CHAPTER 4

Case Studies

4.0 Introduction

Axel Bronstert, Nicole Mölders

In this chapter, 14 examples of coupled modelling studies are presented. They cover a wide range of scientific disciplines, including climate, hydrology, soil sciences, and economic aspects. However, it is obvious that this cannot be a complete survey of recent coupled modelling studies.

For brevity, the presentations of the case studies purposely focus on the description of the couplings only. The case studies are to give an idea of how model couplings can be realised, and do not cover the entire range of recent coupled models. The examples show how models may differ with respect to detail and complexity.

The case studies have been arranged in five groups according to the main coupling issues which are addressed by each specific study: The first group contains six studies which deal with the coupling of different compartments of the hydrological cycle, such as surface and groundwater (case study No. 1, 2, and 3), permafrost and runoff (No. 4 and 6) and atmosphere and various compartments of the terrestrial hydrological cycle (No. 5). The second group comprises three case studies focusing on the linkage of water and energy cycles. Though these studies have a similar focus, they differ strongly concerning their typical scales (spatial scales: from small catchments to global; time scales: from weeks to thousands of years). The major application field addressed in these studies is the evaluation of landscape change effects on atmospheric processes. The next two case studies deal with the coupling of the hydrological cycle with chemical cycles, such as carbon and nutrients. The following group includes examples of coupled models which in addition to natural processes also take into account socio-economic processes, i.e., the economic (e.g., the income of farmers) and sociological impacts (such as demographic development and migration). They cover a regional scale (No. 12) and a global scale (No. 13). Finally, one example of a study is presented which has a strong focus on methodological aspects of coupled models, such as data assimilation and model organisation.

An important feature of the different coupled models presented here is the type of coupling achieved. In this context we speak of a one-way coupling if the results from one discipline are being used as prerequisite information for another scientific discipline, but no feedback effects are considered. A two-way coupling mode includes the consideration of feedback effects. Even within one study, different degrees of coupling may occur, if certain process feedbacks are included and others are not. Case studies 4 and 5, for instance, both apply one-way coupling with respect to the atmospheric component, but use two-way coupling for some other parts. Coupled models can be set up in a mode where two models exchange information (e.g. results from sub-models) via an external interface, i.e. the two (or more) models can also be run in a stand-alone mode, and have been programmed in separate codes. This may be termed a *weak coupling* mode. A model where all coupling has been achieved within a single and consistent computer code, and the exchange of information is organised in time steps and spatial units specifically adjusted to the dynamics and spatial variations of the coupled processes, may be termed a *strong coupling* mode. If a coupled model accounts for feedback effects and at the same time is organised in a strong coupling mode, we may term this an *integrated* mode.

As discussed before, the case studies cover a very wide range of spatial and temporal scales. Some investigate processes at the hillslope scale (No. 10), and others (e.g. No. 9, 13) at the global scale. It is worth noting, however, that most case studies deal with a spatial scale which is termed meso-scale in hydrology, or regional scale in atmospheric sciences. The timescale of the case studies spans from days and weeks (e.g. No. 7, 8) to several thousand years (No. 9). All case studies have in common that the degree of coupling is determined by the question to be addressed by the study, i.e. the temporal and spatial scales and the feedback processes that are relevant at these scales. In this context the same temporal scales may be combined with different spatial scales. Case studies 9 and 10, for instance, aim at a coupling on the local and global spatial scales, respectively, but both on the long term with respect to the temporal scale.

All case studies are presented in a similar way in the following pages. First, the motivation and the objectives of the study are summarised, then the study set-up and the study region are introduced. The next sub-section discusses the complexity addressed in the study and finally an appraisal of the experiences gained with the coupled model is given. Table 4.0-1 lists all the case studies and gives a classification with respect to their type of coupling as discussed above.

Table 4.0-1 Case studies and their classification with respect to the type of coupling as discussed above.

Case study No.	Authors	Name of the model	Topic	Study region	Main spatial scale	Main time scale	Main coupling issue	One-way mode	Two-way mode	Integrated mode
1	Vázquez-Suñé et al.		ground-/ surface water/ salinity	Barcelona (Spain)	meso / regional	seasons - decades	different compartments of the hydrological cycle	X		
2	Holzbecher		ground-water / lakes	Lake Dagow (Germany)	meso / regional	seasons - decades	different compartments of the hydrological cycle		X	
3	Holzbecher	FAST-C	salinity	Nile Delta (Egypt)	meso / regional	--	different compartments of the hydrological cycle		X	
4	Motovilov & Georgiadi	ECOMAG	permafrost & climate change	Kenkeme basin (Russia)	meso / regional	days - seasons	different compartments of the hydrological cycle	X	X	
5	Halldin et al.	MIUU; ECOMAG	boreal region	South Sweden; North Finland	meso / regional	hours - days	different compartments of the hydrological cycle	X	X	
6	Kuchment et al.		runoff in permafrost	Kolyma (Russia)	meso / regional	seasons - decades	different compartments of the hydrological cycle	X		
7	Mölders		land-use change impacts	East Germany	meso / regional	minutes - weeks	water & energy			X
8	Pielke et al.		weather	Florida (USA)	meso / regional	seasonal	water & energy		X	
9	Ganopolski	CLIMBER-2	Earth system modelling	the globe	global	thousands-millions of years	water & energy			X
10	Band & Tague	RHESSys	water, carbon and nutrients	Pond Branch (USA)	hillslope catchment	days - decades	water & biogeochemistry			X
11	Hall	BOREAS	boreal ecosystems	North Canada	local - regional	diurnal - centuries	water & biogeochemistry	X	X	
12	Krol et al.	SIM	regional impacts of climate changes	Northeast Brazil	regional	decades - centuries	water, climate, economy, sociology			X
13	Eickhout & Leemans	IMAGE-2	global impact of climate changes	the globe	global	decades - centuries	water, climate, economy, sociology			X
14	Leavesley & Springer		"virtual watershed"	--	meso / regional	hours - years	methodological aspects	X	X	

4.1 Groundwater Modelling in the Urban Area of Barcelona

Enric Vázquez-Suñé, Jesus Carrera, Xavier Sánchez-Vila, Elena Abarca, Ramón Arandes

4.1.1 Motivation and Objectives

The study of urban groundwater is motivated by the strong interaction between city socio-economic development and groundwater environmental impacts. Urbanisation clearly affects both availability and quality of groundwater resources: seepage from sewage system pollutes groundwater, this leads to abandoning existing wells, which causes groundwater heads (actually, recovery), leading to flooding of basements and other underground infrastructures; and the cycle goes on. These effects have significant social, environmental and economic implications. This kind of problem is being faced by many cities worldwide, but unfortunately, researchers and municipal managers have tended to address them separately, rather than within an integrated framework.

Barcelona groundwater has suffered, and is still suffering, many of the problems associated to urban growth: over-pumping, sea-water intrusion, water-level rises, flooding of subway, pollution (Custodio 1997; Vázquez-Suñé et al. 1997).

The objective of this case study is to present some of the models prepared to address these issues. Specifically, we discuss the city-wide Barcelona model, as shown in Fig. 4.1-2, and a small-scale model, the Besós model, shown in Fig.4.1-4.

4.1.2 Groundwater in Barcelona

Barcelona is located between the mountain range Serra de Collcerola and the Mediterranean Sea. The city is bounded by two rivers, the Besós and Llobregat. There are several aquifers. In the upper parts is a Palaeozoic aquifer, consisting of shales and granites, and Quaternary aquifers formed by the alluvial and deltaic sediments of Llobregat and Besós rivers; in between, are aquifers consisting of piedmont cones and coarse alluvial sediments.

Groundwater levels in Barcelona have followed the typical evolution of an industrial city. Water extracted for industrial uses has increased since the early 20th century and reached a maximum of 60 – 70 million m^3 per year by the early 1970s. Drawdowns in different parts of the city ranged from a few metres to more than 15 m in several areas. Pumping has been severely reduced since the late 70s because of contamination and industrial migration. Water levels have almost recovered to their natural levels except in particular zones. An important part of the subway system and many of the buildings that exist today in Barcelona, were built during the period 1950 – 1975, coinciding with the period of maximum depletion. At that time, neither designers nor constructors were aware that groundwater levels could revert to the original levels. As groundwater levels recover, those constructions face severe flooding and pollution problems. For example, the subway system is suffering seepage problems in many areas, having to pump around 10 -15 million m^3 per year from inside the subway tunnels (Fig. 4.1-1).

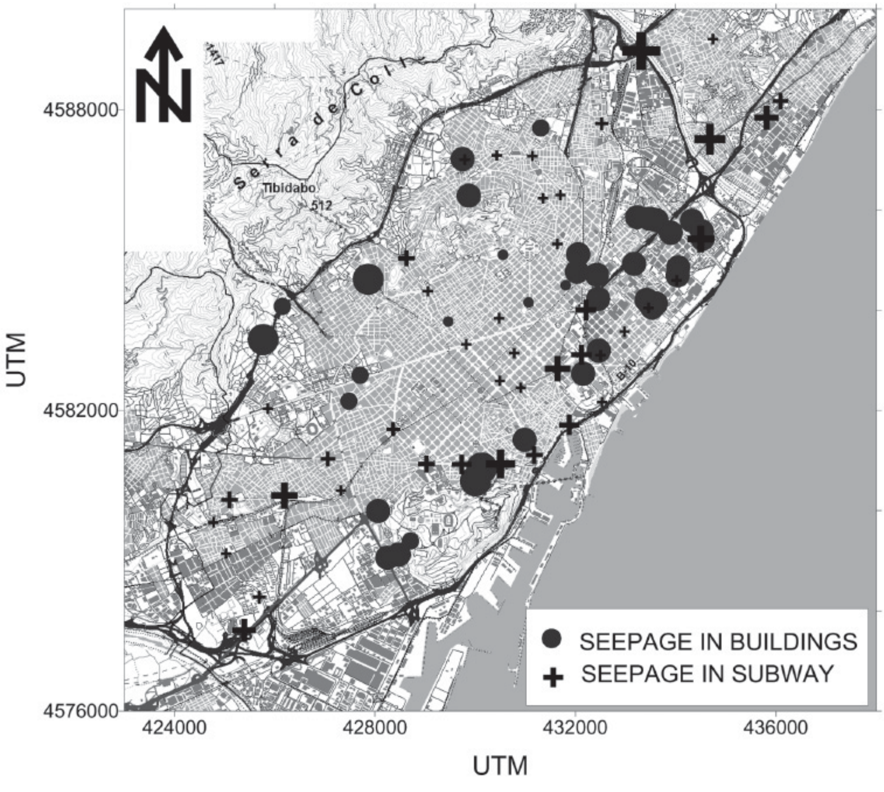

Fig. 4.1-1 Seepage problems in Barcelona city (symbol size is proportional to amount of seepage)

At present, the economic impact of reducing seepage by maintaining groundwater below the foundations of structures is very high. The impact of allowing the levels to stay high (by taking no external actions) is also very significant: To the need for drainage works, such as impermeabilisation, pump installation and water disposal, one must add the energy cost of continuously pumping the rather high flows that have to be evacuated. Moreover, the city sewage system is often used for evacuating the seepage. This is not a good solution because by mixing with wastewater, the seepage becomes polluted, causing an increase in treatment costs. Moreover, portions of the sewage network become saturated, which affects the proper functioning of the system during periods of critical need, such as during storms.

4.1.3 Complexity of the Groundwater Model

Several numerical models have been built with various purposes: integrating different historical data, accounting for the present situation, validating the conceptual model, quantifying groundwater flows (water balance) and predicting the future evolution of groundwater under different scenarios. Additionally, integration efforts helps to reduce uncertainty in hydraulic parameters. The Barcelona groundwater model is unique in several aspects that are relevant to the nature of this case study:

- It takes into account the historical evolution of the urban area. This is achieved by changing over time the sink/source terms associated with changes in soil use (i.e. changing from agricultural or industrial to urban use).

- Areal recharge depends basically on specific factors (notably water and sewage network density), directly related to the density of population and to the time the area was developed.

- Extractions are difficult to evaluate and they are often underestimated. A specific study was made to evaluate the evolution of pumping.

- Urban structures are singular features in a model and they should be addressed individually. In fact, small-scale specific models are needed to address them. One such model is described below.

- Interactions with subway and railway tunnels are modelled by means of appropriate sink/source terms. As head rises, so does the pressure behind the tunnels (and, hence, the flux) and the length of section affected.

- Seawater intrusion is addressed by means of an appropriate boundary condition.

Fig. 4.1-2 Model domain, including street network (grey) and highways (blue), and finite element mesh (red)

From a modelling viewpoint, all these interactions are treated as one-way but in reality, some are two-way interactions. For instance, pollution caused some of the wells to be abandoned. However, this has been incorporated externally into the model. All interactions are subsumed in the flow equation. For the city-wide model, this was solved using the finite element method with the grid shown in Fig. 4.1-2. An output of the model is the quantification of the terms involved in the groundwater balance (Fig. 4.1-3) and its evolution over time. Quantification of the different terms involved in the water balance is important for two reasons: a) knowing which are the main points to be stressed when managing the groundwater resources, and b) suggesting corrective measures.

