*XVth World Water Congress,*
*25-29 May 2015, Edinburgh*
*PS2.2003*

# IMPACT OF INLAND WATER ON BIOGEOCHEMICAL CYCLE THROUGH DEVELOPMENT OF ADVANCED PROCESS-BASED MODEL

***National Institute for Environmental Studies (NIES), Japan***
**Tadanobu NAKAYAMA, Shamil MAKSYUTOV**

1. *Introduction - Background & objective*
2. *Model description of NICE*
3. *Verification of eco-hydrological process in global scale*
4. *Estimation of $CO_2$ evasion by empirical regression model*
5. *Further coupling NICE with biogeochemical cycle model*
6. *Preliminary conclusions and way forwards*

# What is a role of inland water in biogeochemical cycle ?

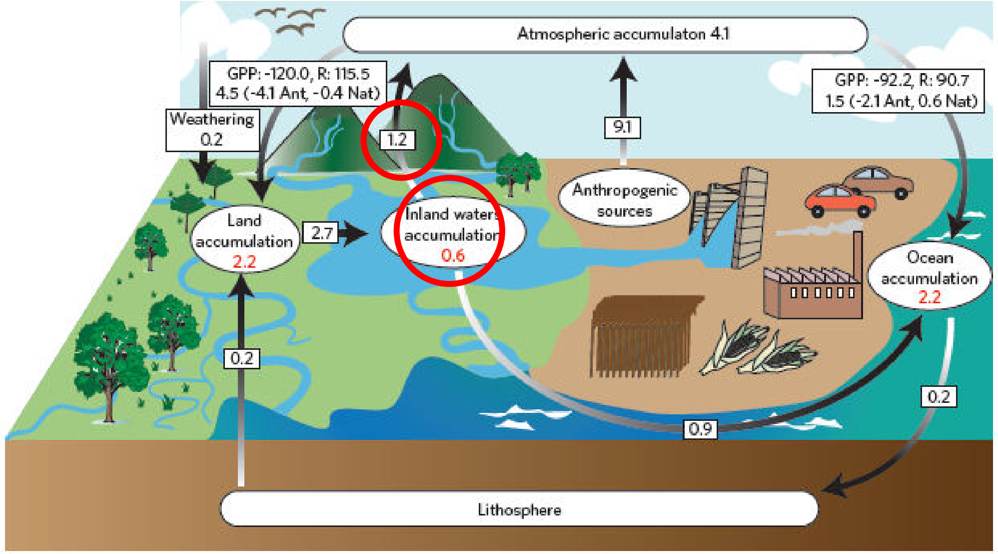



**Figure 1** | The 'boundless carbon cycle'. The schematic highlights carbon fluxes through inland waters[5], and also includes pre-industrial[2] and anthropogenic[3] fluxes. Values are net fluxes between pools (black) or rates of change within pools (red); units are Pg C $yr^{-1}$; negative signs indicate a sink from the atmosphere. Gross fluxes from the atmosphere to land and oceans, and the natural (Nat) and anthropogenic (Ant) components of net primary production — the net uptake of carbon by photosynthetic organisms — are shown for land and oceans. Gross primary production (GPP) and ecosystem respiration (R) are poorly constrained[18,19]; we therefore modified respiration to close the carbon balance. Non-biological dissolution of anthropogenic carbon dioxide by the oceans is included in these fluxes[2]. Fluxes to the lithosphere represent deposition to stable sedimentary basins, and the flux from the lithosphere to land represents erosion of uplifted sedimentary rocks[2].

**(Battin et al., 2009)**

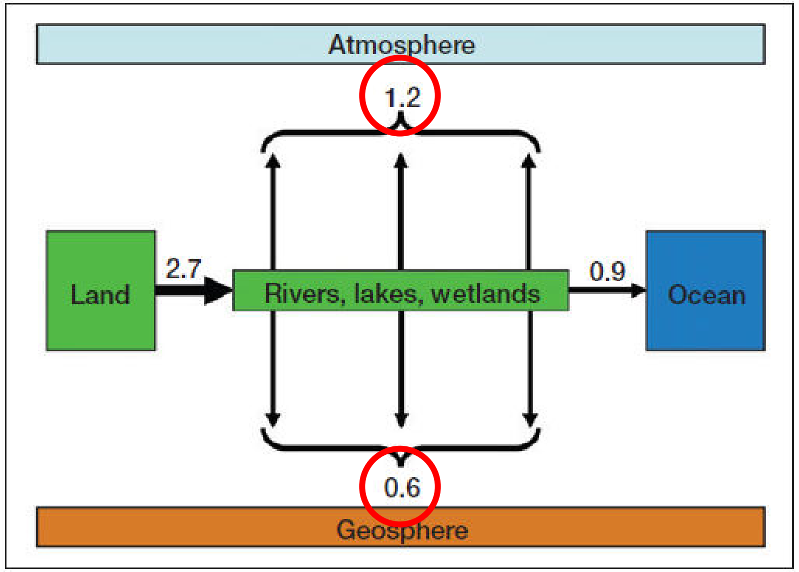



*Figure 3. The coupling of land, oceans, and atmosphere by rivers, lakes, and wetlands. All numbers are fluxes in units of Pg C $yr^{-1}$, with values based on an analysis by Battin et al. (2009); accumulation fluxes within both land and ocean each equal 2.2 Pg C $yr^{-1}$. The $CO_2$ outgassing and continental burial fluxes from Battin et al. (2009) are substantially larger than those published by Cole et al. (2007), primarily on account of more complete consideration of high-latitude lakes. A more balanced inclusion of tropical waters and wetlands, and temperature dependencies on $pCO_2$ and k, as we consider in Table 1, would require a further increase in outgassing fluxes to the atmosphere. These flux values have direct consequences to net C balances on land because of the need to balance the global C budget.*

**(Aufdenkampe et al., 2009)**

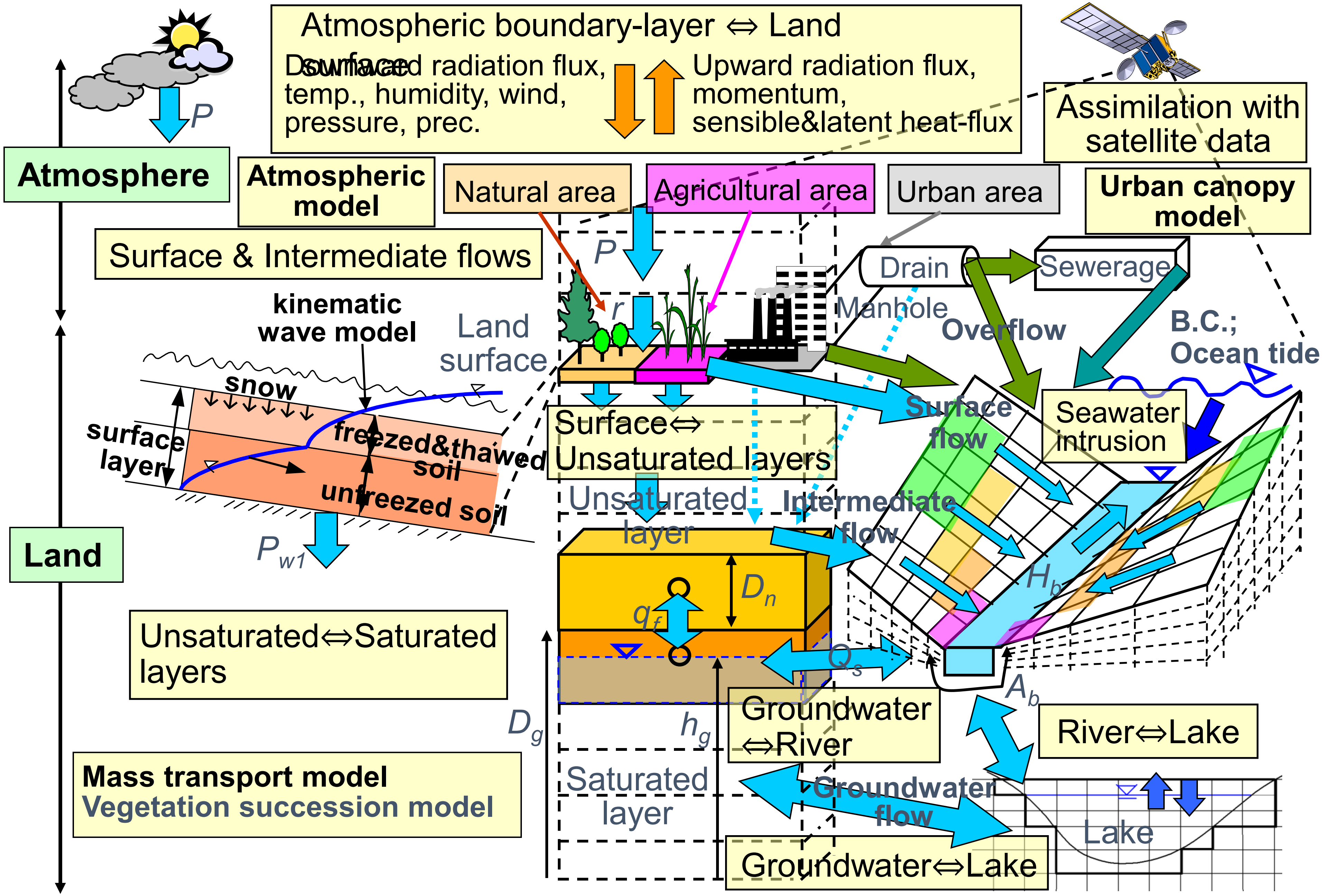
Common knowledge? Terrestrial biosphere was assumed to take up most of carbon on land.

