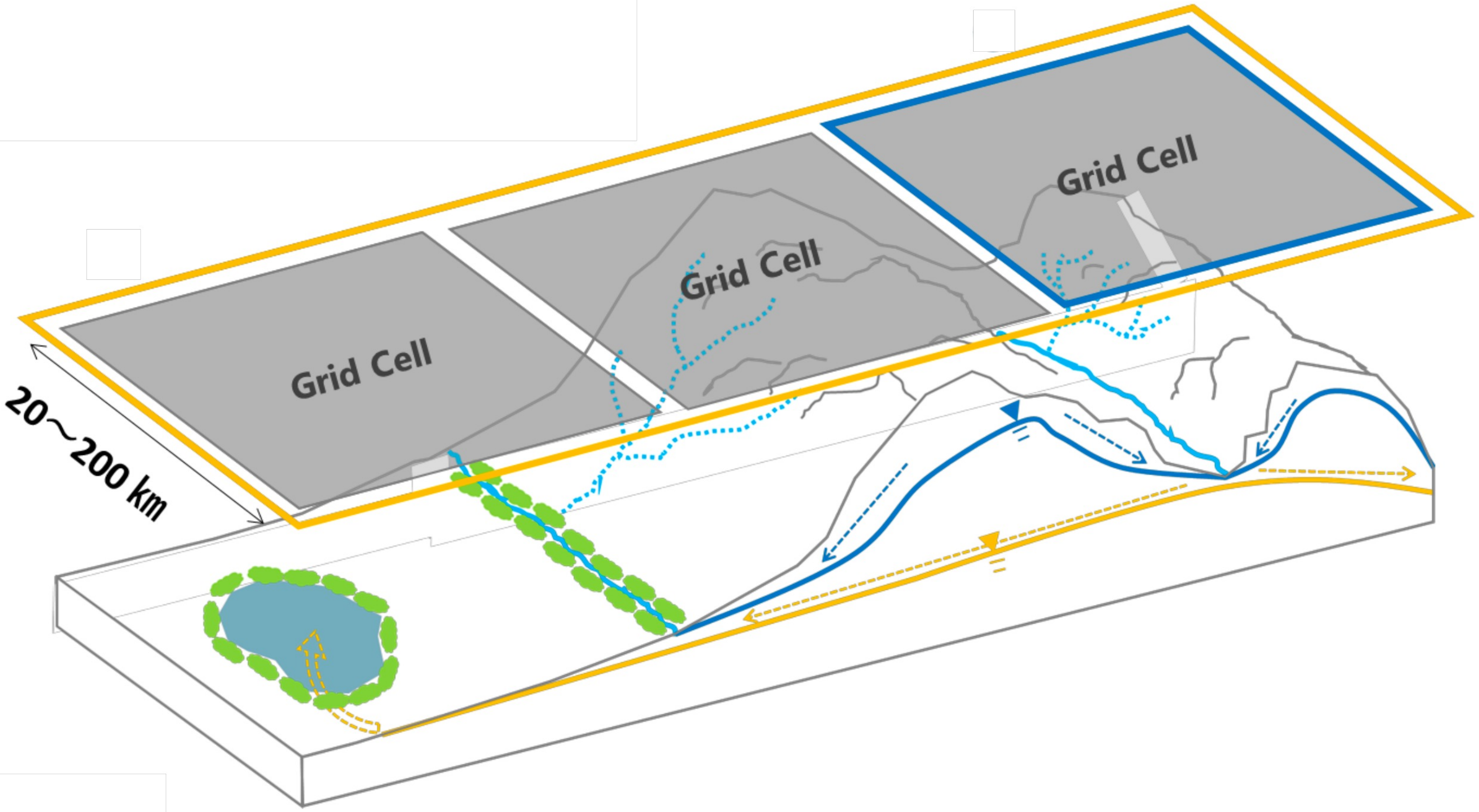
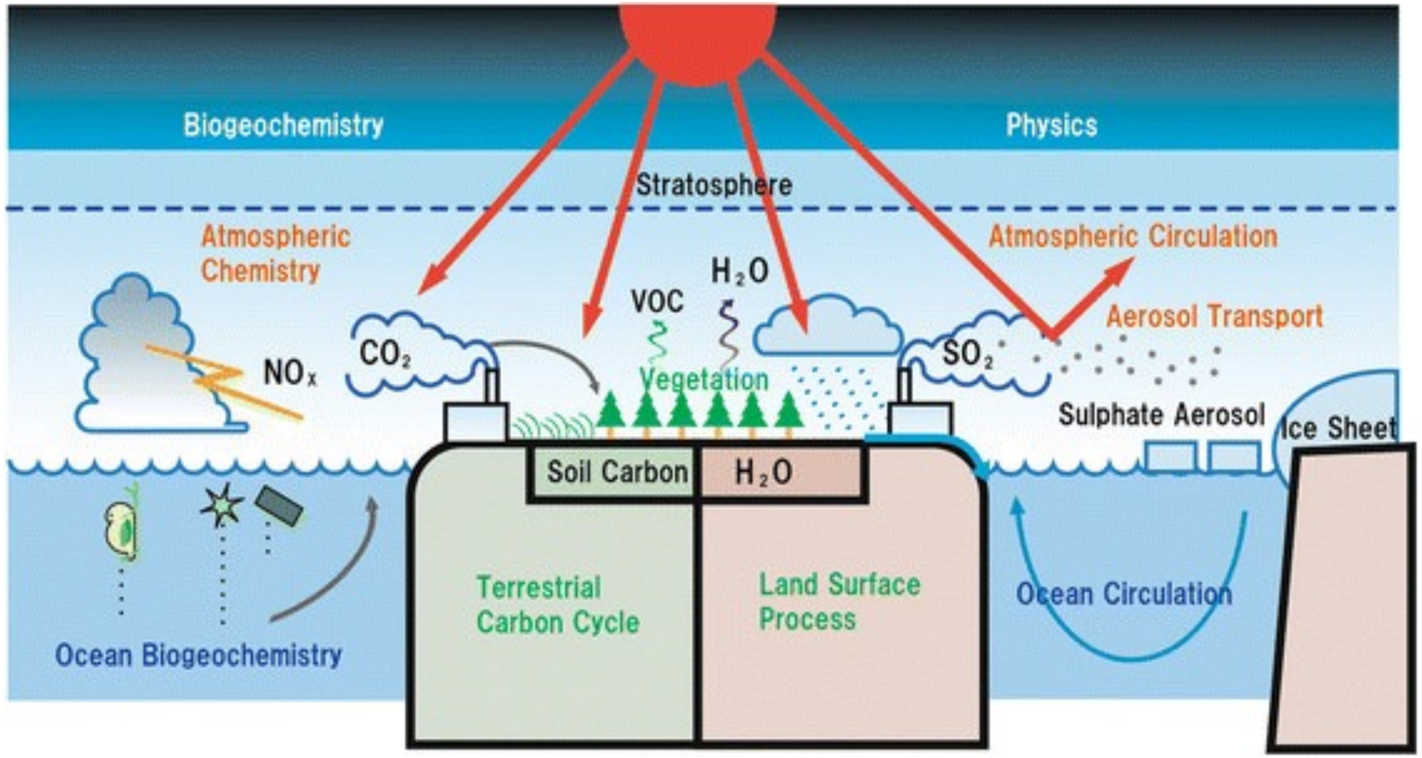
Horizontal water dynamics in land modeling:
A missing link to connect hydrology and biogeochemistry?



Dai Yamazaki
The University of Tokyo

Land surface model, as a component of climate system modelling

Land is an important component of climate system and carbon cycle of the Earth.



Hajima et al. 2014, PEPS [concept of MIROC-ESM]

Water and energy exchange

- Evaporation, Sensible heat flux
  Surface albedo, etc

Carbon fixation/emission

- Vegetation, soil, wetlands

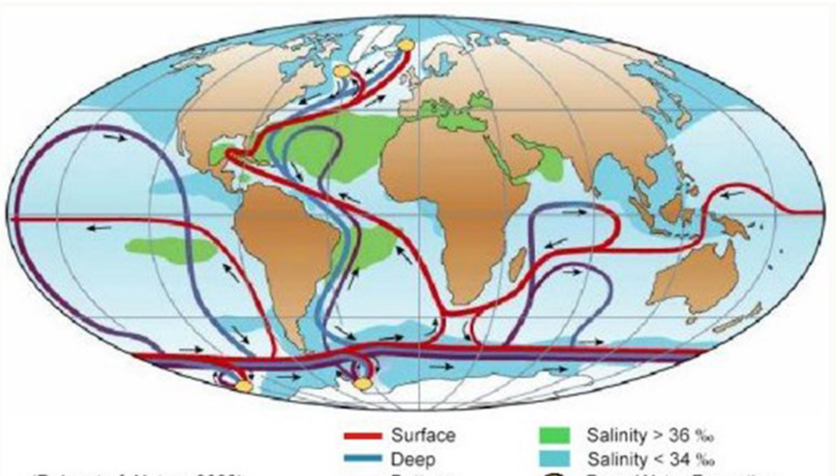
Other material circulation

- Nitrogen, Sulfate, Dust, etc.

Most land processes can be represented as 1D vertical flux exchange

River freshwater transport for ocean dynamics simulation

In addition to 1D vertical fluxes, some horizontal water dynamics processes are important for climate system modelling.



(Rahmstorf, Nature 2002)

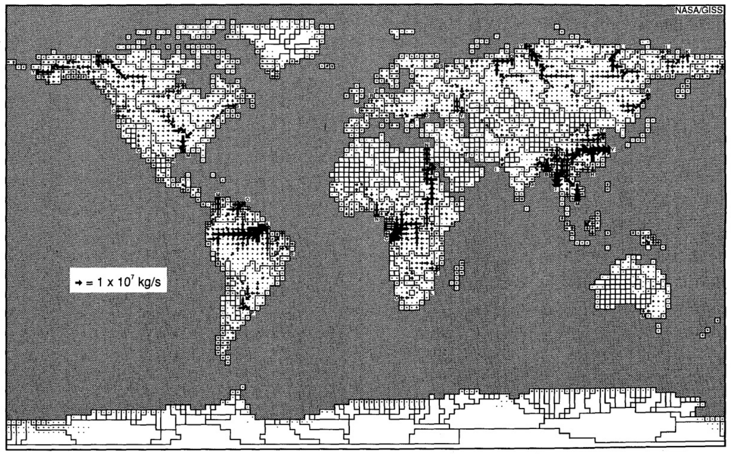


FIG. 2. Total annual river mass flux for the 2° × 2.5° grid boxes. The area of an arrow is proportional to the mass flux out of a grid box. A letter corresponding to the first letter of each river's name is located at the river's mouth.

