Energy-based land-surface modelling

New opportunities in integrated hydrological modelling

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NEW OPPORTUNITIES IN INTEGRATED HYDROLOGICAL MODELLING

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ENERGY-BASED LAND-SURFACE MODELLING:

NEW OPPORTUNITIES IN INTEGRATED HYDROLOGICAL MODELLING

by

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requirements for the Ph. D. degree at

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SUMMARY

The aim of this project is to identify and explore some of the new opportunities that arise from combining energy-based land-surface modelling and integrated hydrological modelling. Focus is on the improved possibilities for linking hydrological modelling, atmospheric modelling and remote sensing.

Initially, an energy-based two-layer land-surface model (LSM) was implemented in the integrated hydrological MIKE SHE model. The new land-surface model was evaluated against data comprising simultaneous measurements of all fluxes required to close the land-surface energy budget (net-radiation and latent, sensible and soil heat). The simulated fluxes were found to compare well to observations, despite significant differences in vegetation development stages and stress conditions in the four periods used in the evaluation.

A sensitivity experiment identified albedo, leaf area index and unstressed stomata resistance as the most important land-surface controls of total evapotranspiration. The largest sensitivities, however, were related to air temperature, air humidity and global radiation, stressing the importance of using climate data with a high quality as well as a high spatial and temporal resolution.

The new LSM permits the simulation of effective land-surface temperatures, which opens for a more efficient use of remote sensing for evaluation purposes. Remotely sensed land-surface temperatures have previously been used to qualitatively evaluate the spatial distribution of land-surface fluxes through a direct comparison of simulated and observed temperatures. This evaluation method is taken one step further here by proposing and testing a method to convert the differences between simulated and remotely sensed surface temperature into a corresponding difference in latent heat flux.

Finally, the energy-based LSM allows for a dynamical coupling between MIKE SHE and a meso-scale atmospheric model. Such a coupled model system will provide a unique framework for investigation of land surface-atmosphere interactions at hydrological scales. The development of such a system is described in detail with a focus on the interface between the two models, and the developed system is evaluated against both land surface and atmospheric observations. Finally, it is being used to investigate the significance of feedback in hydrological impact assessment studies.

DANSK SAMMENDRAG

Målet med dette projekt er at identificere og udforske nogle af de nye muligheder der opstår når energi-baseret fordampningsmodellering kombineres med integreret hydrologisk modellering. Fokus er på den forbedrede sammenhæng mellem hydrologisk modellering, atmosfærisk modellering og remote sensing.

Som udgangspunkt blev en energi-baseret tolags fordampningsmodel implementeret i den integrerede hydrologiske MIKE SHE model. Den nye modelkomponent blev evalueret mod data bestående af simultane målinger af alle de overfladeflukse, der er nødvendige for at lukke energibalancen på jordoverfladen (netto stråling, latent varme, temperaturfluks of jordvarmefluks). De simulerede flukse viste sig at være i god overensstemmelse med de observerede, trods betydelige forskelle i vegetationens udvikling og stress i de fire perioder der blev benyttet til evalueringen.

Et følsomhedseksperiment identificerede albedo, blad-areal-index og ustresset stomata modstand som værende de mest betydningsfulde overfladeparametre for styringen af den totale fordampning. De største følsomheder var imidlertid relateret til lufttemperaturen, luftfugtigheden og kortbølget indstråling, hvilket understreger vigtigheden af at benytte klimadata med en høj kvalitet, såvel som en høj rumlig og tidslig opløsning.

Den nye fordampningskomponent muliggør en simulering af den effektive overfladetemperatur, hvilket åbner for en mere effektiv anvendelse af remote sensing til modelevaluering. Satellitbaserede målinger af overfladetemperaturer er tidligere blevet anvendt til at give en kvalitativ vurdering af modellers evne til at simulere overfladeflukse gennem en direkte sammenligning af observerede og simulerede temperaturer. I dette studie er denne evalueringsform bragt et skridt videre, og der præsenteres og testes en metode til konvertering af forskelle mellem simulerede og observerede overfladetemperaturer til en tilsvarende forskel i fordampningsrate.

Endelig giver en energi-baseret fordampningsmodel mulighed for at etablere en dynamisk kobling mellem MIKE SHE og en meso-skala atmosfærisk model. Et sådan system vil udgøre en unik ramme for undersøgelser af vekselvirkningerne mellem jordoverfladen og atmosfæren på hydrologisk skala. I den sidste del af projektet beskrives udviklingen af et sådan system, og grænsefladen mellem de to modeller diskuteres. Det udviklede system evalueres mod observationer, der beskriver jordoverfladen, såvel som de atmosfæriske forhold. Til sidst anvendes den koblede model til at undersøge betydningen af vekselvirkninger mellem jordoverfladen og atmosfæren i hydrologiske scenariesimuleringer.

PREFACE

The thesis "Energy-based land-surface modelling – new opportunities in integrated hydrological modelling" has been submitted in partial fulfillment of the Ph. D. degree at the Technical University of Denmark (DTU). The study was carried out in the period August 2000 – May 2005 at Environment and Resources DTU and DHI – Water & Environment under supervision of Dan Rosbjerg (DTU) and Michael B. Butts (DHI).

The thesis is organized as a synopsis with four appendixes attached. The synopsis includes a general introduction to the background for this study, mainly intended for readers who do not have an extensive knowledge of the fields covered by the thesis. The synopsis also contains a brief summary of the main scientific results and conclusions, as well as a discussion of the future plans and perspectives. The appendixes constitute the actual scientific work in the form of three papers (appendix A-C). Appendix D contains some of the technical aspects of the developed models not described elsewhere.

A large number of people have been involved in the project, and I would like to sincerely thank all formally and informally involved persons from DHI – Water & Environment, University of Copenhagen, GKSS Forchungszentrum (Germany) and the Technical University of Denmark. The number is too many to list by name, but you know who you are.

Copenhagen, May 2005
Jesper Overgaard

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Appendix D: MIKE SHE LSM – Technical Reference.

Appendix A-D are not included in this www-version but may be obtained from the Library at the Institute of Environment & Resources, Bygningstorvet, Building 115, Technical University of Denmark, DK-2800 Kgs. Lyngby (library@er.dtu.dk).

Chapter 1

INTRODUCTION

With the increasing population and predicted changes in the global climate, the pressure on already scarce water resources is likely to increase in the coming years. This has created a need for integrated models that can assess the available water resource as well as predict the impact of future changes in management and climate. Making such accurate predictions is an immense task that that can only be achieved through joint co-operation between scientists across multiple disciplines. Being located at the borderline between the atmosphere and hydrology, the land-surface provides the link between several scientific disciplines, and land-surface modelling has been subject to intense research in the hydrological, atmospheric, and remote sensing communities in the last decades. Combining these efforts is of vital importance for the successful predictions of future changes.

The purpose of this project is to identify and explore some of the new opportunities that arise from combining efforts across multiple disciplines. Focus will be on the improved link between hydrology, atmosphere and remote sensing that arises from implementing a new land-surface model in an integrated hydrological model. This first chapter summarizes the background for the ideas that led to this thesis. The starting point of the discussion is the common denominator for the three disciplines: Land-surface models.

Especially land-surface models (LSMs) that are based on a solution of the energy balance at the land surface have been subject to intense research. Since the late 1980´s, a large number of advanced energy-based LSMs containing sophisticated parameterizations of vegetation and root zone have been developed, and currently, the energy-based models are probably the most frequently applied LSMs in the scientific community. Three factors motivate this interest in energy-based LSMs.

First of all there is the desire to gain better physical understanding of the land surface–vegetation system through development of more sophisticated and advanced models. In this regard, the physical basis of the energy-based LSMs makes them an attractive alternative to the more conceptual types of evapotranspiration models that have traditionally been applied in hydrological modelling. Most energy-based LSMs are one-dimensional column models that describe the root zone and vegetation in great detail. Applied at the plot scale and evaluated against measured land-surface fluxes, these models have helped to gain important information on the fluxes of heat and water between the land surface and atmosphere for many different vegetation types and under many different climatic conditions. In some cases energy-based LSMs have been successfully applied in spatially distributed frameworks.

Secondly, the atmospheric scientific community has contributed to the development of advanced energy-based LSMs. Recognizing the close connection between the atmosphere and land surface, great effort has, since the early 1990´s, been put into developing advanced LSMs for atmospheric models working at all scales ranging from storm scale to global scale. Providing information on all fluxes and state variables required at the land-surface boundary in atmospheric models, the energy-based LSMs have a great advantage over the conceptual evapotranspiration models that tend to provide only actual evapotranspiration. This has made energy-based LSMs the preferred choice of atmospheric modellers. In atmospheric models, these LSMs are inherently distributed, but the lateral surface and subsurface flows between cells are rarely considered.

Finally, the remote sensing community has an important role in the rapid development of energy-based LSMs. The physical basis of the energy-based LSMs makes them well suited for utilizing the growing amount of land-surface data available from remote sensing, and energy-based models have therefore become the preferred LSM in the remote sensing community.

