Abstract—In this essay we point out the current problems in the modeling of complex biophysical systems, particularly in environmental fluid mechanics, which requires quite new methodological and mathematical approaches. We give a short overview of some epistemological attitudes arisen from the 20th century onwards, which have converged on establishing of endophysics. Then, we generally discuss the establishment of the relations between the two different kinds of reasoning (causal and inferential) by pointing out a possibility of using two-state (teleological) model in modeling of complex systems. Using an example from environmental fluid mechanics, i.e., solving the energy balance equation for the Earth-atmosphere interface, we show that uncertainties can occur in predictions because of non-linear relations in the system under consideration.

Key-words: environmental fluid mechanics, endophysics, complex systems, modeling, epistemology, non-linear processes, deterministic chaos, teleological dynamics

1. Introduction

Regardless of the word “balance” being used either globally or locally in any given context, it is undoubtedly the keyword in the increasing number of environmental problems. The underlined sketch is a proper introduction to the question: Why are the environmental problems in the focus now? One particular answer can be found in the hierarchy of the main scientific problems of the 21st century, as seen by the community mostly consisting of physicists. According to them, in the 21st century the world of the scientific community will be occupied by the problems linked to superconductivity, quantum teleology, and

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environmental problems that are primarily expressed through the problem of climate changes. A unique characteristic of these problems is their close connection with the questions of different aspects of the existence of individual human being, i.e., the questions of technological capability, origin of the consciousness and survival on the Earth. This is the first time in the history of science, when the environmental problems take the place at the front of the sciences. The question, why it is happening now and why it will go on happening in the future, could be answered by the well known fact, that in the scientific as well as in other worlds the main “drama of event” takes place at the interface between either two media or two states (Mihailovic, 2006).

The field of environmental sciences is abundant with various interfaces, and it is the right place for application of new fundamental approaches leading towards better understanding of environmental phenomena. We defined the environmental interface as an interface between the two either abiotic or biotic environments, which are in a relative motion exchanging energy through biophysical and chemical processes and fluctuating temporally and spatially regardless of its space and time scale. To our mind, this definition broadly covers the unavoidable multidisciplinary approach in environmental sciences and also includes the traditional approaches in sciences, that are dealing with the environmental space less complex than any one met in reality. The wealth and complexity of processes at this interface determine that the scientists, policy-makers, and the public, as it often seems, are more interested in a possibility of non-linear dislocations and surprises in the behavior of the environment than in a smooth extrapolation of current trends and a use of the approaches close to the linear physics. To overcome the current situation we have to do the following: (a) to establish a way in approaching non-linear physics and the non-linearity in describing the phenomena in environmental sciences, and (b) to solve or, at least, understand the problem of predictability. These two problems are par excellence problems of the methodology. Their successful solving will help us to avoid the current problems in mathematical, biophysical, and chemical interpretation of the nature, as well as in design of corresponding software. The environmental discipline that will be under consideration in this essay is the environmental fluid mechanics dealing with a broad range of environmental problems, which are, for example, picturesquely described and defined in Cushman-Roisin et al. (2006). Because of the thought behind this essay, this definition will be given in detail.

All forms of life on earth are immersed in a fluid, either the air of the atmosphere or the water of a river, lake, or ocean; even soils are permeated with moisture. So, it is no exaggeration to say that life, including our own, is bathed in fluids. A slightly closer look at the situation reveals further, that it is the mobility of fluids that actually makes them so useful for the maintenance of life, both inside and outside living organisms. For example, it is the flow of air through our lungs that supplies oxygen to our blood stream. The forced air flow
created by our respiration, however, is not sufficient. Namely, without atmospheric motion around us, we would sooner or later choke to death with the carbon dioxide exhaled by ourselves. Likewise, most aquatic forms of life rely on the natural transport of water for their nutrients. Our industrial systems, which release pollution on a continuing basis, would not be permissible in the absence of transport and dilution of nearly all emissions by ambient motions of air and water. In sum, natural fluid motions in the environment are vital, and we have a strong incentive to study the naturally occurring fluid flows, particularly those of air in the atmosphere and of water in all its streams, from underground aquifers to surface flows in rivers, lakes, estuaries, and oceans.

The study of these flows has received considerable attention over the years, and several distinct disciplines have emerged: meteorology, climatology, hydrology, hydraulics, limnology, and oceanography. Whereas the particular objectives of each of these disciplines, such as weather forecasting in meteorology and design of water-resource projects in hydraulics, encourage disciplinary segregation, environmental concerns compel experts in those disciplines to consider problems that are essentially similar: the effect of turbulence on the dispersion of a dilute substance, the transfer of matter or momentum across an interface, the flow in complex geometries, the rise of a buoyant plume, and the impact of flow over a biotic system. The common points encourage interdisciplinarity to a degree, that it is increasing in proportion to the acuteness of our environmental problems. This overlap between various disciplines concerned with the environmental aspects of natural fluid flows has given rise to a body of knowledge, that has become known as environmental fluid mechanics.

