Institute of Industrial Science,
The University of Tokyo

CliMTech

HIROSHIMA UNIVERSITY

Sixth Workshop on Coupling Technologies for Earth System Models (CW2023)

January 18-20, 2023

MIROC-ILS coupling

Coupling multiple land component models to an atmosphere and ocean model with Jcup

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1: The University of Tokyo, 2: CliMTech inc., 3: Hiroshima University

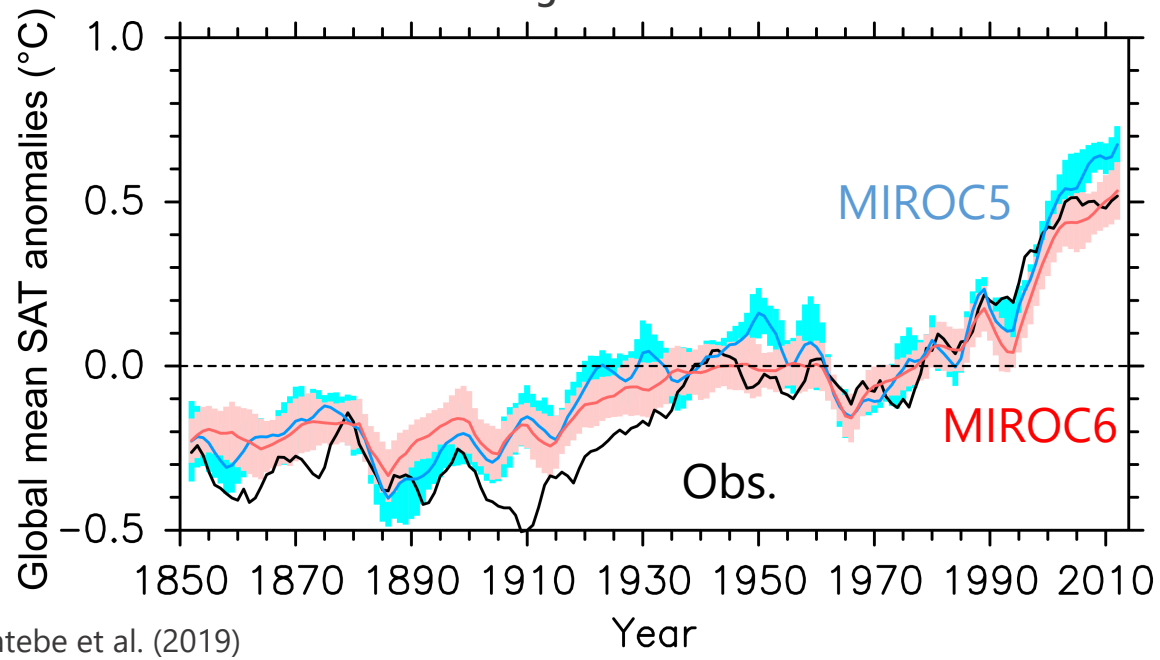
Outline

01 Introduction

Climate model MIROC

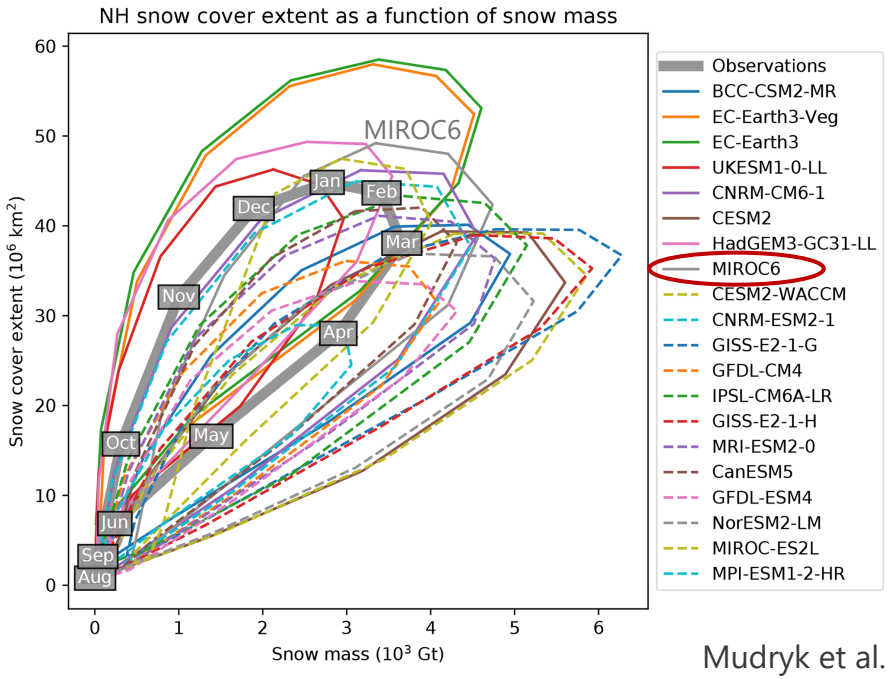
MIROC is a climate model developed by a Japanese modeling community

Time series of the global mean SAT anomalies



Tatebe et al. (2019)

Relationship between NH snow mass and snow cover from CMIP6 simulations



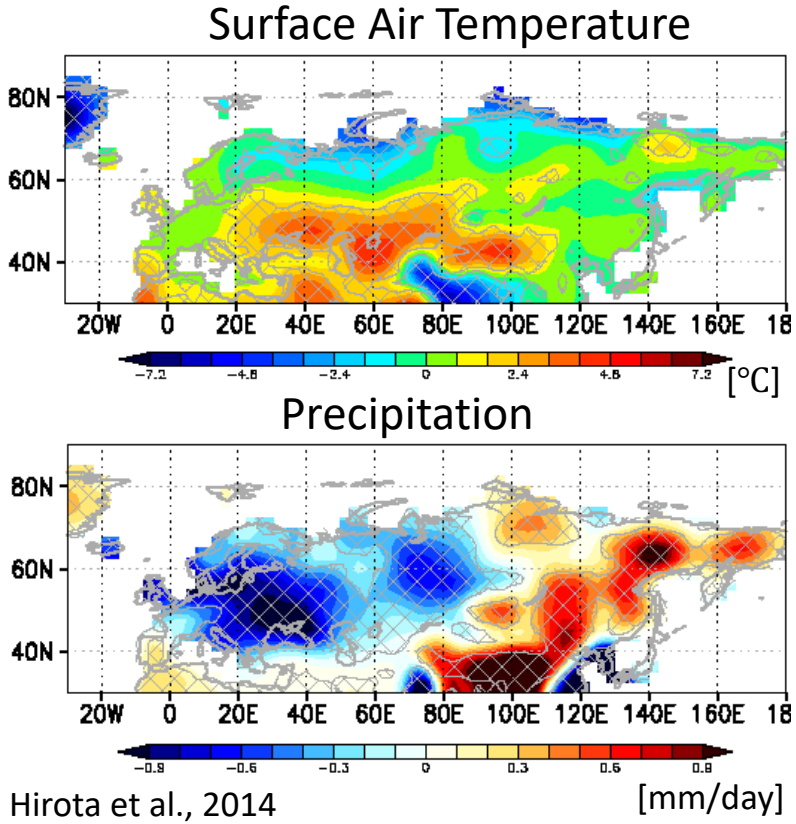
Mudryk et al. (2020)

- MIROC has Participated in MIPs (e.g., CMIPs)
- We are in charge of **land** model development

Land modeling issues

- Land model has a history of being developed as an **atmospheric model parameterization**
  - **Land grid and resolution** are often the same as the atmosphere
  - There are few **land experts** in the core ESM development group

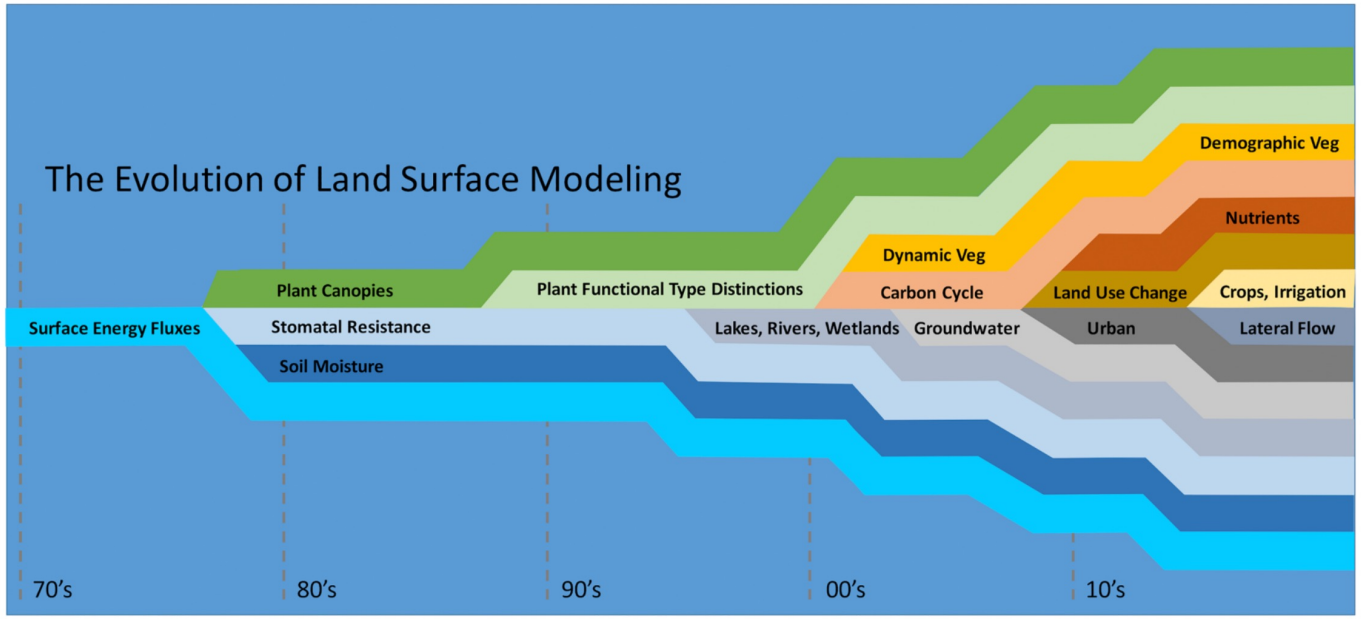
- Systematic biases of climate models may be partially attributed to land processes
  - **Stand-alone models with more precise physics** exist, but there has been no infrastructure to implement them
  - We should involve more land experts in the development of the land model for climate models



Hirota et al., 2014

Land modeling issues

- Because the land area is spatially more **complex/diverse** than the atmosphere/ocean, a **wide variety of processes** must be considered at a relatively high resolution relative to the atmosphere/ocean
- **Human activities** have significantly modified the land area and cannot be represented by natural processes alone

