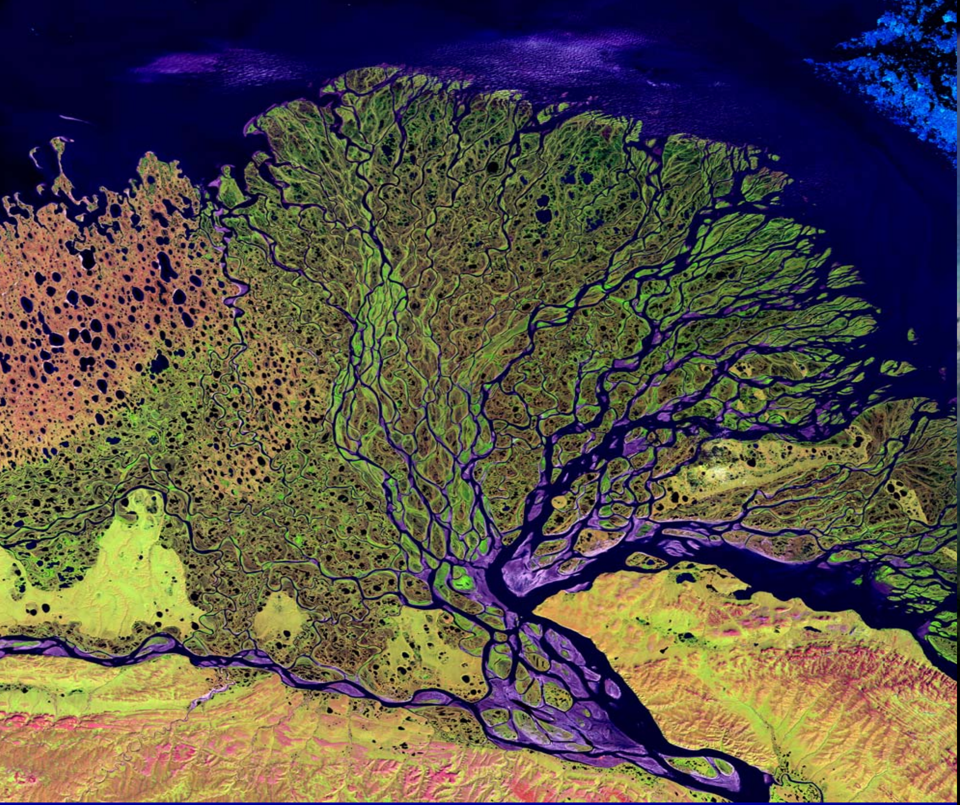
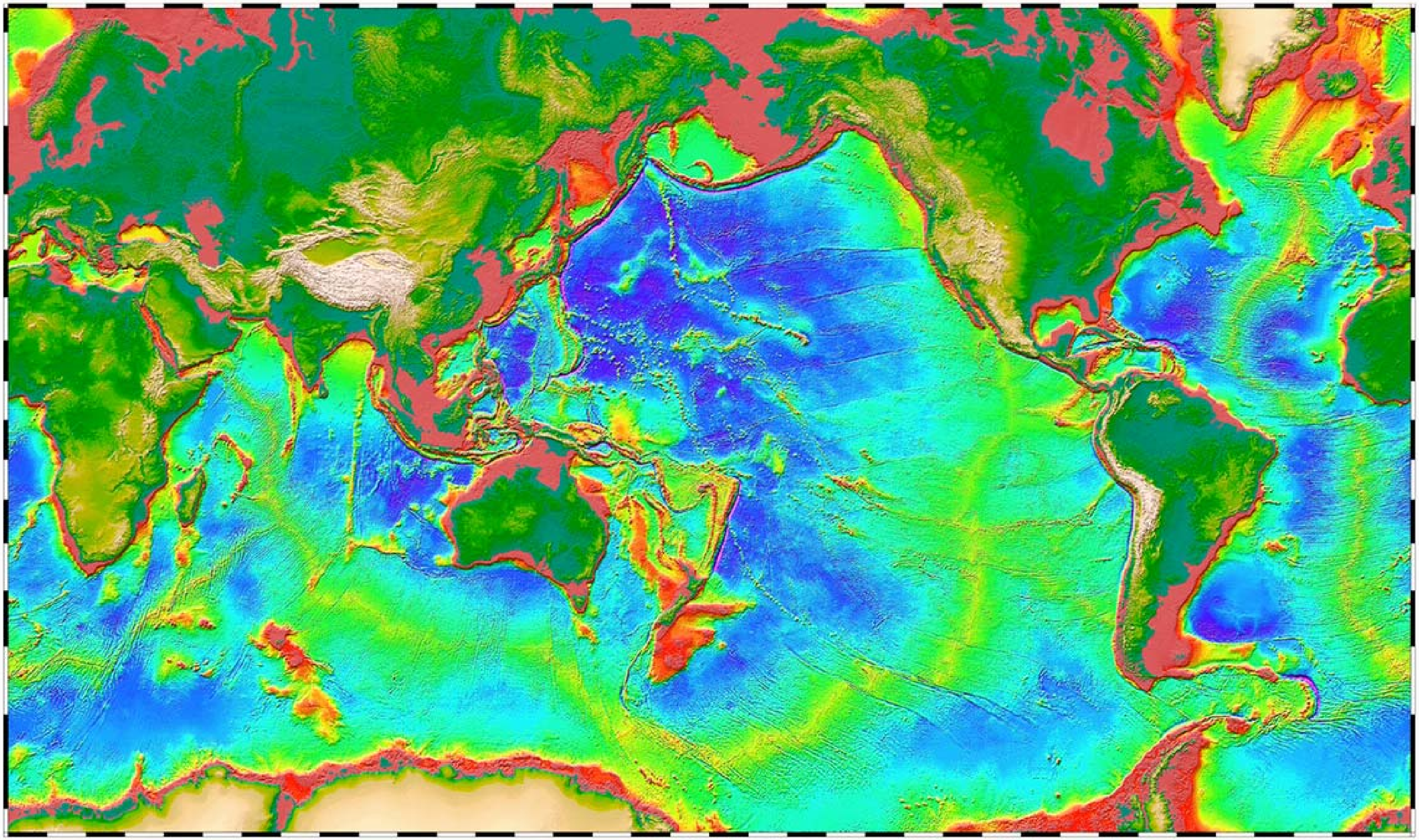


River-dominated Ocean Margins (RiOMar): Linkages with Global Climate Change

Brent McKee
Center for River-Ocean Studies (CeROS)
Tulane University

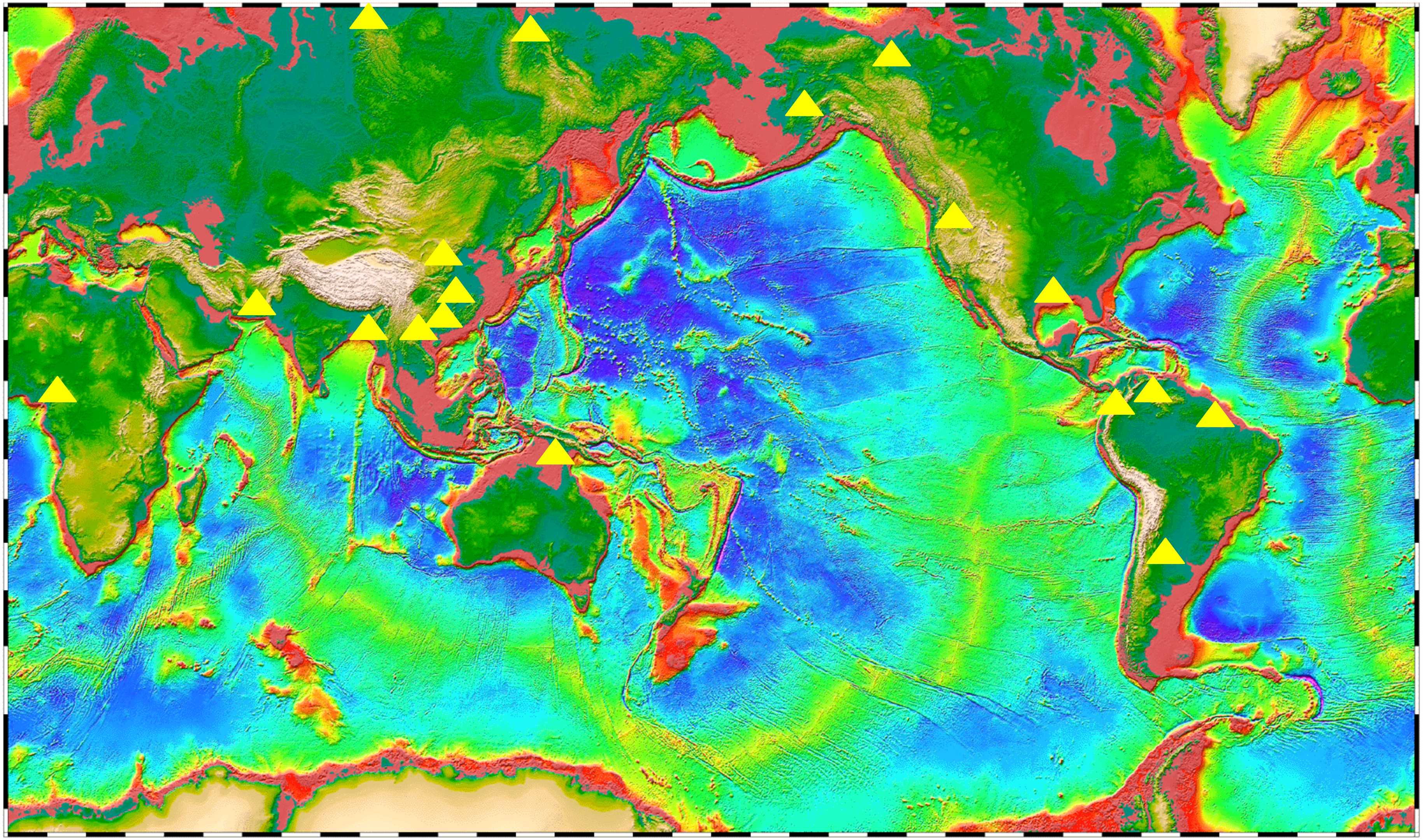
Many ways to characterize margins (in red)



Tectonics: ***Active vs. Passive*** **Geomorphology:** ***Narrow vs. Wide***

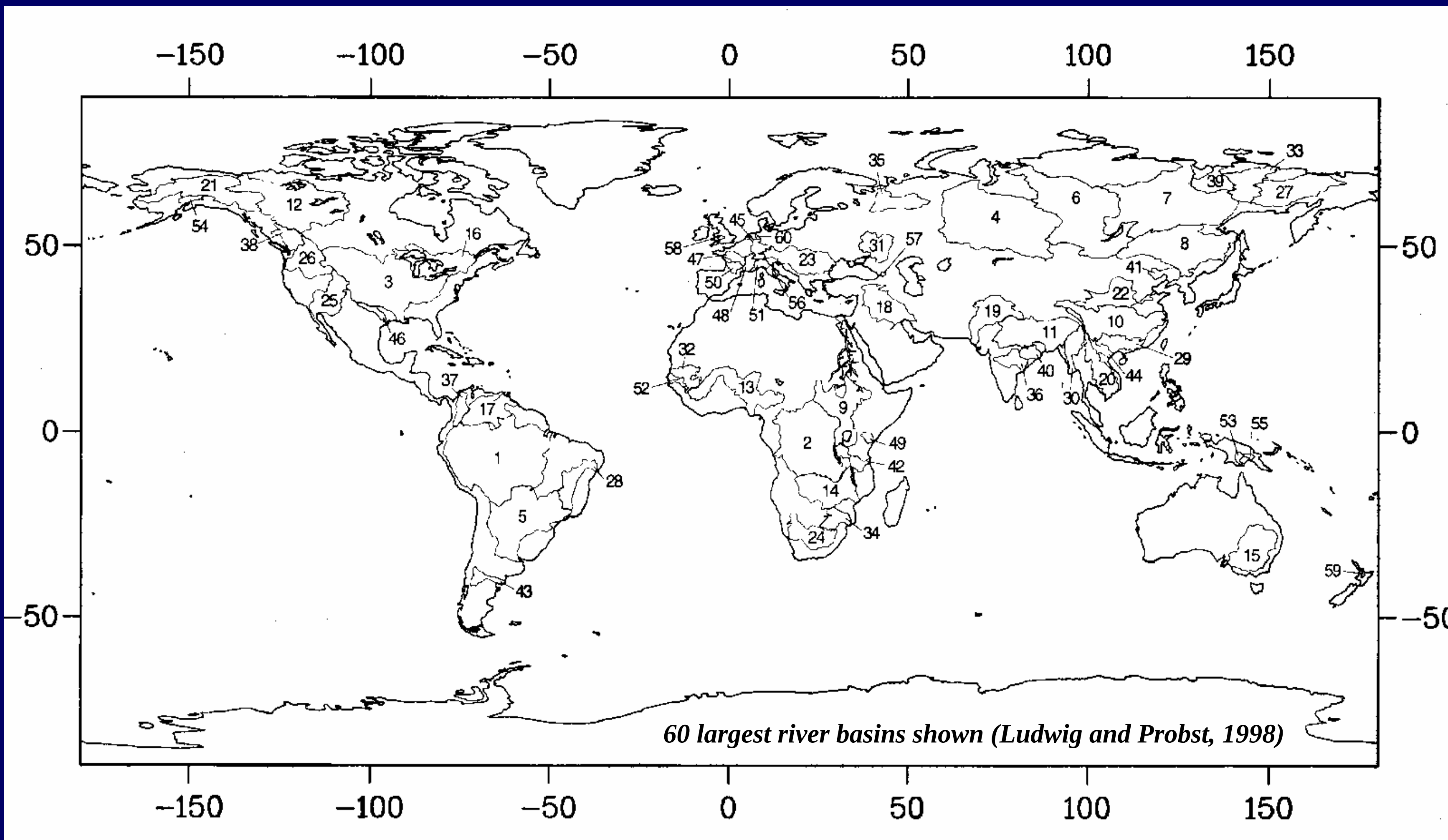
Biogeochemistry: ***Recycling vs. Exporting***

River-dominated Ocean Margins (RiOMar)



"Major Rivers": rivers whose input fluxes have a significant impact on the ocean (freshwater, sediments, dissolved or particulate materials)

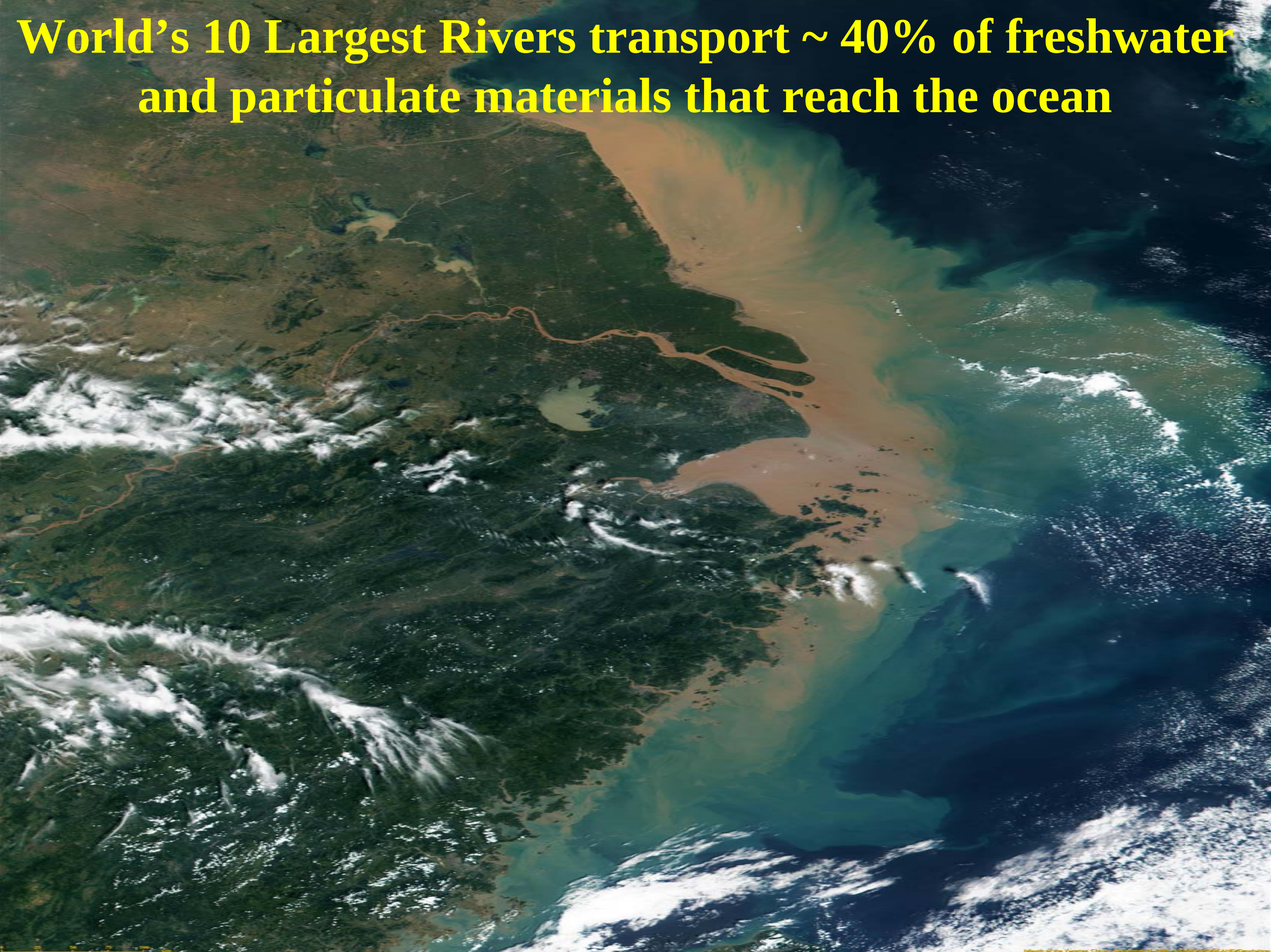
Rivers: the active interface between land and oceans (the 2 largest global sinks for atmospheric CO_2)



60 largest river basins shown (Ludwig and Probst, 1998)

~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



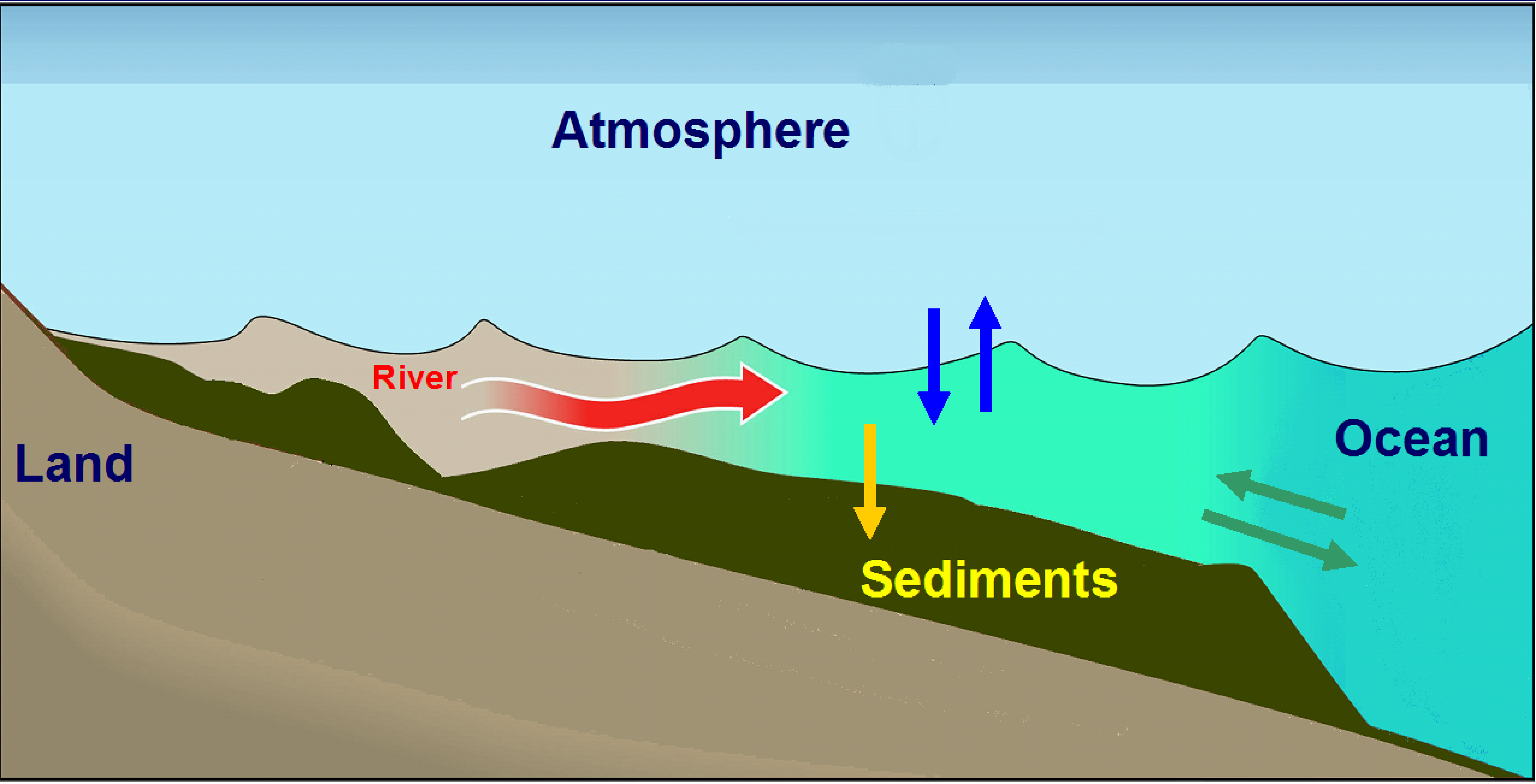
Top 25 Major World Rivers

> 50% of freshwater and particulate flux

	RIVER	Sediment* Discharge 10^6 t yr^{-1}	Sediment* Discharge Rank	Water* Discharge 10^9 m^3 y^{-1}	Water* Discharge Rank	Drainage* Basin Area 10^6 km^2
	Amazon	1150	1	6300	1	6.15
	Zaire	43	22	1250	2	3.82
	Orinoco	150	11	1200	3	0.99
	Ganges-Brahmaputra	1050	3	970	4	1.48
	Yangtze (Changjiang)	480	4	900	5	1.94
*	Yenisey	5		630	6	2.58
	Mississippi	210	7	530	7	3.27
*	Lena	11		510	8	2.49
	Mekong	160	9	470	9	0.79
	Parana/Uruguay	100	14	470	10	2.83
*	St. Lawrence	3		450	11	1.03
	Irrawaddy	260	5	430	12	0.43
*	Ob	16		400	13	2.99
	Amur	52	20	325	14	1.86
	Mackenzie	100	13	310	15	1.81
	Pearl (Xi Jiang)	80	16	300	16	0.44
	Salween	100	15	300	17	0.28
	Columbia	8		250	18	0.67
	Indus	50	21	240	19	0.97
	Magdalena	220	6	240	20	0.24
	Zambezi	20		220	21	1.2
	Danube	40	24	210	22	0.81
	Yukon	60	19	195	23	0.84
	Niger	40	25	190	24	1.21
*	Purari/Fly	110	12	150	25	0.09
*	Yellow (Huang He)	1100	2	49		0.77
*	Godavari	170	8	92		0.31
	Red (Hunghe)	160	10	120		0.12
	Copper	70	17	39		0.06
	Choshui	66	18			0.003
	Liao He	41	23	6		0.17

Data from
Milliman and Meade (1983)
Meade (1996)

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)

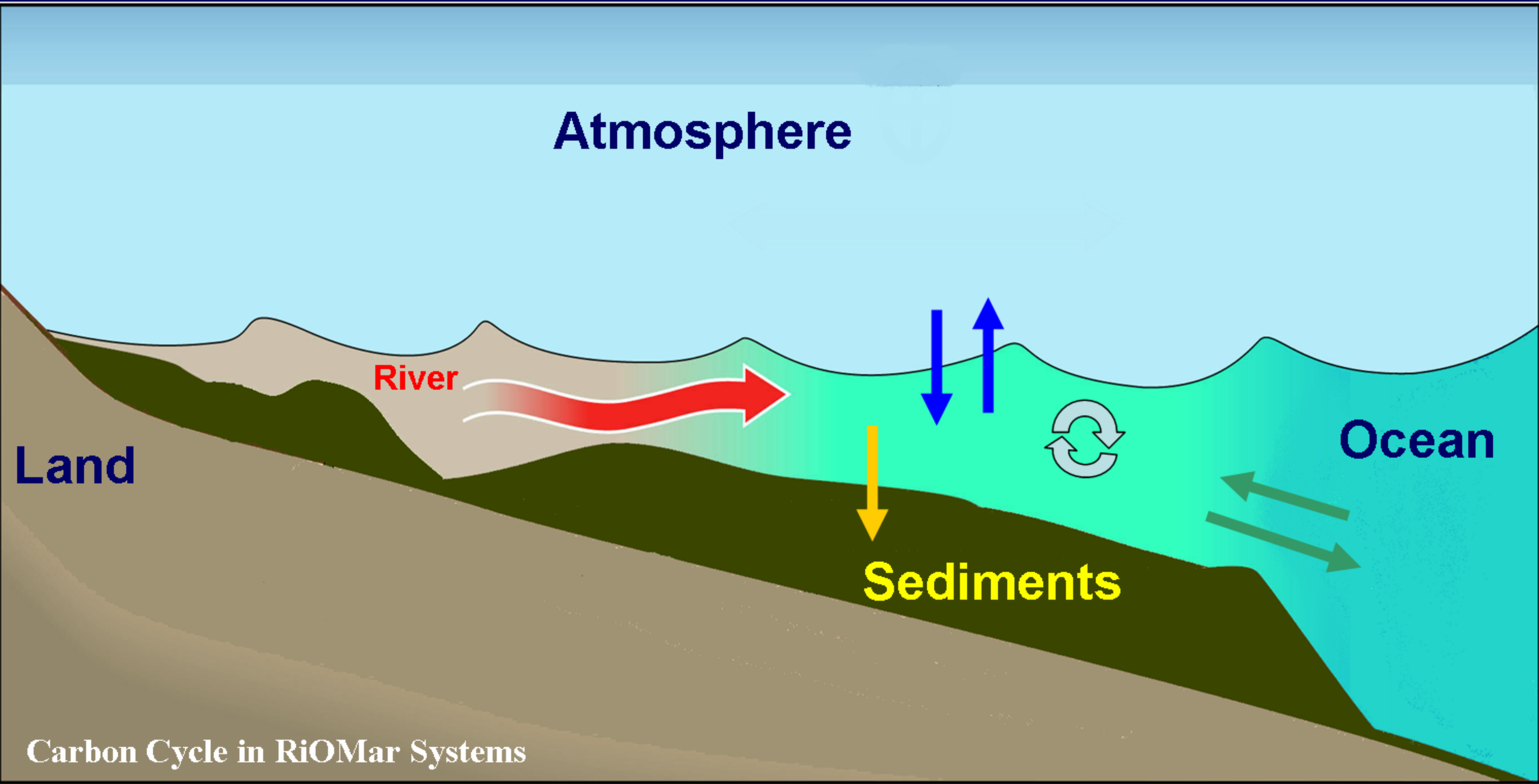
II. What is the best approach to answer critical questions?