This short essay aims just to point out the current problems in modeling of complex biophysical systems, particularly in environmental fluid mechanics, that require quite new methodological and mathematical approaches.

2. A short overview of some epistemological points from the 20th century onwards

Until recently, discussions about scientific truth were filled with numerous metaphysical assumptions. They usually converged at one question (more or less explicitly stated): “How can we reach objective truth about natural processes?” However, during the 20th century, this question first became less important and then gradually disappeared from the epistemological scene as a relict from the age of naive realism. Now, in contemporary epistemology of science, it is well established that there is a fundamental difference between phenomenon and noumenon. Therefore, the object of scientific analysis cannot be the nature by itself, but only highly constructivistic products, i.e., conceptually embedded sets of observer’s experiences. Accordingly, scientific theories are now understood
as logical instruments of organization of human thought, through which we can interpret and organize experimental laws (Nagel, 1961). Also, since they have constructivistic character, their relation to the nature should not be considered through the vocabulary of logic; they are not truth statements and they are not logical derivatives of observed facts, but only sets of rules and guiding principles for analysis of empirical facts (Nagel, 1961). Therefore, in the development of a scientific theory, it is not a problem to make approximations that can never reach reality. It is inevitable. But believing that relations of abstractions are exactly the same as relations in nature can be very problematic. Firstly, it can usually become a source of unfruitful debates about the “true” nature of the nature. Secondly, from such a perspective it is impossible to see and analyze the consequences of the interface perspective, where the observer is within the universe he observes.

A clear example of both mentioned problems can be found in the development of the contemporary physics. At the very beginning of the 20th century, Pierre Duhem asserted that physical theories are not simple (straightforward) reflexions of natural processes, but rigorous logical systems, which operate with abstract symbols and which are connected with nature through system of measurements and scales (Duhem, 1906). Such approaches put forward the process of encoding of natural processes into the domain of formal systems, as the first and crucial step in the development of a physical theory. However, in his opinion, a pattern of encoding depends almost entirely on the previously accepted theories. Therefore, empirical observations cannot be separated from the current state of affairs in a given scientific discipline, since theoretical assumptions determine what will be observed, how it will be observed, and how results will be interpreted. Although Duhem’s approach can be characterized as conventionalism, his contribution to the general trend of development of thought in theoretical physics remains immense.

Few decades later, the explosive growth of quantum mechanics raised some fundamental questions about the status of observation in physics, and how our measurement procedures can affect the observed physical properties (“measurement problem”). In short, Einstein, opposing the Copenhagen interpretation of physical properties of quantum systems, claimed that under ideal conditions, observations reflect the objective physical reality (Einstein et al., 1935). On the other hand, Bohr asserts that in quantum mechanics the measured quantum system and the measuring macroscopic apparatus cannot be considered as separate within a scope of scientific consideration. In other words, the physical properties of quantum systems are essentially dependent on the applied experimental apparatus. One of the most famous moments of the debate is now well-known as Einstein-Podolsky-Rosen paradox (Einstein et al., 1935). In the short paper they showed, that if the quantum mechanic description of reality is complete, then the non commutable operators corresponding to two physical quantities can have simultaneous reality. In other words, quantum
mechanics is inconsistent with the reduction of the wave-packet postulate. Later, Bell (Bell, 1964) revealed, that the EPR paradox stands only under the set of supplementary assumptions, among which there is the assumption of locality. Moreover, within quantum mechanics there is no need to accept them all. Although it can look like a closing chapter in the debate on “measurement problem”, this question evolved from the limited scope of quantum mechanics and took a more general form: “how the observations are affected by the fact that the observer is within the universe he observes?”. This is certainly not a new question in the history of human though, but (until recent partial attempts) in the natural sciences it never gets a formal explanation. In philosophy, after Kant, it is one of the elementary topics, in developmental psychology Piaget clearly demonstrated, that elementary categories of human thought are construed during one’s development, and how externality of cognitive entities is re-structured in accordance with its functional purposes through the process of assimilation of external changes with the operative schematism of that entity (Piaget, 1973a; Piaget, 1973b), and finally, in the world of logic and formal systems, Gödel shook the scientific community with his proof of incompleteness of formal systems (for extensive discussion see Nagel and Newman, 1958; Rosen, 1991). Now, in the natural sciences this problem is finally recognized and dispersed attempts of its formal treatment fall under the umbrella of discipline called endophysics. This term was originally suggested by David Finkelstein in personal communication with Otto Rössler. Later, it was comprehensively elaborated in details by Rössler (1998), although his magnum opus is loaded with inconsistencies.