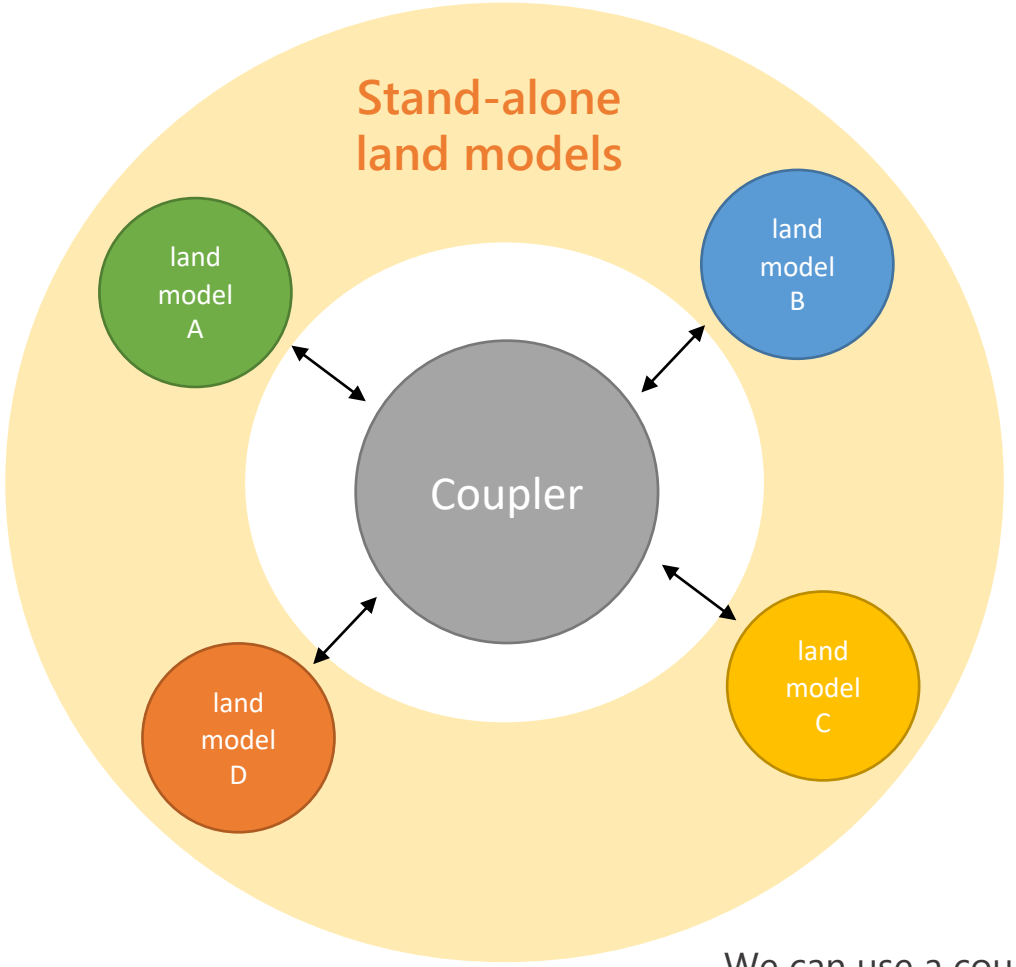


Fisher and Koven (2020)

- Land models are becoming more **complex**
- **Managing complexity** is one of the common challenges, not only for us but also for modeling groups worldwide

Objectives

- Develop a **platform model** consisting of **a group of stand-alone land models** and supporting software including regridding function and coupling tools
- Coupling it with weather, climate, and Earth system models
- It can be applied to other purposes such as flood forecasting



We can use a coupler to develop a land model

02 Integrated Land Simulator (ILS)

Concept

Development of Integrated Land Simulator, ILS (Nitta et al., 2020)

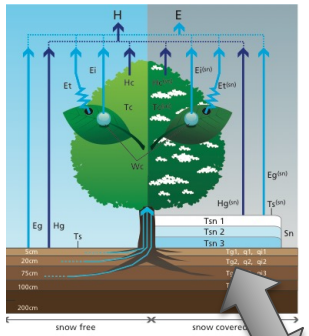
will contribute MIROC7/CMIP7

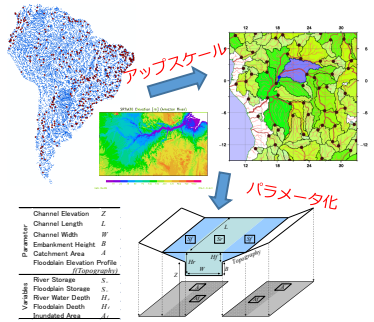
Basic concepts:

- Port the latest stand-alone models with smallest modification of the codes.
- Run the models with their preferred time steps and resolutions, and exchange necessary data with appropriate regridding by the coupler.

1-D Land Model MATSIRO

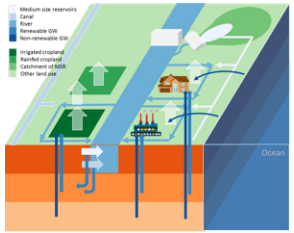
(Takata et al., 2003; Nitta et al., 2014; 2017)





River Model CaMa-Flood

(Yamazaki et al., 2011; 2013)



Human Impact Model H08

(Hanasaki et al., 2008)

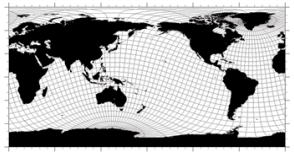
General purpose coupler Jcup (Arakawa et al., 2020)

Environment:

- Spatial coordinates are controlled by regridding tables.
- Regridding table generator SPRING (Takeshima et al., in prep)
- Boundary conditions are also generated by using SPRING
- Gitlab version management
- Benchmarking with iLamb (underway)

AGCMs

MIROC (Tatebe et al., 2019)
NICAM (Sato et al., 2014) etc.

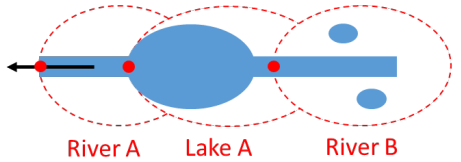


OGCMs

COCO (Hasumi, 2006) etc.

Models to be coupled

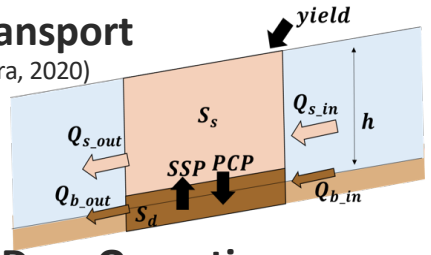
Lake model and Hydrological Energy Transfer (Tokuda et al., 2021)



---: Boundary of unit-catchment
●: Outlet of unit-catchment

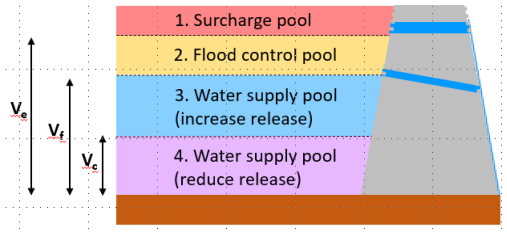
Sediment Transport

(Hatono and Yoshimura, 2020)



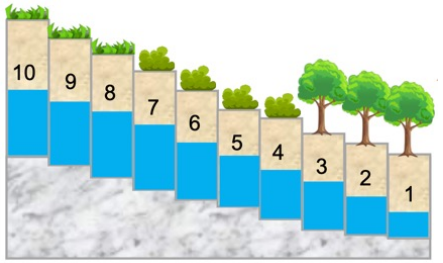
Generalized Dam Operation

(Hanazaki et al., 2022)



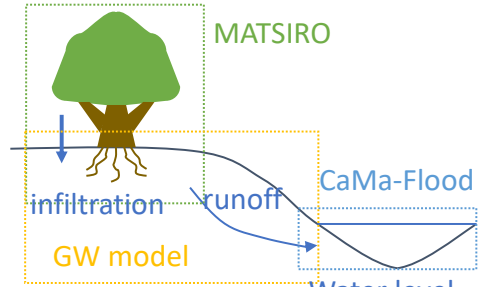
Sub-grid Hillslope Representation

(Li et al., in prep)



3D Groundwater

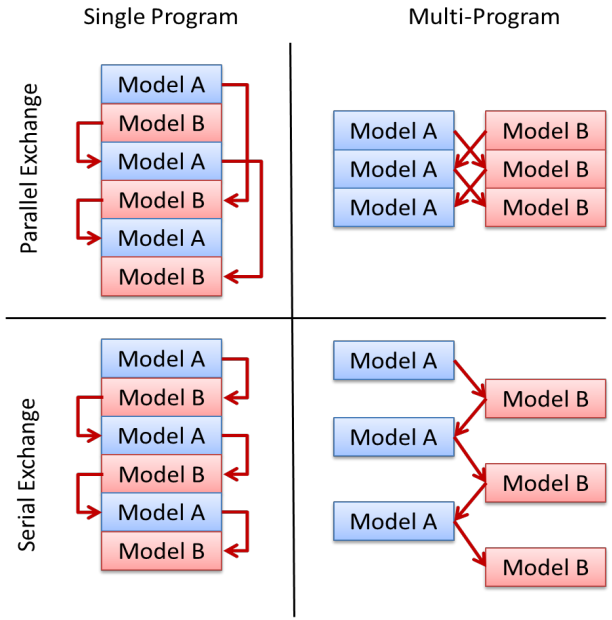
(Miura and Yoshimura, 2020; 2022)



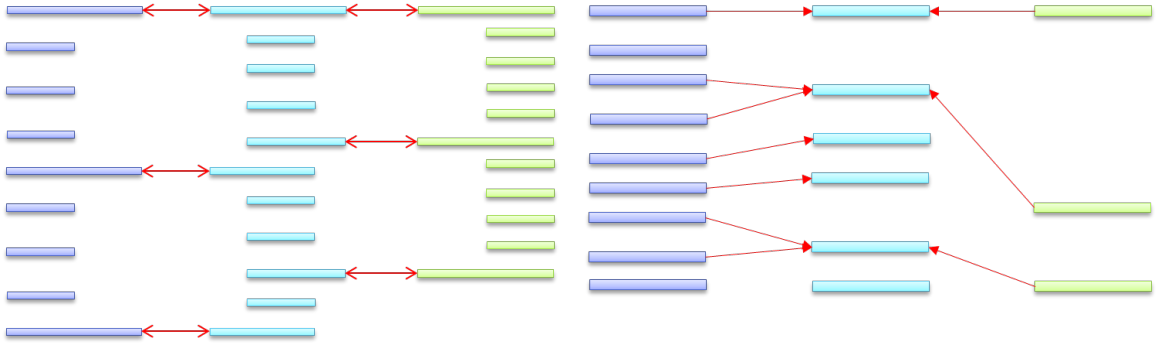
Coupler

Dr. Takashi Arakawa

- We chose a general-purpose coupling library **Jcup** (Arakawa et al., 2020)
  - **Design Concept: provide maximum flexibility for model coupling**
  - Grid structure independent
  - Interpolation calculation code is programable by users.
  - Constant or variable ΔT exchange

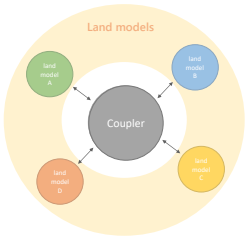


Coupling pattern of Jcup



Constant ΔT exchange

Variable ΔT exchange



Arakawa, T., Inoue, T., Yashiro, H. et al. Coupling library Jcup3: its philosophy and application. Prog Earth Planet Sci 7, 6 (2020). https://doi.org/10.1186/s40645-019-0320-z

