Progress in earth surface modeling

YUE Tianxiang

State Key Laboratory of Resources and Environment Information System, Institute of Geographical Sciences and Natural Resources Research, 100101 *Beijing, China*

Abstract: A definition of earth surface modeling is proposed on the basis of discussing the concept of earth surface. Studies on earth's surface topography modeling and climate system modeling are reviewed, which indicates that it is eagerly necessary to develop simulation methods with high speed, high accuracy and low memory requirement. Introduction of methods for high accuracy and high speed surface modeling (HASM), developed by means of the fundamental theorem of surfaces, might be an efficient way to characterize the states of earth-surface and changes in those states.

Key words: earth surface modeling, high accuracy, high speed, low memory requirement

CLC number: P91 **Document code:** A

Citation format: Yue T X. 2011. Progress in earth surface modeling. *Journal of Remote Sensing*, **15**(6): 1105–1124

1 INTRODUCTION

Earth's surface environment is an active and complex place, at the interface of the lithosphere, the hydrosphere, the atmosphere and the biosphere (Phillips, 1999). The lithosphere is the solid and inorganic material of the earth such as rock, soil and sediment. The hydrosphere encompasses water in all its forms. The atmosphere comprises the envelope of gases that surrounds the planet, mixes with elements of the other planetary spheres, and occupies the spaces or voids in soils, sediments and rocks. The biosphere consists of earth's living things and organic matter. None of these spheres occurs in isolation, but they interacts each other to produce the earth's dynamic systems (Bockheim & Gennadiyev, 2010). In the field of earth surface processes, Earth's surface is defined as a dynamic interface across which the atmosphere, water, biota, and tectonics interact to transform rock into landscapes with distinctive features crucial to the function and existence of water resources, natural hazards, climate, biogeochemical cycles, and life (Committee on challenges and opportunities in earth surface processes, 2010). An earth surface system is a set of interconnected components of the earth surface environment that function together as a complex whole. Earth Surface modelling is generally defined as a spatially explicitly digital description of a component of the earth surface environment or an earth surface system (Yue, 2011).

It should be noted that this paper only reviews studies on earth's surface topography modeling, climate system modeling and simulation systems. Others such as surface modeling in biosphere can be found in a published paper, progress in global ecological modeling (Yue, *et al*., 2011).

2 EARTH SURFACE MODELLING

2.1 Earth's surface topography modeling

Geomorphology stands in the center of the earth's surface science, where strong couplings link human dynamics, biology, biochemistry, geochemistry, geology, hydrology, geomorphology, and atmospheric dynamics (Murray, *et al*., 2009). Information on the earth's relief is a key parameter for almost any geoscientific analysis and for all precise land-oriented applications and planning purposes (Dech, 2005). Understanding earth surface processes relies on modern digital terrain representations and depends strongly on the quality of the topographic data (Tarolli, *et al*., 2009). Terrestrial Laser Scanner (TLS) and Airborne Laser Swath Mapping technology (ALSM) are able to produce sub-meter resolution Digital Terrain Models and high-quality land cover information over large areas. The Shuttle Radar Topographic Mission (SRTM) and the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) have allowed detailed analyses in large regions.

Earth's surface obeys the conditions of uniqueness, continuity, smoothness, and finiteness because the earth's surface height, as a vertical coordinate, is restricted in space by the value of gravity and cannot be infinitely large or infinitely small. Attributes of the earth surface could be specially considered during the process of surface modeling include lines of relief discontinuity, steep and overhanging scarps, acute peaks, niches, caves, karst pits and sinkholes, as well as other elements violating the condition of smoothness. The shape of the earth's surface was first expressed in terms of gravity at ground level (de Gbaaff-Hunter, 1937). The shape of the topographical earth surface was calculated by means of gravity meas-

Received: 2011-05-06; **Accepted**: 2011-06-22

Foundation: The National Science Fund for Distinguished Young Scholars of China(No.40825003); The National Basic Research Program (973 Program) (No.2010CB950904); The State Key Program of National Natural Science of China (No.41023010)

First author biography: YUE Tianxiang (1963—), male, Ph.D., professor. His research interest is earth surface modelling. E-mail: yue@lreis.ac.cn

urements on that surface by solving two integral equations (Bragard, 1965). The possibility of constructing potential expansions, which would converge on the earth's surface, was explored by generalizing the external expansion of the earth's potential in spherical harmonics to the earth's surface (Petrovskaya, 1977).

A completely new method for earth surface modeling has been explored since 1986, by which a mathematical model for cirque morphology was constructed by means of the theorem of curves (Yue & Ai, 1990). The mathematical model for cirque morphology was then developed into the approach to environmental change detection (Yue, *et al*., 2002). A nonlinear descending principle (NDP) was developed to calculate the altitude's limit on the earth's surface (Niu, 1993). An F-approximation method and an S-approximation method were developed to simulate earth's surface topography. The F-approximation of earth surface topography was based on Strakhov method of linear integral representations and represented by means of Fourier integral (Strakhov, *et al*., 1999). The S-approximation was based on the fundamental formula of the theory of harmonic functions and specified by means of the Poisson integral (Stepanova, 2007). The harmonic functions were employed to simulate the earth surface where displacements take place and can be picked up by global positioning system (GPS) (Ionescu & Volkov, 2008).

The equation of earth's surface can be formulated as (Kerimov, 2009), $z=f(x, y)$ where z is an attribute value of the earth's surface at location (x, y). It was found that the initial topography is created due to the addition of the material onto the surface of the layer and after the buildup of the convective motion the topography of the surface of the layer is determined only by the displacements of the material particles lying at this surface (Birger, 2010). This result suggests that the small-scale convection in the mantle is excited by the significant topographic disturbances caused by thrusts occurring at the boundaries of the lithospheric plates in the course of the large-scale convection in the mantle.

2.2 The climate system modeling

Even though the basic components of weather and climate system are the same, the processes are separated by both spatial and time scales, climate occurring on the large scales. Weather is the state of the atmosphere-ocean-land-ice system at any instant of time, while climate is the aggregation of weather or a statistical generalization of weather (Budyko & Izrael, 1991). The climate system of earth is represented by environmental components of earth surface. Causes of global climate change include the solar constant gradually increasing over the life of the earth, tectonic plate movements, orography, ocean circulation, sea level change, greenhouse gas emission, earth surface reflectivity known as albedo, orbital parameter changes, random occurrence such as volcano eruptions, and natural variability.

In 1904, Bjerknes first described the necessary and sufficient conditions for the rational solution of forecasting problems, *i.e*. a sufficiently accurate knowledge of the state of the atmosphere at the initial time and a sufficiently accurate knowledge of the laws according to which one state of the atmosphere develops from another. In 1905, Ekman recognized the impact of the wind on ice and water velocities. In 1922, Richardson presented his predictive method for one small area in Europe by using available observational data, but its forecast of the surface pressure at two points over Europe failed. In 1925, Walker discussed Southern Oscillation and found an alternating pressure pattern involving the normal southeast Pacific high pressure and the low pressure region near the Indian Ocean and western Pacific regions. In 1929, Alt investigated heat balance of earth's surface. In 1939, Rossby and Collaborators recognized the relevance of absolute vorticity advection to large-scale wave motions. In the late 1940s, major developments included the theories of baroclinic and barotropic instability (Charney, 1947), and the concept of equivalent- barotropy (Charney & Eliassen, 1949).

Charney, *et al*. (1950) successfully predicted 24-hr weather by using a barotropic equation. In 1953, an adiabatic three-level quasi-geotrophic model was successfully used to predict the rapid development of a storm observed over the United States in November 1950 (Charney & Phillips, 1953). Black (1956) simulated distribution of solar radiation over earth's surface. Philips (1956) used a set of quasi-geostrophic equations for the first climate general circulation experiment with a two-level baroclinic system in Cartesian coordinates, which included the effects of heating and cooling along with a simple treatment of frictional dissipation circulation experiment recognized the close relationship between the dynamics of cyclones and that of general circulation. Ye, *et al*. (1956) analyzed precipitation distribution of Yellow River Basin in China. Burdecki (1957) analyzed the incoming radiation at the Earth surface and the atmospheric heat field. Mintz (1958) described the primary idea of Mintz-Arakawa model. This model included seasonal changes of solar radiation and long-wave cooling for each layer given as a function of the temperature at the lower level. Ye and Zhu (1958) discussed the major results of atmospheric circulation and proposed an idea on numerical simulation of atmospheric circulation. Phillips (1959) demonstrated that nonlinear computational instability may occur in solutions of the non-divergent barotropic vorticity equation, which was the simplest nonlinear dynamical equation applicable to the real atmosphere.

In 1969, a model with the same two-level vertical structure as that of the Mintz-Arakawa model was developed and its horizontal domain covered the entire globe with uniform grid intervals in both longitude and latitude (Arakawa, 1969). Zeng (1974) proposed a concept of the best information layer for meteorological satellite remote sensing in order to find a general method for selecting a water vapor channel of remote sensing. The first multilevel model included a change of horizontal grid structure, the implementation of a bulk model for the planetary boundary layer (PBL), the inclusion of the Arakawa-Schubert cumulus parameterization, and the prediction of ozone mixing ratio with interactive photochemistry (Schlesinger & Mintz, 1979). In 1981, the horizontal differencing of the momentum equation was based on the energy and potential enstrophy conserving scheme for the shallow water equations (Arakawa & Lamb, 1981). During the period from the late 1980s to the late 1990s, climate models were characterized by a change in the radiation scheme (Harshvardan, *et al*., 1987), inclusion of an orographic gravity wave drag parameterization (Kim & Arakawa, 1995), inclusion of convective downdraft effects in the cumulus parameterization (Cheng & Arakawa, 1997), revision of PBL moist processes (Li, *et al*., 1999), and inclusion of explicit predictions on ice and liquid clouds (Koehler, *et al*., 1997).

Global climate is a result of the complex interactions between the atmosphere, cryosphere, hydrosphere, lithosphere, and biosphere, fueled by the nonuniform spatial distribution of incoming solar radiation (Stute, *et al*., 2001). Global climate models should focus on interactions among atmosphere, ocean, land processes, and sea ice. The theoretical description remains unresolved for global climate models (Washington & Parkinson, 2005). For instances, scientists still do not know how aerosols alter climate processes despite decades of intense research because relatively little is known about the global aerosol size distribution and composition. Other unknowns include the full climatic impacts of ocean temperature anomalies occurring during El Nino and La Nina episodes as well as the full impacts of volcanic eruptions on ozone amounts in the stratosphere and on atmospheric cooling. The precipitation-cloud physics, specifically how condensation, sublimation and freezing of water drops and ice particles occur, is not fully understood. Although clouds play a critical role in the radiation characteristics, their radiative properties are not fully understood. A main weakness of current models is their limited ability to simulate vertical air movement, such as convection in the tropics that lifts humid air into the atmosphere. Schiermeier (2010) pointed out that the simulations of Intergovernmental Panel on Climate Change (IPCC) failed to provide any robust projection of how winter precipitation would change at the end of the current century for large parts of all continents. Even worse, climate models seemingly underestimate how much precipitation has changed already, which further reduces confidence in their ability to project future changes. Phase transitions of water are among the major physical processes that shape the earth's climate, but such processes have not been well characterized in current global climate models. Makarieva, *et al*. (2010) estimated that the global mean power at which this potential energy is released by condensation is around one per cent of the global solar power, similar to the known stationary dissipative power of general atmospheric circulation. They strongly suggested that the phase transitions of water vapor play a far greater role in driving atmospheric dynamics than is currently recognized. They found that previous investigations focused on temporal pressure changes instead of spatial gradients.

In addition, it is eagerly necessary to develop simulation methods with high speed, high accuracy and low memory requirement. Current climate models are operated on very coarse spatial resolution because of their oppressively slow computational speed and huge memory requirement for their used computers. Local topographical gradients of the current climate models are often error due to the coarseness of their spatial resolutions (Washington & Parkinson, 2005). The simulation results of current climate models are questionable on a regional level and are difficult to be applied to assessing climate change impacts on various ecosystems on regional and local levels (Raisanen, 2007).

3 SIMULATION SYSTEMS

3.1 The earth simulator

In 1997, an Earth Simulator was developed to simulate global warming. The primary function was to create a huge-scale supercomputer, which would achieve at least 5teraflop/s for an atmospheric general circulation model. It first conducted simulations of global atmospheric circulation and oceanic circulation on a horizontal resolution of 10 km. According to Descartes' paradigm, nature loves equilibrium and stability; natural system conditions seldom move away from the equilibrium point or the point of stability. However, since nature is an open system through which information, energy, material and flow are always passing in and out, it would appear that nature actually loves non-equilibrium, instability and therefore, nonlinearity. The Earth Simulator provides an important tool necessary for creating a new paradigm of non-equilibrium/nonlinearity/openness (Sato, 2004).