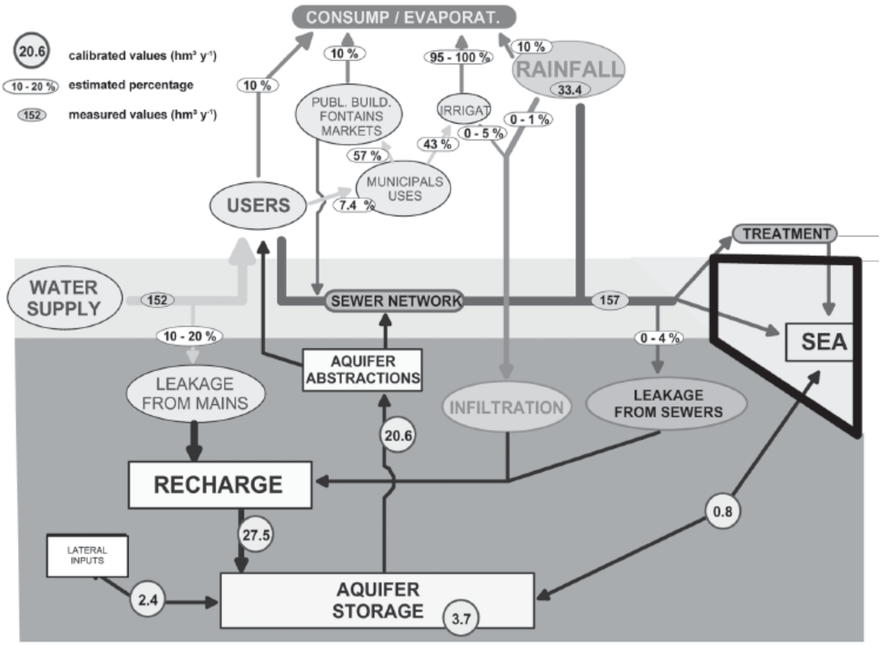

Fig. 4.1-3 Quantification of the terms involved in the urban groundwater balance in Barcelona

Three main sources of pollution have been identified in Barcelona: losses from the sewers system, runoff water infiltration, and seawater intrusion. Regarding seawater intrusion, its growth has been related to rising groundwater levels, and this is correlated directly with the industrial development of the city. In the eastern part of the city, seawater intrusion was detected as far as 2 km inland from the seacoast during the 1970s. The recovery of groundwater levels has reversed the direction of flow and some of the wells that were highly saline are now back to fresh water.

Discrimination among pollution sources can probably be best achieved by performing a mass balance computation involving different chemical species. Many authors compare solute concentrations in different water sources as the way to decide the chemical species that can be used for discrimination purposes (Lerner and Yang 2000). This methodology has been applied to the city of Barcelona to evaluate the total amount of water coming from each source. This has been implemented in the numerical model to compute the percentage of losses in mains, sewers and the contribution of direct infiltration, the river, or the sea.

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We focus here on water management for this new area. Approximately 1 $hm^3 y^{-1}$ must be supplied to the area to irrigate the green areas and to maintain an artificial lake. The first idea was to use water from the local drinking water supply system. An alternative is to use groundwater from wells located nearby. Using water from the river was discarded for quality reasons and to maintain river flow during the summer. The final decision was set within a global management concept where the model presented previously was a key tool.

The numerical model presented previously was used to analyse a number of pumping scenarios. The main scenario studied was the compatibility of pumping 15 $hm^3 y^{-1}$ for water supply plus 1 $hm^3 y^{-1}$ from an abstraction well located beside the Baró de Viver (BVIC) subway station (see Fig.4.1-5). Compatibility is measured in terms of admissible drawdowns. As a further outcome from the model we could gauge the effect of pumping upon the groundwater levels along the subway line.

Groundwater flow in this model is coupled to interaction with the subway tunnel and with the river. Results are shown in Fig.4.1-5. Both interactions are one-way, in the sense that neither river stage nor water level in the tunnel is assumed to be affected by the groundwater level.

4.1.5 Summary

This case study illustrates that urban groundwater displays significant feedbacks. It is strongly influenced by urban growth, which affects recharge and drainage. In turn, groundwater affects social developments. By creating problems, it forces the administration to react by changing water management practices, which in turn affect the urban environment (pumping for park irrigation, reduction of demand over conventional water sources, maintenance of river flow, etc.). The resulting behaviour is complex and rich and can hardly be represented by a model. Yet the models are essential to help in organising knowledge and in understanding the levels of interactions.

4.2 The Lake Dagow Coupled Model for Groundwater and Surface Water

Ekkehard Holzbecher

4.2.1 Motivation and Objectives for the Coupled Approach

Lake Dagow is a sub-catchment of another groundwater lake, Lake Stechlin (Fig. 4.2-1). Since the construction of the Polzow canal between 1745–1750 connecting the lakes Dagow, Stechlin, Nehmitz, and Roofen with the River Havel, the region drains to the North Sea. As a consequence, the groundwater level and the water levels of several lakes sank considerably and the littoral belts were reduced. For Lake Dagow, a further major influence on the water level may be attributed to groundwater withdrawal when water utilities began operating wells in the vicinity of the lake shore in the 1990s. However, groundwater had certainly been withdrawn for private use at a similar rate before this period, although there is a complete lack of data about pumping by land owners in the two villages Dagow and Neuglobsow located on the southern shore.

One of the aims of the model approach presented here is to reconstruct former water levels. Such an aim can be achieved only by a coupled model connecting groundwater and surface water compartments.

4.2.2 Short Description of the Study

Lake Dagow (Dagowsee) is located near the border between Brandenburg and Mecklenburg-Vorpommern, 130 km north of the city of Berlin. The interaction with groundwater is especially important because Lake Dagow is a groundwater lake with no inflow from creeks or rivers, typical of the north German lake district.

Lake Dagow and its catchment (see Fig. 4.2-1) is part of the Northern (Baltic) Land Ridge formed in the latest glacial period – the Weichselian. As a result of the relatively fast melting of glaciers, dead ice was left in the grooves and depressions formed earlier below the ice sheet. The depressions filled with dead ice were later covered with sand and gravel, leading to the present landscape with its numerous lakes and wetlands.

In the region studied, two aquifers are separated by boulder clay 10-30 m thick. The uncovered aquifer consists of fluvioglacial deposits; the sandy aquifer consists of fluvioglacial deposits classified as highly permeable. Both the uncovered aquifer and the surface water comprise one hydraulic system, with the lakes fed from the groundwater of the uncovered aquifer.

4.2.3 Complexity of the Study

A steady-state groundwater model, covering the entire catchment of Lake Stechlin and Lake Dagow, was described in detail by Holzbecher and Ginzel (1998). Holzbecher (2001, 2003) presents quasi steady-state computations, in which the model region is extended to the lake shores of the neighbouring lakes Glietzen, Peetsch and Nehmitz. These models dealt with the groundwater compartment only, for which measured lake levels were used as boundary conditions.

Here, a model variant is outlined which tackles a smaller region, including the entire sub-catchment of Lake Dagow (Fig. 4.2-1). The simulations are based on measured time-series for surface water and several groundwater

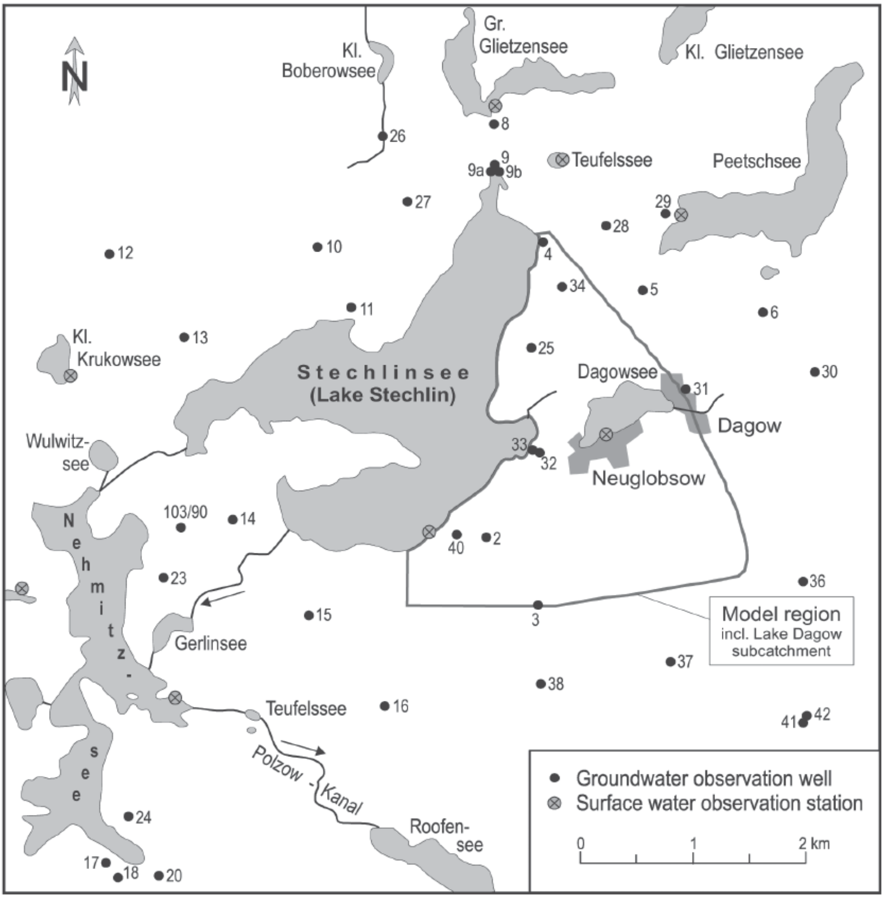


Fig. 4.2-1 Map of Lake Dagow and vicinity showing observation points and model region

observation wells recorded monthly since at least 1959. Moreover, meteorological data, as precipitation, evaporation and evapotranspiration, are also available as monthly time-series (Richter 1997). The measurements of water levels for lakes Stechlin and Dagow serve as boundary conditions for the groundwater model which in turn yield water exchange fluxes between groundwater and surface water. These fluxes are then used in the flux balance for lakes, according to the hydrological balance equation:

$$\Delta S = P - E + I - 0 + R \tag{4.2-1}$$

where ΔS denotes change in water storage within a given time Δt, P the precipitation and E evaporation from the lake surface. I, the sum of inflowing surface water, can be neglected for Lake Dagow (Holzbecher and Nützmann 1999). Also, the amount of outflowing surface water O is negligible. R, denoting the exchange between aquifer and lake, is the only variable on the right-hand side of the balance equation which may take negative values, as happens when the outflow from the lake as groundwater exceeds the amount of fluid inflowing from the aquifer.

For a lake, the water storage change can also be approximated by

$$\Delta S = A \cdot \Delta h \tag{4.2-2}$$

with the mean lake surface denoted by A and the water level change by Δh. This formula may have to be replaced by a more complex one when there are relevant changes in the lake surface area.

The modelling concept for Lake Dagow and its catchment is as follows: balance Eq. 4.2-1 is computed using measured values for P and E, as well as the value for R derived by the groundwater model. Eq. 4.2-2 is then utilised to calculate the change Δh in lake water levels. Head values calculated in this way can be compared to measurements and thus used to improve the groundwater model.

Various input data in the transient model are based on assumptions. Some parameters can only be estimated, like the specific yield and the hydraulic conductance between lakes and aquifer. The temporal development of several variables is unknown, particularly that concerning groundwater withdrawal for private use and groundwater recharge through the unsaturated zone. The values for these parameters and variables can be improved by a calibration or parameter estimation procedure based on the comparison of measured and calculated head values as described above.

In the following, results of the steady state version of the model are reported. Storage ΔS is zero in long-term studies under the assumption of no climatic changes. Thus, the groundwater model was calibrated to produce $\Delta S=0$ in the surface water balance Eq. 4.2-1. The unknown parameter in the groundwater model is groundwater withdrawal for private use. Using such a loosely coupled groundwater–surface water simulation, the inconsistency in the first Stechlin model (Holzbecher and Ginzel 1998) could be corrected.

4.2.4 Experiences

In the beginning it had been assumed that groundwater withdrawal could be neglected because there are no data available from 1959 to 1992, i.e. before the water works went into operation in the vicinity of Lake Dagow with a permitted maximum allowed pumping rate of 200 m^3d^{-1}. A mass balance check for Lake Dagow in a post-processing run for the first groundwater model delivered a value for long-term recharge R of $132 \cdot 10^3$ m^3y^{-1}, while according to the meteorological record, the difference $E - R$ amounts to $17 \cdot 10^3$ m^3y^{-1} only (compare Eq. 4.2-1). The difference of almost one order of magnitude revealed that a relevant term of the water balance was not considered. As groundwater has been pumped for private use during the period under consideration, it is most likely that these water losses from the aquifer represent the missing term. A parameter estimation run showed that the best match between observed and modelled head values were obtained for a groundwater withdrawal rate slightly above the maximum pumping rate of the water works.

Another run of the coupled groundwater and surface water procedure was started, to reconstruct the water level of Lake Dagow for a scenario without groundwater withdrawal. The lake water level was used as an optimisation parameter with the goal (function) given by Eq. 4.2-1. It turned out that the water level would lie more than 0.6 m above the current datum. The procedure had to be extended to take in the local topography, available in a 25 m grid. It then transpires that the surface of Lake Dagow would be extended on the northern and southern shores and, moreover, Little Lake Dagow, the presence of which is reported in historic sources but is nowadays merely a wetland, would re-appear (Fig. 4.2-2).

Feedback between lakes and groundwater is surely the rule and not the exception. Inflow from or outflow to the aquifer is one component of the lake budget while on the other hand hydraulic gradients in the vicinity of the lake – and thus the quantity of water flux – is determined by the water level in the lake.

Various model approaches can be followed to deal with coupled hydrological compartments. In the case study presented, both groundwater withdrawal rate and the lake water level have been used as free parameters in the sub-models for groundwater and surface water; both have a significant effect on the net groundwater exchange with the lake. In most situations, the lack of data will lead to a situation in which not all components of Eqs 4.2-1 and 4.2-2 can be determined using either measured values or the results of a computer model. When only one of the contributions on the right-hand side of the Eqs. 4.2-1 and 4.2-2 is unknown, it may be calculated from the other terms. When, as for example the outflow *O* from a lake is unavailable, it can be computed from the lake balance Eq. 4.2-1 where the change in storage is calculated first as output from a groundwater model. Such an approach was used by Richter (1997) with a simple balance model for groundwater.