Miller et al. 1994, J.Climate

Freshwater runoff from river to oceans alter salinity and water temperature, and impact ocean thermohaline circulation (which is driven by sea water density).

LETTERS TO NATURE

Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean

Syukuro Manabe & Ronald J. Stouffer

Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, New Jersey 08542, USA

TEMPERATURE records from Greenland ice cores[1,2] suggest that large and abrupt changes of North Atlantic climate occurred frequently during both glacial and postglacial periods; one example is the Younger Dryas cold event. Broecker[3] speculated that these changes result from rapid changes in the thermohaline circulation of the Atlantic Ocean, which were caused by the release of large amounts of melt water from continental ice sheets. Here we describe an attempt to explore this intriguing phenomenon using a coupled ocean–atmosphere model. In response to a massive surface flux of fresh water to the northern North Atlantic of the model, the thermohaline circulation weakens abruptly, intensifies and weakens again, followed by a gradual recovery, generating episodes that resemble the abrupt changes of the ocean–atmosphere system recorded in ice and deep-sea cores[4]. The associated change of surface air temperature is particularly large in the northern North Atlantic Ocean and its neighbourhood, but is relatively small in the rest of the world.

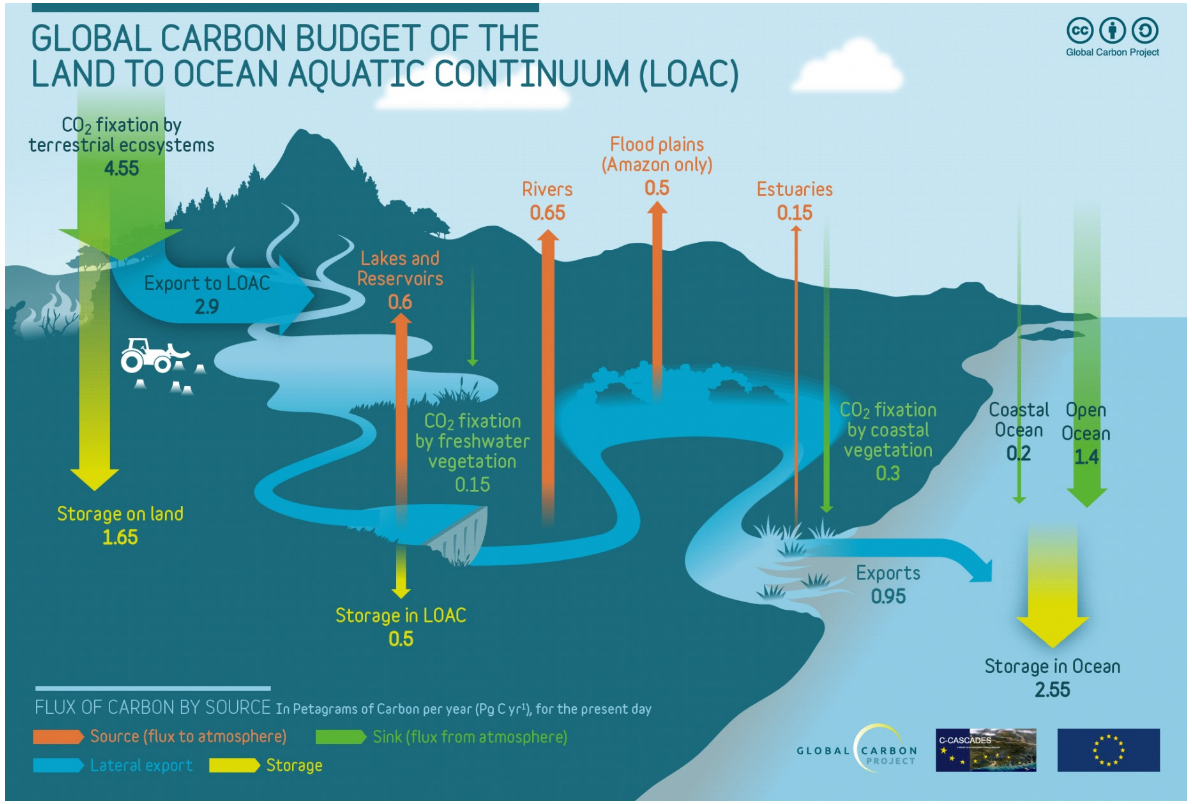
River routing scheme had been implemented to A-O Coupled GCM since 1990s.

Thermohaline circulation had been simulated in coupled climate models.

Impact of freshwater runoff on climate system had been discussed.

Horizontal water transport on land is important for climate system model.

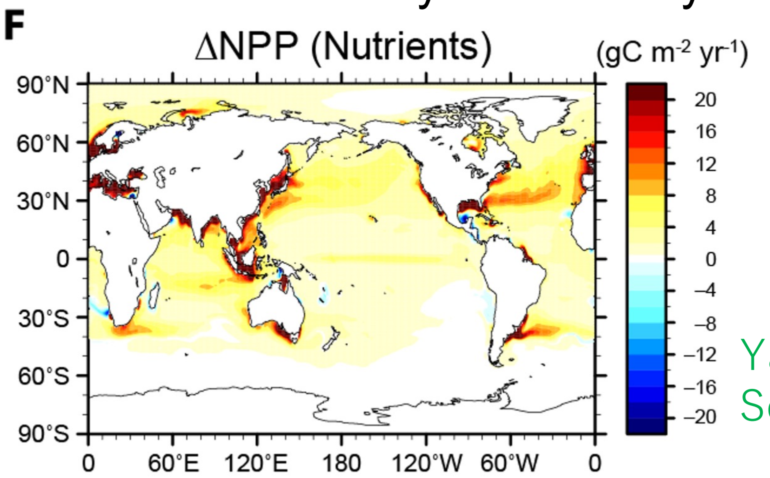
Global biogeochemical cycle related to surface water dynamics



Recently, importance of Land to Ocean Aquatic Continuum (LOAC) on global carbon budget is discussed.

- Carbon input from soil to river, CO2 evasion from rivers
- Lake carbon storage and emission
- Wetland methane dynamics

Nutrient runoff from river to ocean also alters ocean ecosystem activity



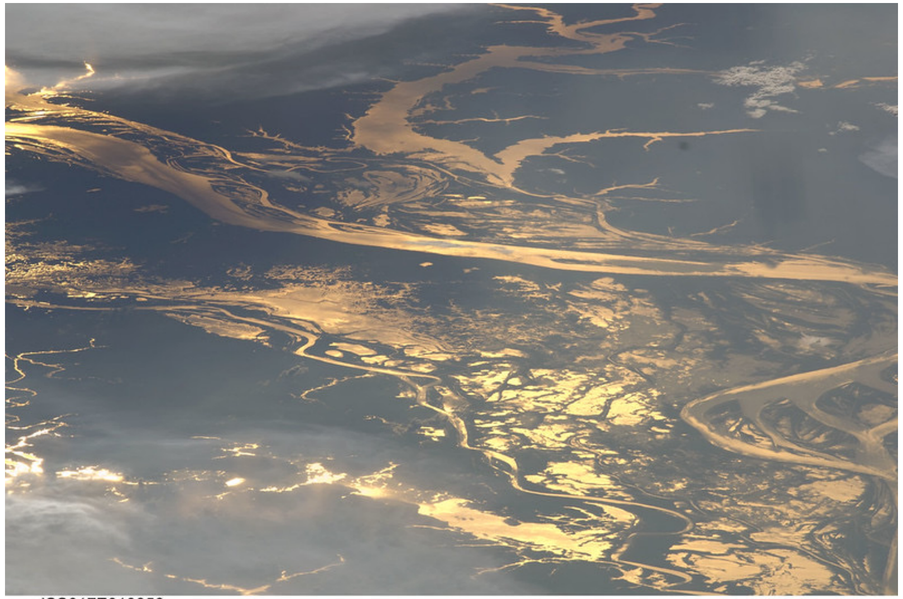
Yamamoto et al. 2022. Sci.Adv.

In this study, we will review:

[1] Recent activities on modelling horizontal water dynamics in land models
[2] How each horizontal process relates to climate and biogeochemistry
[3] What are difficulties and challenges in modelling horizontal water dynamics processes

Recent advances in
modelling horizontal water dynamics on land

Floodplain inundation: Key improvement in river routing process



ISS017E013856

Amazon river from ISS, by NASA

Water excess above channel causes floodplain inundation.
- Flood peak attenuation and delay.
- Water surface area expands
- Highly corresponds to flood hazard and risk

Many river models with floodplain schemes developed in recent 20 years.
- First attempt to simulate Amazon's flood inundation dynamics within large-scale river model. (IBIS-HYDRA model, Coe et al., 2002, JGR)
- Sub-grid floodplain parameterization using topography data (THMB, Coe et al. 2008, HP; ISBA-TRIP; Ducharme et al., 2008 JGR)
- Physically-based representation of flood inundation dynamics (CaMa-Flood, Yamazaki et al. 2011; MGB-IPH, Paiva et al. 2011)
- Global flood models for risk assessment purposes (PCR-GLOBWB, Winsemius 2013; LISFLOOD-FP Global, Sampson 2015)