We see the outside world, i.e., the world of phenomena (ambience) from the observer’s perspective (its inner world). In the ambience there are systems of different level of complexity and their environments. A system in the ambience is a collection of precepts while whatever lies outside, like the component of a set, constitutes the environment. The fate of science lies in the fact that it is focused on the system (Rosen, 1991). Furthermore, to anticipate something, the system gets described by states (determined by observations), while the environment is characterized through its effects on the system. The trend in contemporary science and mathematics is to try to dispense with extralinguistic referents entirely and replace them with purely syntactic structures, that only recognize and manipulate the symbols out of which the propositions are built. This process is called formalization (Kleene, 1952). The crucial thing to bear in mind is that both theory and any formalisation of it are the systems of entailment. It is the relation between them, or more specifically, the extent to which these schemes of entailment can be brought into congruence. That is of primary interest. The establishment of such congruences is the essence of the modeling relation (Rosen, 1991). In the precise sense, the incompleteness theorem of Gödel asserts that formalization, in which each entailment is a syntactic entailment, is too poor in entailment to be congruent with the number
theory, no matter how we try to establish such a congruence. This kind of situation is termed complexity (Rosen, 1977). In this light, Gödel’s theorem says that the number theory is more complex than any of its formalizations. Following the message and the fundamental consequences of this theorem, we call the complex system such a system that is more complex than its any formalization.

Fig. 1. Schematic diagram representing both (i) comparison of two formalisms $F_1$ and $F_2$, and (ii) modeling relation when we have given a natural system $N$, and a formal system $F$.

Fig. 1 schematically depicts a comparison of two formalisms $F_1$ and $F_2$. To compare two formalisms we need to make two dictionaries. The first of them, which translates from $F_1$ to $F_2$, is an **encoding** dictionary while the other, translating from $F_2$ back to $F_1$, is a **decoding** dictionary. Let us note, that we do not require any relation at all between them. If we find the encoding and decoding for which the diagram of Fig. 1 always commutes, in such a case, we have in fact brought at least a part of the inferential machinery of $F_1$ into congruence with a corresponding part of the inferential machinery of $F_1$. We will then say that $F_2$ is a **model** of $F_1$, or equivalently, that $F_1$ is a **realization** of $F_2$. Also we can say that a **modeling relation** exists between the two inferential structures. We can use the inferential structure of the model to study its realization, to **predict**, in effect, from the encoded hypothesis (via the pathway $2 + 3 + 4$ in the diagram in Fig. 1), theorems of $F_1$ from theorems in $F_2$. In mathematics, there are a lot of procedures of formal modeling of one kind of inferential structure into another. It seems that the category theory comprises, in fact, the general theory of formal modeling, the comparison of different modes of inferential or entailment structures.

Fig. 1 also schematically depicts a modeling relation, when a natural system $N$ and a formal system $F$ are given. As before, the two arrows represent the respective entailment structures; inference in formalism $F$, causality in $N$. Now, the two established dictionaries provide an encoding of the phenomena of $N$ into the propositions of $F$ and a decoding of the propositions of $F$ back to the phenomena in $N$. As we said before, there are two paths in the diagram: (1) and (2) + (3) + (4). According to Rosen (1991), the first of them (the path (1)) represents a causal entailment within $N$ (what an observer, simply sitting and watching what happens, will see). The arrow (2) encodes the phenomena in $N$ into the propositions in $F$. In this route we must use these propositions as hypothesis, on which the inferential machinery of the formal system $F$ may operate (denoted by the arrow (3)). It generates theorems in $F$, entailed precisely by the encoded hypotheses. Finally, we have to decode these theorems back into the phenomena of $N$, via the arrow (4). At this point, the theorems become **predictions** about $N$. Then the formal system $F$ is called a **model** of the natural
system N, if we always get the same answer, regardless of the fact, whether we follow path (1) or path (2) + (3) + (4).

