STOCHASTIC MODELING IN LIFE SUPPORT SYSTEMS

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Contents

1. The Concept of Stochastic Modeling

Beyond an initial view that the term "*stochastic modeling*" (SM) is associated with the study of uncertainty in natural sciences, perceptions at a more substantial level regarding SM 's functions and uses are not as uniform as one might think. This should not come as a surprise, in view of the multidisciplinary nature of science. Depending on the application considered, one may refer to stochastic models as hydrologic, geologic, atmospheric, genetic, ecological, epidemic, etc. A common factor in all these cases is that, SM is concerned with the mathematically rigorous and scientifically meaningful representation, explanation, and prediction of natural systems in *uncertain* environments (such uncertainties may be due to measurement errors, heterogeneous data bases, erratic fluctuations in the space/time variation of the underlying processes, insufficient knowledge, etc.). Within such a framework, the main goal of SM has been to provide a realistic system with *spatiotemporal continuity* and *internal physical consistency*. To achieve such a goal, *SM* relies on the powerful blending of two components (Christakos et al., 2005):

(i) a *formal* component focusing on mathematical structure, logical process, and theoretical representations, with
(ii) an *interpretive* component concerned with applying the formal part in real-world situations, including the physical meaning of mathematical structure, specific observation methods and connections to other empirical phenomena.

Formal SM deals with a large variety of mathematical topics, including random fields, probability theory, stochastic differential and integrodifferential equations, random fractals and wavelets, space/time geometries, rules of logical reasoning, analytical and numerical means of calculation, estimation techniques, and multi-objective optimization theories, among others. The challenge of applying sophisticated SM techniques in environmental science is often not in the formal component itself, but in the appropriateness of the application and the validity of the interpretive component which goes beyond mathematics into the realms of common sense, physical knowledge and empirical observation. Interpretation issues are relevant when one needs to establish relationships (also called, *correspondence* or *operational* or *duality* rules) between the natural systems and the formal mathematics which describe them, to measure and test the formal structure, or to justify certain methodological steps (see, also, Section 4, below).

A fruitful interaction of formal and interpretive investigations lies at the heart of SM 's numerous successes in the physical sciences. The SM approach differs significantly from the classical statistics paradigm in this respect: the former is founded on *natural laws* and *phenomenological representations*, whereas the latter mainly uses formal techniques of pattern fitting (trend projection, regression analysis, sampling theory, etc.). This remarkable feature of SM enhances its scientific content and makes it a central force in the study of such diverse phenomena as flow and contaminant transport in porous formations, turbulence, ionospheric scattering, quantization analysis, and electromagnetic wave propagation through the atmosphere. In fact, most natural phenomena governed by field equations include situations that need to be treated from a SM viewpoint. In situations involving uncertain elements and random fluctuations, SM formally casts the governing physical equations into a stochastic form that may involve random field realizations, probability distributions, or space/time moments. As a result of their physical basis, these stochastic equations provide the means for sound *scientific inferences*, as opposed to merely statistical inferences (in terms of minimum variance, bias, efficiency, estimation and confidence tests, etc.; Bury, 1975). Celebrated early SM approaches based on physical laws include Maxwell's and Boltzmann's development of the kinetic theory of gases (in 1860 and 1896), Planck's derivation of the radiation law (in 1900), Gibbs' formulation of statistical mechanics (in 1901), Einstein's and Langevin's analyses of Brownian motion (in 1905 and 1908), Taylor's and von Karman's theories of turbulent motion (in 1921 and 1937), and Heisenberg's and Born's approaches to modern quantum mechanics (in 1925 and 1926). Interesting reviews of these historic SM works may be found in Beran (1968), Gardiner (1990), and Sklar (1993).

The essential connection between the formal and the interpretive components of SM described above has been astonishingly productive, in both ways: (a) formal techniques have generated the means for understanding natural phenomena beyond sense perceptions; and (b) interpretive investigations have produced new and more powerful formal techniques.