3.2 The digital earth system

Digital Earth was defined as a system providing access to what is known about the planet and its inhabitants' activitiescurrently and for any period in historyvia responses to queries and exploratory tools. During the period from 1998 to 2001, the Digital Earth Initiative, coordinated by the NASAled Interagency Digital Earth Working Group (IDEW), tried to realize the integration of existing data from multiple sources in order to improve the application of geospatial data for visualization, decision support, and analysis. During this period, results of the three-year IDEW effort included the Web Mapping Service (WMS) standard, a Digital Earth Alpha Version prototype, and a Digital Earth Reference Model (DERM). The Geospatial Interoperability Reference Model was produced as an extension of the Digital Earth Initiative. Since 1998, many advances have been made. For instance, Earthviewer and GeoPlayer appeared in 2001, while World Wind and Google Earth were released in 2003 and 2005, respectively.

Grossner, *et al*. (2008) proposed the concept of a digital earth system and defined it as a comprehensive, mass distributed geographic information and knowledge organization system. The digital earth system was distributed because: (1) there were necessarily multiple, geographically dispersed data stores providing content; and (2) the processing load of serverbased query and analytical processes needed to be shared for performance reasons. Geographic information refers to very broad information about well-defined locations on the earth's surface.

3.3 European network for earth system modelling

In December 2001, European Union funded a project of Program for Integrated Earth System Modeling (PRISM) to undertake a pilot infrastructure towards the establishment of a distributed European network for Earth System Modeling (ENES). PRISM presently includes atmospheric general circulation models (AGCMs), atmospheric chemistry models (AC), ocean general circulation models (OGCMs), ocean biogeochemistry models (OC), land-surface (LS) and sea-ice (SI) models. All of these components can be either global or regional models.

ENES aims at developing the PRISM infrastructure as a European system of portable, efficient and user-friendly earth system models and associated diagnostic software under standardized conventions that can be accessed by all European scientists. ENES comprise all major climate modeling groups and climate computer centers in Europe as well as many industrial partners. To ensure that all researchers have equal access to such facilities across Europe, ENES has proposed a three-step approach: (1) organize a collective development of a shared software infrastructure and standard physical interfaces for the European climate scientific community; (2) provide an integrated European service to access and use this infrastructure for executing multi-institutional ESM simulations; and (3) provide and manage hyper computing access and resources for climate research at the European level by 2010 (Valcke, *et al*., 2006).

3.4 The planet simulator

The Planet Simulator was a Model of Intermediate Complexity (MIC) that could be used to run climate and paleo-climate simulations for time scales up to 10 thousand years or more in an acceptable real time (Fraedrich, *et al*., 2005a, b). The Planet Simulator was built to support numerical experiments for understanding the dynamics of the climate of the earth and earth-like planets.

The model was composed of a dynamical core, parameterizations and subsystems, and a graphical user interface. The dynamical core of the Planet Simulator was based on the moist primitive equations representing the conservation of momentum, mass and energy. The dimensionless set of equations consisted of the prognostic equations for the vertical component of vorticity and horizontal divergence, the first law of thermodynamics, the equation of state with hydrostatic approximation, the continuity equation and the prognostic equation for water vapor. The parameterizations and subsystems included boundary layers and diffusions, radiation, moist processes, clouds and dry convection, land surface and soil, and ocean and sea ice.

The Planet Simulator was configured and set up by the module graphical user interface, Model Starter. Model Starter was the fastest way to get the model running, allowing access to the most important parameters of the model preset to the most frequently used values. The graphical user interface for running the Planet Simulator had two main purposes. The first was to display model arrays in suitable representations; the second was to facilitate the interaction part of the graphical user interface, allowing the user to change selected model variables during the model run.

3.5 Australian community climate and earthsystem simulator

In 2005, Australia lunched the Australian Community Climate and Earth-System Simulator (ACCESS). ACCESS is a coupled climate and earth system simulator to be developed as a joint initiative of the Bureau of Meteorology and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in cooperation with the university community in Australia. ACCESS consists of an atmospheric model, carbon cycle models, an ocean and sea-ice model, developed by 7 research teams of atmospheric modelling, ocean modelling, landsurface modelling, coupled modelling, data assimilation, model evaluation and modelling system.

A 22-yr simulation from 1979 to 2000 was carried out with the atmospheric component of the ACCESS climate model (Brown, *et al*., 2010). The first operational weather forecasts produced by ACCESS became available late in 2009. Already forecasts developed during the ACCESS research phase are proving superior to those produced by the current forecasting system. ACCESS will begin producing detailed climate projections for the globe and Australian region by 2011–2012. Australian scientists will use ACCESS to produce better climate projections with the intention of contributing to the next Assessment report for the Intergovernmental Panel on Climate Change in 2014 (Hirst, 2010).

4 DISCUSSION

The use of the earth's surface was discussed by many scientists because of the considerable impacts of human actions on the composition and physical conditions of the atmosphere, the hydrosphere and the lithosphere, on the rates of transfer of solid matter from one point of the crust to another, and on the loss of many plant and animal species (Cendrero, 1992).

Committee on Challenges and Opportunities in earth surface processes (2010) identified nine overarching scientific challenges: (1) what does our planet's past tell us about its future? (2) how do geopatterns on earth's surface arise and what do they tell us about processes? (3) how do landscapes influence and record climate and tectonics? (4) how does the biogeochemical reactor of the earth's surface respond to and shape landscapes from local to global scales? (5) what are the transport laws that govern the evolution of the earth's surface? (6) how do ecosystems and landscapes coevolve? (7) what controls landscape resilience to change? (8) how will earth's surface evolve in the "anthropocene"? (9) how can earth surface science contribute toward a sustainable earth surface?

To characterize the states of earth-surface and changes in those states and to meet the challenges, methods for high accuracy and high speed surface modeling (HASM) were developed by means of the fundamental theorem of surfaces (Yue, 2011; http://www.crcpress.com/product/isbn/9781439817582). The fundamental theorem of surfaces makes sure that a surface is uniquely defined by the first and second fundamental coefficients. The first fundamental coefficients of a surface yield information about some geometric proper ties of the earth surface, by which we can calculate lengths of curves, angles of tangent vectors, areas of regions and geodesics on the earth surface. The second fundamental coefficients reflect the local warping of the surface, which can be observed outside the earth by remote sensing.

Remote sensing is first of all a measuring technique for obtaining data about the earth's surface and the atmosphere without coming into physical contact with the objects to be measured. Data from earth observation instruments have been received for about 40 years. A large variety of sensors on board satellites launched by a growing number of countries feeds the receiving and archiving stations with an impressive quantity of data (Escadafal & Chehbouni, 2008). According to United States Geological Survey (USGS), their archive mainly dedicated to optical imagery was more than 3 million gigabytes in 2004. Earth observation from space allows spatially integrated and continuous recording of measurements covering large areas and at various scales ranging from the global views to the local perspectives. These data are converted into various geophysical or biophysical information layers with the help of physical-mathematical algorithms.

Remote sensing can frequently supply surface information, but the remotely sensed information is not continuous in terms of time. Remotely sensed data can serve as the driving fields of HASM for describing many earth processes. Data from ground-based observations and samples have higher temporal resolution, but they are not continuous spatially. The ground observed data can be used as optimum control constraints of HASM. In other words, HASM is an efficient method for assimilating multiscale data from various sources.

Earth-surface science will not move forward with maximum efficiency without data collection and model development (Murray, *et al*., 2009). However, most modeling and observation efforts have tended to focus on relatively small scales or very coarse resolutions until recently. A hierarchical suite of earth-surface models such as HASM is necessary to most effectively achieve explanatory and predictive power for earth-surface phenomena over the vast range of scales involved. Development of new analytical and computing tools has markedly increased our ability to examine earth's surface at high spatial and temporal resolution and to develop models that can help to understand the speed and magnitude over which surface processes interact and affect changes (Committee on challenges and opportunities in earth surface processes, 2010).

REFERENCES

Alt E. 1929. Der Stand des meteorologischen Strahlungsproblems. *Meteorologische Zeitschrift*, **46**(12): 50–54

Arakawa A. 1969. Parameterization of cumulus convection // Proceedings of the WMO/IUGG Symposium on Numerical Weather Prediction. Tokyo, 1968: IV–8–1–IV–8–6

Arakawa A and Lamb V R. 1981. A potential enstrophy and energy conserving scheme for the shallow water equations. *Monthly Weather Review*, **109**: 18–36 DOI: 10.1175/1520-0493(1981)109<0018:APEAEC>2.0.CO;2

Birger B I. 2010. Excitation of small-scale convection in the continental lithosphere by disturbances in the topography of the Earth's surface. *Izvestiya*, *Physics of the Solid Earth*, **46**(7): 627–635

Bjerknes V. 1904. Das Problem von der Wettervorhersage, betrachtet vom Standpunkt der Mechanik und der Physik. *Meteorologisch Zeitung*, **21**: 1–7

Black J N. 1956. The distribution of solar radiation over the Earth's surface. *Theoretical and Applied Climatology*, **7**(2): 165–189 DOI: 10.1007/BF02243320

Bockheim J G and Gennadiyev A N. 2010. Soil–factorial models and earth–system science: a review. *Geoderma*, **159**(3-4): 243–251 DOI: 10.1016/j.geoderma.2010.09.005

Bragard L. 1965. Method to determine the shape of the topographical earth surface by means of gravity measurements on that surface by solving two integral equations. *Studia Geophysica et Geodaetica*, **9**(2): 108–112 DOI: 10.1007/BF02607316

Brown J R, Jakob C and Haynes J M. 2010. An evaluation of rainfall frequency and intensity over the Australian region in a global climate model. *Journal of Climate*, **23**(24): 6504–6525 DOI: 10.1175/2010jcli3571.1

Budyko M I and Israel Y A. 1991. Anthropogenic Climate Change. Tucson: University of Arizona Press

Burdecki F. 1957. Remarks on the distribution of solar radiation over the surface of the Earth. *Theoretical and Applied Climatology*, **8**(3-4): 326–335 DOI: 10.1007/BF02243300

Cendrero A. 1992. Planning the use of the Earth's surface: an overview. *Lecture Notes in Earth Sciences*, **42**: 1–22 DOI: 10.1007/BFb0038629

Charney J G. 1947. The dynamics of long waves in a baroclinic westerly current. *Journal of Meteorology*, **4**(5): 135–162

Charney J G and Eliassen A. 1949. A numerical method for predicting the pertubations of the middle latitude westerlies. *Tellus*, **1**(2): 38–54 DOI: 10.1111/j.2153-3490.1949.tb01258.x

Charney J G, Fjörtoft R and von Neumann J. 1950. Numerical integration of the barotropic vorticity equation. *Tellus*, **2**(4): 237–254 DOI: 10.1111/j.2153-3490.1950.tb00336.x

Charney J G and Phillips N A. 1953. Numerical integration of the quasi–geostrophic equations for barotropic and simple baroclinic flows. *Journal of Meteorology*, **10**(2): 71–99 DOI: 10.1175/1520-0469(1953)010<0071:NIOTQG>2.0.CO;2

Cheng M D and Arakawa A. 1997. Inclusion of rainwater budget and convective downdrafts in the Arakawa–Schubert cumulus parameterization. *Journal of the Atmospheric Sciences*, **54**(10): 1359–1378 DOI: 10.1175/1520-0469(1997)054<1359:IORBAC>2.0.CO;2

Committee on Challenges and Opportunities in Earth Surface Processes. 2010. Landscapes on the Edge: New Horizons for Research on Earth's Surface. Washington DC: The National Academies Press

de Gbaaff-Hunter J. 1937. The shape of the Earth's surface expressed in terms of gravity at ground level. *Bulletin Géodésique*, **56**(1): 191–200 DOI: 10.1007/BF02526095

Dech S. 2005. The Earth surface // Feuerbacher B, Stoewer H, eds. Utilization of Space. Bonn: Springer: 53–90

Ekman V W. 1905. On the influence of the Earth's rotation on ocean-currents. *Archive for Mathematics*, *Astronomy and Physics*, **2**(11): 1–52

Escadafal R and Chehbouni A G. 2008. Monitoring arid land surfaces with earth observation techniques: examples of intense and extensive land uses // Qi J, Evered K T, eds. Environmental Problems of Central Asia and Their Economic, Social and Security Impacts. Springer Science, Business Media BV: 59–72 DOI: 10.1007/978-1-4020-8960-2_4

Fraedrich K, Jansen H, Kirk E and Lunkeit F. 2005a. The planet simulator: green planet and desert world. *Meteorologische Zeitschrift*, **14**(3): 305–314 DOI: 10.1127/0941-2948/2005/0044

Fraedrich K, Jansen H, Kirk E, Luksch U and Lunkeit F. 2005b. The planet simulator: towards a user friendly model. *Meteorologische Zeitschrift*, **14**(3): 299–304 DOI: 10.1127/0941-2948/2005/0043