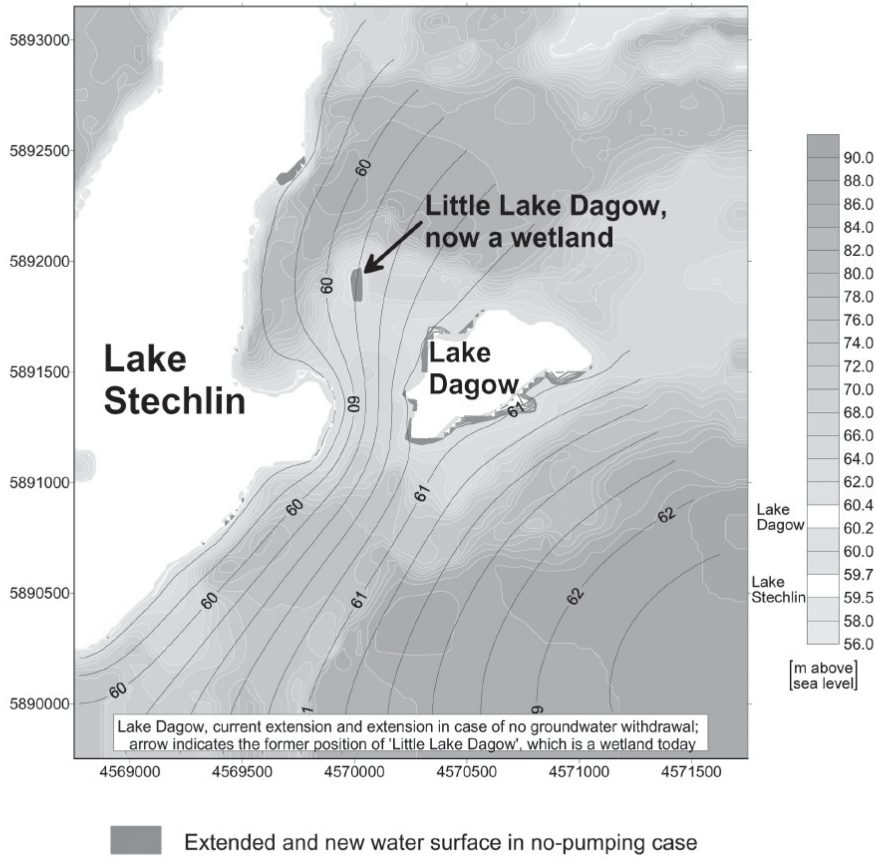


Fig. 4.2-2 Lake Dagow catchment and vicinity in a no-pumping scenario; topography (white contours), groundwater hydraulic head (black contours), water surfaces

4.3 Modelling the Hydrology of the Nile Delta

Ekkehard Holzbecher

4.3.1 Motivation and Objectives for the Coupling Approach

The connection between the hydrological compartments considered in the study is simplified, with no inter-compartmental feedback. The influences on groundwater from surface water, the atmosphere and the sea are taken into account, but effects in the reverse direction are not included in the model. The case chosen here is an example of intra-compartmental two-way coupling. In problems dealing with salinisation, a two-way coupling of flow and transport is usually necessary, while in hydrology there are good reasons to neglect the link between transport (salinity) and water flow.

4.3.2 Short Description of the Study

The Nile delta is the major supplier of the increasing food demand in Egypt. Although Egypt is the outflow recipient of the Nile drainage basin, which covers almost 10% of the African continent, the water requirements of the fast growing population has begun to outstrip its allocated water supply. There are problems of both water quantity, as water is a scarce resource in an arid region and also with water quality, particularly concerning the salt content.

The Nile delta is located around and between the two major branches of the River Nile, the Damietta and Rosetta, before the Nile reaches the Mediterranean Sea. Covering an area of more than 23.000 km^2 and stretching more than 150 km from east to west at the coast, it forms a giant oasis within the Sahara desert. The underlying Pleistocene aquifer, consisting of permeable sands, has a north–south extension of more than 100 km, reaching from the Mediterranean to the city of Cairo. The aquifer is limited on both sides by the desert. The main source of water into the region is the Nile river, which bifurcates into the two delta arms, Damietta and Rosetta, 20 km north of Cairo. The depth of the aquifer, from a maximum of 1000 m, decreases gradually with the distance from the sea.

In an interdisciplinary project managed by the Technical University Berlin (TUB), a hydrological model was set up which takes into account the main components of the water and salt balance. The project was coordinated by TUB within the Special Research Project “Arid and Semiarid Areas”

(SFB 69) and included hydrogeologists, sedimentologists, hydrologists and hydromechanics. A major aim of the project was an evaluation of the saltwater intrusion into the Nile delta aquifer.

4.3.3 Complexity of the Study

The two main compartments of the model are the surface model and the aquifer model. Aside from the hydrosphere, the surface model also includes the biosphere, as different crop patterns and time periods are considered. The aquifer model covers the saturated fluid phase within the geosphere. The coupling between the two compartments is one way only, as described below. The coupling term is groundwater recharge and a two-way coupling between the water and salt balance is implemented. Using the terms introduced above, there is intra-compartmental feedback but no inter-compartmental feedback.

The surface model considers surface water inflow from the Nile and groundwater withdrawal. There is outflow through drainage channels into the Mediterrranean. Outflow from the Nile river to the Mediterranean is relevant only in the Rosetta branch; outflow through the Ismailiya canal is even smaller. Precipitation and evaporation observations were taken from 27 climate stations distributed throughout the model region (Arlt 1995). The CROPWAT code (FAO 1991) was used to compute evapotranspiration, depending on climatic conditions, crop pattern and agricultural practice, once for the winter season and then for the summer season. Groundwater recharge was calculated as a missing variable from the fluxes mentioned and used as input for the groundwater model (Baumann 1995)

The aquifer model considers the following sources: direct inflow from the Nile river and from the Ismailiya canal, groundwater recharge and inflow from the Nile river aquifer. Aside from groundwater withdrawal, groundwater is lost from the aquifer into the adjacent Wadi Natrun and the Moghra aquifers and to the Mediterranean (Baumann 1995). Fig. 4.3-1 shows the flux balance of the aquifer.

The vertical cross-section in the north-south axis through the aquifer was selected as representative for the set-up of a two-dimensional model. The model region reaches from the Mediterranean for 100 km (approximately two-thirds the distance to Cairo) to the south (along the symmetry axis of the delta) and has a maximum depth of 1 km at the northern boundary. The permeability of the Pleistocene aquifer has been obtained on the basis of numerous pumping tests reported in former publications (Zaghloul 1959; Farid 1980). The hydraulic conductivity is $6 \cdot 10^{-4}$ m s^{-1}. Some semi-permeable

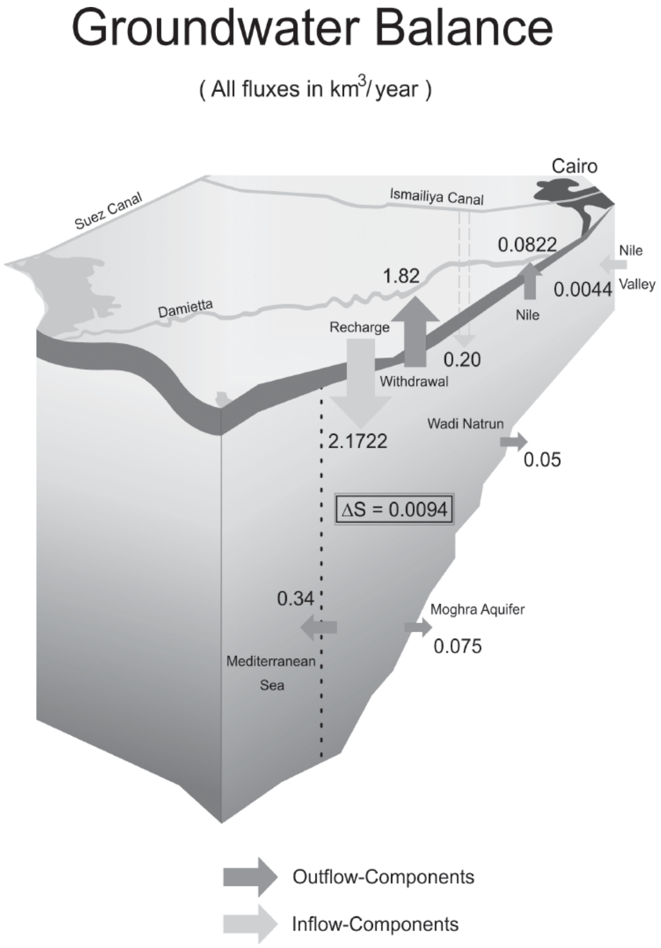


Fig. 4.3-1 Fluid balance terms of the Nile-delta aquifer according to Baumann (1995)

lenses with a conductivity of $1{\cdot}10^{-7}$ m s^{-1} were taken into account. In most parts the aquifer is confined by a clay cap with a conductivity of $2.8{\cdot}10^{-9}$ m s^{-1}. The clay cap originates from Nile river sediments in the Holocene and its depth reaches from a few metres in the south up to 75 metres below today's coastline. There is groundwater recharge through the semi-permeable clay in the southern part and discharge in the northern part of the delta.

The computer model is based on the mixing approach, i.e. on the fact that saline and fresh waters mix and that a transition zone is built up. Water flow and salt transport are calculated in a coupled approach. Boundary conditions for both flow and salinity need to be given. The flow boundary conditions at the surface and at the inflow boundary in the south are determined from the hydrological budget of the Nile-delta region. Of relevance to the aquifer model is the difference between groundwater recharge (2.17 $km^3 y^{-1}$) and groundwater withdrawal (1.82 $km^3 y^{-1}$). Although of minor importance, exchange between different bodies of surface water and groundwater is considered. Top boundary flow conditions are specified according to the discharge/recharge characteristic in the clay cap. At the bottom of the model the no-flow condition is required. At the vertical boundary below the seaside, there must be no vertical component of the velocity.

The FAST-C(2D) code used for the aquifer model is designed for modelling saline or thermal, steady or transient convection in a porous media in two-dimensional regions. The code was tested on several cases, including Henry's classical saltwater intrusion set-up (Henry 1964; Holzbecher 1998) and the transient movement of a saltwater front in a saline disaster in Japan (Holzbecher and Kitaoka 1993). Various scenarios – transient and steady state – were simulated in order to evaluate the potential consequences of increased use of groundwater resources (Baumann 1995).

Within the project, extensive field trips in 1991 and 1992 were carried out. Water analyses were taken from new drilled boreholes. The analyses show a gradual change from NaCl-type waters in the north to $CaHCO_3$-type in the south of the delta. The field measurements down to a depth of 330 m indicated seawater concentrations (35 000 ppm) only along the coastline. Moreover, they show that the transition zone reaches about 40 km inland. Freshwater concentrations (less than 1000 ppm) were found in the middle of the delta only, using measuring electrical conductivity (Baumann 1995; Arlt 1995). The output of the FAST-C(2D) model corresponds well with these measurements.

4.3.4 Experiences

The results from the computer model simulated a total saltwater intrusion of no more than 40 km for water with a total dissolved solids (TDS) concentration of ca. 1000 $mg\ l^{-1}$. Variations in grid spacing and in the discretisation method for first-order derivatives demonstrate the extreme influence of numerical dispersion on the computational results. Saltwater intrusion in the Nile Delta has been overestimated in previous models because grids had been used which were too coarse. The Ghyben-Herzberg relation (Herzberg 1901; Holzbecher 1998), which relates the subsurface seawater-freshwater interface to freshwater head above the mean sea level, was found to be invalid for the Nile Delta aquifer: this is probably due to a question of scale (the classical rule can be questioned in long shallow aquifers with high aspect ratio e.g. length/height ≥ 100). The numerical results agree well with new measurements of salt concentrations (Arlt 1995). A severe and deeply penetrating salinisation problem in the Nile Delta aquifer was not discernable from the data obtained and evaluated.

Not addressed in the project was the problem of rising groundwater tables due to increased irrigation in some parts of the delta – a problem that is well-known in other regions of the world. Aside from other problems caused by rising groundwater tables, there is an additional loss of water by evaporation from the soil and by evapotranspiration. Increasing salinity in near-surface ground and soil water indicates that the water balance could be affected significantly in these regions. The feedback from the subsurface compartment to the surface compartment should not be neglected, at least locally, as it has been in the reported project.

4.4 Modelling the Changes in Hydrological Cycle Processes for Small and Middle River Basins in Conditions of Permafrost under Climate Change

Yuri G. Motovilov, Alexander Georgiadi

4.4.1 Objectives and Motivation

The objective of the model ECOMAG is the analysis, mathematical description and modelling of hydrological cycle processes of river basins in conditions of permafrost. This includes research into the effects of climate change and human activity on hydrological systems with, in particular, the development of parameterisation of the subgrid effects of hydrological cycle processes in climatic models.