2. SM Metaphors and Reality Levels

It was Heidegger who said, "we cannot describe the real world without recourse to *metaphors*". Indeed, metaphors are essential ingredients for scientific exploration, and they have been used to extend scientific theories into new domains. Generally, the purpose of a metaphor is to probe and conceptualize unknown or little understood domains by means of more familiar quantities. Like most tools of scientific inquiry, SM makes use of metaphors by which it conceptualizes important environmental entities, such as space/time distribution, natural heterogeneity, biological variation, and uncertainty. The *spatiotemporal continuum* metaphor conceptualizes space/time as a set of points associated with a continuous spatial arrangement of events combined with their temporal order. SM associates a physical geometry to the spatiotemporal continuum; this is not a purely mathematical affair but depends on local properties of space/time and on physical constraints imposed by the environment. Hence, the space/time metaphor is instrumental in forming a useful picture of the real world. The *field* metaphor associates mathematical entities (scalars, vectors, or tensors) with sets of values of the natural processes at the space/time points. According to the *complementarity* metaphor uncertainty manifests itself as an ensemble of possible field realizations that are in agreement with what is known about the environmental phenomenon of interest.

Mathematization of the conceptual metaphors generally leads to *models*. For example, as we shall see in the following section, putting the three metaphors together, and translating them into the mathematical language we get the spatiotemporal random field model. Thus, metaphors play a central role in SM, for they allow the mathematical constructs of the formal component to be linked to the environmental phenomena of the interpretive component and to be regarded as scientific theories. On the other hand, the predictions obtained from these theories are non metaphorical, since they can be tested empirically. The implementation of metaphors in empirical investigations has made possible the derivation of a large number of useful models, which involve spatiotemporal random fields, stochastic partial differential equations, physical geometry, geostatistics, scaling techniques, knowledge integration principles, cause-effect associations, optimal decision-making, risk assessment, epidemic modeling, etc. (a relevant review may be found in Christakos, 1992, 2000; and in Christakos and Hristopulos, 1998, Christakos et al., 2005).

Metaphors have been shown to be instrumental in forming useful, realistic pictures of the actual phenomenon. Depending on one's conceptual system and its ability to function optimally in a given environment, different metaphors can be associated with a particular natural phenomenon, which, in turn, lead to different mathematical models of the situation. In fact, actual reality can only be observable or describable in terms of such models on different *levels*. In most cases, these modeling levels are not precise but rather useful pictures of the real world (e.g., Schommers, 1994). In SM these reality levels are arranged vertically in accordance with their degree of generality (Fig. 1a; the sequence of SM levels is denoted as "$\ldots, N, N+1, N+2, \ldots$"). Thus, a level with a higher degree of generality lies above one with a lower degree, in which case the former may be generated by improving the latter. A scientific law, e.g., belongs to a SM level which lies above the level of measuring