Where to focus efforts

How to examine

Carbon Fluxes

- River Inputs
- Net Atm-Ocean Exchange
- Burial
- Net Export to Ocean

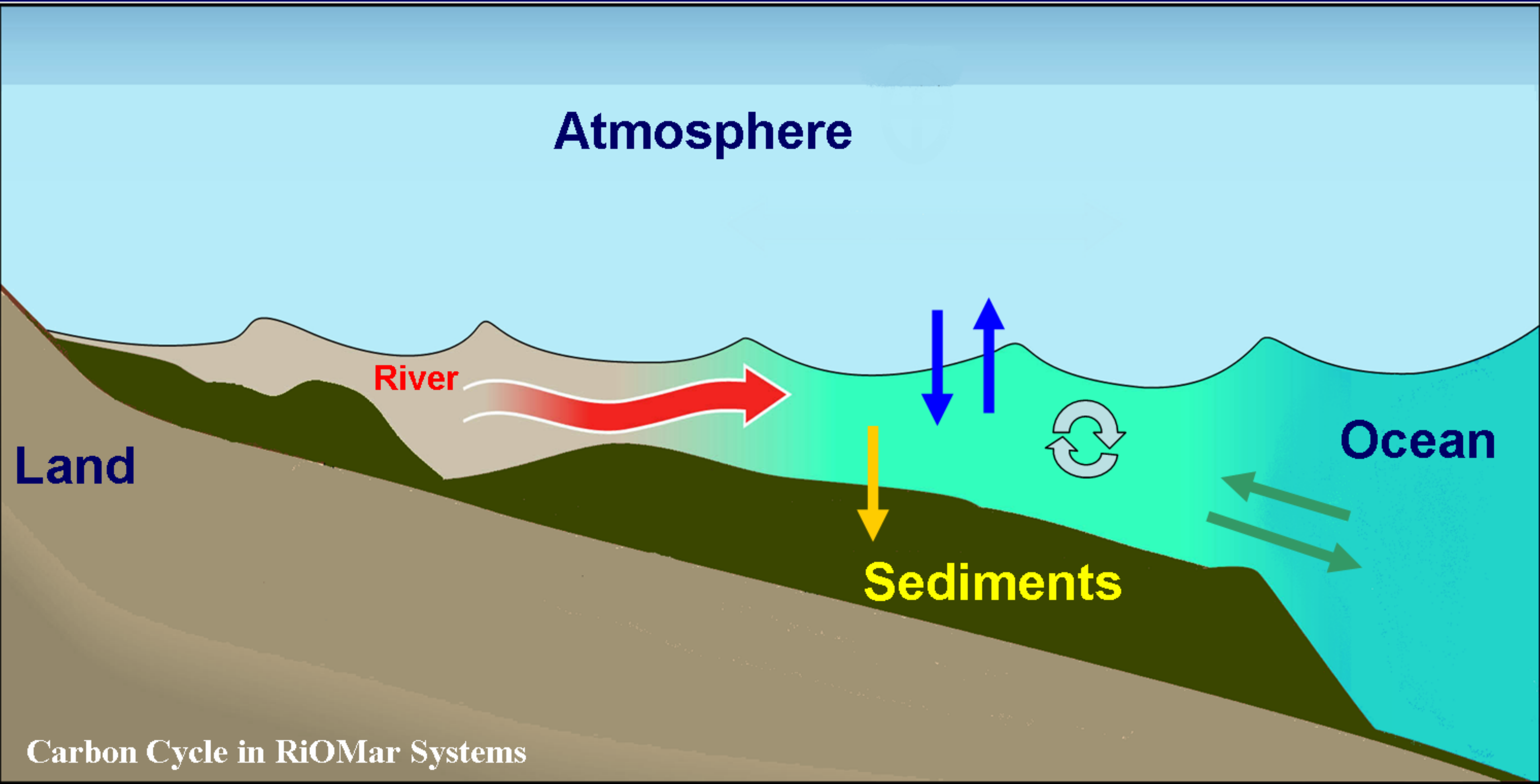


What is the magnitude of these fluxes?

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**




River
Inputs

Riverine C flux same order as net air-to-sea CO_2 transfer

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

% anthropogenic?

[1] Meybeck, 1993	[9] Aitkenhead and McDowell, 2000
[2] Meybeck and Vörösmarty, 1999	[10] Hedges et al, 1997
[3] Degens et al., 1991	[11] Stallard, 1998
[4] Spitzy and Ittekkot, 1991	[12] Berner, 1982
[5] Schlunz and Schneider, 2000	[13] Hedges and Keil, 1995
[6] Lyons et al., 2002 (and references within)	[14] Berger, 1989
[7] Ittekkot and Laane, 1991	
[8] Spitzy and Leenheer, 1991	

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

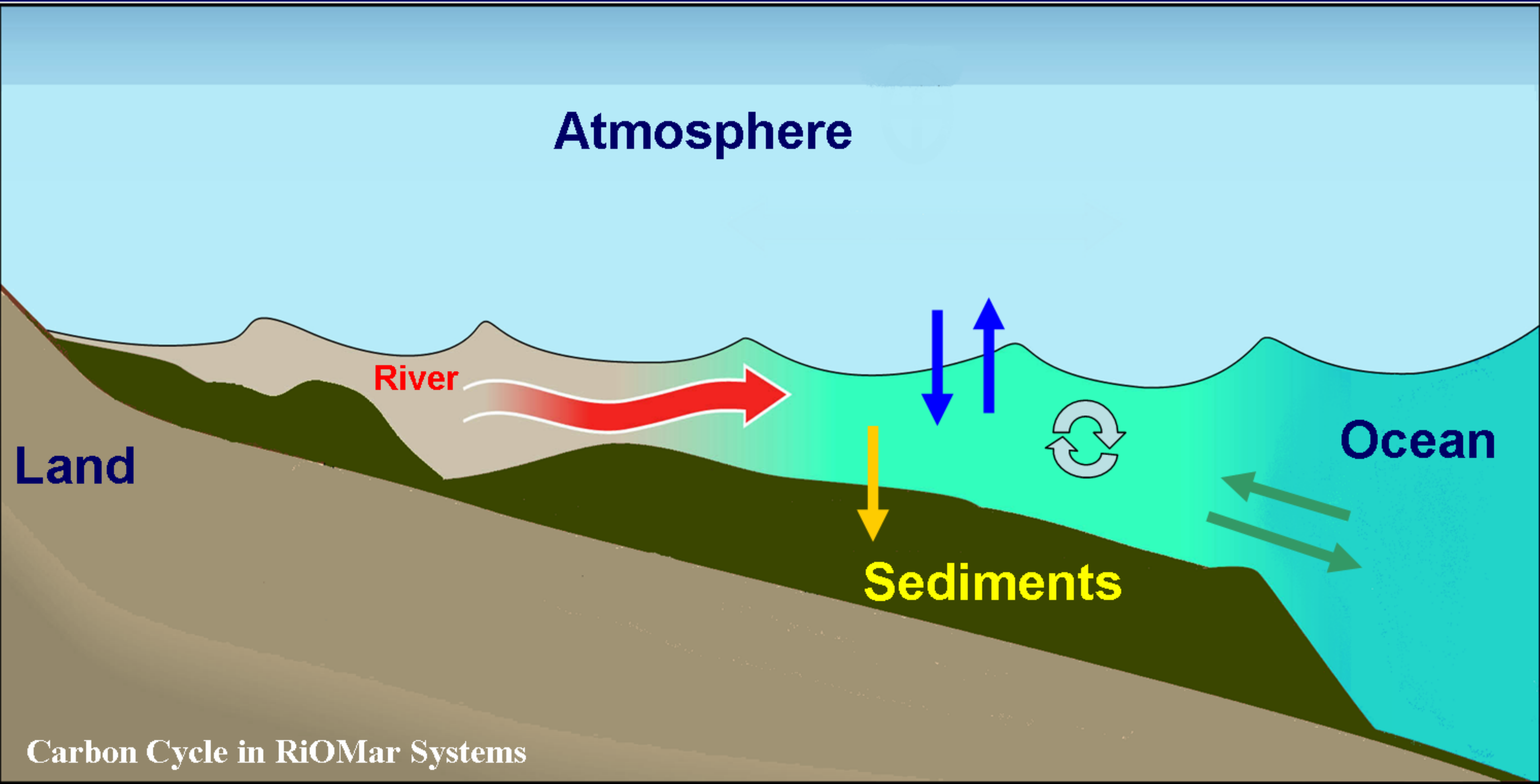
- **Inherent problem with "endmember" river stations**

What is the magnitude of these fluxes?

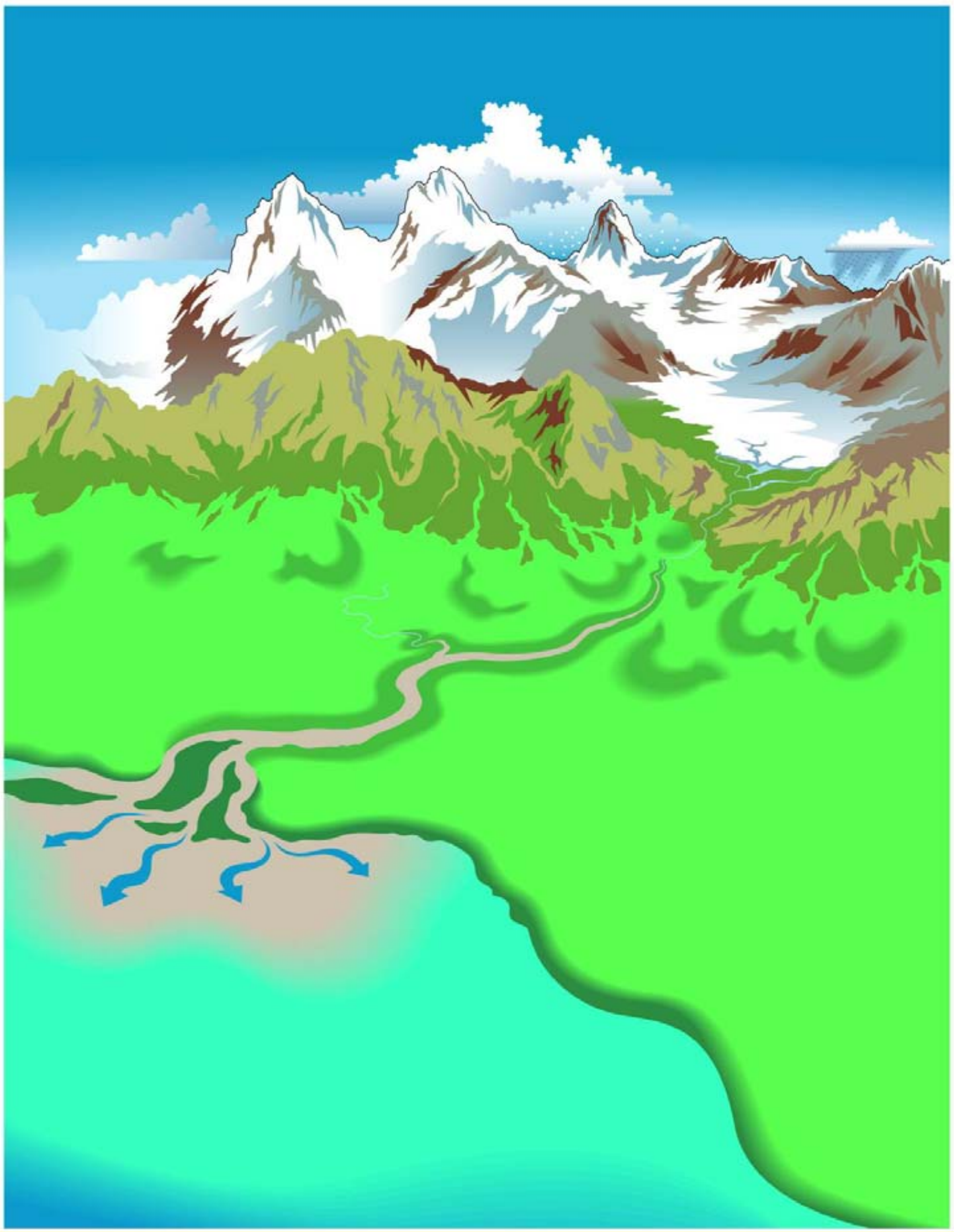
What controls them?

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

- River Inputs
- Atm-Ocean Exchange
- Burial
- Net Export to Ocean



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
- CO_2 evasion

Within the Watershed

Two major terrestrial processes that sequester atmospheric CO_2

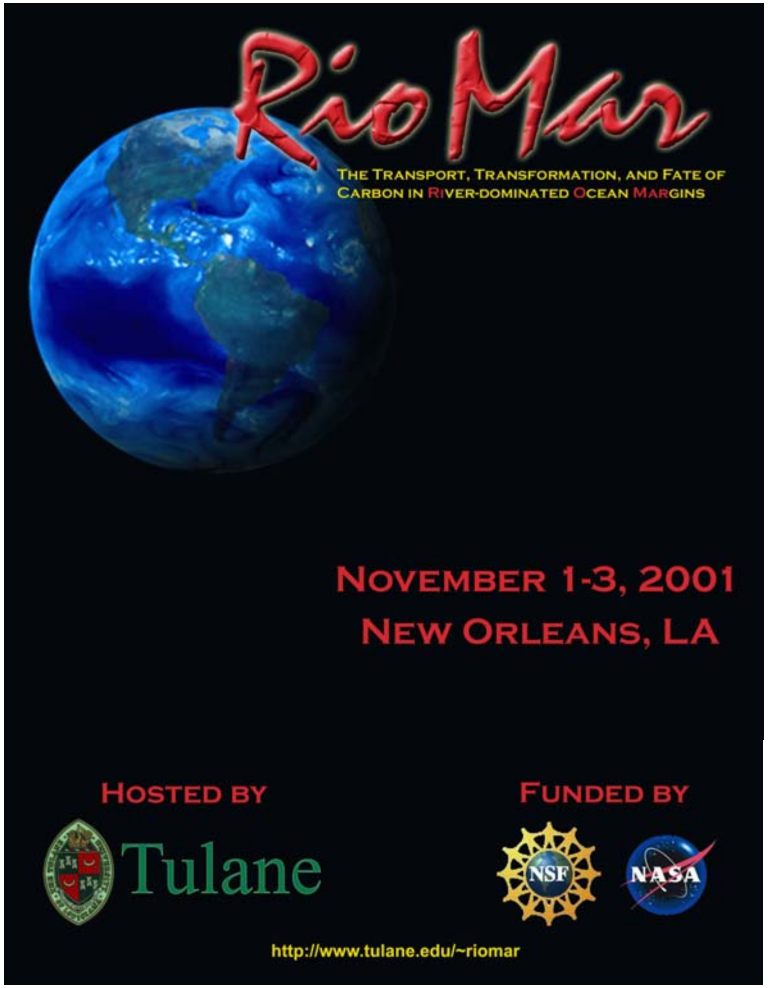
1) Net Organic C production

- **Stored on land or**
- **Exported via rivers**

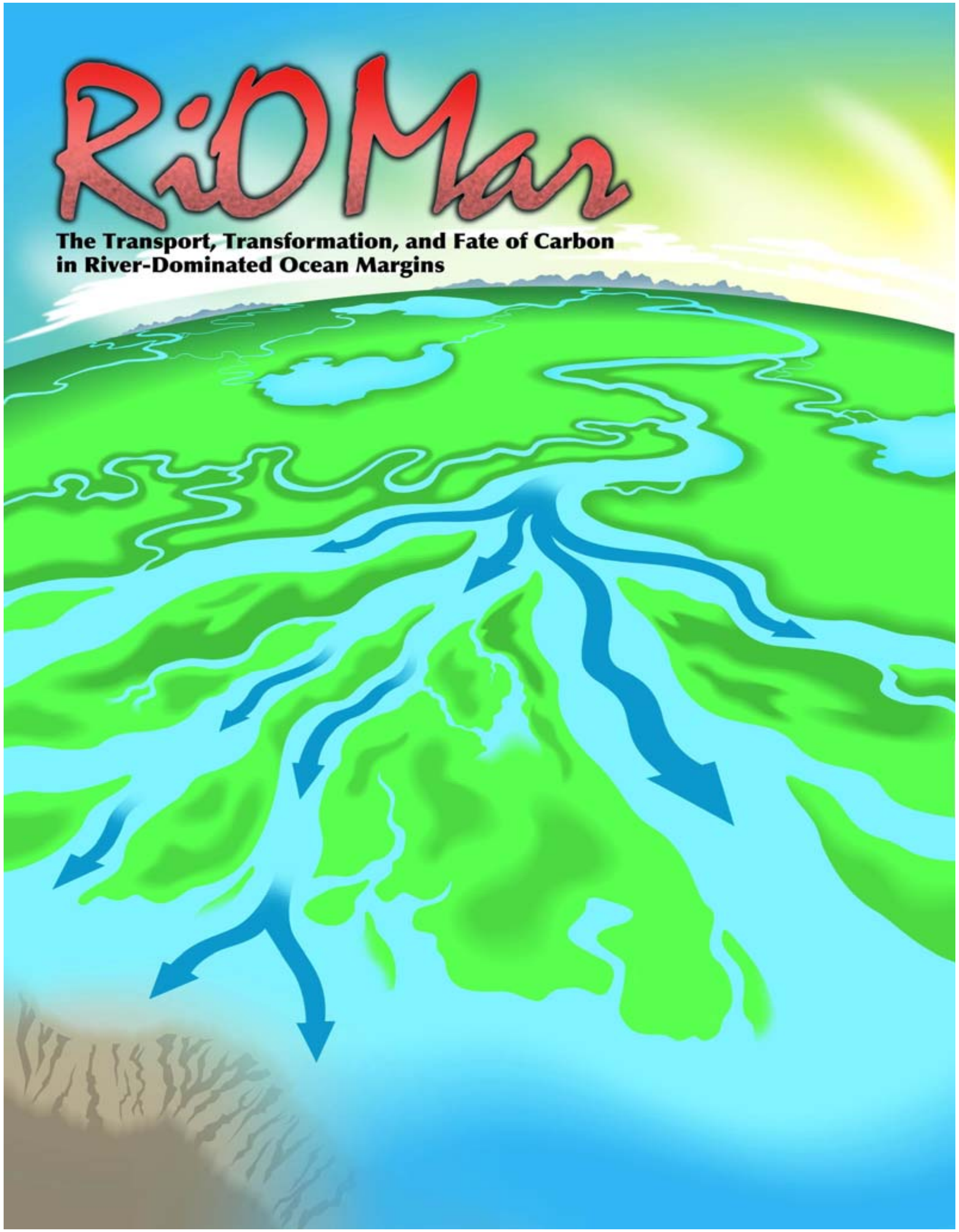
2) Terrestrial production of excess Alkalinity during chemical weathering

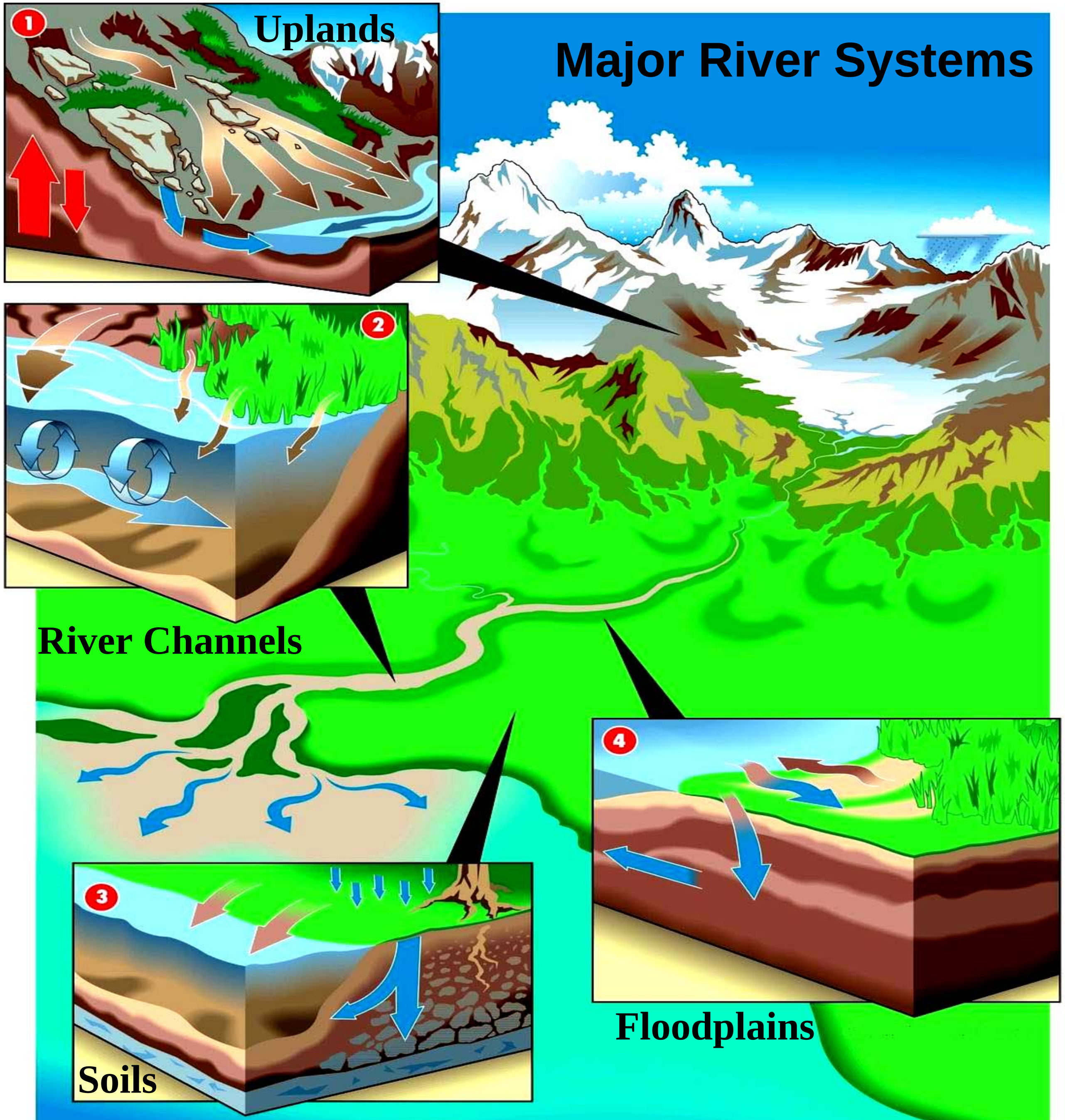
- **Can be transported to ocean margin**
  - **Weathering of silicates sequester atm CO_2 longer (millions of years) than the weathering of carbonates (100's to 1000's years) because of reverse weathering in margins**

