Principles for modeling Earth's surface systems and their eco-environmental components

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A raster expression of a region or one of its eco-environmental properties can be abstracted to a mathematical surface. The mathematical surface is uniquely defined by the intrinsic and extrinsic properties in terms of the fundamental theorem of surfaces. The intrinsic properties can be gathered from local information, which might come from detailed ground observations and spatial sampling. The extrinsic properties can be gathered from satellite observations and the simulation results of spatial models on large scales. The urgency and necessity of integrating the extrinsic and intrinsic properties have been discussed at various scales

Surface modeling is a process of constructing a surface model for dynamically describing an Earth's surface system or a specific component of the Earth's surface environment. Various methods have been developed for surface modeling since the 1950s. They include the Kriging suite of geostatistical methods, spline function, irregular triangular network and inverse distance weighting, for which error and scale issues are long-term challenges.

To find solutions for the error and multi-scale problems, a method for high accuracy surface modeling (HASM) has been developed since 1986, which integrates the extrinsic and intrinsic properties. The need to combine extrinsic information with intrinsic information is a frequently discussed topic in eco-environmental surface modeling. For instance, ground observation can obtain high accuracy data at observation points, but the observations at fixed positions are confined within some limited dispersal points. Satellite remote sensing can frequently supply surface information of eco-environmental processes, but remote sensing description is not able to directly obtain process parameters. Satellite and ground observations provide two different types of information about the Earth's surface. Global models and ground observations provide abundant information, but neither provides the complete picture. A global model, to be as accurate as possible, must supplement information from the currently available ground observations.

Although HASM solved the error and multi-scale problems, it could only be used with small areas because it must use the master equation set for simulating each lattice of a surface, which incurs a huge computation cost. To speed up the computation of HASM, the authors developed a multi-grid method of HASM (HASM-MG), an adaptive method of HASM (HASM-AM), an adjustment computation of HASM (HASM-AC), and a preconditioned conjugate gradient algorithm of HASM (HASM-PCG). These algorithms solved the low computational speed and large memory requirement problems.

HASM was successfully applied for constructing digital elevation models, filling voids in the Shuttle Radar Topography Mission (SRTM) dataset, simulating climate change, estimating carbon stocks, fusing satellite observations and the Total Carbon Column Observing Network (TCCON) measurements of the column-averaged dry air mole fraction of CO_2 ($XCO_{2)}$, filling voids on remotely sensed XCO2 surfaces, modeling surface soil properties and soil pollution, and analyzing ecosystem responses to climatic change. In all of these applications, HASM produced more accurate results than the classical methods.

The fundamental theorem for earth surface system modeling (FTESM) was proposed on the basis of developing the HASM methods and their successful applications. FTESM is based on a combination of surface theory, system theory, and optimal control theory. The FTESM corollaries of spatial interpolation and data fusion were used in the Methodological Assessment Report on Scenarios and Models of Biodiversity and Ecosystem Services (IPBES, 2016). The role of this methodological assessment is defined by the Plenary of Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) as "guiding the use of scenario analysis and modeling in all work under IPBES to ensure the policy relevance of its deliverables". The FTESM was, in turn, referenced by The Global Assessment Report on Biodiversity and Ecosystem Services (IPBES, 2019).

However, the terminology used by the FTESM does not match the conceptual system of IPBES. Thus, a fundamental theorem for eco-environmental surface modeling (FTEEM) has been developed for eco-environmental surface modeling, from which several corollaries have been deduced, corresponding to spatial interpolation, spatial upscaling, spatial downscaling, data fusion and model-data assimilation, respectively. The eco-environmental surfaces include surfaces of nature, surfaces of nature's contributions to people, and surfaces of the driving forces of natural changes. Nature includes biodiversity and ecosystems as well as earth system. Nature's contribution to people consists of ecosystem services and nature's gifts. Driving forces of nature change was classified into direct driving forces and indirect driving forces. The FTEEM and FTESM have the same meaning with respect to the underlying theory but the terms mean this can be easily understood by different research fields.

Former president of The International Society for Ecological Modeling (ISEM), Perof. Sven Erik Jörgensen, stated: "Error problems and slow-computational-speed problems are the two critical challenges currently faced by Geographical Information Systems (GIS) and Computer-Aided Design Systems (CADS). High-accuracy and high-speed methods for surface modeling (HASM) provide solutions to these problems that have long troubled GIS and CADS." (Jörgensen, 2011)

Former President of the International Association of Ecology, Prof. Wolfgang Haber, pointed out that "All of the findings above described the essential significance of both extrinsic and intrinsic information, but the challenge is how to combine these two kinds of information. FTESM and FTEEM provide a solution to this challenge. FTEEM and FTESM as well as their corollaries for interpolation, upscaling, downscaling, data fusion and model-data assimilation together form the theoretical basis of eco-environmental informatics. I am convinced that the publication of "a fundamental theorem for eco-environmental surface modeling and its applications" (Yue et al., 2020) will serve as a landmark paper in the development of the theoretical underpinnings for a science of eco-environmental informatics moving forward." (Haber, 2020)

"To the best of our knowledge," wrote the 39 researchers, "this work first represents the fundamental theorem for eco-environmental surface modeling, which is serving as a landmark paper in the development of the theoretical underpinnings for a science of eco-environmental informatics moving forward. "

More information: Tianxiang Yue et al, A fundamental theorem for eco-environmental surface modelling and its applications, *Science China Earth Sciences* (2020). DOI: 10.1007/s11430-019-9594-3

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