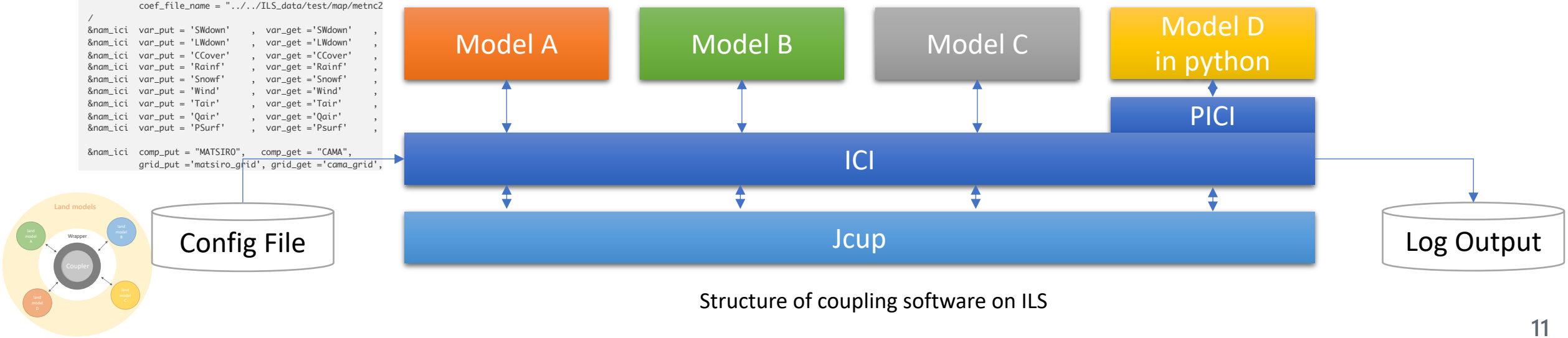
Coupler

Dr. Takashi Arakawa

- Jcup is flexible but “too” flexible to use
- Wrapper layer suitable for individual coupling environments
- **ILS Coupling Interface (ICI)**
  - Coupling configuration via an external configuration file
  - Exchange data monitor
  - Python API

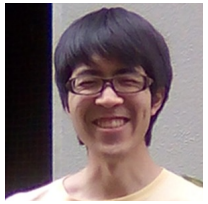
```
&nam_ici  comp_put = "ILSIO",   comp_get = "MATSIRO",
          grid_put ='io_grid2', grid_get ='matsiro_grid',
          intpl_map_size = 311304,
          map_file_name = "../../ILS_data/test/map/metnc2m
          coef_file_name = "../../ILS_data/test/map/metnc2
/
&nam_ici  var_put = 'SWdown'    ,  var_get ='SWdown'    ,
&nam_ici  var_put = 'LWdown'    ,  var_get ='LWdown'    ,
&nam_ici  var_put = 'CCover'    ,  var_get ='CCover'    ,
&nam_ici  var_put = 'Rainf'     ,  var_get ='Rainf'     ,
&nam_ici  var_put = 'Snowf'     ,  var_get ='Snowf'     ,
&nam_ici  var_put = 'Wind'      ,  var_get ='Wind'      ,
&nam_ici  var_put = 'Tair'      ,  var_get ='Tair'      ,
&nam_ici  var_put = 'Qair'      ,  var_get ='Qair'      ,
&nam_ici  var_put = 'PSurf'     ,  var_get ='Psurf'     ,

&nam_ici  comp_put = "MATSIRO",   comp_get = "CAMA",
          grid_put ='matsiro_grid', grid_get ='cama_grid',
```



Structure of coupling software on ILS

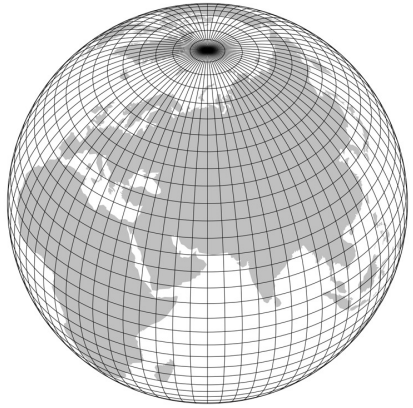
Regridding tool SPRING



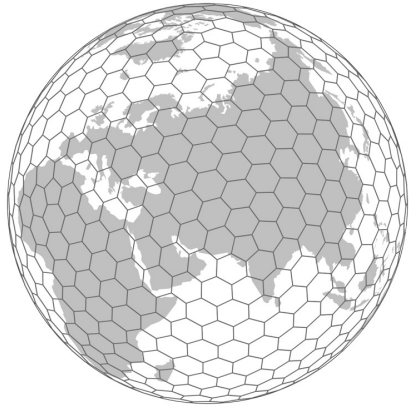
Akira Takeshima

- SPRING (**SP**heroidal coordinates **R**egridding **IN**terpolation table **G**enerator)
  - A package of the programs for regridding among spheroidal coordinates
  - Applicable to lat/lon grid, polygon grid and raster grid
    - Spheroidal coordinate is limitted to lat/lon grid and raster grid
    - Polygon grid can be treated only in the spherical coordinate
  - 1st-order conservative regridding

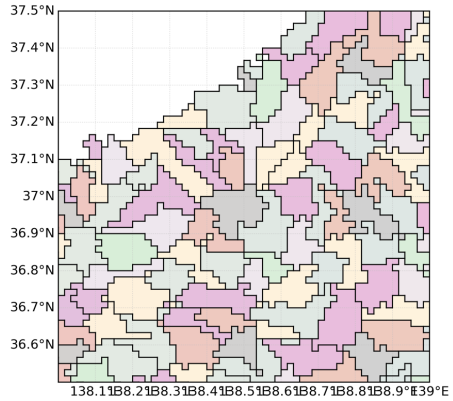
- Independent of Jcup
- Can be used for general interpolation purposes



(a) LatLon grid. It can be considered to be a special case of polygon grid, but distinguished for the convenience.



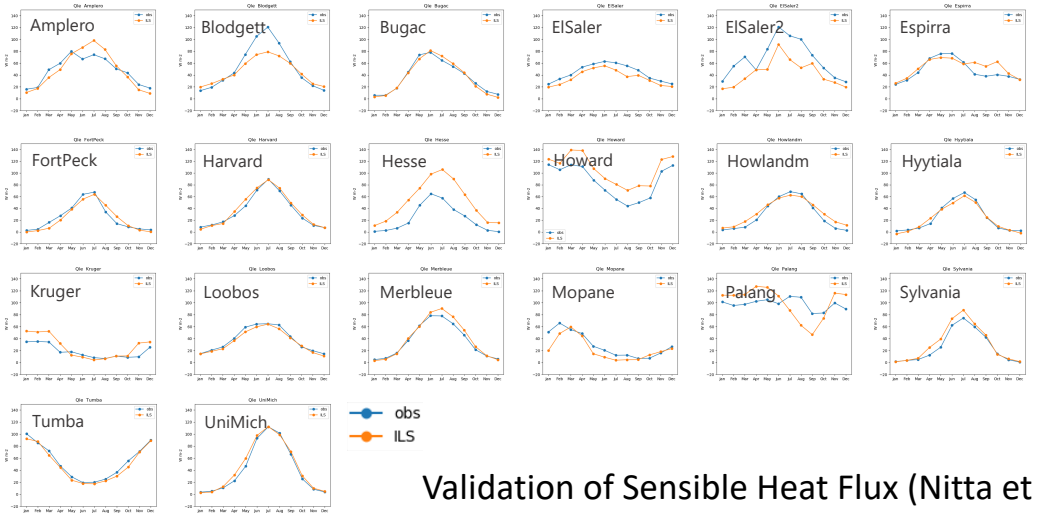
(b) Polygon grid. It consists of arbitrary polygons including concave ones.



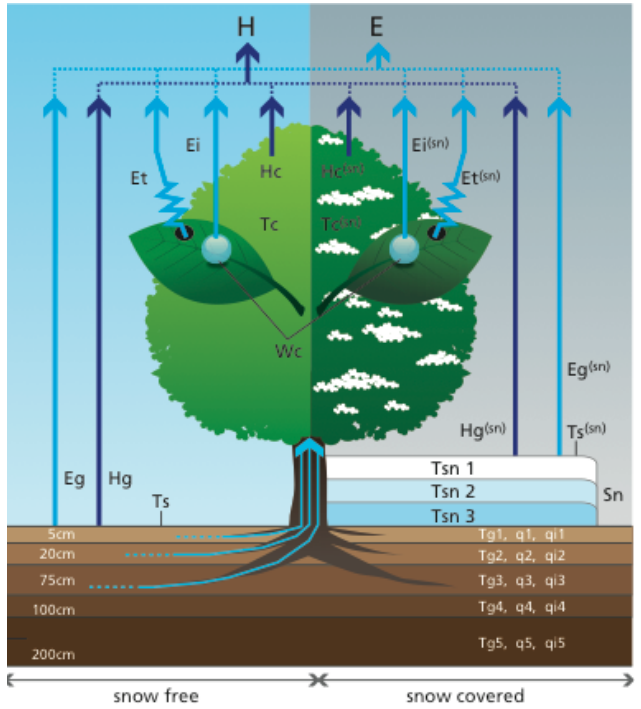
(c) Raster grid. Each grid consists of high resolution cells called raster. CaMa-Flood uses this grid system to represent the unique shapes of the water catchments.

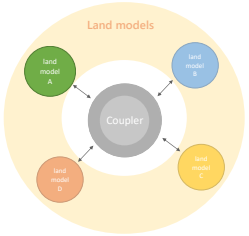
MATSIRO

- MATSIRO is a land model of MIROC and NICAM models
- It consists of 6 soil layers (14m in total), 3 snow layers, and a single canopy layer and includes various land physics (e.g., radiation transfer, bulk coefficient, snow, runoff, soil property…) and a tile scheme
- In MIROC6, MATSIRO was part of the atmospheric model.
- The source code was rewritten as an independent land model.



Validation of Sensible Heat Flux (Nitta et al., 2020)

