead and McDowell, 2000
10. Hedges et al., 1997
11. Stallard, 1998
12. Berner, 1982
Burial  (what we need to know)

1. About 75-80% of modern Org. C burial is in RiOMar sediments? However, strong evidence for extensive and rapid remineralization-------what is the balance?

2. Only ~10% of terrestrial Org. C identified as buried Remainder is either:
   - oxidized (mechanisms not completely known)
   - exported
   - or unrecognized as terrestrial
Burial  (what we need to know)

3. Surprisingly few carbon budgets for major river ocean systems
   a) those that exist have either raised important questions (where did all the Amazon carbon go?) or
   b) have large gaps to fill----burial flux is usually one

   Burial fluxes poorly constrained

4. Bulk carbon burial budgets exist for ~10 of top 25 RiOMar systems
   a) only 2-3 of these are reasonably complete

5. Complications due to analytical challenge of identifying % of terrestrial vs. marine Org C buried
Burial (how much is preserved)

Preservation less than other similar sedimentary environments

- Co-metabolism
- Role of metal oxides as oxidants
- Resuspension

Aller, 1998
About 60% of terrestrial POC is oxidized within RiOMars

Some replacement by marine Org. C as coatings

Keil et al., 1997

Aller and Blair, 2005
Terrestrial $C_{\text{org}}$ loading decreases progressively (~ order of magnitude) 100’s of km down dispersal system

Mechanism?

Fluid Muds?

Aller and Blair, 2005
What is the magnitude of these fluxes?

What controls them?

How will each be affected by global changes (climate and human)?
Export

1. “Continental Shelf Pump”  
   (Tsunogai et al., 1999)

2. Turbidity currents down submarine canyons  
   (Congo, Ganges-Brahmaputra, Mississippi ?)

3. Transport over narrow shelves  
   (high mountainous rivers)

4. Transported by sea-ice  
   (high latitude rivers)

5. Unrecognized mechanisms  
   (low frequency; event scale)
Particulate Organic Carbon Export

Type I: Deltaic

Type II: Subaqueous

Type III: Shelf Escape A

Type IV: Combined

McKee et al. 2004
### Particulate Export

As many as 10 out of 25 largest rivers (sediment discharge) may be Type III or IV.

**RIVER** | **Sediment* Discharge** | **Burial** | **Location** | **Type**
--- | --- | --- | --- | ---
Amazon, Brazil | 1150 | II | | |
Zaire, Zaire | 43 | IIIb | | |
Orinoco, Venezuela | 150 | I | | |
Ganges-Brahmaputra, Bangladesh | 1050 | IV(I,II,III) | | |
Yangtze, China | 480 | II | | |
Yenisey, USSR | 5 | II | | |
Mississippi, USA | 210 | Atchafalaya (I) | Balize (IIIa) | |
Lena, USSR | 11 | I | | |
Mekong, Vietnam | 160 | I (or IV?) | | |
Parana/Uruguay, Brazil | 100 | II? | | |
St. Lawrence, Canada | 3 | minimal | | |
Irrawaddy, Burma | 260 | I (or IV?) | | |
Ob, URRS | 16 | II | | |
Amur, USSR | 52 | II | | |
Mackenzie, Canada | 100 | I | | |
Pearl (Xi Jiang), China | 80 | II? | | |
Salween, Burma | 100 | (I or IV?) | | |
Columbia, USA | 8 | II | | |
Indus, Pakistan | 50 | IIIb | | |
Magdalena, Colombia | 220 | I | | |
Zambezi, Mozambique | 20 | II? | | |
Danube, Romania | 40 | I | | |
Yukon, USA | 60 | I | | |
Niger, Africa | 40 | I | | |
Purari/Fly, New Guinea | 110 | II | | |
Yellow (Huang He), China | 1100 | IV(I,II) | | |
Godavari, India | 170 | I (or IV) | | |
Red (Hunghe) Vietnam | 160 | II? | | |
Copper, USA | 70 | I | | |
Choshui, Taiwan | 66 | ? | | |
Liao He, China | 41 | ? | | |

McKee et al. 2004
What is the best approach to answer critical questions?
Where to focus efforts

- Focused studies of whole systems (along with some strategic comparative studies of subsystems or processes between RiOMar systems)

- Which systems? (can’t do top 25---probably not even top 10)
Arctic
- Changes will be seen first (already observed)
- Biggest climate stresses, different responses—less well known (e.g., Ice; Permafrost; larger CO$_2$ sink as ice free period lengthens?)
Arctic

- Importance of shelves
- Yukon and Mackenzie (NA and important fluxes)
Temperate and Subtropical

- Good quality data bases
- Large human impacts
- Mississippi (NA, 2 river approach)
  - Logistics
Wet Tropics

- Largest Fluxes
  (~40% DOC; ~50% POC)

- Most dramatic increase in human impacts

- Drier climate effects
Most Previous Studies of Large River Systems Conducted in the “Expedition” Mode
Observation networks (coordinated with NACP--observatories further up river system)
High frequency data collection + process studies in major river margins (enduring legacy of JGOFS)
- Better Input flux estimates (magnitude, partitioning, composition, lability)
Process work

Have to be able to track Org. C through RiOMar system (at least from lower river across the margin)
Process work
Multi-disciplinary; Inter-disciplinary
Earth and Ocean scientists

- Moored Time-Series
- Shipboard Time-Series
- VOS surface pCO₂
- Remote sensing
- Repeat Trans-basin Sections
- Process Studies
- Time
  - centuries
  - decadal
  - Inter-annual
  - seasonal
  - daily
  - hourly
- Space
  - 1 m²
  - 1 km²
  - Regional (10⁶ km²)
  - Ocean Basin
  - Globe

C.Sweeney
What is the best approach to answer critical questions?
How to examine

- Data archives (mining of rich data sets)
- High resolution sediment record
- Coupled physical, sediment transport and biogeochemical models