Intensification of human activity, connected with using and transforming natural resources, causes essential changes to geosystem status and frequently promotes intense ecological changes: the quality of air, water in the rivers and reservoirs is worsened, degradation of soils and forests is amplified, all of which change hydrological cycle processes on the land and in the atmosphere. The hydrological cycle is an important component of the geosphere and biosphere, dependent upon global changes and also influencing these changes. In this connection, creating a logical and uniform chain of the diverse processes within geosystems requires a mathematical description of hydrological cycle processes which uses the same approaches and conceptual language applied in other geophysical sciences. This has resulted in the development of physically-based, space-distributed models of the hydrological cycle on land. At present, such models are most suitable for investigating processes in catchments on a regional scale. However, in the near future, further improvement of such models will be necessary for a more detailed description of hydrological processes, such as the influences on water quality, thermal condition of soils and biological processes. Necessary improvements will include estimation of changes in the hydrological characteristics through human influence or as a result of climate changes, as well as estimation of the exchange processes operating at the land-surface/atmosphere interface for better hydrological representation in atmospheric models. Such research is very important, in particular for the permafrost zones such as in Siberia or the Far East, where human activity can result in irreversible changes in the hydrological behaviour of territories, resulting in catastrophic economic and ecological consequences.

4.4.2 Short Description of the Study

Distributed hydrological models allow the determination of the water balance and its variation across river basins. Several such models are in common use (i.e. SHE-model, Abbott et al. 1986; TOPMODEL, Beven and Kirkby 1979; WATBAL Knudsen et al. 1986) but none of them explicitly contains components reflecting important characteristics of the boreal and permafrost landscape. The hydrological model ECOMAG (Motovilov and Belokurov 1996; Motovilov et al. 1999) has been developed for application to boreal and permafrost conditions.

ECOMAG (ECOlogical Model for Applied Geophysics) is a space-distributed, physically-based model of hydrological cycle and pollution transformation on a catchment at a regional scale.

The model consists of two main submodels:

1) The hydrological submodel describes the main processes of the terrestrial hydrological cycle: infiltration into the soil, evapotranspiration, thermal and water regime of soil, snow cover formation and snowmelt, formation of surface, subsurface, groundwater flow and runoff in the river network (Fig. 4.4-1).

2) The geochemical submodel describes the processes of contaminant accumulation on the earth surface, dissolution and penetration of soluble pollutants into the soil, their interactions with soil solution and soil matrix, biochemical degradation, transport of pollutants by surface and underground waters, transformation through the river channels.

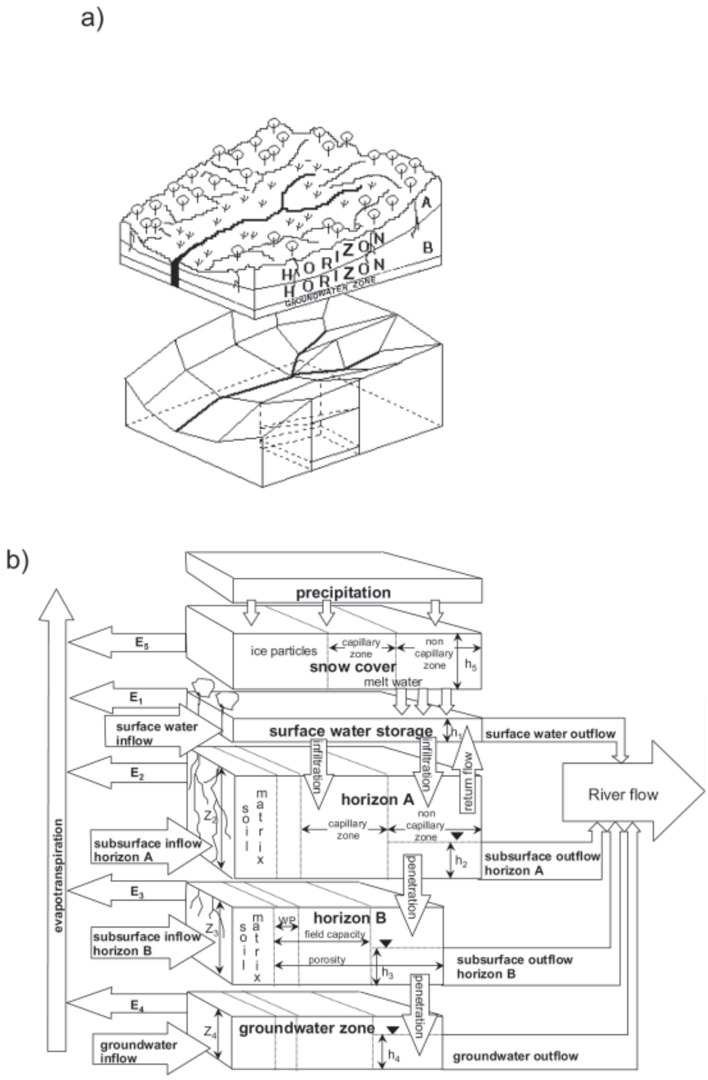


Fig. 4.4-1 Block-scheme of the ECOMAG model; a) Schematisation of a catchment; b) Vertical structure of ECOMAG for a landscape element

The model has been applied to hydrological cycle processes under different scenarios of climatic change for the Kenkeme river basin near Yakutsk (Yakutia-Sakha Republic of the Russian Federation, Fig. 4.4-2). The Kenkeme river basin extends to about 10,000 km^2 in a region of permafrost.

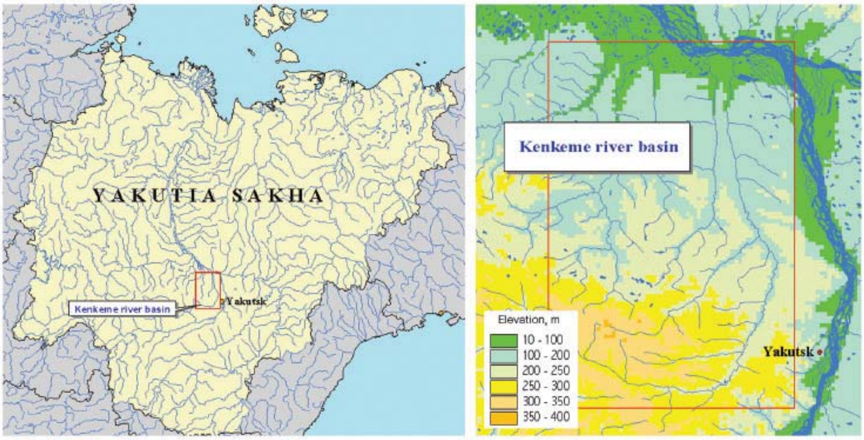


Fig. 4.4-2 Location of Kenkeme river basin

ECOMAG uses daily time steps resolution: the necessary minimum information needed for hydrological calculations includes standard meteorological observations as daily precipitation, temperature and humidity. Data on discharges, characteristics of snowcover, soil moisture, evapotranspiration, groundwater level, soil frost and thawing depth may be involved in calibration and validation of the model.

Space schematisation of the river basin (the allocation of river network, sub-catchments of tributaries, slope elements) is executed on the basis of thematic maps using GIS techniques. A drainage basin is approximated by regular square elements (grid cells from 100 m × 100 m to 4 km × 4 km, depending on the type of task and size of catchment), taking into consideration the peculiarities of topography, soil, vegetation and land-use types. The model has been applied to river basins in a range from 4 to 70,000 km^2.

The ECOMAG model is intended to help decision-makers with a wide range of hydrological and environmental river basin monitoring problems. In particular, it allows one to:

- Investigate the sensitivity of hydrological systems to the natural variations in climatic conditions as well as anthropogenic loads on the catchment;
- Simulate migration and transformation of polluting substances in river basins from point and non-point sources of industry and agriculture.

The formulation of the ECOMAG model for a specific river basin includes the following main stages:

- Collection of data necessary for calculation and calibration of model parameters (electronic thematic maps of a region, hydrological and meteorological data);

- Estimation of sensitivity, calibration of parameters and validation of the model on archival series of observations;

- Simulation of environmental characteristics on various levels (surface, soil, groundwater zone, river runoff) under different hydrometeorological conditions and anthropogenic loads.

4.4.3 Complexity of the Study

Hydrologists are studying climate-change effects on water resources using sensitivity analysis. The main approach for assessing the patterns of climatic change for the future is through modelling the climate system with General Circulation Models (GCMs). Then standard methods are usually used for generation of meteorological input from the results of GCMs into hydrological models. The mean monthly climatic differences in temperature and precipitation from GCM simulations are added to the daily values of each climatic variable during the hydrological simulation period.

Many studies of climate change impact on the terrestrial hydrological cycle and river runoff have been carried out using different hydrological models, scenarios of climate changes, river basins, geographic zones, continents. These sensitivity analyses contain two main types of uncertainty. The first depends on the adequacy of the hydrological model applied under the assumed climatic scenario: different types of hydrological models have been used to estimate climate change impact on river runoff, from regression equations to detailed physically-based models. Unfortunately, most of them were not validated by the Klemes hierarchic test-system (Klemes 1986) and, therefore, care should be taken with the conclusions made on the basis of such models. The second type of uncertainty is connected with the climatic scenario, which forms the basis for runoff simulations: GCMs give the climatic projection for the whole century but the precision of such forecasts are not known.

In the coming years, a further improvement in hydrological models and GCMs is necessary for a more detailed description of hydrological processes, especially in permafrost regions. There is a need to estimate the feedbacks and exchange processes at the land-surface/atmosphere interface to gain better hydrological representation in atmospheric models as well as better estimation of changes in the hydrological characteristics under the influence of human activity or as a result of climate changes.

4.4.4 Experiences

Primarily, the ECOMAG model was constructed and applied in Russia for regional environmental monitoring (Motovilov and Belokurov 1996). Since 1995, this version of the model has been improved for boreal and permafrost conditions in co-operation with L. Gottschalk and his group at Oslo University, Norway. The model was applied to regional simulation of the terrestrial water cycle during the international projects NOPEX (NOrthern hemisphere climate Processes land-surface Experiment; Gottschalk et al. 1998, 2001; Motovilov et al. 1999) and GAME-Siberia (GEWEX Asian Monsoon Experiment; Motovilov and Belokurov 1997). The studies included among others:

- Climate change impact on the hydrological cycle of river basins (Motovilov 1998);
- Estimating the influence of diffuse agricultural pollution on water resources in the Baltic Sea;
- The estimation of environmental damage around the new Oslo International Airport;
- Environmental monitoring in areas where rocket stages return to Earth;
- Simulation of inflow into reservoirs of Volga river basin.

4.5 Modelling Atmospheric and Hydrological Processes in the Boreal Region

Sven Halldin, Lars Gottschalk, Sven-Erik Gryning

4.5.1 Motivation and Objectives

Hydrological model applications have traditionally been done by setting parameter values and boundaries. When computer constraints alone are no longer a limitation on modelling capability, it has become clear that the real predictability constraint is not model-structure detail but place-specific characteristics and processes. New developments in computer technology will allow implementation of integrated models of large areas of the landscape, even if not whole countries. When climate change is a possible threat to our societies and the world-water scarcity is emerging as a major international problem, the integration of atmospheric and hydrological properties over different scales becomes a key modelling issue.

Studies of elements for such new models for the boreal landscape are one of the focal points for the NOPEX project (Northern Hemisphere Climate-Processes Land-Surface Experiment; Halldin et al. 1999, 2001). The estimation of regional fluxes of sensible and latent heat are central. Flux estimations are made with mesoscale hydrological and atmospheric models. It has been a challenge to compare flux estimates critically and evaluate them in a systematic way. Such a comparison has helped to identify problems in coupling atmospheric and hydrological approaches for flux estimation, related to critical processes and differences in scale.

4.5.2 Description of the Study

Area

The NOPEX project is carried out in two regions. The southern NOPEX region, around Uppsala, central Sweden, is characteristic for the southern edge of the boreal zone. The northern NOPEX region is situated at the northern boreal edge around Sodankylä, north Finland. The NOPEX project is based on two experimental activities. Intensive, time-limited Concentrated Field Efforts (CFEs) focus on comprehensive studies of the boreal-forest climate system, especially the spatial variation in fluxes and states over a region of size similar to a GCM grid cell. CFE1 (summer 1994), CFE2 (summer 1995), and CFE3 (winter/spring 1997) will be followed by CFE4 (winter) to finish NOPEX. Long-term monitoring of the land-surface/atmosphere climate and its components has been carried out since May 1994 in the Continuous Climate Monitoring (CCM) programme in order to follow climatic trends, capture seldom-occurring but important events, and to allow initiation, validation and comparisons of models and analyses at different time scales. The NOPEX regions and main scientific results are described in the two NOPEX Special Issues of *Agricultural and Forest Meteorology* (Halldin et al. 1999) and *Theoretical and Applied Climatology* (Halldin et al. 2001). Both issues include a CD with measurements from the campaigns.

Modelling approach

Three modelling approaches have been used to estimate regional fluxes and to identify critical processes at the land-surface/atmosphere interface. The mixed-layer-evolution model, the atmospheric mesoscale MIUU model, and the hydrological ECOMAG model (see also Sect. 4.4).

The mixed-layer-evolution model (Batchvarova et al. 2001) is based on a zero-order mixed-layer growth model for near-neutral and unstable atmospheric conditions and is applicable when the mixed-layer height is well above the height where individual surface heterogeneities are felt. The model requires wind speed and temperature profiles obtained from radio soundings, remote-sensing, or radio-acoustic systems extending above the blending height.

The MIUU model (Enger 1990) solves prognostic equations for horizontal wind components, potential temperature, specific humidity and turbulent kinetic energy. A terrain-influenced coordinate system is used to introduce topography in the model. The second-order turbulence closure is level 2.5 whereas the advection scheme is of third order, both in time and space, and has been corrected for numerical diffusion. Each grid is divided into a vegetated and a non-vegetated part. The latent and sensible heat fluxes from these are calculated separately and the total flux to the atmosphere is obtained as a weighted sum. The land-surface parameterisation uses a bulk-canopy model which calculates the ground and canopy energy balances separately. The soil is modelled with a two-layer force-restore method. The canopy parameterisation includes influences of both ground and canopy albedos and emissivities, leaf area index, stomatal resistance and roughness characteristics. The grid resolution is 1.5 km × 1.5 km in the central part of the model domain and expanding towards the boundaries.