Grossner K E, Goodchild M F and Clarke K C. 2008. Defining a digital earth system. *Transactions in GIS*, **12**(1): 145–160 DOI: 10.1111/j.1467-9671.2008.01090.x

Harshvardan R D, Randall D A and Corsetti T G. 1987. A fast radiation parameterization for atmospheric circulation models. *Journal of Geophysical Research*, **92**(D1): 1009–1016 DOI: 10.1029/JD092iD01p01009

Hirst T. 2010. Climate change. *Chemistry in Australia*, **77**(6): 32–33

Ionescu I R and Volkov D. 2008. Earth surface effects on active faults: An eigenvalue asymptotic analysis. *Journal of Computational and Applied Mathematics*, **220**(1-2): 143–162 DOI: 10.1016/j.cam.2007.08.004

Kerimov I A. 2009. F–approximation of the Earth's surface topography. *Izvestiya Physics of the Solid Earth*, **45**(8): 719–729 DOI: 10.1134/S1069351309080114

Kim Y J and Arakawa A. 1995. Improvement of orographic gravity wave parameterization using a mesoscale gravity wave model. *Journal of the Atmospheric Sciences*, **52**: 1875–1902 DOI: 10.1175/1520-0469(1995)052<1875:IOOGWP>2.0.CO;2

Koehler M, Mechoso C R and Arakawa A. 1997. Ice cloud formulation in climate modelling // Proceedings of the 7th Conference on Climate Variations. Long Beach, CA: American Meteorological Society, February 2-7, 1997: 237–242

Li J L F, Mechoso C R and Arakawa A. 1999. Improved PBL moist processes with the UCLA GCM // Proceedings of the 10th Symposium on Global Change Studies. Dallas: American Meteorological Society: 423–426

Makarieva A M, Gorshkov V G, Sheil D, Nobre A D and Li B L. 2010. Where do winds come from? A new theory on how water vapor condensation influences atmospheric pressure and dynamics. *Atmospheric Chemistry and Physics Discussions*, **10**(10): 24015–24052 DOI: 10.5194/acpd-10-24015-2010

Mintz Y. 1958. Design of some numerical general circulation experiments. *Bulletin of the Research Council of Israel*, **76**: 67–114

Murray A B, Lazarus E, Ashton A, Baas A, Coco G, Coulthard T, Fonstad M, Haff P, McNamara D, Paola C, Pelletier J and Reinhardt L. 2009. Geomorphology, complexity, and the emerging science of the Earth's surface. *Geomorphology*, **103**(3): 496–505 DOI: 10.1016/j.geomorph.2008.08.013

Niu W Y. 1993. Some theoretical conclusions of morphological systems on the earth's surface. *Quaternary Sciences*, **13**(2): 129–141

Petrovskaya M S. 1977. Generalization of Laplace's expansion to the Earth's surface. *Journal of Geodesy*, **51**(1): 53–62 DOI: 10.1007/BF02521541

Phillips N A. 1956. The general circulation of the atmosphere: a numerical experiment. *Quarterly Journal of the Royal Meteorological Society*, **82**(352): 123–164 DOI: 10.1002/qj.49708235202

Phillips N A. 1959. An example of nonlinear computational instability // Bolin B, ed. The Atmosphere and Sea in Motion. Rossby Memorial Volume. New York: Rockefeller Institute Press: 501–504

Phillips J D. 1999. Earth Surface Systems. Oxford: Blackwell Publishers

Richardson L F. 1922. Weather Prediction by Numerical Process. Cambridge: Cambridge University Press

Rossby C G and Collaborators. 1939. Relation between variations in the intensity of the zonal circulation of the atmosphere and the displacements of the semi-permanent centers of action. *Journal of Marine Research*, **2**(1): 38–55

Sato T. 2004. The earth simulator: roles and impacts. *Parallel Computing*, **30**(12): 1279–1286 DOI: 10.1016/j.parco.2004.09.003

Schiermeier Q. 2010. The real holes in climate science. *Nature*, **463**(7279): 284–287 DOI: 10.1038/463284a

Schlesinger M E and Mintz Y. 1979. Numerical simulation of ozone production, transport and distribution with a global atmospheric general circulation model. *Journal of the Atmospheric Sciences*, **36**: 1325–1361 DOI: 10.1175/1520-0469(1979)036<1325:NSOOPT>2.0.CO;2

Stepanova I E. 2007. S–Approximation of the Earth's Surface Topography. *Izvestiya*, *Physics of the Solid Earth*, **43**(6), 466–475 DOI: 10.1134/S1069351307060055

Strakhov V N, Kerimov I A and Strakhov A V. 1999. Linear Analytical Approximations of the Earth's Surface Topography // Proceedings of the 1st All-Russia Conference on Geophysics and Mathematics. OIFZ RAN, Moscow: 198–212 [in Russian]

Stute M, Clement A and Lohmann G. 2001. Global climate models: past, present, and future. *Proceedings of the National Academy of Sciences of the United States of America,* **98**(19): 10529–10530 DOI: 10.1073/pnas.191366098

Tarolli P, Arrowsmith J R and Vivoni E R. 2009. Understanding earth surface processes from remotely sensed digital terrain models. *Geomorphology*, **113**(1-2): 1–3 DOI: 10.1016/j.geomorph.2009.07.005

Valcke S, Guilyardi E and Larsson C. 2006. PRISM and ENES: a European approach to Earth system modelling. *Concurrency and Computation*: *Practice and Experience*, **18**(2): 231–245 DOI: 10.1002/cpe.915

Walker G T. 1925. Correlation in seasonal variations of weather—a further study of world weather. *Monthly Weather Review*, **53**(6): 252–254 DOI: 10.1175/1520-0493(1925)53<252:CISVOW>2.0.CO;2

Washington W M and Parkinson C L. 2005. An Introduction to Three Dimensional Climate Modeling. Sausalito: University Science Books

Ye D Z, Yang J C and Gao Y X. 1956. Precipitation in Yellow River Basin. Beijing: Science Press

Ye D Z and Zhu B Z. 1958. Several Basic Issues of Atmospheric Circulation. Beijing: Sicenc Press

Yue T X. 2011. Surface Modelling: High Accuracy and High Speed Methods. New York: CRC Press

Yue T X and Ai N S. 1990. A mathematic model of cirque morphology. *Journal of Glaciology and Geocryology*, **12** (3): 227–234

Yue T X, Chen S P, Xu B, Liu Q S, Li H G, Liu G H and Ye Q H. 2002. A curve-theorem based approach for change detection and its application to Yellow River Delta. *International Journal of Remote Sensing*, **23**(11): 2283–2292 DOI:10.1080/01431160110106041

Yue T X, Jorgensen S E and Larocque G R. 2011. Progress in global ecological modeling. *Ecological Modelling*, **222**: 2172–2177

Zeng Q C. 1974. Principles for Atmospheric Infrared Remote Sensing. Beijing: Science Press

地球表层建模研究进展

岳天祥

中国科学院地理科学与资源研究所，资源与环境信息系统国家重点实验室，北京 100101

摘　要：本文在讨论地球表层概念和地球表层建模定义的基础上，总结分析了地球表面形态表达、地球气候系统模拟、生态系统空间模拟分析和地球表层模拟系统等主要研究进展。分析结果表明，误差问题、多尺度问题、地球表层模拟速度问题和三维实时可视化问题是地球表层建模面临的主要挑战。为了解决这些问题，必须发展和采用诸如以遥感数据为初始场、以地面实测数据为优化控制条件的高精度高速度曲面建模新方法和新思路。

关键词：地球表层建模，误差问题，多尺度问题，运算速度，三维实时可视化

中图分类号：P91　　**文献标志码：**A

引用格式：岳天祥. 2011. 地球表层建模研究进展. 遥感学报，**15**(6): 1105–1124

Yue T X. 2011. Progress in earth surface modeling. *Journal of Remote Sensing*, **15**(6): 1105–1124

1 引　言

地球表层是岩石圈、大气圈、水圈和生物圈的交接面，它包括上至大气对流层顶层，在极地上空约8 km^2，赤道上空约17 km^2，平均约10 km^2；下至岩石圈的上部，陆地上深5–6 km^2，海洋下平均深4 km^2(钱学森，1983)。地球表层包括相互嵌套的四个空间尺度层次：局地(local)、区域(regional)、国家(national)和全球(global)。太阳辐射是地球表层的主要能源，地球接受的太阳辐射能总计为1.73×10^{17} W，进入地球表层潮汐能为3.5×10^{13} W，太阳辐射能占地球表层所获取能量的99.98%。太阳辐射能进入地球表层后推动大气循环，全球的大气环流模式就是能量稳定的对流传递的方式，太阳辐射能引起的水循环，带动了地球表层大量物质的循环运动，形成地形地貌的侵蚀堆积过程。有机体固定的太阳辐射能是地球表层全部生命运动的能量基础(浦汉昕，1983)。近年来，一些学者(周俊，2004；张猛刚和雷祥义，2005)将地球表层的空间范围外延为包括地球表面上下的岩石圈、水圈、大气圈、生物圈和近地物理(能量)场及其相关作用在内的地球空间，其下界是软流圈，其上界为大气圈最外层。地球表层系统是地球表层环境中一组相互关联要素形成的复杂功能整体。地球表层建模可定义为在某一坐标系中通过空间位置明确的格点对地球表层系统或地球表层环境要素的数字表达。

2 地球表层建模研究进展

自19世纪中期以来，地球表层建模研究的主要进展可概括为生物圈生态建模、地球气候系统模拟、地球表层形态表达和地球表层模拟系统等4个方面。

2.1 生物圈的生态建模

生物圈的生态建模始于19世纪中期，但直到19世纪80年代之前，数学在生物圈的应用几乎没有进展(Israel和Gasca，2002)。1884年，统计分析和初等

收稿日期：2011-05-06；**修订日期：**2011-06-22

基金项目：国家杰出青年科学基金(编号：40825003)；国家重点基础研究计划(973计划)(编号：2010CB950904)；国家自然科学基金(编号：41023010)

第一作者简介：岳天祥(1963—　)，男，博士，研究员，目前正在发展以遥感数据或模型模拟数据为驱动场、以地面实测数据为优化控制条件的高精度高速度地球表层建模方法体系。E-mail: yue@lreis.ac.cn。

定量技术开始被用于处理生物信息(Galton，1884)。1916年，概率论在先天病理形态研究中得到应用(Ross，1916)。1920年，逻辑斯蒂曲线被引入理论生物学(Pearl和Reed，1920)。1925年，统计方法在处理种群基因学问题中得到了发展(Fisher，1925)。1926年，常微分方程和积分微分方程运用于建立生物群丛的理性力学(Volterra，1926)。这一时期的生物圈建模过程可归纳如下：(1)识别所研究自然现象的固有特性；(2)用数学术语进行概括描述；(3)用定性方法确定参数；(4)将定量模拟结果与现实进行比较。在20世纪20年代后期和30年代初起，自然选择和进化的数学模型开始兴起(Haldane，1927；Wright，1931)。然而，这些特定的定量研究局限于小尺度系统和很少的几个过程。

生物圈定量建模在经历第二次世界大战的间断之后，于20世纪40年代后期逐渐复苏。而且，定量方法不仅限于经典的生物统计方法和微分方程，而且诸如对策论、系统论和信息论等新的数学工具也被用于建模研究。例如，Leslie (1945，1948)开发了人口增长模型； (Sullivan，1961) 和Skellam (1951) 开发了人口空间分布模型；Beverton和Holt (1957)开发了鱼类族群间关系动态模型。

这些早期研究的成功激发了一系列定量模型的发展。例如，通过模仿电路建立的模型用于分析光合生产力、群集代谢、生物量和物种变异(Odum，1960)。尽管Lotka–Volterra受到许多学者的批评(Smith，1952)，但在20世纪60年代，仍有学者探讨它的改进问题(Garfinkél，1962，1967a，1967b；Garfinkél和Sack，1964)。通过建立简单数学模型分析动物种群过程(Holling，1964)。建立了一维辐射对流平衡模型(Manabe和Strickler，1964)。通过生态学与计算技术密切配合，构建了东亚飞蝗中长期数量预测模型(马世骏　等，1965)。运用线性微分方程组模拟了浮游生物种群动态(Davidson和Clymer，1966)，开发了模拟大马哈鱼资源系统的数字模拟模型(Paulik和Greenough，1966)。

在20世纪70年代，开发了许多面向计算机的生态系统数学模型。例如，包括40个状态变量和几百个参数的草地生态系统模型(Bledsoe　等，1971；Patten，1972；Anway　等，1972)； 重现混合树种林木种群动态的森林生长半机械计算机模型(Botkin　等，1972)；模拟湖泊生态系统的通用模型(Park　等，1974)；模拟国民生产总值与人口增长相互关系的世界模型(Jørgensen，1975a)。这一时期也出现了许多描述生态系统特性的各种模型。例如，分析生产力–稳定性关系的线性微分方程模型(Rosenzweig，1971)和分析多样性–稳定性关系的各种模型(Gardner和Ashby，1970；May，1972)。