The LSMs have, beyond any doubt, benefited from the combined efforts across multiple scientific disciplines, and in many studies state-of-the-art models have proven to perform well at the plot scale, and in some cases, also when applied in spatially distributed frameworks.

However, when moving from the one-dimensional column models to fully distributed models, it becomes increasingly important to describe the spatial variations in soil moisture to ensure an accurate simulation of the land-surface fluxes. Variations in soil moisture may be induced by factors such as precipitation, soil texture, drainage, irrigation, flooding and shallow groundwater. While most of the energy-based LSMs applied in distributed frameworks include a detailed description of the vegetation and root zone, the interactions between groundwater, root zone and surface water, as well as the lateral surface and subsurface flows, are normally neglected, and consequently these models will fail to produce accurate results in areas where such interactions are important.

Contrary to this, hydrologists have a long tradition for developing and applying distributed models that take these interactions into consideration, but so far the energy-based LSMs are rarely applied in integrated hydrological modelling, and ironically, most of the integrated hydrological models that claim to be physically based do, in fact, contain rather conceptual evapotranspiration components. There are several reasons for this. Probably the most important one is that the conceptual evapotranspiration models seem to serve their purpose well, and hence there has been no obvious need to replace them with more advanced alternatives. Moreover, the applicability of the energy-based LSMs has, at least until recently, mainly been limited to intensely monitored experimental areas due to the lack of detailed land-surface and climate data required by these models. To ensure the general applicability of the integrated hydrological models, the conceptual evapotranspiration models requiring less data have been the preferred alternative so far.

The increasing quantity as well as improved quality and resolution of land-surface and near-surface climate data obtained from remote sensing has, however, significantly improved the perspectives of using energy-based LSMs in distributed hydrological modelling. Assisted by the rapid increase in computing power that allows more advanced models to be applied for larger areas and longer periods, energy-based LSMs may now begin to provide an attractive alternative to the conceptual models currently implemented in most hydrological models.

Taking the view that being able to efficiently utilize more of the available information will lead to more accurate simulations, hydrological models and hence hydrologists should, in the cases where accurate spatial data are available, benefit from replacing the less data-demanding conceptual evapotranspiration models with the more data-demanding energy-based LSMs.

But not only hydrologists would benefit from more advanced parameterizations of the land-surface processes. The improved spatial description of soil moisture dynamics will most likely lead to more accurate spatial simulations of land-surface fluxes in areas with complex hydrology, and in those cases, an energy-based LSM implemented in an integrated hydrological model would provide a framework that is well-suited for testing and developing new distributed remote sensing techniques. An energy-based LSM in an integrated hydrological model would also improve the perspectives of hydrologists to benefit directly from existing as well as future developments in remote sensing.

Finally, as stated earlier in this chapter, one of the main drivers behind the development of energy-based LSMs was the desire to produce an accurate description of the land surface in atmospheric models. Being able to provide the land-surface fluxes required by an atmospheric model, an energy-based LSM in an integrated hydrological model opens for the possibility to couple dynamically to an atmospheric model. Such a coupled model system will provide a unique framework for investigation of land surface - atmosphere interactions in areas where surface- and groundwater are closely connected. Both atmospheric scientists and hydrologists would potentially benefit from a better physical understanding of the complex interactions between the land surface and atmosphere in such areas.

The project has resulted in three papers, which can be found in appendix A - C. A brief introduction to each paper and a presentation of the main results and conclusions are given in the remaining chapters.

Chapter 2 is an introduction to the paper 'Applicability and sensitivity of a two-layer land-surface model in an integrated modelling framework' (Appendix A), and contains a brief review of the developments in energy-based land-surface modelling, as well as the considerations leading to the selection, implementation and evaluation of an energy-based LSM in the integrated hydrological MIKE SHE model. The main results and conclusions are presented. Appendix D contains a description of some of the technical details not covered by the paper. This includes the radiation component as well as the technical reference for the numerical solutions of the LSM and the soil heat transfer model.

Chapter 3 contains an introduction to the second paper 'Evaluation of a distributed land-surface model by remotely sensed information' (Appendix B) and addresses the application of remotely sensed surface temperature for evaluation of distributed models. The main results and conclusions are presented.

Chapter 4 contains an introduction to the third paper 'Dynamic coupling of hydrological and atmospheric models using a shared land-surface scheme' (Appendix C). Besides a brief introduction to land surface - atmosphere interactions, this chapter contains a summary of the main results of the evaluation of the coupled modelling system, as well as the results of two applications.

Finally, chapter 5 summarizes the main conclusions, and discusses the future plans and perspectives.

Chapter 2

LAND-SURFACE MODELLING

The total radiation absorbed at the land-surface is balanced by emission of thermal infrared radiation to the atmosphere, latent heat loss associated with evaporation and transpiration, sensible heat losses and diffusion of energy into the soil. The basic task of any land-surface model is to accurately simulate the partitioning of net radiation at the land surface into these component fluxes, provided with the relevant information on land surface and climate data.

A widely used approach to land-surface modelling is to consider the land surface as an electrical analogue. Basically, the electrical analogue expresses that the rate of exchange, F, of a quantity between two points A and B (e.g. the land surface and surrounding atmosphere) is driven by a difference in potential of the quantity, X, (e.g. vapour pressure, temperature or carbon-dioxide), and controlled by a number of resistances, r, that depend on the local climate as well as the internal properties of the land surface and vegetation:

$$F = C\frac{X_B - X_A}{r_{AB}} \tag{1}$$

C is a constant, depending on the quantity being considered. One of the earliest, and most well-known, models that estimate evaporation using the electrical analogue was developed by Penman (1948), who described evaporation from a wet surface by linking the resistance analogue to the surface energy balance, and furthermore eliminated the need for surface potentials by linearising the saturation vapour pressure as function of temperature. This was, and continues to be, very useful since surface potentials are rarely measured. In more recent computer models, however, an iterative solution of the surface energy balance is introduced, whereby the surface temperature appears as a by-product of the calculation of surface fluxes.

Penman assumed that the only resistance between the wet surface and the surrounding atmosphere was the so-called atmospheric resistance. The atmospheric resistance expresses the ability of the air to transport a given quantity away from the surface. In unstable conditions, occurring when the surface is strongly heated, buoyancy will enhance the vertical motions allowing a faster transport, and hence lower the resistance. Under stable conditions, for example on a clear night with light winds, vertical motion is dampened by the stable stratification of air near the surface, leading to higher resistances. Penman's model is illustrated in figure 1a.

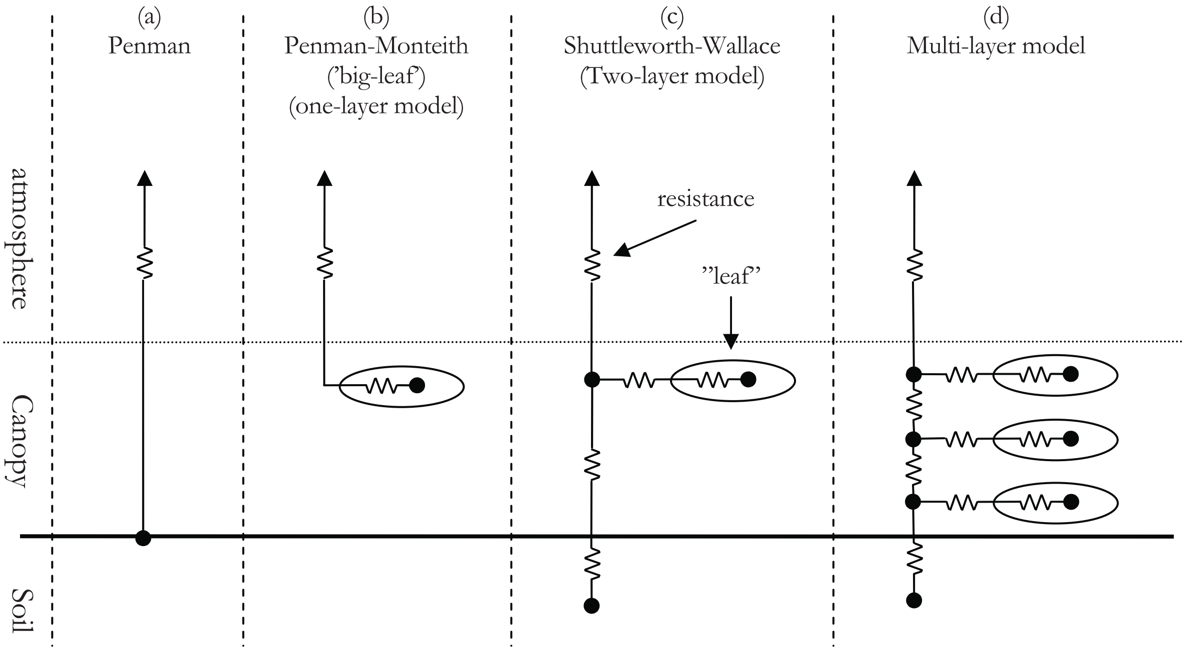

Figure 1 Illustration of the different resistance models discussed in chapter 2.