The distributed ECOMAG model (Gottschalk et al. 2001) was developed for boreal conditions and describes soil infiltration, evapotranspiration, thermal and water regimes of soil – including freezing, surface and subsurface flow, groundwater and river flow, and also snow accumulation and snowmelt. In its original version, a drainage basin is approximated by irregular triangular or trapezoidal elements, depending on topography (size, form and slope), soil types (peat, clay, sand, till, bedrock), vegetation and land use (open area, forest, lake, mire, urban area). This version has been widely applied in Russia. A modified version of the model was developed within NOPEX that uses a regular grid (2 km × 2 km) to allow coupling with the MIUU model and radar-derived precipitation data. The basic assumption of the model is that a river basin can be divided into a mosaic of irregular or regular elements, each to be viewed as a landscape hydrological unit. The soil is divided into a top layer, an intermediate layer, and a capillary zone just above the groundwater surface. The vertical extension of these layers is a dynamic variable controlled by the position of the groundwater. The quotient of actual to potential evaporation equals unity under wet conditions and decreases linearly with soil moisture below a threshold. A kinematic wave equation is used for water transport in rivers, which constitutes the only water transport between elements.

4.5.3 Complexity of the Study

Three specific scales can be identified in a boreal landscape. The first is related to the hillslope flow dynamics, which determine the rate of runoff formation and flow into the permanent river network, lakes and bogs. The second is connected to the dynamics of a river basin in a representative landscape mosaic of hillslopes, lakes, bogs, etc. The third scale is defined from the soil–vegetation–atmosphere interactions in a representative landscape mosaic of different soils, vegetation and land use. The two latter scales might be related, but the boundary for the first one is set by the watershed or basin edge.

The wind near the ground changes ceaselessly over the various surfaces, trying to reach a balance with each one. The size of the dominant eddies increases with height, so the signatures of individual surface features are blended efficiently at the so-called blending height. The vertical influence of individual roughness elements, such as tree tops, is confined to the *roughness sub-layer*. The trees are organised in forested areas, separated by agricultural fields, mires, and lakes on the scale of kilometres or more. The influence of such a heterogeneity extends up to the *blending height,* loosely defined as the level above which the flow becomes horizontally homogeneous. Fluxes of surface momentum and heat are often modelled with similarity theory and require roughness lengths for momentum, z_{0m}, and for heat z_{0h}. Because momentum transport is enhanced by pressure fluctuations, z_{0m} can be greater than z_{0h}. Topography and isolated objects also enhance momentum flux through form drag but this hardly contributes to area-averaged heat flux. The thermal roughness length can be very small compared to z_{0m} when using surface radiation temperatures. The use of similarity theory to estimate the heat flux over a terrain with heterogeneous radiation temperature is complicated because heat flux can be counter to the temperature gradient. Spatially-averaged radiation temperature can, for example, be dominated by snow-covered open fields with negligible heat fluxes, while considerable positive daytime heat fluxes are typical for the northern boreal forest. Transfer coefficients for counter-gradient flux are negative and z_{0h} is not defined.

The hydrological response in a landscape with till deposits depends on the soil moisture in the unsaturated zone and the depth of the groundwater table. The soil-moisture and groundwater conditions in the NOPEX region varies between hydrological response units with different surface deposits or topographical characteristics, whereas the dynamics in units with similar characteristics are often identical. Soil-moisture and groundwater conditions in environments with till deposits are dominated by variations in topography, vegetation and soil characteristics at a length scale of less than 2 km. This means that there are no gradients in soil-moisture content or groundwater levels between sub-catchments at this spatial scale, and consequently, all lateral water transfer occur as runoff in the river network. It has been suggested that this scale should be used as a common spatial denominator for work with coupled atmospheric–hydrological modelling in the NOPEX regions.

MIUU and ECOMAG model parameters are “effective” since they are assigned a value for each grid cell according to land-use and soil type, and eventually adjusted by calibration. The direct relation to scale-aggregated values is therefore lost. An important use of the NOPEX process-scale-identification results is in the parameterisation of hydrological and atmospheric models. If the grid size is chosen in accordance with the hillslope scale, the parameterisation process implicitly includes the hillslope runoff formation processes down to its entrance to the river net and the transport between grid cells is limited to river flow. A smaller grid size would require the modelling of groundwater transport between the cells. A distinction between hillslope and catchment scales for the Scandinavian boreal zone is still problematic. The sizes of lakes, mires and bogs vary considerably. Even when a hillslope scale has been chosen as the proper size of a fundamental unit, each such element may still contain mires, bogs and lakes. A proper parameterisation at this scale needs to consider the interaction between hillslope dynamics and lakes, mires and bogs. There will also be cells occupied totally by larger lakes, mires and bogs. An obstacle for choosing the catchment scale as a base for defining a proper size of a computational element is that, from a hydrological point of view, it should correspond to the watershed boundary. This hampers the possibilities for coupling with meteorological models based on regular grid cells. A way out of this dilemma is to use a grid of fundamental units as a common denominator for catchments in the hydrological model component and another larger grid in the meteorological component.

Conditions at the northern NOPEX region during late winter are characterised by low solar elevation angles and days and nights of equal length. Measurements have revealed (Gryning et al. 2001) that forest-induced sensible heat flux could reach more than 100 W m^{-2} under these conditions (Fig. 4.5-1). The trees absorb short-wave radiation efficiently whereas the snow-covered ground reflects it. The heat flux above the forest comes mainly from tree warming, while that from the forest floor is small.

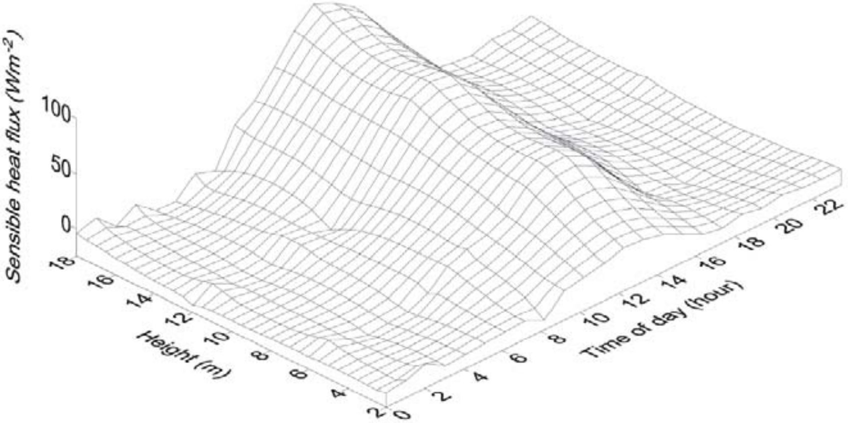


Fig. 4.5-1 Sensible heat flux in and above a sparse 9-m forest as function of height and time of day. The plot is based on half-hour measurements at 2, 6, 12 and 18 m height on 13-24 March 1997 in the northern NOPEX region

The latent heat flux, which originates mainly from snow sublimation, is ten times lower, typically 10–20 W m^{-2}. Simulations with a new parameterisation scheme showed that the forest heat flux under cloud-free conditions was controlled primarily by tree shading and not forest coverage, contrary to the situation for overcast conditions. Satellite- and aircraft-derived albedos are, thus, not relevant when modelling short-wave radiation absorption under cloud-free conditions during the boreal winter.

The mixed-layer-evolution model was used to estimate regional heat flux over the southern NOPEX region for different summer days. The regional flux was lower than the flux over the forest and higher than over agricultural fields, and agreed reasonably well with the land use-weighted average. The model was used in a similar way for winter days over the northern NOPEX region. In this case, the forest controlled regional fluxes of momentum and heat in a different way. The regional momentum flux was 10-20% smaller than the measured forest flux, and the regional sensible heat flux was 30-50% of the forest values. Good agreement was found (Fig. 4.5-2).

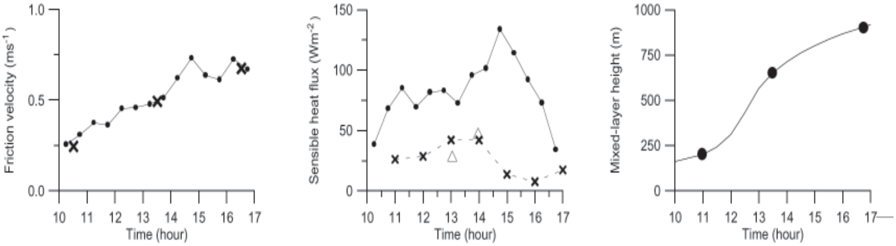


Fig. 4.5-2 Late winter conditions (CFE3) in local standard time. Left: Measured local friction velocities over forest at the northern NOPEX region (•, full line), and regional friction velocities from the mixed-layer-evolution model (×). Middle: Measured local sensible heat flux over forest (•, full line), derived regional sensible heat flux (×, broken line), and flight-track mean values (Δ). Right: Mixed-layer heights from radio soundings (•)

The ECOMAG and MIUU models were run in parallel for separate days during the NOPEX CFE1 (Fig. 4.5-3). A fundamental obstacle with this comparison is the fact that the meteorological model can only be run for 24-hour time slots and not continuously for the time period of the hydrological model. Changes in state variables of the hydrological model during 24-hour slots are minor, especially during summer months. Their role in initialisation of the meteorological model can, therefore, not be evaluated realistically. Initialisation of hydrological model states is, on the other hand, in its infancy and is presently done by "tuning in" the model for a preceding period of several months.

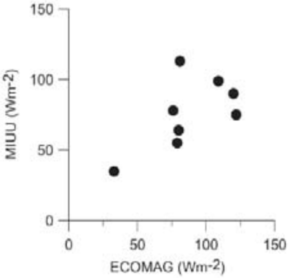


Fig. 4.5-3 Estimated latent heat fluxes from the atmospheric MIUU and the hydrological ECOMAG mesoscale models over the southern NOPEX region for selected summer days (CFE1/2)

4.5.4 Experiences

The boreal region is one of the most heterogeneous landscapes in the world and models developed elsewhere are not always applicable. New experimental studies, especially in wintertime, have revealed the importance of so far unrecognised processes, such as the effect of low solar angles on sensible-heat production. It is likely that further experiments will be needed to identify all critical processes needed to model the land-surface/atmosphere system at northern latitudes.

Results of NOPEX studies have highlighted issues that should be resolved before coupled hydrological and meteorological models can be applied successfully in the boreal region:

- Most hydrological and meteorological models define their grids and boundaries differently. They are normally only meaningful if operated with different time spans and temporal resolution. These incoherencies hide fundamental process-related problems, different for different landscapes and regions of the world;

- The selection of scale is intimately linked with the parameterisation requirements for subgrid-scale processes. A grid scale of 2 km seems suitable for both atmospheric and hydrological models in the boreal region but this conclusion needs to be confirmed with data from more sites;

- The ECOMAG model concept has been applied successfully to the southern NOPEX region (Gottschalk et al. 2001) but the parameterisation of physical processes at the hillslope and catchment scale requires further consideration;

- New procedures for parameter-value estimation, traditionally by calibration in hydrology, must be developed, based on remote-sensing data. Surface albedo, e.g. cannot be used in its traditional form for winter conditions. Retrieval of parameter values will be crucial, especially when developing macroscale hydrological models to be coupled to regional-scale atmospheric models.

4.6 A Distributed Model of Runoff Generation in the Permafrost Regions

Lev S. Kuchment, Alexander N. Gelfan, Victor N. Demidov

4.6.1 Objectives and Motivation

The permafrost regions cover approximately one-quarter of the land surface of the world, more than 60% of Russia and one-half of Canada. Because of low population density, expensive access and limited human activity, these regions have a sparse and extremely unevenly distributed hydrometeorological network. The extensive collection of field-measurements during recent decades has increased the available information on the hydrometeorological processes in the cold regions considerably but most of these data are too fragmentary. As a result, the peculiarities of permafrost hydrology has been investigated but weakly. At the same time, the comprehensive physically-based models of runoff generation (for example Abbott et al. 1986; Kuchment et al. 1983, 1986) developed for the temperate latitudes cannot be applied to the permafrost river basins because of differences in the main processes and the lack of adequate hydrometeorological data and basin characteristics.

4.6.2 Short Description of the Model

A Runoff Generation Model in Permafrost Region (RGMPR), a physically-based distributed model of snowmelt and rainfall runoff generation, has been developed for the permafrost regions (Kuchment et al. 2000). It is based on experience with modelling runoff generation processes in different geographical zones as well as on the use of the unique hydrometeorological data collected at the Kolyma water balance station (Fig. 4.6-1). Runoff generation observations have been made at this station since 1948 for seven representative basins with drainage areas from 0.3 to 21.2 km^2. The data collected include the standard meteorological measurements of solar radiation, snow-cover characteristics, soil moisture and snow evaporation, temperature and soil moisture, groundwater levels, runoff, chemical content of runoff. The model describes snow-cover formation and snowmelt, thawing of the ground, evaporation, basin-water storage dynamics, overland, subsurface and channel flow. The main difference between the RGMPR model and models of runoff generation for regions with moderate climate is the small role given to infiltration of water into soil and a larger dependence of runoff losses

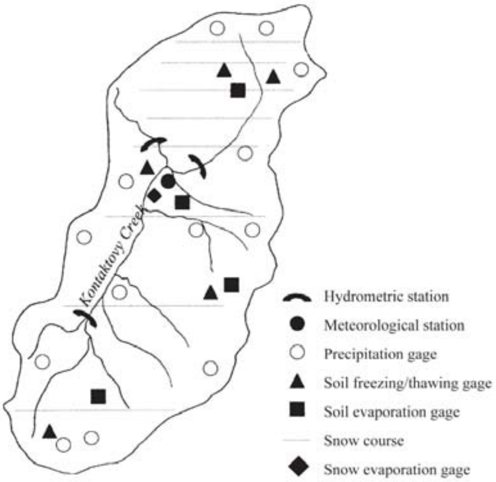


Fig. 4.6-1 Plan of the Kolyma water balance station

on the depth of thawed ground. The thaw of the frozen ground increases significantly the water input and the water storage capacity, changing the ratio between surface and subsurface flow. The choice of the structure of the model is based on the analysis of the long-term observations of the runoff generation processes at the Kolyma water balance station and is orientated towards the standard hydrometeorological information available in the cold regions.