1975年，首个关于生态系统模拟的学术期刊，Ecological Modelling，诞生。该期刊试图将数学建模、系统分析和计算机技术与生态学和环境管理有机的结合起来 (Jørgensen，1975b)。但这一时期的模型存在着许多问题，包括缺少数据和获取数据的调查方法、缺乏适当的建模理论、模型预测的不确定性很大、以及无法解决误差传播问题等(Patten，1972；Shugart和O’Neill，1979)。这一时期的大多数模型只强调生态系统结构和功能在点上的时间变化，没有考虑空间问题(Neuhold，1975)。

随着遥感和地理信息系统技术与空间数据的积累，自20世纪70年代末以来，生态系统空间模拟有了较快的发展。阳含熙(1979)发展了植物群落数量分类模型。李文华和周沛村(1979)建立了暗针叶林在欧亚大陆分布数学模型。李文华和王德才(1980)发展了生物生产量和植被分布模拟模型；马世骏和王如松(1984)提出了经济–社会–自然复合生态系统模型；牛文元(1984)建立了生态系统空间分布模型。Sklar 等人(1985)开发了空间动态模拟模型，将沿海湿地的栖息地变化表达为沼泽类型、水文、沉降和沉积运输的函数。张新时(1989a，1989b，1993，1996)在对中国自然植被类型与气候之间的关系进行分析的基础上，模拟修正了中国HLZ植被生态系统分类模型的暖温带与亚热带界线和雪线界线，揭示了中国荒漠区植被地带性分布规律和中国山地植被垂直带系统。Turner等人(1989)评价了空间模拟模型的性能。高琼(1990)发展了植被系统中植物与环境相互作用的动态模拟模型。Costanza 和 Maxwell (1991)开发了生态系统空间模拟工作站。徐冠华(1993)在分析遥感图像识别、农林牧估产、水文过程模拟、荒漠化估计和土地资源评价模型的基础上，指出了陆地生态系统数学模型的研究重点和发展方向。Gao(1996)提出了用于模拟空间异质生态系统的建模方法。Reich等人(1997)模拟了主要禾本草本植物与非禾本草本植物的空间依赖性。Wu和Levin (1997)发展了基于斑块的空间建模方法。周广胜和张新时(1995)根据植物的生理生态学特点及联系

能量平衡方程和水量平衡方程和区域蒸散模式建立了联系植物生态学特点和水热平衡关系的植物的净第一生产力模型。李文华和罗天祥(1997)根据中国1006块样地资料，建立了联系叶面及指数分布规律和地植物学知识的生物生产力水热相关模型与地理分布模型。Friend(1998)提出了可在0.5度空间分辨率运行的日天气生成器。Öezesmi和Öezesmi(1999)用人工神经网方法发展了沼泽地繁殖鸟类栖息地选择的空间模型。傅伯杰等人(1999，2001)在中国自然区划、气候区划和植被区划的基础上，利用有关的生态模型对中国生态区划的综合指标进行定量研究分析，并实现了中国生态区划。

Ji和Jeske(2000)提出了可模拟野生种群地理分布的基于地理信息系统的空间建模方法。欧阳志云等人(2000)在中国生态功能区划的研究中，利用有关生态模型对各种生态因子进行定量分析，从而对植被生态系统类型的空间分布进行了区划和分类。Beaujouan等人(2001)建立了模拟土壤与地下水空间相互作用的集成模型。方精云等人(2001，2007)利用大量的生物量实测数据，结合中国50年来的森林资源清查资料及相关的统计资料，建立了基于生物量换算因子连续函数法的中国陆地植被碳库及其时空变化模型。Perry和 Enright(2002)开发了探索干扰变化如何影响景观结构的格网模型。Lehmann等人(2003)运用回归方法建立了响应变量和空间指标之间的相互关系模型。刘纪远等人(2002)在对遥感影像进行判读识别并建立基于遥感影像的中国土地覆盖分类体系的基础上，建立了土地利用变化时空分析模型。(岳天祥和杜正平，2005；Yue 等，2005，2007c，2008，2010c)为了解决生态建模的误差问题和多尺度问题，建立了高精度曲面建模方法和多尺度曲面建模方法，完成了基于遥感数据和地面数据的中国生态系统空间格局自1960年以来的变化趋势和未来90年情景的模拟与分析、中国人口空间分布自1930年以来变化趋势和未来20年情景的模拟分析、中国陆地生态系统人口承载能力模拟分析、中国土地覆盖未来90年情景的模拟分析。Baskent和Keles (2005)提出了将混合建模技术运用于森林空间建模的设想。Williamsona等人(2006)将数字大陆方案用于模拟陆地能量、水和碳储量以及与大气的交换。全球气候变化情景模型(IPCC，2000)已运用于研究气候变化对生态系统、碳汇、食物安全、生物量、水资源、虐疾分布和洪灾等的影响(Hulme 等，1999；Parry 等，2004；Rokityanskiy 等，2007)。空间自相关被用于分析景观异质性(Uuemaa 等，2008)。高精度高速度曲面建模方法被运用于模拟高空间分辨率的全球生态系统、气候变化和生物量的空间格局和未来情景(Yue，2011)。

除此之外，元胞自动机模型、神经网络模型、遗传算法等智能模型正逐渐在城市、土地利用、生态恢复等生态领域运用发展。

2.2 地球气候系统模拟

地球气候系统可通过地球表层环境要素来表达。全球气候变化的原因包括地球生命中太阳常数的逐渐增加、板块运动、海洋环流、海平面变化、温室气体排放、地表反照率变化、轨道参数变化、火山爆发等随机事件以及自然变异等(Budyko和Izrael，1991)。

地球气候系统研究可追溯到20世纪初。Bjerknes (1904)首次讨论了预测问题有理解的充分必要条件。1905年，Ekman发现了风对冰和水速的影响。Richardson(1922)发表了他运用观测数据预测小范围气候的方法。Walker(1925)讨论了南方涛动，发现了包括东南太平洋高压和印度洋、西太平洋附近区域低压的交替气压型。Alt(1929) 研究了地球表层的热量平衡。Rossby(1939) 及其合作者发现了绝对涡度平流与大尺度波动的关系。在20世纪40年代后期的主要进展包括斜压和正压不稳定性理论(Charney，1947)以及等量正压分布概念(Charney和Eliassen，1949)等。

Charney等人(1950)运用正压方程成功预测了24小时天气。1953年，3层绝热准向地性模型被成功用于模拟1950年11月美国上空观测到的暴风雨发展过程(Charney和Phillips，1953)。Black(1956)模拟了太阳辐射在地球表面的空间分布；Phillips (1956) 运用准地转近似方程进行了首次大气环流实验；叶笃正等人(1956)分析了黄河流域的降水分布和特点。Burdecki(1957)分析了地表入射辐射和大气热力场。Mintz(1958)提出了Mintz–Arakawa模型的基本思路，这个模型包括太阳辐射的季节变化和长波冷却效应；叶笃正和朱抱真(1958)讨论了大气环流研究的主要研究成果，提出了大气环流数值模拟的研究方法。Phillips(1959)证明，非线性计算的不稳定性发生在非发散正压涡度方程的求解过程。

1969年，形成了覆盖全球的两层垂直结构气候模型(Arakawa，1969)。1974年，提出了气象卫星遥感的最佳信息层概念，并试图给出选择水汽遥感通道的普遍原则和方法(曾庆存，1974)。1979年发表的第一个多层气候模型与两层模型相比，有许多改进之处，包括水平网格结构的调整、行星边界层主模型的安装启用、增加了Arakawa–Schubert积云参数和臭氧混合率的预测(Schlesinger和Mintz，1979)。1981年，发展了动量方程的水平差分(Arakawa和Lamb，1981)。20世纪80年代后期到90年代后期，气候模型的主要发展包括辐射方案的修正(Harshvardan 等，1987)、地形重力波拖曳参数化 (Kim和Arakawa，1995) 及向下气流对积云参数化的影响 (Cheng和Arakawa，1997)、云液态水和冰的准确预测(Koehler 等，1997)以及行星边界层多雨过程的修正(Li 等，1999)。

全球气候是由入射太阳辐射不均匀空间分布驱动及大气圈、冰圈、水文圈、岩石圈和生物圈相互作用的结果(Stute 等，2001)。全球气候模型应聚焦于大气、海洋、陆地过程和海冰的相互作用。全球气候模型有许多尚未解决的理论问题(Washington和Parkinson，2005)。例如，由于对气溶胶的组成和空间分布知之甚少，科学家仍然没有搞清楚气溶胶如何改变气候过程；当厄尔尼诺现象和拉尼娜现象发生时，海洋温度异常如何对气候产生影响；火山爆发如何影响平流层中的臭氧量，其冷却效应如何；云–雨物理学尚不十分清楚；云在辐射特性中发挥着非常重要的作用，但我们对其知之不多；现有气候模型的主要弱点是模拟垂直空气流动的能力很有限。Wang等人(2004)发现，全球气候模型不适合在季风区使用。Schiermeier(2010)指出，气候变化政府间组织(IPCC)的模拟结果对全球大部分地区冬季降雨在本世纪末如何变化没有提供任何具有说服力的预测；更糟糕的是，这些气候模型低估了已经发生的降雨变化，这就降低了它们预测未来气候变化的可信度；水的相变是地球气候的主要物理过程，但这个过程在现有的全球气候模型中没有很好的刻画。Makarieva等人 (2010)的研究表明，凝结所释放的潜能大约是全球太阳功率的1%，类似于大气环流的固定耗散功率；他们认为水汽的相变在驱动大气动态中发挥着远大于目前所认识到的作用。

2.3　地球表面形态表达

地球表面形态是地球表层研究的核心，它与人类活动、生物学、生物化学、地球化学、地质学、水文学、地貌学和大气动力学密切相关(Murray 等，2009)。 地表起伏是几乎所有地理科学分析的一个关键参数 (Dech，2005)。数字地面模型和地形数据质量对认识地表过程尤为重要(Tarolli，2009)。

地表高程在空间受重力的约束，不可能无限的大，地球表面一般服从唯一性、连续性、光滑性和有限性条件。对破坏光滑性条件的地形不连续性裂缝、悬崖、陡峰、窑洞和深渊等地表属性，可以作为个例进行特别处理。de Gbaaff–Hunter(1937)首先根据地面重力场描述了地表的形态。Bragard(1965)根据地表重力通过求解两个积分方程，计算了地球的表面形态。Petrovskaya(1977)探索了通过球谐函数中地势向地表外扩的广义化，构建了潜在膨胀的可能性。自1986年起，中国学者开始尝试建立全新的地球表层模拟模型，并于1990年完成了基于曲线论的冰斗形态数学模型(岳天祥和艾南山，1990)，此模型的理论方法在2000年被成功发展为环境变化探测模型(Yue 等，2002)。牛文元(1993)应用均衡河流剖面的规律，从理论上推演了地表海拔高度—面积分布的宏观趋势。为了表达地球表面形态，俄罗斯科学院构建了F逼近法和S逼近法。地球表面形态的F逼近法基于线性积分的Strakhov方法(Strakhov 等，1999)。S逼近法基于谐和函数的基本公式(Stepanova，2007)。谐和函数用于模拟全球定位系统可捕捉到的位移发生时的地球表面(Ionescu和Volkov，2008)。俄罗斯科学院研究成果表明(Kerimov，2009)，地球表面形态可表达为$z=f(x, y)$，其中z为位置(x, y)处的海拔高度；基于地表形态表达的这一理论成果，中国科学院建立了高精度高速度地球表层建模方法(Yue 等，2010a，2010b；Yue和Wang，2010)。

2.4　地球表层模拟系统

近几年来，随着海量数据的积累和高性能计算机的发展，使建模工作者更系统、更全面地模拟分析地球表层成为可能。日本建立了地球模拟器、英国建立了地球系统建模框架、德国建立了行星模拟器、美国

提出了数字地球系统框架。

1997年日本地球模拟器研究与发展中心开始研制地球模拟器，历经5年时间，于2002年按预定计划完成。地球模拟器是由640个处理器节点(包括5120个算术处理器)组成的超级并行计算机系统。其主要目的是模拟全球气候变化，在计算机上形成一个虚拟的陆地表层(Sato，2004)。

1998年，时任美国副总统的 Albert Arnold Gore Jr. 提出了数字地球的概念，将其定义为可以嵌入海量地理数据的、多分辨率的和3维的地球表示。1999年，美国国家航空和宇宙航行局(NASA)主导的数字地球工作组将数字地球定义为地球的虚拟表达，其目标是发展通用的建模软件和协议，通过交互运行相互独立的多种模型以达到综合集成。2005年，Google公司在Keyhole卫星图像公司成果的基础上发布了Google Earth。2008年，美国加利福尼亚大学提出了数字地球系统的框架设计，将其概括为一个综合的、大量的分布式地理信息和知识的组织系统(Grossner 等，2008)。