Examining River Inputs: Different Perspectives (Measuring fluxes vs. predicting fluxes)



www.tulane.edu/~riomar



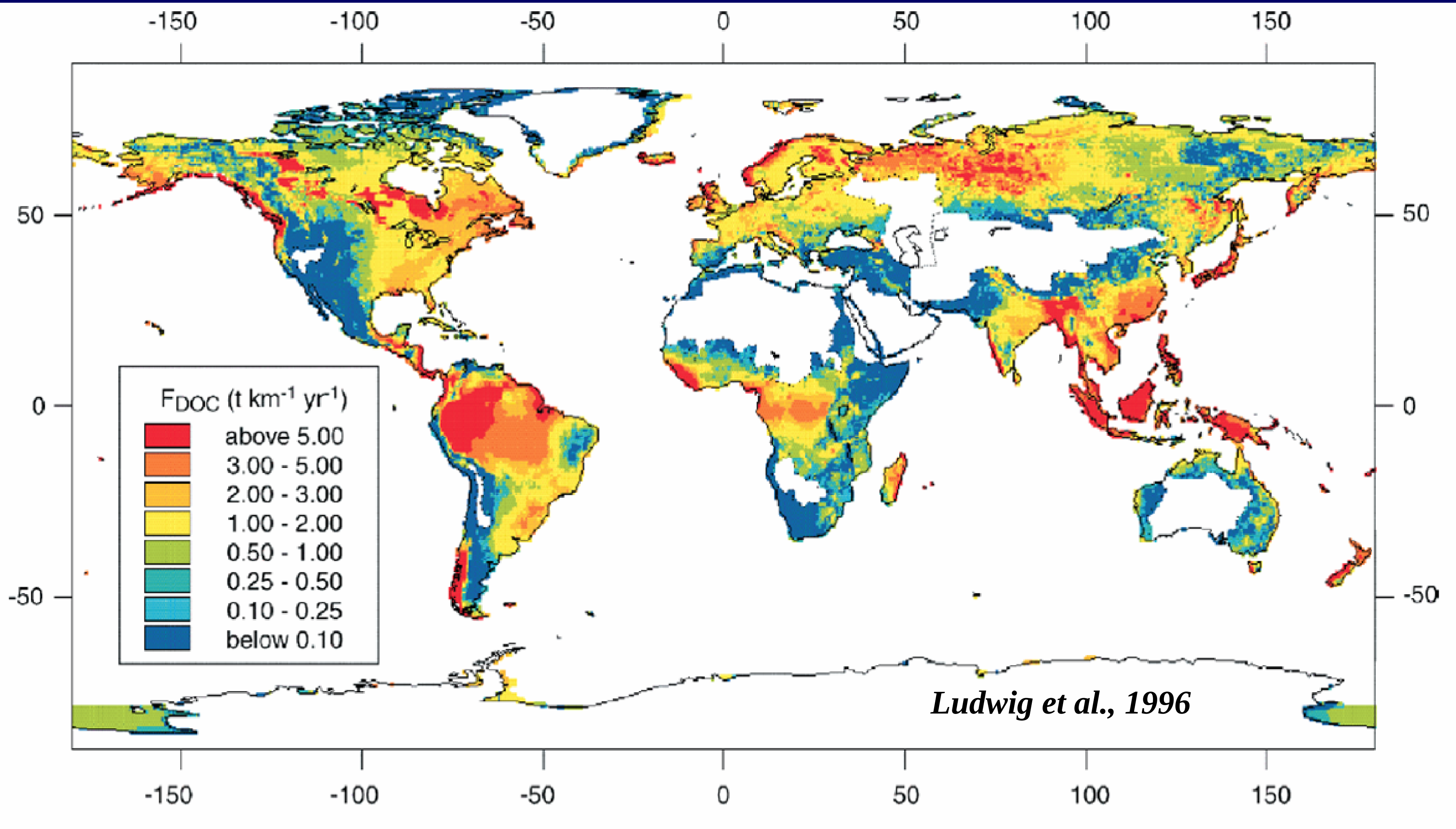


Predict Changes in Riverine Flux?

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:

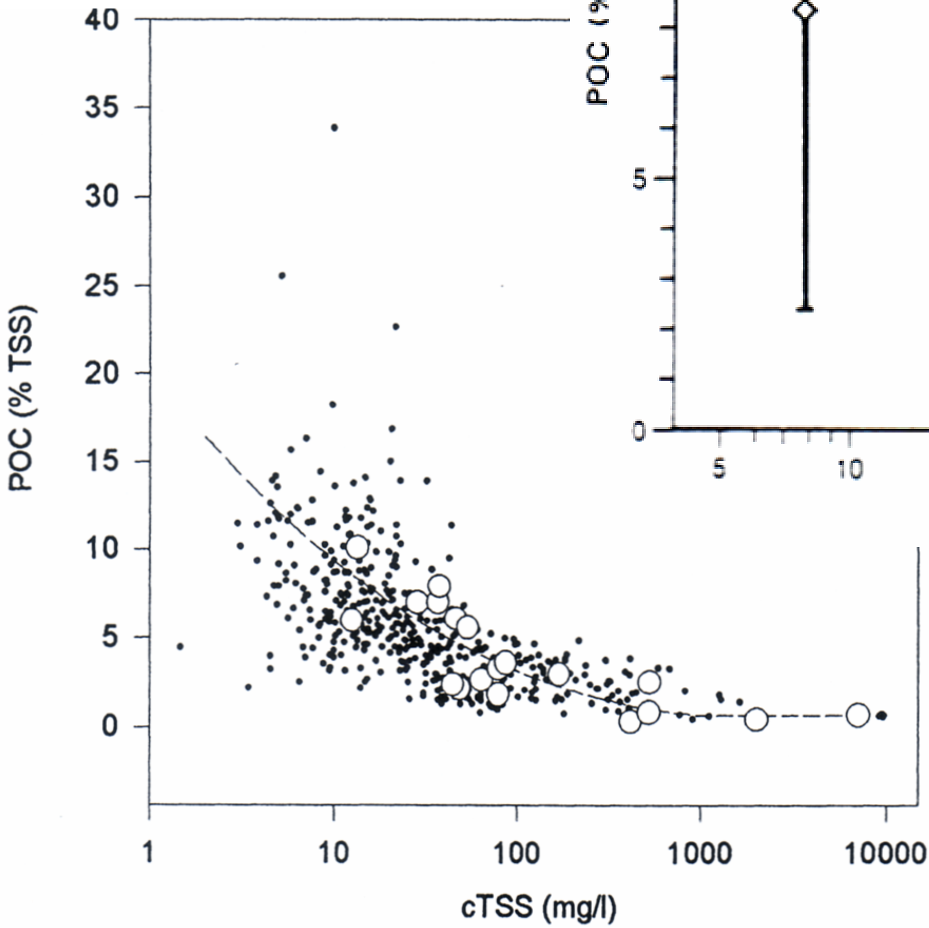
→ **Climate** (rainfall variability and runoff intensity)

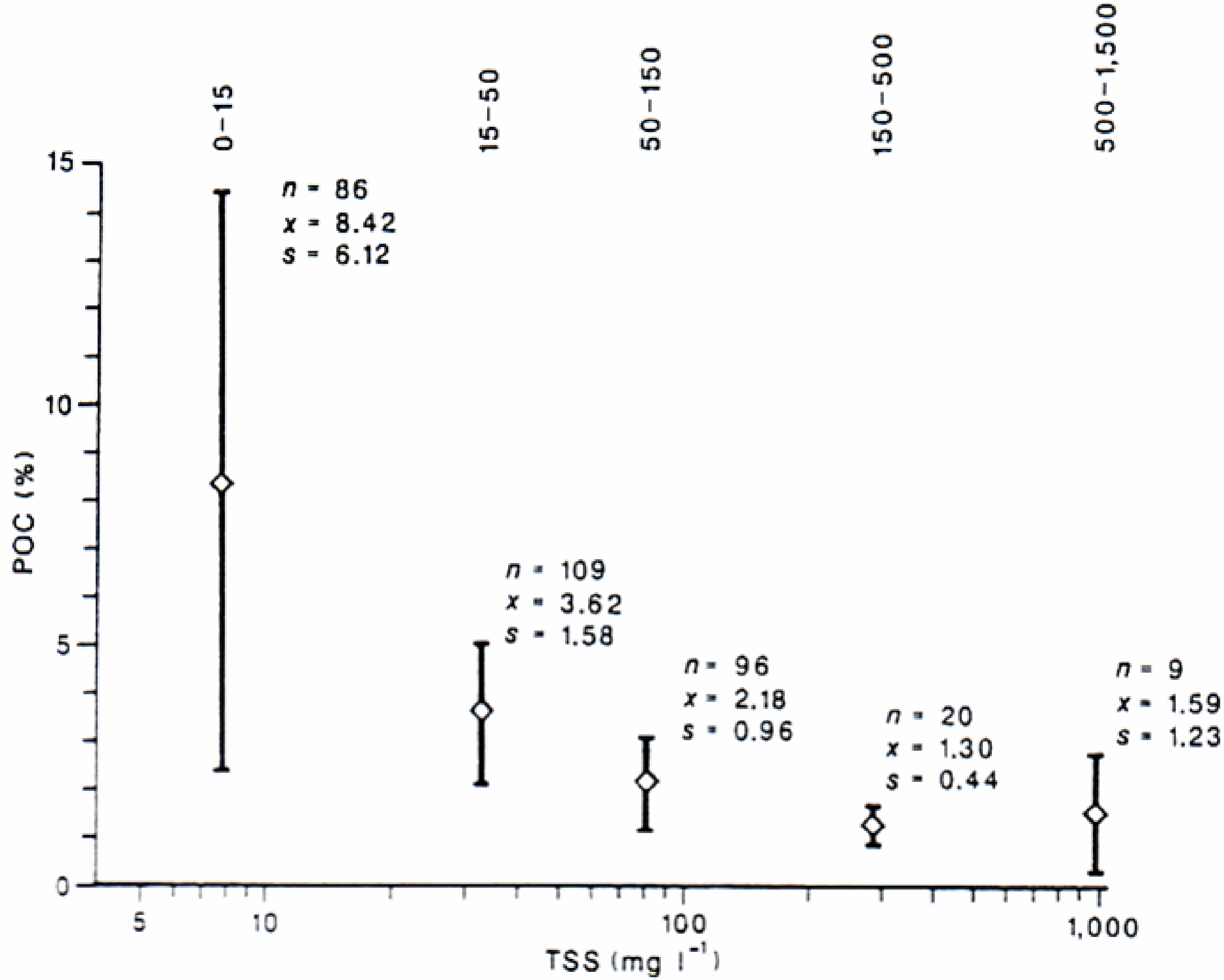
Geology

Basin relief (elevation and slope)

→ **Land Use** (including vegetation cover)

Pleistocene history

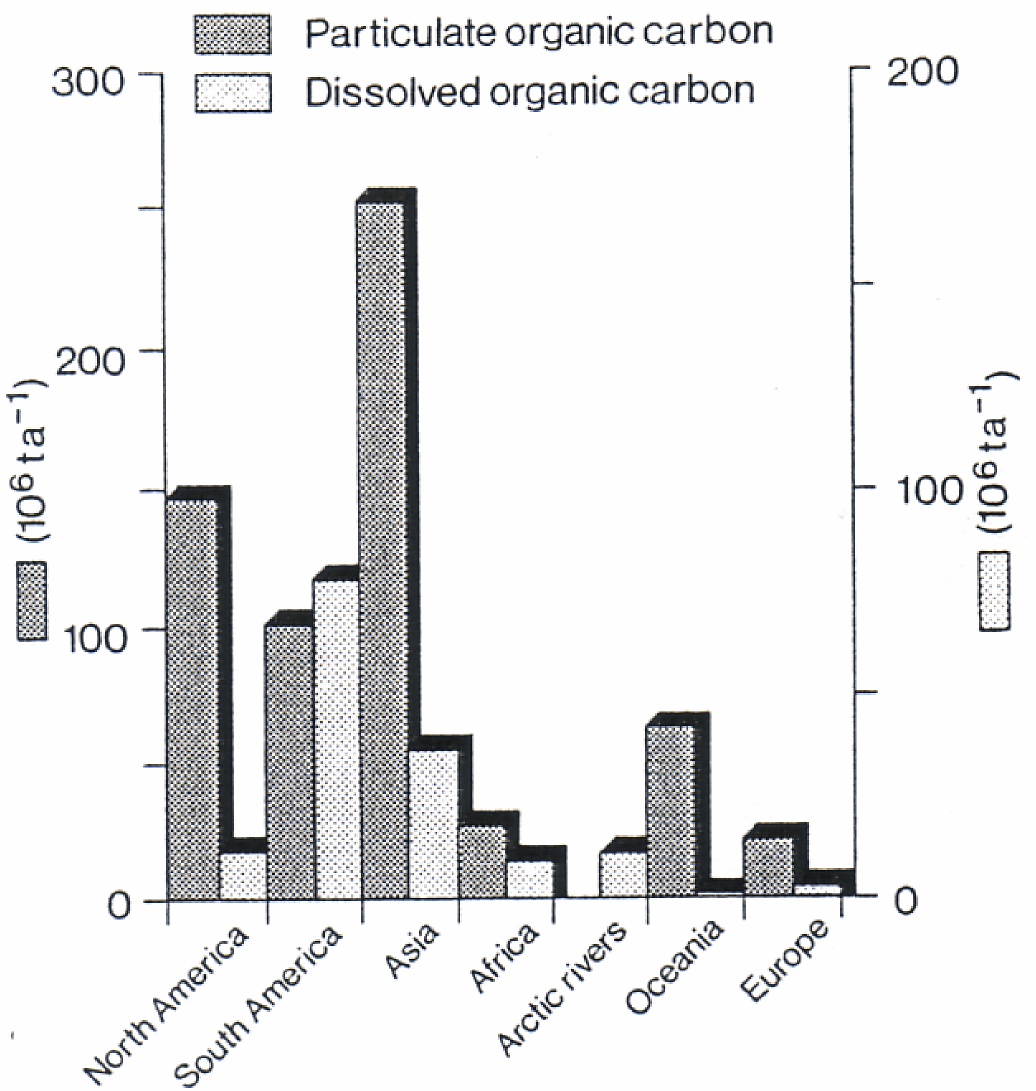




Surface area?

In situ production?

Dilution?



World Average

DOC : POC ~ 1

Range 0.1 – 10.0

TSM range (mg/l)	DOC/POC
5–15	10.8
15–50	5.8
50–150	3.4
150–500	2.3
500–1500	0.9

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)

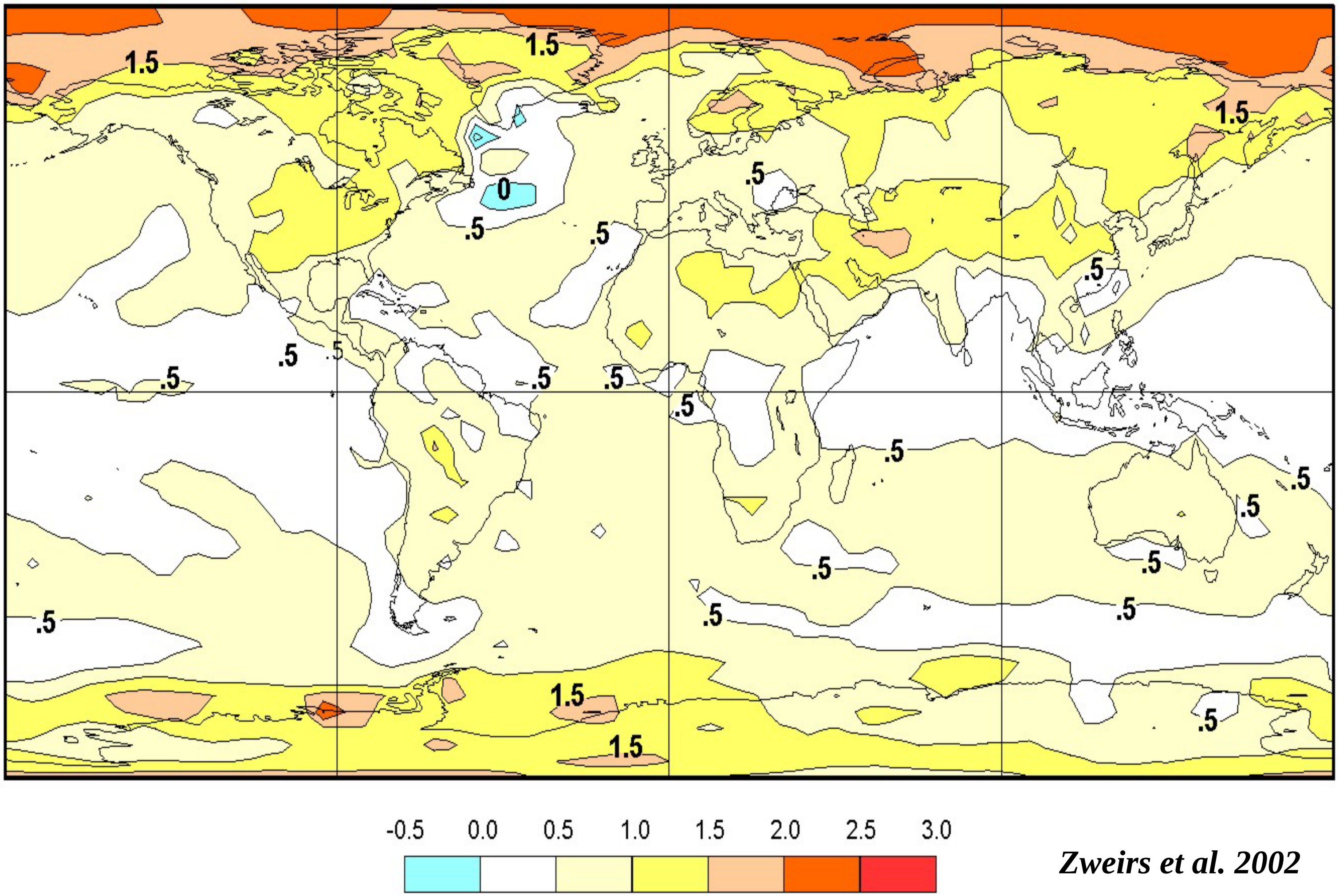
Change in phases: ice/water, permafrost

Hydrological cycle: discharge peak and timing

Changes in mean temperature

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

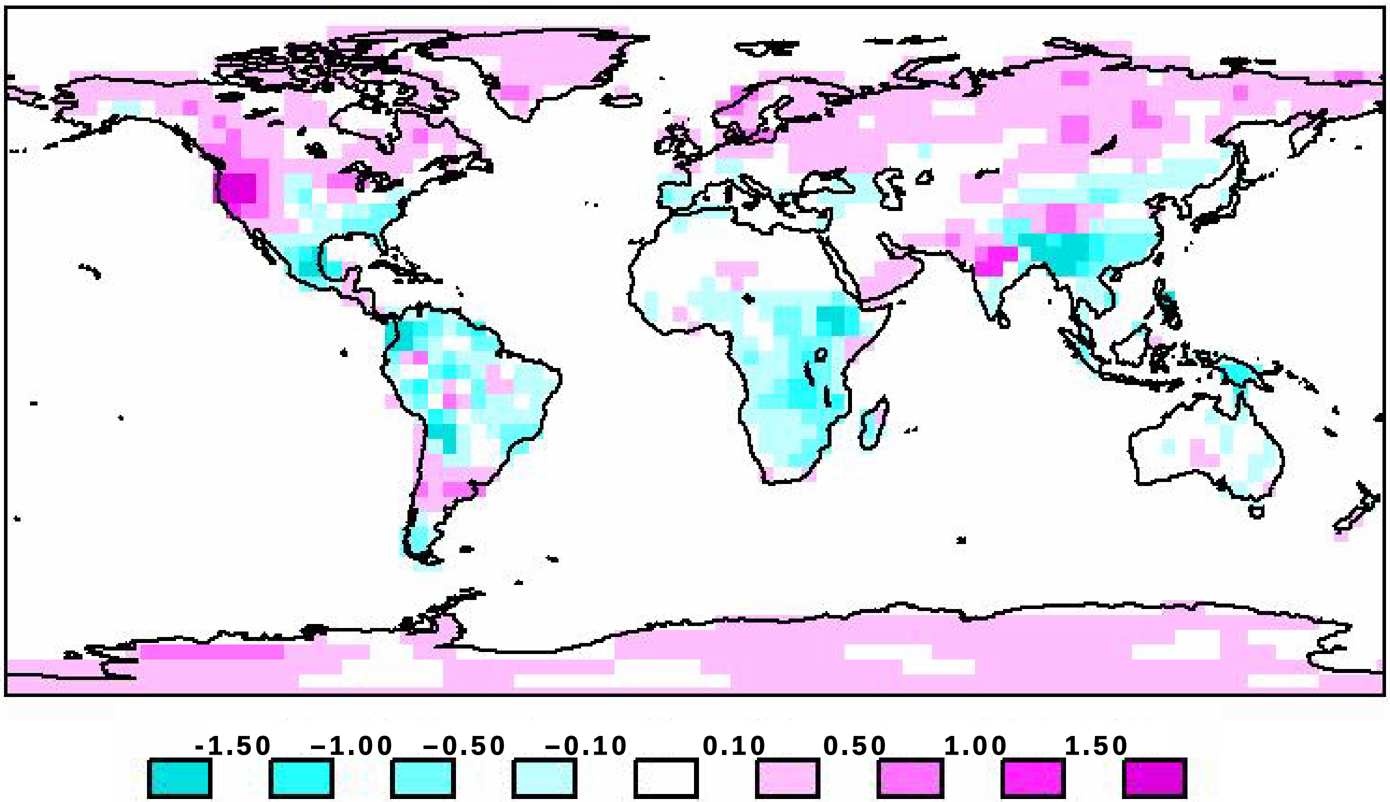
Temperature Change (2020-2030 relative to 1990-2000)



Zweirs et al. 2002

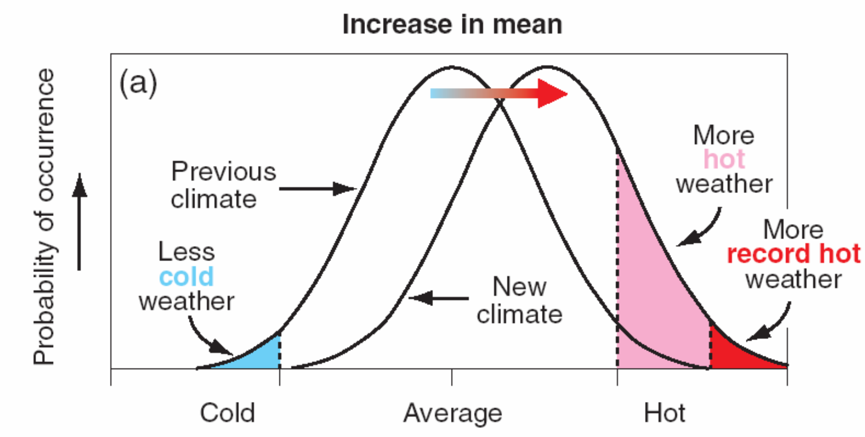
Predicted: Increase in precipitation over high latitude regions and decrease in tropics and subtropics

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

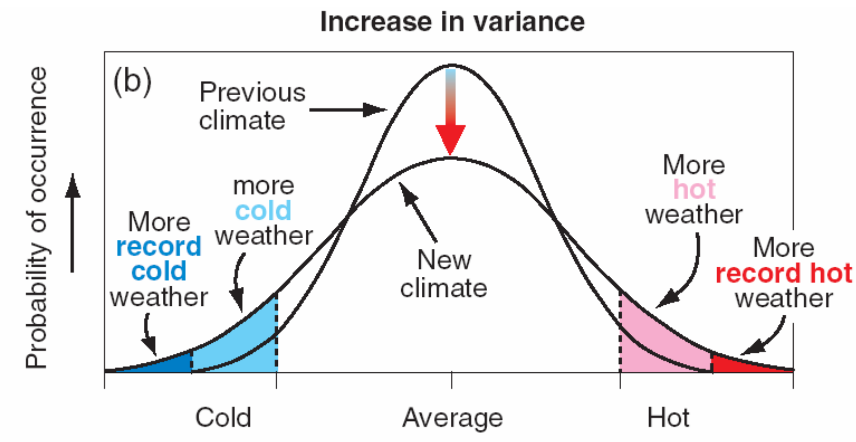


Arora et. al. (2003)

Changes in mean and variability of temperature and precipitation



Beniston (2004)