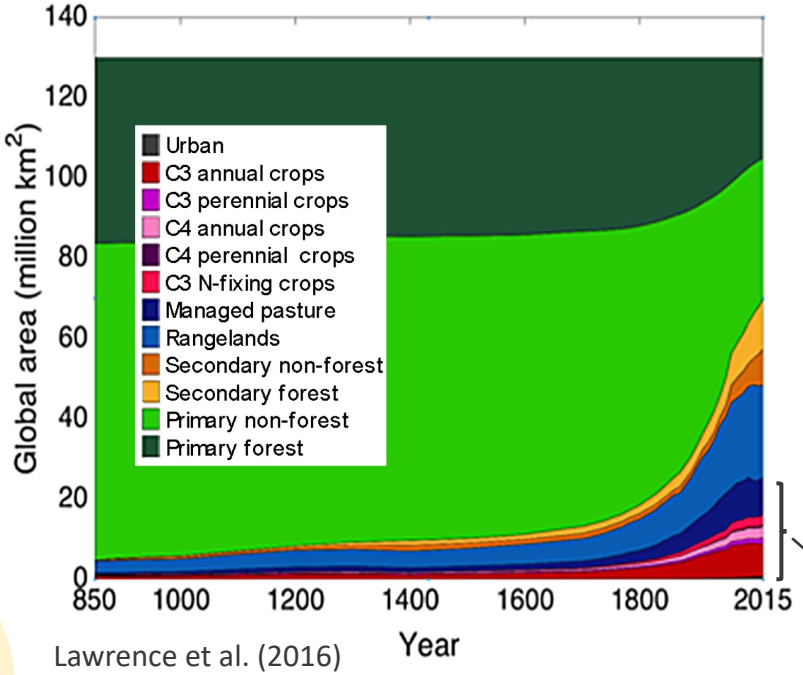




Boundary condition tool for MATSIRO

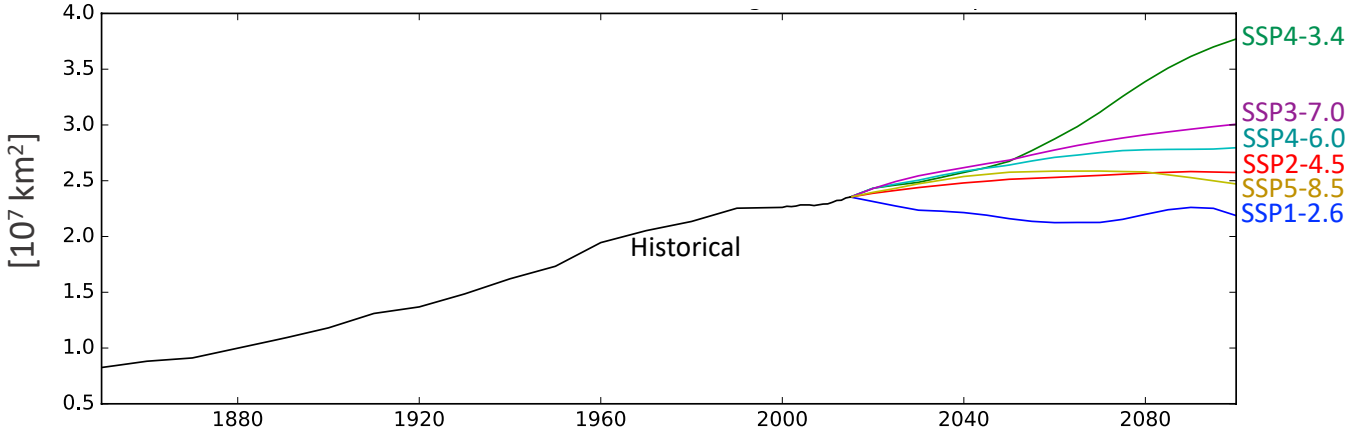
- A tool for preparing boundary condition condition of MATSIRO has been also added to ILS
- Regridding tables from SPRING are also used here

Land Use Harmonization 2 (Hurtt et al. 2020)

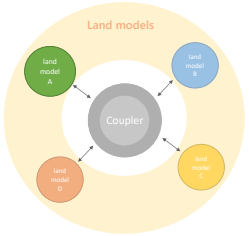


Lawrence et al. (2016)

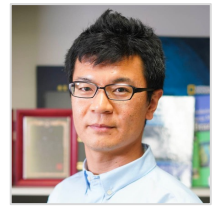
Global Area of Cropland in MATSIRO



MATSIRO uses 6 categories as cropland

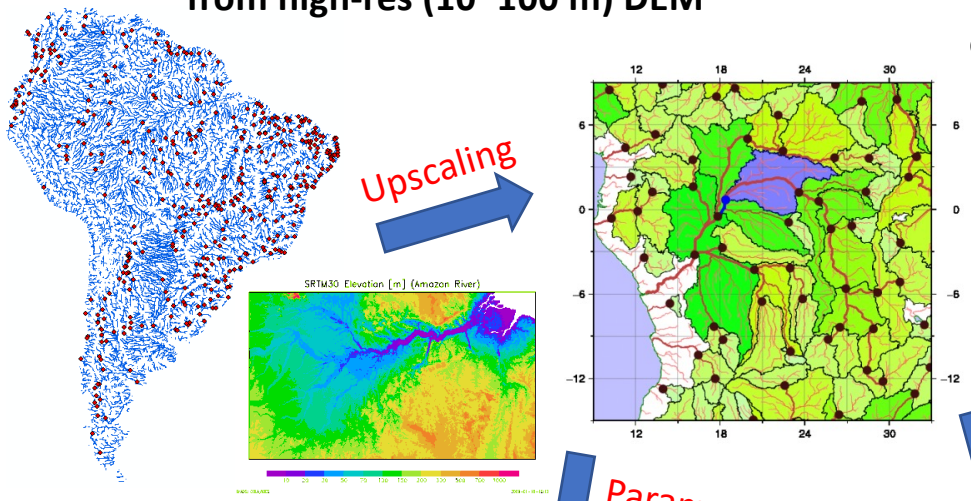


CaMa-Flood

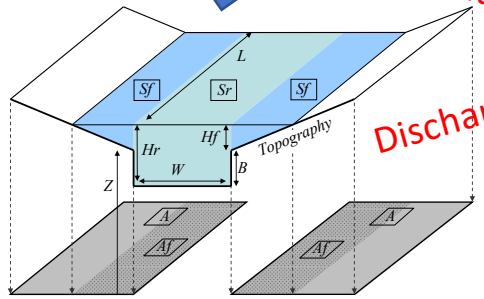


Dr. Dai Yamazaki

Abstract sub-grid topographic characteristic from high-res (10~100 m) DEM



Parameter	Channel Elevation	Z
	Channel Length	L
	Channel Width	W
	Embankment Height	B
	Catchment Area	A
	Floodplain Elevation Profile	$f(Topography)$
Variables	River Storage	S_r
	Floodplain Storage	S_f
	River Water Depth	H_r
	Floodplain Depth	H_f
	Inundated Area	A_f

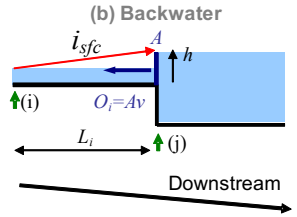


Diffusive Wave Equation
Depending on water level, "backwater" occurs.

$$\frac{1}{g}\frac{\partial v}{\partial t}+\frac{v}{g}\frac{\partial v}{\partial x}+\frac{\partial h}{\partial x}+i_0-i_f=0$$

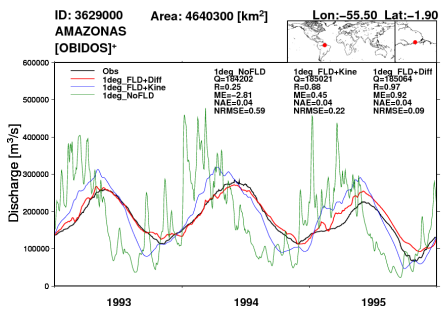
Dynamic | Diffusive | Kinematic

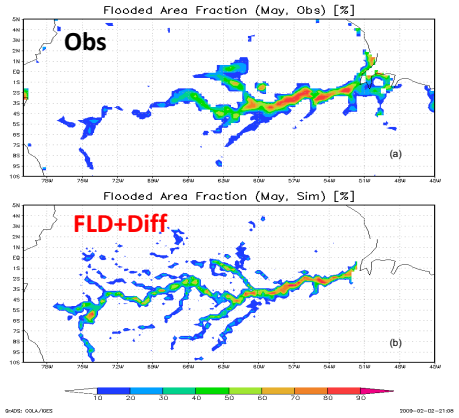
St. Venant Momentum Equation



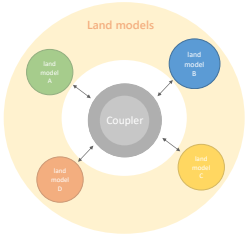
In addition to river discharge, water level altitude and inundation area is simulated.
→ comparable to satellite-based estimates.

Discharge, w-level, inundation are predicted.





Each grid represents basin shape with sub-grid topographic parameters. River water depth and inundation area is explicitly calculated.



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Development of Integrated Land Simulator

Tomoko Nitta, Takashi Arakawa, Misako Hatono, Akira Takeshima & Kei Yoshimura

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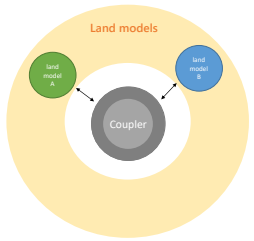
Abstract

Accurate simulations of land processes are crucial for many purposes, such as climate simulation, weather, flood, and drought prediction, and climate change impact assessment studies. In this paper, we present a new land simulator called the Integrated Land Simulator (ILS). The ILS consists of multiple models that represent processes related to land (hereafter, referred to as "land models"). They are coupled by a general-purpose coupler, Jcup, and executed using the Multiple Program Multiple Data approach. Currently, ILS includes a physical land surface model, the Minimal Advanced Treatments of Surface Interaction and Runoff model, and a hydrodynamic model, the Catchment-based Macro-scale Floodplain model, and the inclusion of additional land models is planned. We conducted several test simulations to evaluate the computational speed and scalability and the basic physical performance of the ILS. The results will become a benchmark for further development.



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Section

2. Atmospheric and hydrospheric sciences

Collection

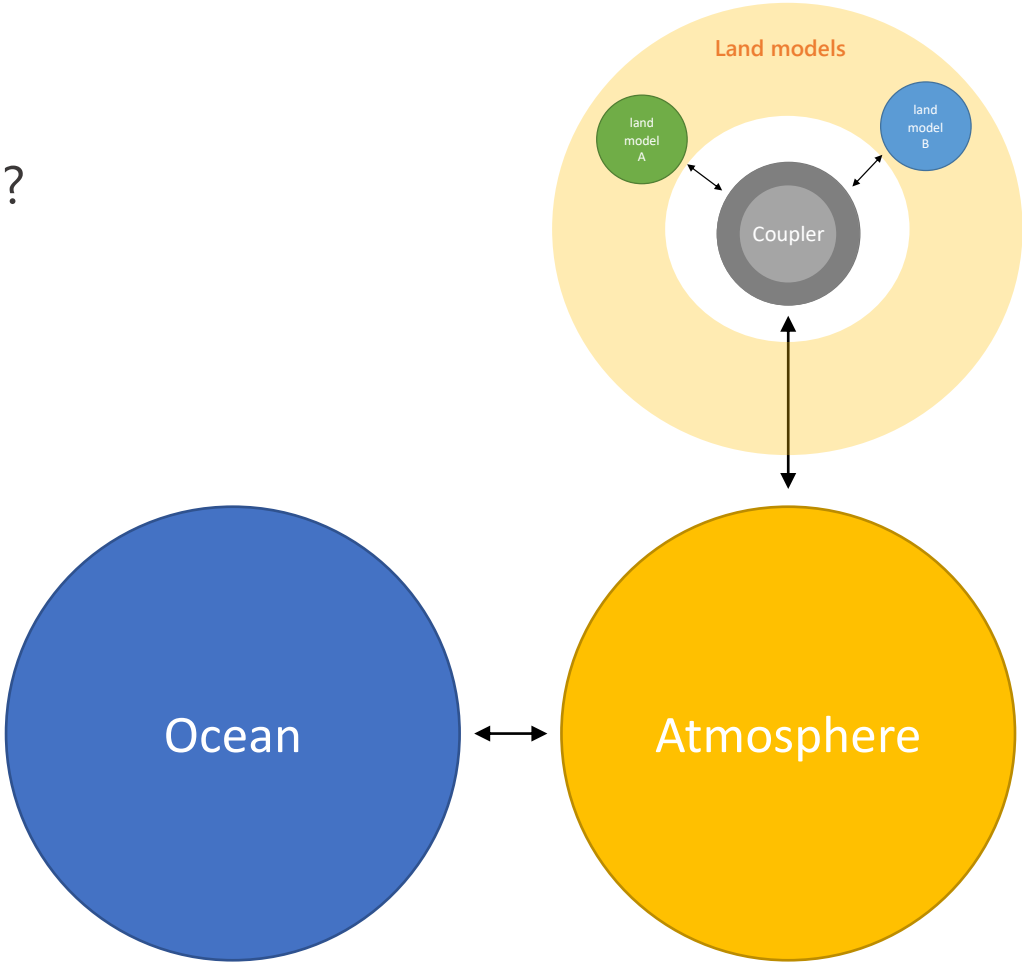
Projection and impact assessment of global change

03 Coupling ILS to MIROC

Coupling with MIROC

- The same framework is applied to couple atmospheric and oceanic models

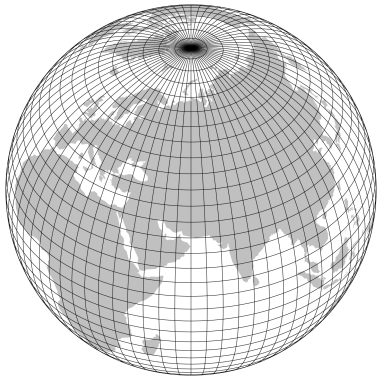
- Questions
  - Water and heat fluxes are conserved?
  - Computationally efficient?
  - Any impacts on climate fields?