Inland waters process large amounts of organic carbon and must be considered in strategies to mitigate climate change.

Necessity to clarify mutual interaction between hydrologic, geomorphic, and ecological processes.

# National Integrated Catchment-based Eco-hydrology (NICE) model

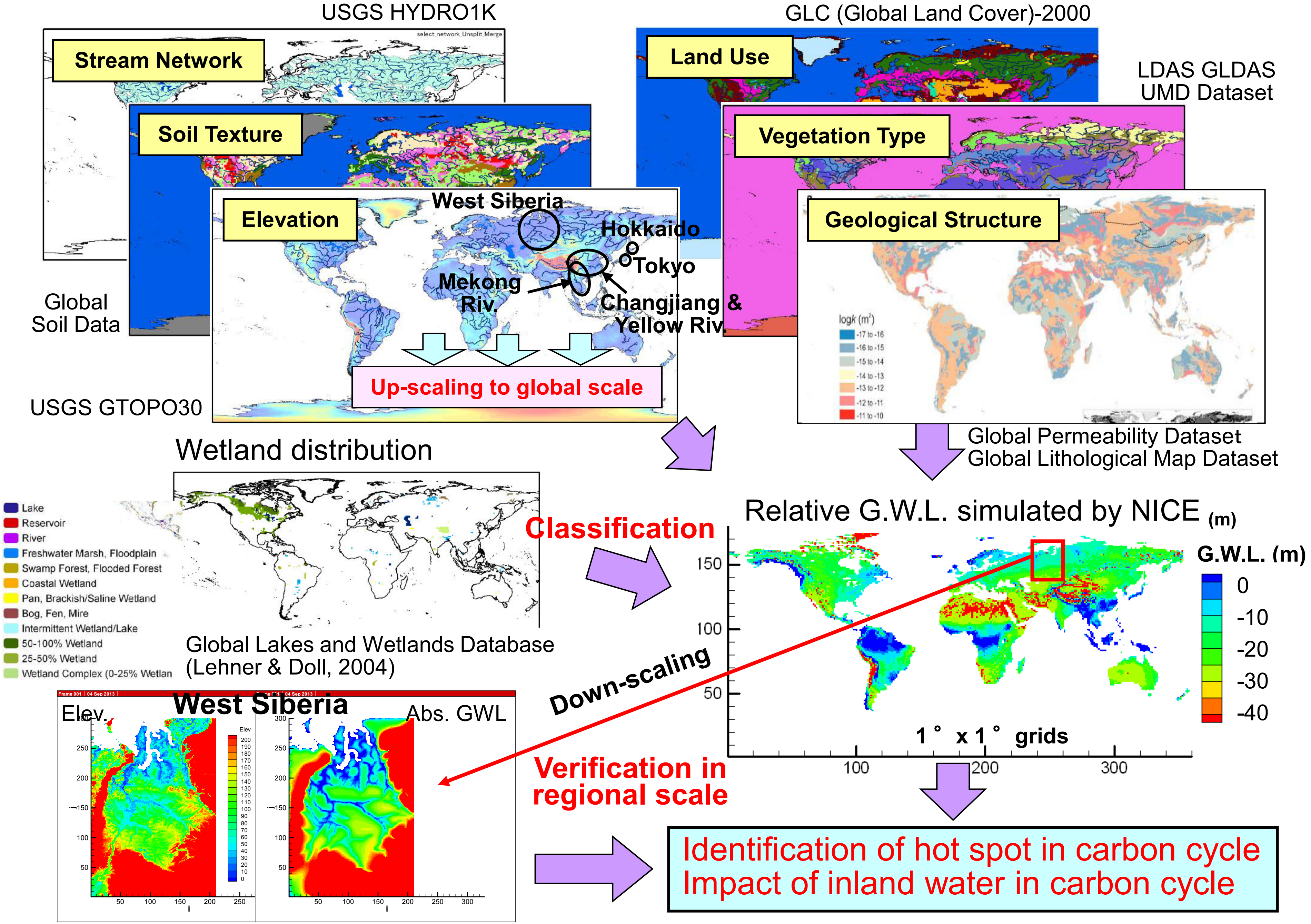
**(Nakayama et al., *WRR*2004; *HESSD*2006; *HP*2006,2008,2011,2012,2013; *STOTEN*2007; *ECOMOD*2008; *FORECO*2008; *GPC*2008,2010,2013; *RRA*2010; *LAND*2010; *ENPO*2011; *AGMET*2011; *WST*2012; *ECOHYD*2013)**



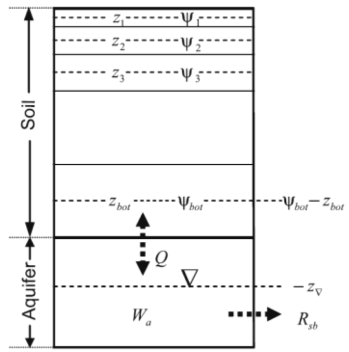
## Objective of this study
## - Role of inland water on biogeochemical cycle -

1. Developing 3-D process-based model (NICE) which simulates hydrologic cycle, mass transport, and vegetation succession processes iteratively, by combining with previous researches.
2. Verification of eco-hydrological process with previous global simulated results (single-layer aquifer for climate-groundwater interaction or simple two-dimensional model at equilibrium water table).
3. Estimation of $CO_2$ evasion (degassing) in inland water by empirical regression model (combining NICE simulated result, global dataset, and previous data). Evaluation of total flux, heterogeneous distribution of degassing, and hot spots.
4. Further extension of NICE to include biogeochemical cycle accompanied by hydrologic cycle in inland water; Reaction between inorganic and organic carbons (DOC, POC, DIC, pCO2, etc.), and its relation to nitrogen and phosphorus, etc.
5. This process might be beyond a residual or not within error/uncertainty range in global carbon cycle, and also help to diminish the uncertainty of carbon cycle as much as possible.