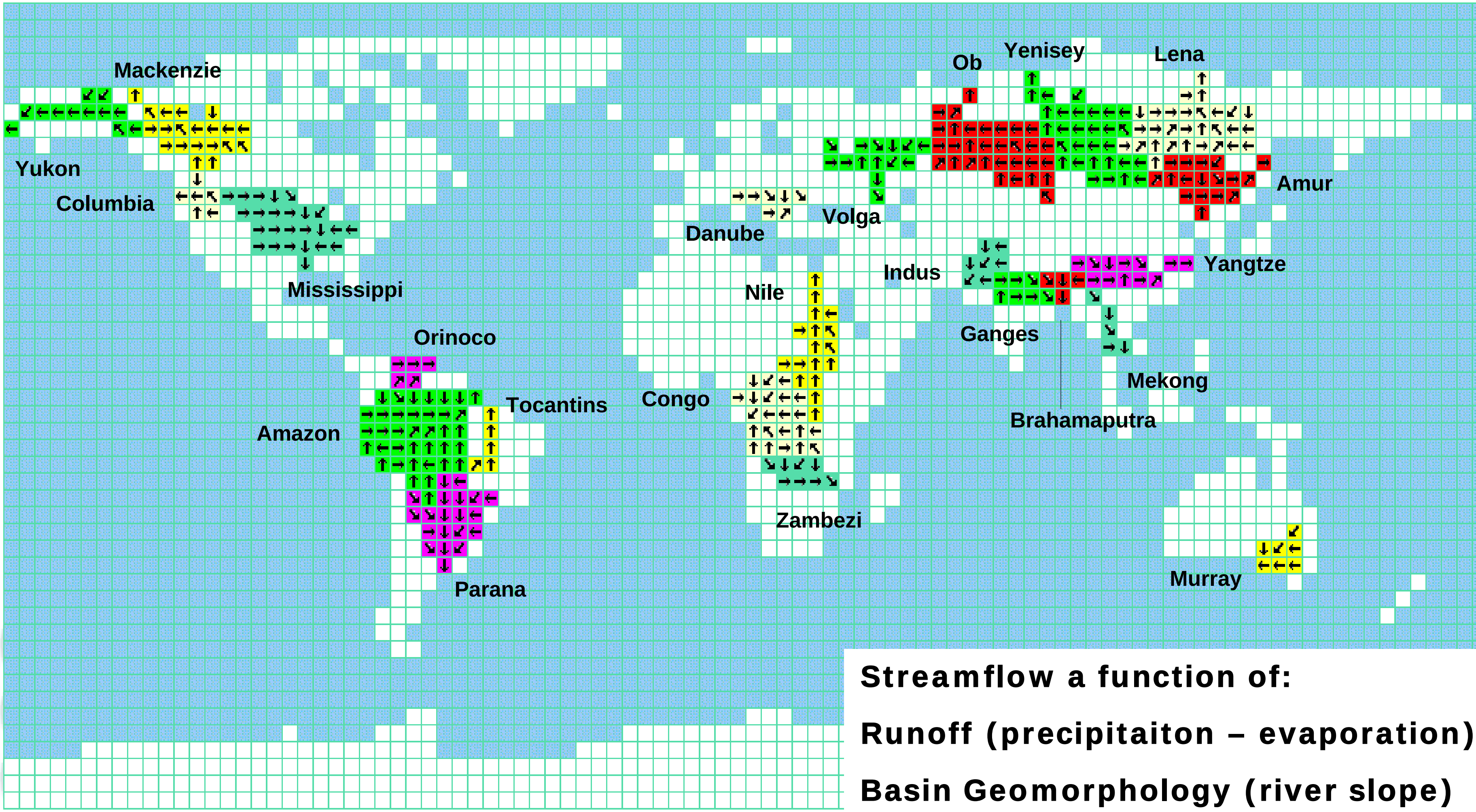
Schär *et al.* (2004)

- **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:

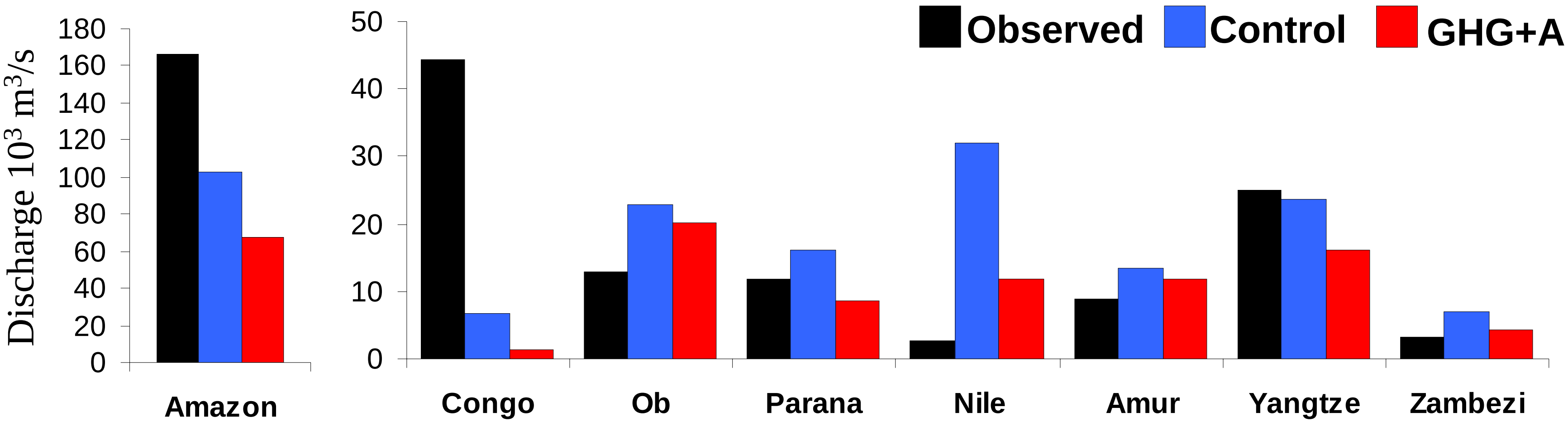
Runoff (precipitaiton – evaporation)

Basin Geomorphology (river slope)

Canadian Centre for Climate Modelling and Analysis
Centre canadien de la modélisation et de l'analyse climatique

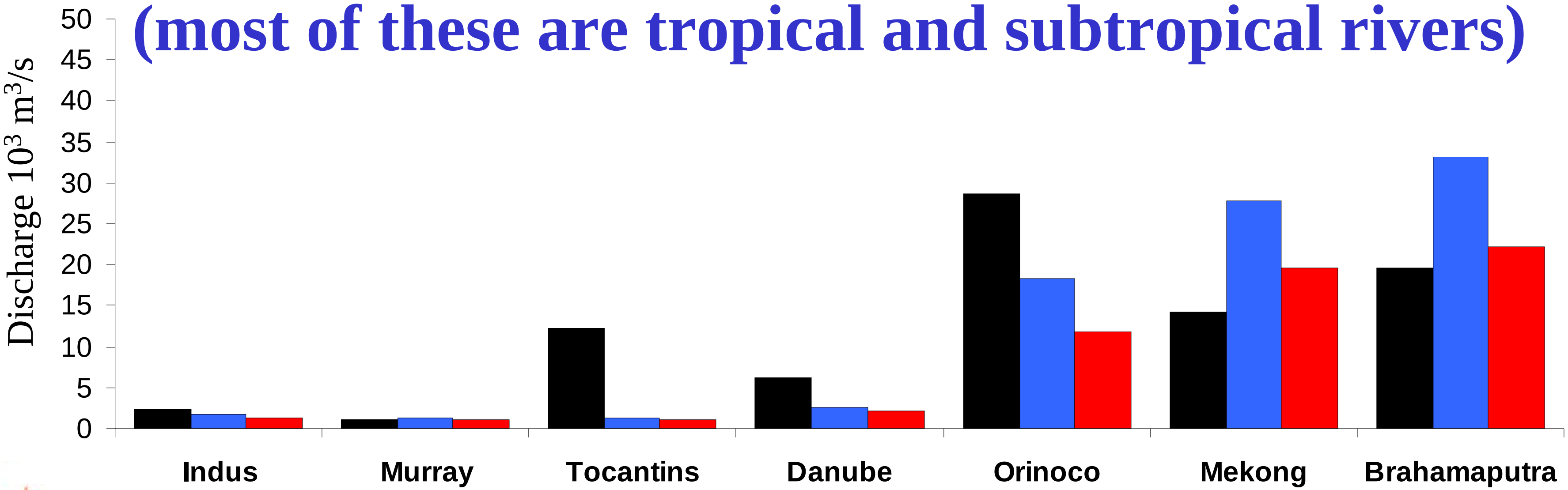
Arora et al, 2003

Changes in mean streamflow



Mean annual discharge of 9 out of 23 rivers goes DOWN

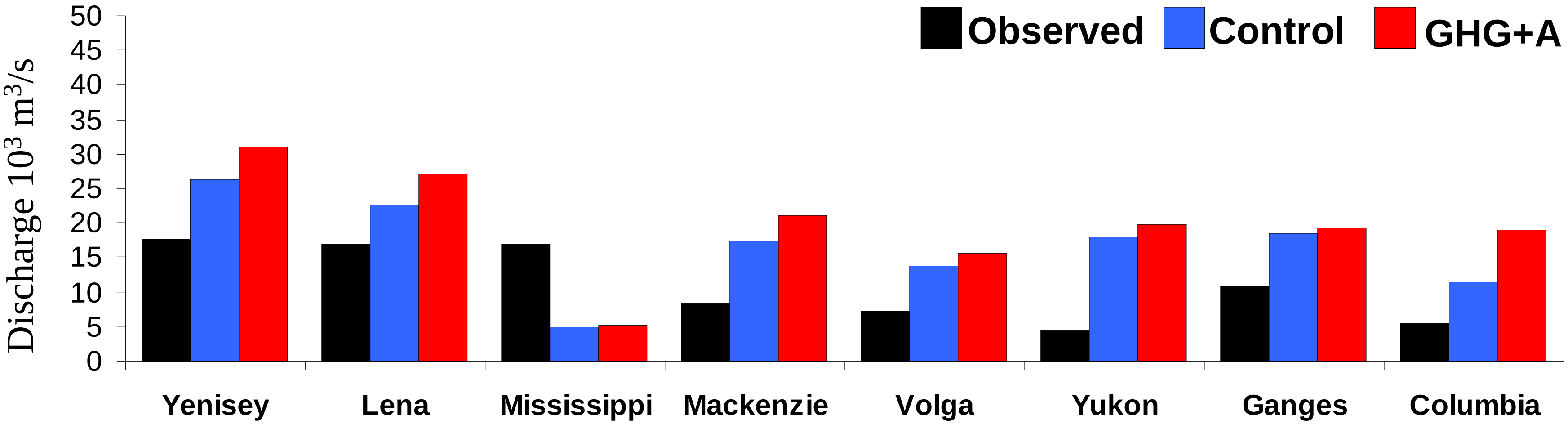
(most of these are tropical and subtropical rivers)



Canadian Centre for Climate Modelling and Analysis
Centre canadien de la modélisation et de l'analyse climatique

Arora et al, 2003

Changes in mean streamflow



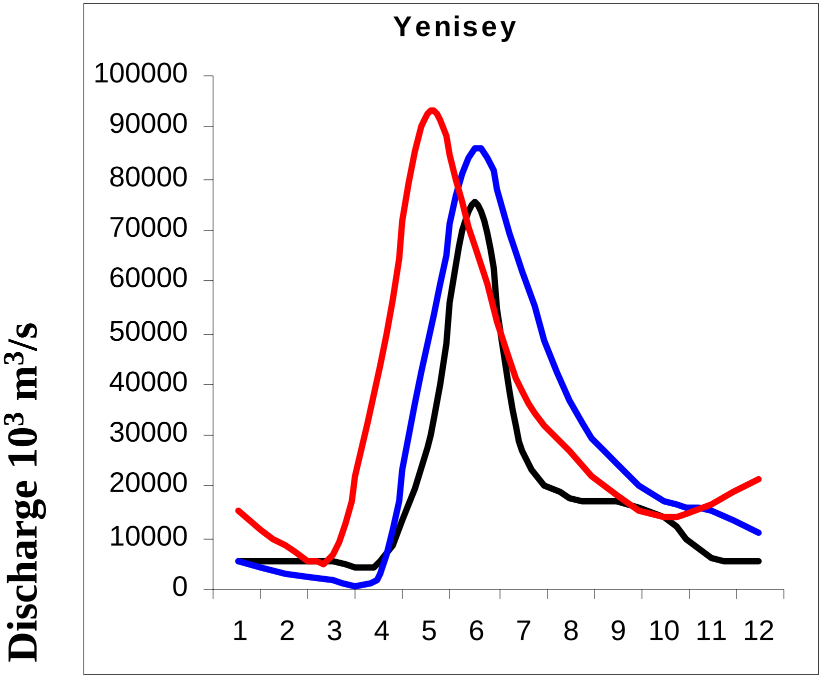
Mean annual discharge of 6 out of 23 rivers goes UP

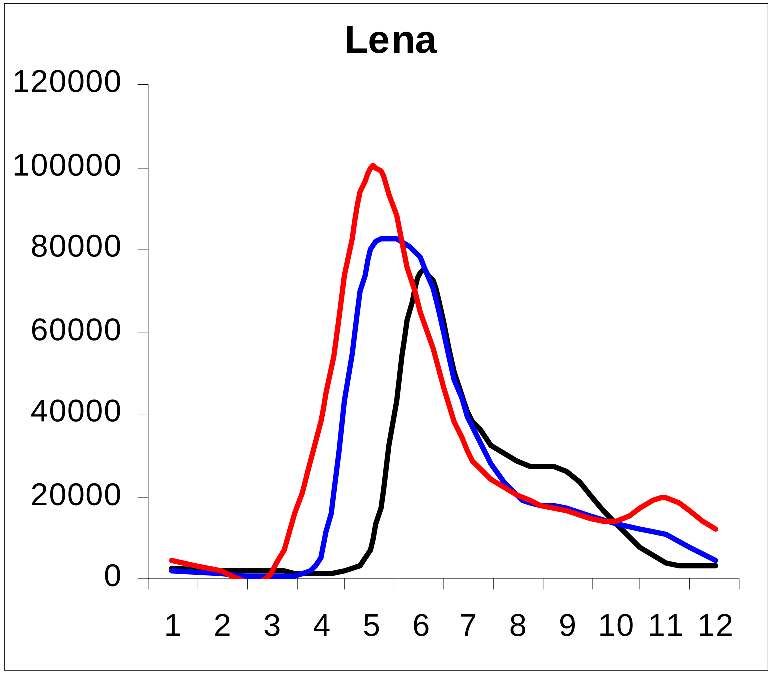
(most of these are mid-high latitude rivers)

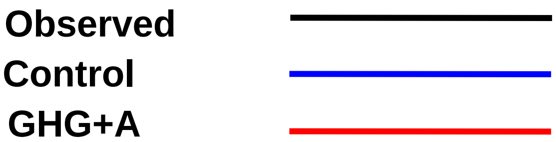
Arora et al, 2003

Changes in streamflow seasonality

Mid-high latitude rivers





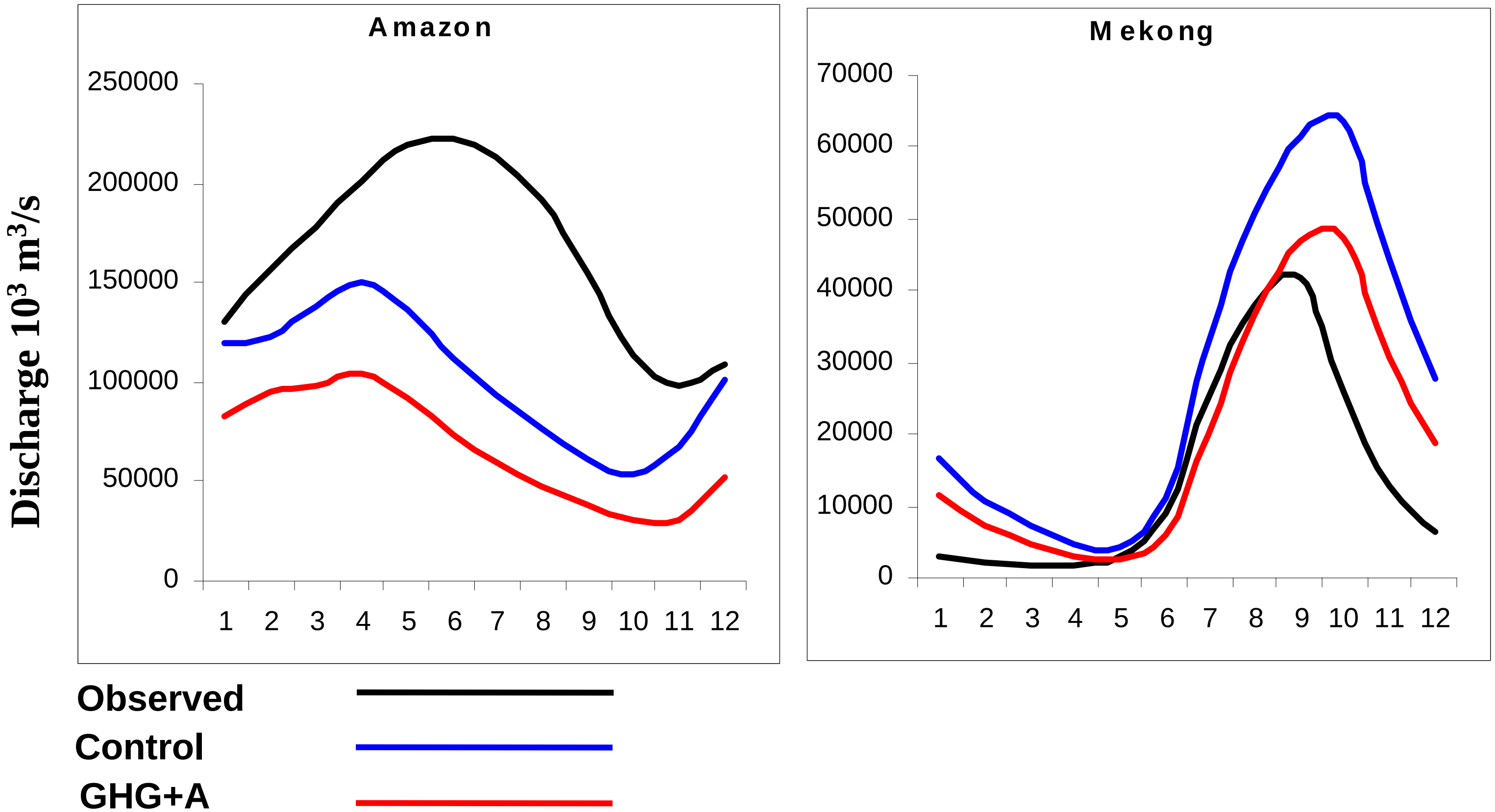


Seasonality of streamflow for river basins characterized by snow **changes significantly**.

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 <u>high-latitude rivers</u>, is expected to increase delivery of DOC**

- **NPP of <u>tropical and subtropical regions</u> 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 <u>increase in sediment load</u> 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

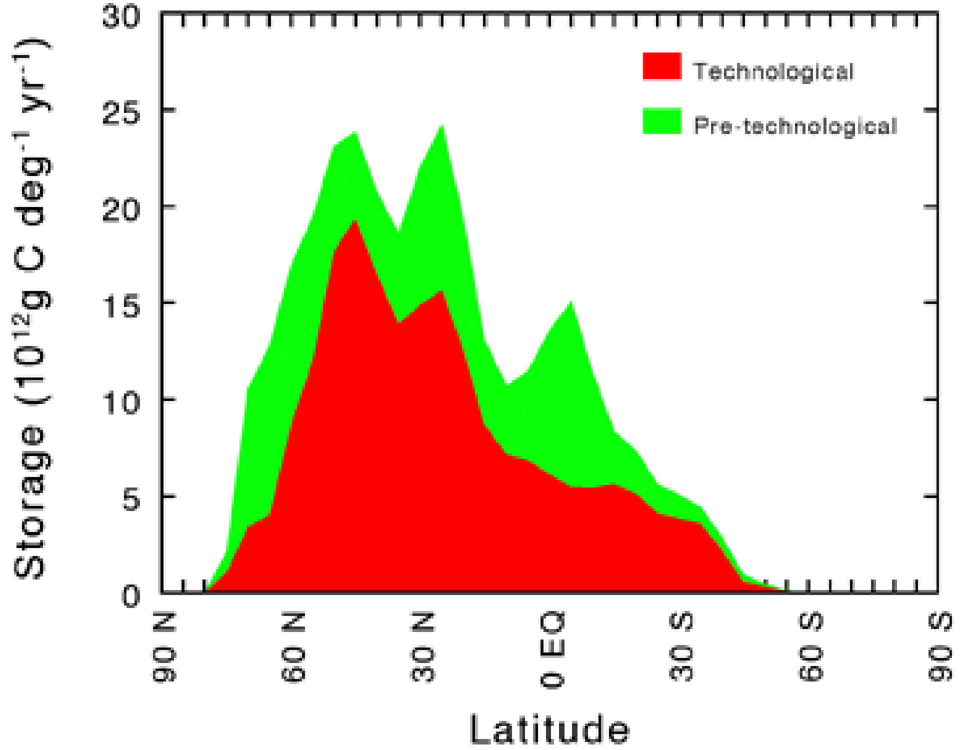
1) Terrestrial Sediment Storage

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)



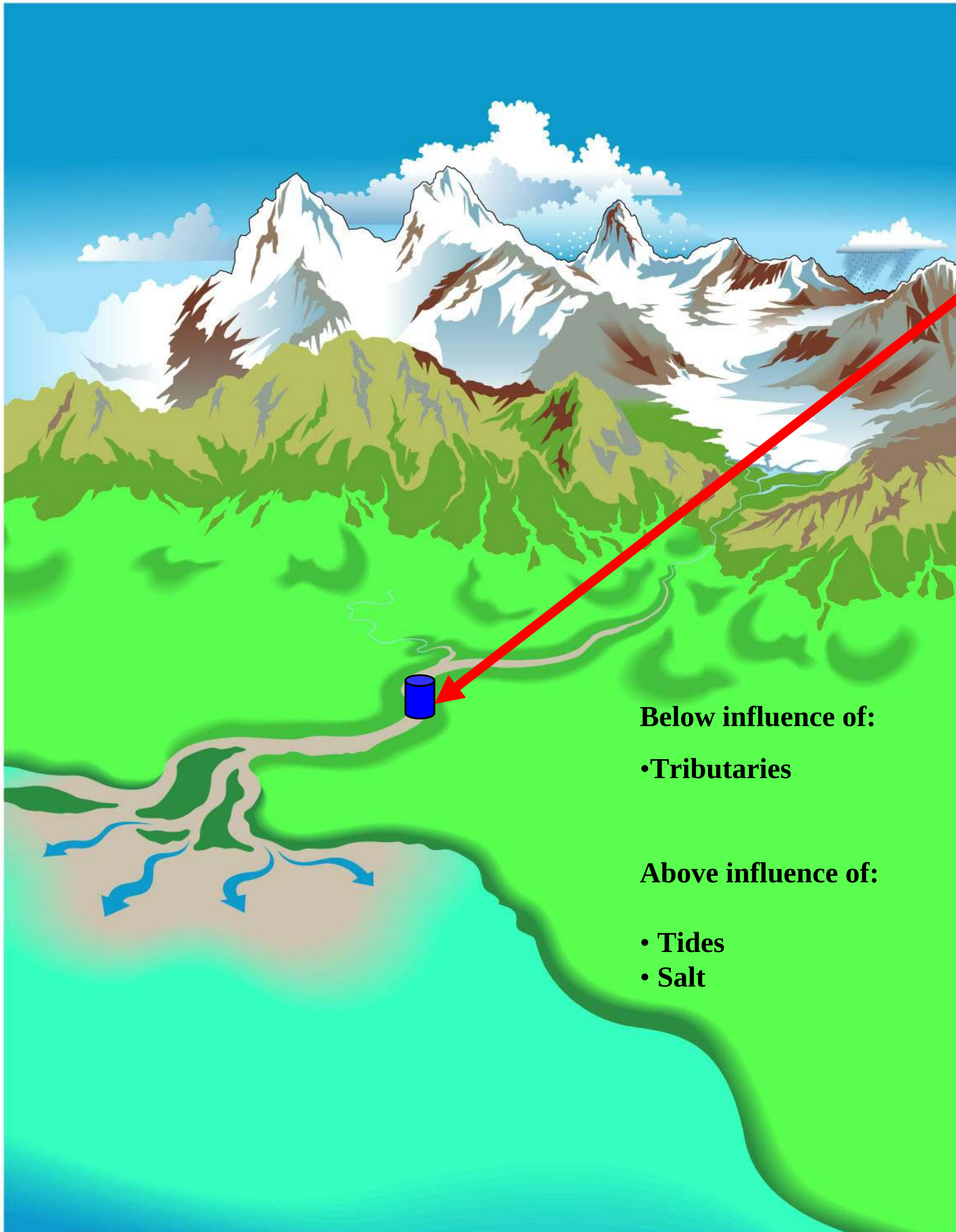
- ~ 4X annual river POC flux
  ---not in equilibrium

- 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



"Delivery to the Ocean"

