Integrating simulation models into environmental information systems - model analysis

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Abstract

Although environmental information systems have become very popular, the use of simulation models within such systems has not increased at the same rate. Mostly, new and specialized models will be implemented rather than integrating existing ones. This mainly results from the absence of helpful documentations and knowledge about the admissible spatial and temporal scales of the models.

This article mainly deals with the necessary steps to analyze simulation models. In particular, the application of long-term simulations (e.g. Global Change) demands precise mathematical knowledge about a models' specific behaviors. similar to signal processing, various methods for analyzing and filtering are necessary to protect model systems against intrinsic conflicts, e.g. interfering scales.

In this text we focus on model analysis with the Wavelet transformation. Utilizing this technique, the detection of periodicities within model inputs and outputs is possible. Similar to the Fourier transformation, the Wavelet analysis effects a scale-by-scale decomposition of time series or spatial data. But, in contrast to spectral analysis, the Wavelet transformation retains location information. Concluding with an example, this article shows that the Wavelet approach meets the requirements of model analysis.

Keywords

environmental information systems, simulation models, wavelet transformation

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1 INTRODUCTION

Producing information from interdisciplinary data is a major goal of integrated environmental information systems. Environmental assessments, sustainable development and climate change research demand long-term simulations with the help of complex model and information systems. Furthermore, an efficient connection to databases and geographic information systems for the purpose of data acquisition is desirable. But unfortunately, there are only a few special purpose information systems which satisfy these requirements. More often, new models are implemented rather than reusing existing ones because of the lack of documentation and knowledge about the admissible temporal and spatial scales of the model. For the same reason, the linking of models to more complex systems was rarely done in the past. So, it is not a real surprise, that simulation models did not find the way into municipal or authoritative environmental information systems yet, as e.g. Fürst (1995) stated. To improve this situation, we have developed a sophisticated model analysis method, which bases on Wavelets. This text should give a first impression about its opportunities and advantages in contrast to other analysis approaches. We start with a short description of our project to introduce the environment in which this approach has been developed.

2 THE ENVIRONMENTAL INFORMATION SYSTEM KERIS

The environmental information system KERIS (Kiel Ecosystem Research Information System) is presently under development at the Ecology Center of the University of Kiel, Germany (Clemen, 1996). Since 1988, a lot of interdisciplinary work has been done in the main research area at the Bornhoeved Lake District in Schleswig-Holstein in northern Germany. The measurements and the additional step of modeling of parts of the ecosystems result in a bulky mass of data, digital maps, and simulation models. KERIS was designed to cope with this information. It was useful to split the design model of KERIS into three layers. The bottom layer is called the *kernel*. It includes databases, a geographical information system, and a set of simulation models. In the first step of integrating such heterogeneous data objects, a hierarchically organized thesaurus was implemented within the second part of KERIS, the *service* layer. Each data item receives a set of well defined keywords. With the help of the navigation tool EcoRISK (Hansen and Katofsky, 1996; Dieckmann et al., 1995) a keyword-oriented access to database tables, digital maps, the documentation of simulation models, and various other information has been provided. In addition, an ecosystem process description structure was established. It consists of a set of matrices which describe the different fluxes of matter, energy, and information within and between ecosystems. The thesaurus and the matrices set up a powerful information 'turntable' within KERIS. The topmost (*application*) layer contains the user interfaces of KERIS. Each of them realizes a different view to the system depending on the aim and the knowledge of the specific usergroup. We are working on designing unified graphical model interfaces as well as on the documentation of models (Asshoff et al., 1996), and their mathematical analysis. This paper mainly deals with the latter.

3 THE WAVELET APPROACH

The integration of simulation models into environmental information systems and their link-up with other simulation programs to model systems, demands precise knowledge about their mathematical behavior. Supposable, the lack of this knowledge and the respective documentations about the admissible spatial and temporal scales of the models has prevented their integration into information systems in the past. For Rykiel (1996) gives a very comprehensive overview about the validation of simulation models, we can start immediately with the validation criteria we particularly used.

Usually, ecosystem processes depend on high-frequency as well as on low-frequency fluctuations. We are testing the frequency spectra of the model input and output, and frequently check them against the spectra of observed data. To determine the input/output spectra of a model, one may use the Fourier transformation. Unfortunately, this transformation method is global, i.e. important localization information corresponding to the original signal is lost. Thus, you may detect which frequencies are included in the signal, but you cannot realize where they occur.