One of the earliest land-surface models that used the Penman approach, and hence assumed that the land surface evaporated water at the same rate as a wet surface, was the 'bucket' model by Manabe (1969). The bucket model holds a maximum of water, which evaporates at the same rate as a wet surface.

However, the land surface acts as a free water surface only during and immediately after a precipitation event, when the foliage is wet. At all other times, evapotranspiration has two important controls. First, evaporation from bare soil is greatly reduced when the uppermost soil layer dries out, and equally important, the plant retards the transpiration rate because of resistance of the stomata to molecular diffusion of moisture.

Recognizing the influence of surface controls on the total evapotranspiration, Monteith (1965) further developed the Penman equation to take the land surface controls into consideration by introducing an additional surface resistance. This resistance depends on the vegetation type, soil moisture conditions and local climate. This model structure is illustrated in Figure 1b.

Models of the Penman - Monteith type is often referred to as 'one-layer', or 'big-leaf' models because they do not distinguish between soil evaporation and transpiration, but treat the land surface as one homogeneous surface. Their simplicity and physically sound basis has lead to the wide application of one-layer models. In densely vegetated canopies such 'big-leaf' models have proven sufficient to describe evapotranspiration (Monteith and Unsworth, 1990). Examples of 'big-leaf' models are the TOPUP model by Schultz et al. (1998) and PROMET by Mauser and Schlädich (1998).

In distributed models the land surface is often divided into grids inside which the land surface model is applied. In cases where the area covered by a grid consists of clusters of vegetation surrounded by bare soils, the 'big-leaf' assumption tends to break down. This initiated the development of the so-called patch-, tile- or mosaic type of models, where the area covered by a grid is divided into patches of bare soil and vegetation, and the one-layer model is applied separately for each with parameters corresponding to the actual patch. The patch-type model was first introduced by Avissar and Pielke (1989). Examples of models that implement the patch approach to distinguish between soil evaporation and transpiration are the ISBA land-surface model by Noilhan and Mahfouf (1996), and SEWAB by Mengelkamp et al. (1999). Patch models are considered to be one-layer models as the fluxes from each patch are not allowed to interact.

In cases where homogeneous, but sparse vegetation is covering the land, fluxes from the soil surface and vegetation are known to interact. The interaction between soil surface and canopy fluxes has been proven experimentally as well as numerically. Ham and Heilmann (1991) observed that for a cotton crop with a leaf area index (LAI) of 1.6 the sensible heat flux generated at the soil surface accounted for one third of the energy available for transpiration. A similar result was found for a Texas vineyard by Heilman et al. (1994), and the numerical experiments described in Paper I (appendix A) show that stomata resistance exerts a significant influence on soil evaporation in a sparse canopy due to internal feedbacks in the soil surface – canopy system. In such cases one-layer models will fail to accurately describe the land-surface fluxes, and this has led to the development of two-layer models.

Two-layer models consist of a single, semi-transparent canopy layer located above the soil surface such that the only way for heat and moisture to enter or leave the surface layer is through the canopy layer, whereby the component fluxes are allowed to interact. A widely used structure for two-layer models was proposed by Shuttleworth and Wallace (1985). This structure incorporates a bulk stomata resistance for the vegetation similar to that used in 'big-leaf' models, but also introduces a resistance at the substrate surface to control soil evaporation. By assuming that the aerodynamic mixing within the canopy is sufficient to allow the hypothetical existence of a 'mean canopy air-stream', this formulation allows the fluxes of heat and water from the substrate and canopy to interact before they are exchanged with the atmosphere. Two-layer models of this type include three aerodynamic resistances, which control the transfer (1) between the leaf-surface and mean canopy air-stream, (2) between the soil-surface and mean canopy air-stream and, (3) from the mean canopy air-stream to a reference height located above the crop. The Simple Biosphere (SiB2) model by Sellers et al. (1996) represents this type of model. The structure of two-layer models is shown in Figure 1c.

Some studies have questioned the use of a soil resistance to describe soil evaporation. Daamen and Simmons (1996) found that the use of a single soil resistance depending solely on the soil moisture content will provide a reasonable estimate of cumulative evaporation from soils over a period of several days if well calibrated, but also that this method is considerably less accurate on a daily or hourly basis. This, and results from similar studies, has led to the development of a modified type of two-layer models where soil evaporation is accounted for by alternative methods.

Examples of such modified models are the DAISY SVAT by van der Keur et al. (2001) and SWEAT by Daamen and Simmonds (1994, 1996) and Daamen (1997). In both models, the use of soil resistance formulations were circumvented by calculating soil evaporation as a function of the evaporative demand and limited by the hydraulic properties of the upper soil layer.

From a structural point of view the two-layer approach is easily extended to include more than one vegetation layer. In such multi-layered models the effects of the vertical canopy structure are considered, which may be required to describe the fluxes, e.g. from a forest/understory system or other vegetation types with a complex vertical structure. The biophysical exchange rates are calculated for each layer, and the canopy-scale fluxes are obtained by integration of these fluxes over the canopy depth. Examples of such models are given by Gu et al. (1999) and Baldocchi and Harley (1995). Gu et al. (1999) distinguish between incomplete and complete multi-layer models. They define incomplete multi-layer models as models that describe the vertical differentiation in the solar radiation environment and wind speed, whereas other factors, such as air temperature and air humidity, are assumed to be constant over the canopy depth. In contrast, complete multi-layer models predict vertical changes of these variables in an attempt to achieve a better representation of the physical and biological reality. Application of these models requires detailed information on crop canopy architecture, crop physiology, turbulence etc. on a layer-by-layer basis, and they are in most cases computationally very demanding. The structure of the multi-layer models is shown in Figure 1d, here exemplified by a four layer model (three canopy layers and one surface layer).

Finally, a new generation of land-surface parameterizations has emerged in recent years. In these models, exchange of water and heat at the vegetated land surface is linked to the exchanges of CO_2. This linkage emerges from the fact that the physiological control of evapotranspiration by plants seems to act as an optimization mechanism that seeks to maximize carbon fluxes by photosynthesis, and to reduce the water loss from the plant by closing stomata. These mechanisms have been implemented both in two-layer models (e.g. SiB2, Sellers et al., 1996) and in multi-layer models (e. g. Gu et al., 1999).

2.1 Model selection

As pointed out by Raupach and Finnigan (1988), the choice of model in any given situation is a trade-off between the desirable but incompatible traits of realism and simplicity.

Realism is desirable from the point of view that realistically structured, and consequently very detailed models, will provide realistic results. The more of the physical processes involved in the generation of land-surface fluxes we can parameterize, the more likely it is that we can predict the behaviour of the land surface under different conditions. This is, of course, only true if we can measure or realistically estimate all parameters in such detailed models, preferably at the scale of application.

Simplicity is desirable from the point of view that simple models will require less parameters, which will extend the applicability of the model outside the intensely monitored experimental areas. Moreover, simple models tend to be less computational demanding. However, simplicity comes with a cost: by replacing the physically-based model structure with the simpler conceptual models that require less data, the resulting conceptual parameters become increasingly difficult to infer from observations, and the dependence on calibration data increases.

Realizing that no single model will be the 'best' choice for all possible applications, the background for selection of an 'appropriate' complexity of a land-surface model for the current study will be discussed in the next sections.

2.1.1 Multi-layer models?

As noted in the previous section, the resistance networks are easily extended into multi-layered models, assuming that the resistance analogy holds true for such models. However, as discussed by Finnigan and Raupach (1987) and Raupach (1988), the diffusion theory on which the resistance networks is based frequently fails inside and just above the canopy, where pronounced counter-gradient fluxes of heat and water have been observed (Denmead and Bradley, 1985, 1987). The basic reason for this failure is that the eddy motions responsible for the vertical turbulent transfer within the canopy have vertical length scales comparable to those of the canopy height. Hence the assumption of 'fine-grained' mixing required by the diffusion theory breaks down. Van den Hurk and McNaughton (1995) showed that the non-diffusive part of the transport processes in two-layer resistance models could be accounted for by adding a 'near-field' resistance to the leaf-boundary layer resistance, but found the effect to be small, and later concluded that diffusion theory seems to be an adequate basis for two-layer models (McNaughton and van den Hurk, 1995). This was further supported in studies by Sauer and Norman (1995), Sauer et al. (1995) and Wilson et al. (2003). It does, however, seem likely that the dense discretization of the vegetation in multi-layer models make diffusion theory insufficient, and the gradient diffusion theory has therefore been replaced by the more advanced Lagrangian Random-Walk theory in several multi-layer models (e .g. Gu et al., 1999; Baldocchi and Harley, 1995; Wilson et al., 2003). This, and the fact that these models require a very large number of parameters that would be very difficult to obtain in a spatially distributed setting, leads to the conclusion that multi-layer models being inevitably complex will primarily remain a research tool for understanding the physically processes that control the exchange of mass and energy between the land surface and atmosphere. Consequently, these models are not considered to be suitable for implementation in a distributed hydrological model.

Eliminating multi-layer model from the list of candidates, the choice has to be made between the single- and two-layer model types.