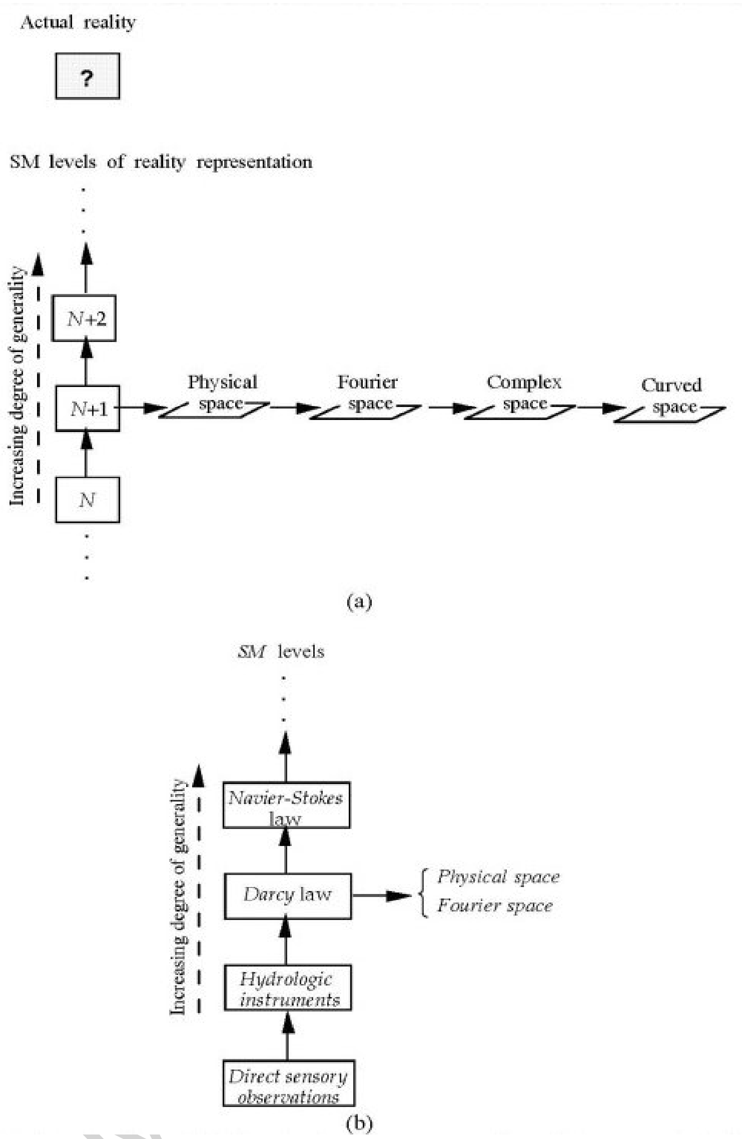

Figure 1: (a) Actual reality and SM levels of reality representation. (b) An example of SM levels from stochastic subsurface hydrology

instruments (allowing the observation of regions that are not accessible to the naked eye), which, in turn, lies above the level of everyday life observations (i.e., theory-free, direct sensory observations). This arrangement, basically, reflects Popper's view that the aim of science should be the development of laws and theories with higher degrees of *verisimilitude* (likeness to truth; Popper, 1934)). We may accept the view that all existing laws and theories are likely to be false and yet also holds that they are closer to truth than their predecessors. As a matter of fact, we usually have a series of scientific theories regarding the phenomenon of interest with varying degrees of generality and verisimilitude. Each one of these theories corresponds to a different conceptual metaphor and associated mathematical model, and using the one or the other should depend on the goals of our investigation. Clearly, no upper limit exists for the number of SM levels. In many cases, in addition to the vertical direction, a classification of models along the horizontal direction is also possible. Two or more SM developments are equivalent when they belong to the same level vertically, but are developed in different spaces horizontally. Therefore, a scientific law associated with a specific SM level may be established in various representation frames, such as the physical space, the Fourier space, the complex space, or the curved space (an example is shown in Fig. 1b). While they are structurally different from each other, all these frames are equivalent (from an information viewpoint) and belong to the same vertical position in the hierarchy of SM levels).

3. Spatiotemporal Random Field Models

Accurate representations of environmental exposure and its health effects in space and time are closely related to the adequate characterization of the natural variability of the media in which the pollutants are transported (both physical and biological), as well as the adequate processing of the information available regarding the essential parameters of the phenomenon. If these problems are not adequately addressed in risk analysis or in calculating pollution levels and clean-up times, erroneous policy decisions may be made (e.g., Sarewitz *et al.*, 2000). A powerful solution to this kind of problems is provided by the SM metaphors we discussed above. In particular, putting the three preceding metaphors (i.e., spatiotemporal continuum, field, and complementarity) together, and translating them into a mathematical language we get the *spatiotemporal random field* (STRF) model. This model plays a central role in all aspects of SM, for it allows the rigorous characterization of complex natural variabilities and uncertain effects, accounts for various sources of information and generates space/time maps of exposure to environmental pollutants and health effects. A visual representation of the basic concept underlying the random field model is given in Fig. 2. From a stochastic viewpoint, a STRF is fully characterized by its