# Hydrologic simulation for better understanding of global biogeochemical cycle



# Comparison of groundwater level simulated by NICE with previous researches



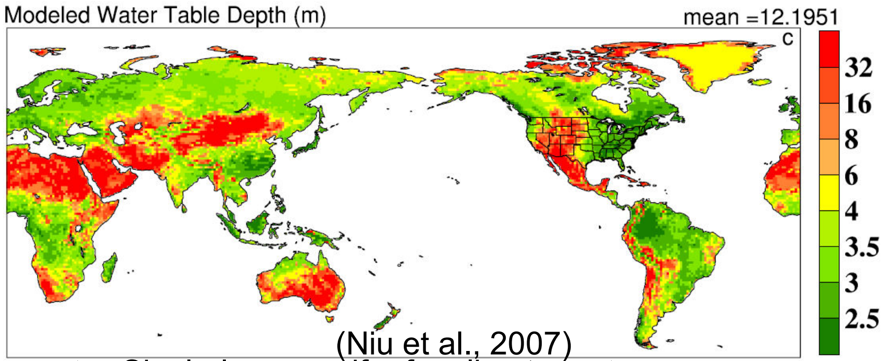

**SIMGM (Simple Groundwater Model)**

・Single-layer aquifer below the model soil column

・Lateral transport of groundwater is parameterized through TOPMODEL baseflow formulation (decay factor)

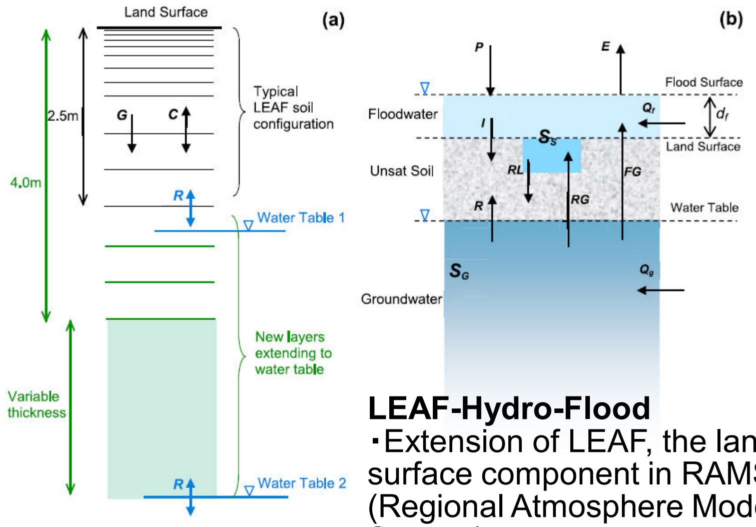
・Does not explicitly account for groundwater from cell to cell and exchange with streams

## Groundwater level in previous researches




(Niu et al., 2007)

Single-layer aquifer for climate-groundwater interaction → Vast plain area



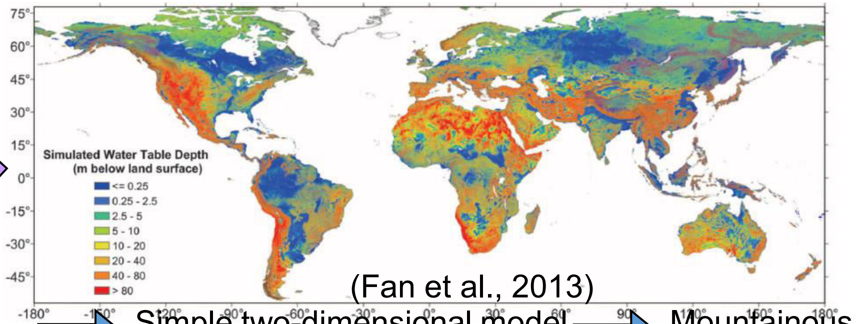

**LEAF-Hydro-Flood**

・Extension of LEAF, the land-surface component in RAMS (Regional Atmosphere Modeling System)

・New layers extending to water table

・Water table at equilibrium state

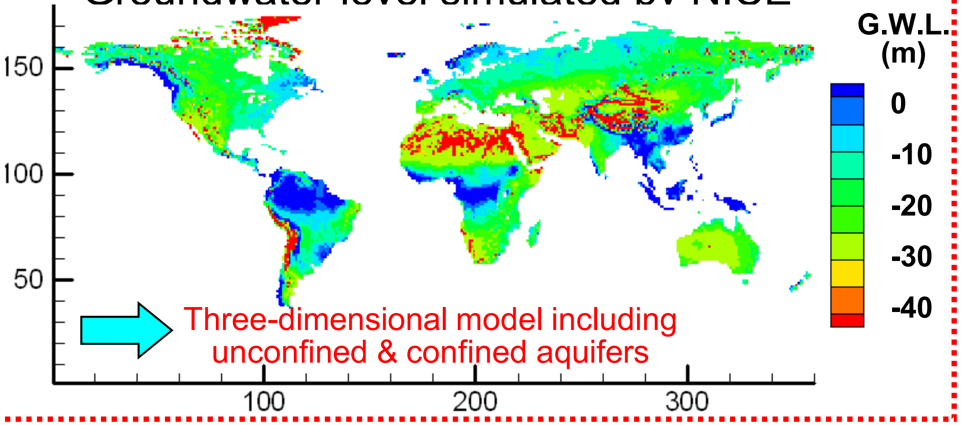
・Include lateral exchange with adjacent cells and exchange with streams (Darcy's law)




(Fan et al., 2013)