"Endmember" Stations

Amazon (Obidos) 640 km

Changjiang (Datong) 511 km

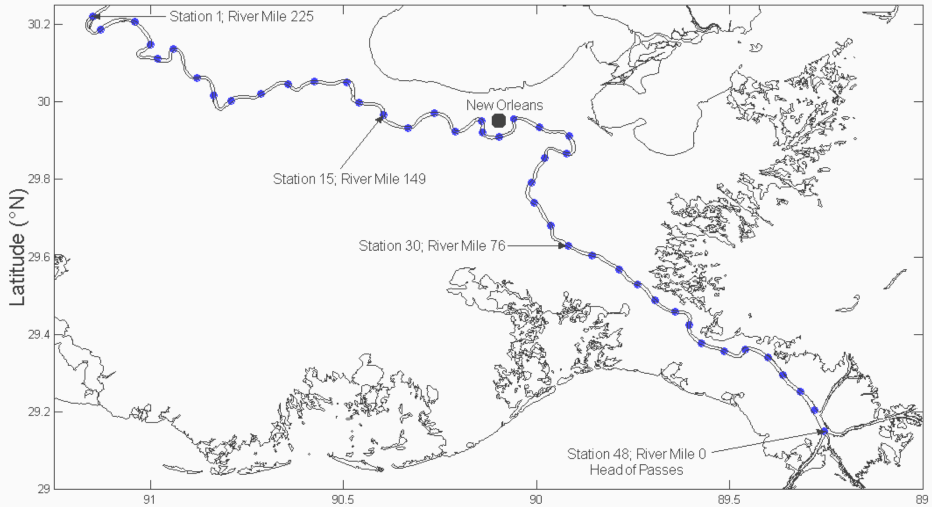
Mississippi (Tarbert Landing) 495 km

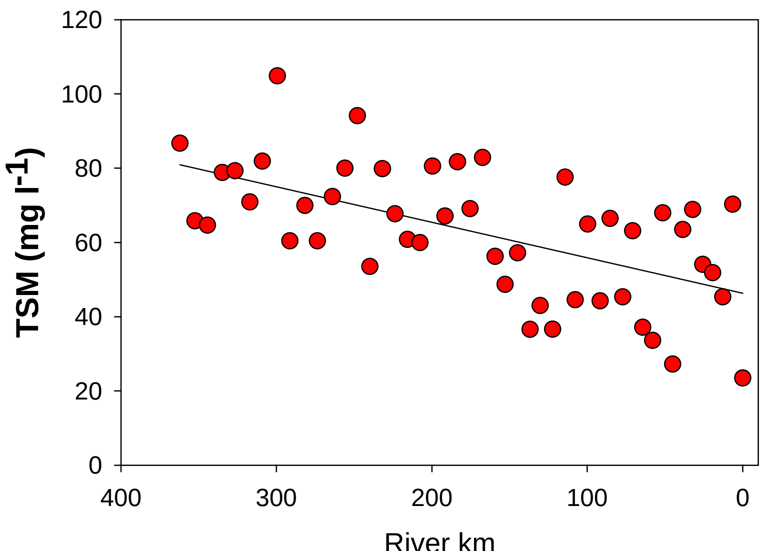
Ganges (Paksay) 390 km

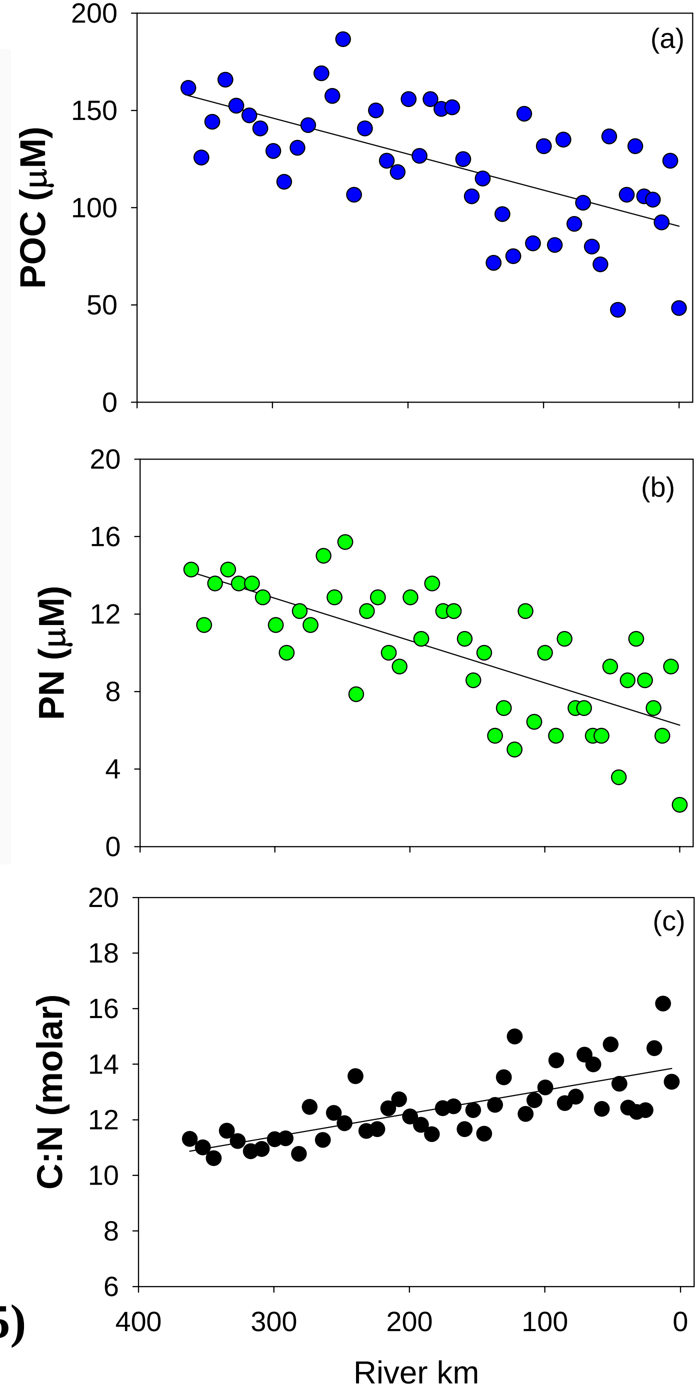
Brahmaputra (Bahadurabad) 348 km

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

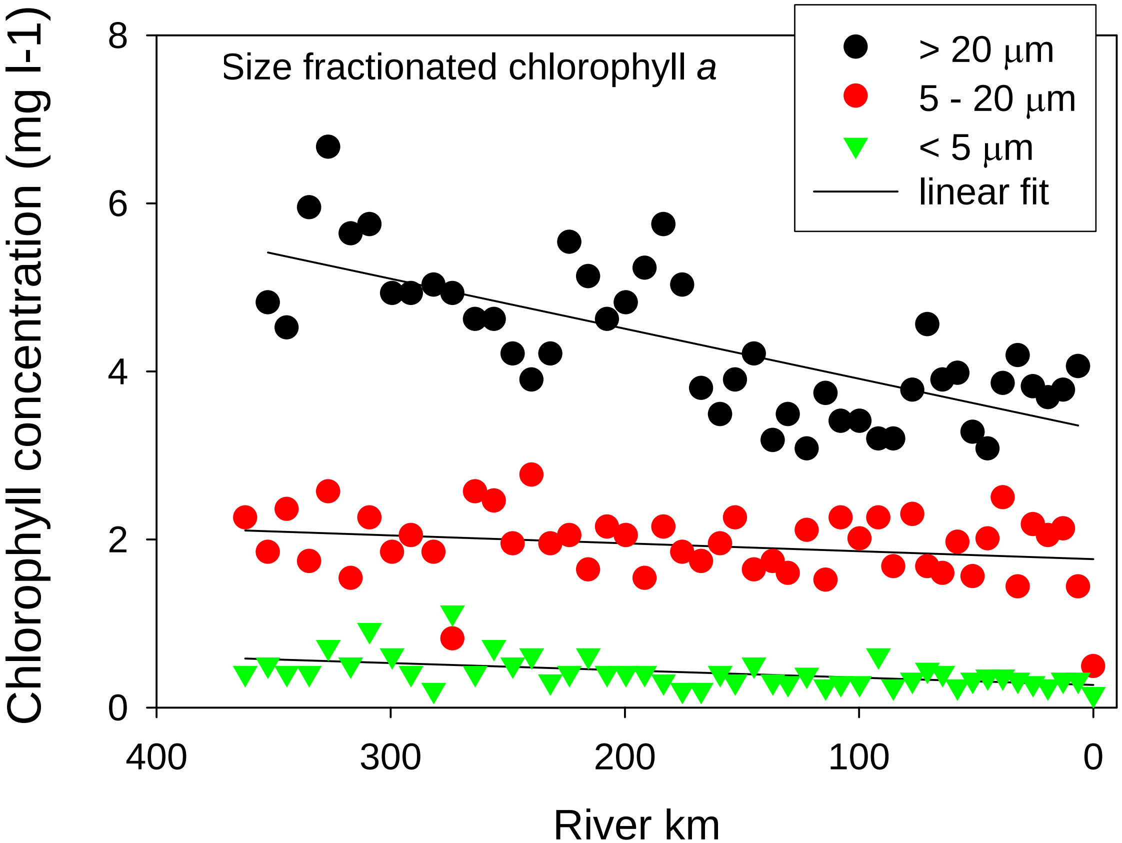






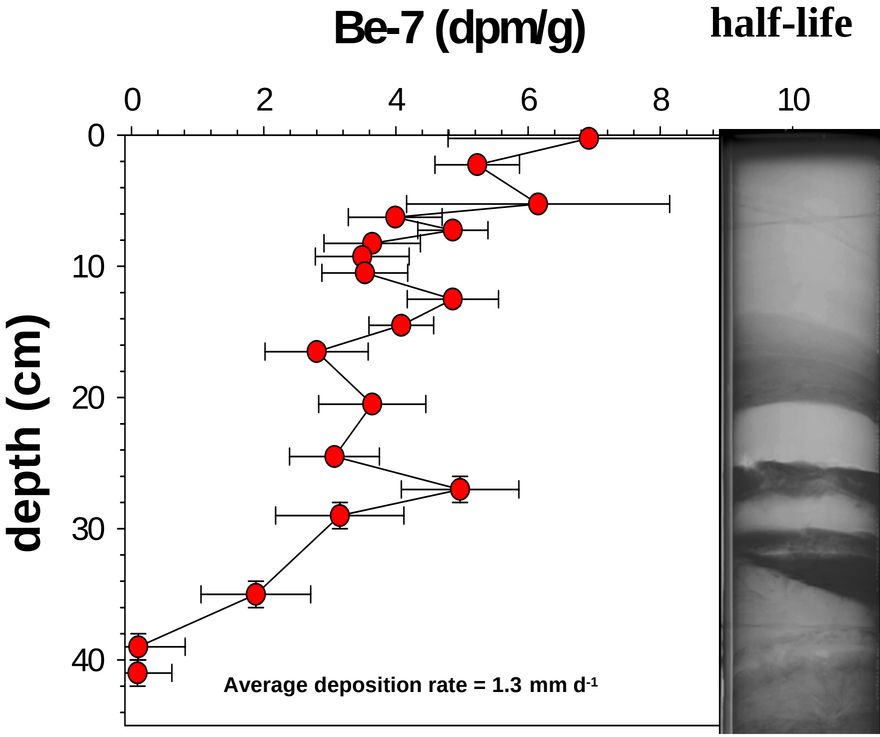
(Dagg et al., 2005)

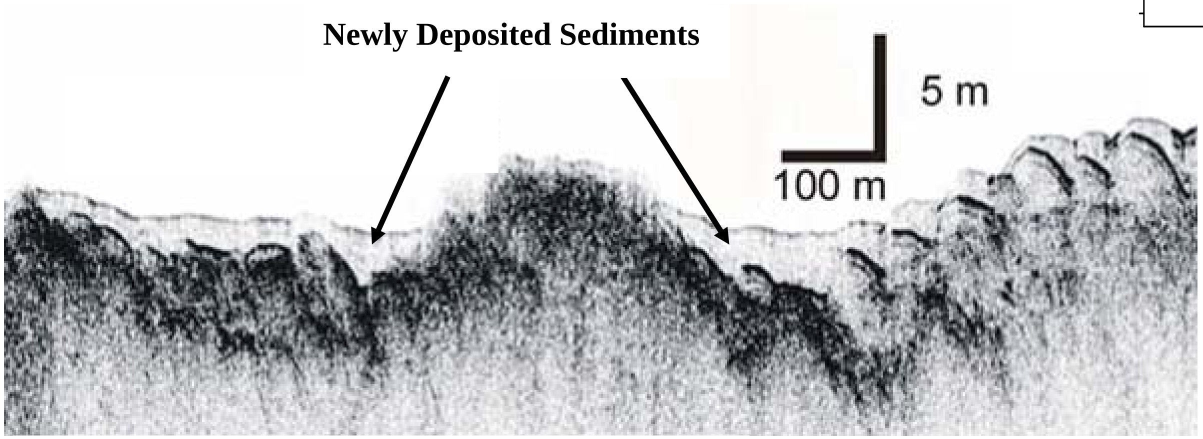
Preferential settling of larger particulate material



Downriver Sampling June 2003
(Dagg et al., 2005)

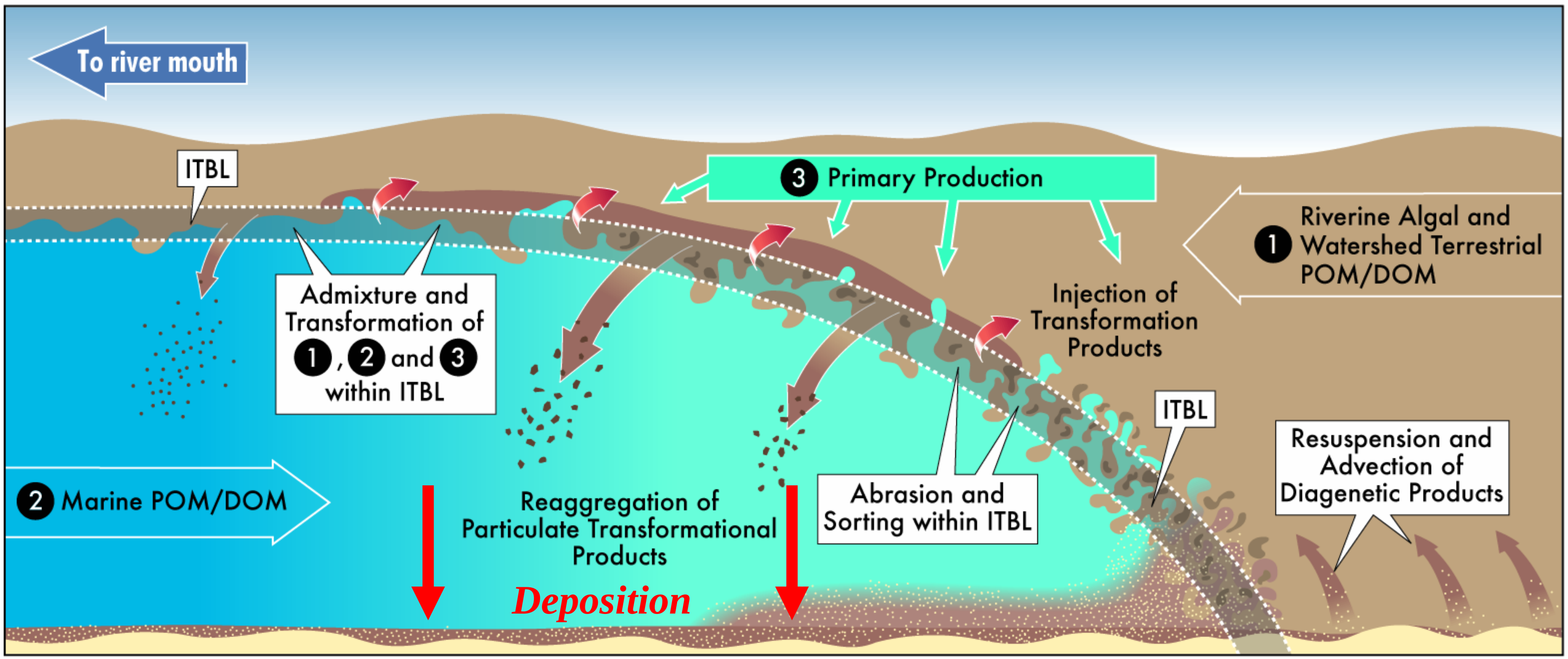
> 15% of Annual Sediment Discharge is Deposited in Lower River during Low Flow Stages





from Galler and Allison, 2005

Newly Deposited Sediments Remain on the Riverbed from 1 to 6 months (mean ~ 3 months)

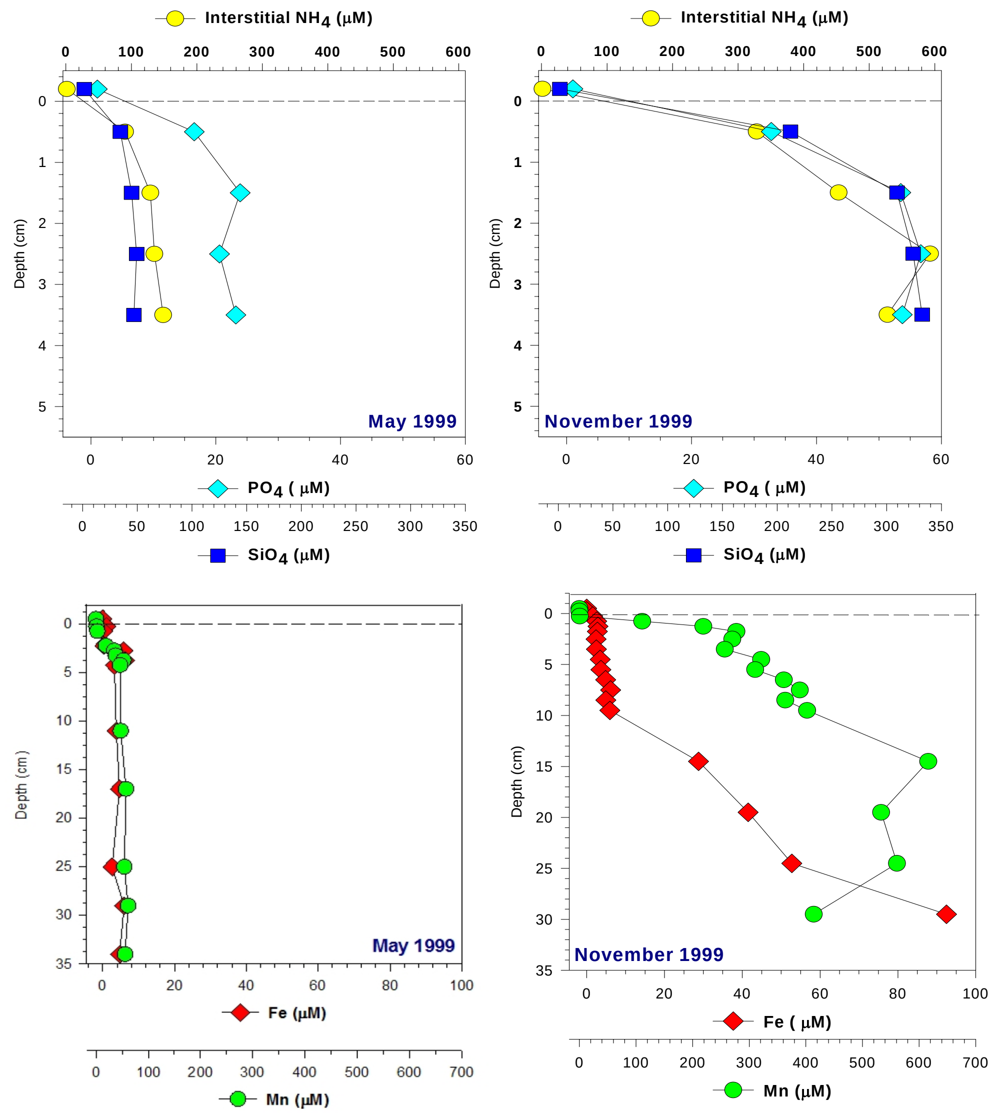


Seasonal Storage

➢ **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)

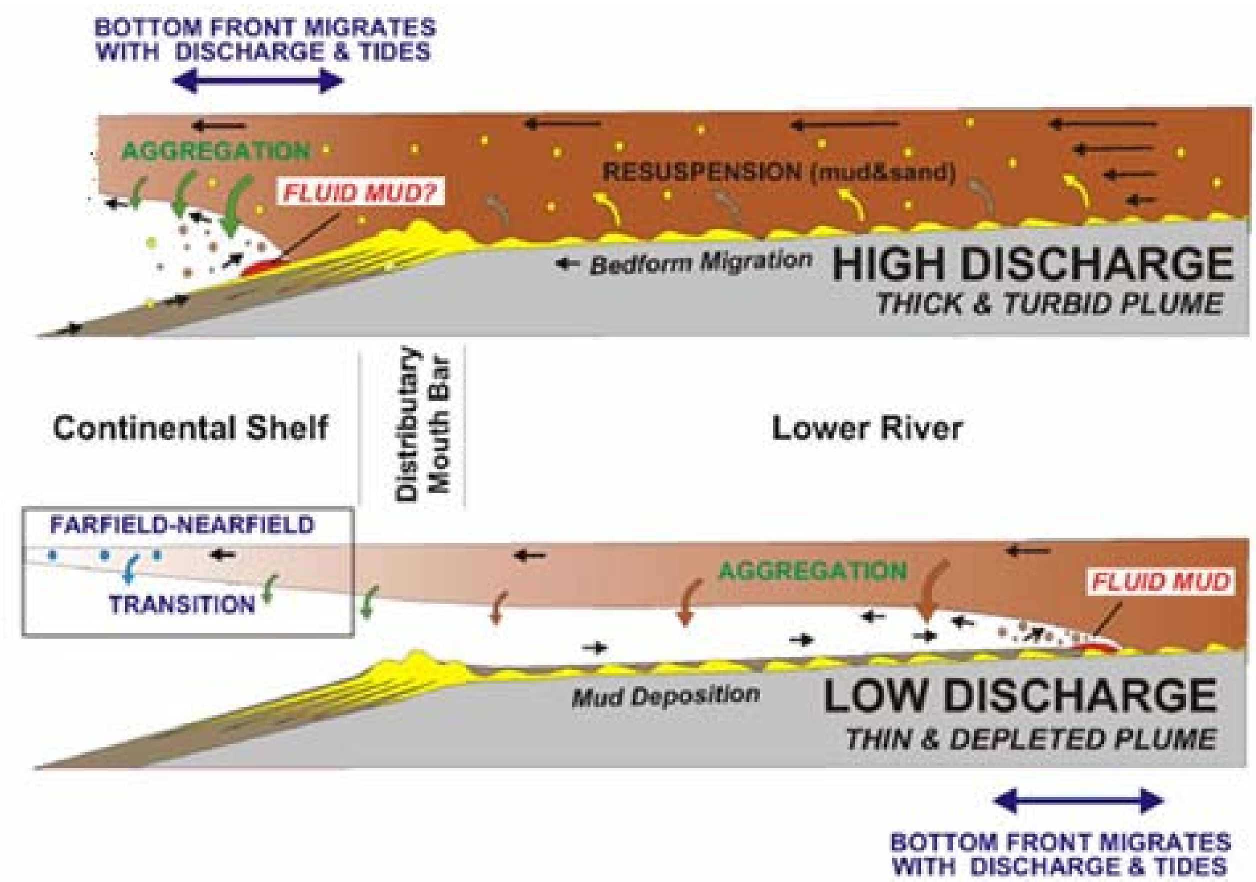


Increases in Porewater Concentrations Over 162 Days:

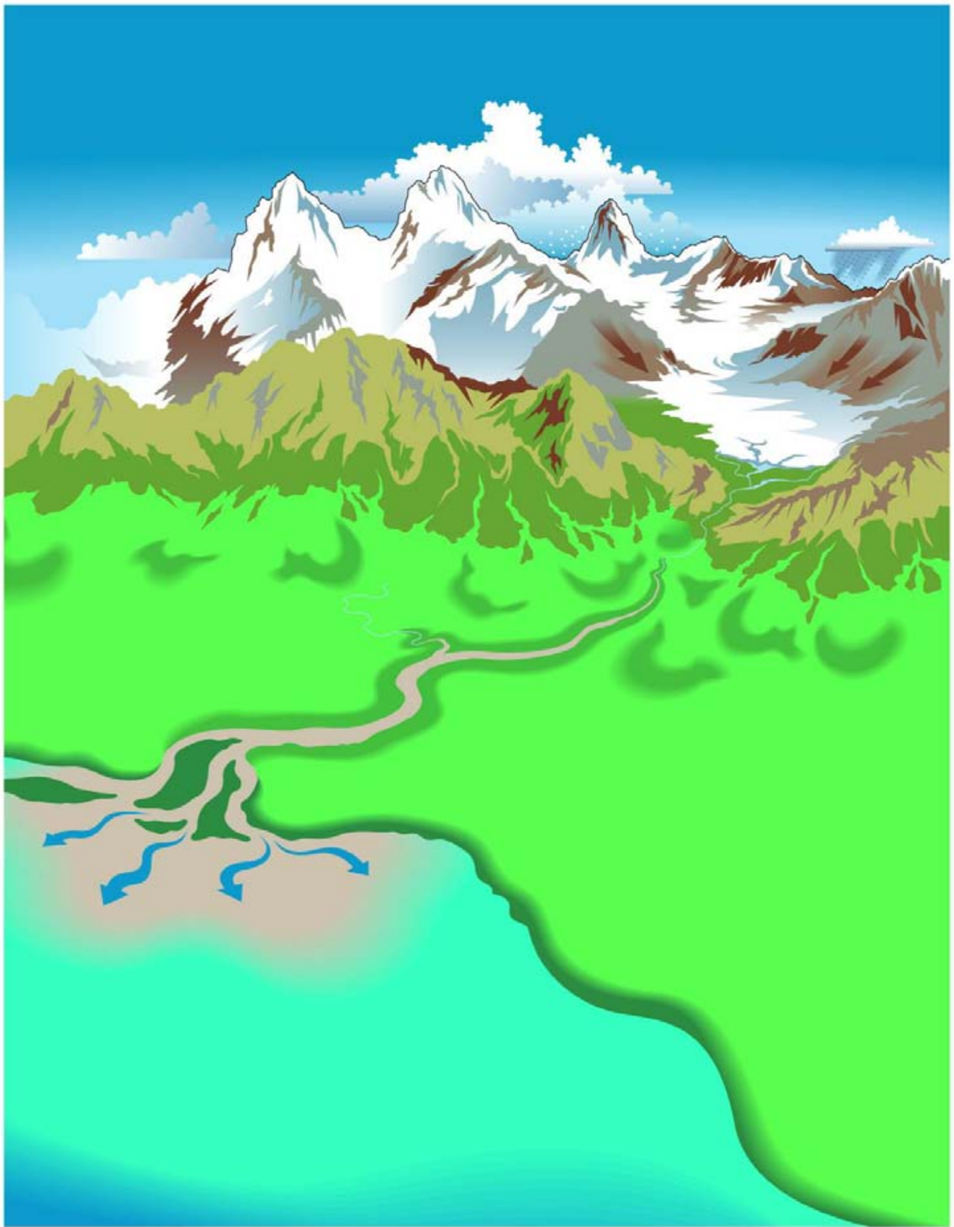
- **2 fold for PO_4**
- **5-6 fold for NH_4 and SiO_4**
- **15 fold for Mn**
- **20 fold of Fe**

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 – Desorprtion
- Aggregation/coagulation/settling

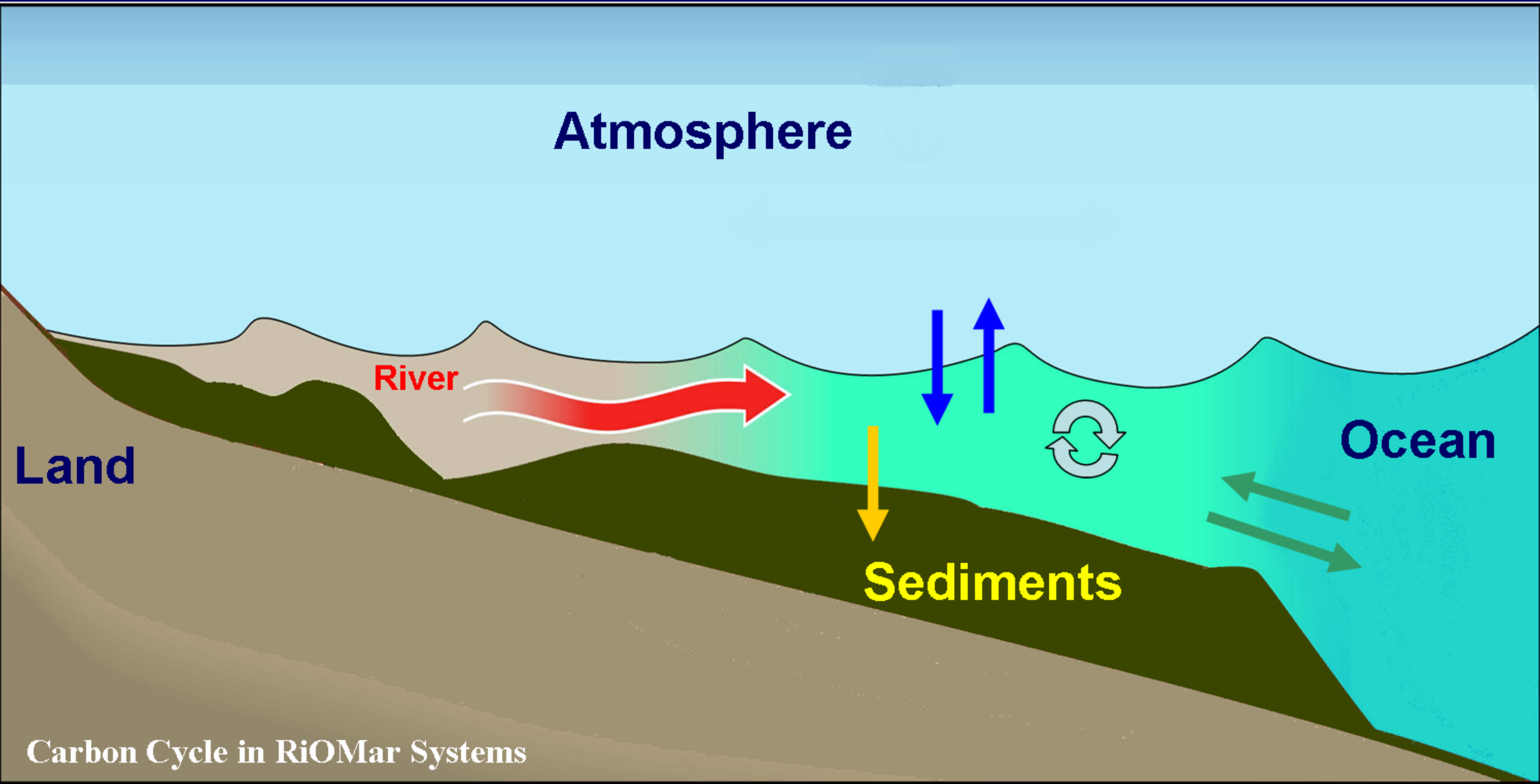
Benthic processes
- Deposition and Resuspension
- Diagenesis
- Flux across sediment-water interface
- Burial / Storage
- BBL Export

What is the magnitude of these fluxes?

What controls them?

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

- River Inputs
- Atm-Ocean Exchange
- Burial
- Net Export to Ocean

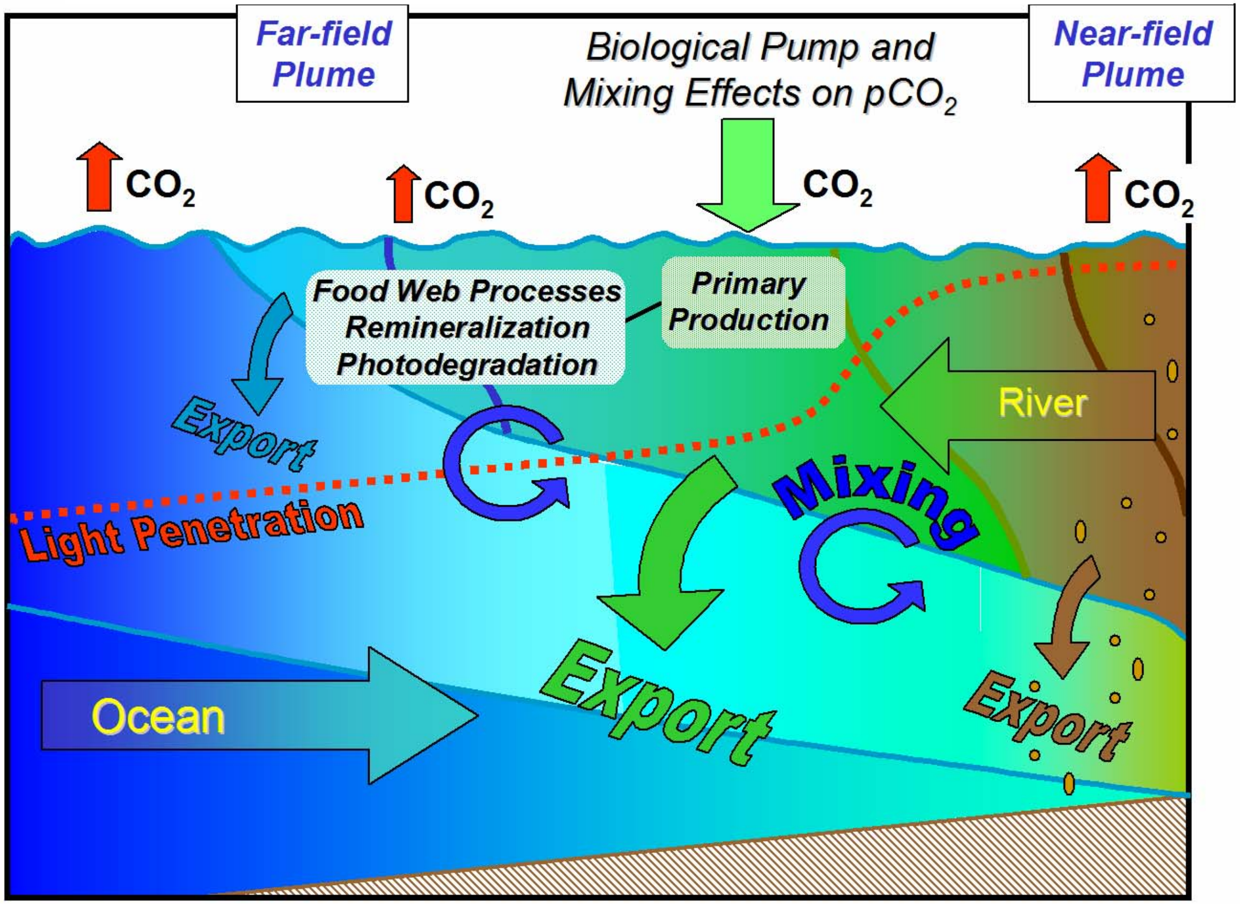


Net Atmosphere-Ocean Exchange

Limited direct measurements of Atm-Ocean CO_2 fluxes demonstrate:
large C sinks (Tsunogai, 1999; Frankignoulle, 2001; Thomas, 2004) AND
large C sources (Cai, 2003; Goyet, 1998; Lefevre, 2002)

What about RiOMar environments?

High productivity fueled by riverine nutrients and nutrient upwelled nutrients from buoyancy effect (Chen et al. 2003)

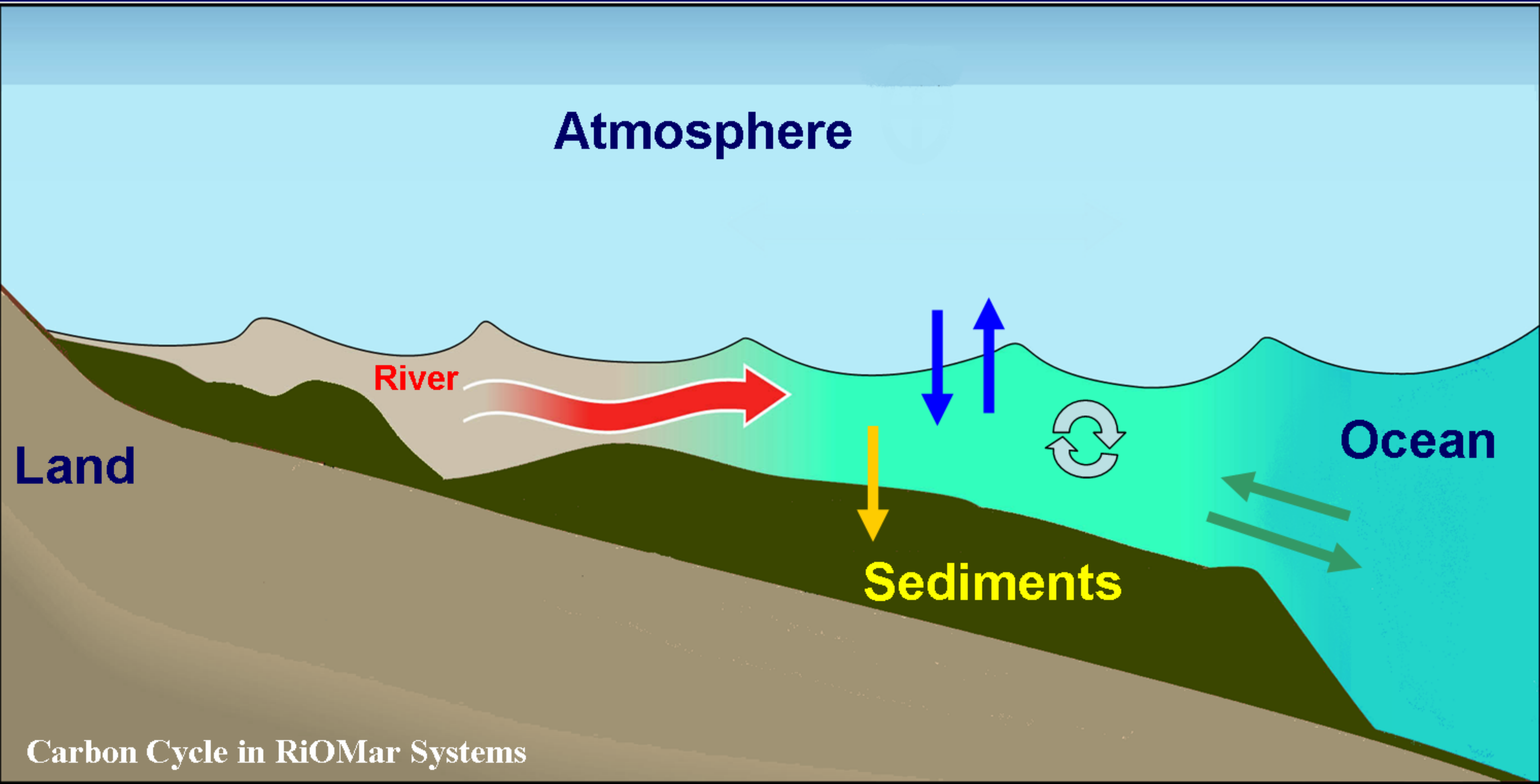


What is the magnitude of these fluxes?

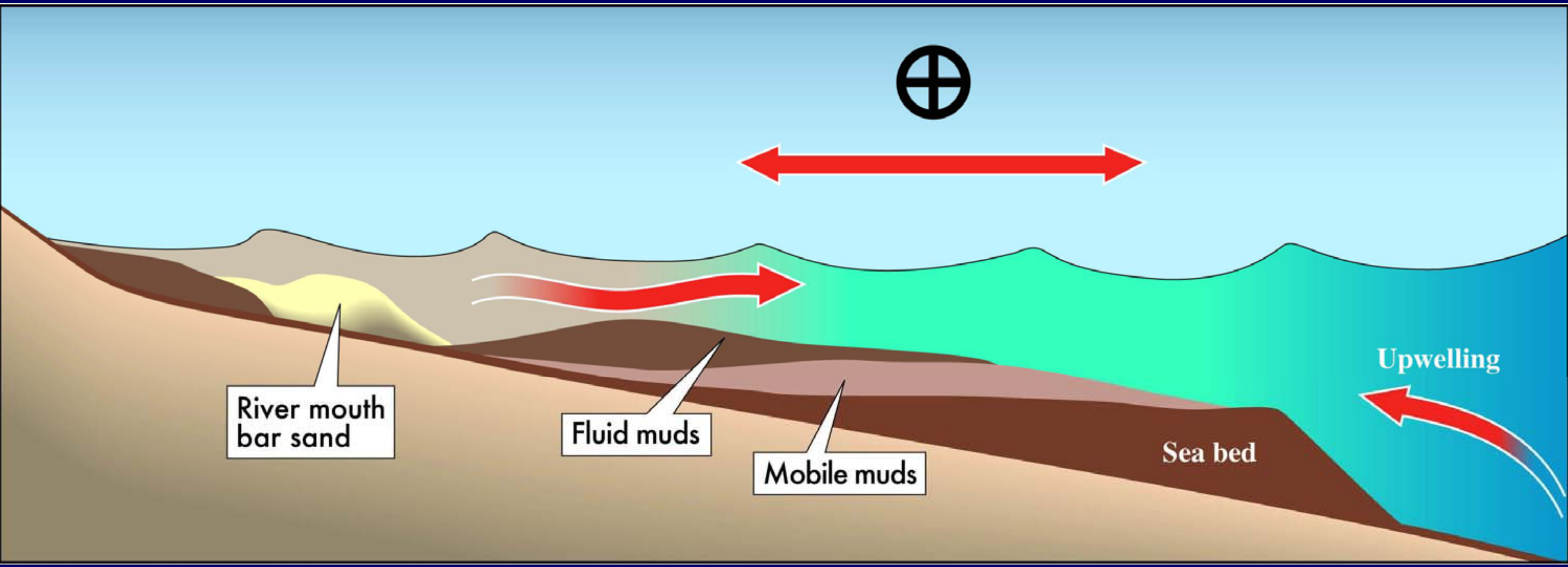
What controls them?

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

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



Benthic Boundary Layer (BBL) /Seabed Processes:



Burial

	Range	"Best" Value	Reference
	(Tg C yr^{-1})	(Tg C yr^{-1})	
Burial in River-Margin Sediments	98-159	115	5,12,13
Allochthonous Organic Carbon	43-104	60	5,12
Autochthonous Organic Carbon	55	55	5,14

Note:

- Org. C input ~ 550 Tg C yr^{-1}
- Primary Production
- Terrestrial: Marine Org. C in RiOMar sediments ~ 1:1

[1] Meybeck, 1993	[9] Aitkenhead and McDowell, 2000
[2] Meybeck and Vörösmarty, 1999	[10] Hedges et al, 1997
[3] Degens et al., 1991	[11] Stallard, 1998
[4] Spitzy and Ittekkot, 1991	[12] Berner, 1982
[5] Schlunz and Schneider, 2000	[13] Hedges and Keil, 1995
[6] Lyons et al., 2002 (and references within)	[14] Berger, 1989
[7] Ittekkot and Laane, 1991	
[8] Spitzy and Leenheer, 1991	

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)

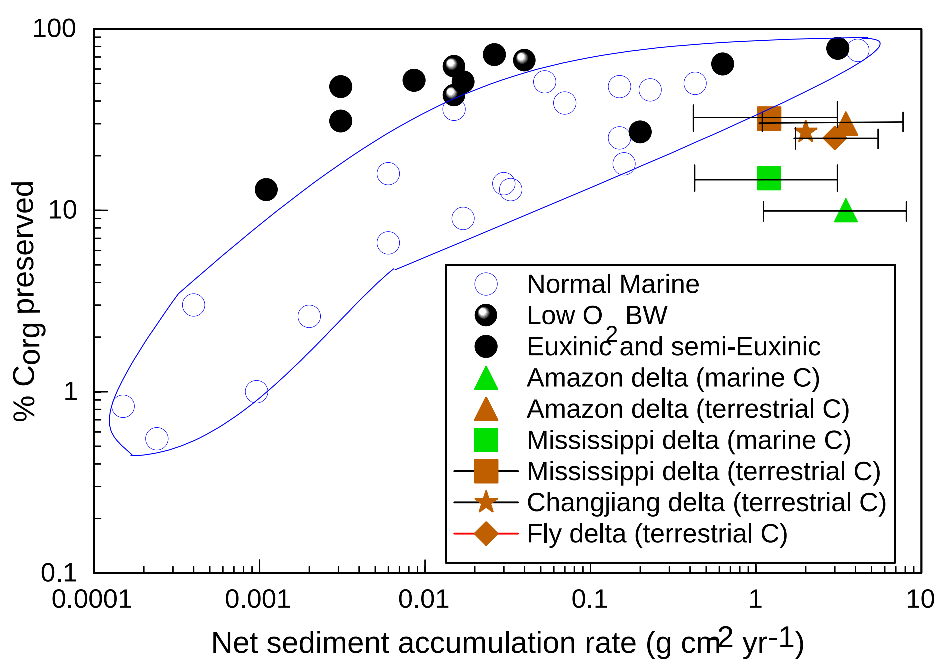
3. Surprisingly few carbon budgets for major river ocean systems
   a) those that exist have either raised important questions (where did all the Amazon carbon go?) or
   b) have large gaps to fill----burial flux is usually one

   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

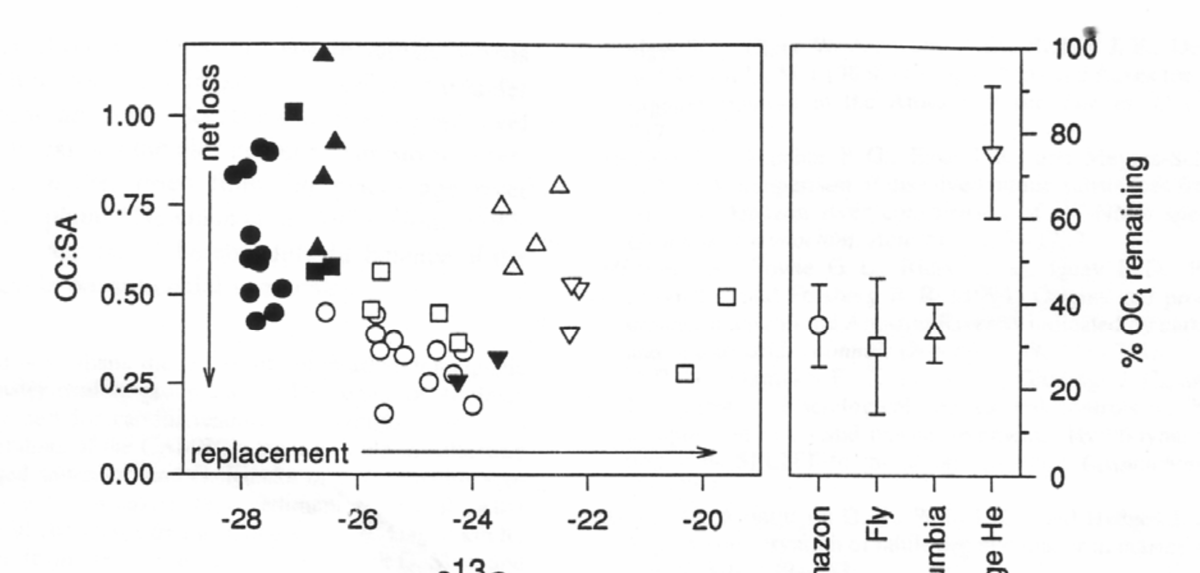
Burial (how much is preserved)



Preservation less than other similar sedimentary environments

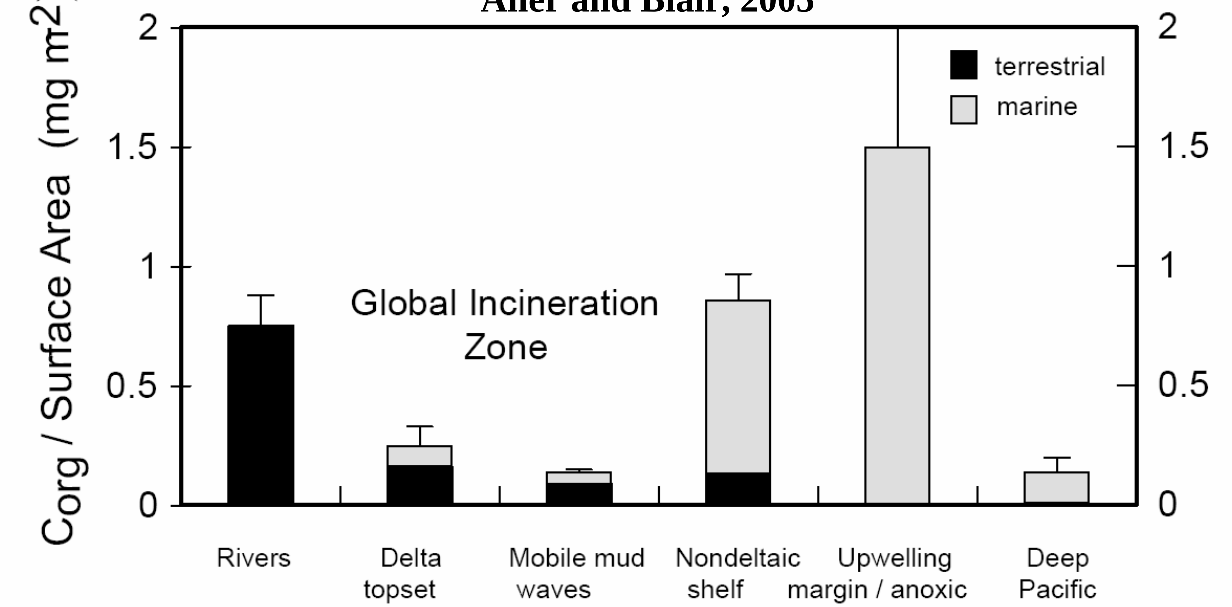
- **Co-metabolism**
- **Role of metal oxides as oxidants**
- **Resuspension**

