Coupled Simulation Technology for Visualizing Environmental and Economic Social Cycles

Masahiro Maruyoshi, Yuichi Muto, and Daisuke Tokunaga

Abstract

Maintaining sustainability of human society in harmony with the environment into the future is regarded as the most-important issue on Earth. Accordingly, the NTT Digital Twin Computing Research Center is taking up the grand challenge of inducing inclusive equilibrium solutions for the Earth and its social and economic systems by making the interrelationships between them as computable as possible. Our efforts to meet this challenge are described in this article.

Keywords: climate and economic society, coupled simulation, circulation system

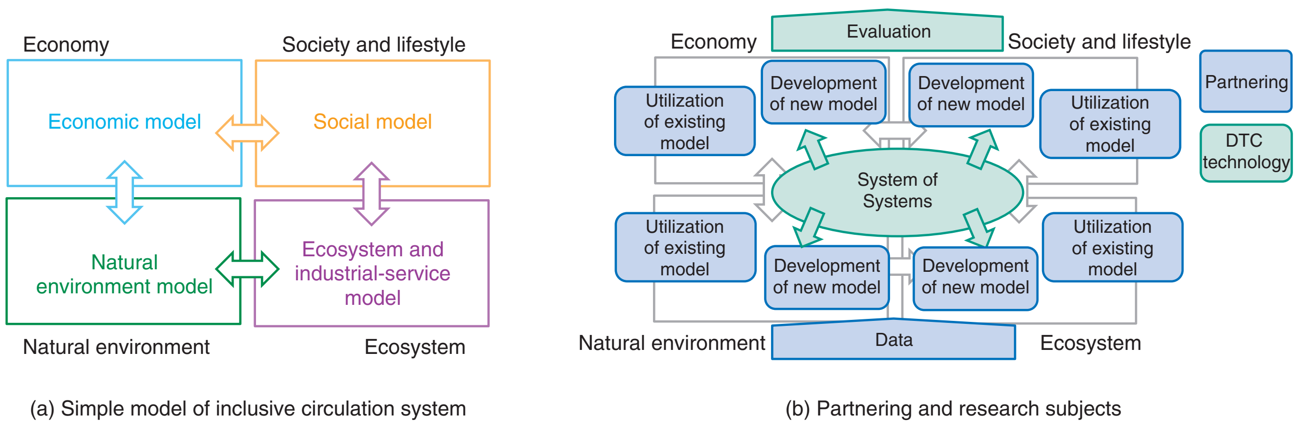
1. Inclusive sustainability of the environment and socioeconomics

Against the background of the social impact of recent global climatic and environmental changes (such as the increase in global heat waves, sudden torrential rain, droughts and wildfires, and changes in ecosystems symbolized by increases in numbers of endangered species and changes in crop production), discussions on the reconstruction of social systems to maintain the Earth's environment have begun.*1 The Earth's environment has its own autonomy. Problematic environmental changes are a result of the influence of human economic and social activities on this autonomy. This complex chain reaction can be viewed as an inclusive *circulation system* that includes the environment, economy, and society on a global scale.

Discussions on impact assessment of climate change*2 and reconstruction of social systems are supported by science and technology, which experts in various fields have been improving over the years. Scientific approaches in various fields have made it possible to analyze in detail phenomena that are highly uncertain and difficult to observe. Integrated assessment modeling (IAM) provides direct impact assessments spanning various fields (such as the environment and economy) by using macroscopic and statistical indicators. It is necessary to take an inclusive view of the Earth as a circulation system rather than considering each problem individually to solve various problems related to the environment and people's lives on a global scale toward the future. We believe that the development of computational technologies that enable the construction of models with high-accuracy and cross-field collaboration will accelerate. At the NTT Digital Twin Computing Research Center, we set the goal of contributing to achieving inclusive sustainability of the environment

*1 Example discussion on reconstruction of social systems: The World Economic Forum called for a "Great Reset" as its theme for 2021. Although this theme was set forth in the wake of the COVID-19 pandemic, discussions have started with an awareness of environmental and ecological issues such as global climate change.