Simple two-dimensional model at equilibrium water table → Mountainous area

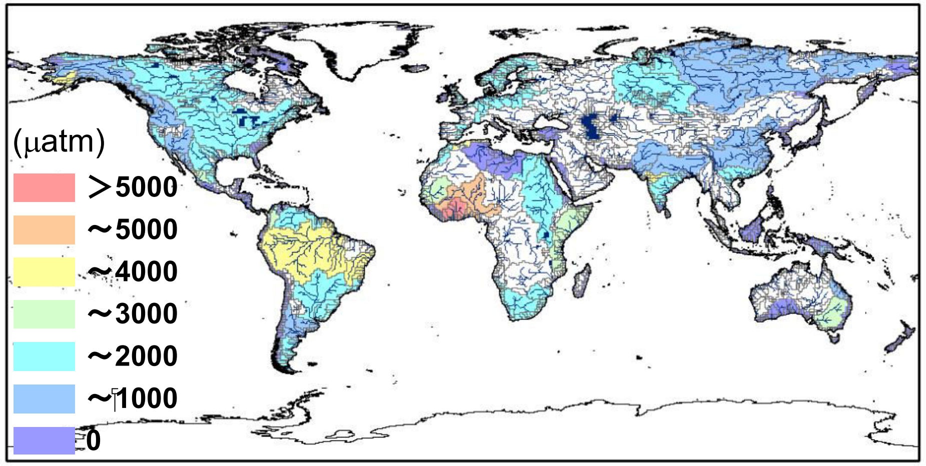
## Groundwater level simulated by NICE



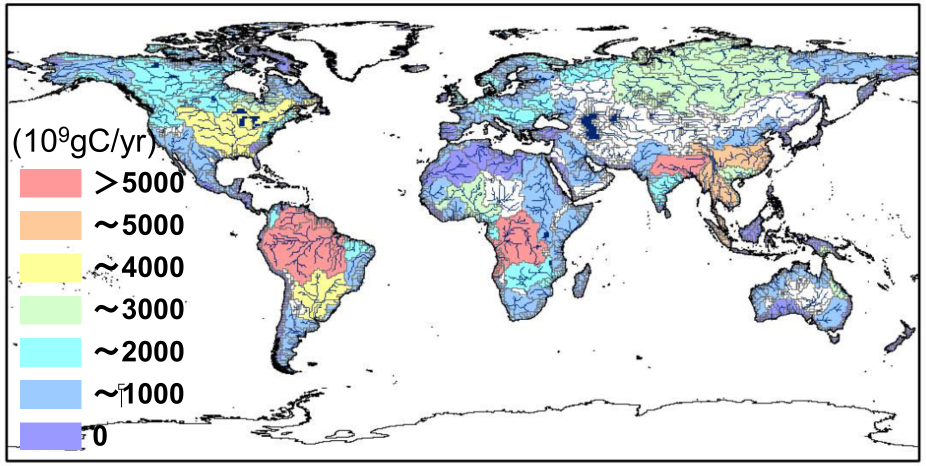

Three-dimensional model including unconfined & confined aquifers

# How about carbon cycle in inland water ???

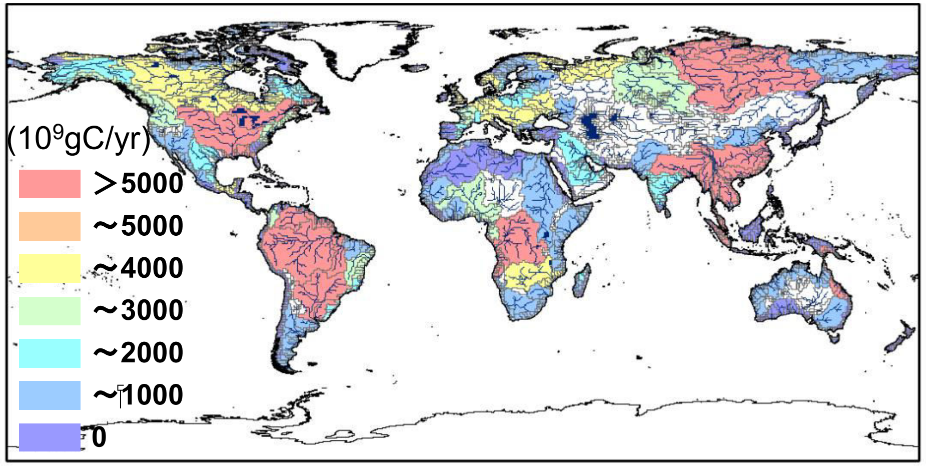
pCO$_2$ (Partial Pressure of CO$_2$)



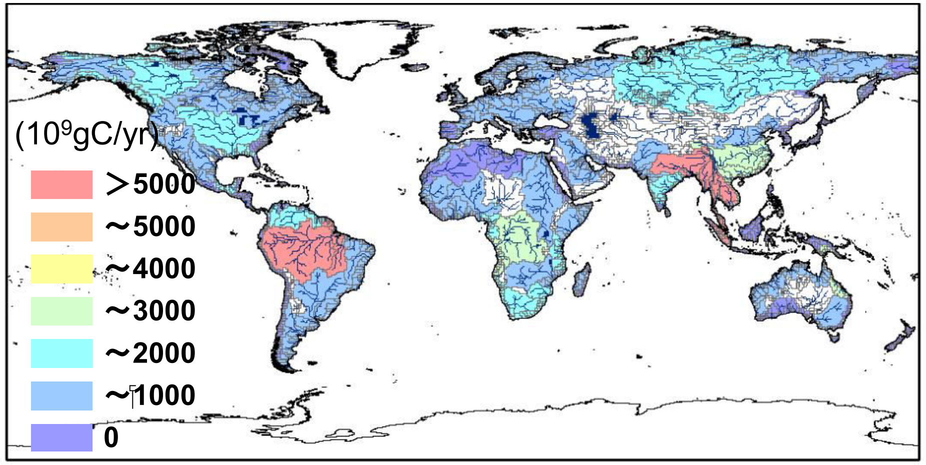

DOC (Dissolved Organic Carbon)




DIC (Dissolved Inorganic Carbon)




POC (Particulate Organic Carbon)

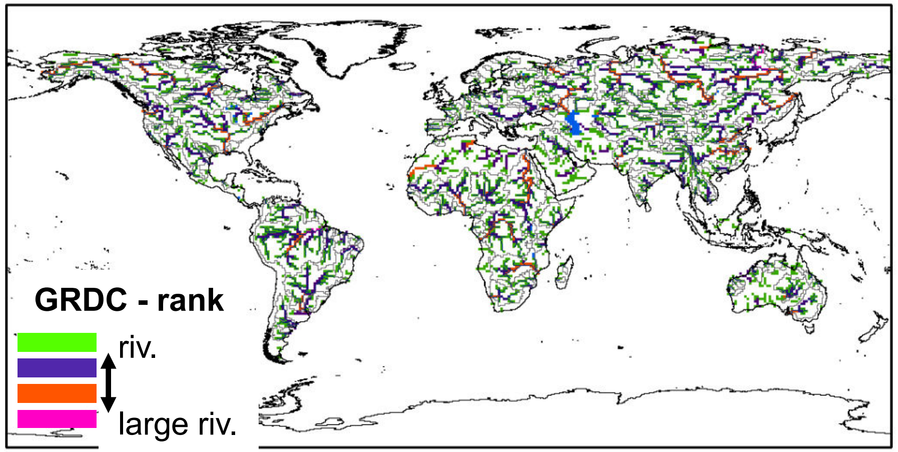



**Closely related to pCO$_2$, DOC, DIC, and POC in inland water !**

- **pCO$_2$ is important to evaluate CO$_2$ flux to the atmosphere (evasion)**
- **DOC, DIC, and POC are important to evaluate CO$_2$ flux to the ocean**

(Yao et al., 2007; Zeng et al., 2010; Aufdenkampe et al., 2011; Butman & Raymond, 2011; Global River Chemistry Database, 2013; Laruelle et al., 2013, etc.)

rank_order3-6(空白域も考慮)




**1 deg mesh: total river = 1138**
**All river length of each stream order (1 - 6) at each grid were calculated by ArcGIS software.**

| Order (ω) | GRDC | n | Mean | SD | Predicted mean (eq. 7) | Median | Trapezoidal mean (m) |
|---|---|---|---|---|---|---|---|
| 1 | | 46 | 1.9 | 1.1 | 1.2 | 1.6 | 0.8 |
| 2 | | 48 | 2.6 | 1.8 | 2.8 | 1.9 | 1.8 |
| 3 | | 50 | 7.5 | 6.3 | 6.4 | 5.5 | 3.7 |
| 4 | | 59 | 27.5 | 42.0 | 14.6 | 11.0 | 8.3 |
| 5 | | 41 | 72.7 | 98.1 | 33.3 | 47.5 | 29.3 |
| 6 | 1 | 68 | 194.2 | 338.7 | 76.0 | 99.0 | 73.3 |
| 7 | 2 | 58 | 245.0 | 263.4 | 173.4 | 164.0 | 131.5 |
| 8 | 3 | 32 | 511.6 | 483.3 | 395.2 | 365.0 | 264.5 |
| 9 | 4 | 11 | 988.5 | 746.9 | 901.0 | 852.0 | 608.5 |
| 10 | 5 | 3 | 1028.0 | 371.1 | 2053.9 | 1125.0 | 988.5 |
| 11 | 6 | 1 | 481.0 | — | 4682.1 | 481.0 | 803.0 |
| 12 | | 1 | 5676.0 | — | 10673.4 | 5676.0 | 3079.0 |