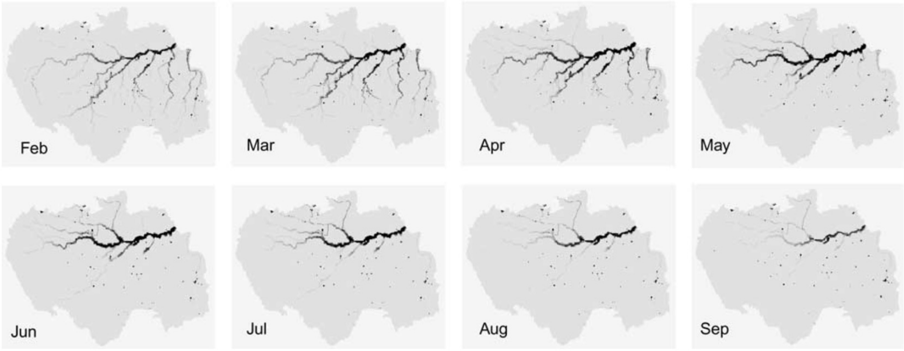
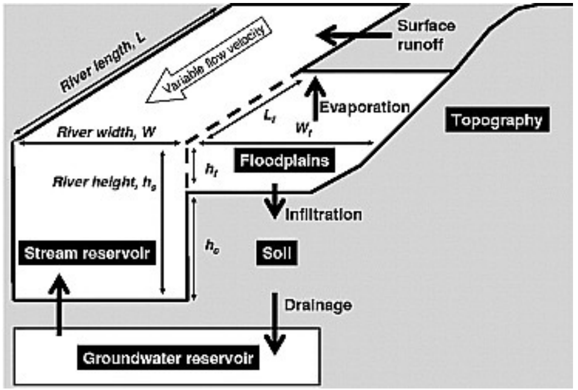
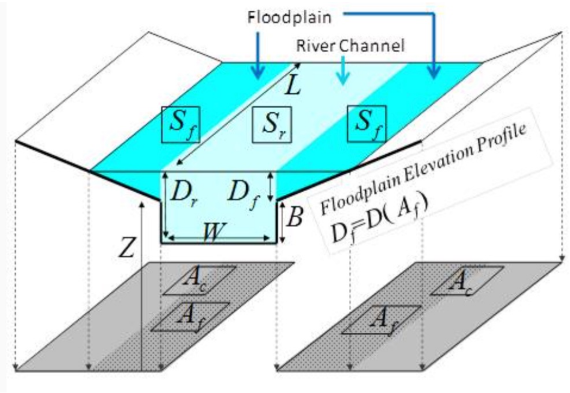


Figure 11. Time series of simulated mean monthly flooded area in the Amazon River basin for the period 1939–1998. Shading indicates the fraction of the 5′ grid cell covered with water; black being 100% flooded.

First large-scale flood inundation simulation [Coe et al. 2002, JGR]

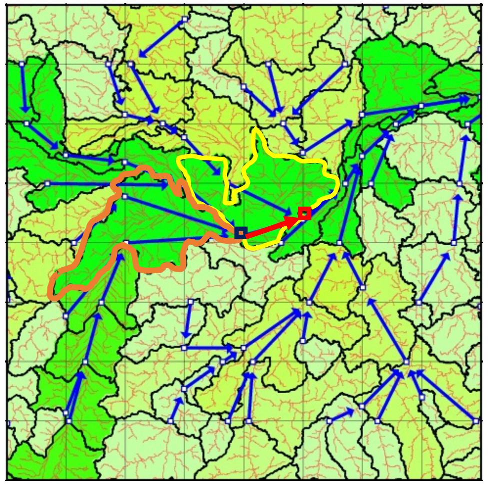


ISBA-TRIP; Ducharme et al., 2008

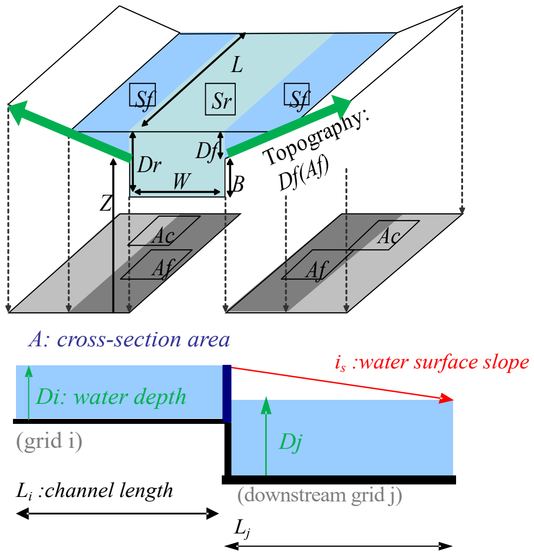


CaMa-Flood, Yamazaki et al. 2011

Physically-based representation of river-floodplain hydrodynamics



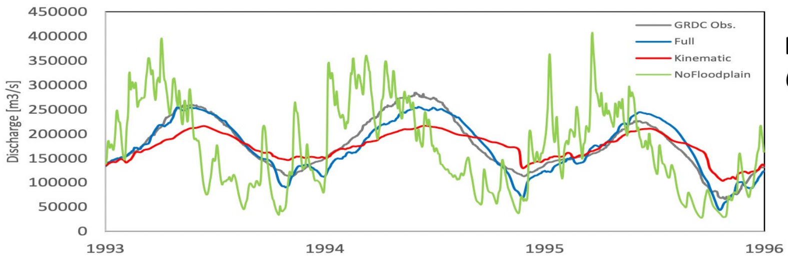
CaMa-Flood, Yamazaki et al. 2011



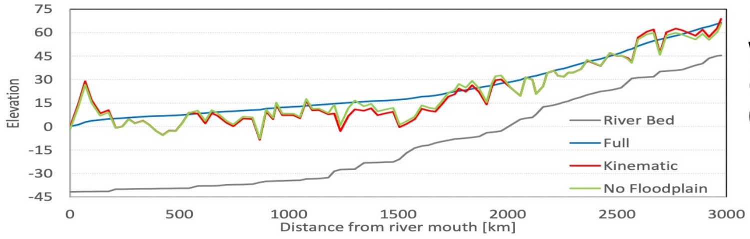
Realistic simulation is achieved (e.g. CaMa-Flood / MGB-IPH).

- Using high-resolution river topography (e.g. MERIT Hydro) for sub-grid parameters delineation, with catchment-based approach.
- Realistic relationship between water storage and water level+extent.
- More physically-based flow equation (shallow-water equation)

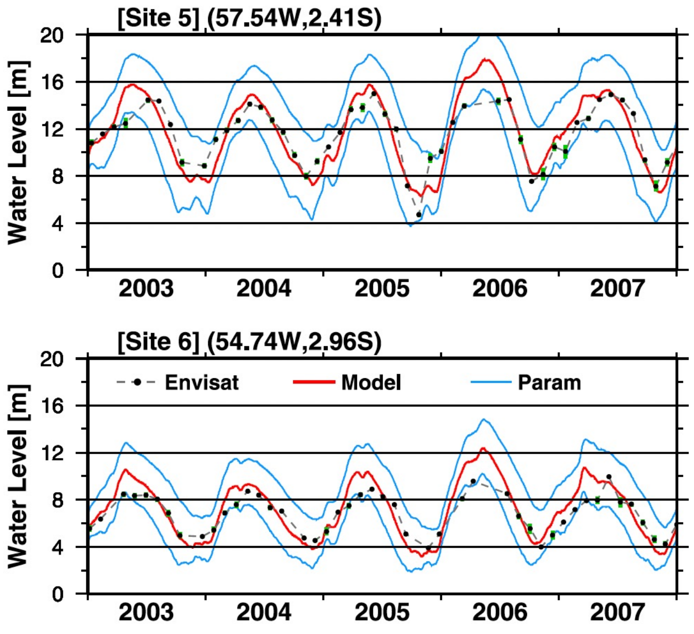
Realistic simulation of discharge, water level, flood extent
→ Comprehensive model evaluation/calibration/data assimilation using satellites becomes possible.



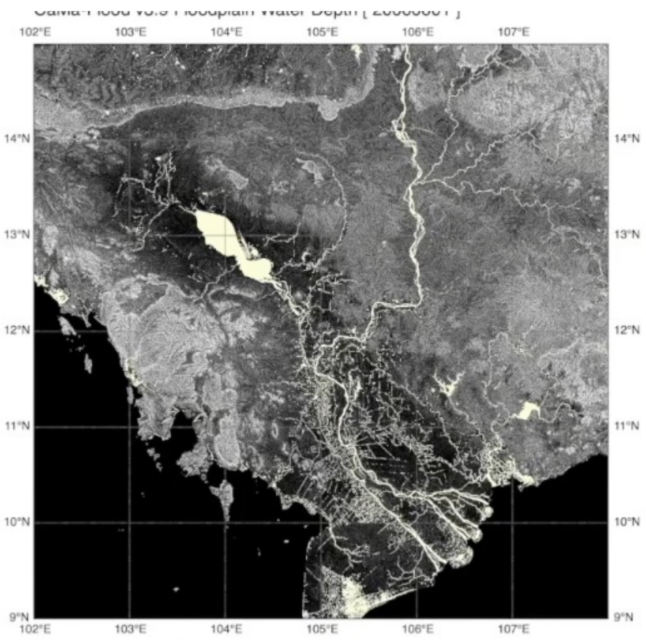
Daily River Discharge @ Obidos



Water Surface Elevation @ Amazon Mainstem (May monthly ave.)

