CHAPTER 5

5.0 Summary and Outlook

The primary goal of this book is to provide a current, state-of-the-art review of coupled modelling within hydrology and in integrated Earth system models at a level appropriate for graduate students entering the field. Then, on the basis of this review, to assess the value of coupled modelling, to clarify where and when their use is appropriate and beneficial, and to identify areas of opportunity and need. A systematic procedure for representing a complex, interacting system using coupled models has been attempted. In addition, the book documents examples of the application of coupled models to show how such models can be used in practice within hydrology and related sciences.

5.1 When and Why is it Appropriate to Use Coupled Models?

This book discusses many issues on the motivations for and methodologies employed when creating complex models. It is important to assess whether there is a need for a complex coupled model when addressing a specific task. Increasingly, hydrologists are asked to perform integrated analyses of environmental interactions that involve feedbacks between atmospheric, ecological and hydrological systems, as well as human society. In such cases, it is often the feedbacks between systems that are of greatest interest because they may produce unanticipated responses in a range of processes in reaction to natural or human-induced changes.

In generic terms, typical situations can be specified in which the application of coupled models is essential, for example, when:

- It is not feasible, economic, or accurate to impose a boundary between compartments in the modelled hydrogeobiosphere system and thereby isolate them;
- Observations of two or more state variables that are coupled cannot be modelled simultaneously without the processes that couple them also being included in the model;
- The science that is being addressed is beyond the normal range of activity and interest of specialists in individual coupled processes, and unforeseen whole-system behaviour may occur due to inherent non-linearity and/or non-linear feedbacks implicit in the coupling;
- Assessing the vulnerability and risk of coupled systems, as an alternative to the more conventional paradigm of forecasting.

Experiences within integrated assessments based on using coupled models have also shown that adopting a systematic procedure, or at least a well-defined coupling task, often leads to interdisciplinary cross-fertilisation and broader education of the scientists involved. This is a very high-value feature of such projects.

From a hydrological perspective, some issues may be of particular interest for integrated systems analysis based on a coupled modelling approach, including:

- Wetland eco-hydrology, including interactions of surface water bodies, shallow groundwater aquifers, vegetation dynamics, and water and energy fluxes;

- Management of river-delta systems, including interactions of surface water bodies, groundwater resources, seawater, geo-chemistry, and land-use management;

- Multi-objective water resources management has traditionally been approached recognising the coupled nature of the problem to account for the interdependency between different water resources and between the needs of different water sectors. This is of particular relevance when managing extreme water shortage situations, i.e. droughts, because the reliability of water resources systems may alter in response to local, regional and global environmental change. Hence, the corresponding impact analysis calls for a stringently integrative approach that recognises all the relevant aspects and their interactions;

- Integration of socio-economic processes into hydrological sciences has gained increasing attention recently, and the inclusion of feedback processes between nature and the anthroposphere is of particular relevance in this context.

Examples outlined in this book include the coupling of complex systems involving a range of different processes and a variety of scientific disciplines. The first six case studies focus on interactions between different compartments of the hydrological cycle. They illustrate examples of model coupling that include land-surface interactions and feedbacks at large and at catchment scale, and models that incorporate smaller scale feedbacks between canopy form, ecosystem cycling, and soil moisture content, dynamics and pathways.

Four case studies are then presented that all deal with the integration of dynamic land-surface, atmospheric and hydrological processes, including interfacial fluxes that produce non-linear feedbacks. The specific space and time scales involved in these examples vary greatly, depending on the motivation of the study and on the specific task. These examples broaden the scope of land-atmosphere-interaction studies significantly from the traditional view of the atmosphere having a one-way impact on the surface, to surface change impacts within the climate system, and the resulting two-way interactions.

Other examples in catchment ecosystem dynamics and non-point source pollution are also given that integrate biogeochemical with hydrological processes, and yield new insight into the generation and transport of non-point source pollution at catchment scale. This has been achieved by incorporating biogeochemical transformation and transport processes into hydrological models at this spatial scale.

Finally, two cases are described where the focus is on incorporating socio-economic processes and feedbacks into the natural system as part of a state-of-the-art vulnerability assessment.

However, it is important to bear in mind that there are a large range of more bounded problems in hydrology, such as, for example, storm event runoff production, flood routing, and crop water use that may be addressed more efficiently and accurately using conventional (non-coupled) analytical and modelling frameworks. In these cases, the complexity of coupled models may, indeed, provide an impediment to efficiency because of difficulties in parameterisation and model uniqueness.

5.2 Progress in Coupled Models

Over the past two decades, advances have been made in interfacing different Earth system components within hydrological models. As a result, it is becoming increasingly apparent that, as discussed above, a number of problems cannot be properly simulated separately, rather they need to be addressed by coupling subsystems together. A new paradigm is thus emerging in hydrology that emphasises the need to interact with other branches of knowledge, notably atmospheric sciences, but also soil sciences, geochemistry, biology and sociology. Several observations are apparent, including:

- Understanding the parts does not imply understanding the whole;
- Scale issues are important. Processes that dominate system behaviour at small scales may become irrelevant at large scales and new processes may emerge as being important in response to the change in scale;

- Feedbacks are ubiquitous. This, together with non-linearity and scale problems, is what causes prediction difficulties and it is one of the motivations for using coupled models;

- Spatial variability of fluxes (e.g. rainfall), properties (e.g. hydraulic conductivity) and state variables (e.g. soil humidity) often leads to unexpected system responses;

- Understanding the effects of memory may also be important. For example, land-surface and subsurface states, particularly soil moisture, affect the persistence of drier or wetter atmospheric conditions. This is of particular significance for the occurrence of large floods or droughts;

- Human feedbacks are no less important than natural feedbacks.