2001年，欧洲联盟为了建立地球系统建模欧洲网(ENES)，资助了集成地球系统建模计划(PRISM)项目，其内容目前主要包括全球和区域尺度的大气环流模型、大气化学模型、 海洋环流模型、海洋生物地理化学模型以及陆面和海冰模型。地球系统建模欧洲网旨在发展一个便携式的、高效的和用户界面友好的地球系统模型欧洲体系，形成具有标准化协议、所有欧洲科学家准入的可视化软件。地球系统建模欧洲网包括欧洲的所有气候建模研究组、气候计算机中心和行业合作伙伴。为了保证欧洲所有研究人员对这些设施具有同等的准入权限，地球系统建模欧洲网采取3个步骤：(1)为欧洲气候科学共同体组织共有的共享软件和标准的物理端；(2)为执行多元化的地球系统模拟提供综合集成的服务准入；(3)在2010年之前，在欧洲层面为气候研究提供超级计算准入和资源(Valcke 等，2006)。

2003年英国南安普敦大学和东英格兰大学与微软高性能计算研究所合作，建立了网格集成的地球系统建模框架，它可以将海洋、大气、陆地表层、海冰、冰盖和生物地理化学等要素通过模型分解、执行和管理，灵活地在不同分辨率进行耦合，并形成有能力在千年时间尺度对地球表层进行模拟的高效气候模型(Lenton 等，2006)。

2005年，德国汉堡大学完成了由全球大气环流模型及海洋/海冰模块和陆地土壤/生物圈模块组成的、以并行计算机为硬件支撑的行星模拟器，其主要目的是支持地球和类地球行星的气候动力学数值实验(Fraedrich 等，2005a，2005b)。

2005年，澳大利亚开始发展澳大利气候与地球系统模拟器(ACCESS)研究。澳大利气候与地球系统模拟器是由欧澳大利亚气象局和澳大利亚联邦科学与工业研究组织(CSIRO)共同发起、并与大学界合作开展的项目，包括大气模型、海洋模型、陆表模型、模型耦合、数据同化、模型评价和建模系统等7个研究组。澳大利气候与地球系统模拟器由大气模型、碳循环模型和海冰模型组成，它将为2014年政府间气候变化专门委员会(IPCC)评估报告进行气候预测(Hirst，2010)。

3 地球表层建模存在的主要问题

3.1 误差问题

误差问题的主要根源是经典地球表层系统建模方法存在着较大的理论缺陷。经典地球表层系统建模方法包括趋势面分析法、反距离加权法、三角网模型、克里根法和样条基函数法。趋势面分析法是生成曲面的一种最简单方法，它在空间坐标系中通过最小二乘回归将离散点拟合为一个趋势面；因为模拟区域每一部分的变化和光滑处理都会影响整个曲面任何部分的拟合，所以它丢失了模拟对象的真实细节信息。反距离加权法通过在采样点邻域内建立反距离加权函数，模拟采样点邻域；忽视了空间结构信息和邻域以外的信息联系。三角网模型是地理信息系统使用最广泛的地球表层系统建模方法，它通过对每3个采样点建立线性函数来模拟此3个采样点的所在区域，丢弃了非线性信息和空间结构信息，不能描绘悬崖和洞穴等曲面现象。克里根法是一种广义的最小二乘回归方法，它通过有效数据的加权平均来估计模拟对象，它的目标是估计的平均误差为零、误差的方差达到最小；由于估计的误差和误差的方差总是未知的，所以克里根的理想目标在实践中很难达到；在实际应用中，通过已知数据建立可以计算估计误差和误差方差的模型来

确定计算采样点附近模拟点值的权重，达到最佳(估计误差的方差达到最小)线性无偏(估计的平均误差为零)估计的目标，它丢失了非线性信息，同时引入了大量的人为主观因素。样条基函数法将所有曲面近似的用一系列样条基函数进行连续的拼凑模拟，只适用于很有限的一部分特殊曲面； 因此大多数情况下，样条基函数法都会产生较大的模拟误差。

许多学者已对地球表层系统建模的误差问题进行了长期不懈的研究。例如，Goodchild(1982)将布朗分形过程引入地面模拟模型以提高地球表层系统建模的精度。Walsh等人(1987)发现，通过识别输入数据的固有误差和运算误差，可以使总体误差达到最小。Hutchinson和Dowling(1991)为了构建反映流域自然结构的数字高程模型，引入了试图消除假深洼信息的流域强迫规则。Unwin(1995)在回顾了有关研究成果之后提出，检验地理信息系统在运算过程中误差传播的通用工具有助于提高地球表层系统建模的精度。Wise (2000)认为，为了提高地球表层系统建模的精度，当使用地理信息系统的时候，必须区分栅格模型和像元模型，存储在栅格中的信息只与网格的中心点有关，而存储在像元的值代表整个网格。美国地质调查局(1997)数字高程模型质量控制系统的主要内容包括精度统计检验、数据文件物理与逻辑格式检验和视觉检验。Shi等人(2005)提出了减小地球表层系统建模误差的高次插值方法。Podobnikar (2005)认为，通过使用一切可用的数据源(甚至没有高程属性的低质量数据集)，可以提高数字地面模型的精度。然而，所有这些方法都没能从根本上解决地球表层系统建模的误差问题。

3.2 多尺度问题

20世纪60年代，地球表层学者就注意到了尺度问题的重要性。20世纪90年代以来，多尺度问题被称为地球表层研究的新前缘，受到高度重视。例如，为了认识生态格局、过程和尺度之间的关系和解决有关科学问题，美国环保局建立了多尺度实验生态系统研究中心(MEERC)；为了确定地质变化和植被动态之间的相互作用，Phillips提出了4种尺度指标；为了解决全球变化影响的跨尺度问题，Peterson引入了等级理论； Stein 等用地统计方法确定环境变量的最恰当空间和时间尺度；Valdkamp 等提出了农业经济研究的多尺度系统方法；Gardner 等提出了实验生态学的多尺度分析理论；Schulze分析了气候变化农业水文响应的尺度问题、尺度类型和尺度转换的关键问题；Milne和Cohen根据分形的自相似性建立了针对MODIS数据的尺度转换方法；Konarska等通过比较NOAA–AVHRR和Landsat TM数据集的分析结果，提出了空间尺度对生态系统服务功能评价影响的分析方法。

20世纪80年代初，多尺度模拟成为地理信息系统的基本问题。1983年美国国家航空和宇宙航行局召集领衔科学家讨论了地理信信息系统的研究重点，多尺度问题被遴选为研究重点之一。20世纪90年代初，多尺度表达成为地理信息科学界的共同研究主题。1996年，多尺度问题被确定为美国地理信息系科学大学联盟(UCGIS)的十大研究重点之一。20世纪90年代末，欧洲共同体的自动化综合新技术(AGENT)项目进一步推动了多尺度问题研究。2000年，测量与遥感国际协会(ISPRS)成立了多尺度问题工作组。2003年，美国地理信息系科学大学联盟将多尺度问题确定为长期研究重点之一。尺度转换、跨尺度相互作用、空间尺度与时间尺度相互关联和多空间尺度数据处理问题是多尺度问题需要研究的重要内容。

尺度转换问题：尺度转换可区分为自下而上的尺度转换(upscaling)和自上而下的尺度转换(downscaling)。自下而上的尺度转换是指高分辨率研究结果向低分辨率的转换；自上而下的尺度转换是指低分辨率研究结果向高分辨率的转换。地球表层系统建模需要研究的主要尺度转换问题包括：如何进行观测过程和数学模型的尺度转换，尺度转换如何影响变量灵敏性、空间异质性和系统可预测性，非线性响应被放大或减小的环境条件等。

跨空间尺度相互作用问题：当某一空间尺度的事件或现象影响其他空间尺度的事件或现象时，就产生了跨尺度的联系和相互作用。然而，以往的大多数生态地理研究是在特定的空间尺度进行的，对跨尺度相互作用的分析非常有限。地球表层系统建模需要研究的主要问题包括：在不同空间尺度同时发生作用的驱动力分析，跨尺度相互作用的识别，生态地理事件在不同空间尺度的相互作用机制，跨尺度相互作用产生的非线性问题，跨尺度相互作用如何影响环境管理以及在政策制定中如何考虑跨尺

度相互作用问题。

空间尺度和时间尺度的关联问题：生态地理过程的空间尺度和时间尺度往往是密切相关的。例如，食物生产可以在一年的时间尺度和局部的空间尺度进行仿真分析；生态系统的水调节功能可以在多年的时间尺度和区域的空间尺度进行仿真分析；生态系统的气候调节功能必须在至少几十年的时间尺度和全球的空间尺度进行仿真分析。也就是说,大空间尺度的变化对应大时间尺度的生态地理过程。空间尺度和时间尺度的这种关联是否在地球表层系统建模中可以作为一种普遍规则运用是需要研究的重要内容之一。

多空间尺度数据处理问题：地球表层系统建模必须处理各种不同空间尺度的数据。目前，在生态地理问题的研究中，一般使用低(粗)分辨率数据，既是有高(细)分辨率数据，由于计算机计算容量的制约，大多数仿真分析也是将其进行平均处理后转换为低分辨率数据。这种处理几乎损失了所有局部格局信息和非线性特征信息。如何将高分辨率数据和低分辨率数据结合起来分析生态系统的结构、空间格局和过程是地球表层系统建模面临的首要挑战。

3.3 三维实时可视化问题

时间可表征为自然时–空4维空间的第四维。静态对象可定义为在短时期内不变化的对象。地理信息系统一般处理的是静态信息。然而，在许多情况下，地理信息系统需要处理的信息是动态变化的，往往需要将静态信息和动态信息结合起来。实时指事件发生时的片刻瞬间。一般情况下，信息的实时更新是不可能的，都会有一些拖延。一个实时系统的可接受拖延时间长短取决于过程的动态性和决策的时间阈值。虽然当代地理信息系统软件还没有实时功能，但随着计算机技术的迅速发展，实时空间分析和实时数据可视化已势在必行。然而，有关研究表明，地理信息系统是作为制图工具逐渐发展起来的，最近几年才开始开拓建模和模拟功能。然而，当代地理信息系统与模拟模型的集成，还不能实现实时功能。

目前，虽然二维地理信息系统可以用于大量的空间分析和应用，但大多数地理信息系统的研究和发展仍然没有跳出局限于二维数据可视化的传统方法范畴(Brooks和Whalley，2008)。三维地理信息系统不能付诸实践的主要原因是不能实现实时可视化。通过对ArcGIS (ESRI，2007)、Imagine Virtual GIS (ERDAS，2007)、PAMAP GIS Topographer (PCI-GEOMATICS，2007)和 Geomedia Terrain (Integraph，2007) 的总结分析发现，三维空间数据和空间对象的可视化已经有了一些初步进展，但需要将地理信息系统数据导入可视化软件。

3.4 地球表层模拟速度问题

为了实现高分辨率全球尺度地球表层模拟、解决三维实时可视化问题，亟待发展高速度、低内存需求模拟方法。目前，由于地球表层模型极其缓慢的运算速度和巨大的内存需求，全球尺度模拟在很粗的空间分辨率运行。由于空间分辨率过粗，其运行结果在区域尺度误差太大，很难在实际中得到应用(Washington and Parkinson，2005)，尤其是全球气候模式和区域气候模式，其运行结果在区域尺度问题很大，几乎无法用来评估气候变化对区域尺度和局地尺度各种生态系统的影响(Raisanen，2007)。

4 讨　论

自1884年以来，地球表层建模经历了从简单统计分析、线性数学模型、非线性模型、综合集成模型到模拟系统的发展过程(表1)。没有模型的开发，地球表层研究很难取得有效进展(Murray 等，2009)。新的分析技术和新的计算工具的发展，使我们有能力模拟高空间分辨率、高时间分辨率的地球表层变化(Committee on Challenges and Opportunities in Earth Surface Processes，2010)。

根据曲面论基本定律，地球表层由第一类基本量和第二类基本量唯一决定。第一类基本量提供了地球表层的一些几何性质，据此可在地球表面上计算曲线长度、切向量角、区域面积和测地线等；第二类基本量是在地球表面之外可观测到的地球表层局部变形，也就是局部地球表层在所关注点与切平面的偏离。也就是说，要达到地球表层的准确表达，地表之上和地表之外的观测信息缺一不可，必须发展基于卫星观测和地面实测一体化的地球表层建模方法。