*2 Example assessment of impact of climate change: The Intergovernmental Panel on Climate Change (IPCC) released the Working Group I (WGI) report of the Sixth Assessment Report stating that "There is no doubt about the impact of human activities on climate change." WGII and WGIII are scheduled to report on impact assessment and adaptation measures.



DTC: Digital Twin Computing

Fig. 1. Partnering strategies for realizing the grand challenge.

and socioeconomics by promoting the development of computational technologies and making it possible to model an inclusive global circulation system.

Our strategy for achieving this goal is conceptualized in **Fig. 1**. It is assumed that the inclusive circulation system is that shown in Fig. 1(a). Economic impact on the environment affects industry and ecosystem services (e.g., food production and resource circulation), and changes in those conditions affect social aspects (e.g., health, inequality, and well-being). These changes in social aspects create the power to accelerate and decelerate the economy and change the state of the economy, and that economic change further propagates the impact on the environment. These changes can be viewed as a system that circulates inclusively in this manner. As mentioned above, experts in each field comprising the system have spent many years developing models and simulators that analyze and predict phenomenon using a scientific approach. We aim to construct a circulation system by connecting these models and simulators, which are becoming ever more accurate. Therefore, we believe that computational technologies that can determine the causality of these models, adjust the scale differences, and evaluate the stability of the circulation system are important (Fig. 1(b)). In this article, the challenges related to the system of systems (SoS), which is an important computational technology, and the status of developing a proof of concept (PoC), which is our initial effort to evaluate the circulation system, are discussed.

2. Heterogeneous-simulator coupling technology for reproducing the chain between the environment and society

The environment and socioeconomic activities have each been modeled on the basis of past-to-present data obtained from many years of observations, and those models have evolved as simulation technologies for predicting the future from the present. However, precisely predicting the relationship between the actual global environment and people's economic activities is difficult by only simulating a single domain because various domains are intricately connected.

A similar problem exists in the field of industrial production, and is in the process of being solved with an SoS by combining several single-domain simulation techniques. For example, coupled simulation technology has been applied to the design of automobiles and space satellites, which consist of multiple systems (such as engines and transmissions) supplied by different vendors. An *emergent property* is a property that an entity gains when it becomes part of an SoS. Such properties are also true for visualizing environmental and economic social cycles to discover emergent properties through simulations as an SoS. However, it has not yet been put to practical use because of the huge amount of computation and problems related to the coupling between simulators when the global environment and people's economic activities are involved.

3. Three challenges concerning coupling of heterogeneous simulators and NTT's efforts

To develop a heterogeneous simulator that can reproduce the chain linking the environment and society, we are researching and developing ways to address the following three major challenges.

3.1 Challenge 1: Coupling of heterogeneous simulators

As technologies for coupling multiple types of simulators, under the guidance of the US Department of Defense, High-Level Architecture (HLA) was standardized by the Institute of Electrical and Electronics Engineers (IEEE) as IEEE1516 [1] and Functional Mock-up Interface (FMI) [2] was standardized by Daimler AG. HLA is often used to simulate discrete events such as traffic congestion, evacuation guidance, and development of space satellites, while FMI is often used to simulate continuous events such as coupled control of various devices in a running car. To reproduce the chain linking the environment and society, it is necessary to (i) incorporate discrete events into continuous events and (ii) develop execution-control technology to couple both events. Moreover, as the number of simulators to be coupled increases, it becomes more difficult to analyze problems related to processing speed and simulation accuracy. In addition, HLA and FMI do not have functions for executing analysis, so users need to monitor and analyze performance information themselves.

3.2 Challenge 2: Resolving differences in resolution of processing data between different simulators

When simulating phenomena occurring on the Earth's surface, for ease of computation, it is common to process them on a unit-area and unit-time basis. To do this processing, we build a mathematical model that can be solved with the data obtained in the past. However, the spatial resolution (unit area), temporal resolution (unit time), and time period to be covered will vary in accordance with the data to be handled. It is therefore necessary to unify the differences in the spatial and temporal resolutions of the simulators when they are coupled. To unify these differences, it is easy to convert the fine-resolution data into coarse-resolution data by averaging, etc. However, simulation results with the desired resolution cannot be obtained with the coarse data. When only single-domain results are available from simulations based on coarse data, it is necessary to downscale to finer resolution on the basis of physical (mechanical) laws or statistical and empirical relationships.