2.2.2 Single or two-layer models?

Besides the canopy resistance and aerodynamic resistance required in single-layer models, two-layer models require three additional resistances to be parameterized. This represents a step up in complexity, as the parameterization of each resistance require a number of additional parameters to be specified. If all model parameters should be inferred through calibration, the problem of equifinality and over-parameterization will arise.

Beven (1989) was the first to address the problem of over-parameterization and equifinality in distributed hydrological modelling and Franks et al. (1997) specifically address the question on how much complexity in a land-surface model can be supported by the available observations. They showed that even when using a relatively simple one-layer model (TOPUP, Schultz et al., 1998), there appears to be too many degrees of freedom in terms of fitting the model predictions to calibration data, and they showed that good fits may be achieved in many areas of the parameter space. They (and others) argue that the complexity of land-surface models needs to be reduced in order to eliminate the problem of equifinality.

They did not, however, assign a-priori knowledge to any of the parameter values, and they allowed all parameter values to vary within relatively wide intervals of equal probability. In most applications some a-priori knowledge will be available.

Demarty et al. (2004) applied a multi-objective approach for retrieving quantitative information about the surface properties from different surface measurements to determine the potential of a land-surface model to be applied with ‘little’ a-priori information, and their results suggested that complex LSMs can be driven with limited a priori information. Future research along these lines may help to gain more insight in the problem of equifinality for advanced land-surface models.

Also, when reducing the number of model parameters, it may become more difficult to infer the parameters from e.g. remote sensing, so lowering the problem of over-parameterization and equifinality by reducing model complexity may not necessarily make the models more applicable.

The bulk-surface resistance used in one-layer models illustrates this dilemma. It basically represents the four resistances in two-layer models, which reduces the number of parameters that need to be specified. However, as pointed out by Raupach and Finnigan (1988), the cost of lumping four resistances into one is that the bulk surface resistance tend to be less well-behaved in comparison to the individual resistances in the two-layer formulation.

Considering the above arguments, the two-layer model was found to be a reasonable compromise between realism and simplicity.

The two-layer models have been successfully tested for many different types of vegetation and under different climatic conditions. Schelde et al. (1997) used a two-layer model to simulate fluxes from a Danish broad-leaved forest, and Iritz et al. (1997) tested it for a mixed boreal forest stand in Sweden. Daamen (1997) and Lund and Soegaard (2003) tested it on sparse millet crops in Niger, Brisson et al. (1998) and Braud et al. (1995) on soybeans in France, Seen et al. (1997) on grassland in Niger, Dolman (1993) on tropical savannah in Niger, tropical rainforest in Brazil and agricultural crops in France, and LaFleur and Rouse (1990) tested it for sub-artic wetland.

For completeness, the issue of scale is finally briefly mentioned.

2.2 The issue of scale

It has been argued that due to the mismatch between the scale for which the theory behind the developed models are assumed valid (typically point scale), and the scale of the typical application, the parameters in physically-based models are in reality conceptual, and that even when mean parameters are available, the highly non-linear behaviour of most land-surface models cannot be expected to simulate the mean response of a particular area.

This has led to a number of land-surface models that take the sub-grid variability into consideration (e.g. Kavvas et al., 1997; Famiglietti and Wood 1994). As pointed out by Beven (1995), any theory to take the sub-grid variability into consideration must be based on some knowledge about the sub-grid variability and that this would appear to make any scaling theory a very distant prospect, given the data gathering techniques that were available in 1996. At least at the scale of a typical MIKE SHE application (50-500 meter), this still holds true today for most areas located outside a limited number of experimental areas.

Sellers et al. (1997) analyzed the consequences of using simple averages of topographic slopes, vegetation parameters and soil moisture in a two-layer LSM (SiB, Sellers et al., 1986). They found that the relationships describing the effects of moderate topography on the surface radiation budget are near-linear and thus largely scale-invariant, and so was the relationship linking the canopy conductance to transpiration. The relationship linking root zone soil moisture content to transpiration was found to become increasingly non-linear as the soil dried out. However, their results showed that soil wetness variability decreases significantly as the soils dries out, which partially cancels out the effect of the non-linear functions. They conclude that, for practical purposes, the two-layer model seems to be relatively robust and scale-invariant with respect to these variables.

Dolman and Blyth (1997) also investigated the influence of small-scale land-surface heterogeneity and concluded that in most cases it is possible to find effective parameters for surface resistances by taking simple geometric or arithmetic averages of the component resistances, but that the use of more sophisticated techniques could improve calculations.

The findings discussed above provide the background for not including any sub-grid parameterizations in the MIKE SHE LSM at the current stage.

Paper I (Appendix A) contains a description of the selected model as well as the results from an evaluation study and a sensitivity experiment. A summary is given in the next section.

2.3 Summary of Paper I: Applicability and Sensitivity of a Two-Layer Land-Surface Model in an Integrated Modelling Framework

A pre-requisite for the improved link between remote sensing, atmospheric modelling and integrated hydrological modelling, as discussed in the previous chapters, is the implementation of an energy-based land-surface model. This first paper describes the implementation, evaluation and sensitivity of a two-layer LSM in an integrated, spatially distributed hydrological MIKE SHE model (Graham and Butts, 2005). The selected LSM consists of a two-layer system (soil-canopy) linked by a network of resistances (Shuttleworth and Wallace, 1985).

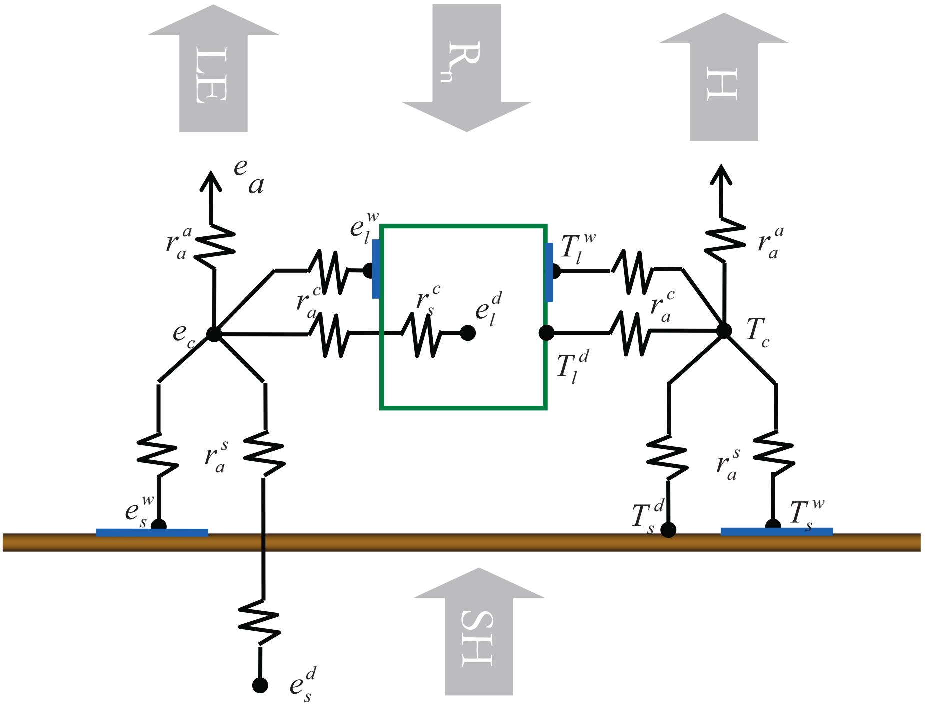

Figure 2 Model structure. The box illustrates a leaf and the blue lines are water on the soil and leaf surfaces. Temperatures and humidities at the wet and dry (superscript w and d, respectively) surfaces (subscript l: leaf surface; s: soil surface; c: mean canopy level) are denoted T and e. The transport of latent heat (LE) and sensible heat (H) is illustrated on the left- and right-hand side of the figure, respectively. R_n is net radiation, and SH is soil heat flux. The resistances are denoted r.

Compared to the original model structure, as proposed by Shuttleworth and Wallace (1985), the model presented here has been extended to include evaporation and sensible heat flux from water ponded on the soil surface and on the leaves. This was done to facilitate the use of the model in wetlands. The model structure is illustrated in Figure 2.

The model was evaluated against observations of heat fluxes collected during the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) (Sellers et al., 1992). FIFE was conducted in a 15x15 km area near Manhattan, Kansas, in and around the Konza Prairie. Observations from four Intensive Field Campaigns (IFC1: June 1 – June 6, IFC2: June 25 – July 13, IFC3: August 3 – August 24, IFC4: October 5 – October 16) were used. The four intensive field campaigns cover different vegetation development stages as well as different climate and soil moisture conditions, resulting in varying degrees of vegetation stress.

The predominant vegetation type in the FIFE area is grass. The green leaf area index (LAI) was measured in a number of places in the area, and the variability was found to be rather large (0<LAI<3). Consequently, LAI was initially considered a tuning parameter within the range of variability found inside the entire FIFE area, but the calibrated values turned out to close to the mean measured values. Except for the extinction coefficient, no other parameters were subject to calibration. The summary statistics for each IFC are shown in Figure 3.