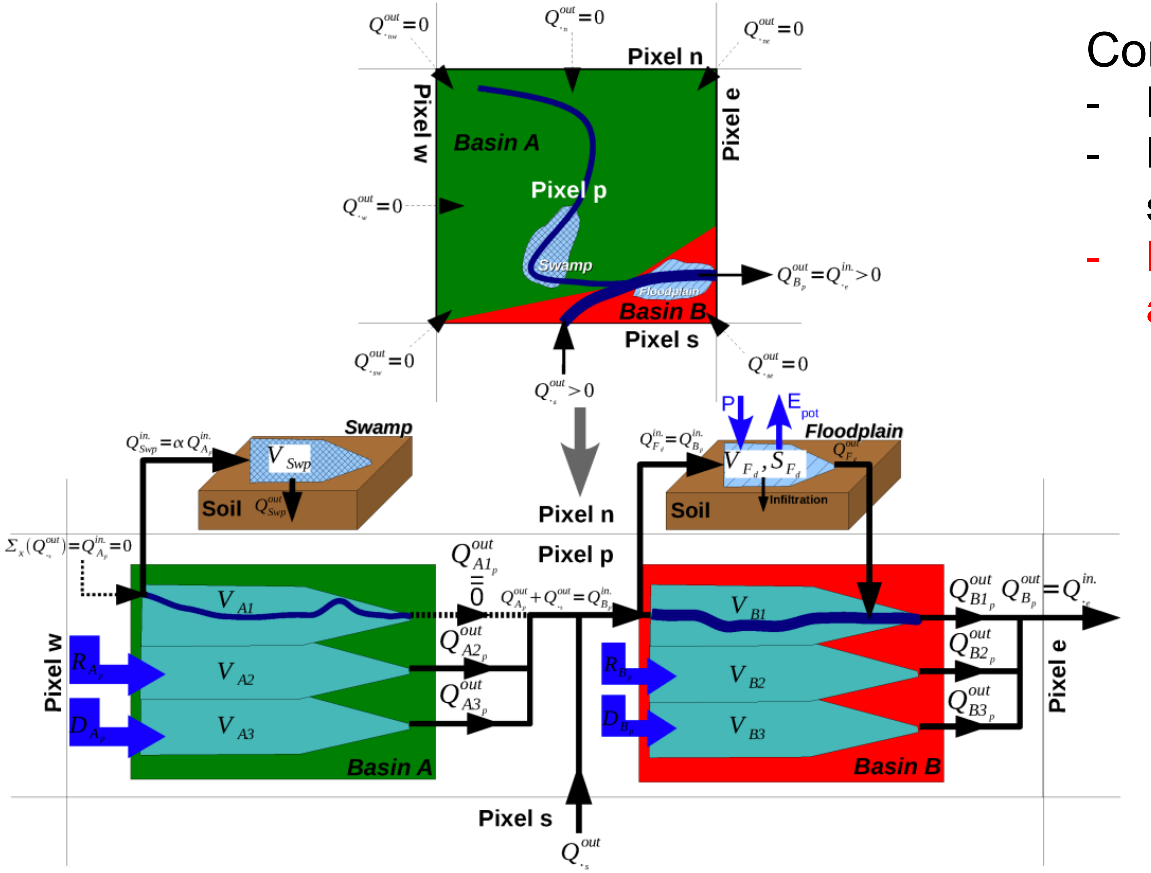


Water level compared against altimetry , Yamazaki et al. 2012



Flood extent simulation (downscaled) , Zhou et al 2021

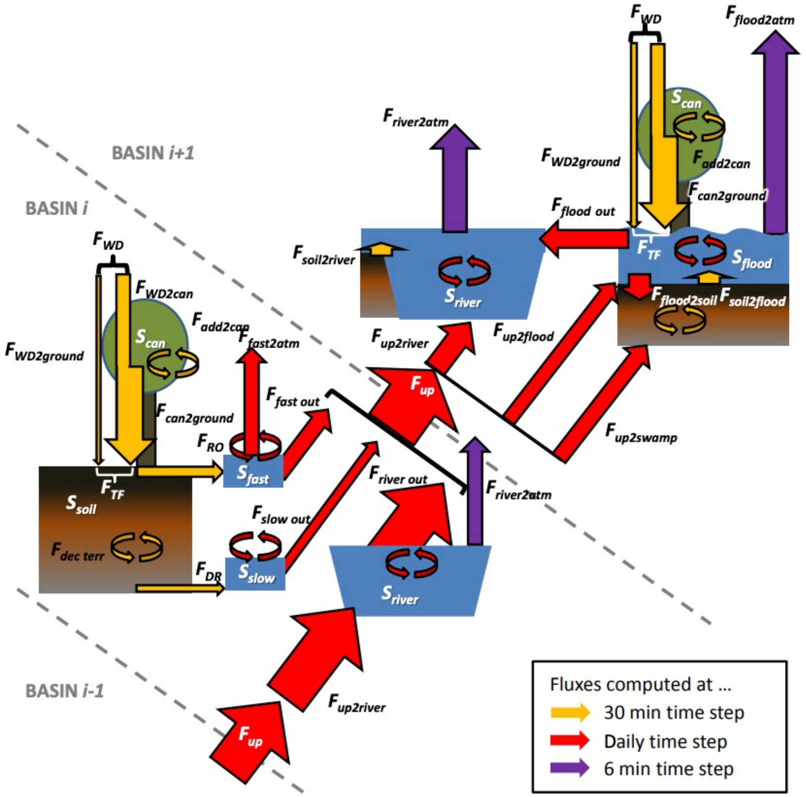
Conceptual river representation to enhance system interactions



Water flux calculation scheme in ORCHIDEE (Guimberteau et al. 2012) considering river-swamp-floodplain links and interaction with soil & atmosphere

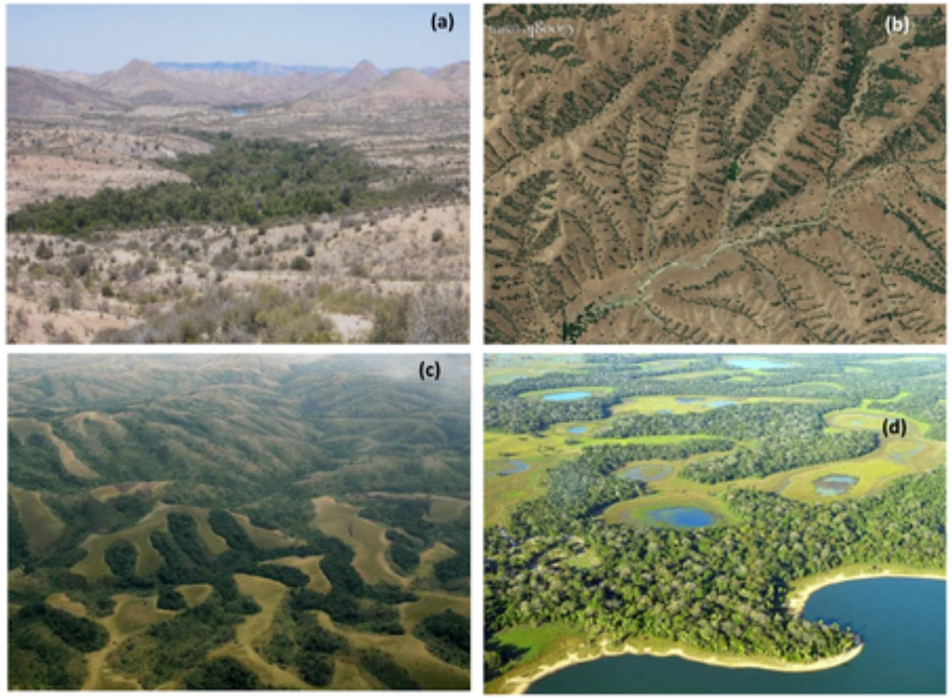
Conceptual representation focuses more on system interactions.

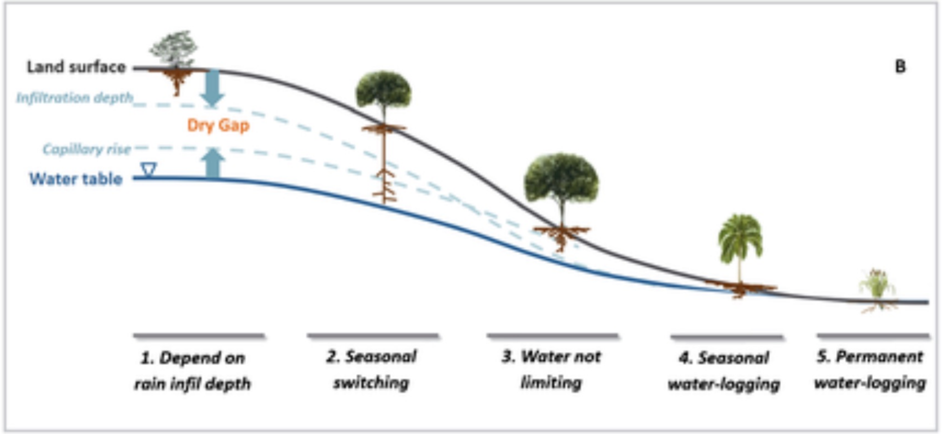
- Extract essence of river-floodplain dynamics.
- Reasonably simplify each process, but consider interaction among systems. e.g. ORCHIDEE routing (Guimberteau 2012)
- Much easy to represent interactions with other systems (soil, atmosphere, carbon cycle), compared to physically-based approach.



Water & carbon flux scheme in ORCHILEAK (Lauerwald et al. 2017). Carbon transport is considered in addition to water flux.

Hillslope hydrology: local-scale process in global modelling





Landscape regulated by hillslope hydrology [Fan et al, 2019]

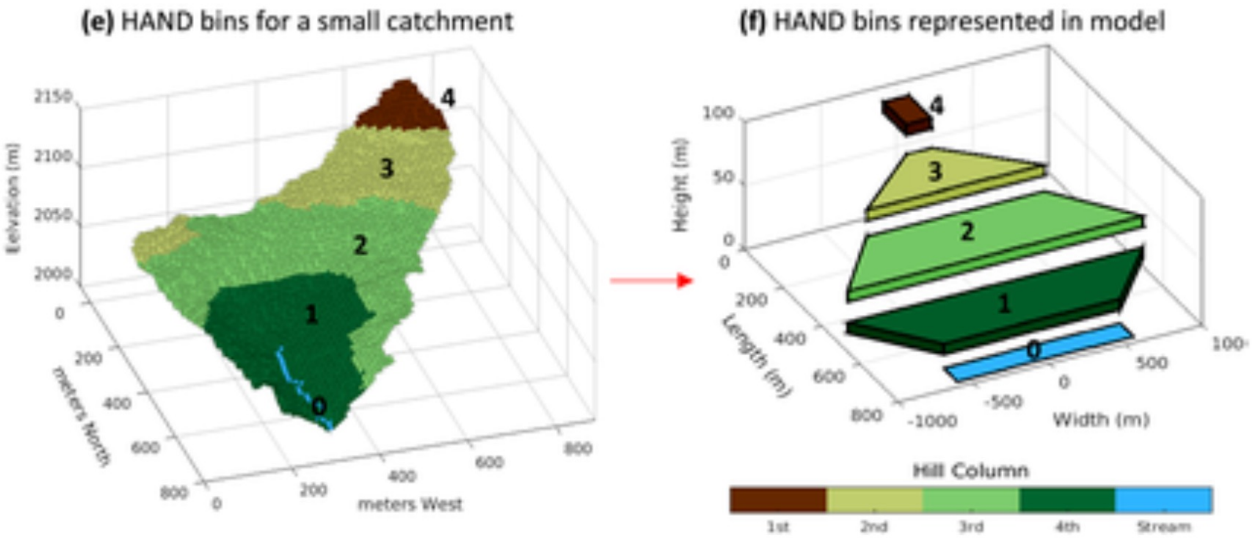
Moisture redistribution in hillslope is a recent hot topic.