The Wavelet transformation, which has been developed by Daubechies (1988) recently, retains this location information. Therefore, this method is used in several disciplines, like image processing, geophysics, or medicine. One of the first applications in ecology can be found in Gao and Li (1993). The first Wavelet supported model analysis was proposed in Clemen (in print).

While the Fourier transformation convolutes the input signal with infinite trigonometric functions, the Wavelet transformation uses limited Wavelets which vary in phase and width. Consider the definition of the Wavelet transformation Ψ_p of a signal $h(t)$:

$$\Psi_p(a, b) = \int_{-\infty}^{\infty} h(t) g_{a, b, p}(t) dt = \frac{1}{a^p} \int_{-\infty}^{\infty} h(t) g\left(\frac{t-b}{a}\right) dt. \tag{1}$$

The dimensionless dilatation parameter a ($a \in \Re^+$) defines the width and the amplitude of the Wavelet *g(t)*. b ($b \in \Re$) is called the translation parameter and marks the origin of the shifted Wavelet. In literature, the parameter p ($p \in \Re$) is mainly set to $p = 1$ or $p = 1/2$ (Collineau and Brunet, 1993). The so called 'mother Wavelet' *g(t)* is defined by a real or complex valued function with a mean value of zero and finite energy (e.g. the first and second order derivation of the Gauss function).

From an informal point of view, the transformation algorithm 'compares' the original signal with a set of dilated and shifted Wavelets. Similar to other correlation and cross-correlation functions, maximum values result from maximal correspondence. This algorithm produces an $a \times b$-matrix. Each vector represents a well-defined frequency; in terms of ecology you may also speak of a well-defined scale. Usually, a graphical plot of the matrix emphasizes dominant scales and their localization within the signal. Sometimes it may be useful to integrate across the translation parameter b to sum up all portions of a scale. The result is called the Wavelet variance and looks similar to other periodograms. In combination with the original transformation matrix it may give an impression about the qualitative influence of dominant scales due to the signal.

4 EXAMPLE

This example is taken from the FEUWA model which is described in Kluge and Theesen (1996). FEUWA is one part of a model system which aims to quantify the transfers and buffer functions of spatial compartments between terrestrial and aquatic ecosystems (ecotones). For the use in this paper we simulated the water level in an alder bog over the period between June, 15th, and September, 19th, 1990. This ecotone represents the transition between a terrestrial slope ecosystem and a lake. Hence, it will be influenced by both systems in different manners.

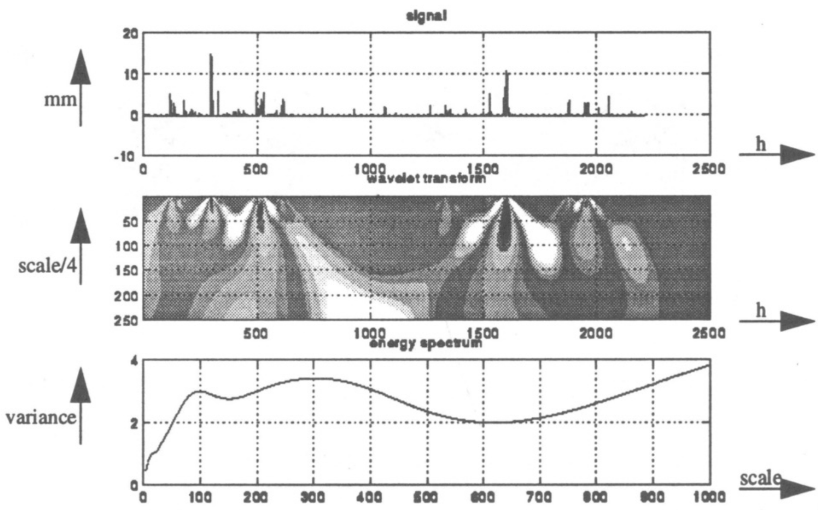

Figure 1 Precipitation (measured [mm/h])

We start the analysis of the model with some considerations about four important input streams. Notice, that all figures consist of three diagrams. The topmost one