3.3 Challenge 3: Reducing the overall computational complexity of the simulation

Simply coupling simulations in areas such as the atmosphere, climate, and oceans, for which highly accurate predictions are becoming possible, would result in an explosion of computational complexity that cannot be handled in a practical amount of time. To solve this problem, it is necessary to develop a technology for model transformation involving (i) creating a surrogate model by applying machine learning, deep learning, etc. using observation data and prediction data obtained from the original simulation as learning data and (ii) reducing the amount of calculation when executing a simulation.

4. Developing a PoC as an initial approach to evaluating circulation systems

Using the above-mentioned technologies, we are also developing a PoC for simulation of environmental and socioeconomic linkages. Through these efforts, we will communicate our values, i.e., achieving inclusive sustainability of the environment and socioeconomics, while exploring new research topics by implementing and evaluating our technologies.

A large number of models are involved in reproducing global-scale chains. To start formulating the PoC, we first focused on the water cycle, which is closely related to both the natural environment and social economy. The water cycle is a phenomenon, the value of which remains the same regardless of scale and appears on a wide range of scales, from cycles limited to countries and basins to global cycles such as the entire globe.

We implemented a circulation simulation of a water cycle and water use by implementing a prototype execution control of the following three simulators using the coupled technology of heterogeneous simulators described in Challenge 1 (**Fig. 2**).

- Meteorological simulator (simulating simulator output using rainfall data in AMeDAS*3)
- River simulator (MIKE)
- Economic-water-use simulator (simple uniquely implemented model)

By coupling meteorological and river simulations,

*3 AMeDAS: Automatic Meteorological Data Acquisition System. A weather observation system developed by the Japan Meteorological Agency.