Finally, in this section we cannot avoid the question of time in the modeling relation. A usual approach in physics is that the present state is strictly a result of its evolution from the past. However, recently it has been shown that some phenomena in the real world can be explained, if we accept that the present state of a system is defined by its past, in the sense that the past determines the possible states that are to be considered, and by its future, in the sense that the selection of a possible future state determines the effective present state (Nedeljkovic and Nedeljkovic, 2003a; Nedeljkovic and Nedeljkovic, 2003b among others); regarding that a concise and illustrative differentiation between causal and teleological dynamics is given by Van Loocke (2002). According to them, in a large part of the present-day physics, the fundamental physical laws are compatible with the teleological as well as with the causal dynamics (the term ‘causal’ is used in the restricted sense of ‘governed by influences from the past’). Considering a system that is characterized by a set of variables \( x_i(t) \) \( (I = 1,\ldots,n) \), where \( t \) is the time variable, he makes a differentiation between the causal and the teleological dynamics by the following definitions:

(1) A system behaves causally and deterministically if there is a law that determines the values of \( x_i(t) \) given the values of \( x_i(t-1) \) at the previous time step.

(2) A system behaves causally and non-deterministically, if there is a law that produces the probability distributions for possible values of \( x_i(t) \) giving the probability distributions for possible values of \( x_i(t-1) \) at the previous time step.

(3) A system is teleological and deterministic if there is a law that determines the values of \( x_i(t) \) giving the values of \( x_i(t+1) \) at the next time step.

(4) A system is teleological and non-deterministic, if there is a law that produces the probability distribution for possible values of \( x_i(t) \) giving the probability distributions for possible values of \( x_i(t+1) \) at the next time step. We will not further speculate with the question about time. This is just a short reminder for the environmental fluid mechanics community that, in the modeling of complex biophysical processes, we should bear in mind a possibility of using two-state (teleological, Nedeljkovic and Nedeljkovic, 2003a) models.
3. An example of modeling at the Earth-atmosphere interface

There is still no information available in the environmental fluid mechanics literature about the application of the methods and approaches of the endophysics as mentioned in Section 2. Recently Sivertsen (2005) discussed the hypothetico-deductive principle, bearing in mind an observer who looks at the ambience representing the biological world. More precisely, he was dealing with a biological system reacting to the atmospheric environment through meteorological parameters. The outcome of the discussion in this paper, which is an extension of the work in Sivertsen (2004), is a proposal of a documentation system for the quantitative meteorological and biological parameters, either measured or the parameters derived by model calculation. Undoubtedly, a growing demand for modeling of more complex systems in environmental fluid mechanics will shift the attention towards the endophysics and the methods of modeling of the complex systems. In this section, we will give an example of the modeling at the Earth-atmosphere interface. In particular, we will point out some uncertainties, which can occur in prediction, because of the non-linear relations in system under consideration.

Environmental fluid mechanics modelers base their calculations on mathematical models for simulation and prediction of different processes, which are exclusively non-linear, describing relevant quantities in the field of consideration. Many investigators, for example Boccaletti et al. (2000), have proved that complex dynamical evolutions lead to chaotic regime. Finite precision computer realizations of non-linear models give unrealistic solutions, because of the deterministic chaos, a direct consequence of round-off error growth in iterative numerical computations, which doubles on average for each iteration of iterative computations. Round-off error propagates to the mainstream computation and gives unrealistic solutions for different geophysical models, which incorporate thousands of iterative computations in longer-term numerical integration schemes (Selvam and Fadnavis, 1998). Also, in solving of the model partial differential equations, depending on numerical procedure, the problem of sensitivity to initial conditions may occur. Namely, a small “tuning” of initial conditions may lead the numerical model to instability, if the system is a chaotic one. The aforementioned instabilities can be generated in temporal fluctuations on all space-time scales ranging from turbulence to climate. These kinds of uncertainties take place preferably at the interface between two mediums in geophysical space (Mihailovic et al., 2001). The land-atmosphere interface is a suitable area for the occurrence of irregularities in the temporal variation of some geophysical quantities. Here we will analyze the occurrence of deterministic chaos in the surface temperature obtained by solving the energy balance equation, which describes the exchange of energy at the land-atmosphere interface.
Solar radiation provides almost all of the energy received on the surface of the Earth. Some of the radiant energy is reflected back to space. The Earth also radiates, in the thermal waveband, some of the energy received from the sun. The quantity of the radiant energy remaining on the earth surface is the net radiation \( R_n \) (the net radiation energy available on the surface, when all inward and outward streams of radiation have been considered). The net radiation drives certain physical processes important to us. The energy balance may be expressed as

\[
C_g \frac{\partial T_g}{\partial t} = R_n - H - \lambda E - S - PS - M, \tag{1}
\]