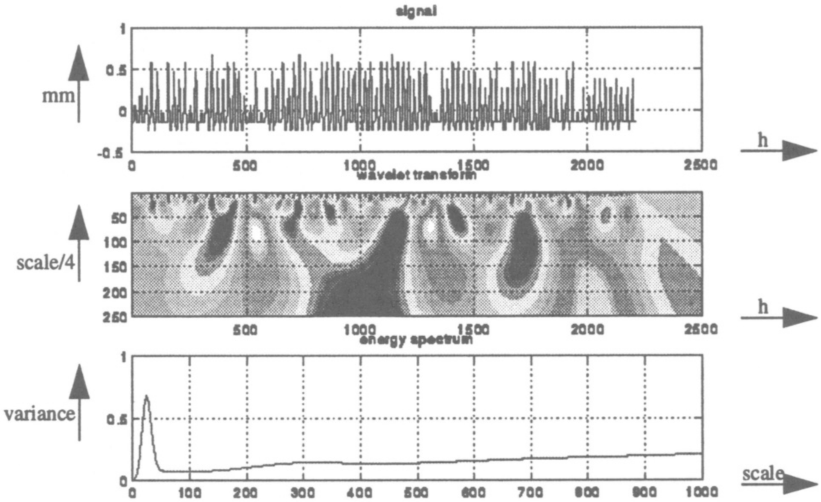

Figure 2 Actual evapotranspiration (measured [mm/h])

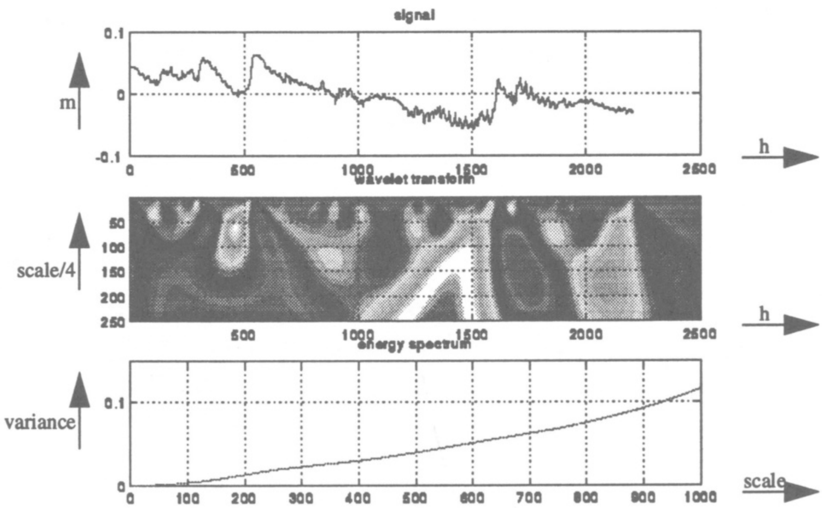

Figure 3 Groundwater level of the slope (measured [m])

displays the original signal. The mean value was removed because of representation reasons. Beneath, one finds the Wavelet matrix, which is followed by the according Wavelet variance.

The figures 1 to 4 display the four most sensitive input streams of the model:

1. Precipitation:
   Dark values in the Wavelet matrix reflect strong precipitation events. The

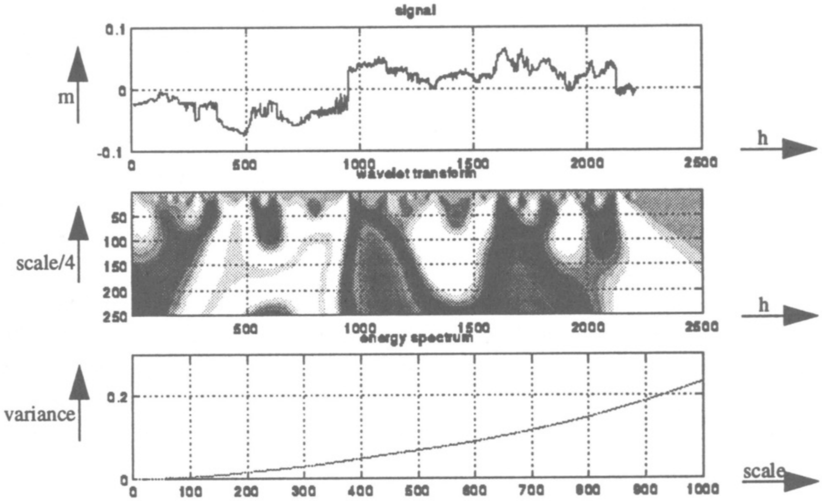

Figure 4 Water level of the lake Belau (measured [m])