为此，2001年开始探索将曲面论运用于地球表层

建模(Yue和Liu，2001c；岳天祥和刘纪远，2001a，2001b)。自2004年起，发表了一系列关于解决地理信息系统误差问题的高精度曲面建模(HASM)学术论文(岳天祥 等，2004，2007a，2007b；岳天祥和杜正平，2005，2006a，2006b；Yue 等，2007d)。为了大幅度提高HASM的运算速度和对海量数据的处理能力，建立了高精度曲面建模的多重网格法、自适应法(Yue 等，2010a)、共轭梯度法(Yue 等，2010b)和平差算法(Yue和Wang，2010)，形成了以遥感数据或模型模拟数据为驱动场、以地面实测数据为优化控制条件的高精度高速度地球表层建模方法体系，在PC计算机上的计算能力可达到模拟7 km^{2}空间分辨率的全球问题(Yue，2011)。高精度高速度地球表层建模方法的应用和发展，将从理论上解决误差问题、多尺度问题、地球表层模拟速度问题和三维实时可视化问题。

表1 按时间先后顺序的重要发表

事 件	参考文献
统计分析和初等定量技术开始被用于处理生物信息	Galton，1884
地球气候系统预测问题有理解的充分必要条件	Bjerknes，1904
逻辑斯蒂曲线被引入理论生物学	Pearl和Reed，1920
运用观测数据预测小范围气候的方法	Richardson，1922
常微分方程和积分微分方程运用于建立生物模型	Volterra，1926
基于地面重力场的地表形态概念模型	de Gbaaff–Hunter，1937
种群增长模型	Leslie，1945
种群空间分布模型	Skellam，1951
Mintz–Arakawa模型概念框架	Mintz，1958
飞蝗数量预测模型	马世骏 等，1965
基于地表重力的地球表面形态数学模型	Bragard，1965
两层垂直结构气候模型	Arakawa，1969
多样性—稳定性关系模型	Gardner和Ashby，1970
草地生态系统模型	Bledsoe 等，1971
气象卫星遥感的最佳信息层概念	曾庆存，1974
植物群落数量分类模型	阳含熙，1979
生物生产量和植被分布模拟模型	李文华和王德才，1980
经济–社会–自然复合生态系统模型	马世骏和王如松，1984
生态系统空间分布模型	牛文元，1984
中国山地植被垂直带系统	张新时，1989
陆地生态系统数学模型	徐冠华，1993
地球表面形态的F逼近法	Strakhov 等，1999
中国生态区划模型	傅伯杰 等，1999
中国陆地植被碳库及其时空变化模型	方精云 等，2001
景观结构格网模型	Perry和Enright，2002
土地利用变化时空分析模型	刘纪远 等，2002
高精度曲面建模方法	岳天祥 等，2004
地球模拟器	Sato，2004
行星模拟器	Fraedrich 等，2005
地球系统建模欧洲网	Valcke 等，2006
地球系统建模框架	Lenton 等，2006
地球表面形态的S逼近法	Stepanova，2007
数字地球系统框架	Grossner 等，2008
澳大利气候与地球系统模拟器	Hirst，2010

REFERENCES

Ahlberg J H, Nilson E N and Walsh J L. 1967. The Theory of Splines and Their Application. New York: Academic Press

Alt E. 1929. Der Stand des meteorologischen Strahlungsproblems. *Meteorologische Zeitschrift*, **46**(12): 50–54

Anway J C, Brittain E G, Hunt H W, Innis G S, Parton W J, Rodell C F, and Sauer R H. 1972. ELM: Version 1.0. U.S./IBP Grassland Biome Tech. Rep. No. 156. Fort Collins: Colorado State Univesity

Arakawa A. 1969. Parameterization of cumulus convection // Proceedings of the WMO/IUGG Symposium on Numerical Weather Prediction. Tokyo, 1968: IV–8–1–IV–8–6

Arakawa A and Lamb V R. 1981. A potential enstrophy and energy conserving scheme for the shallow water equations. *Monthly Weather Review*, **109**: 18–36 DOI: 10.1175/1520-0493(1981)109<0018:APEAEC>2.0.CO;2

Baskent E Z and Keles S. 2005. Spatial forest planning: a review. *Ecological Modelling*, **188**(2-4): 145–173 DOI: 10.1016/j.ecolmodel.2005.01.059

Beaujouan V, Durand P and Ruiz L. 2001. Modelling the effect of the spatial distribution of agricultural practices on nitrogen fluxes in rural catchments. *Ecological Modelling*, **137**(1): 93–105 DOI: 10.1016/S0304-3800(00)00435-X

Beverton R J H and Holt S J. 1957. On the Dynamics of Exploited Fish Populations. London: Her Majesty's Stationery Office

Bjerknes V. 1904. Das Problem von der Wettervorhersage, betrachtet vom Standpunkt der Mechanik und der Physik. *Meteorologisch Zeitung*, **21**: 1–7

Black J N. 1956. The distribution of solar radiation over the Earth's surface. *Theoretical and Applied Climatology*, **7**(2): 165–189 DOI: 10.1007/BF02243320

Bledsoe L J, Francis R C, Swartzman G L and Gustafson J D. 1971. PWNEE: A Grassland Ecosystem Model. U.S. IBP Grassland Biome Tech. Rep. No. 64. Fort Collins: Colorado State University

Bockheim J G and Gennadiyev A N. 2010. Soil–factorial models and earth–system science: a review. *Geoderma*, **159**(3-4): 243–251 DOI: 10.1016/j.geoderma.2010.09.005

Bragard L. 1965. Method to determine the shape of the topographical earth surface by means of gravity measurements on that surface by solving two integral equations. *Studia Geophysica et Geodaetica*, **9**(2): 108–112 DOI: 10.1007/BF02607316

Brown J R, Jakob C and Haynes J M. 2010. An evaluation of rainfall frequency and intensity over the Australian region in a global climate model. *Journal of Climate*, **23**(24): 6504–6525 DOI: 10.1175/2010jcli3571.1

Budyko M I and Israel Y A. 1991. Anthropogenic Climate Change. Tucson: University of Arizona Press

Burdecki F. 1957. Remarks on the distribution of solar radiation over the surface of the Earth. *Theoretical and Applied Climatology*, **8**(3–4): 326–335 DOI: 10.1007/BF02243300

Cendrero A. 1992. Planning the use of the Earth's surface: an overview. *Lecture Notes in Earth Sciences*, **42**: 1–22 DOI: 10.1007/BFb0038629

Chapman S. 1957. Annals of the International Geophysical Year. Volume 1: The Histories of the International Polar Years and The Inception and Development of the International Geophysical Year. London: Pergamon Press

Charney J G. 1947. The dynamics of long waves in a baroclinic westerly current. *Journal of Meteorology*, **4**(5): 135–162

Charney J G and Eliassen A. 1949. A numerical method for predicting the pertubations of the middle latitude westerlies. *Tellus*, **1**(2): 38–54 DOI: 10.1111/j.2153-3490.1949.tb01258.x

Charney J G, Fjörtoft R and von Neumann J. 1950. Numerical integration of the barotropic vorticity equation. *Tellus*, **2**(4): 237–254 DOI: 10.1111/j.2153-3490.1950.tb00336.x

Charney J G and Phillips N A. 1953. Numerical integration of the quasi–geostrophic equations for barotropic and simple baroclinic flows. *Journal of Meteorology*, **10**(2): 71–99 DOI: 10.1175/1520-0469(1953)010<0071:NIOTQG>2.0.CO;2

Cheng M D and Arakawa A. 1997. Inclusion of rainwater budget and convective downdrafts in the Arakawa–Schubert cumulus parameterization. *Journal of the Atmospheric Sciences*, **54**(10): 1359–1378 DOI: 10.1175/1520-0469(1997)054<1359:IORBAC>2.0.CO;2

Committee on Challenges and Opportunities in Earth Surface Processes. 2010. Landscapes on the Edge: New Horizons for Research on Earth's Surface. Washington DC: The National Academies Press

Costanza R and Maxwell T. 1991. Spatial ecosystem modelling using parallel processors. *Ecological Modelling*, **58** (1-4): 159–183 DOI: 10.1016/0304-3800(91)90034-X

Davidson R S and Clymer A B. 1966. The desirability and applicability of simulating ecosystems. *Annals of the New York Academy of Sciences*, **128**: 790–794 DOI: 10.1111/j.1749-6632.1965.tb11699.x

de Gbaaff-Hunter J. 1937. The shape of the Earth's surface expressed in terms of gravity at ground level. *Bulletin Géodésique*, **56**(1): 191–200 DOI: 10.1007/BF02526095

Dech S. 2005. The Earth surface // Feuerbacher B, Stoewer H, eds. Utilization of Space. Bonn: Springer: 53–90

Ekman V W. 1905. On the influence of the Earth's rotation on ocean-currents. *Archive for Mathematics*, *Astronomy and Physics*, **2**(11): 1–52

Escadafal R and Chehbouni A G. 2008. Monitoring arid land surfaces with earth observation techniques: examples of intense and extensive land uses // Qi J, Evered K T, eds. Environmental Problems of Central Asia and Their Economic, Social and Security Impacts. Springer Science, Business Media BV: 59–72 DOI: 10.1007/978-1-4020-8960-2_4

Fang J Y, Chen A P, Peng C H, Zhao S Q and Ci L J. 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. *Science*, **292**(5525): 2320–2322 DOI: 10.1126/science.1058629

Fang J Y, Guo Z D, Piao S L and Chen A P. 2007. An estimation on carbon storage of land vegetation in China between 1981 and 2000. *Science in China D*, **37**(6): 804–812

Fisher R A. 1925. Statisitcal Methods for Research Workers. Edinburgh: Oliver and Boyd

Fraedrich K, Jansen H, Kirk E and Lunkeit F. 2005a. The planet simulator: green planet and desert world. *Meteorologische Zeitschrift*, **14**(3): 305–314 DOI: 10.1127/0941-2948/2005/0044

Fraedrich K, Jansen H, Kirk E, Luksch U and Lunkeit F. 2005b. The planet simulator: towards a user friendly model. *Meteorologische Zeitschrift*, **14**(3): 299–304 DOI: 10.1127/0941-2948/2005/0043

Friend A D. 1998. Parameterisation of a global daily weather generator for terrestrial ecosystem modeling. *Ecological Modelling*, **109**(2): 121–140 DOI: 10.1016/S0304-3800(98)00036-2

Fu B J, Chen L D and Liu G H. 1999. Objectives, tasks and characteristics of ecological zoning in China. *Acta Ecologia Sinica*, **19**(5): 591–595

Fu B J, Liu G H, Chen L D, Ma K M and Li J R. 2001. Scheme of ecological zoning in China. *Acta Ecologia Sinica*, **21**(1): 1–6

Galton F. 1884. Life History Album. London: Macmillan and CO Limited

Gao Q. 1990. Dynamic modelling of plant-environment interactions in a vegetation system. *Chinese Journal of Plant Ecology*, **14**(4): 305–311

Gao Q. 1996. Dynamic modeling of ecosystems with spatial heterogeneity: A structured approach implemented in Windows environment. *Ecological Modelling*, **85**(2-3): 241–252 DOI: 10.1016/0304-3800(94)00149-9

Gardner M R and Ashby W R. 1970. Connectance of large dynamic (cybernetic) systems: critical values for stability. *Nature*, **228**(5273): 784 DOI: 10.1038/228784a0

Garfinkél D. 1962. Digital computer simulation of ecological systems. *Nature*, **194**(4831): 856–857 DOI: 10.1038/194856a

Garfinkél D. 1967a. A simulation study of the effect on simple ecological systems of making rate of increase of population density-dependent. *Journal of Theoretical Biology*, **14**(1): 46–58 DOI: 10.1016/0022-5193(67)90092-6

Garfinkél D. 1967b. Effect on stability of Lotka–Volterra ecological systems of imposing strict territorial limits on populations. *Journal of Theoretical Biology*, **14**(3): 325–327 DOI: 10.1016/0022-5193-(67)90085-9

Garfinkél D and Sack R. 1964. Digital computer simulation of an ecological system based on a modified mass action law. *Ecology*, **45**(3): 502–507 DOI: 10.2307/1936103

Grossner K E, Goodchild M F and Clarke K C. 2008. Defining a digital earth system. *Transactions in GIS*, **12**(1): 145–160 DOI: 10.1111/j.1467-9671.2008.01090.x

Haldane J B S. 1927. A mathematical theory of natural and artificial selection, part V: selection and mutation. *Mathematical Proceedings of the Cambridge Philosophical Society*, **23**(7): 838–844 DOI: 10.1017/S0305004100015644

Harshvardan R D, Randall D A and Corsetti T G. 1987. A fast radiation parameterization for atmospheric circulation models. *Journal of Geophysical Research*, **92**(D1): 1009–1016 DOI: 10.1029/JD092iD01p01009

Holling C S. 1964. The analysis of complex population processes. *The Canadian Entomologist*, **96**(1-2): 335–347 DOI: 10.4039/Ent96335-1

Hulme M, Mitchell J, Ingram W, Lowe J, Johns T, New M and Viner D. 1999. Climate change scenarios for global impacts studies. *Global Environmental Change*, **9**(S1): S3–S19 DOI: 10.1016/S0959-3780(99)00015-1