4.6.3 Complexity of the Study

A case study with the model has been performed for the Upper Kolyma River basin (99,400 km^2) in which the Kolyma water balance station is situated (Fig. 4.6-2). The river basin is in the zone of continuous permafrost, interrupted only by patches of unfrozen ground under the river beds. The dominant soils are coarse-grained mountain-tundra podzols with large gravel content. The peatlands occupy about 2% of the basin area. The depth of the active layer is controlled by elevation, exposure, vegetation and presence of rivers and lakes. On the slopes of northern exposure, the average depth of the active layer is 0.2 - 0.8 m; on the slopes of southern exposure, the average depth of the active layer reaches 1.5 - 3.0 m. On the

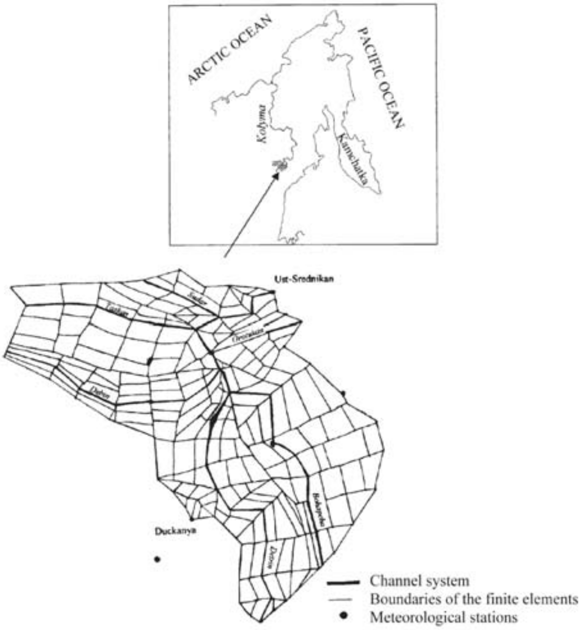


Fig. 4.6-2 Finite-elements schematisation of the Upper Kolyma River basin

basis of hydrometeorological data for the Upper Kolyma River basin and the literature on permafrost hydrology, the following general scheme for runoff generation is proposed (Fig. 4.6-3). First, the snowmelt water fills up the free storage capacity in topographic depressions in the peat mats and the ground,

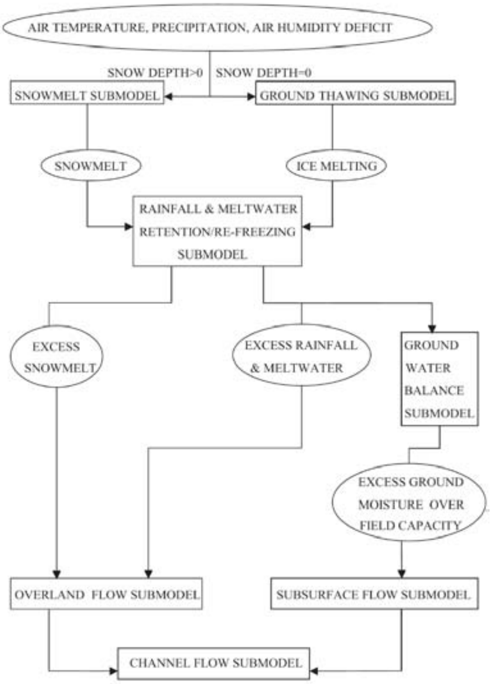


Fig. 4.6-3 Schematic diagram illustrating the major components of the model

where this water freezes. It is assumed that the basin storage capacity is distributed statistically over the basin and the mathematical expectation of this distribution before snowmelt depends only on the wetness of the ground in the antecedent summer-autumn period (before snowmelt the ground is deeply frozen). During the warm period, the storage capacity increases with increasing depth of thawed ground. Excess snowmelt and rainfall water over the free storage capacity forms overland flow. Ice melting and evaporation of soil moisture begin at the snow-free areas of the river basin. The melting of ice in the ground and in the depressions produces the subsurface flow and increases the basin storage capacity. The subsurface flow occurs above the frozen layer of the ground. The water retained by the capillary forces does not take part in subsurface flow. The infiltration of rainfall into the ground is quick and does not depend on the ground moisture conditions. It is assumed that the horizontal hydraulic conductivity decays exponentially with the depth. To calculate the characteristics of snow cover during snowmelt, the system of vertically averaged equations of snow processes at a point has been applied. This system includes the description of temporal change in snow depth, ice and liquid water content, snow density, snowmelt, sublimation, re-freezing melt water, snow metamorphism.

To take account of the spatial mosaic variability of the snowpack characteristics before melting, the Upper Kolyma River basin is divided into 16 approximately equal sub-areas, corresponding to the available snow course network. It is assumed that the spatial stochastic variations in the snow water equivalent within each sub-area can be described by log-normal statistical distribution. The movement of the front of ground thawing is described by the system of equations accounting for heat transfer in snow, frozen and unfrozen ground. It is assumed that the spatial distribution of the free storage capacity of the river basin can be described by exponential law. The evaporation rate is determined as a function of the air humidity deficit.

To model overland, subsurface and channel flow, a finite-element schematisation of the Upper Kolyma River basin and kinematic wave equations have been applied. The channel river system is represented by the main channel of the Kolyma River and by six tributaries (Fig. 4.6-2). The channel system is divided into 44 reaches (finite elements) taking into account the topography and the river network structure; the basin area is separated into strips, adjacent to the channel finite elements and along which one-dimensional flow to river channels is presupposed. The strips are also divided into finite elements with different topography, soil and vegetation characteristics.

The RGMPR model includes 12 constants. A set of numerical experiments had estimated the sensitivity of the runoff hydrographs to changes in different model parameters before calibration. It established that the porosity and the evaporation coefficient is the most important. These two parameters control accumulation and discharge of water in the ground during the entire period of runoff generation. The parameter controlling snowmelt has a significant influence on overland flow but during a short period only. The free basin storage before snowmelt strongly influences the form of the runoff hydrograph at both snowmelt and rainfall input.

The influence of the routing parameters of the roughness coefficients for overland river channel flow as well as the horizontal hydraulic conductivity is relatively small because of large variability of the slopes. Most of the used parameters variate in relatively narrow ranges and may be considered as regionally general. Some of these parameters can be determined using the

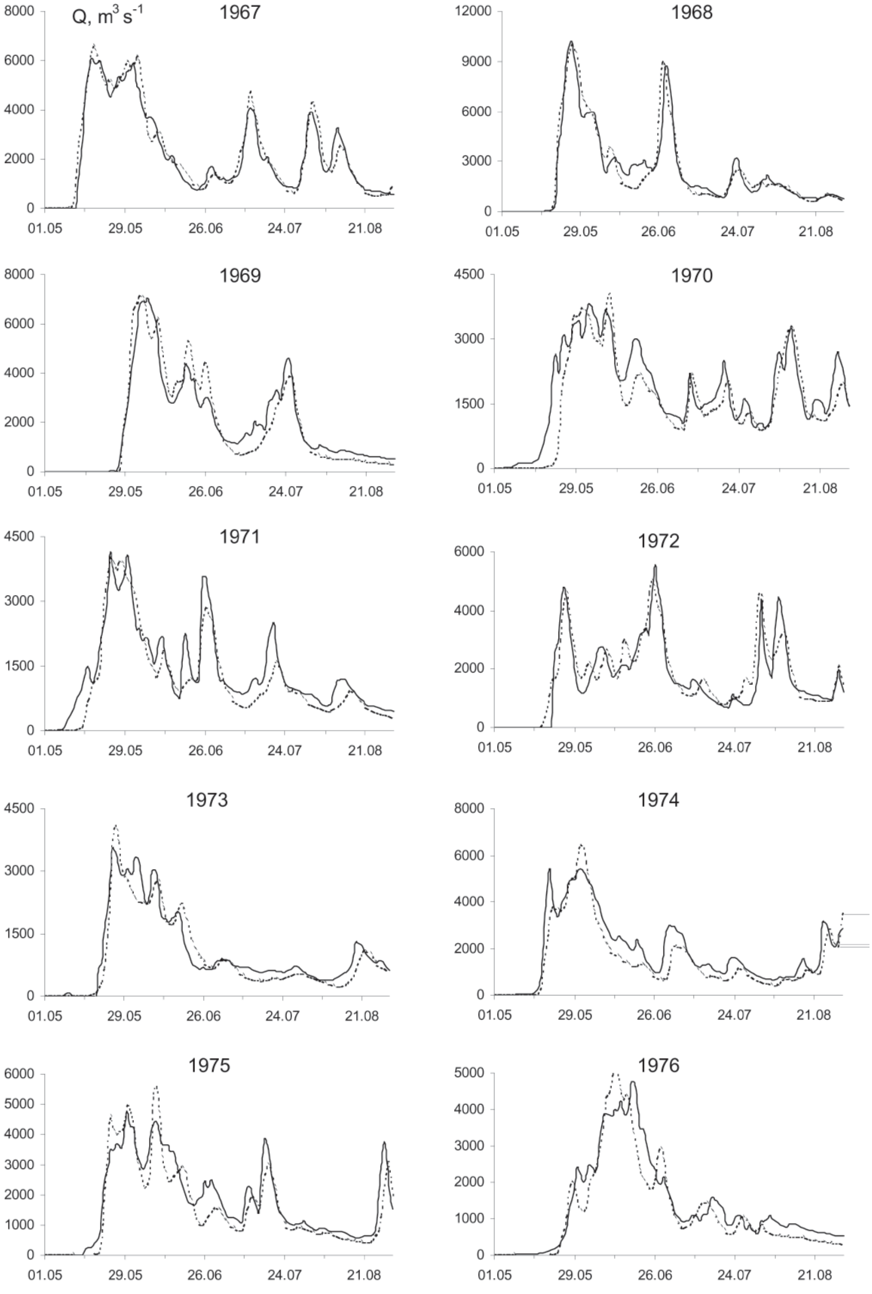


Fig. 4.6-4 Comparison between measured (continuous line) and calculated (dashed line) hydrographs

measurements on a small area within the river basin or on the basis of data taken from the literature.

To calibrate and to verify the RGMPR model for the Upper Kolyma River basin, daily hydrometeorological measurements from 1 May to 31 August during 10 years (1967–1976) were used. The meteorological data include records at eight sites. Five constants have been assigned on the basis of measurements of these constants at the Kolyma water balance station: two constants have been calibrated, using the hydrometeorological observations at this station and five have been calibrated with the aid of the hydrographs of the Kolyma River.

4.6.4 Experiences

The validation of the RGMPR model has shown that the model simulates satisfactorily the main peculiarities of runoff generation in cold regions (Fig. 4.6-4). The standard error of the calculated runoff hydrographs is 482 $m^3 s^{-1}$ (the standard deviation of the measured hydrographs is 1434 $m^3 s^{-1}$). The standard error of the calculated peak discharges is 490 $m s^{-1}$. The largest relative error of the peak discharges is 18% (for 1974); the largest relative error of the runoff volume are 14% (for 1971) and 13% (for 1970).

An important part of the model is the interaction between heat transfer processes in the snow and the soil and basin characteristics that control water movement. Basin storage is directly affected by melting and freezing water at the surface and at different depths in the soil. The thaw of the frozen ground increases runoff losses significantly and changes the ratio between surface and subsurface flow.

4.7 Investigations on the Impact of Land-use Changes using an Integrated Hydrometeorological Model

Nicole Mölders

4.7.1 Motivation and Objectives

With an increasing world population as well as changing climate and land-use conditions, the availability of water becomes a central question of research interest. Water availability, amongst other things, depends on precipitation, infiltration, surface runoff, as well as on the exchange of heat, matter and momentum at the earth-atmosphere interface. Because they depend on both the land and the atmospheric parts of the water cycle, studies on water availability require a detailed consideration of the water cycle to guarantee the applicability of models for future planning tasks. As an example, the role of surface runoff in the regional water cycle and its meaning for water availability under changed land-use conditions is examined.

4.7.2 Short Description of the Study

Area

Simulations with and without surface and channel runoff are performed for northern Saxony and southern Brandenburg, Germany. These simulations and their results are referred to hereafter as *ho* and *so*. In addition, these simulations are performed for a modified landscape wherein the water meadows along the rivers are changed to willow-forest, denoted as *hm* and *sm*, respectively.