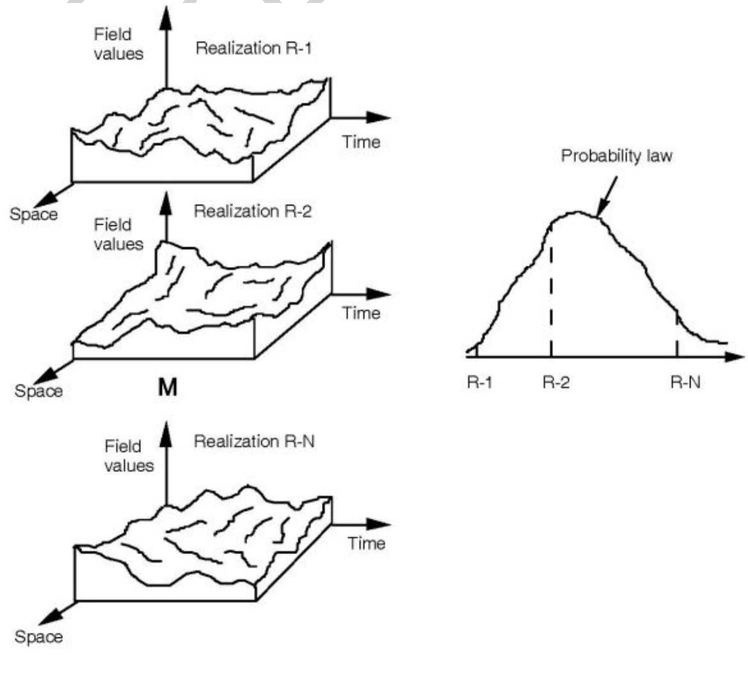

Figure 2: A representation of the random field model

multivariate probability law for all possible realizations. These realizations provide access into possible worlds that can become actual ones. Because it can investigate the different forms of space/time correlation that are allowed by the data, a random field model can provide multiple permissible scenarios (realizations) and can also characterize their likelihood for occurrence. Space/time variability is treated in an integrated manner that accounts for local non-linear trends, temporal non-stationarity, random spatial fluctuations, and their cross-effects.

There is a rich variety of *ordinary* and *generalized* STRF models that are used in environmental sciences. Various classes of such models are reviewed in Christakos (1992, 2000). In Fig. 3, a classification is shown on the basis of, (a) natural space/time

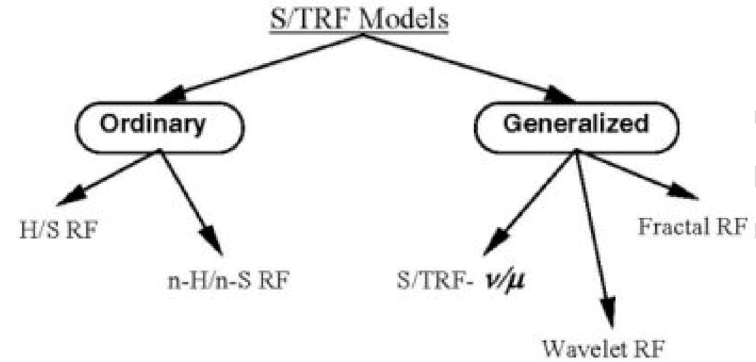

Figure 3: A classification of STRF models on the basis of natural space/time heterogeneity conditions and physical localization conditions. SH: spatially homogeneous/ TS: temporally stationary, SNH: spatially non-homogeneous/ TNS:temporally non-stationary, ν and μ parameters characterizing respectively the orders of spatial non-homogeneous and temporal non-stationary.

heterogeneity conditions (homogeneous/stationary vs. non-homogeneous/non-stationary patterns, space/time trends, etc.) and (b) physical localization conditions (local smoothness properties, etc.).

Other classifications --based on different criteria-- are also possible. In practice, the implementation of one specific STRF model over another depends on the form of space/time variations and natural heterogeneities considered. It may also depend on the correspondence rules that join non-observable terms (e.g., mean kinetic theory of gas molecules) with observational terms (e.g., temperature). These rules provide the means to calculate the statistics of non-observable quantities involved in a theoretical law from the statistics of the observable quantities of an empirical law. The functional form of these statistics will influence the choice of the STRF model to represent the phenomenon.

Random field representations of environmental pollutants and subsequent exposures can be combined with other types of information, such as population density, exposure duration, etc., in order to analyze sensitivity and assess the damage caused by population exposure. As we shall see in the following sections, random field models have led to considerable advances in the analysis and mapping of composite space/time heterogeneities, which are used in real world environmental and human health situations (analysis of water quality indicators, mapping of pollutant distributions, modeling of health effect variations, studying levels of excess over limits, etc.). Random field models have been, also, used in biology to represent embryonic formative processes. These fields are usually called morphogenetic. Each kind of cell, tissue, organ, and organism is assumed to have its own kind of field, which shape and organize developing micro-organisms and stabilize the forms of adult organisms on the basis of their own spatiotemporal organization (Sheldrake, 1988).

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