- Valley is wetter, hilltop is dryer. Due to sub-surface water flow.
- Vegetation cover can be different due to different moisture condition. (Forested valley in water limit region. Water logging in wetlands).

  Note: climate difference due to altitude should be small.

Land cover heterogeneity due to hillslope moisture dynamics could be underrepresented in current Land Surface Models.

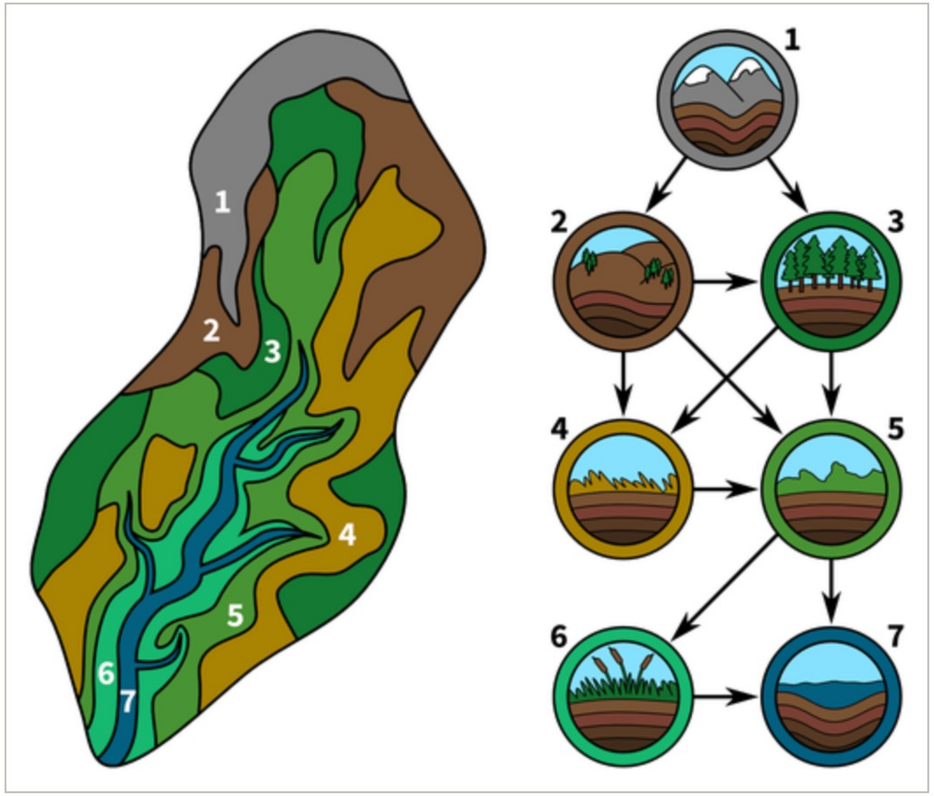
- Land-atmosphere interaction might be affected.
- Efforts ongoing on modelling hillslope hydrology in global land model



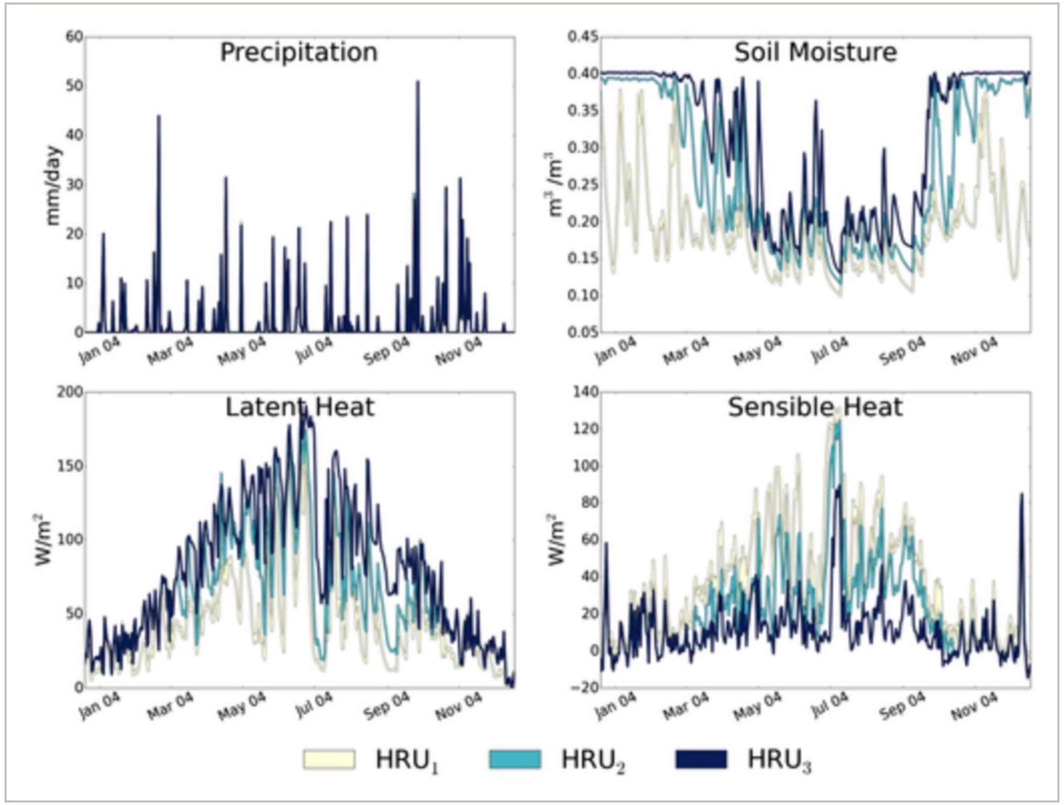
Hillslope hydrology: local-scale process in global modelling

Conceptual representation of hillslope hydrology (Chaney et al. 2016)

- Consider water movement from hilltop to downvalley
- Represent land cover difference and different response to atmospheric forcing
- In wetter valley: higher soil moisture + larger latent heat.



Landscape regulated by hillslope hydrology [Fan et al, 2019]

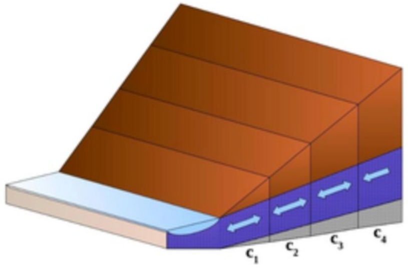


Hillslope hydrology: local-scale process in global modelling

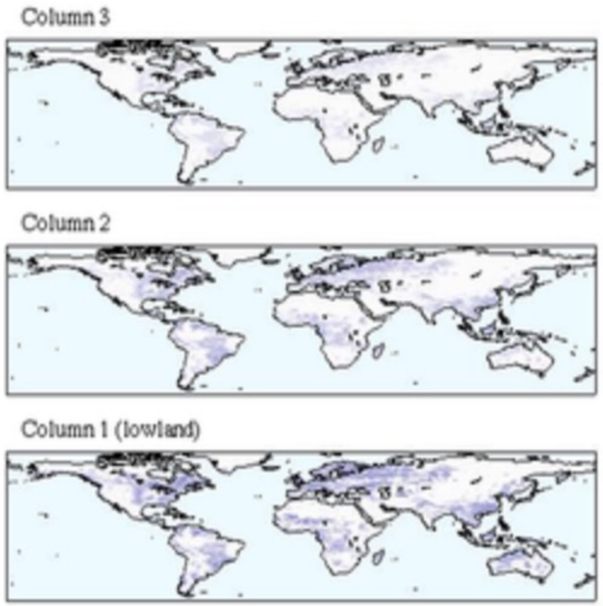
Physically-based representation of hillslope hydrology (Swenson et al. 2019)

- Explicitly represent sub-surface lateral water dynamics using hillslope column.
- Ground water level in each hillslope column calculated explicitly
- Physically-based horizontal water dynamics (Darcy's law), including interaction with river water.

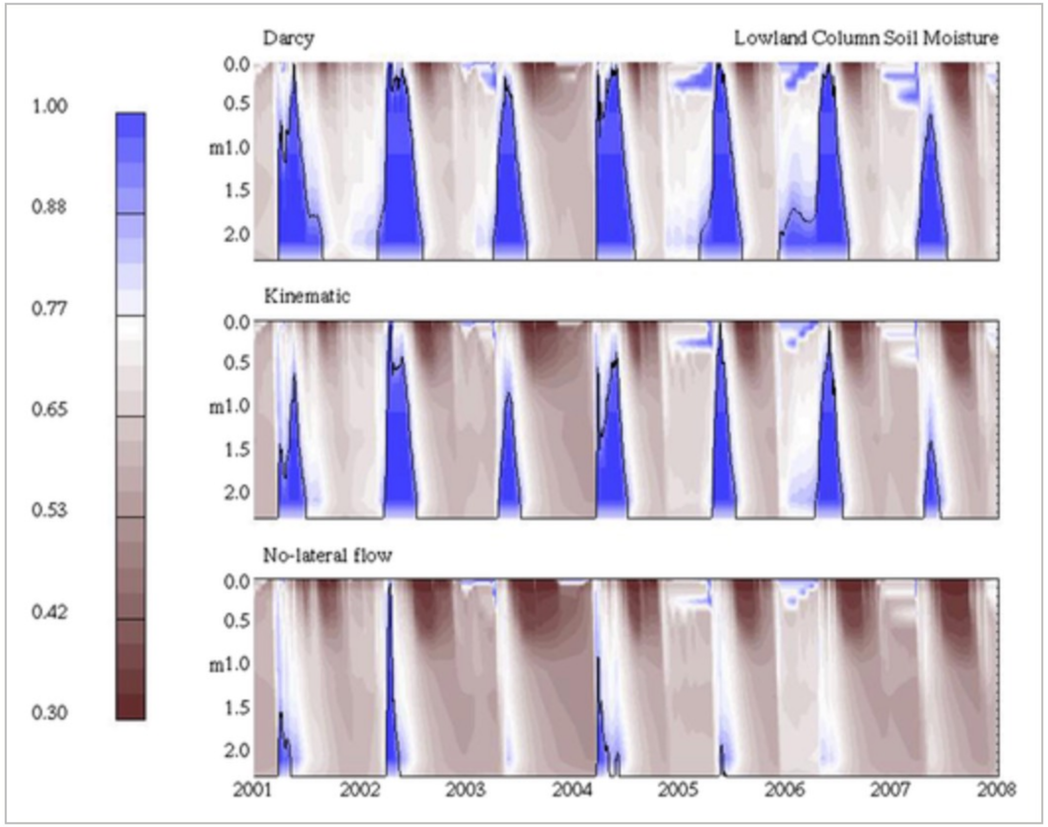
→ Realistic representation of runoff-generation process, in addition to hillslope moisture redistribution.