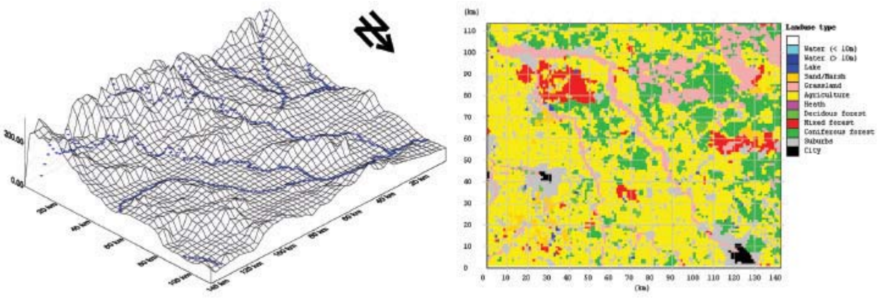


Fig. 4.7-1 Schematic view of terrain elevation and river network in southern Brandenburg/northern Saxony and land use (after Mölders and Rühaak 2002)

Coupled processes and compartments

A module to explicitly predict surface and channel runoff was developed (Mölders and Rühaak 2002) and coupled to the hydro-thermodynamic soil-vegetation scheme (HTSVS; Kramm et al. 1994, 1996) that was coupled with a mesoscale-β meteorological model as a hydrometeorological model (see Chapter 3.3).

Surface runoff and river runoff are described by the St.Vernant equation. Every subgrid cell may receive surface runoff from its neighbouring subgrid cells. Rivers are fed by surface runoff. There is no recharging of soil moisture by the rivers. Darcy's law and the Richards equation are used in the vertical direction, i.e. no horizontal transport within the soil is considered. The heat- and moisture-processes occurring within the soil are described by balance equations for soil-temperature and volumetric water content. The Ludwig-Soret-effect (i.e. a temperature gradient is able to generate a change of soil volumetric water content) and the Dufor-effect (i.e. a moisture gradient may alter soil temperature) are taken into account. The volumetric heat capacity of moist soil, soil albedo and hydraulic conductivity are functions of soil volumetric water content. Infiltration is determined by an explicit formulation of the Green-and-Ampt approach. The parameterisation of vegetation includes a mixture approach to consider bare soil and/or vegetation simultaneously within the grid cell. This heterogeneity at the microscale is relevant for the near-surface stratification of the atmosphere (stability) and the atmospheric fluxes of sensible and latent heat. Transpiration of water by plants is calculated by a bulk-stomatal resistance approach.

Spatial and temporal scales

The time step is 10 s as required by the atmospheric model part to fulfil the Courant-Levy-criteria. The horizontal grid resolution of this part of the model is 5 × 5 km^2. Surface and channel runoff are simulated on a subgrid having a horizontal resolution of 1 × 1 km^2. The river network is divided into pieces of different flow direction, length, slope and boundary conditions for inflow and outflow (Fig. 4.7-1). Each subgrid cell has its own in- and outflow conditions. An explicit subgrid scheme is applied for aggregation and disaggregation (e.g. Mölders et al. 1999).

4.7.3 Complexity of the Study

Type of feedbacks involved

Primary differences between the simulations with and without the runoff module result from runoff. Whenever or wherever the precipitation rate exceeds the infiltration rate, water is ponded on the surface and will contribute to runoff in *ho* or *hm*. Neglecting surface runoff means that the water will be ponded if precipitation rate exceeds infiltration rate, and the ponded water will be infiltrated later in *so* or *sm* than in *ho* or *hm*. Consequently, in the areas of heavy precipitation, the total infiltrated water amounts of *so* and *sm* exceed that of *ho* or *hm*, respectively. Conversely, in the latter simulations, infiltration also occurs in regions without precipitation that are downhill of the areas receiving precipitation because of the surface runoff of ponded water. Furthermore, since water flows downhill, it can reach areas where the precipitation rate is less than the possible infiltration rate. Thus, here infiltration is higher in simulations incorporating runoff than in those without (see Mölders and Rühaak 2002).

The modified infiltration yields to altered distributions of soil volumetric water content, soil temperature, surface temperature and surface moisture as well as water availability. Consequently, neglecting runoff also affects evapotranspiration (Fig. 4.7-2). Thus, in the simulations with and without the runoff module, different amounts of water vapour are supplied to the atmosphere for which cloud- and precipitation-formation differ. This means that the simulated local recycling of previous precipitation is affected by the inclusion or omission of surface runoff. The altered precipitation again yields to differences in ponded water, infiltration, evapotranspiration, water availability and groundwater recharge. In general, the differences between the simulations with and without the runoff module grow with increasing simulation time.

Simplifications

The interaction between rivers and groundwater, lateral soil water fluxes as well as evaporation from the water surface of rivers are all neglected. A constant water flux into the rivers that flow into the model domain is assumed at its boundaries. The temporal change of plant physiological parameters (e.g. albedo, emissivity, root depth, LAI, aerodynamic and hydraulic roughness length, stomatal resistance, etc.) and the possible variation of soil type with depth are also neglected.

Internal processes and external factors

The land-use changes mean a change in plant physiological and surface parameters (e.g. stomatal resistance, aerodynamic and hydraulic roughness, albedo, emissivity, etc.). During daytime, surface moist static energy flux will not be altered by the parameter modifications if moist static energy does not change. The partitioning between the sensible and latent heat fluxes may be affected and, hence, the Bowen-ratio may change. An increase in Bowen-ratio means a decrease in moist static energy that potentially reduces convection. In the case of a change from agriculture to deciduous forest, albedo is enhanced. For the change from grassland to deciduous forest the opposite is true: reducing albedo increases the moist static energy.

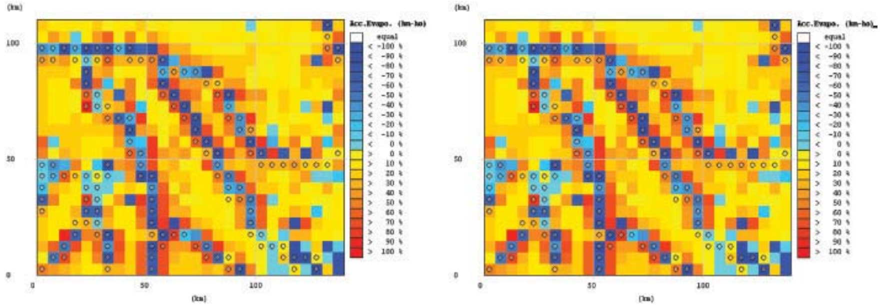


Fig. 4.7-2 Percentage difference of 24 hours accumulated evapotranspiration as obtained by *hm – ho* scaled by *ho* (left), and *sm – so* scaled by *so* (right). Modified after Mölders and Rühaak (2001)

Fig. 4.7-2 shows the percentage difference of 24 hours accumulated evapotranspiration. First, differences in evapotranspiration occur in the areas of the land-use changes. Later on, in the unchanged leeward-side regions of the land-use changes, further difference in evapotranspiration result from the modified wind, temperature and moisture states of the surface layer, the altered recycled precipitation and insolation due to differences in cloud distribution. As a consequence of the changed evapotranspiration, the surface moisture distribution and water availability differ. In addition to the altered water vapour supply to the atmosphere, the modified vertical mixing and heating affect cloud- and precipitation-formation. The changed pattern, rates and amounts of precipitation again affect infiltration, ponded water, evapotranspiration, runoff, water availability, and groundwater recharge.

Neglecting runoff can yield an underestimation of the secondary effects of land-use changes in the areas downwind and/or downwards of the land-use changes. In the simulation incorporating surface runoff, the land-use changes contribute to a stronger change in infiltration, soil water fluxes and groundwater recharge than in that without surface runoff. Comparing the percentage differences in ponded water with and without consideration of runoff, for instance, shows that neglecting surface runoff can lead to an underestimation of the effect of land-use changes. The absolute percentage difference in infiltration caused by the land-use changes will be less than about 10%, on average, if runoff is neglected, but will be much higher when runoff is taken into account.

Coupled natural cycles

The processes of the hydrosphere, biosphere, geosphere and atmosphere are coupled, as depicted in Fig. 3.3-4. The anthropogenic impact on these processes is examined by assuming land-use changes to willow forest along the rivers. The sensitivity of bulk-stomatal resistance in the transpiration process to photosynthetic active radiation, water vapour deficit between leaf and ambient air, leaf temperature, soil water deficit and CO_2 concentration of the air is considered by correction functions that range from 0 to 1.

Treatment of uncertainty

Various studies were performed to examine the sensitivity of the integrated model (or parts of it) on the choice of plant physiological and surface physical parameters, parameterisations (e.g. Mölders 2001) as well as boundary conditions.

4.7.4 Experiences

Difficulties

Detailed data sets of river characteristics (e.g. Manning coefficients, form, width and depth of the river, etc.) are scare for small rivers. At the boundary of the model domain, river inflow has to be defined by observations or else prescribed reasonably. Furthermore, for long-term simulations the meteorological model has to be nested into a meteorological (global) model with coarser resolution for which assumptions are required on the nesting (one-way, two-way) at its boundaries.

Conclusions

The results of the simulations with and without runoff confirm the general impact of runoff on the regional water cycle found by Mölders et al. (1999) when applying a tightly two-way coupled system of a conceptual hydrological and meteorological model. Note that although they carried out their studies with the same meteorological model, they also applied another SVATS (force-restore method for soil moisture, heat diffusion for soil temperature) than that used in this case study.

The sensitivity of water availability to land-use changes was found to be greater when surface runoff is taken into account. Since very many rivers are of subgrid-scale with respect to the grid- or subgrid-resolution of mesoscale atmospheric models, one has to expect that the impact of land-use changes on water availability predicted by mesoscale atmospheric models without consideration of surface runoff may be underestimated if the patch-size of the land-use changes is assumed realistically. Secondary differences in water availability result from the altered surface moisture and evapotranspiration and, hence, different local recycling of previous precipitation. Based on the findings of this study, one may conclude that investigations on the regional water availability and its modification by land-use changes should include surface and channel runoff.

Further applications

In the future, studies will have to use measurements of river inflow at the boundaries of the hydrometeorological model domain. The hydrometeorological model should be driven by data from a coarser atmospheric model nested into a global model to allow for long-term studies. Doing so ensures capturing large-scale atmospheric phenomena (e.g., cyclones) and propagating them into the hydrometeorological model domain. As these phenomena build on scales much larger than those covered by mesoscale-β models, these models can only simulate time scales of a day or so when run on their own.

4.8 The Influence of Anthropogenic Landscape Changes on Weather in South Florida

Roger A. Pielke Sr., Curtis Marshall, Robert. L. Walko, Louis T. Steyaert,
Pier-Luigi Vidale, Glen E. Liston, Walter A. Lyons, Thomas N. Chase

4.8.1 Motivation and Objectives

Model simulations in two studies were used to assess the extent to which land-use change in south Florida may have affected local precipitation during the summer season. A more detailed discussion of this work appeared in Pielke et al. (1999) and Marshall et al. (2004). Previous studies in other geographic areas demonstrated that landscape patterns can generate local atmospheric circulations due to contrasting surface properties that can be as strong as a sea breeze caused by a land-water contrast (see Pielke 2001, for a review).

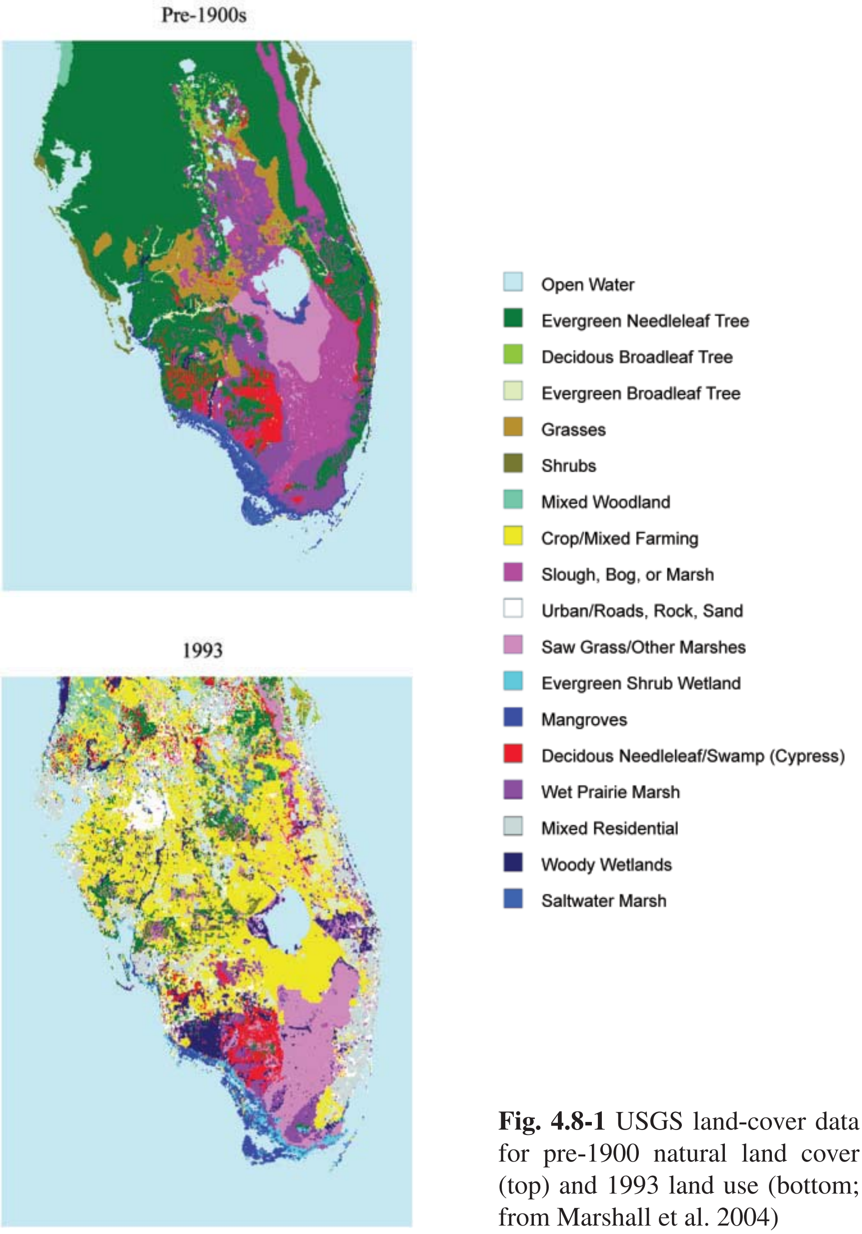
4.8.2 Description of the Study

The Regional Atmospheric Modeling System (RAMS) Version 4.3 was used for the numerical simulations presented in this study (Marshall et al. 2004). All of the simulations were performed on a nested grid configuration with an outer grid of 42 × 48 points at a 40 km interval covering the southeast Atlantic and Gulf Coast states, southward to the latitude of the Yucatán Peninsula. An inner grid with 42 × 50 points at 10 km spacing was nested to cover central and south Florida and adjacent coastal waters. Both grids extended over 30 vertical levels, with the lowest level nearly 100 m above ground level. The vertical grid spacing was geometrically increased with height to a maximum of 1 km at the model top (20 km). Initial conditions and outer grid lateral boundary conditions were provided by the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) global analysis dataset (Kalnay et al. 1996). During the integration of the simulations, the reanalysis data were updated every 6 h and nudged over the five outer grid points at each time step.