where \( C_g \) is the surface heat capacity, \( T_g \) is the surface temperature, \( S \) is the flux heat out of the soil, \( H \) is the flux of sensible heat between the surface and air, \( \lambda E \) is the flux of sensible heat between the surface through vaporization (evaporation) of water condensation, \( PS \) is the energy fixed in plants photosynthesis, and \( M \) is the energy involved in a number of miscellaneous processes as respiration and heat storage in the crop canopy. Eq. (1) is applicable on the scale of a single plant or cropped field, explaining how energy is provided to warm up the soil crop and to evaporate water. The equation is not less valid on the global scale, explaining how energy is provided to the continents and oceans, where vast quantities of heat and vapor are delivered to or extracted from the atmosphere (Rosenberg et al., 1983). Neglecting terms \( M \) and \( PS \), which have much smaller values comparing to other terms, leads us to the equation (Mihailovic and Lalic, 2006)

\[
C_g \frac{\partial T_g}{\partial t} = R_n - H - \lambda E - S, \tag{2}
\]

that is more appropriate for further analysis. In the resistance representation, the last equation gets the form

\[
C_g \frac{\partial T_g}{\partial t} = C_R \left( T_g - T_r \right) - C_L \left[ E(T_g) - e_r \right] - C_H \left( T_g - T_r \right) - C_D \left( T_g - T_r \right), \tag{3}
\]

where the symbols introduced have the following meaning: \( C_R \) is a constant in the net radiation term (Bhumralkar, 1975; Holtslag and van Ulden, 1983), \( T_r \) is the air temperature at the reference level, \( C_L \) is the water vapor transfer coefficient, \( E(T_g) \) is the saturated water vapor pressure at the surface temperature, \( e_r \) is the water vapor pressure at the reference level, \( C_H \) is the heat transfer coefficient, and \( C_D \) is the coefficient of conduction. To solve Eq. (1) numerically, for simplicity we use the foreword difference scheme, as it is usual in environmental fluid mechanic modeling, which has the form

\[
T_g^{n+1} = T_g^n + \Delta t F^n / C_g, \tag{4}
\]
where $F^n$ is the right hand side term of Eq. (1) at the $n$th time step, while $\Delta t$ is the time step. Because Eq. (1) is a non-linear partial differential equation, it could be expected that its solution exhibits not only periodic but even chaotic behavior under some conditions. One set of those conditions leading to chaotic behavior of the surface temperature is considered in Mihailovic (2006). Under those conditions, Eq. (3) can be written as

$$\frac{\partial \xi}{\partial t} = [a_c - C_L b E(T_r) / C_g] \xi - [C_L b^2 E(T_r) / 2 C_g] \xi^2,$$

where $a_c = C_R - C_H - C_D$ and $\xi = T_g - T_r$, while $b = 0.06337$ J K$^{-1}$ is a constant for temperatures around 20°C (Hrigan, 1978), which occurs in expanding the expression for $E(T_g)$ in Taylor’s series. If we write Eq. (5) in the finite difference form, we reach the equation having the form

$$\xi_{n+1} = A_1(C_g) \xi_n - A_2(C_g) \xi_n^2,$$

where the symbols introduced have the following meaning

$$A_1(C_g) = (C_R - C_L b E(T_r) \Delta t / C_g) + 1$$

and

$$A_2(C_g) = C_L b^2 E(T_r) \Delta t / (2 C_g).$$

Eq. (6) is one form of the so-called logistic equation. As a non-linear equation, it can produce a chaotic solution for some values of $A_1$ and $A_2$. It is very interesting to analyze Eq. (6), in the $(L, \Delta t)$ phase space, for different values of $A_1$ and $A_2$. Here we define the Lyapunov exponent $\lambda_L$ for this equation, which has a single degree of freedom $\xi$ depending on discrete “time” $n$. It has the form

$$\lambda_L = \lim_{n \to \infty} \frac{1}{n} \sum_{j=1}^{n} \ln \left| F' \left( \xi_n \right) \right|,$$

where $F(\xi) = A_1(C_g) \xi - A_2(C_g) \xi^2$.

Fig. 2. Dependence of Lyapunov exponent $\lambda_L$ on soil surface heat capacity $C_g$ (Mihailovic, 2006).

Fig. 2 depicts the changes of exponent depending on the variation of the surface heat capacity. It is seen from this figure, that the considered dynamical system, i.e., the soil-atmosphere interface, mostly exhibits chaotic behavior manifested through the positive value of $\lambda_L$, while the soil surface heat capacity takes the values from the 92,500–107,500 J m$^{-2}$ °C$^{-1}$ interval. Outside of this interval the considered system is stable, since the Lyapunov exponent takes the negative values. This example points out, that the way to the phenomenon of N via the arrow (4) in Fig. 1 is not a simple one, even in the case of a relatively
simple model. In other word, that attempt is methodologically difficult in the non-linear world.

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References

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