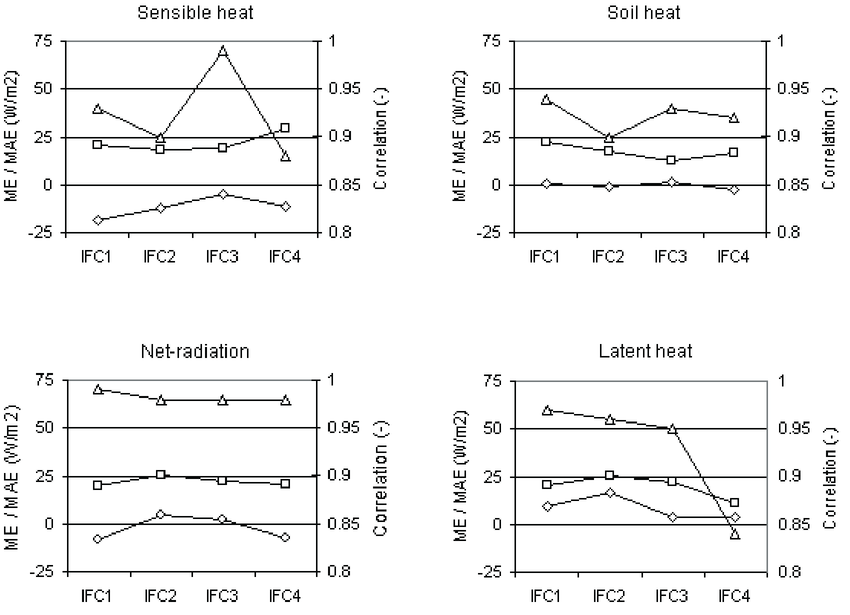

Figure 3 Simulation statistics for net radiation, latent heat, sensible heat and soil heat flux. The triangles indicate the correlation coefficient for each intensive field campaign (right axis), the squares are the mean absolute error (MAE), and the diamonds indicate the mean error (ME).

The model was found to perform equally well in all the four periods despite significant differences in development stage and stress conditions.

For the purpose of identifying the parameters for which accurate spatial information is required before the application of the implemented LSM can be justified, a sensitivity study was carried out. The calculated sensitivities of the total evapotranspiration to changes in key land surface parameters are shown in Figure 4.

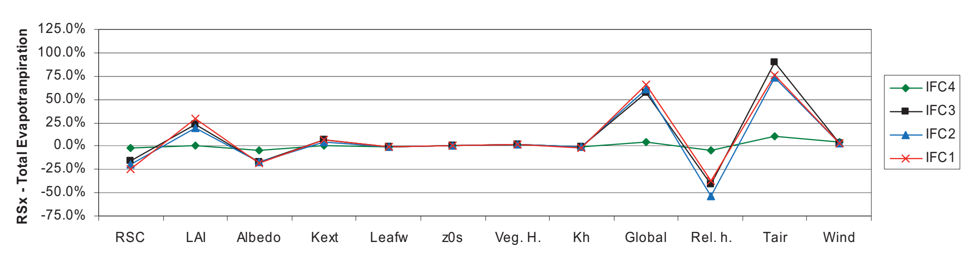

Figure 4 The relative sensitivity of total evapotranspiration to changes in key land-surface parameters (RSC: unstressed stomata resistance, Kext: extinction coefficient, Leafw: leaf width, z0s: soil surface roughness, Veg. h: vegetation height, Kh: heat conductance of the first soil layer) and climate parameters (Global: global radiation, Rel. H: relative humidity, Tair: air temperature, Wind: wind speed).

Total evapotranspiration showed the largest sensitivities to the climate parameters. Except for the wind speed that showed limited sensitivity inside the range of variation, the remaining climate parameters all showed relative sensitivities above 50%, stressing the need for high-quality and high-resolution climate data in distributed models. Failure to take spatial as well as temporal variability into consideration may potentially lead to large errors in the simulated fluxes.

For the land-surface parameters, the analysis showed that under the conditions on the Konza Prairie the total evapotranspiration was most sensitive to changes in leaf area index, unstressed stomata resistance and albedo. For the remaining parameters, which included the extinction coefficient (k_{ext}), average leaf width, substrate roughness, vegetation height and thermal conductance of the soil, the sensitivity was found to be very small. The small sensitivity to k_{ext} was, however, a result of compensating changes of the transpiration and soil evaporation, which both showed significant, but opposite, sensitivities to changes in the extinction coefficient.

From a remote sensing perspective, the strong dependence on parameters such as leaf area index and albedo is interesting, since these parameters are now available on an almost global basis with a resolution and quality that may allow a direct use in distributed models.

Combining the land-surface component presented here with procedures to handle time-varying map data in an efficient way, the MIKE SHE model provides a framework for testing new approaches in remote sensing as well as for utilizing existing remote sensing products in both scientific and practical applications. Moreover, the energy-based land-surface component facilitates a consistent two-way coupling between MIKE SHE and an atmospheric model. These new possibilities will be explored in the remaining two papers.

Chapter 3

APPLICATION OF REMOTE SENSING FOR EVALUATION OF DISTRIBUTED LAND-SURFACE MODELS

Remote sensing (RS) is simply defined as the observation of a target by a sensor without physical contact. From a hydrological point of view, RS is the process of inferring (near-) surface parameters from measurements of the reflected and emitted electromagnetic radiation from the land surface. Both active sensors that send a pulse and measure the reflected pulse and passive sensors that measure emissions and reflectance of natural sources are used in this context. Conversion of the measured electromagnetic fluxes into physical land-surface parameters that can be utilized both for monitoring and modelling purposes is currently a major research topic.

The quality and resolution of remote sensing data products have improved much in recent years and have provided a valuable source of distributed information with a promising potential for application in distributed hydrological models (Schultz, 1998; de Troch et al., 1996; Tenhunen at al., 1999; Warning and Running, 1999). Designing models to utilize this distributed information in land-surface modelling is of great importance (Wessmann et al., 1999), since spatial information obtained from RS is the only source for distributed data that can be characterized as realistic at scales above plots and small experimental catchments (Refsgaard, 2001).

This chapter, and Paper II, addresses the use of remote sensing data for evaluation of distributed models.

3.1 Application of remote sensing for model evaluation

General methodologies for calibration and evaluation of distributed hydrological models have been subject to much discussion during the last decades (Beven, 1989, 1996, 2001, 2002; Konikow and Bredehoeft, 1992; de Marsily et al., 1992; Refsgaard, 1997, 2001, Refsgaard and Henriksen, 2004, Rosbjerg and Madsen, 2005), mainly due to the large number of parameters that are allowed to vary during calibration, and the lack of methods to perform a truly distributed evaluation of the model performance. Still today one of the most commonly used evaluation approaches in distributed hydrological modelling is evaluation against measured river discharge, while the utilization of spatial data is rare (Refsgaard, 2001). While discharge remains an excellent indicator of how well a model is able to reproduce the water balance in a river basin, it does not necessarily give any information on the performance of a model at scales smaller than the area upstream the gauge. This has led some authors to express doubts about the applicability of this calibration/evaluation method in distributed models (Beven, 1989; Bergström, 1991; Refsgaard, 1997, 2001).

Ideally, a distributed evaluation of any land surface model would require distributed observations of the land surface fluxes that make up the energy balance. However, since none of these can be measured directly with the current RS technology, models will have to be evaluated against derived measures, such as surface temperatures, or by deriving the relevant surface fluxes of heat and water from the data types that are more easily derived from RS. These topics are addressed in the next sections.

3.1.1 Distributed evaluation against thermal observations

Thermal observations of the Earths surface have long been recognized as a valuable source of information for evaluation of the surface energy balance over large regions (Price, 1980), and the direct, but complex relationship between surface temperature and evapotranspiration has been illustrated in several studies (Rivas and Caselles, 2005; Jackson et al., 1981; Shuttleworth and Gurney, 1990; Mauser and Schädlich, 1998). Recognizing this close relationship, remotely sensed maps of land-surface temperatures have previously been used to evaluate model performance by comparing maps of simulated surface temperatures to their observed counterpart

Mauser and Schädlich (1998) utilized the close relationship between latent heat flux and surface temperature to evaluate the one-layer PROMET model in a 100 x 150 km area in Bavaria, Germany. They compared remotely sensed NOAA-AVHRR surface temperatures to simulated surface temperatures and found the spatial pattern of surface temperatures simulated by PROMET to be very similar to the observed. Through a pixel-by-pixel comparison between simulated evapotranspiration and observed surface temperature they found a clear trend of increasing simulated evapotranspiration with decreasing observed surface temperature.

Silberstein et al. (1999) used a number of Landsat-TM images to evaluate the performance of the COUPLE model at the small catchment scale (~1 km^2) in two catchments in Australia. They concluded that their model gave excellent results when compared to Landsat-TM data. They found that the temperature difference between pasture and forest can be more than 15 °C in summer and 2-3°C in winter.