Aller, 1998

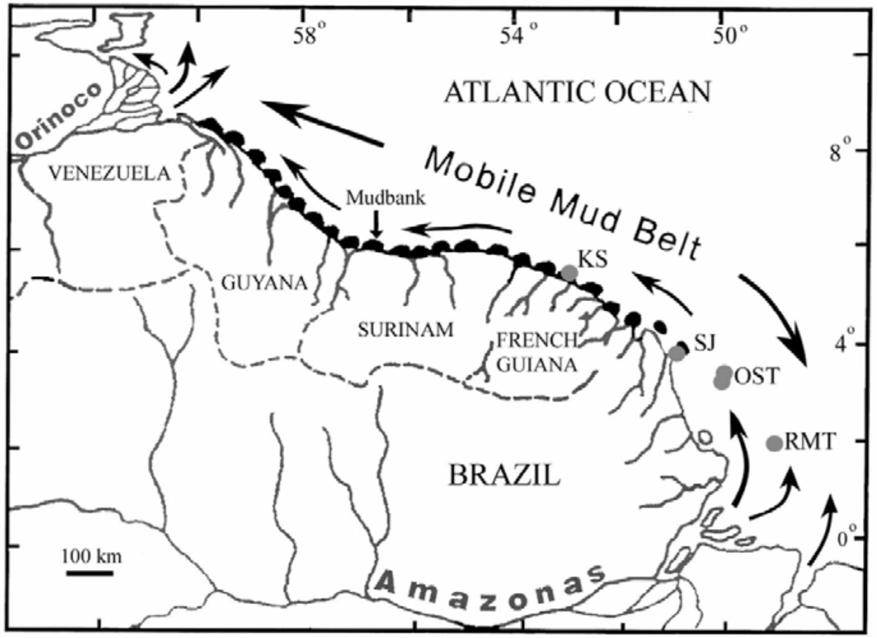


Keil et al., 1997

About 60% of terrestrial POC is oxidized within RiOMars


Aller and Blair, 2005

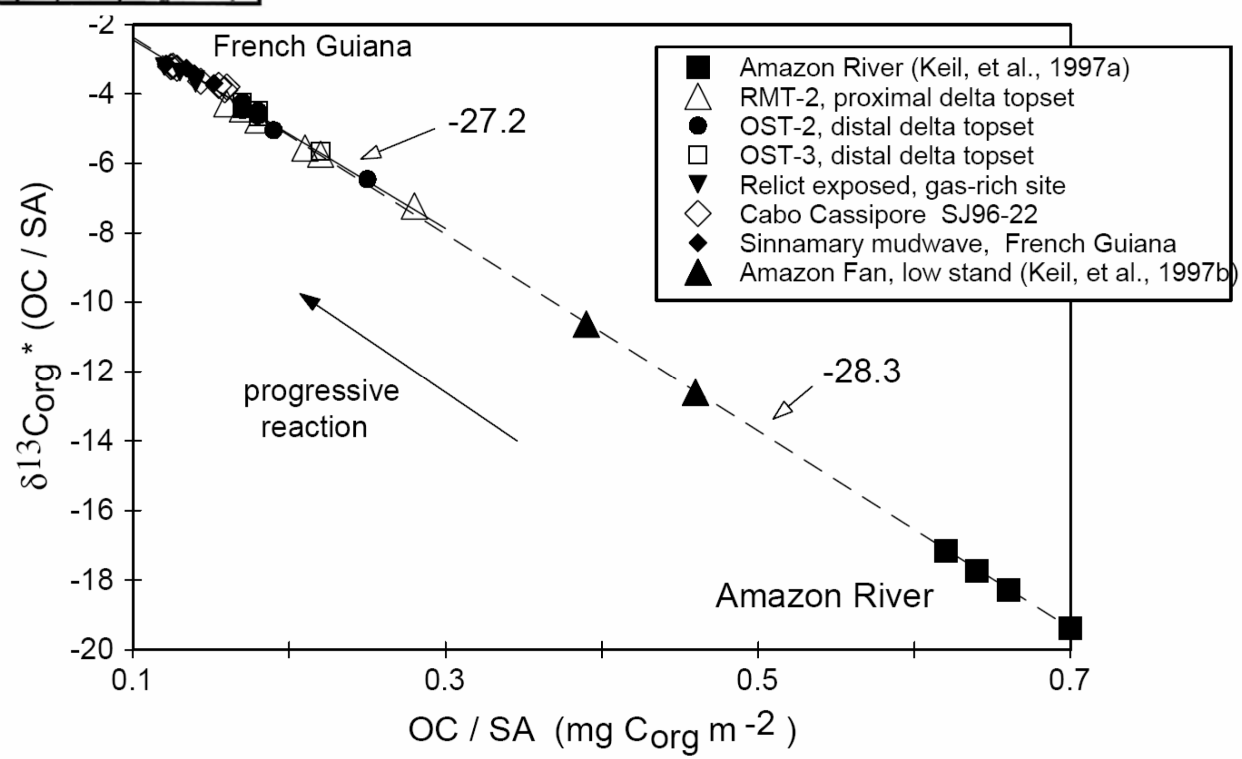
Some replacement by marine Org. C as coatings



Terrestrial C_{org} loading decreases progressively (~ order of magnitude) 100's of km down dispersal system

Mechanism?

Fluid Muds?



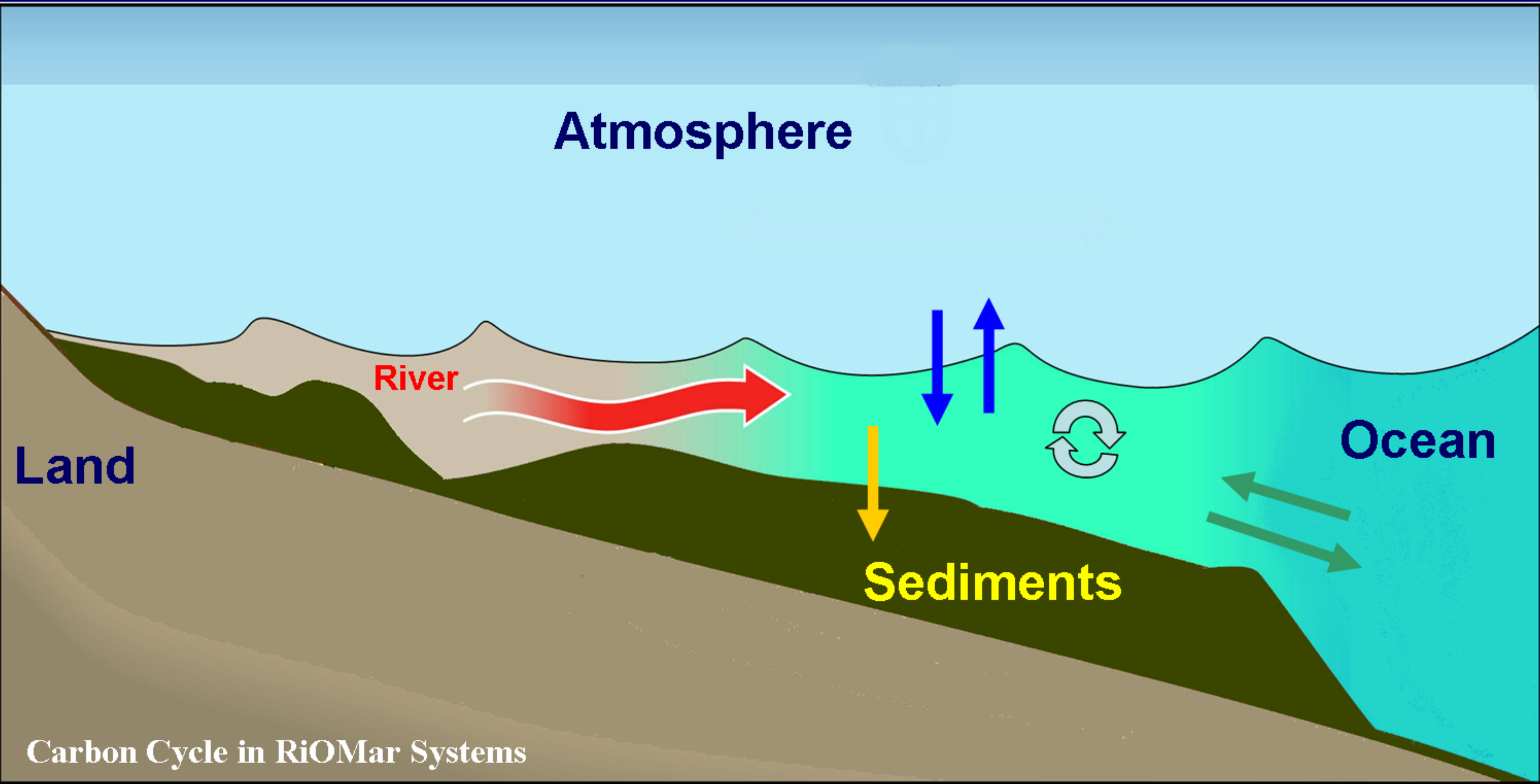
Aller and Blair, 2005

What is the magnitude of these fluxes?

What controls them?

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

- River Inputs
- Atm-Ocean Exchange
- Burial
- Net Export to Ocean



Export

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

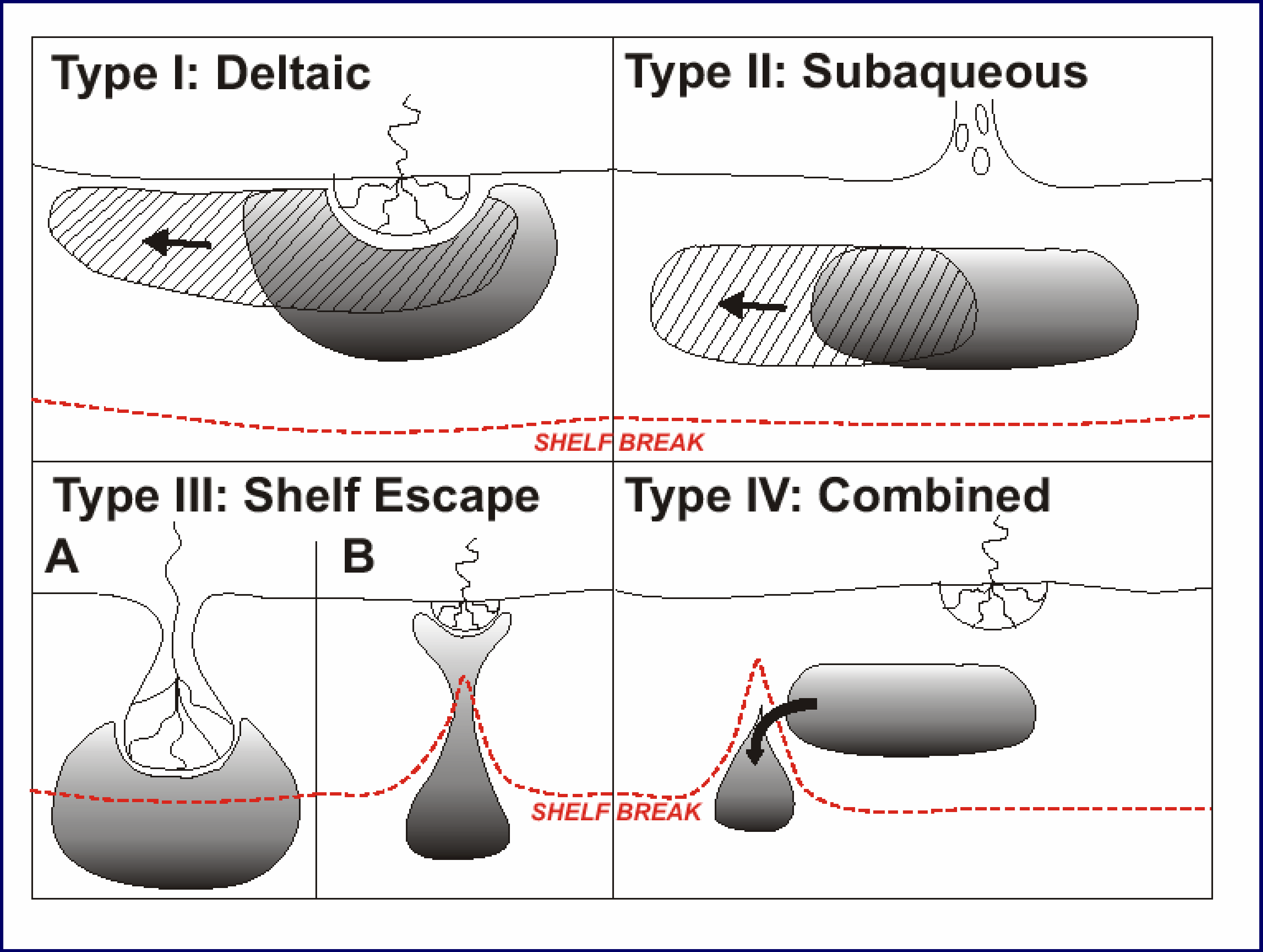
2. Turbidity currents down submarine canyons
   (Congo, Ganges-Brahmaputra, Mississippi ?)

3. Transport over narrow shelves
   (high mountainous rivers)

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

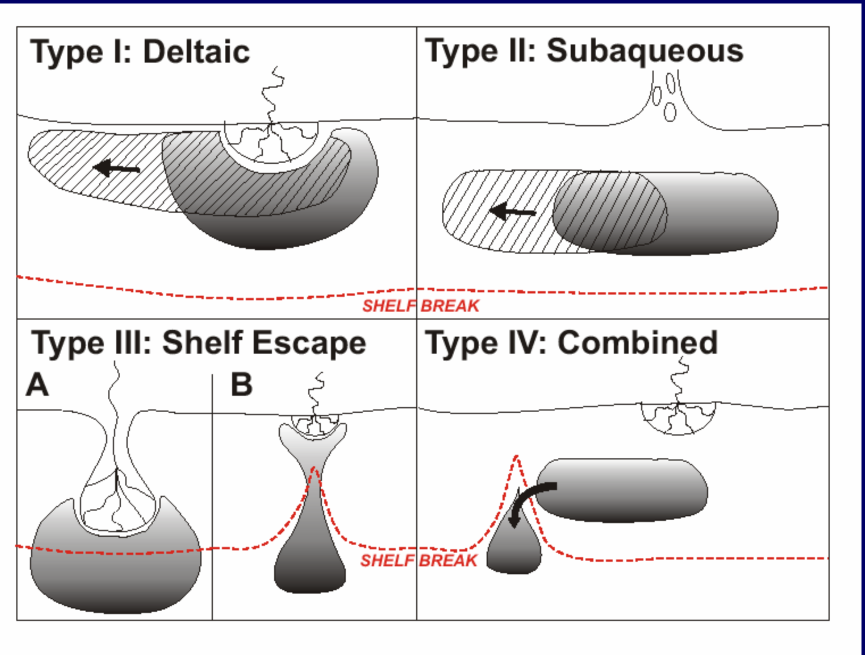
5. Unrecognized mechanisms
   (low frequency; event scale)

Particulate Organic Carbon Export



McKee et al. 2004

Particulate Export



RIVER	Sediment* Discharge 10^6 t yr^{-1}	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	Balize (IIIa) Atchafalaya (I)
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	?

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

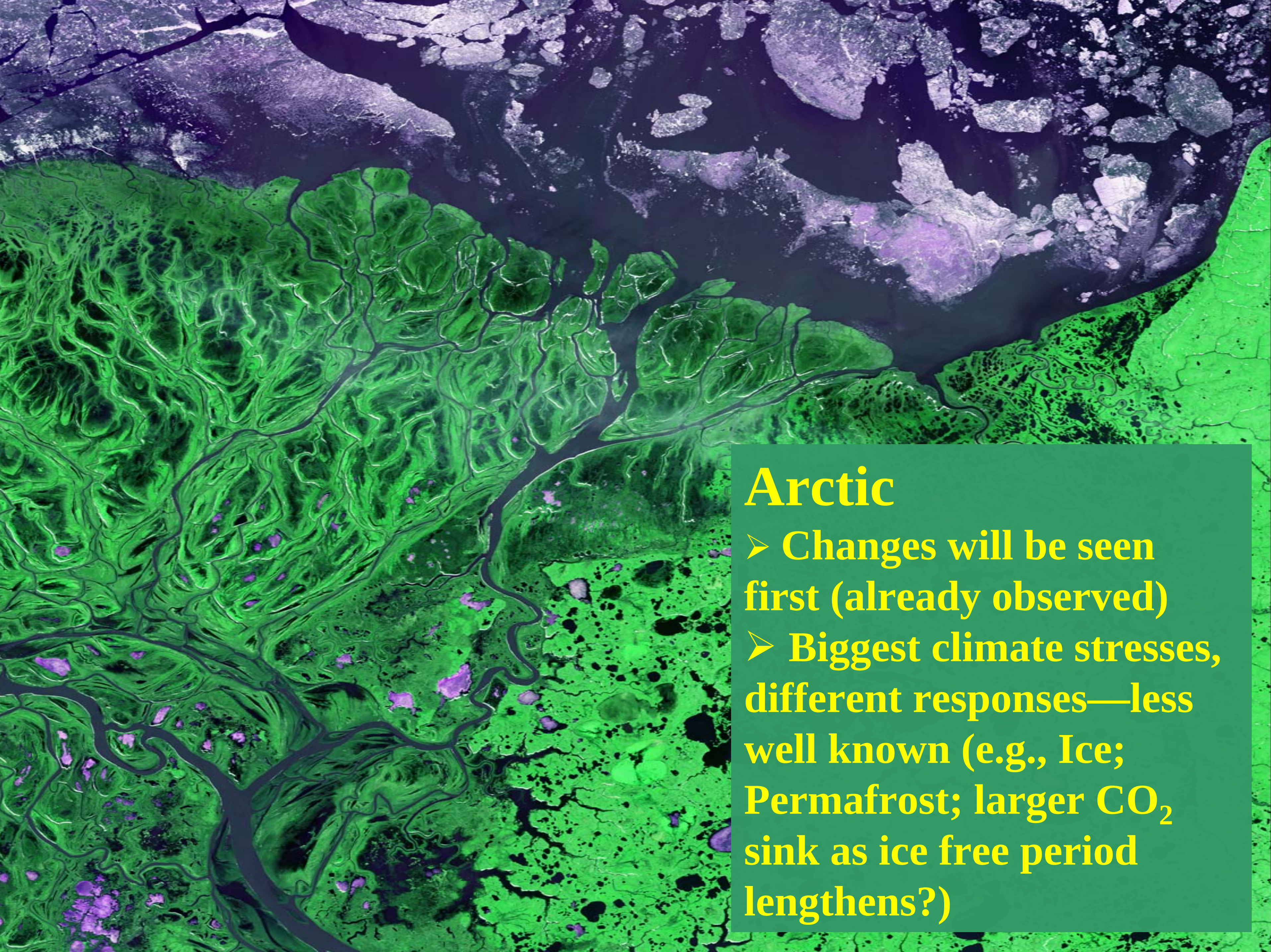
McKee et al. 2004

What is the best approach to answer critical questions?

Where to focus efforts

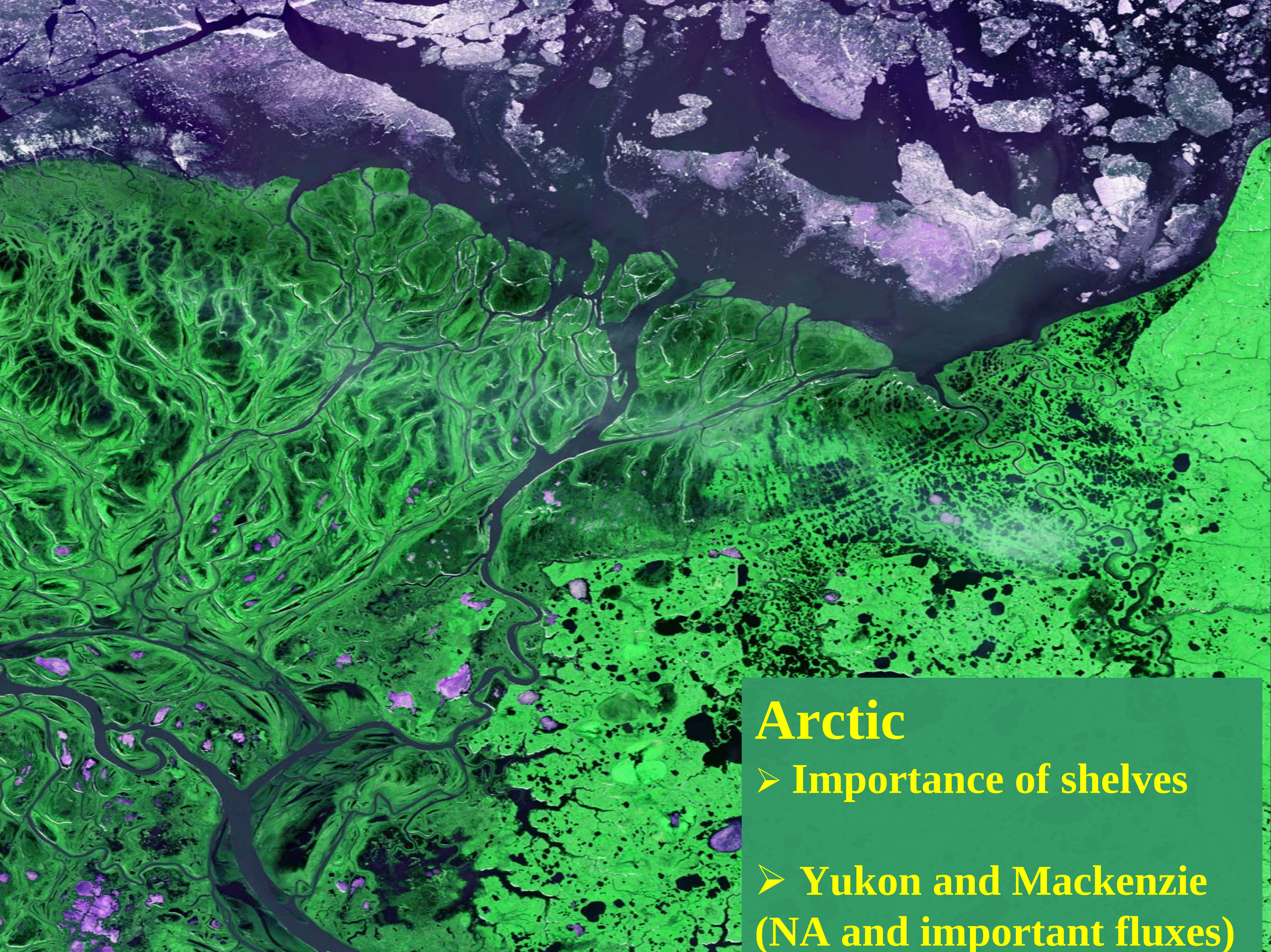
- **Focused studies of whole systems (along with some strategic comparative studies of subsystems or processes between RiOMar systems)**

- **Which systems? (can’t do top 25---probably not even top 10)**



Arctic

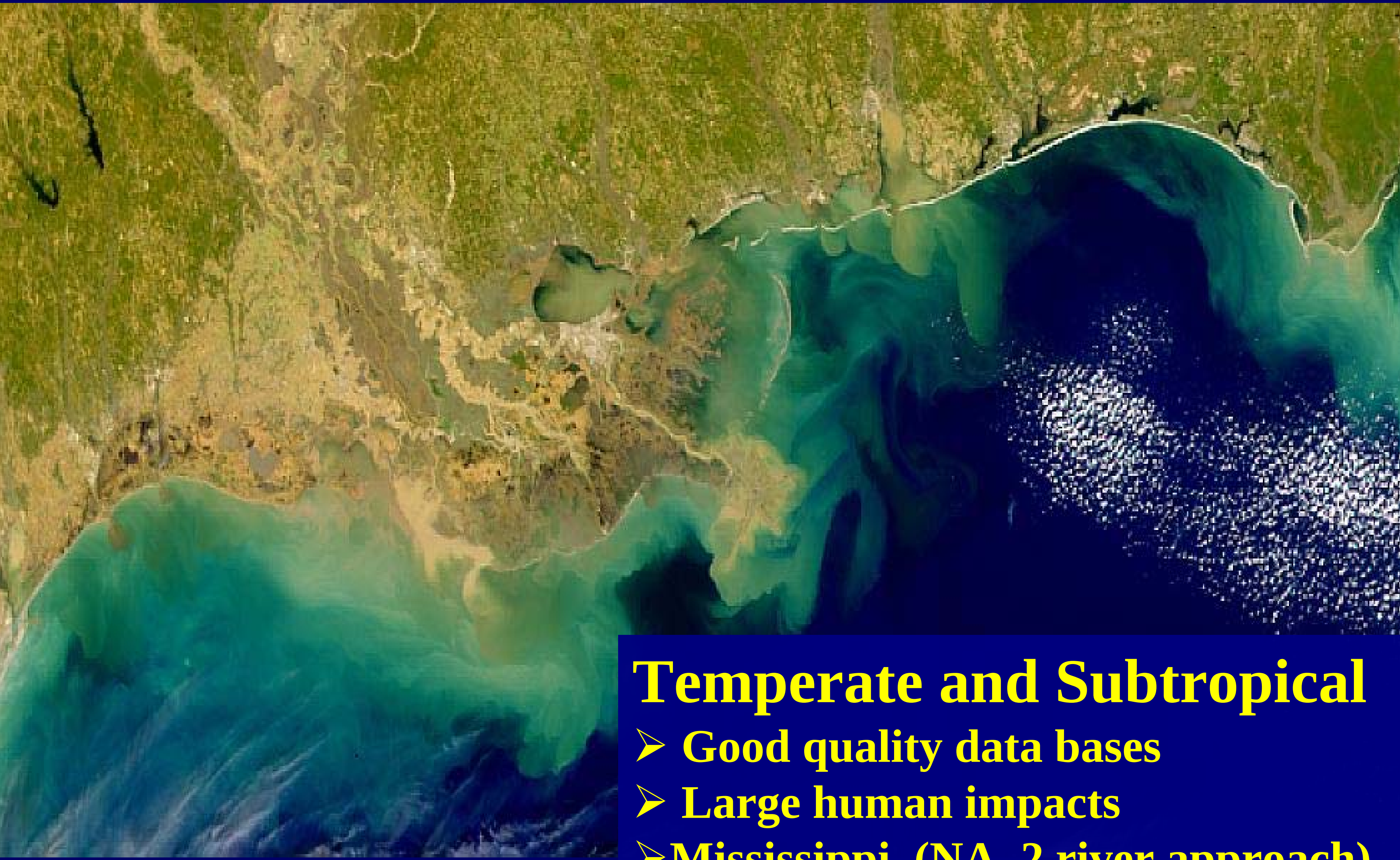
- Changes will be seen first (already observed)
- Biggest climate stresses, different responses—less well known (e.g., Ice; Permafrost; larger CO_2 sink as ice free period lengthens?)