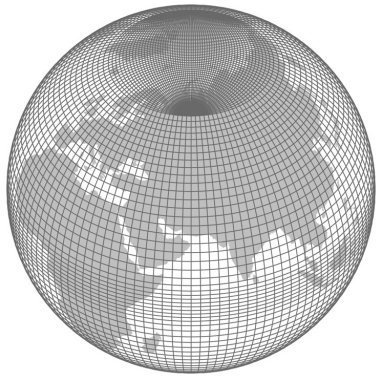
Grids and resolutions

	Grid	Resolution
Atmosphere	Spectral	T85 (1.4 deg.)
Ocean	Tripolar	1 deg.
Land	Basin-shape	0.5 deg.

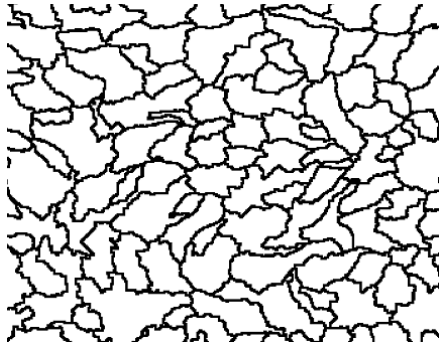
Atmosphere



Ocean

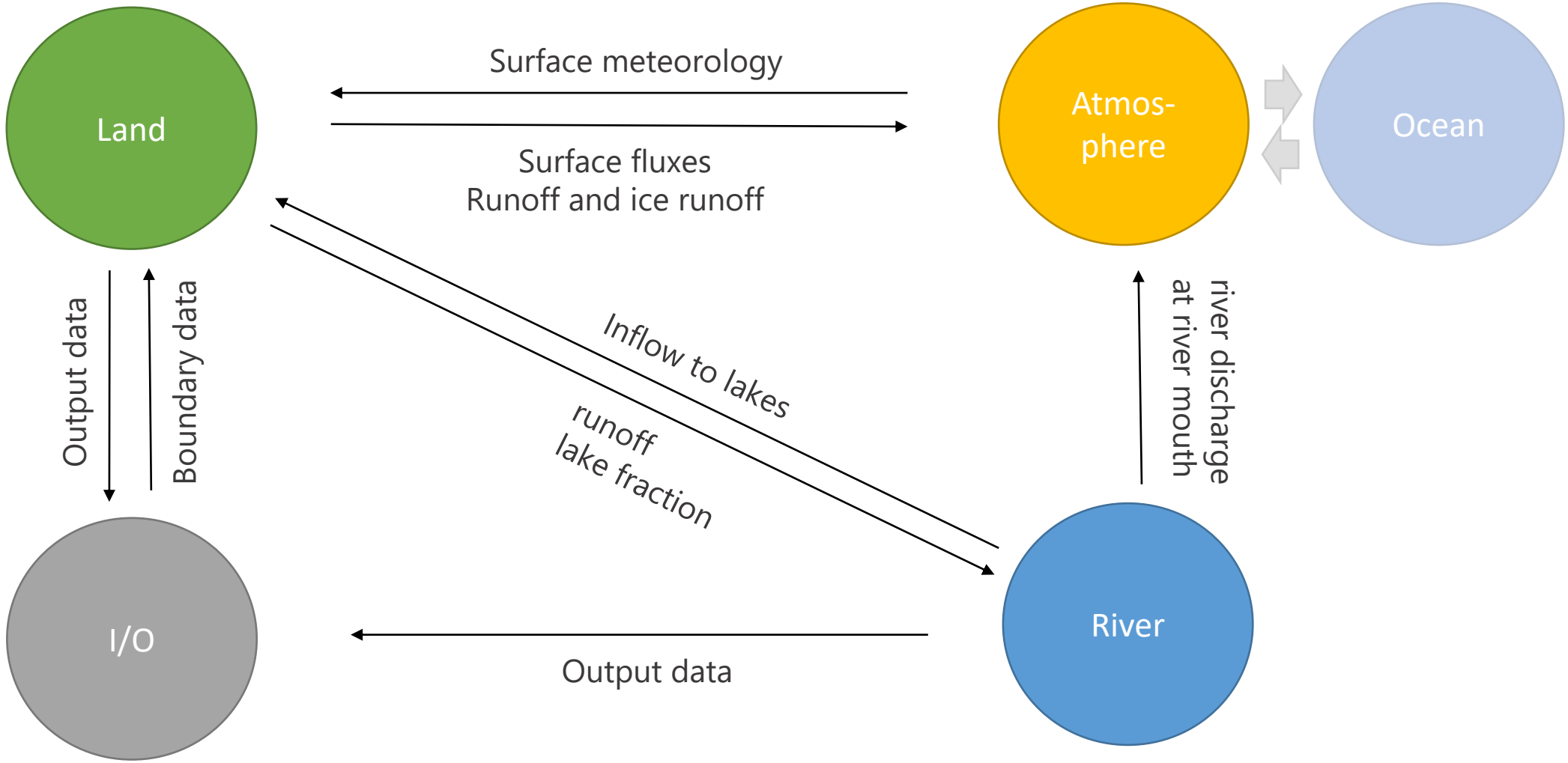


Land



- In the MIROC6, the land grid was the same as the atmosphere
- In the present study, land grid is basin-shape grid with a higher resolution than atmosphere and ocean

Data exchange

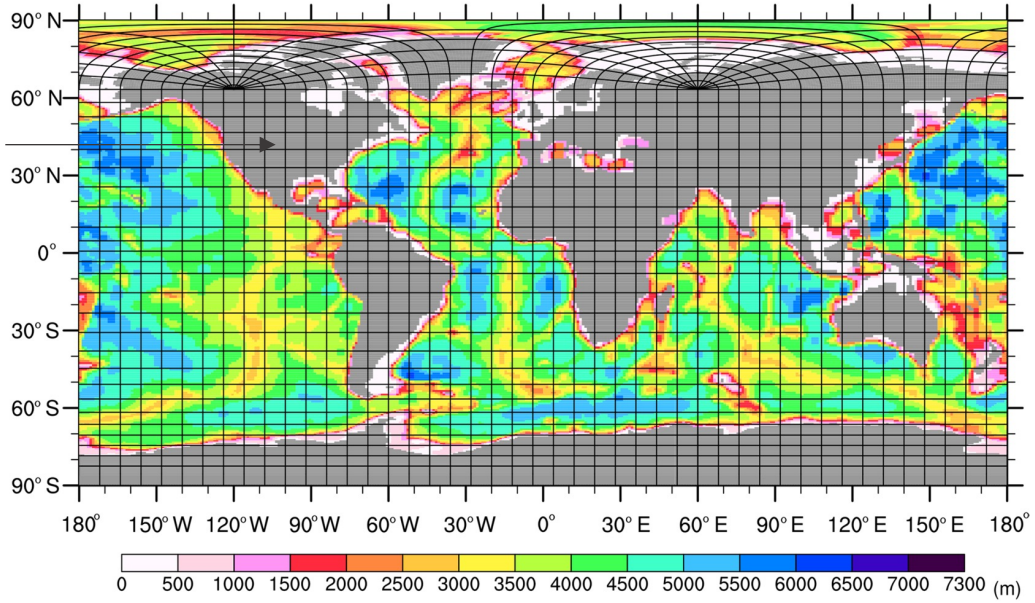


171 variables are exchanged in total.

Horizontal flux conservation

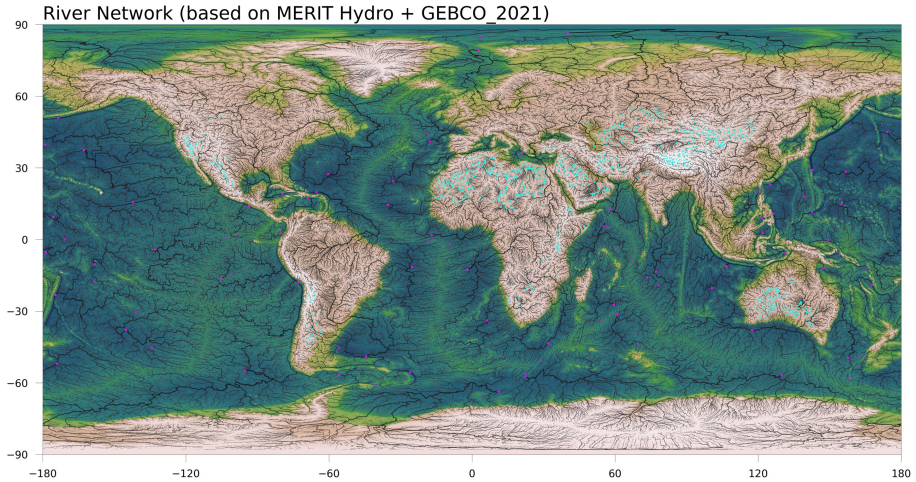
Horizontal grid and bathymetry of the ocean model

land

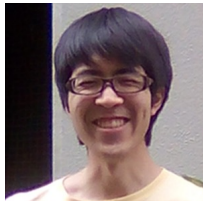


Tatebe et al. (2019)

Hydrological digital elevation model including ocean

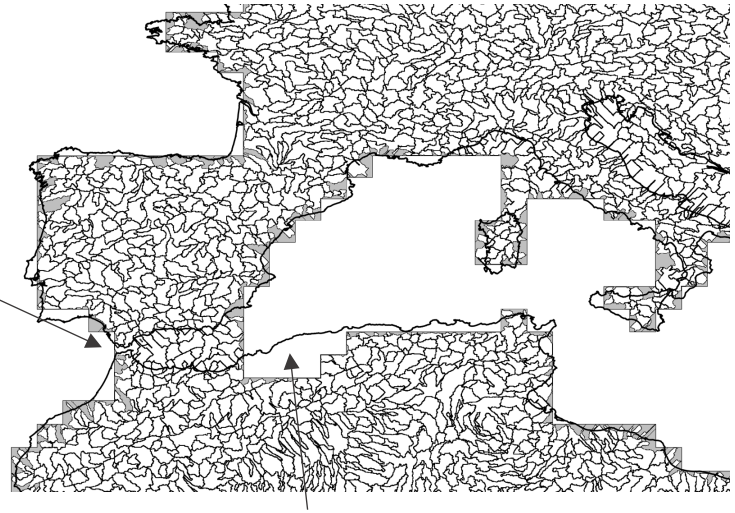


Yamazaki et al. (in prep)