Biftu and Gan (2001) used NOAA-AVHRR and Landsat-TM surface temperatures for evaluation the semi-distributed DPHM-RS model for the Paddle River Basin, Alberta. They compared average simulated and observed surface temperature for four different land use classes and found that their model was able to reproduce observed surface temperatures within 2°C on clear days.

The studies described here are all examples of how surface temperatures have been included in the evaluation procedure, whereby a truly independent measure of the distributed performance has been obtained. Such comparison is an important step toward a distributed evaluation, as it allows for an identification of areas where a difference between simulated and observed temperatures indicates that there may be inconsistencies between the model and reality.

It does, however, not provide any direct information on how a difference in surface temperature translates into a difference in latent heat flux. This makes it difficult to determine when a deviation between simulated and observed surface temperature should be considered 'significant', and a logical extension of the pure temperature evaluation seems to be evaluation against flux-maps derived from remote sensing.

3.1.2 Distributed evaluation against latent heat fluxes

The conversion of remote sensing data into surface fluxes for monitoring purposes and to improve evaluation of land-surface models has been subject to intense research.

To eliminate the need for determining plant stress parameters and near-surface humidity, a common approach to estimation of latent heat (LE) from remote sensing is to calculate latent heat as the residual of the land-surface energy balance.

$$LE = R_n - H - G \tag{2}$$

where R_n is net-radiation, H is sensible heat and G is soil heat flux.

Soil heat is normally considered a fixed fraction of the net-radiation (Norman et al., 1995; Anderson et al., 1997; Boegh et al., 2000, 2002, 2004) and since previous studies have shown that net-radiation can be accurately determined from RS data (e.g. Boegh et al., 1999), the main task becomes the determination of sensible heat flux from remote sensing data.

Generally, the sensible heat flux is modeled using the electrical analogue. Using the one-layer approach, the sensible heat flux is written

$$H = \rho c_p \frac{T_c - T_a}{r_a} \tag{3}$$

Here, ρ [kg/m^3] denotes the density of the air and c_p [J/kg/K] is the specific heat of air at constant pressure. T_c [K] is the aerodynamic temperature of the mean canopy air-stream, which is different from the radiometric surface temperature, T_r [K], that is obtained from remote sensing. It has been shown that T_r and T_c may differ by several degrees (Stewart et al., 1994). A way to compensate for this difference between T_r and T_c is to add an extra resistance to r_a in equation 3, whereby the aerodynamic surface temperature can be substituted by the radiometric surface temperature. The excess resistance r_{ex} is calculated using the kB^{-1} factor:

$$r_{ex} = \frac{kB^{-1}}{ku_*} \quad \textbf{(4)}$$

k is the von Karman constant, u_* is the friction velocity, and $kB^{-1} = \ln(z_0/z_{0h})$ where z_0 is the roughness length for momentum and z_{0h} is the roughness length for heat. The need for this excess resistance arises from the fact that heat transfer near a surface is controlled primarily by molecular diffusion, whereas momentum exchange takes place as a result of both viscous shear and local pressure gradients (Chehbouni et al., 1997).

Usually kB^{-1} has to be determined empirically by calibration. Especially for sparse vegetations the value of KB^{-1} is seen to vary widely, and a dependence on vegetation type and conditions as well as climate has been observed in several studies (Troufleau et al., 1997; Massman, 1999; Lhomme et al., 2000). This had led some to question the usefulness of the kB^{-1} approach for sparse canopies (Lhomme et al., 1997; Verhoef et al., 1997).

Moran et al. (1996) proposed a one-layer approach that did not require estimation of the excess resistance. They combined the Penman-Monteith equation with the NDVI-T_r (NDVI: Normalized Difference Vegetation Index) relationship and by computing the theoretical boundaries on the NDVI-T_r relationship (the boundaries represent zero and potential evapotranspiration) they derived the actual evapotranspiration based on the distance from the observed (T_r, NDVI) to its upper and lower boundary.

Boegh et al. (2002) also proposed a method to derive spatial estimates of atmospheric resistance, surface resistance, and evapotranspiration, while eliminating the need for the excess resistance by relating the vapor pressure at the surface to the air-humidity through the decoupling coefficient by Jarvis and McNaughton (1986). The decoupling coefficient expresses the degree of coupling between the atmosphere and land-surface, as a function of the relative importance of surface and atmospheric resistance. When the land surface is poorly coupled to the atmosphere, water vapor will accumulate near the surface and get close to saturation. Under strongly coupled conditions, the vapor content near the surface will approximately equal the vapor content in the air above the canopy.

By explicitly calculating the aerodynamic temperature at the mean source height, two-layer models eliminate the need for the excess resistance. However, only the effective surface temperature (T_r), which is a combination of foliage (T_l) and soil surface temperature (T_s) is obtained from satellites. Norman et al. (1995) expresses the relationship as:

$$T_r = \left(f(LAI,\varphi)T_l^4 + (1 - f(LAI,\varphi))T_s^4 \right)^{1/4} \quad \textbf{(5)}$$

The function f expresses the vegetation coverage as a function of leaf area index (LAI) and sensor view angle (φ). Hence, to derive the component temperatures from the effective temperature, some additional knowledge that ties the two component temperatures to each other is required. This 'additional relationship' has been investigated in a number of studies.

Norman et al. (1995) developed a method where transpiration is initially accounted for by the Priestley-Taylor equation, whereby they were able to relate the canopy temperature to air temperature. This allows both canopy and soil surface temperature to be determined from a single effective surface temperature. The initial guesses of component temperatures were used in an iterative procedure to derive soil evaporation and transpiration that satisfied the energy balance. Anderson et al. (1997) coupled this model with a time-integrated component connecting surface sensible heating with planetary boundary layer development, whereby they eliminated the need for specifying air-temperatures. They tested the model on data collected during FIFE (Sellers et al., 1992) and Monsoon '90 (Kustas and Goodrich, 1994), and found that the model yielded uncertainties comparable to those achieved by models that do require air-temperature as input.

Lhomme et al. (1994) attempted to establish an empirical relationship between T_s to T_l. There are, however, strong indications that such relationships may vary with experimental data (Zahn et al., 1996) and that it is probably related to plant characteristics (McNaughton and van den Hurk, 1995).

Recognizing the influence of leaf area index on the relationship between aerodynamic and radiometric surface temperature, Chehbouni et al. (1996) used results from a soil-vegetation-atmosphere-transfer (SVAT) model coupled to a crop growth model to derive a relationship between aerodynamic and radiometric surface temperature for LAI between 0.05 and 1. They later tested this approach at two different sites and concluded that this approach showed some signs of being generally applicable, but that more applications were needed to test its generality (Chehbouni et al., 1997).

Boegh et al. (1999, 2000) used the relationship between the Landsat-TM surface temperature and the normalized difference vegetation index (NDVI) representing the fractional vegetation cover to derive the vegetation temperature from the surface temperature.

Finally, some have attempted to solve this problem by measuring the radiometric surface temperature from two different angles, whereby two equations in the two unknowns T_l and T_s can be established from equation 5 (Kustas and Norman, 1997, 1999; Francois et al., 1997; Chehbouni et al., 2001; Merlin and Chehbouni, 2004). View angle effects are most pronounced for sparse canopies, where a change in view angle will cause a large difference in the fraction of soil and vegetation within the footprint of the radiometer. Moreover, while the view-angle approach has proven useful for ground-based measurements, only one viewing angle is usually available for satellite images.

It should be clear from this brief review that converting land-surface temperature into latent heat fluxes requires a number of model assumptions, and knowing that different assumptions lead to deviating fluxes (e.g. Zahn et al., 1996), a comparison between simulated and RS-derived land-surface fluxes will, in reality, be a comparison between two models, usually being based on different structures and assumptions. Hence, it will be difficult to identify the model that is 'most correct'. This is probably part of the reason why few have attempted such a direct flux comparison (one example is Boegh et al., 2004). This leads to the subject of Paper II.

3.2 Summary of Paper II: Evaluation of a distributed land-surface model by remotely sensed information

One of the purposes of the current project is to strengthen the link between hydrology and remote sensing, which was partially accomplished by implementing an energy-based LSM in MIKE SHE and ensuring that the time-varying maps of climate and land-surface parameters can be handled efficiently. Here remotely sensed maps of LAI and albedo are among the data types used to describe the land surface in a detailed set-up on an intensively monitored 10 km^2 agricultural area in Denmark.

The new LSM facilitates the simulation of effective land-surface temperatures, and as discussed in the previous chapter this opens for a more efficient use of remote sensing for evaluation purposes. This is the main subject of this second paper. Remotely sensed land-surface temperatures have previously been used to qualitatively evaluate the spatial distribution, through a direct comparison of simulated and observed temperature, but this evaluation method is taken one step further here. A method is proposed to convert the differences between simulated and remotely sensed surface temperature into a corresponding difference in latent heat flux, while eliminating the error due to different model structures.

Initially, the model is evaluated at the plot scale using measured fluxes of latent heat. Field data from four flux-sites representing three of the four vegetation classes identified in the area are used. The model was found to perform satisfactory at all flux-sites in two distinct evaluation periods.