Hillslope column, connected by lateral sub-surface flow



Valley becomes wetter



Hillslope lateral flow in CLM [Swenson et al. 2019]

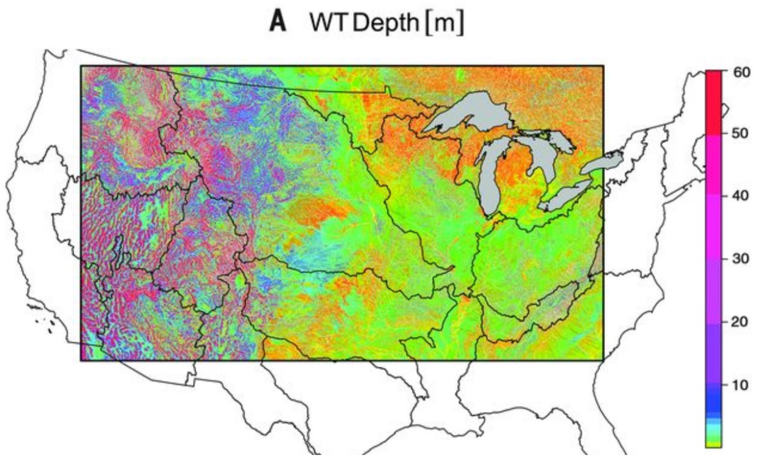
← Wetter soil due to runoff suppression by high river water

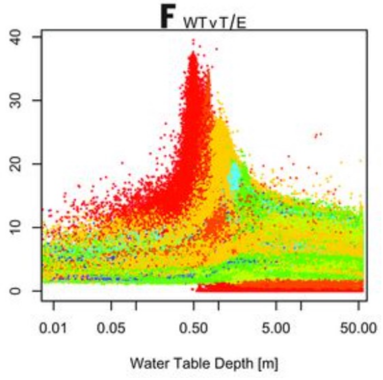
← Moisture supply from hilltop Is important.

Ground water dynamics: another hot issue in land modelling

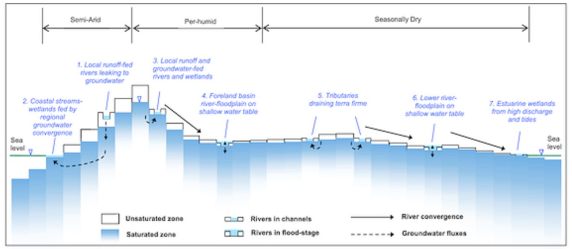
Modelling horizontal ground-water dynamics

- Large-scale groundwater flow, in addition to hill-slope scale lateral flow.
- Modelling effort at multiple special scales, considering interaction with soil and vegetation.
- Both physically-based approach and conceptualized approach are used.



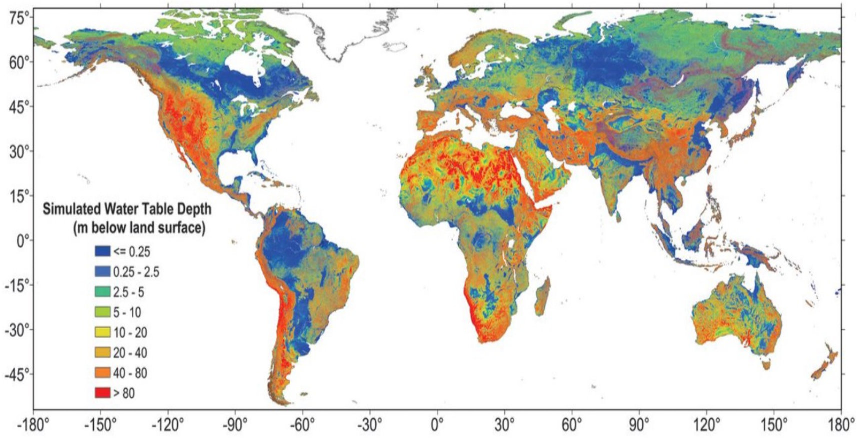


High-res groundwater model + interaction with soil ET. [Maxwell & Condon, 2016]



Groundwater flow in large-scale land model [Migues-Macho & Fan 2012]

Ground water table climate equilibrium [Fan et al. 2013]



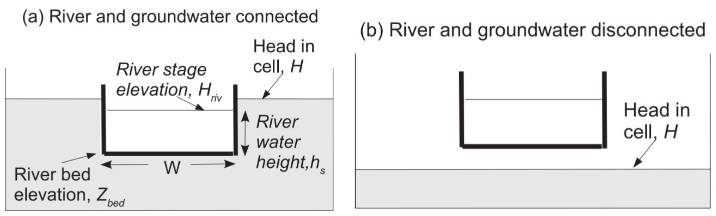
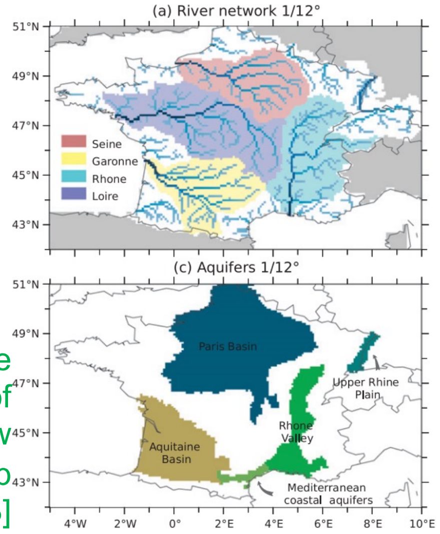


FIG. 1. Groundwater–river interactions with river and groundwater (a) connected and (b) disconnected.



Climate-model scale representation of groundwater flow using aquifer map [Vergnes et al. 2013]

Challenges in

modelling horizontal water dynamics on land

How can we handle land heterogeneity?

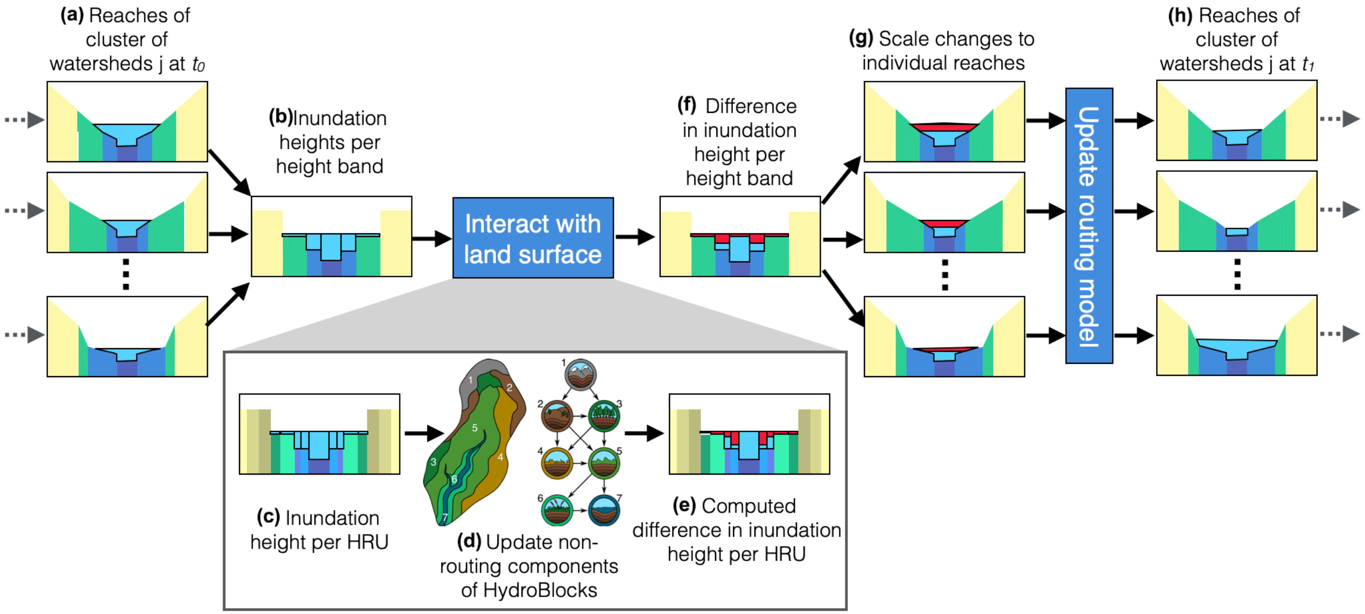
Hyper-resolution approach

- Relatively easy to develop model (though horizontal dynamics should be added to classical 1D model).
- High computational cost might limit coupling with climate models.

Medium-resolution with sub-grid physics approach

- Computationally efficient and coupling to climate models becomes relatively easy.
- Appropriate discretization land surface into calculation unit is needed (catchment, hill-slope, land cover)
- Difficult to develop an appropriate sub-grid approximation of complex process.