Ionescu I R and Volkov D. 2008. Earth surface effects on active faults: An eigenvalue asymptotic analysis. *Journal of Computational and Applied Mathematics*, **220**(1-2): 143–162 DOI: 10.1016/j.cam.2007.08.004

Israel G and Gasca A M. 2002. The Biology of Numbers. Berlin: Birkhaeuser Verlag

IPCC. 2000. Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press

Ji W and Jeske C. 2000. Spatial modeling of the geographic distribution of wildlife populations: a case study in the lower Mississippi River region. *Ecological Modelling*, **132**(1-2): 95–104 DOI: 10.1016/S0304-3800(00)00307-0

Jørgensen S E. 1975a. A World model of the growth in production and population. *Ecological Modelling*, **1**(3): 199–203 DOI: 10.1016/0304-3800(75)90017-4

Jørgensen S E. 1975b. About “Ecological Modelling”. *Ecological Modelling*, **1**(1): 1–2 DOI: 10.1016/0304-3800(75)90002-2

Kerimov I A. 2009. F–approximation of the Earth’s surface topography. *Izvestiya Physics of the Solid Earth*, **45**(8): 719–729 DOI: 10.1134/S1069351309080114

Kim Y J and Arakawa A. 1995. Improvement of orographic gravity wave parameterization using a mesoscale gravity wave model. *Journal of the Atmospheric Sciences*, **52**: 1875–1902 DOI: 10.1175/1520-0469(1995)052<1875:IOOGWP>2.0.CO;2

Koehler M, Mechoso C R and Arakawa A. 1997. Ice cloud formulation in climate modelling // Proceedings of the 7th Conference on Climate Variations. Long Beach, CA: American Meteorological Society, February 2-7, 1997: 237–242

Legendre L and Legendre P. 1983. Numerical Ecology. Amsterdam: Elsevier Scientific Pul Co

Lehmann A, Overton J M and Leathwick J R. 2003. GRASP: generalized regression analysis and spatial prediction. *Ecological Modelling*, **160**(1-2): 165–183 DOI: 10.1016/S0304-3800(02)00354-X

Lenton T M, Williamson M S, Edwards N R, Marsh R, Price A R, Ridgwell A J, Shepherd J G and Cox S J. 2006. Millennial timescale carbon cycle and climate change in an efficient Earth system model. *Climate Dynamics*, **26**(7-8): 687–711 DOI: 10.1007/s00382-006-0109-9

Leslie P H. 1948. Some further notes on the use of matrices in population mathematics. *Biometrika*, **35**(3-4): 213–245

Leslie P H. 1945. On the use of matrices in certain population mathematics. *Biometrika*, **33**(3): 183–212

Li J L F, Mechoso C R and Arakawa A. 1999. Improved PBL moist processes with the UCLA GCM // Proceedings of the 10th Symposium on Global Change Studies. Dallas: American Meteorological Society: 423–426

Li W H and Zhou P C. 1979. Distribution of dark coniferous forest in the Eurasian continent and its mathematical model. *Natural Resources*, **3**(1): 21–34

Li W H and Wang D C. 1980. Applications of computer graphs in ecology and natural resources research. *Natural Resources*, **4**(4): 70–81

Li W H and Luo T X. 1997. Productivity patterns and mathematical models of spruce-fir forest in China. *Acta Ecologia Sinica*, **17**(5): 511–518

Liu J Y, Liu M L, Zhuang D F, Zhang Z X and Deng X Z. 2002. Spatial patterns of recent land use change in China. *Science in China D*, **32**(12): 1031–1043

Long G E. 1980. Surface approximation: A deterministic approach to modeling patially variable systems. *Ecological Modelling*, **8**: 333–343 DOI: 10.1016/0304-3800(80)90045-9

Ma S J, Ding Y Q and Li D M. 1965. Quantitative prediction in middel and long term of locusta migratoria manilensis. *Acta Entomologica Sinica*, **14**(4): 319–338

Ma S J and Wang R S. 1984. Social-economic- natural complex ecosystem. *Acta Ecologia Sinica*, **4**(1): 1–9

Makarieva A M, Gorshkov V G, Sheil D, Nobre A D and Li B L. 2010. Where do winds come from? A new theory on how water vapor condensation influences atmospheric pressure and dynamics. *Atmospheric Chemistry and Physics Discussions*, **10**(10): 24015–24052 DOI: 10.5194/acpd-10-24015-2010

Manabe S and Strickler R F. 1964. Thermal equilibrium of the atmosphere with a convective adjustment. *Journal of the Atmospheric Sciences*, **21**(4): 361–385 DOI: 10.1175/1520-0469-(1964)021<0361:TEOTAW>2.0.CO;2

May R M. 1972. Will a large complex system be stable? *Nature*, **238**(5364): 413–414 DOI: 10.1038/238413a0

Mintz Y. 1958. Design of some numerical general circulation experiments. *Bulletin of the Research Council of Israel*, **76**: 67–114

Murray A B, Lazarus E, Ashton A, Baas A, Coco G, Coulthard T, Fonstad M, Haff P, McNamara D, Paola C, Pelletier J and Reinhardt L. 2009. Geomorphology, complexity, and the emerging science of the Earth’s surface. *Geomorphology*, **103**(3): 496–505 DOI: 10.1016/j.geomorph.2008.08.013

Neuhold J M. 1975. Introduction to modeling in the Biome // Patten B C, ed. Systems Analysis and Simulation in Ecology. New York: Academic Press: 7–12

Niu W Y. 1984. Spatial distribution of ecosystems. *Acta Ecologia Sinica*, **4**(4): 299–309

Niu W Y. 1993. Some theoretical conclusions of morphological systems on the Earth’s surface. *Quaternary Sciences*, **13**(2): 129–141

Odum H T. 1960. Ecological potential and analogue circuits for the ecosystem. *American Sciences*, **48**(1): 1–8

Öezesmi S L and Öezesmi U. 1999. An artificial neural network approach to spatial habitat modelling with interspecific interaction. *Ecological Modelling*, **116**(1): 15–31 DOI: 10.1016/S0304-3800-(98)00149-5

Ouyang Z Y, Wang X K and Miao H. 2000. China’s eco-environmental sensitivity and its spatial heterogeneity. *Acta Ecologia Sinica*, **20**(2): 9–12

Park R A, Mankin J B, Hoopes J A, Peterson J L, O’Neill R V, Bloomfield J A, Shugart H H Jr, Booth R S, Goldstein R A, Koonce J F, Scarvia D, Adams M S, Clesceri L S, Colon E M, Dettmann E H, Huff D D, Katz S, Kitchell J F, Kohberger R C, LaRow E J, McNaught D C, Titus J E, Weiler P R, Wilkinson J W and Zahorcak C S. 1974. A generalized model for simulating lake ecosystems. *Simulation*, **23**(2): 33–50 DOI: 10.1177/003754977402300201

Parry M L, Rosenzweig C, Iglesias A, Livermore M and Fischer G. 2004. Effects of climate change on global food production under SRES emissions and socio–economic scenarios. *Global Environmental Change*, **14**(1): 53–67 DOI: 10.1016/j.gloenvcha.2003.10.008

Patten B C. 1972. A simulation of the shortgrass prairie ecosystem. *Simulation*, **19**(6): 177–186 DOI: 10.1177/003754977201900602

Paulik G J and Greenough J W Jr. 1966. Management analysis for a salmon resource system // Watt K E F, ed. Systems Analysis in Ecology. New York: Academic Press: 215–252

Pearl R and Reed L J. 1920. On the rate of growth of the population of the United States since 1790 and its mathematical representation. *Proceedings of the National Academy of Sciences of the United States of America*, **6**(6): 275–288 DOI: 10.1073/pnas.6.6.275

Perry G L W and Enright N J. 2002. Spatial modelling of landscape composition and pattern in a maquis–forest complex, Mont Do, New Caledonia. *Ecological Modelling*, **152**(2-3): 279–302 DOI: 10.1016/S0304-3800(02)00004-2

Petrovskaya M S. 1977. Generalization of Laplace’s expansion to the Earth’s surface. *Journal of Geodesy*, **51**(1): 53–62 DOI: 10.1007/BF02521541

Phillips N A. 1956. The general circulation of the atmosphere: a numerical experiment. *Quarterly Journal of the Royal Meteorological Society*, **82**(352): 123–164 DOI: 10.1002/qj.49708235202

Phillips N A. 1959. An example of nonlinear computational instability // Bolin B, ed. The Atmosphere and Sea in Motion. Rossby Memorial Volume. New York: Rockefeller Institute Press: 501–504

Phillips J D. 1999. Earth Surface Systems. Oxford: Blackwell Publishers

Pu H Q. 1983. Earth surface systems and their evolution. *Chinese Journal of Nature*, **6**(2): 126–128

Qian X S. 1983. Engineering technology for environmental protection—environmental systematic engineering. *Envionmental Protection*, **6**: 1–4

Reich R M, Bonham C D and Metzger K L. 1997. Modeling small–scale spatial interaction of shortgrass prairie species. *Ecological Modelling*, **101**(2-3): 163–174 DOI: 10.1016/S0304-3800-(97)01976-5

Richardson L F. 1922. Weather Prediction by Numerical Process. Cambridge: Cambridge University Press

Rokityanskiy D, Benítez P C, Kraxner F, McCallum I, Obersteiner M, Rametsteiner E and Yamagata Y. 2007. Geographically explicit global modeling of land–use change, carbon sequestration, and biomass supply. *Technological Forecasting and Social Change*, **74**(7): 1057–1082 DOI: 10.1016/j.techfore.2006.05.022

Rosenzweig M L. 1971. Paradox of enrichment: destabilization of exploitation ecosystems in ecological time. *Science*, **171**(3969): 385–387 DOI: 10.1126/science.171.3969.385

Ross R. 1916. An application of the theory of probabilities to the study of a priori pathometry. *Proceedings of the Royal Society A*: *Mathematical*, *Physical and Engineering Sciences*, **92**(638): 204–230 DOI: 10.1098/rspa.1916.0007

Rossby C G and Collaborators. 1939. Relation between variations in the intensity of the zonal circulation of the atmosphere and the displacements of the semi-permanent centers of action. *Journal of Marine Research*, **2**(1): 38–55

Sato T. 2004. The earth simulator: roles and impacts. *Parallel Computing*, **30**(12): 1279–1286 DOI: 10.1016/j.parco.2004.09.003

Schiermeier Q. 2010. The real holes in climate science. *Nature*, **463**(7279): 284–287 DOI: 10.1038/463284a

Schlesinger M E and Mintz Y. 1979. Numerical simulation of ozone production, transport and distribution with a global atmospheric general circulation model. *Journal of the Atmospheric Sciences*, **36**: 1325–1361 DOI: 10.1175/1520-0469-(1979)036<1325:NSOOPT>2.0.CO;2

Schroeder L D and Sjoquist D L. 1976. Investigation of population density gradients using trend surface analysis. *Land Economics*, **52**(3): 382–392 DOI: 10.2307/3145535

Shugart H H and O'Neill R V. 1979. Systems Ecology. Stroudsgurg: Dowden, Hutchinson & Ross Inc

Skellam J G. 1951. Random dispersal in theoretical populations. *Biometrika*, **38**(1-2): 196–218

Sklar F H, Costanza R and Day J W Jr. 1985. Dynamic spatial simulation modeling of coastal wetland habitat succession. *Ecological Modelling*, **29**(1–4): 261–281 DOI: 10.1016/0304-3800-(85)90056-0

Smith F E. 1952. Experimental methods in population dynamics: a critique. *Ecology*, **33**(4): 441–450. DOI: 10.2307/1931519

Stepanova I E. 2007. S–Approximation of the Earth's Surface Topography. *Izvestiya*, *Physics of the Solid Earth*, **43**(6), 466–475 DOI: 10.1134/S1069351307060055

Stott J P. 1977. Review of surface modelling // Proceedings of Surface Modelling by Computer. London: Royal Institution of Chartered Surveyors and the Institution of Civil Engineers, 1976: 1–8

Strakhov V N, Kerimov I A and Strakhov A V. 1999. Linear Analytical Approximations of the Earth's Surface Topography // Proceedings of the 1st All-Russia Conference on Geophysics and Mathematics. OIFZ RAN, Moscow: 198–212 [in Russian]

Stute M, Clement A and Lohmann G. 2001. Global climate models: past, present, and future. *Proceedings of the National Academy of Sciences of the United States of America*, **98**(19): 10529–10530 DOI: 10.1073/pnas.191366098

Sullivan W. 1961. Assault on the Unknown. New York: McGraw-Hill Book Company INC

Tarolli P, Arrowsmith J R and Vivoni E R. 2009. Understanding earth surface processes from remotely sensed digital terrain models. *Geomorphology*, **113**(1-2): 1–3 DOI: 10.1016/j.geomorph.2009.07.005