Akira Takeshima

Ocean in reality
but land in the model

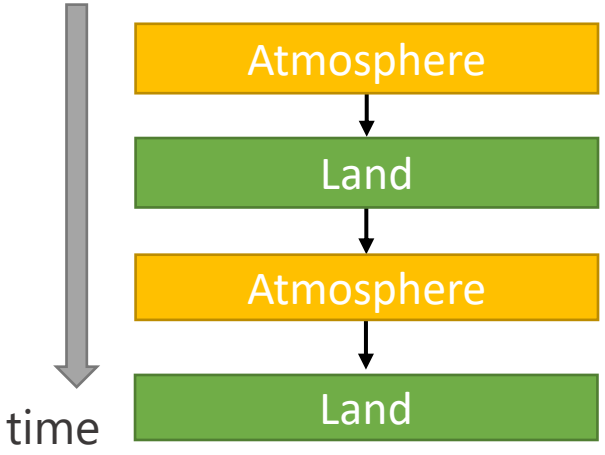


Land in reality but ocean in the model

- Assume the sphere with the same earth radius
- Land-sea mask follows the ocean model
- Allocate basin-shape grids and fill the gap with additional land grids
- SPRING was used for creating regridding tables with area weighting method

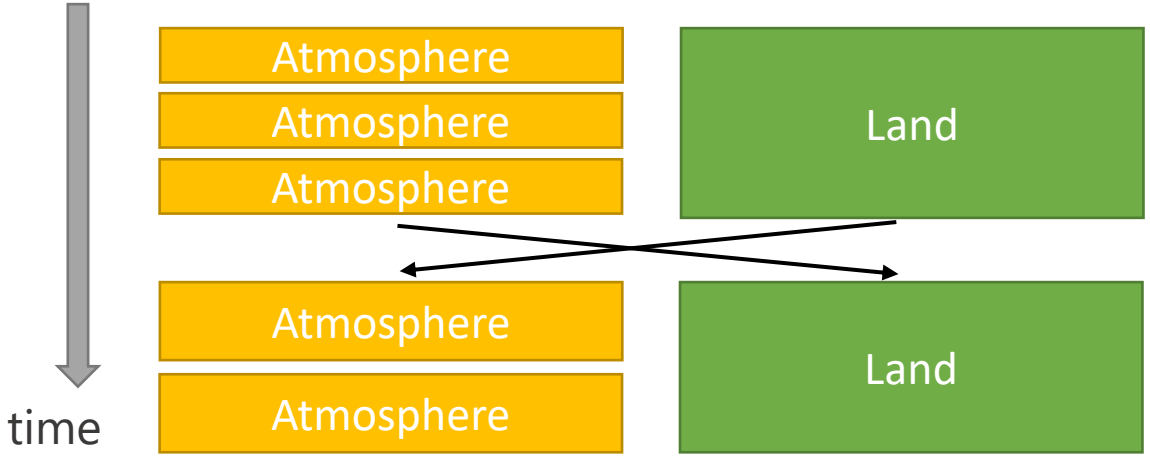
Temporal flux exchange and conservation

Original MIROC6



- Atmosphere and land are simulated seqentially
- Adaptive time step was used for the atmosphere

MIROC-ILS coupling



- Data exchange interval is fixed to conserve fluxes
- Consistency between the atmospheric field and surface fluxes is checked to avoild negative vapor in the atmosphere
- Adaptive time step is applied within the exchange interval
- Restart function is added to the wrapper of the coupler

04 Problems and lessons learned

We had many problems...

- We implemented the framework and tested it, but we had many problems.

- Examples
  - A bug in the coupler caused an error in an aerosol scheme in the atmosphere
  - A mistake by user (land modeler) in the configure file caused an error in the coupler
  - Conservation issues
  - A bug was found in a different environment
  - If a land model is not assumed to couple an atmosphere model in developing, fluxes may not be conserved or loop structure is not suitable to the coupling

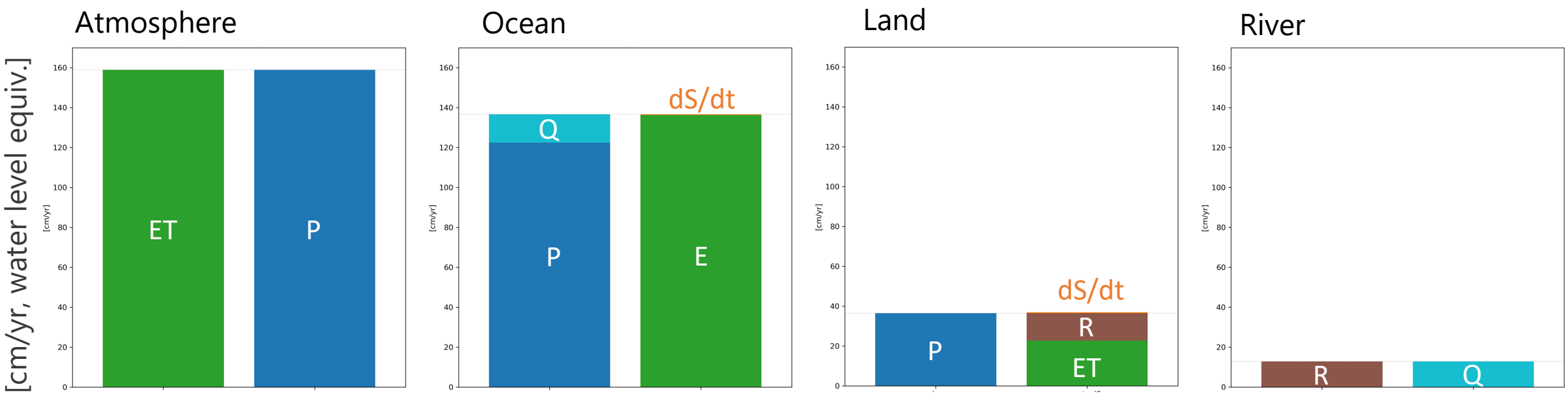
Lessons learned

ILS Couplethon

- Communication between the coupler developers and land modelers is important!
  - More than 200 hours of meeting in 5 years
  - Slack, Wiki
  - Workshops (Couplethon; hackathon for coupling models)
- Logging
  - Monitor exchanging data, configuration
- Testing in multiple environments
  - Unit testing for new code and data

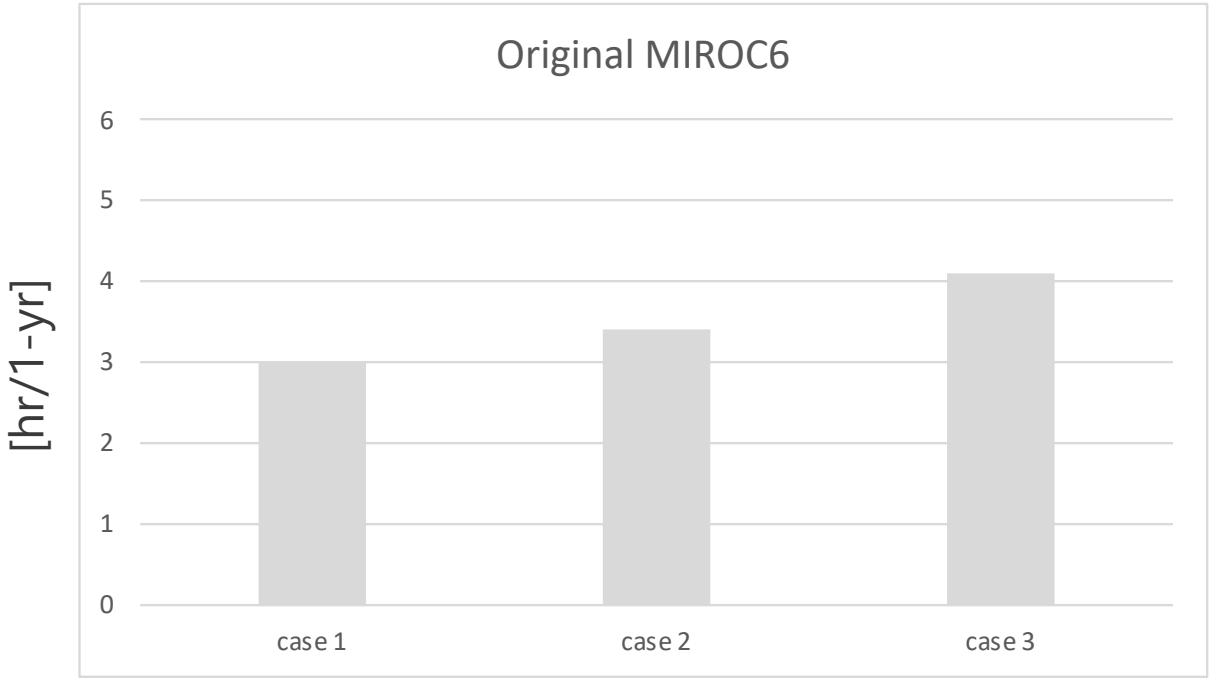
05 Results

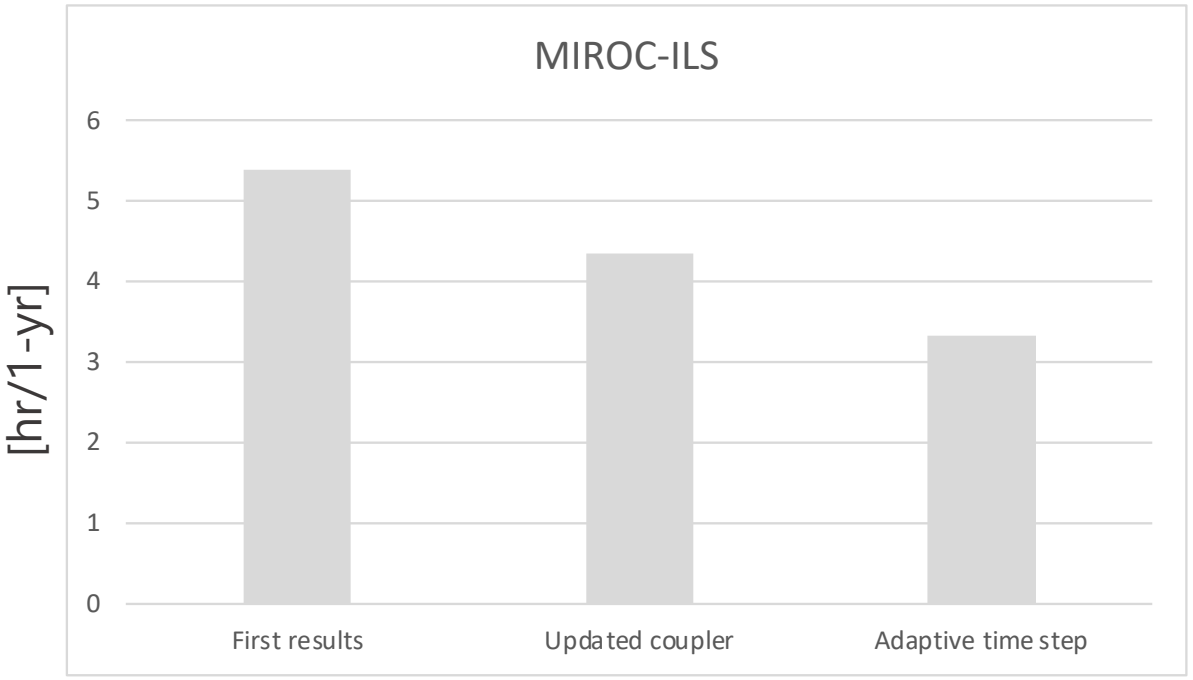
Water budget



- Compared input/output fluxes and water storage changes for each model
- Confirmed that the water balance is closed with sufficient accuracy
- Largest error is from land (sublimation from bare ice) and will be considered for correction