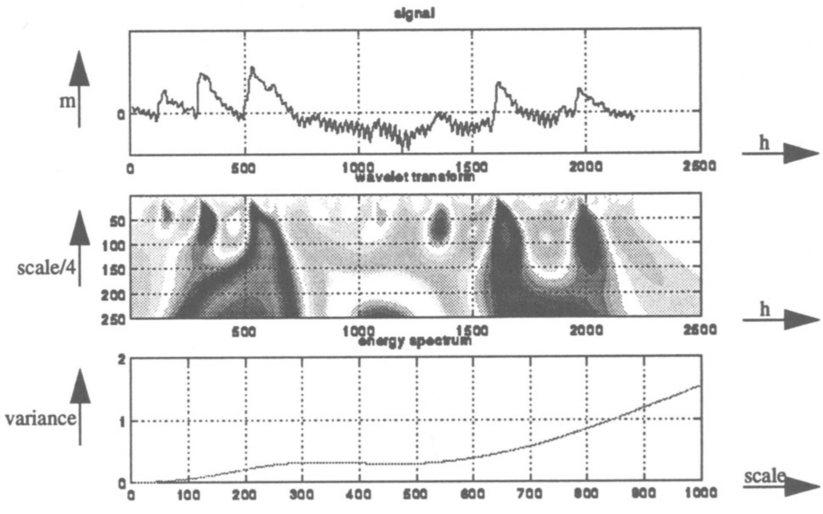

Figure 5 Water level of alder bog (simulated [m])

Wavelet variance shows three peaks: 30 hours, about 100 hours, and about 310 hours. Exceptionally, these values do not mean 'real' periodicities but the average duration of precipitation events.

2. Actual evapotranspiration
Not surprisingly, the diagram shows a dominant peak on 24 hours.

3. Groundwater level of the slope/water level of Lake Belau
   Depending on the properties of the ecosystem, precipitation events results in more or less high peaks. They are followed by significant peaks due to evapotranspiration.

Figure 5 shows one result of the simulation process. The operational buffer effect between the slope and the lake, will becomes clearly, if one compares the major peaks within the Wavelet matrices of the Figures 3 to 5. Strong dark regions correspond to ascendant gradients within the signal, whereas bright regions mark descendent gradients. In particular, the evapotranspiration event at about 1100 hours and the strong precipitation events at about 300, 500, 1600, and 1850 have influenced the results in a significant manner. In our further work, we have to test, if the Wavelet matrix of the simulated water level matches that one of observed data. Anyway, it can be stated, that FEUWA describes the buffer process for a small temporal and spatial scale sufficiently correct

5 CONCLUSIONS

We hope, it becomes clear, that the wavelet analysis will help to detect natural as well as disliked gradients (and frequencies) within the input or output of simulation models. Some readers may criticize, that the results of the Fourier transformation looks similar to those of the Wavelet variance. These colleagues have to take into account, that the preservation of the original localization with respect to the input signal is certainly a big advantage in contrast to the Fourier algorithm.

But even though the results of our approach look very promising, we have to check some mathematical properties in the future. How does the shape of the mother Wavelet influences the results of the wavelet transformation? Why does the energy spectra sometimes hide some scale information?

Another point of interest is the utilization of these results within environmental information systems. In terms of the design model of KERIS, this paper deals with aspects of the *kernel* layer, only. But the consequences in respect to the *service* and the *application* layer are still open presently. Nevertheless, the future will show, if such powerful methods will increase the integration of simulation models into environmental information systems. In addition, this Wavelet approach may also be one step, to define a generally accepted method to model validation.

6 ACKNOWLEDGMENTS

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8 BIOGRAPHY

Thomas Clemen is the leader of the working group for environmental computer sciences and information systems at the Ecology Center of the University of Kiel, Germany. He graduated in computer sciences at the University of Dortmund in 1993. After spending one year in a wilderness cabin in the Yukon Territories in Canada, he is currently working on the integration of ecological simulation models into environmental information systems. This year, he is giving a lecture on environmental computer sciences and simulation at the University for Applied Sciences (Fachhochschule) in Hamburg.