**Relation between Strahler stream order & stream width**
(Downing et al., 2012)

## Calculation of $CO_2$ fluxes (mg C $m^{-2}$ $d^{-1}$) to the atmosphere

$$F_{CO2} = k \times k_h \times [(pCO_{2water}) - (pCO_{2air})]$$

**k (m/d) : $CO_2$ exchange velocity coefficient**

**$k = k_{600}(Sc/600)^{-n}$ : n=0.5** (Jahne et al., 1987)

$$k_{600} = (1-f) \times 0.31u^2 + f \times 0.35w$$

**f : dominant ratio of inland water calculated by GIS**

**w (cm/s) : water velocity simulated by NICE**

**u (m/s) : wind speed calculated by meteo. dataset**

**$k_h$ : Henry's constant corrected for temperature**

**$= 10^{-(1.11+0.016xT-0.00007xT^2)}$ for temp.(T) in ℃**

**Global database**

**$pCO_{2water}$ & $pCO_{2air}$ : partial pressure $CO_2$ (μatm)**

**$pCO_{2water}$ : given data** (Laruelle et al., 2013)

**Assumption $pCO_{2air}$ = 370 ppm (global average in 2000)**

**Depend on methods ?**

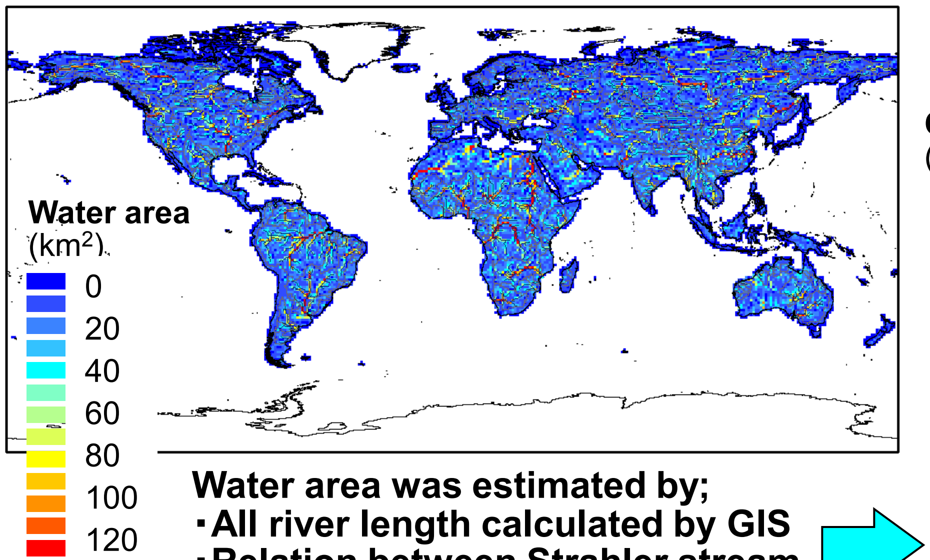
**Large uncertainty**

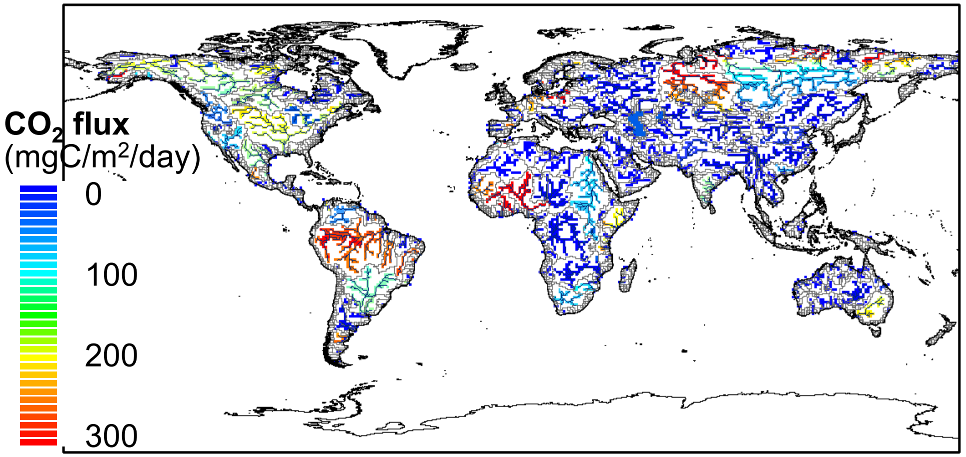
**Necessity to develop process-based model of carbon cycle !**

### Other estimation of k

- wind-based approach (Cole & Caraco, 1998)
- small eddy version of surface renewal model (MacIntyre et al., 1995)
- wind-based model including diel heating & cooling (MacIntyre et al., 2010)
- function of discharge & wind (Alin et al., 2011)
- etc.

# Estimation of $CO_2$ evasion in inland water by empirical regression model




**Water area was estimated by;**
**・All river length calculated by GIS**
**・Relation between Strahler stream order & stream width**

**Total area = 0.30 x $10^6$ (km$^2$)**

→ **Total $F_{CO2}$ (PgC/yr) = 0.69 < 1.2** (Aufdenkampe et al., 2011)

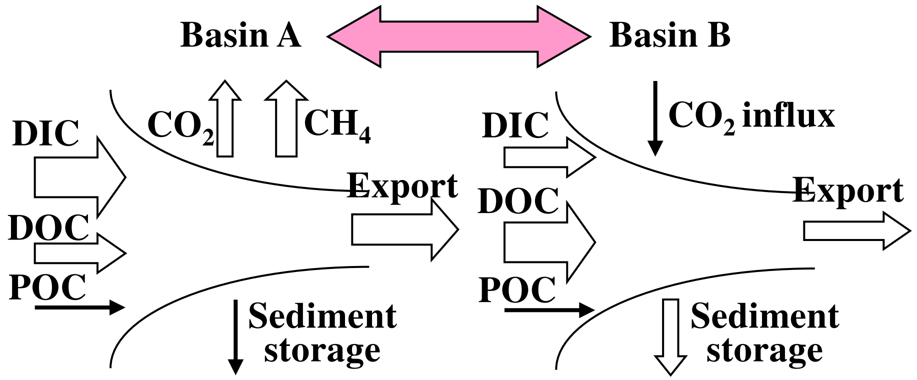
**Possibility to underestimate $CO_2$ evasion !**