In part because of these and other advances in understanding, coupled models have demonstrated some successful predictive capabilities. These have been accomplished in a range of model frameworks, including those that involve loose coupling by passing data between separate model codes through a database management system (e.g. GIS), to more tightly coupled codes in which representation of media and domains are more closely integrated. Some examples of successful coupled models have been discussed as case studies in Chapter 4.

Despite these successes, there is a perceived need to be more systematic when applying coupled models, particularly when addressing problems that relate to social policies. Chapter 2 (Sect. 2.3) seeks to respond to this need. The opinion of the authors is that the very basic approaches used in model building (conceptualisation, discretisation, calibration, error analysis, model selection and validation) need to be revised. Uncertainty needs to be addressed more formally. Sensitivity analysis, error propagation and risk assessment are addressed. However, much remains to be done. Coupling may, for example, introduce such complexity that model predictions are rendered unreliable: this is discussed below. In part because of this, emphasis in coupled modelling now appears to be shifting towards risk and vulnerability assessment. This is the topic of Sect. 5.4.

5.3 How much Coupling is Needed ?

A coupled approach may not always be desirable or feasible. In addition to the labour and costs required, developing a coupled model often involves technical and conceptual constraints, e.g. the development of increasingly complex, coupled, non-linear systems usually increases model uncertainty, compromises prediction and forecasting skill, and may reduce model identifiability**.**

In addition, there is an interesting dichotomy in the development of interdisciplinary models that integrate different Earth system compartments in that it results in the proliferation of adjustable model parameters and more model variables that require initialisation, and in more interacting, non-linear components. The latter contributes towards the potential development of a chaotic system, which is enhanced by the uncertainties in model parameters and in the initial values of variables. Because the number and density of observations available to initialise, calibrate or validate model predictions are often small compared to the inherent degrees of freedom built into complex models, it is often possible for a number of model structures/parameterisations to be consistent with the limited observational data available. While the motivation for constructing complex models is to increase the physical realism of the simulation in terms of the feedbacks and processes that characterise the Earth system, the end result may well be a complex model with limited forecasting or predictive capability. Consequently, by analogy with the well known phrase

*"Scientific approaches should be as simple as possible,
but not simpler",*

in the context of coupled modelling, we recommend:

"Couple as few processes as possible, but not less".

5.4 Emphasising the Vulnerability and Assessing the Risks of Coupled Systems

As an alternative to the "forecasting" paradigm hitherto much used in hydrology, a set of research initiatives and projects investigating complex system behaviour have preferred to assess vulnerability or risk (Kabat et al. 2004; Pielke and Guenni 2004). This reverses the usual sequence of building a complex model and then using it to forecast a scenario or set of scenarios. The first step becomes to identify what attributes or potential changes in the state of the environmental system have most societal significance. There is a specific evaluation of environmental consequences so that the most critical changes can be identified. A complex modelling approach can then be used to identify stable and unstable system behaviour relative to these conditions when expected or unexpected perturbations occur, that may be natural, human-induced or, more likely, of mixed origin. Thus, the emphasis is shifted to seeking the existence of stable equilibria within the environmental system and specifying those conditions that may cause a migration from one stable mode to another.

Although with this paradigm, emphasis is taken off the development of forecasting skill, there is clearly still a need to adequately reproduce system feedbacks and non-linearity. An important task facing the scientific community is to decide the level of process specification and detail required to allow identification of regions of system stability and instability. The level of detail will, of course, depend on the nature of the questions posed, but it is clear that the complexity incorporated into model frameworks needs to carefully balance the ability to reproduce key feedbacks and non-linearities with parsimonious parameterisation, that can either be met by information that is available or that can be generated by current or developing technology. This indicates that the advancement of complex models will ultimately depend on the development of a carefully planned and maintained data infrastructure and on advancements in observational technology.

5.5 Future Research

This book has shown that there is great potential for creating new knowledge and gaining insight into and the functioning of complex systems by the development and application of integrated, coupled models. It advocates a procedure for making the development of coupled models more systematic, and describes several methods of model parameterisation to give guidance on how to deal with the several important challenges involved.

Although there is a wide range of future research that is required, our recommendation is that there should be enhanced emphasis on:

- Technical aspects of how the coupling is to be performed in an adequate manner and on how to best parameterise interface conditions;

- Identifying system conditions that tend to be stable when perturbed (i.e. damped system states) and states that are unstable and may move towards new equilibria;

- Defining the range of perturbations over which the system remains stable and/or that can generate instability;

- Assessing the importance of feedbacks so as to facilitate the removal of unnecessary feedbacks and/or addition of important but missing feedbacks;
- Incorporating societal values as part of vulnerability assessments. The examples of coupling with socio-economic processes given herein reflect the current state of the art, but defining and introducing coupling between natural and social sciences is still rudimentary in coupled models;
- Using data assimilation with coupled models;
- Establishing the credibility of coupled models by validation.

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