Turner M G, Costanza R and Sklar F H. 1989. Methods to evaluate the performance of spatial simulation models. *Ecological Modelling*, **48**(1–2): 1–18 DOI: 10.1016/0304-3800(89)90057-4

Uuemaa E, Roosaare J, Kanal A and Mander Ü. 2008. Spatial correlograms of soil cover as an indicator of landscape heterogeneity. *Ecological Indicators*, **8**(6): 783–794 DOI: 10.1016/j.ecolind.2006.12.002

Valcke S, Guilyardi E and Larsson C. 2006. PRISM and ENES: a European approach to Earth system modelling. *Concurrency and Computation*: *Practice and Experience*, **18**(2): 231–245 DOI: 10.1002/cpe.915

Volterra V. 1926. Fluctuations in the abundance of a species considered mathematically. *Nature*, **118**(2972): 558–560 DOI: 10.1038/118558a0

Walker G T. 1925. Correlation in seasonal variations of weather—a further study of world weather. *Monthly Weather Review*, **53**(6): 252–254 DOI: 10.1175/1520-0493(1925)53<252:CISVOW>2.0.CO;2

Wang B, Wan H, Ji Z Z, Zhang X, Yu R C, Yu Y Q and Liu H B. 2004. Design of a new dynamical core for global atmospheric models based on some efficient numerical methods. *Science in China Series A*, **47**(Supp1): 4–21 DOI: 10.1360/04za0001

Washington W M and Parkinson C L. 2005. An Introduction to Three Dimensional Climate Modeling. Sausalito: University Science Books

Williamsona M S, Lentona T M, Shepherd J G and Edwardsd N R. 2006. An efficient numerical terrestrial scheme (ENTS) for Earth system modeling. *Ecological Modelling*, **198**(3-4): 362–374 DOI: 10.1016/j.ecolmodel.2006.05.027

Wright S. 1931. Evolution in Mendelian populations. *Genetics*, **16**(2): 97–159

Wu J G and Levin S A. 1997. A patch–based spatial modeling approach: conceptual framework and simulation scheme. *Ecological Modelling*, **101**(2-3): 325–346 DOI: 10.1016/S0304-3800(97)00056-2

Xu G H. 1993. Mathematical models used in remote sensing and geographical information system and their applications. *Quaternary Sciences*, **13**(2): 170–184

Yang H X, Lu Z Y and Yang Z N. 1979a. Quantitative classification of vegetation communities: association analysis and principle component analysis. *Forest Science*, **15**(4): 244–255

Yang H X, Lu Z Y and Yang Z N. 1979b. Quantitative classification of vegetation communities: information analysis and principle coordinate analysis. *Natural Resources*, **1**: 14–20

Ye D Z, Yang J C and Gao Y X. 1956. Precipitation in Yellow River Basin. Beijing: Science Press

Ye D Z and Zhu B Z. 1958. Several Basic Issues of Atmospheric Circulation. Beijing: Science Press

Yue T X. 2011. Surface Modelling: High Accuracy and High Speed Methods. New York: CRC Press

Yue T X and Ai N S. 1990. A mathematical model for cirque shape. *Journal of Glaciology and Geocryology*, **12**(3): 227–234

Yue T X, Chen C F, and Li B L. 2010. An adaptive method of high accuracy surface modeling and its application to simulating elevation surfaces. *Transactions in GIS*, **14**(5): 615–630 DOI: 10.1111/j.1467-9671.2010.01213.x

Yue T X, Chen S P, Xu B, Liu Q S, Li H G, Liu G H and Ye Q H. 2002. A curve–theorem based approach for change detection and its application to Yellow River Delta. *International Journal of Remote Sensing*, **23**(11): 2283–2292 DOI:10.1080/01431160110106041

Yue T X and Du Z P. 2005. High accuracy surface modeling: a core modulus for new generation of GIS and CAD. *Progress in Nature Science*, **15**(4): 423–432

Yue T X and Du Z P. 2006a. Comparative analyses of errors of high accuracy surface modeling with the ones of classic methods. *Progress in Nature Science*, **16**(8): 986–991

Yue T X and Du Z P. 2006b. Numerical tests of high accuracy surface modeling for its optimum formulation. *Geo-Information Science*, **8**(3): 83–87

Yue T X, Du Z P and Liu J Y. 2004. High accuracy surface modeling and its error analysis. *Progress in Nature Science*, **14**(3): 300–306

Yue T X, Du Z P and Song D J. 2007a. High accuracy surface modeling and spatial real time simulation. *Journal of Image and Graphics*, **12**(9): 1659–1664

Yue T X, Du Z P and Song D J. 2007b. High accuracy surface modelling: HASM4. *Journal of Image and Graphics*, **12**(2): 343–348

Yue T X, Du Z P, Song D J and Gong Y. 2007c. A new method of surface modeling and its application to DEM construction. *Geomorphology*, **91**(1-2): 161–172

Yue T X, Fan Z M and Liu J Y. 2007d. Scenarios of land cover in China. *Global and Planetary Change*, **55**(4): 317–342 DOI: 10.1016/j.gloplacha.2006.10.002

Yue T X, Fan Z M, Liu J Y and Wei B X. 2006. Scenarios of major terrestrial ecosystems in China. *Ecological Modelling*, **199**(3): 363–376 DOI: 10.1016/j.ecolmodel.2006.05.026

Yue T X and Liu J Y. 2001a. A digital model for multi-sources information fusion. *World Sci-tech R & D*, **23**(5): 1–4

Yue T X and Liu J Y. 2001b. The digital model for transforming information at various scales. *Journal of Image and Graphic*, **6**(9): 907–911

Yue T X and Liu J Y. 2001c. A Digital Model for Transforming Information at Various Scales. Proceedings of International Conference on Land Use/Cover Change Dynamics. Beijing: 297–308

Yue T X, Song D J, Du Z P and Wang W. 2010. High-accuracy surface modelling and its application to DEM generation. *International Journal of Remote Sensing*, **31**(8): 2205–2226 DOI: 10.1080/01431161003668982

Yue T X, Song Y J, and Fan Z M. 2010. The multi-grid method of high accuracy surface modelling and its validation. Computers and Geosciences (Accepted)

Yue T X, Tian Y Z, Liu J Y and Fan Z M. 2008. Surface modeling of human carrying capacity of terrestrial ecosystems in China. *Ecological Modelling*, **214**(2-4): 168–180 DOI: 10.1016/j.ecolmodel.2008.01.025

Yue T X and Wang S H. 2010. Adjustment computation of HASM: a high–accuracy and high–speed method. *International Journal of Geographical Information Science*, **24**(11): 1725–1743 DOI: 10.1080/13658810903569580

Yue T X, Wang Y A, Liu J Y, Chen S P, Qiu D S, Deng X Z, Liu M L, Tian Y Z and Su B P. 2005. Surface modelling of human population distribution in China. *Ecological Modelling*, **181**(4): 461–478 DOI: 10.1016/j.ecolmodel.2004.06.042

Zeng Q C. 1974. Principles for Atmospheric Infrared Remote Sensing. Beijing: Science Press

Zhang M G and Lei X Y. 2005. Discussion on earth surface system. *Geology in Northwest China*, **38**(2): 99–101

Zhang X S. 1989a. The potential evapotranspiration (PE) index for vegetation and vegetation–classification (I)—an introduction of main methods and PEP program. *Chinese Journal of Plant Ecology*, **13**(1): 1–9

Zhang X S. 1989b. The potential evapotranspiration (PE) index for vegetation and vegetation–classification (II)—an introduction of main methods and PEP program. *Chinese Journal of Plant Ecology*, **13**(3): 197–207

Zhang X S. 1993. A vegetation-climate classification system for global change studies in China. *Quaternary Sciences*, **13**(2):157–169

Zhang X S, Yang D A and Ni W G. 1993. The potential evapotranspiration (PE) index for vegetation and vegetation – classification (II) — an introduction of main methods and PEP program. *Chinese Journal of Plant Ecology*, **17**(2): 97–109

Zhou G S and Zhang X S, 1995. A natural vegetation NPP model. *Chinese Journal of Plant Ecology*, **19**(3): 193–200

Zhou J. 2004. "The second discussion on the Earth's surface layer". *Journal of Natural Disasters*, **13**(6): 1–7

附中文参考文献

方精云，郭兆迪，朴世龙，陈安平．2007．1981—2000年中国陆地植被碳汇的估算．中国科学D辑，**37**(6): 804–812

傅伯杰，陈利顶，刘国华．1999．中国生态区划的目的、任务及特点．生志学报，**19**(5): 591–595

傅伯杰，刘国华，陈利顶，马克明，李俊然．2001．中国生态区划方案．生态学报，**21**(1): 1–6

高琼．1990．植被系统中植物与环境因子相互作用的动态模拟．植物生态学报，**14**(4): 305–311

李文华，罗天祥．1997．中国云冷杉林生物生产力格局及其数学

模型. 生态学报，**17**(5): 511–518
李文华，王德才. 1980. 电子计算机符号图在生态学和自然资源研究中的应用. 自然资源，**4**(4)：70–81
李文华，周沛村. 1979. 暗针叶林在欧亚大陆分布的基本规律及其数学模型. 自然资源，**3**(1): 21–34
刘纪远，刘明亮，庄大方，张增祥，邓祥征. 2002. 中国近期土地利用变化的空间格局分析. 中国科学D辑，**32**(12): 1031–1043
马世骏，丁岩钦，李典谟. 1965. 东亚飞蝗中长期数量预测的研究. 昆虫学报，**14**(4): 319–338
马世骏，王如松. 1984. 社会–经济–自然复合生态系统. 生态学报，**4**(1): 1–9
牛文元. 1984. 生态系统的空间分布. 生态学报，**4**(4): 299–309
牛文元. 1993. 地球表层形态分析的定量注记. 第四纪研究，**13**(2): 129–141
欧阳志云，王效科，苗鸿. 2000. 中国生态环境敏感性及其区域差异规律研究. 生态学报，**20**(2): 9–12
徐冠华. 1993. 遥感与地理信息系统中的数学模型及其应用. 第四纪研究，**13**(2): 170–184
阳含熙，卢泽愚，杨周南. 1979a. 植物群落数量分类的研究一. 关联分析和主分量分析. 林业科学，**15**(4): 244–255
阳含熙，卢泽愚，杨周南. 1979b. 植物群落数量分类的研究二. 信息分析和主坐标分析. 自然资源，(1): 14–20
叶笃正，杨建初，高由禧，等. 1956. 黄河流域的降水. 北京: 科学出版社
叶笃正，朱抱真. 1958. 大气环流的若干基本问题. 北京: 科学出版社
岳天祥，艾南山. 1990. 冰斗形态的数学模型. 冰川冻土，**12**(3): 227–234
岳天祥，杜正平. 2005. 高精度曲面建模: 新一代GIS与CAD的核心模块. 自然科学进展，**15**(4): 423–432
岳天祥，杜正平. 2006a. 高精度曲面建模与经典模型的误差比较分析. 自然科学进展，**16**(8): 986–991
岳天祥，杜正平. 2006b. 高精度曲面建模最佳表达形式的数值实验分析. 地球信息科学，**8**(3): 83–87
岳天祥，杜正平，刘纪远. 2004. 高精度曲面建模与误差分析. 自然科学进展，**14**(3): 300–306
岳天祥，杜正平，宋敦江. 2007a. 高精度曲面建模与实时空间模拟. 中国图象图形学报，**12**(9): 1659–1664
岳天祥，杜正平，宋敦江. 2007b. 高精度曲面建模: HASM4. 中国图象图形学报，**12**(2): 343–348
岳天祥，刘纪远. 2001a. 多源信息融合数字模型. 世界科技研究与发展，**23**(5): 1–4
岳天祥，刘纪远. 2001b. 第四代地理信息系统研究中的尺度转换数字模型. 中国图像图形学报A辑，**6**(9): 907–911
曾庆存. 1974. 大气红外遥测原理. 北京: 科学出版社
张猛刚，雷祥义. 2005. 地球表层系统浅论. 西北地质，**38**(2): 99–101
张新时. 1989a. 植被的PE可能蒸散指标与植被–气候分类一: 几种主要方法与PEP程序介绍. 植物生态学与地植物学学报，**13**(1): 1–9
张新时. 1989b. 植被的PE可能蒸散指标与植被–气候分类二: 几种主要方法与PEP程序介绍. 植物生态学与地植物学学报，**13**(3): 197–207
张新时. 1993. 研究全球变化的植被–气候分类系统. 第四纪研究，**5**(2): 157–169
张新时，杨奠安，倪文革. 1993. 植被的PE可能蒸散指标与植被–气候分类三: 几种主要方法与PEP程序介绍. 植物生态学与地植物学学报，**17**(2): 97–109
周广胜，张新时. 1995. 自然植被净第一性生产力模型初探. 植物生态学报，**19**(3): 193–200
周俊. 2004. “地球表层再讨论”. 自然灾害学报，**13**(6): 1–7