**Cf. k=2.0m/d(=const)→Total $F_{CO2}$ (PgC/yr) = 1.17**

- **Depend on methods**
- **Large uncertainty**

→ **Necessity to develop process-based model of carbon cycle in inland water !**

## Carbon budgets at various basins/catchmnts

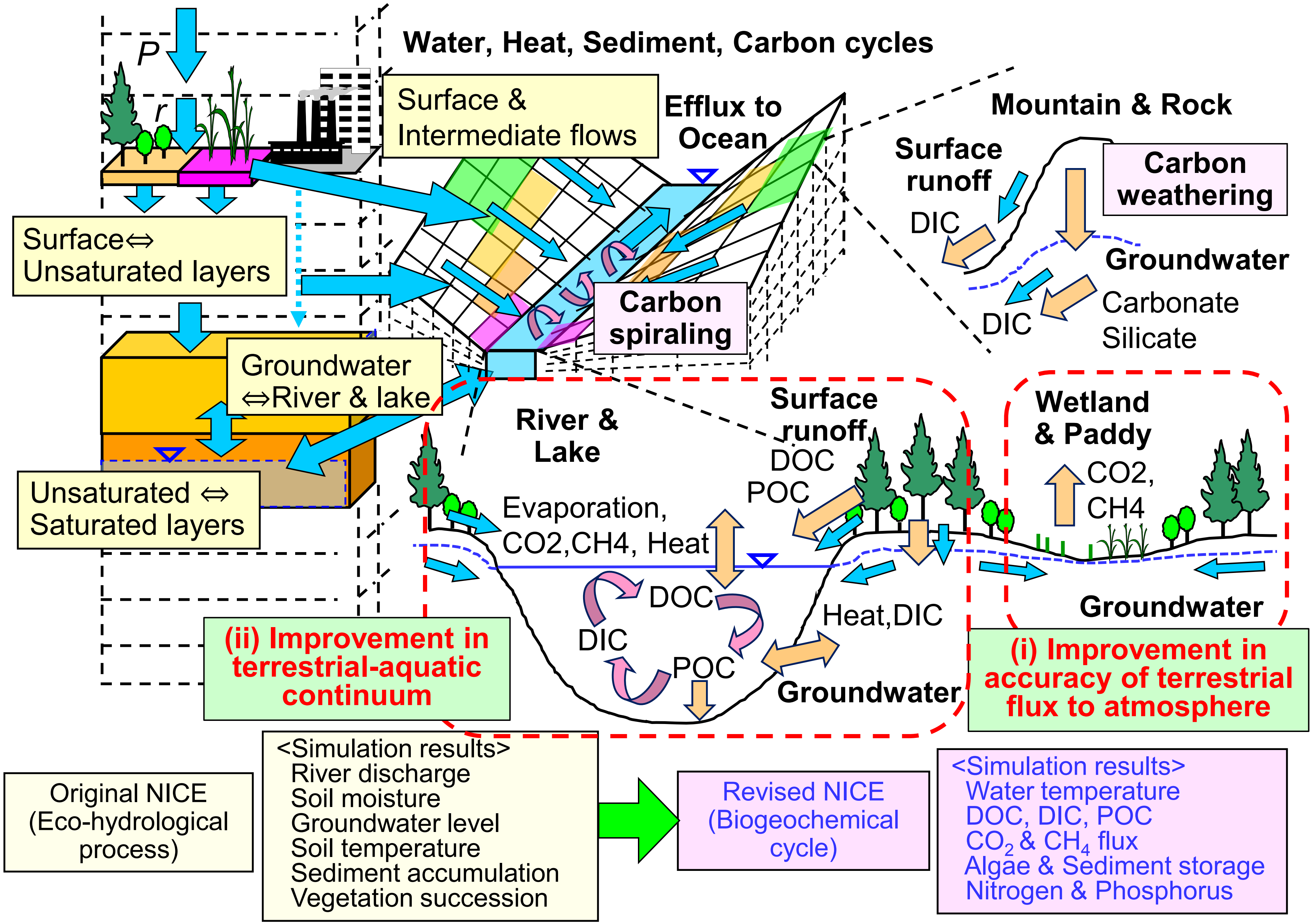



→ **Closely related to $pCO_2$, DOC, DIC, and POC in inland water !**

→ **・$pCO_2$ is important to evaluate $CO_2$ flux to the atmosphere (evasion)**
**・DOC, DIC, and POC are important to evaluate $CO_2$ flux to the ocean**

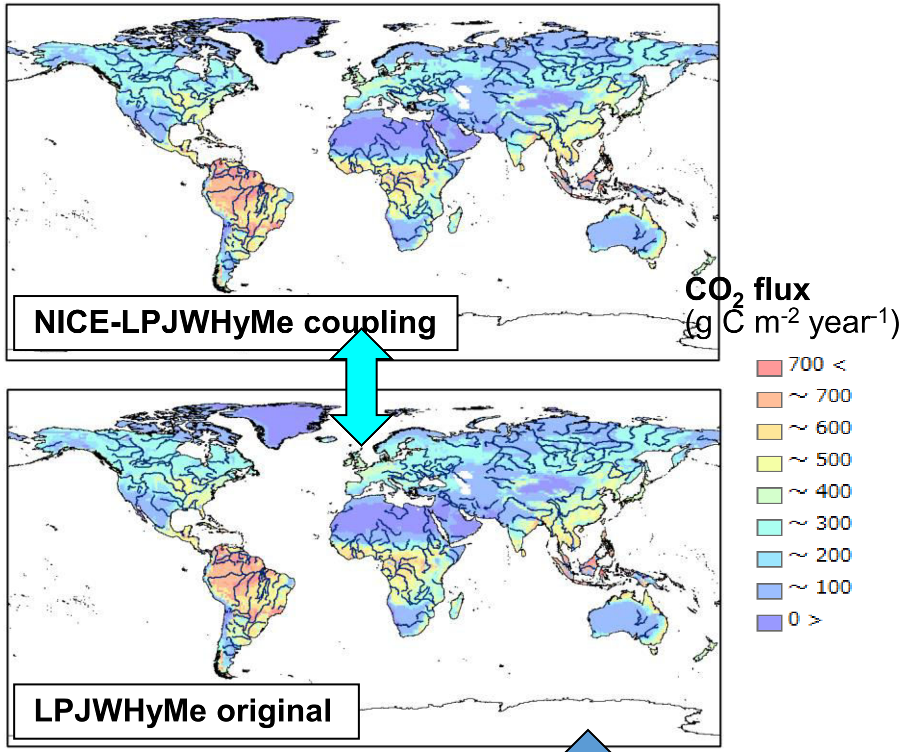
→ **Need to estimate from the view point of terrestrial-aquatic continuum !**

# Coupling between eco-hydrological process and carbon cycle in NICE

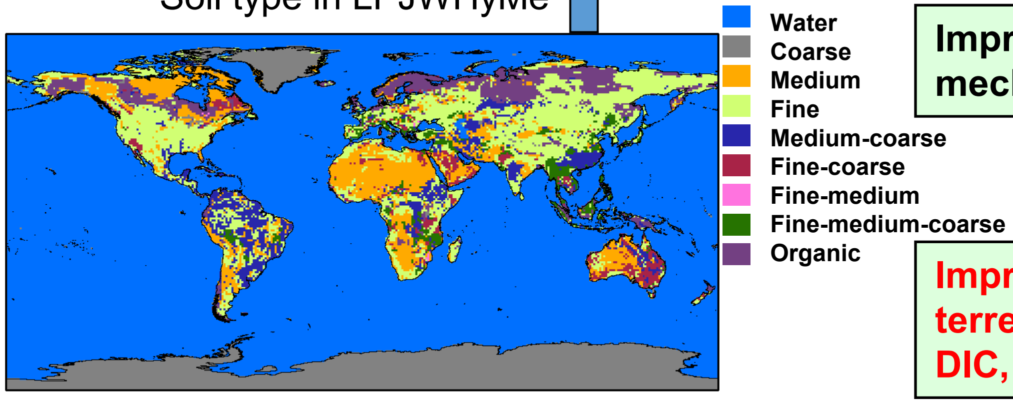


# Improvement of carbon cycle in terrestrial ecosystem by coupling NICE with LPJWHyMe

Effect of G.W.L. on annual heterotrophic respiration (1998)




Soil type in LPJWHyMe




**LPJ-WHyMe (LPJ Wetland Hydrology and Methane)**

- Water balance component similar to SiB2 (Simple Biosphere Model 2), a land-surface sub-model in NICE
- Water table is calculated by Granberg et al.'s approach (function of water volume, acrotelm porosity and depth, etc

**Directly input to LPJWHyMe**

- Evaporation is calculated as a linear function of water table
- Surface runoff in peatlands is calculated as an exponential function of water table
- Moss (*Sphagnum*) photosynthesis capacity depends on water table
- Gross primary production in flood-tolerant C3 graminoids depends on water table