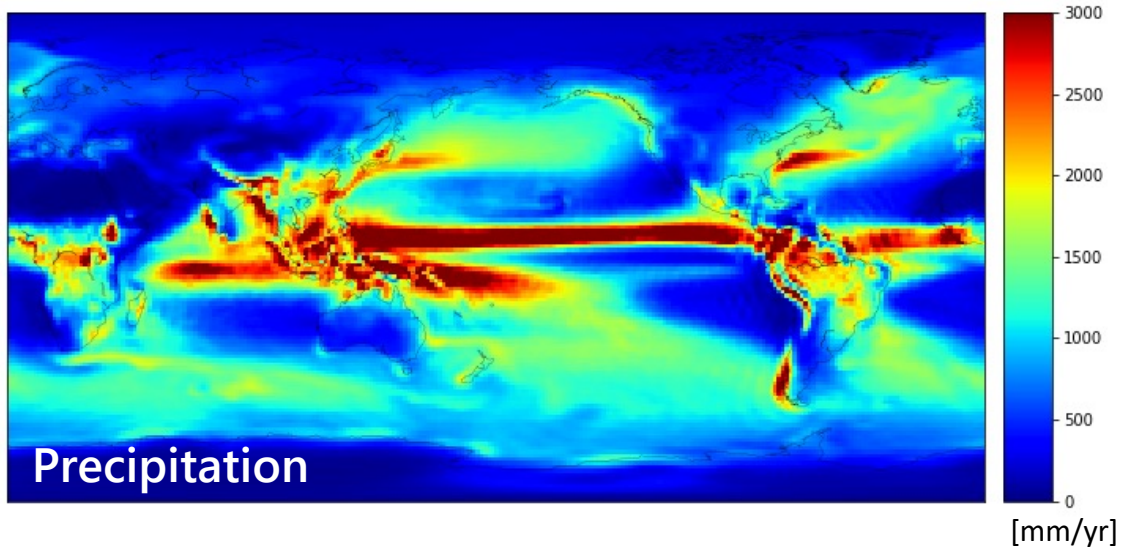
Computation time

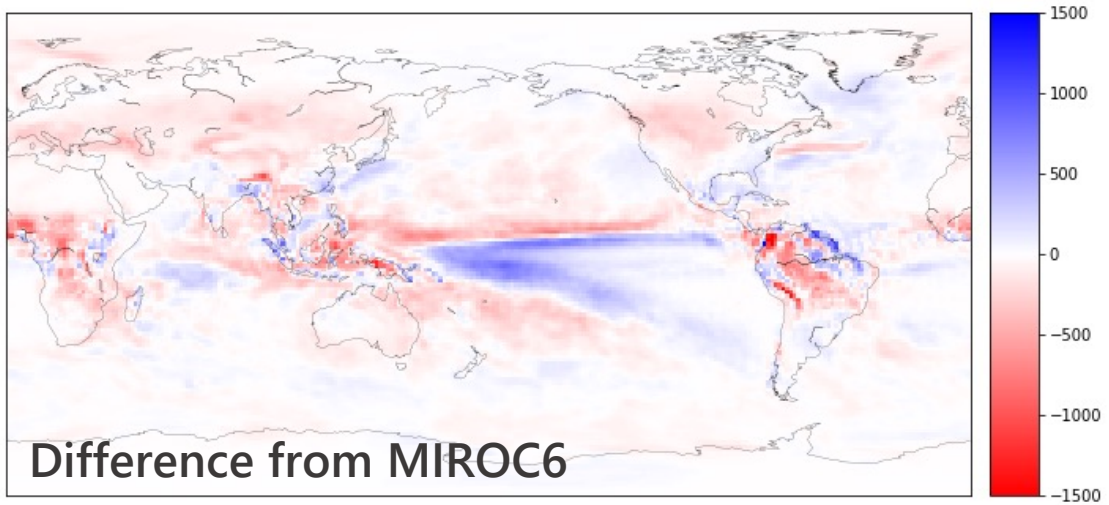


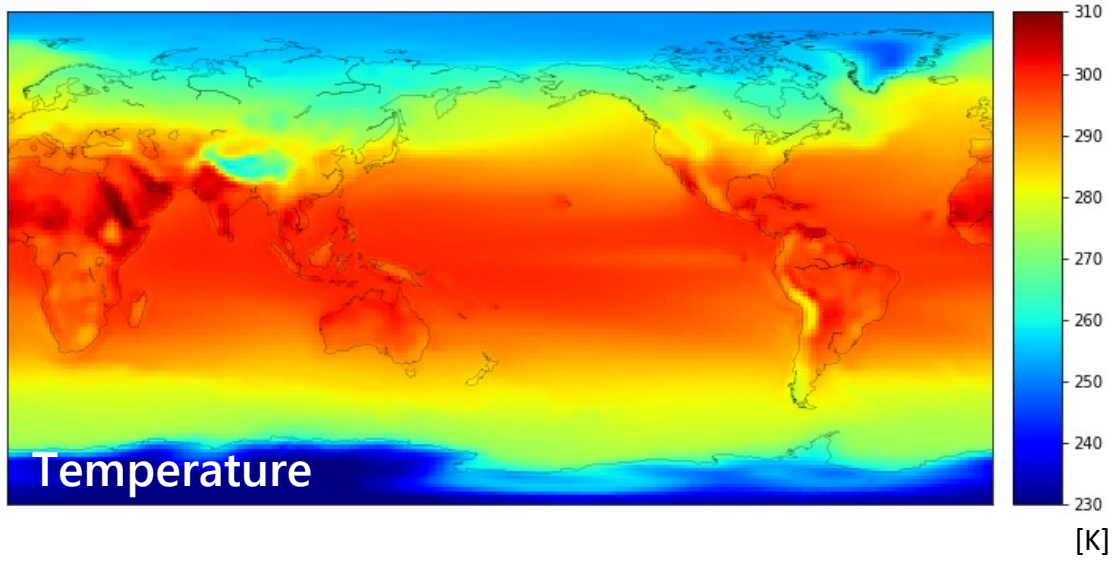


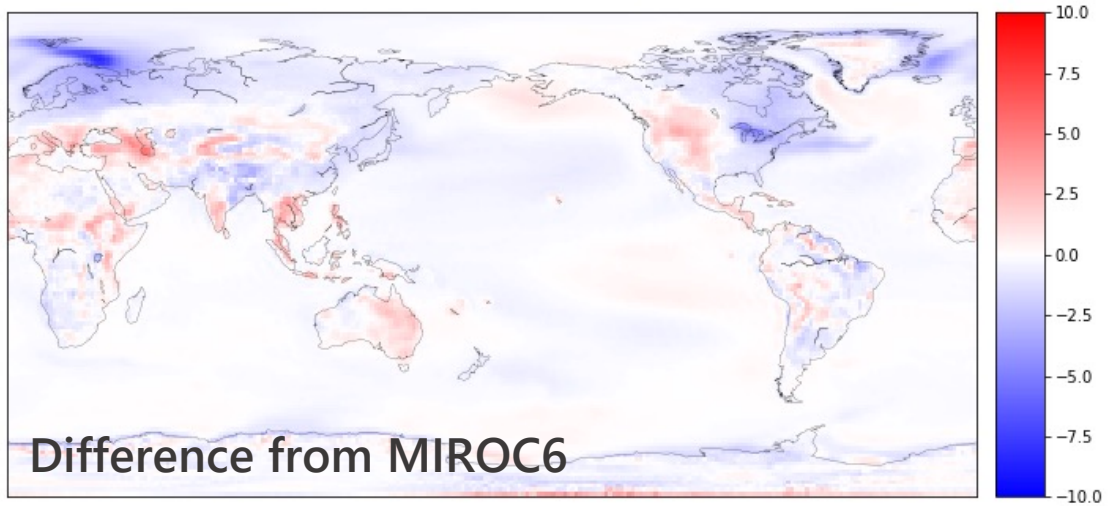
- First simulation took about 5.4 hours for 1-year simulation
- This can be attributed to the overhead of the coupler and the fixed time step of the atmosphere
- Updated coupler and adaptive time step reduce of the atmosphere the computational time