The Ob River [~100km * 100km]



HydroBlocks v0.2: Chaney et al. 2021, GMD

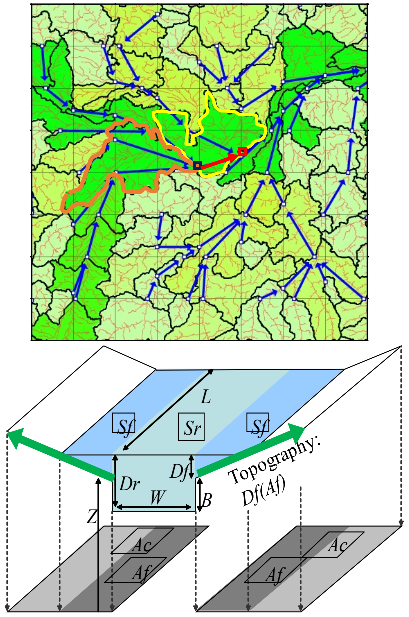
Physically-based representation or Conceptual representation

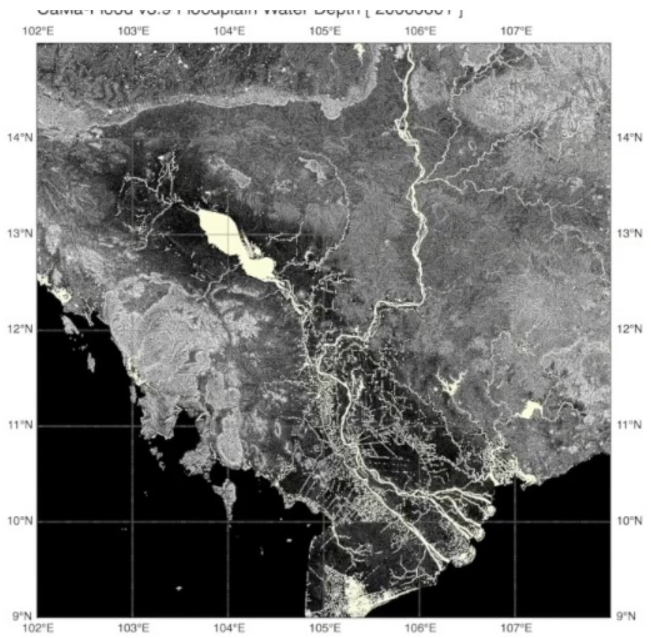
Physically-based representation

- Realistic representation of water dynamics (water level, flood extent)
- Comprehensive model evaluation using more variables (in addition to discharge)
- Required appropriate sub-grid modelling and high-precision topo/soil datasets
- Complex model makes mode coupling difficult?

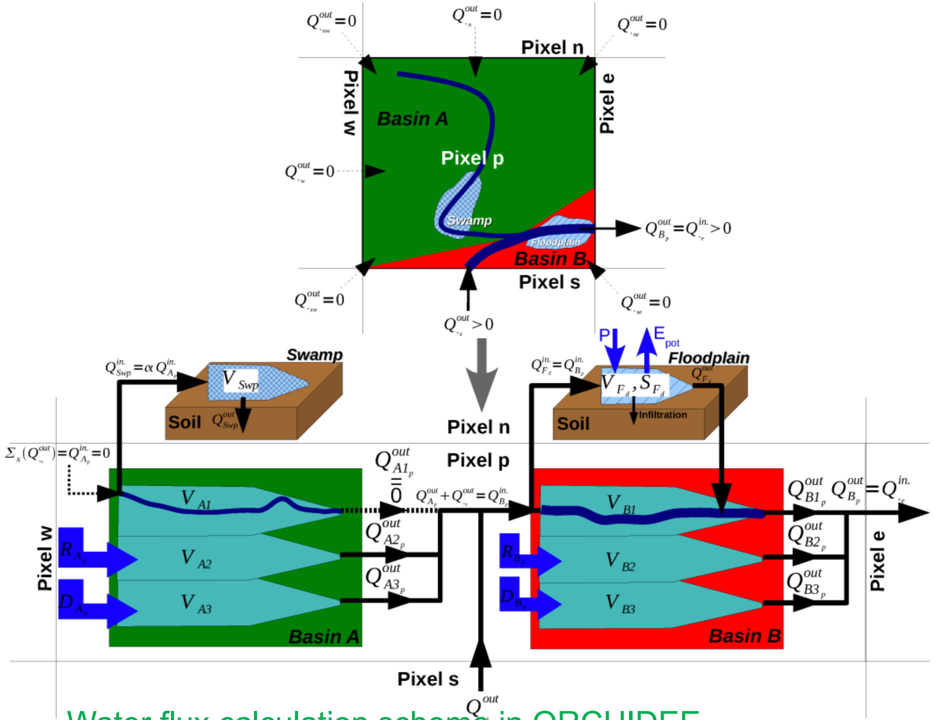
Conceptual representation approach

- Extract essence of processes with simple equations
- Focuses more on system interactions. (surface water & soil, vegetation, carbon, etc).
- Less calculation cost, easy to couple with climate model?
- Water dynamics (level, extent) are usually simplified, and direct comparison to observations are difficult.





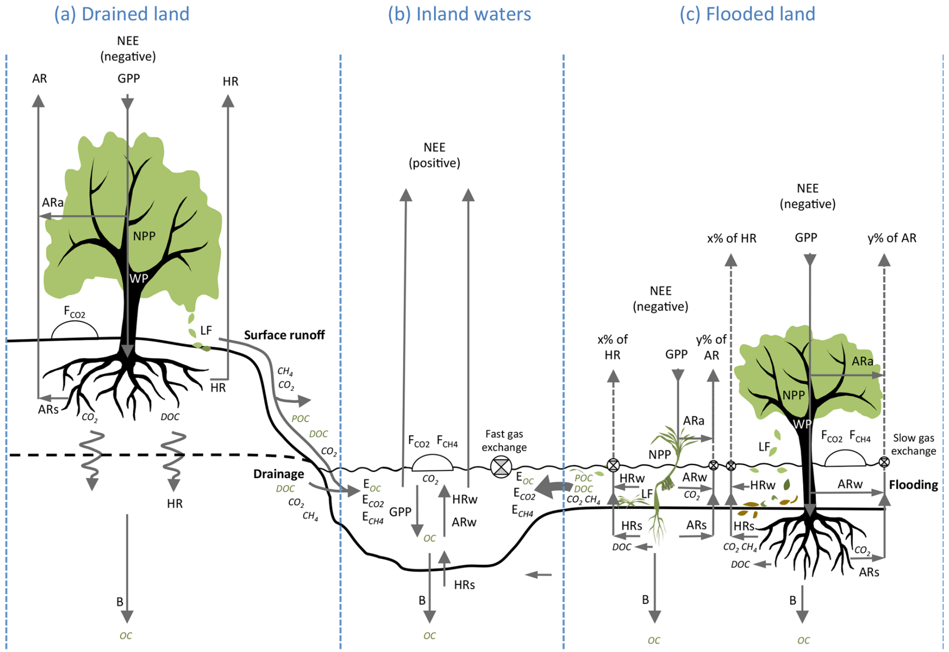
Realistic representation of topography & water dynamics
CaMa-Flood: Yamazaki et al. 2011; Zhou et al. 2021



Water flux calculation scheme in ORCHIDEE,
Guimberteau et al. 2012

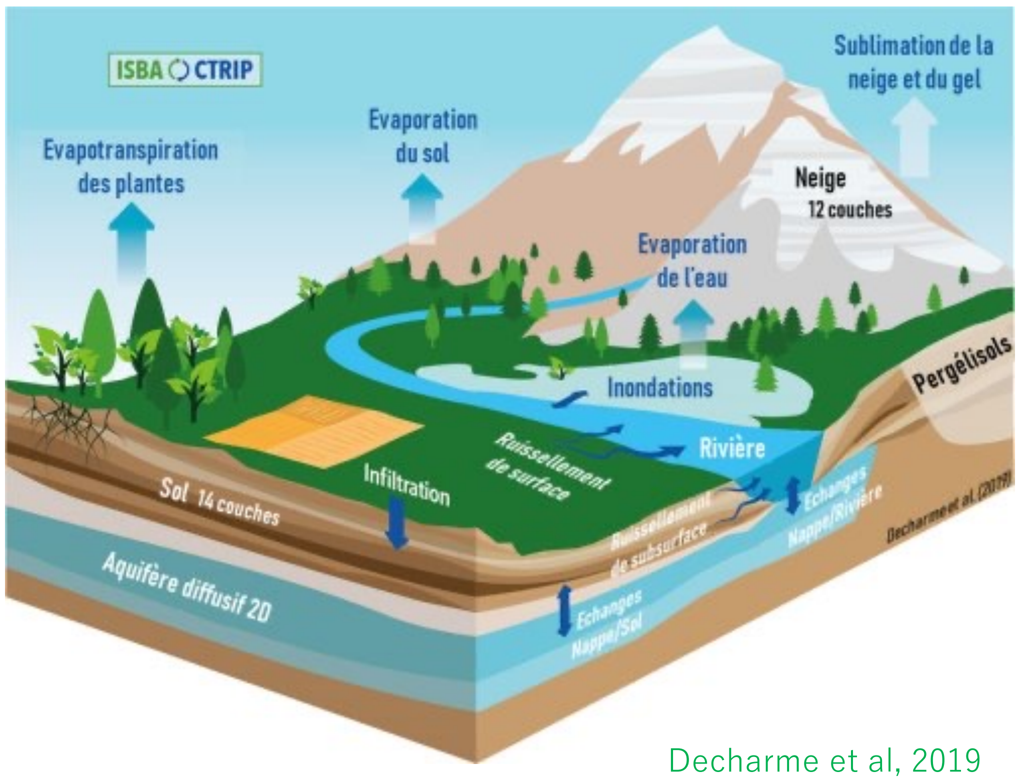
Needs on horizontal water scheme as a part of LSM/GCM/ESM

Both "realistic water dynamics" & "flexible coupling with other ESM process" are needed.
- Biogeochemical processes are regulated by water level (plant root, wetland carbon cycle)
  Without modelling water level dynamics, projection of future biogeochemical process could be wrong.
- System interaction representation in global land/climate model is essential to understand Earth system.
  Without model coupling, we cannot evaluate the impact of hydrological processes on biogeochemistry



Functional differences of carbon metabolism and hydrological export in well-drained and flooded land.