**Coupling NICE with LPJWHyMe**

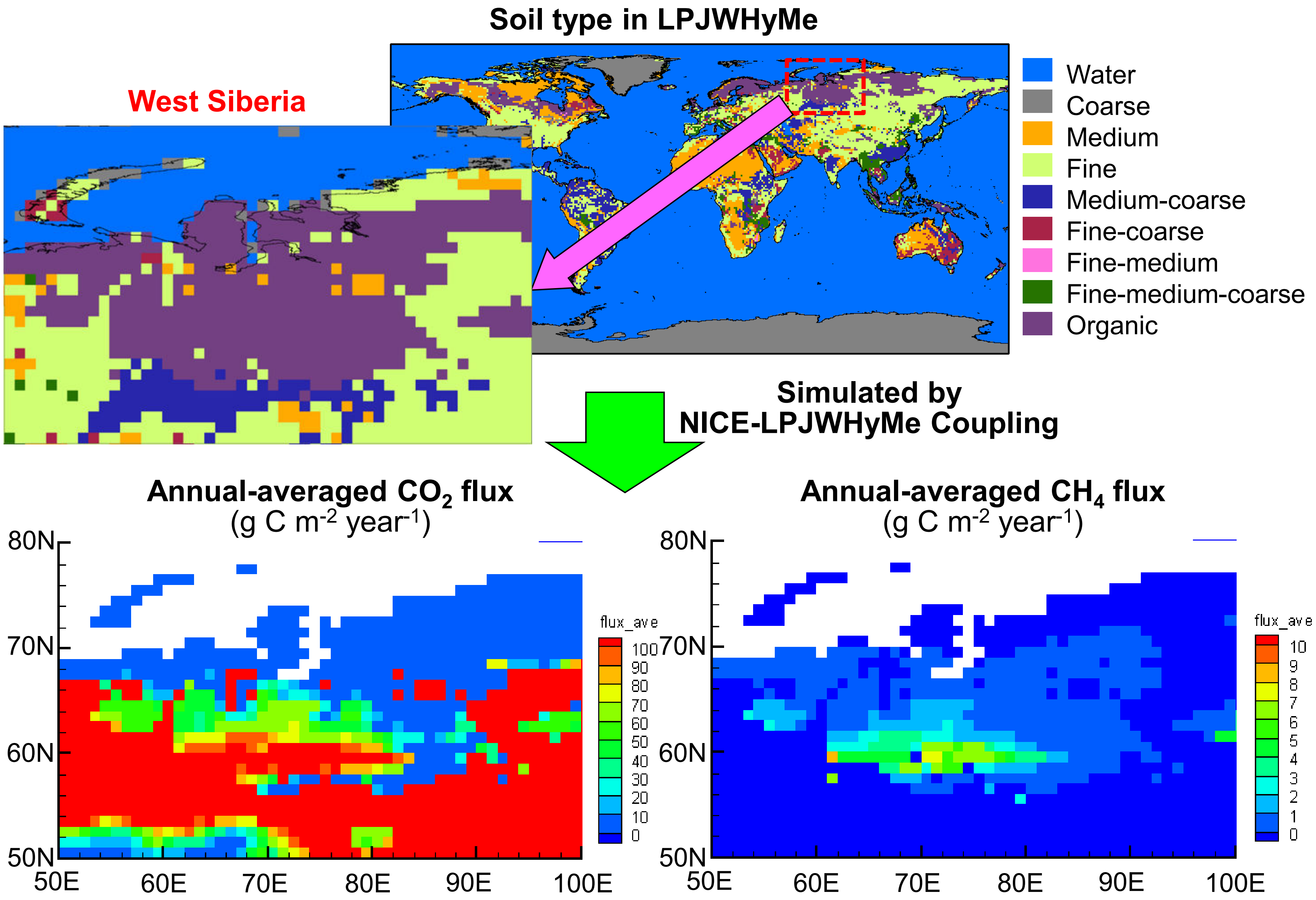
**Water table was replaced by daily value simulated by NICE (3-D groundwater flow sub-model)**

**Improvement in accuracy of inundation stress mechanism (photosynthesis & primary production)**

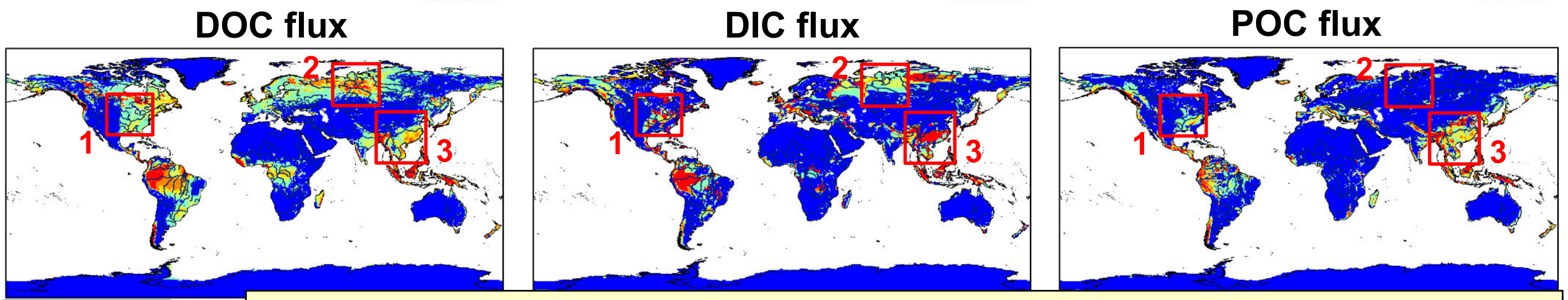
**Coupling NICE with water quality model in aquatic ecosystem**

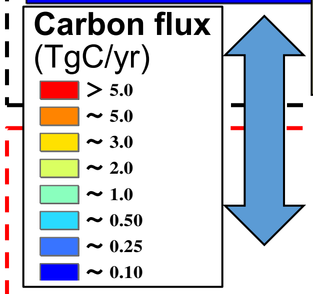
**Improvement in accuracy of carbon cycle in terrestrial-aquatic continuum ($CO_2$ & $CH_4$ flux, DOC, DIC, etc.)**

# Down-scaling to evaluate hot spot of carbon cycle



# Comparison of annual carbon flux in inland water in regional scales



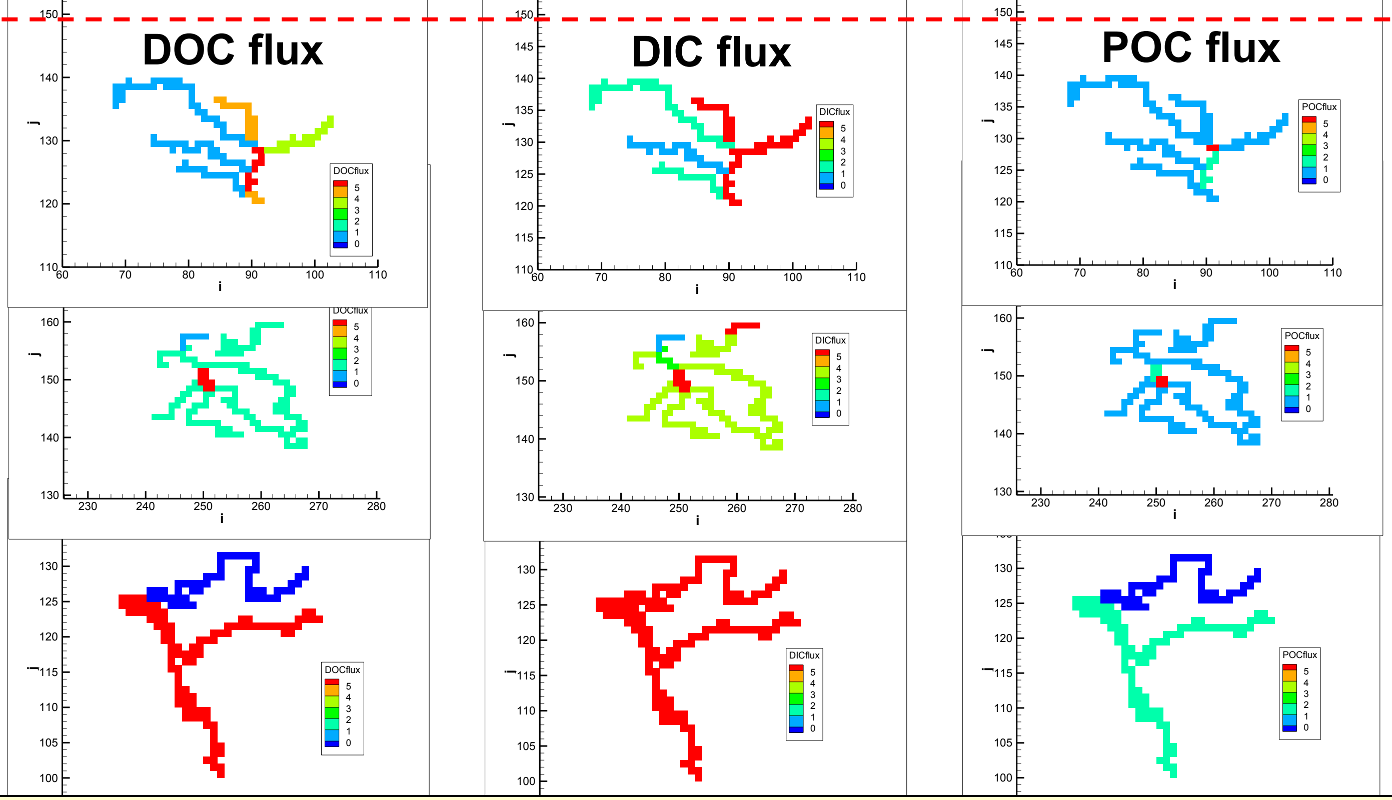




**Flux are functions (empirical relations) of drainage intensity, lithology, rock hardness, slope, organic carbon content, and sediment concentration.** (ISLSCP II; Ludwig et al., 2011)