Impacts on simulated precipitation and temperature

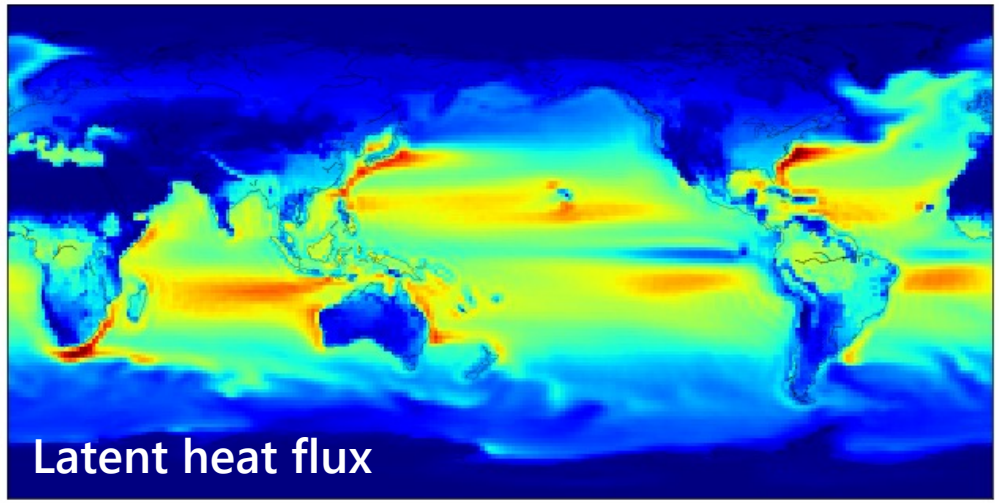


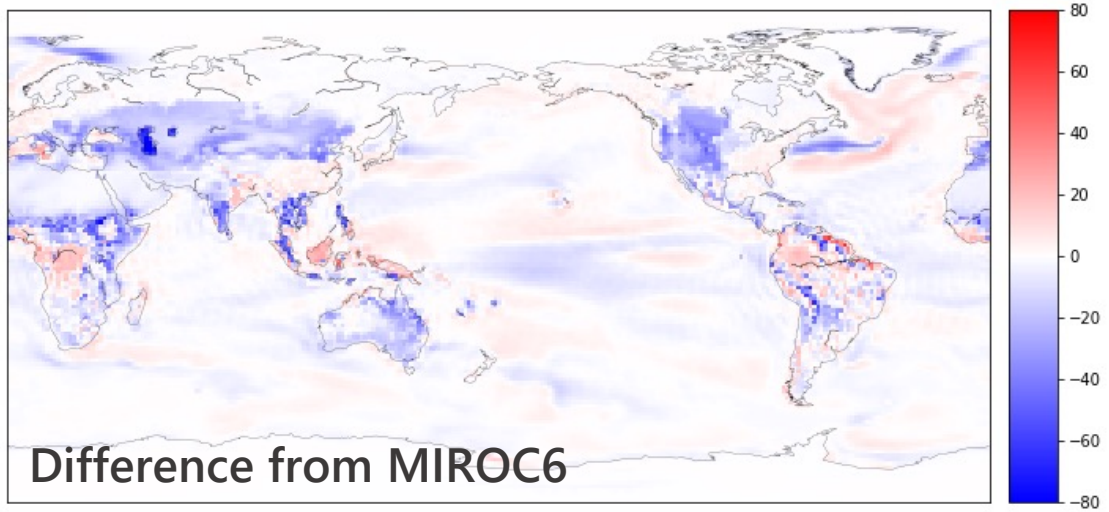


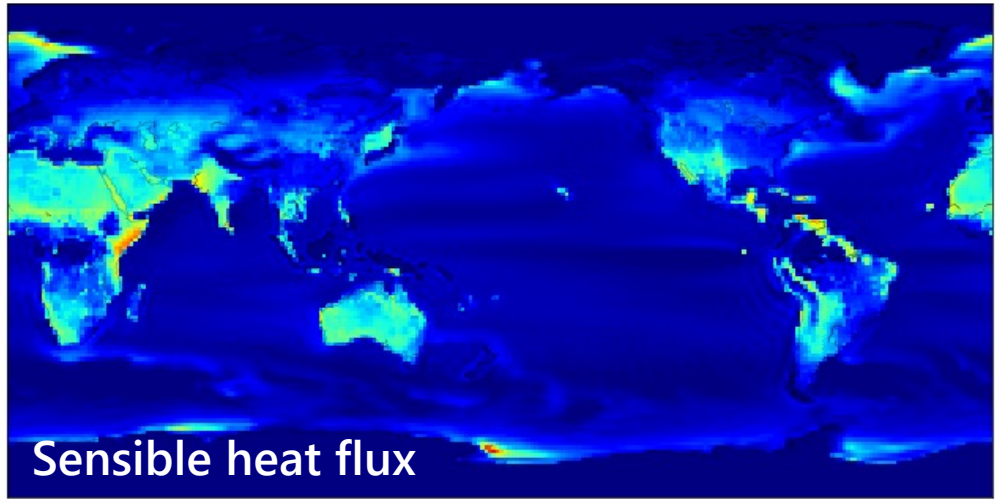


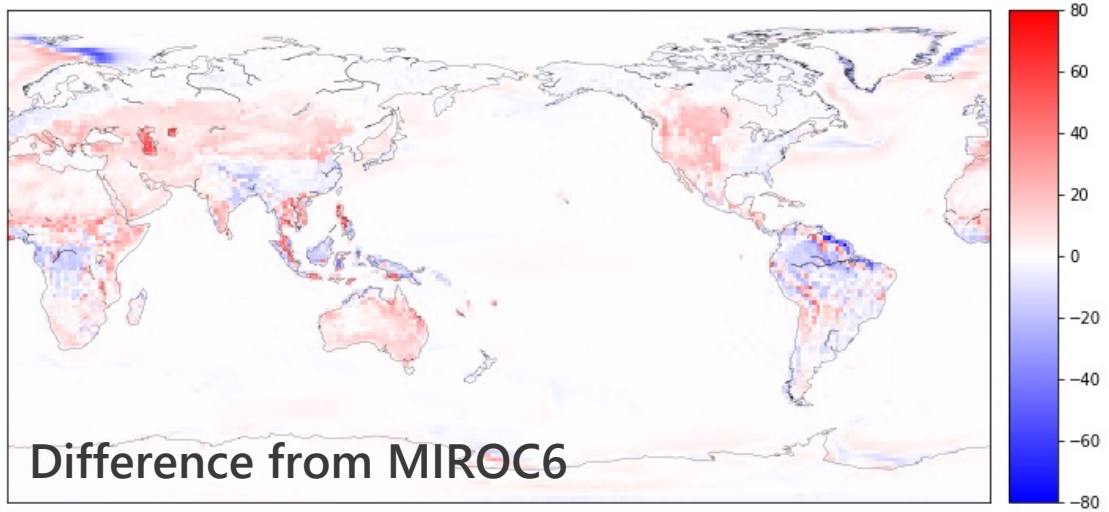


Impacts on simulated latent and sensible heat fluxes



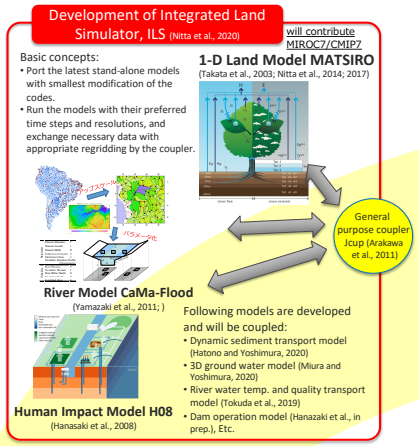


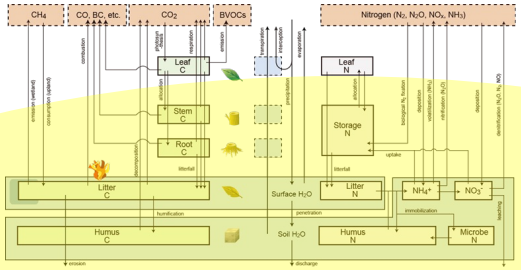




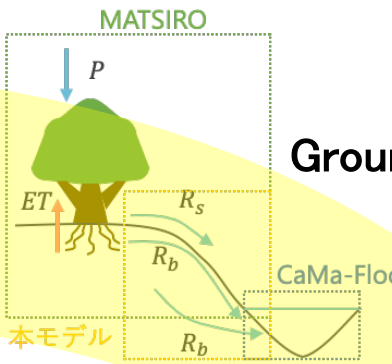
06 Future directions

Community effort of land model development



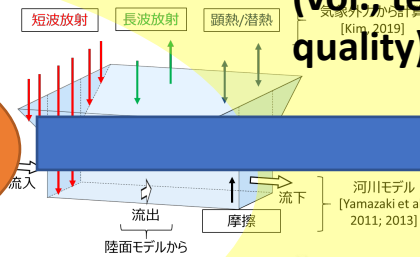


Ecological C/P/N cycle



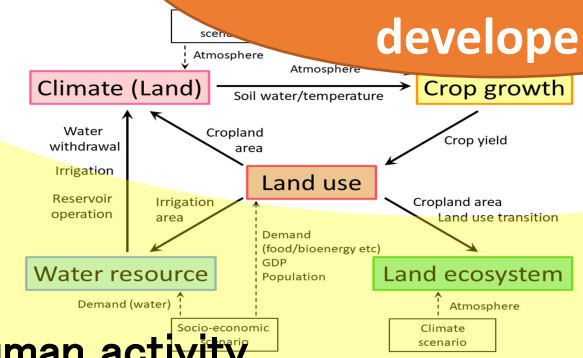
Groundwater

River / lake (vol., temp., & quality)

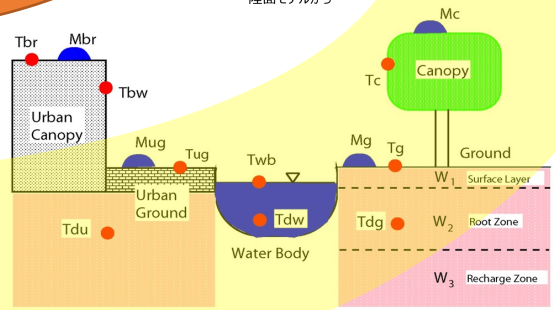


Strengthen collaboration among individual model developers

Sediment

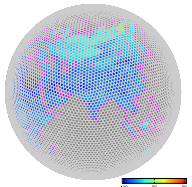


Human activity, land use change, crop yield



Inundation (incl. paddy field), urban canopy

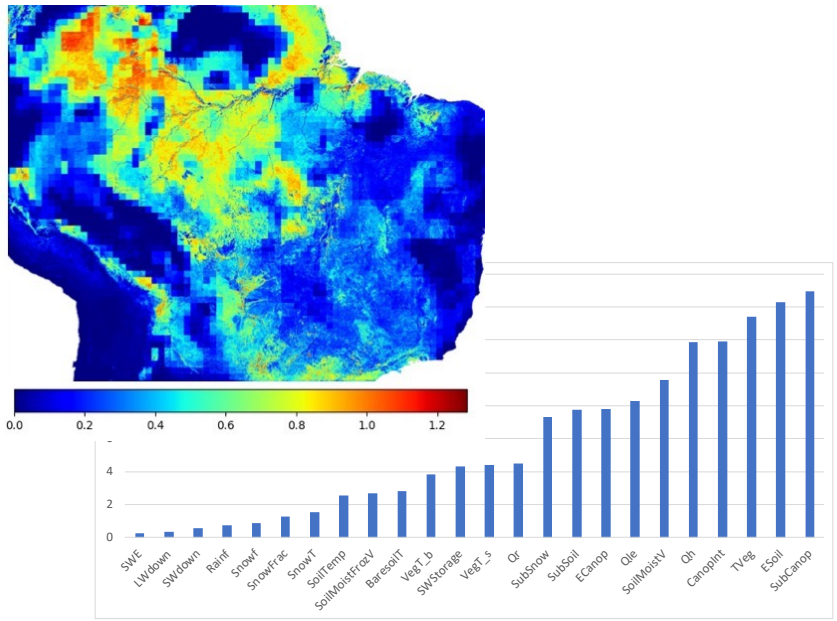
Construction of a platform model consisting of a group of stand-alone models and maintenance of various peripheral softwares incl. regridding and coupling.



Coupling to Weather, Climate, and Earth System Models

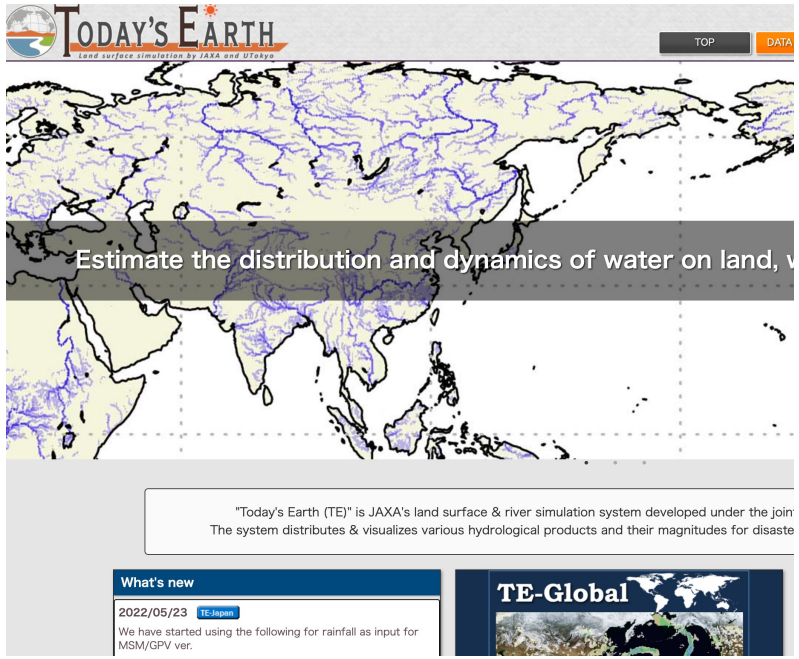
Application to other purposes

- Hyper-resolution land simulations using super computers (e.g., Fugaku)



Global 1-km land simulation

- Floood forecast



https://www.eorc.jaxa.jp/water/

Thank you!