Abril & Borges, 2019, Biogeosciences

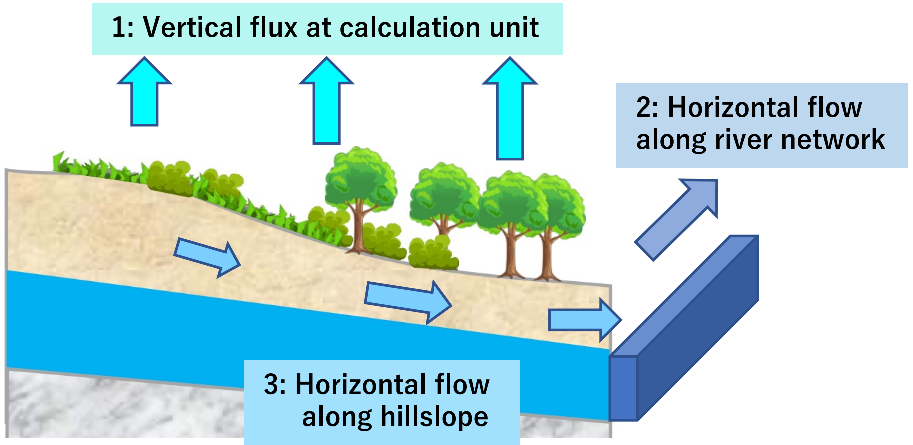


Decharme et al, 2019

Wrap-up & inputs for discussions

Horizontal water dynamics on land is an important component of Earth's climate system.

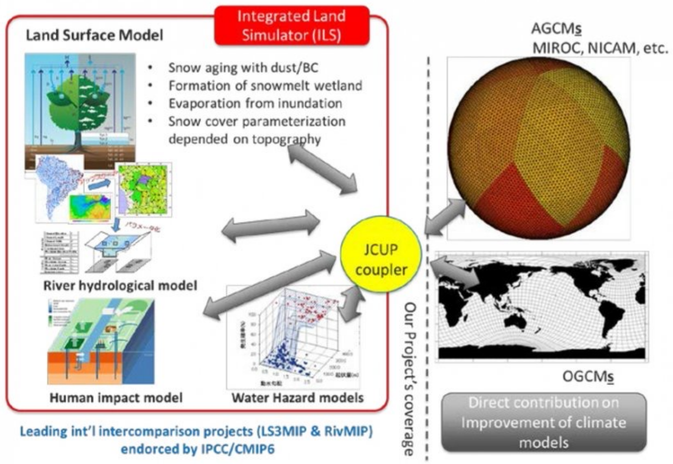
- Efforts are ongoing to better represent horizontal water dynamics
  (River and floodplain dynamics, hillslope lateral flow, groundwater flow, in addition to vertical water flux)



Modelling **hillslope lateral flow** in LSM is interesting/important.

- Land water dynamics finally becomes 3-Dimentional
- Hillslope flow physically connects 1D soil water budget with runoff generation and river-soil water interactions.
- Related to key ecosystem processes related to carbon cycle (groundwater and vegetation root, water table dynamics in wetlands)

Integrated Land Simulator
New coupling framework for
land components & climate model
Nitta et al. ,2020



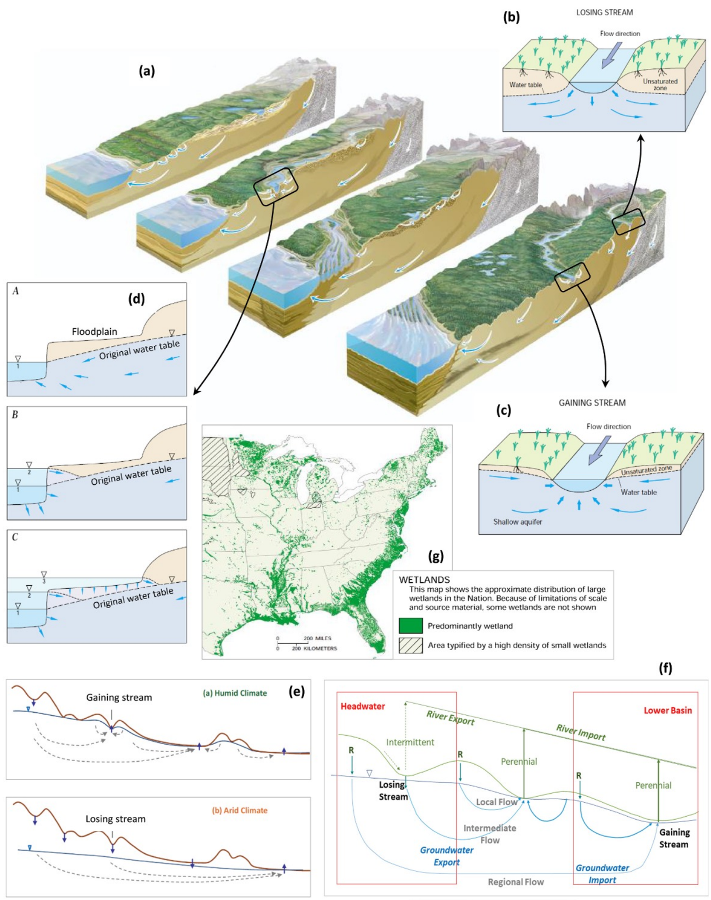
Various modelling approaches exists.

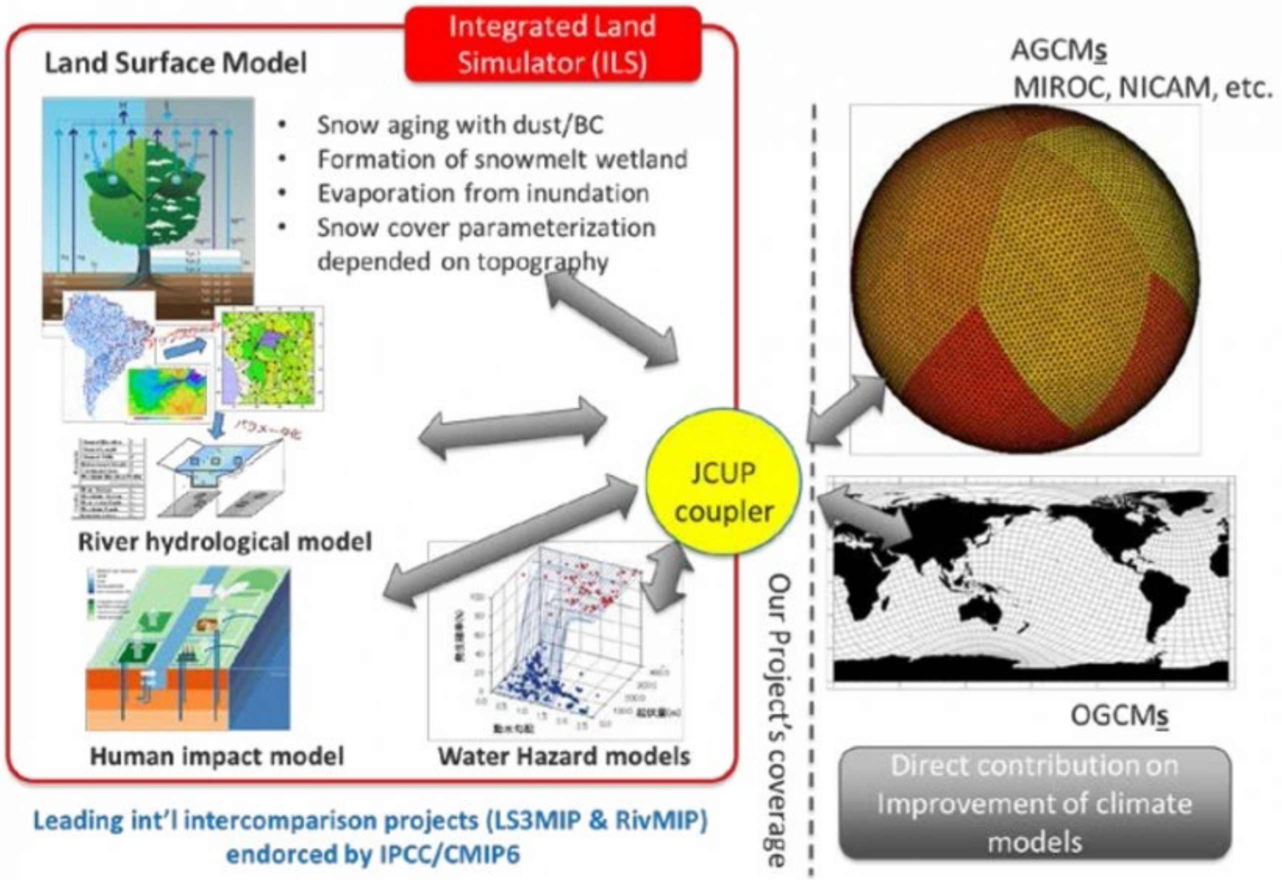
- Hyper-resolution, or Sub-grid physics in medium resolution.
- Physically-based representation for higher accuracy, or conceptual representation for flexible coupling.

Both "realistic water dynamics" & "flexible coupling with ESM process" are needed.

- Primary target of LSM is to represent land processes important for climate simulations.
- We need process-level improvement (e.g. wetland water level & extent) and comprehensive coupling (ecosystem + carbon)
- Moreover, fully coupling recently-developed land hydrology processes to GCM/ESM is essential to understand which process is important for climate projections.

Sumarry


(a)
(b)
LOSING STREAM
Flow direction
Water table
Unsaturated zone
(d)
A
Floodplain
Original water table
B
Original water table
C
Original water table
GAINING STREAM
(c)
Flow direction
Unsaturated zone
Water table
Shallow aquifer
(g)
WETLANDS
This map shows the approximate distribution of large wetlands in the Nation. Because of limitations of scale and source material, some wetlands are not shown
Predominantly wetland
Area typified by a high density of small wetlands
Gaining stream
(a) Humid Climate
(e)
Losing stream
(b) Arid Climate
(f)
Headwater
River Export
Lower Basin
River Import
Intermittent
Perennial
Perennial
Losing Stream
Local Flow
Intermediate Flow
Gaining Stream
Groundwater Export
Groundwater Import
Regional Flow


Integrated Land Simulator (ILS)
Land Surface Model
• Snow aging with dust/BC
• Formation of snowmelt wetland
• Evaporation from inundation
• Snow cover parameterization depended on topography
River hydrological model
Human impact model
Water Hazard models
JCUP coupler
AGCMs
MIROC, NICAM, etc.
OGCMs
Our Project's coverage
Direct contribution on Improvement of climate models
Leading int'l intercomparison projects (LS3MIP & RivMIP) endorced by IPCC/CMIP6