**1. Mississippi Riv. (North America)**

**2. Ob Riv. (West Siberia)**

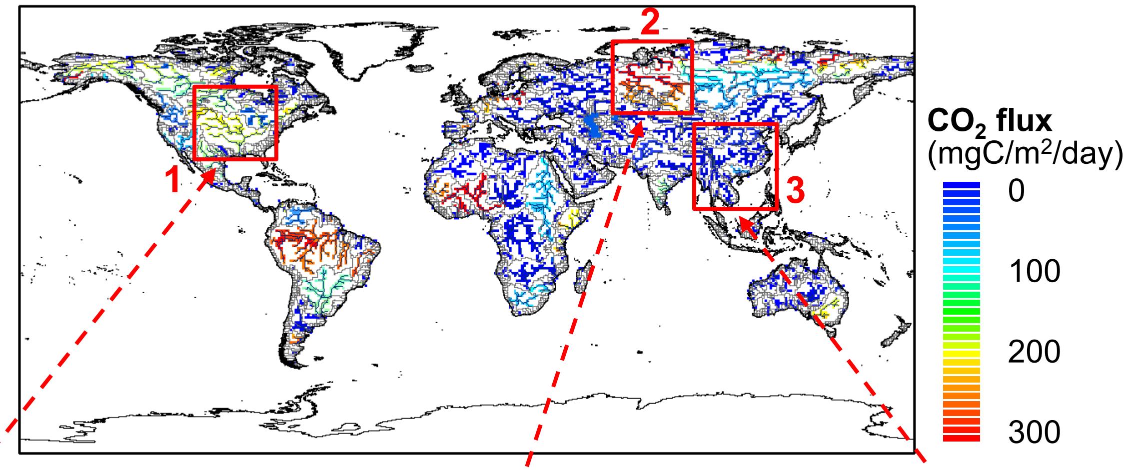
**3. Mekong, Changjiang, Yellow Riv. (South Asia)**



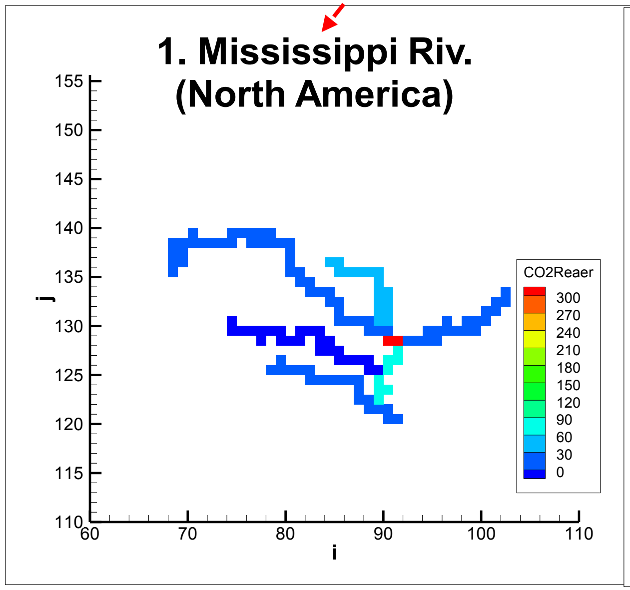

**Flux are simulated by coupling NICE & biogeochemical cycle models (process-based).**

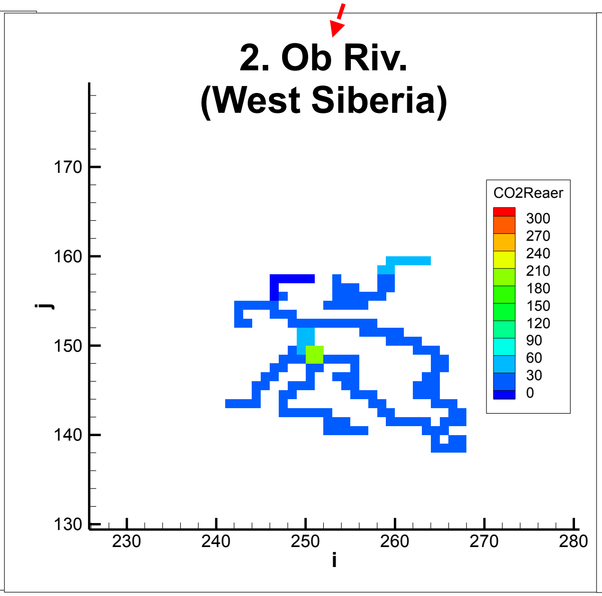
# Simulation of $CO_2$ evasion in inland water by process-based model

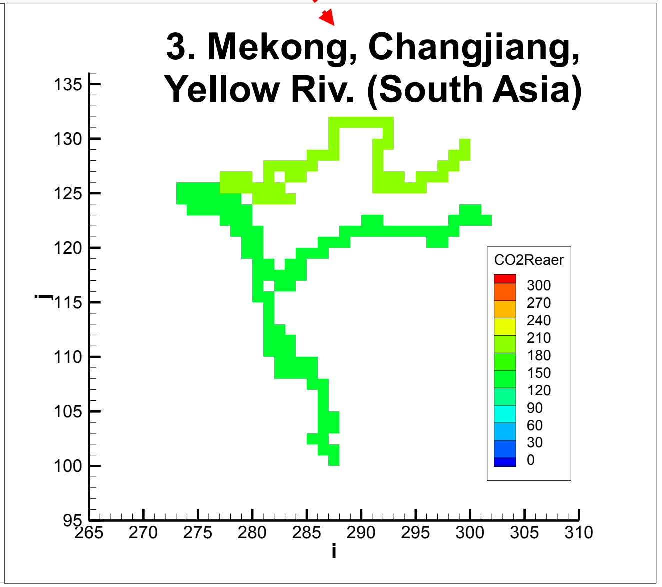
**Empirical regression model (NICE + global dataset)**




**NICE & biogeochemical cycle coupled (process-based) model**



# Preliminary conclusions and way forwards

1. Development of multi-scaled model (both down-scaling and up-scaling) in order to improve the accuracy in complex feedback between hydrology, geomorphology, and ecology.
2. Reproduction of hydrologic cycle including groundwater level and river discharge in global scale (1 deg mesh - tentative). Incorporation of nonlinear interaction between surface water and groundwater.
3. Development of empirical regression model to estimate $CO_2$ flux from rivers (about 1.0 PgC/year). Suggestion of $CO_2$ exchange velocity coefficient as function of both discharge and wind.
4. Further extension of NICE to include biogeochemical cycle accompanied by hydrologic cycle in inland water; Reaction between inorganic and organic carbons (DOC, POC, DIC, $pCO_2$, etc.), and its relation to nitrogen and phosphorus, etc.
5. Necessity to improve the accuracy of biogeochemical cycle through inland water and along terrestrial-aquatic continuum. Further comparison with carbon cycle estimation without effect of inland water.
6. If this effect is important, the terrestrial $CO_2$ sink may prove to be smaller than thought so far.

# Acknowledgement;

G. Pelletier, Dept. of Ecology, USA
R. Wania, Canada
R. Srinivasan, Texas A&M University, USA
J. Hartmann, Universitat Hamburg, Germany
W. Ludwig, Universite de Perpignan, France
P. Amiotte-Suchet, Universite de Bourgogne, France

Japanese Ministry of the Environment
Other colleagues

# Question ?

Mail to: T. Nakayama (nakat@nies.go.jp)

Ministry of the Environment
Government of Japan