Considering the spatial variability of the land-surface properties, even for a small area such as the one used here, there is a need for a more detailed evaluation of the spatial distribution of the latent heat flux. This was obtained by including RS-based maps of radiometric surface temperature (RS surface temperature) in the evaluation procedure. The second stage in the evaluation consisted of a direct comparison between simulated effective radiometric surface temperature and RS surface temperature. Overall, the model was found to reproduce the spatial pattern of surface temperature well, although the model produced significantly less variation than observed in the RS surface temperature. The smaller variation was mainly attributed to the variability of soil, climate and land-surface properties not resolved by the model. The model was found to perform equally well for all values of LAI and all four vegetation classes.

The direct comparison between observed and simulated surface temperature indicated that the model generally reproduces the spatial pattern of land-surface fluxes well at the time of the satellite overpass. However, since no information on the corresponding differences in latent heat flux is provided, and due to the non-linear relationship between surface temperature and latent heat flux as well as the influence of the land-surface properties on this relationship, it remains very difficult to determine where and when a temperature difference is 'significant'.

The third stage of the evaluation address this issue, and aim at converting the temperature differences into the corresponding difference in latent heat fluxes. A method is proposed to convert the observed surface temperatures to latent heat, using exactly the same two-layer model formulation as used in MIKE SHE, whereby the uncertainty due to different model structure is eliminated.

A comparison between simulated latent heat fluxes and latent heat derived from remote sensing showed that the model accurately simulated the spatial distribution, as well as area mean. An underestimation of the small-scale variability did, however, give rise to some deviations at the pixel scale. The mean absolute difference at the pixel-scale was found to be 30 W/m^2.

It is concluded that the approach proposed here will be a valuable supplement to the pure temperature evaluation, as it provides a first step towards quantifying the performance of distributed land-surface models at much smaller scales than has been possible by use of more traditional data sources.

Chapter 4

COUPLING BETWEEN ATMOSPHERIC AND HYDROLOGICAL MODELS

Understanding the interaction between the terrestrial microclimate, hydrology and ecology is the key to determining the effect of land use and climate change on the hydrological system, and the strong coupling between the land surface and atmosphere is well proven at both local and regional scale. A brief review is given in this chapter.

4.1 Land surface - atmosphere interactions

Land surface-atmosphere interactions arise from the fact that if the fluxes of heat and water from the land surface to the atmosphere changes, humidity, temperature and air pressure in the atmosphere will consequently change. Since the climate exerts a significant influence on the land-surface fluxes, the changed conditions in the atmosphere may in turn affect the land-surface, working to either dampen or amplify the changes in land-surface fluxes.

A very important factor in determining the significance of such feedback effects is scale. If, e.g., transpiration from a single plant changes, the conditions in the atmosphere will remain unaffected, and hence there will be no feedback effects. However, if transpiration from a large area changes, it will be felt throughout the whole PBL and feedback effects may be pronounced.

It is common practice to perform impact assessment studies of, e.g., land-use changes in hydrological models that are driven by time series of measured climate data. In those cases, a potential change in land-surface fluxes is not allowed to affect the state of the atmosphere, and hence feedback is neglected.

The consequences of neglecting feedback at the regional scale were examined by Jacobs and de Bruin, (1992) who coupled a 'big-leaf' land-surface model to a one-dimensional PBL model. They found that PBL feedback has a significant influence on the sensitivity of latent heat to changes in land-surface parameters. Similar conclusions were later drawn by Brubaker and Entekhabi, (1996) and Kim and Entekhabi (1998), who conclude that it is necessary to examine the impact of any change in land-surface parameters (e. g. land-use change scenarios) in a coupled model system, and that failure to do so may result in model sensitivities that are not only wrong in magnitude, but in sign as well.

Others have investigated the influence of the land-surface properties on the local and regional climate, and the close relationship is now well proven.

At the local scale Segal et al. (1988) investigated the influence of vegetation on thermally induced meso-scale circulations due to non-uniform vegetation cover. They found that when extended areas of dense vegetation not under water stress are adjacent to bare soil areas, thermal circulations comparable in intensity to sea-breezes can be induced. They found that there was no substantial difference in the thermally induced meso-scale circulations generated by a sharp thermal contrast along a flat terrain when compared to that generated by an equivalent, but gradual change from dense vegetation to bare soils, along distances less than 30 km.

Similar conclusions were reached by Hong et al. (1995) who investigated the effects of different soil types on the thermally induced circulations between vegetated and bare soil areas, and found that the intensity of the 'vegetation breeze' is strongly related to soil characteristics.

Such vegetation induced circulations were experimentally confirmed by micro-meteorological observations from the HAPEX-MOBILHY field experiment (Pinty et al., 1989).

Cuenca et al. (1996) investigated the impact of soil water parameterization on atmospheric boundary layer formation using an atmospheric model coupled to a plant-soil model. They found little difference in the dry and wet ends of the scale, but significant differences were found for intermediate soil moisture contents, resulting in differences in planetary boundary layer depths of up to 1000 m.

Song et al. (1997) used a meso-scale atmospheric model coupled to an advanced land-surface model to simulate the local climate over the 15x15 km FIFE site. They found that, even for this relatively homogeneous grassland, local variations in the land-surface fluxes induced to up to 2°C spatial variations in the near-surface air-temperature.

At the regional scale van den Hurk et al. (2002) compared the results obtained for the Baltic Sea catchment using two different land surface schemes coupled to the same regional atmospheric mode (RACMO). They found that the temporal and spatial distribution of precipitation is sensitive to the choice of land-surface scheme. They conclude that the strong coupling between local evapotranspiration and local precipitation results in clear hydrological feedback mechanisms.

Zeng et al. (2002) investigated the effect of land-surface heterogeneities on the regional climate and found that surface heterogeneities in roughness length and stomata resistance greatly affect the simulation of surface fluxes as well as the wind, temperature and precipitation fields.

Due to this well-proven relationship between the land surface and atmosphere, advanced land surface schemes have now been implemented in many atmospheric models. However, while most of these describe the canopy and root zone in great detail, the interactions between groundwater, root zone, and surface water are normally neglected, which may lead to inaccurate model predictions in areas where groundwater and surface water are closely connected (Chen and Hu, 2004; York et al., 2002).

In contrast, the most advanced integrated hydrological models (e.g. MODHMS, Panday and Huyakorn, 2004; MIKE SHE, Graham and Butts, 2005) describe the sub-surface and surface flows as well as the interactions between surface water and groundwater in great detail, but treat the climate in a very simplistic way, usually being driven by prescribed atmospheric conditions. This implies that any changes in land surface or hydrological properties are not allowed to feed back to the atmosphere. As earlier described, previous studies have shown that this lack of feedback may potentially lead to errors in scenario simulations dealing with changes in hydrological and land-surface properties

The simplifications described above are required to limit the computational requirements and to ensure the practical applicability of both hydrological and atmospheric models. It does, however, imply that there is still a gap between the simplified hydrological models components implemented in atmospheric models and the state-of-the-art integrated hydrological models, as well as a gap between the very simplistic treatment of climate data in hydrological models and state-of-the-art atmospheric modelling.

Closing this gap by coupling an advanced hydrological model to a meso-scale atmospheric model through a shared land-surface model will provide a unique, fully dynamically coupled, framework for investigating issues related to land surface-atmosphere interactions at hydrological (catchment) scales.

While such a coupled model system probably will be too computationally expensive to be used for long simulations of large domains, it has the potential to provide important insight on the interactions between land surface and atmosphere in areas where the parameterizations of the land-surface models implemented in atmospheric models do not suffice.

Moreover, a coupled modelling system could provide hydrologists with information on how the atmosphere will respond to changes in the hydrological and land-surface properties at the hydrological scale, and equally important, provide information about the consequences of neglecting atmospheric feedback in hydrological scenario simulations. The third paper addresses the development, testing and application of such a coupled model system.

4.2 Summary of Paper III: Dynamic coupling of hydrological and atmospheric models using a shared land-surface model

The new LSM facilitates a consistent integration of integrated hydrological modelling and atmospheric modelling through a dynamic coupling between two such models through a shared LSM. A coupled modelling system will provide a unique framework for investigation of land surface-atmosphere interactions at hydrological scales, which is the subject of the third paper.

The first part of the paper describes how the new LSM was used couple MIKE SHE dynamically to a non-hydrostatic meso-scale atmospheric model. After discussing the location of the shared land-surface model and identifying the variables that have to be exchanged dynamically between the two models, the coupling was obtained by providing the hydrological as well as the atmospheric model with code interfaces following the guidelines provided by the Open Modelling Interface standard (OpenMI, Gregersen and Blind, 2004). By using the OpenMI standard it is ensured that any of the two model components can be replaced by any other OpenMI compliant model that has an interface designed to provide and receive the variables identified in this paper.

The coupled model system was initially tested using data from FIFE, comprising both observations of land-surface fluxes and atmospheric profiles of potential temperature. The temperature profiles were used to track the development of the PBL. Using a one-dimensional model set-up, it was shown that the fluxes at the land surface, as well as the development of the PBL, were accurately predicted by the coupled model system.