Arctic

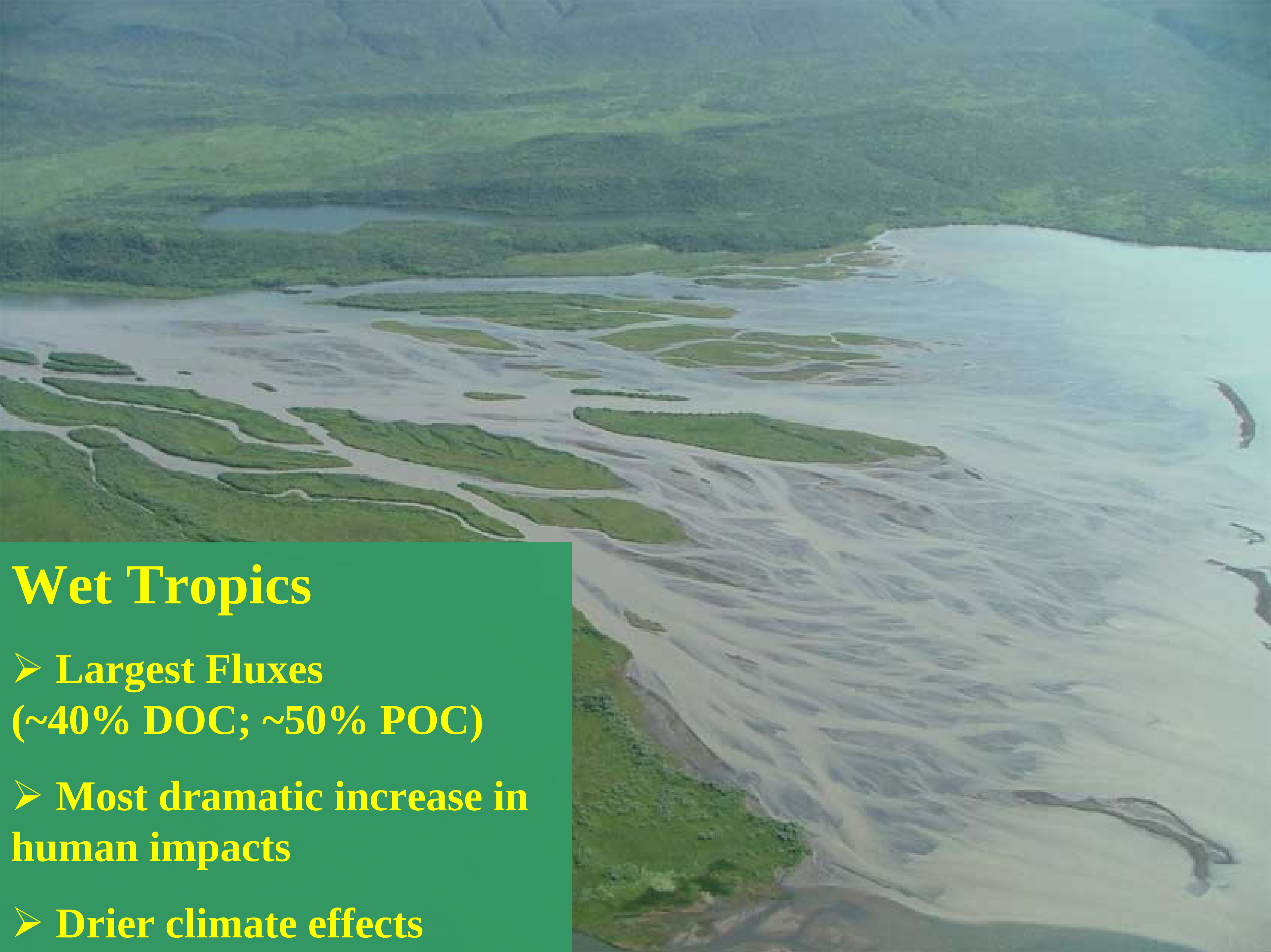
- Importance of shelves

- Yukon and Mackenzie (NA and important fluxes)



Temperate and Subtropical

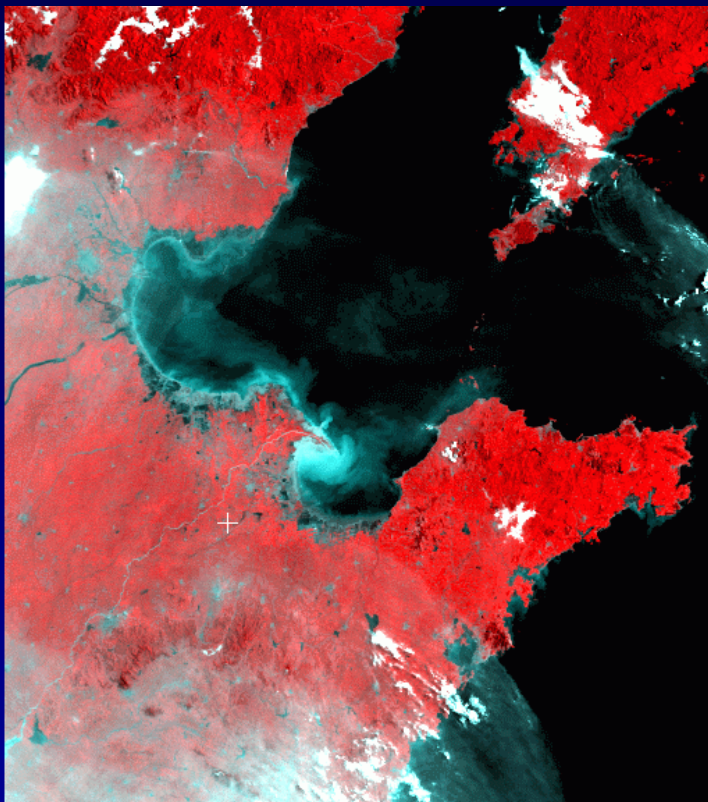
- ➢ Good quality data bases
- ➢ Large human impacts
- ➢ Mississippi (NA, 2 river approach)
- Logistics

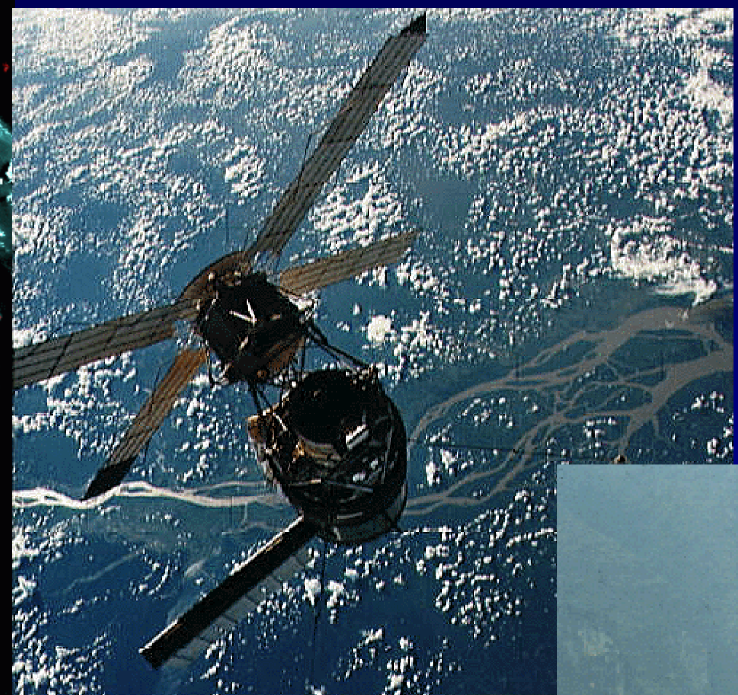


Wet Tropics

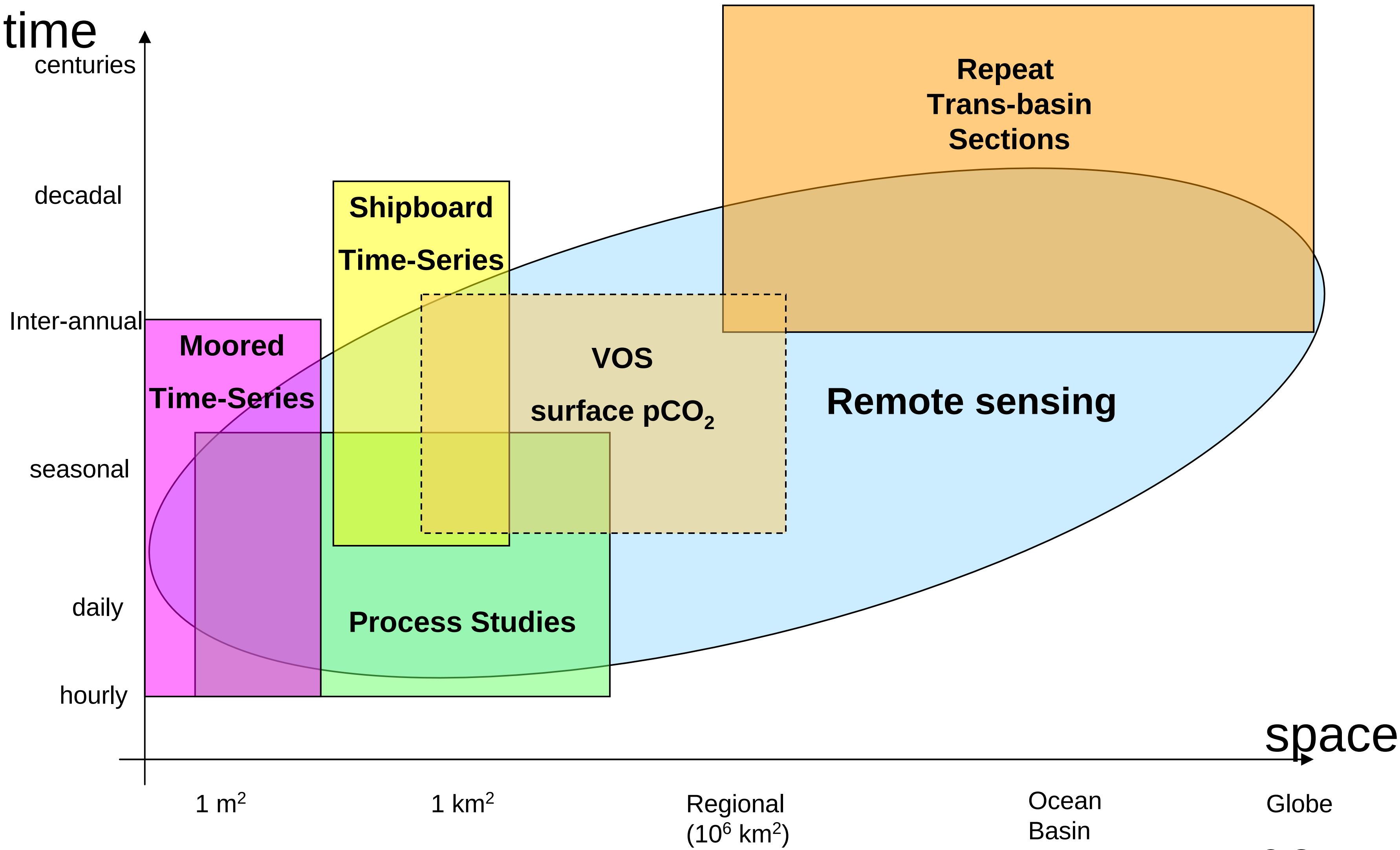
- **Largest Fluxes (~40% DOC; ~50% POC)**
- **Most dramatic increase in human impacts**
- **Drier climate effects**

Most Previous Studies of Large River Systems Conducted in the "Expedition" Mode





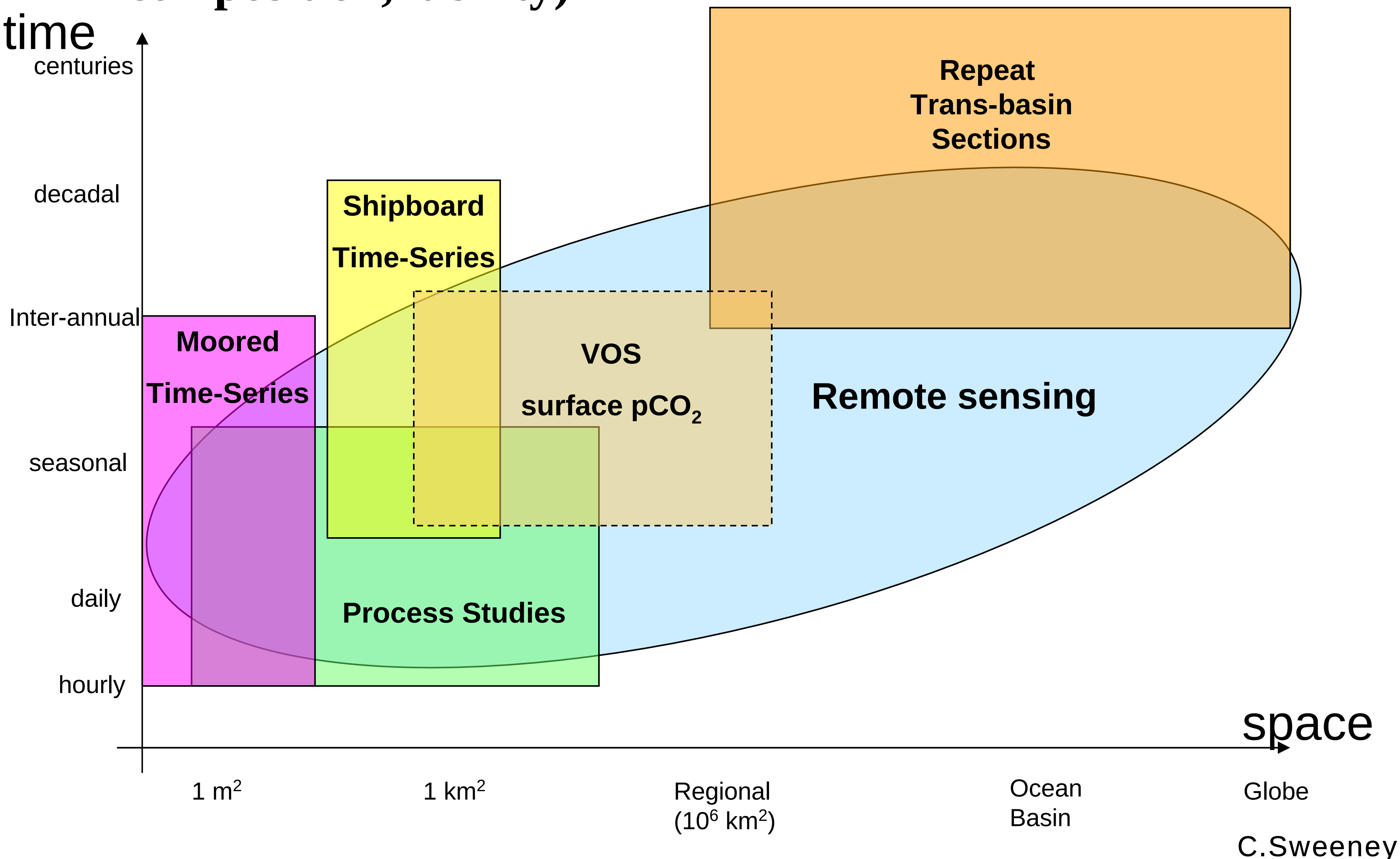
➢ Observation networks (coordinated with NACP--observatories further up river system)



C.Sweeney

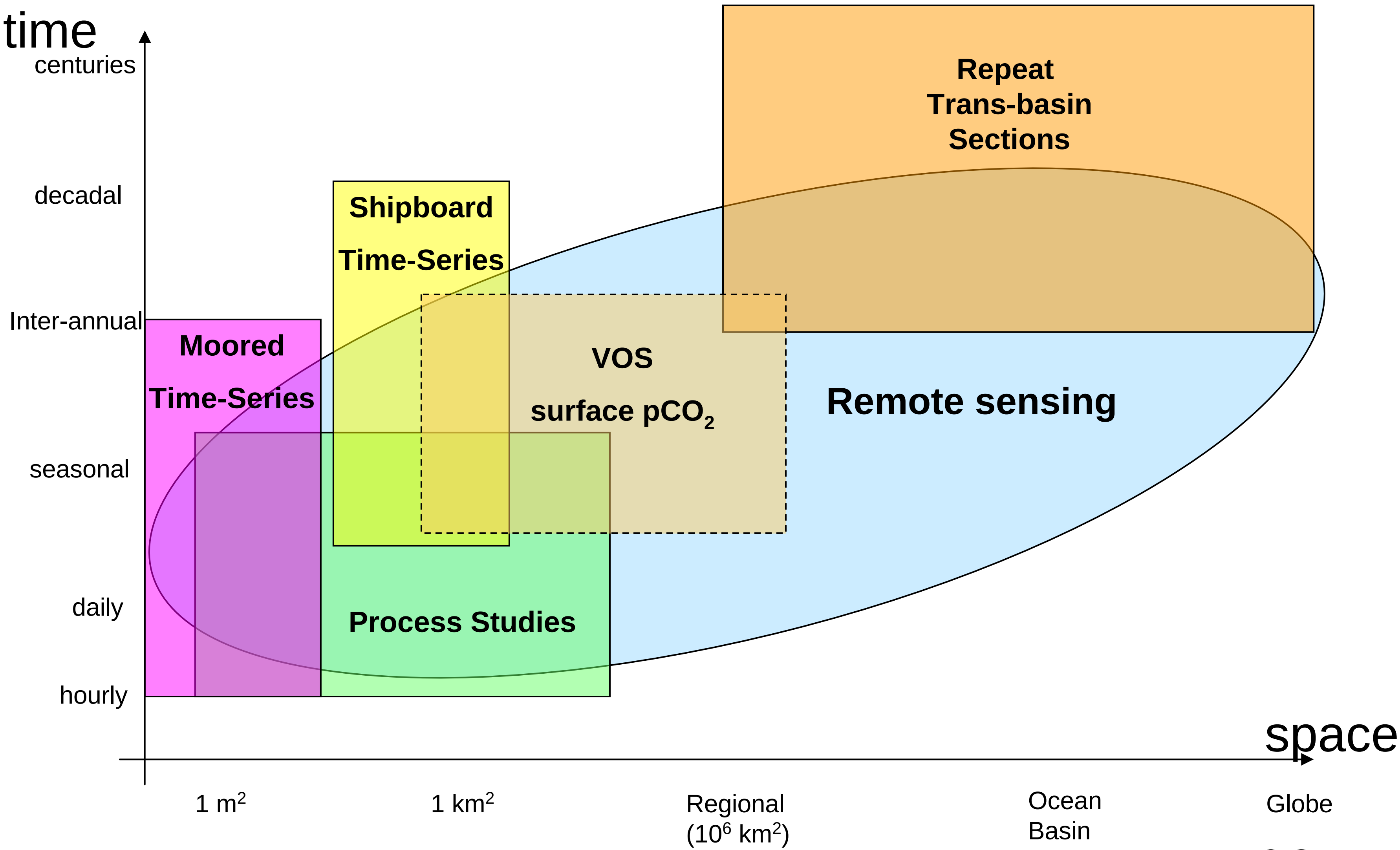
➢ **High frequency data collection + process studies in major river margins (enduring legacy of JGOFS)**

- **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)



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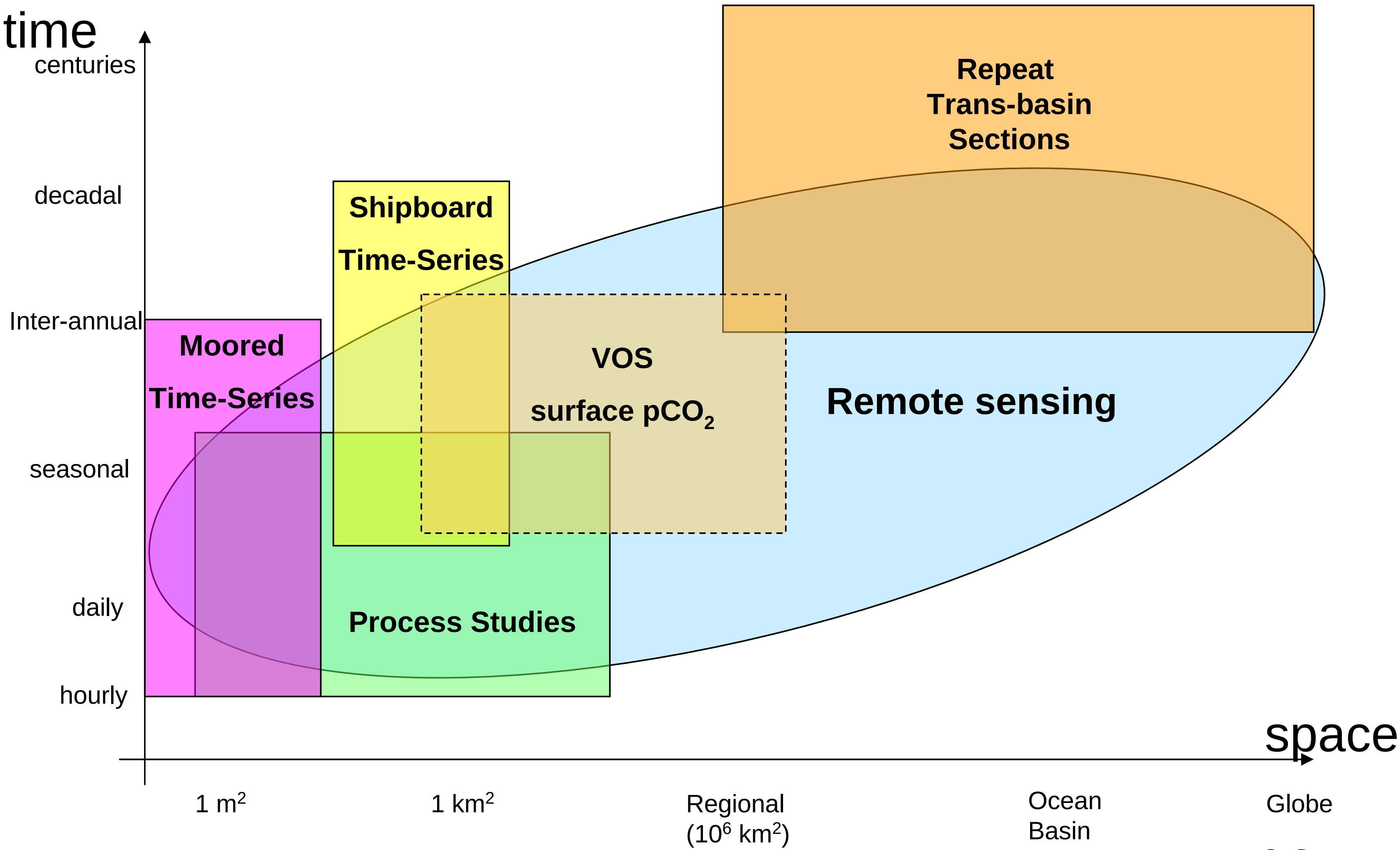
➢ Process work

Multi-disciplinary; Inter-disciplinary

Earth and Ocean scientists



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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**