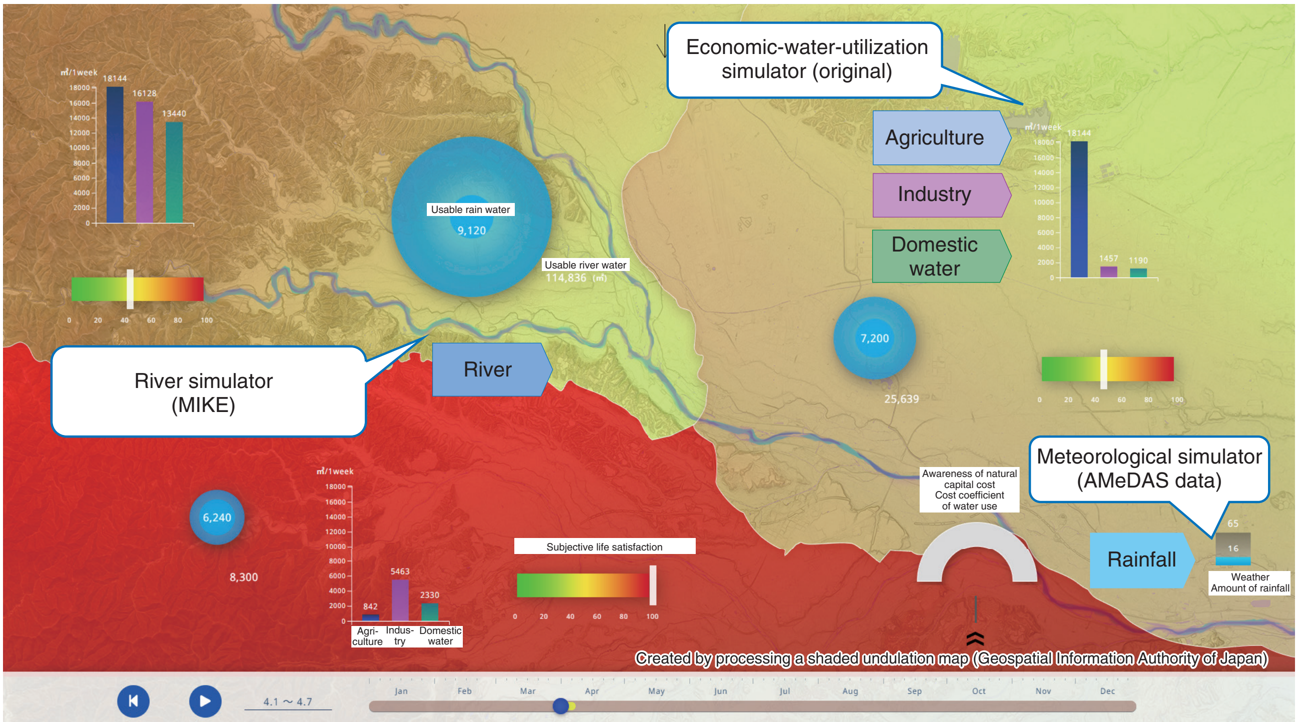


Fig. 2. Example circulation simulation of water cycle and water use.

we can reproduce the amount of river water on the basis of the amount of rainfall that flows into the river. By coupling economic water-utilization simulations, we were able to reproduce a water cycle that takes into account water taken from rivers for economic activities (agriculture, industry, and domestic water), consumed, and returned as reusable water to the rivers.

To reproduce rainfall, change in the volume of river water, water consumed by humans, and temporal water environmental load, it is necessary to resolve the difference in resolution of the data handled by each simulator. With this PoC, the spatial and temporal differences described in Challenge 2 appear as differences in the scales and unit time of water-volume data for water cycle and water use. We handled such differences by implementing the conversion process and optimizing the simulation settings.

For example, rainfall data output by meteorological simulations are given in units of amount of water per mesh, while river inflow data required for input to river simulations is given in units of amount of water inflow per watershed area. Although both units represent water volume, they have different spatial resolutions. For our PoC, we are trying to convert rainfall data into inflow-water volume on the basis of the watershed area and inflow efficiency of the region.

In terms of temporal resolution, it is also necessary to match the temporal units of water volume exchanged by rainfall, rivers, and water use. For this PoC, we designed and coupled all the simulations to operate at the temporal resolution of water volume per hour. We are planning to design downscaling technology that will make it possible to handle such differences in resolution.

There is currently no limit placed on the consumption of water in our daily activities, and that unlimited use puts a burden on the water cycle. We developed a model that assumes a society that adopts the concept of *natural capital cost*, which considers the consumption of natural resources such as water as a reasonable cost in the resource cycle. With this model, we confirmed that it is possible to simulate the effects of changes in water use and the load on the water cycle by changing the intensity of awareness of natural capital costs.

The PoC we are currently developing has implemented a specific basin-type water-cycle model. It focuses on water resources as a natural environmental system and water use as a socioeconomic activity. To reproduce the global cycle, it is necessary to incorporate and integrate various models of the natural environment and socio-economy. Accordingly, we will continue our research and development by forming partnerships with various experts and external organizations.

References

[1] IEEE 1516-2010: IEEE Standard for Modeling and Simulation (M&S) High Level Architecture (HLA)-- Framework and Rules.

[2] FMI, https://fmi-standard.org/

Masahiro Maruyoshi

Senior Research Engineer, Supervisor, NTT Digital Twin Computing Research Center.

He received a B.E. and M.S. in information engineering from Nagoya University, Aichi, in 2000 and 2002. He joined NTT in 2002 and was engaged in research and development of software-defined network technologies. Since 2020, he has been in charge of research for Digital Twin Computing at NTT Digital Twin Computing Research Center.

Daisuke Tokunaga

Senior Research Engineer, NTT Digital Twin Computing Research Center.

He received an M.S. in information science from Kyushu Institute of Technology, Fukuoka, in 1999 and joined NTT the same year. His research interests include large-scale application system technologies. Since 2020, he has been in charge of research on Digital Twin Computing at NTT Digital Twin Computing Research Center.

Yuichi Muto

Senior Research Engineer, NTT Digital Twin Computing Research Center.

He received a B.E. and M.S. in information science from Tohoku University, Miyagi, in 1998 and 2000. He joined NTT in 2000 and was engaged in research and development concerning the Communication Traffic & Service Quality Project at Service Integration Laboratories. Since 2021, he has been in charge of research for Digital Twin Computing at NTT Digital Twin Computing Research Center.