The evaluation was followed by two one-dimensional applications of the coupled system. The two applications showed that even in impact assessment studies involving relatively moderate changes, feedback may have a significant influence on the simulated impact. The first application showed that the relative sensitivity of the total latent heat flux to changes in selected key parameters in some cases differed by more than a factor of two in the coupled and uncoupled model, and that feedback can work both to amplify and dampen the effect of a parameter perturbation, depending on the parameter being investigated.

In a hypothetical grassland-to-agriculture scenario, it was shown that neglecting atmospheric feedback led to a 40% overestimation of the change in evapotranspiration. Overall, this implies that in some cases, depending on the scale and significance of the imposed changes, impact assessment studies using uncoupled models will fail to produce reliable predictions.

Chapter 5

OUTLOOK

In this chapter, some of the perspectives and future plans not specifically addressed elsewhere in the project are discussed.

Implementation of the energy-based land-surface model in MIKE SHE has strengthened the link to remote sensing, and made it possible to utilize some of the RS data currently available more efficiently. The link between remote sensing and distributed hydrological modelling is considered vital for most future applications, and the strengthened link to remote sensing is already being utilized in an ongoing study aiming at determining the water balance in one of the most complex wetland areas in the World, the Okavango Delta in Africa (Okavango Delta Management Plan, Jacobsen, 2005).

In the Okavango project, MIKE SHE is being forced with 8-day MODIS composites of leaf area index and albedo, and a comparison with the results obtained with the more conceptually based Kristensen and Jensen (1972) LSM (an alternative LSM option currently available in MIKE SHE) will help quantifying the potential benefits of using a more complex evapotranspiration model.

The Okavango Delta will also be the first large area used to test the evaluation method proposed in the second paper, which will hopefully provide more insight in the usefulness of this approach.

Although not addressed directly in this project, it seems very likely that impact assessment of changes in the hydrological system, such as drainage or restoration of wetlands, changes in irrigation practices, or construction of reservoirs, in uncoupled models may lead to errors similar in magnitude as for land use changes. Overall, this implies that in some cases, depending on the scale and significance of the imposed changes, impact assessment studies in uncoupled models will fail to produce reliable predictions. A coupled model system such as the one presented here will provide the means to identify the situations where feedback will significantly affect the simulated impact and in those cases help to produce more accurate predictions.

The plug-compatibility between existing MIKE SHE set-ups and any OpenMI compliant atmospheric model, across differences in time step and spatial resolutions will ensure that these coupled simulations can be carried out with an absolute minimum of effort. This will hopefully lead to more investigations of real-life situations where feedback and inter-patch interactions may play a role, overall leading to a better understanding of the land surface – atmosphere interactions.

Predicting the impact of future climate changes will continue to be a major focus area for both hydrologists and atmospheric scientists in the coming years. To the author's knowledge, no meso-scale atmospheric models are currently capable of running in climate mode, and considering the scale of application of the current regional climate models (RCM), a coupling between a complex hydrological model and a RCM does not seem feasible at the present time. However, the development of climate models working at the meso-scale is currently being subject to research, and when these models become operational they will, if provided with an OpenMI interface, couple directly to MIKE SHE and the coupled model will be ideal for climate change impact assessment studies.

Before the MIKE SHE LSM will be generally applicable for climate change scenarios, it must, however, be extended to include parameterizations for snow and ice.

MIKE SHE was recently provided with a conceptual groundwater component (DHI, 2005a) consisting of a number of interconnected linear reservoirs. This allows the model to be applied at much larger scales than when the fully three-dimensional groundwater component is employed (e.g. Andersen et al., 2002). Using conceptual groundwater and overland flow components coupled to the MIKE11 (DHI, 2005b) river model, MIKE SHE is currently being tested as a flood forecasting system (Butts et al., 2004) within the framework of the FloodRelief project (http://projects.dhi.dk/floodrelief). Provided with the ability to couple dynamically to an atmospheric model, it may be possible to apply MIKE SHE for real-time flood-forecasting as a part of a coupled modelling system in the near future.

It has been a priority to ensure that the land-surface model developed here, as well as the coupled model system, will be kept alive beyond this Ph. D. study, and continue to be used and further developed. Hopefully, a continued use will be guaranteed by making the LSM part of the official MIKE SHE releases, starting from 2006.

While the new LSM in many applications represent a step forward compared to the more conceptual Kristensen and Jensen (1972) alternative, there is still much room for improvements, and future studies may show that alternative parameterizations of the individual processes that make up the model could be a better choice.

The hope is that such future improvements, developments and testing can be carried out through joint projects between DHI - Water & Environment and Universities, such as the Ph. D. project leading to this report.

This process has already started, and Ph. D. students at the University of Copenhagen are currently using the MIKE SHE LSM to test the applicability of distributed climate and land-surface data derived from RS in MIKE SHE for the Senegal River Basin. The issue of scale in relation to RS data applied in MIKE SHE LSM will also be addressed in these studies. Investigations of the feedbacks between precipitation, soil moisture and evapotranspiration are also being planned in this context.

Finally, as earlier stated, the MIKE SHE LSM will have to be extended to include parameterizations for snow and ice, before being generally applicable for climate change scenarios. The possibilities for a continued LSM development by expanding to snow and ice conditions are currently being considered jointly by DHI and DTU.

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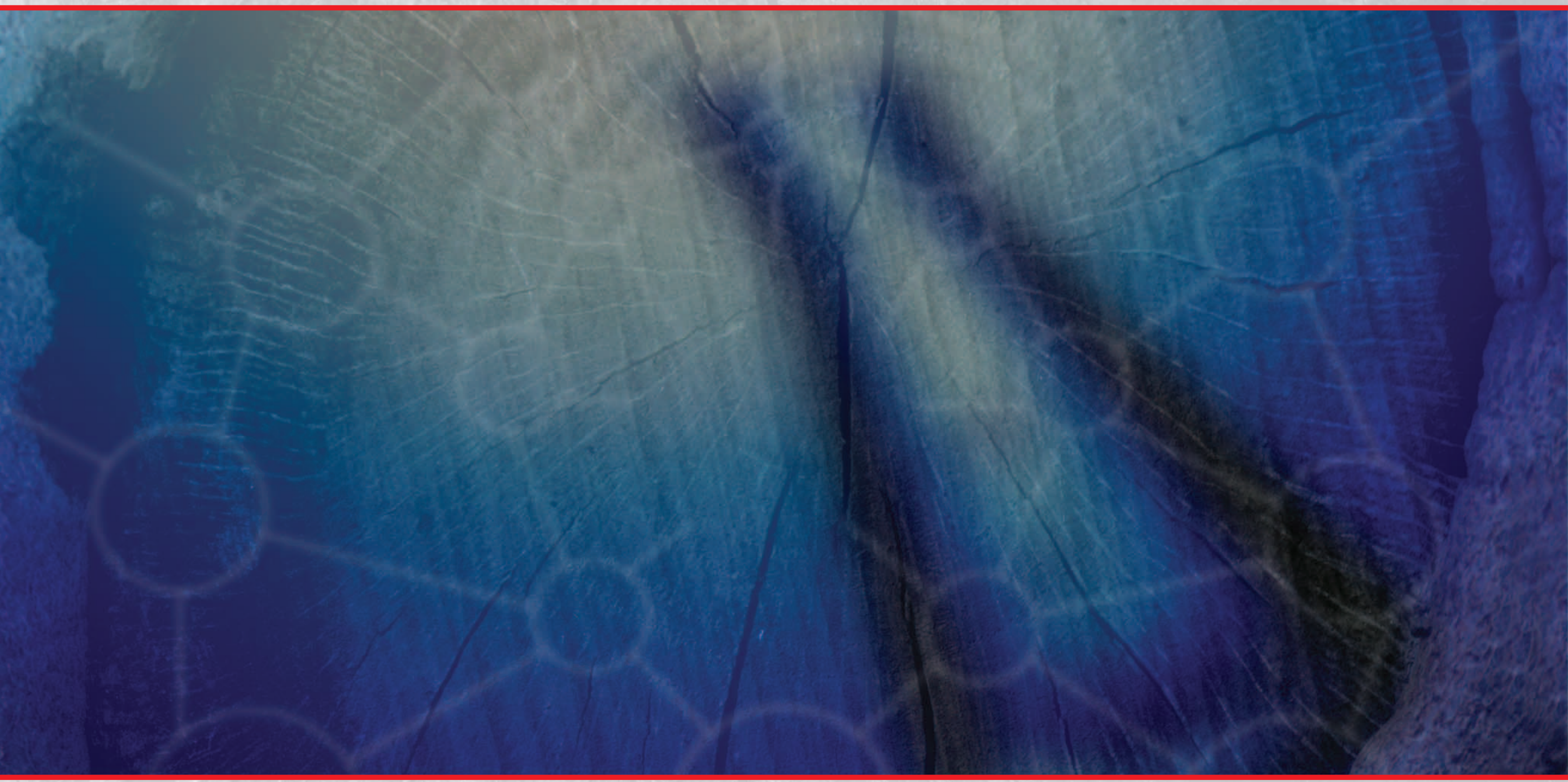

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