4.8.3 Complexity of the Study

The experiments differed solely in the definition of land-use category and initial soil moisture. The observed land-use change is illustrated in Fig. 4.8-1.

The land-use change is prescribed (a one-way feedback to the atmosphere), with the biophysical effect of sensible and latent turbulent heat fluxes two-way interactive between the soil, vegetation and the atmosphere.



Pre-1900s

1993

Fig. 4.8-1 USGS land-cover data for pre-1900 natural land cover (top) and 1993 land use (bottom; from Marshall et al. 2004)

The representation of the surface heat energy and moisture budgets used the LEAF-2 scheme (Walko et al. 2000). LEAF-2 provides algorithms to partition incoming net radiation into sensible heat fluxes, physical evaporation and transpiration based on landscape type and more rapidly varying land-surface conditions such as soil moisture. Sea surface temperatures were obtained from the global climatological files at the National Center for Atmospheric Research (NCAR). The July and August average values are used.

4.8.4 Results

Fig. 4.8-2 shows the accumulated two-month deep cumulus precipitation for July-August 1973 using pre-1900 land cover and 1993 land use from the Marshall et al. (2004) study. The difference between these two model simulations is shown in the right panel. The differences exceed 100 mm and more in places, along with an altered spatial pattern. The human-caused landscape change has apparently had a major effect on the hydrology of the region. The spatial pattern of the simulated rainfall for the 1973 model run is consistent with the climatological pattern of rainfall. The area-averaged rainfall decrease is over 10%. This reduction in rainfall reduces the amount of water that reaches the Everglades areas. The average maximum surface air temperature occurring for the entire period has increased in the model by about 2° C for many inland areas.

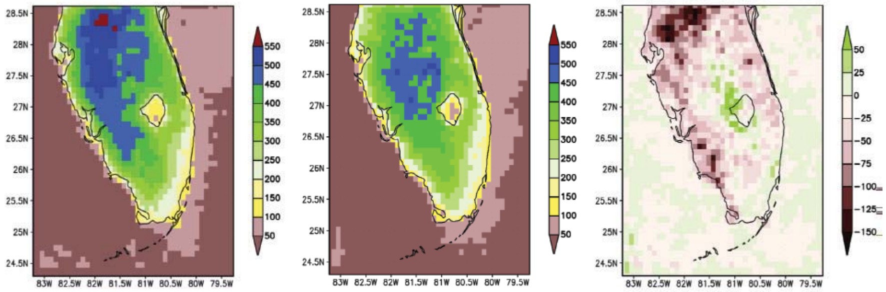


Fig. 4.8-2 Accumulated convective rainfall (mm) from the model simulations of July-August 1973 with pre-1900 land cover (left), 1993 land use (middle), and the difference field for the two (right; 1993; minus pre-1900 case). From Marshall et al. 2004

There are, unfortunately, only limited data available with which to evaluate temporal trends over south Florida, which makes comparison with the model results difficult. Fig. 4.8-3 shows regionally-averaged precipitation data during July and August for at least part of this past century. The model results indicate that if land-use change was the only factor influencing rainfall, we would expect a general decrease in rainfall over the interior, although there is considerable grid-point to grid-point variability near Lake Okeechobee and the coastlines. Some locations along the coast show a modest increase in rainfall.

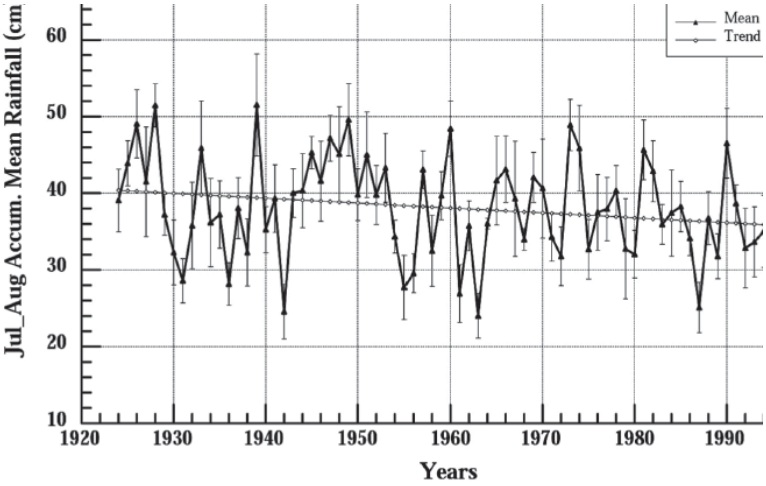


Fig. 4.8-3 Regional average time series of accumulated convective rainfall (cm) from 1924 to 2000, with corresponding trend based on linear regression of all July-August regional average amounts. The vertical bars overlain on the raw time series indicate the value of the standard error of the July-August regional mean (from Marshall et al. 2004)

The differences in precipitation in the model are due to the alteration in the spatial pattern of transpiration and physical evaporation due to the land-cover change. The reduction in this water flux to the atmosphere results in less precipitation in the interior of the peninsula from thunderstorms and a spatial displacement in the rainfall pattern.

Fig. 4.8-4 presents regionally-averaged maximum temperature trends. The observed increase in maximum averaged temperature for July and August is consistent with the model-simulated warming in response to land-use change.

4.8.5 Conclusions

Over south Florida during the past 100 years, there has been a widespread conversion of natural vegetation to urban and agricultural land, and into grassy shrubland. These landscape changes are likely to have altered the

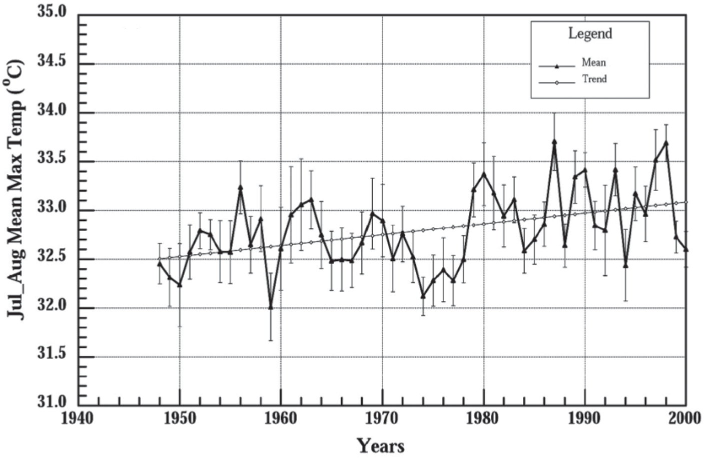


Fig. 4.8-4 Same as Fig. 4.8-3 except for daily maximum shelter-level temperature in degrees C

local weather patterns, with average summer rainfalls for south Florida decreasing by 10% or more. This reduction in precipitation due to land-cover changes would be in addition to precipitation variability (which is also evident in Fig. 4.8-3) caused by year-to-year variability and long-term trends in synoptic weather features.

Along with the reduction in deep cumulus rainfall, the model indicated that surface temperatures should warm in response to the landscape conversion. A warming is observed in the regional averaged maximum temperatures. These results indicate that unless land-use change effects on weather are included in climate trend analyses, the reasons for climate change can be concluded erroneously. In addition, because of the permanent landscape changes in the regions around the Everglades, it will be impossible to restore the climate in this region to what it was prior to the landscape change, thereby making the restoration of the Everglades ecosystem even more difficult. Rainfall, for example, is likely to be permanently less in the absence of changes in larger scale climate influences.

Acknowledgements

Portions of this work were originally reported in Marshall et al. (2004). This research was supported by USGS Contract #1434-CR-97-AG-00025, Task 7, and NASA Grant No. NAG5-11370.

4.9 CLIMBER-2: An Earth System Model of Intermediate Complexity

Andrey Ganopolski

4.9.1 Motivation and Objectives of the Study

The growing understanding that the Earth system functions in a complex, strongly nonlinear way, where separate components (atmosphere, hydrosphere, biosphere, etc.) are closely interlinked, stimulates development of a new class of computer models: Earth System Models of Intermediate Complexity (EMICs). Among the crucial questions which can be addressed with such models is the physical and geochemical interaction between the geosphere and biosphere on global and long-term scales. Due to the complexity of the Earth system and the large range of temporal scales of the different components of the system (up to a thousand years and longer) it is quite natural to synthesise our knowledge of the Earth system through a relatively simple computer model and with coarse spatial resolution. This strategy is behind a hierarchy of EMICs under developments at the Potsdam Institute for Climate Impact Research. CLIMBER-2 (CLIMate-BiosphERe model; see detailed description in Petoukhov et al. 2000) represents the medium level of this hierarchy, and it has been used for a variety of studies of past and future climate changes, as well as for the sensitivity and stability analysis of the Earth system.

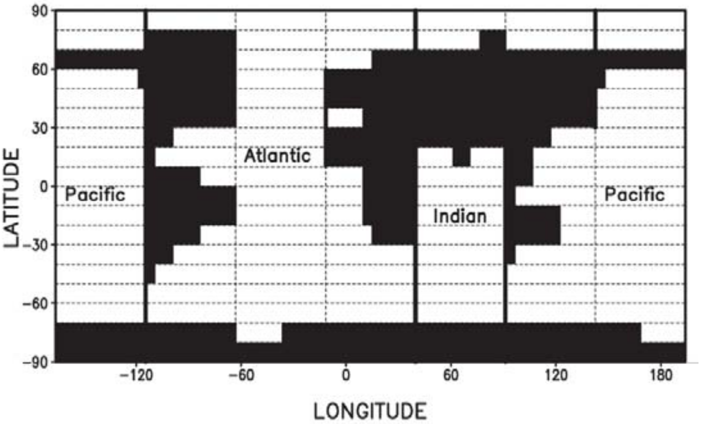


Fig. 4.9-1 Representation of the Earth´s geography in the model. The black area represents the areas of land. Dashed lines show the atmospheric grid, solid lines separate ocean basins

4.9.2 Short Description of the Study

The basic strategy in the development of EMICs is to achieve a high level of integration of the components of the Earth system and high computational efficiency by simplification in description of individual components (e.g. atmosphere or ocean) and by using a relatively coarse spatial resolution. The CLIMBER-2 model has a spatial resolution (Fig. 4.9-1) which resolves only individual continents or subcontinents and ocean basins: latitudinal resolution is 10^{o} in the atmosphere and land models (2.5^{o} in the ocean) and in the longitudinal direction the Earth is represented by seven equal sectors. CLIMBER-2 encompasses six modules, as shown in Fig.4.9-2:

1) an atmospheric module;

2) an ocean and sea-ice module;

3) a vegetation module;

4) an inland-ice module;

5) and modules of marine biota and

6) oceanic biogeochemistry.

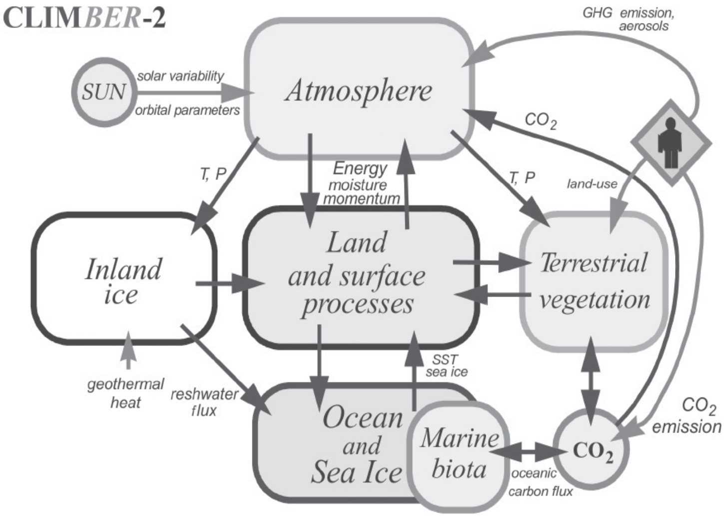


Fig. 4.9-2 Principal scheme of the CLIMBER-2 model. Grey arrows show external forcings, black arrows show exchange of information between individual modules

All components are fully interactively and bi-directionally coupled via fluxes of energy, moisture, momentum and carbon without using any explicit information about present day climate state (e.g. flux-correction). This allows us to use the model for simulations of the past and future climates which differ considerably from the modern one. Anthropogenic activities, such as land use and emission of greenhouse gases, are given as external boundary conditions. Due to low computational costs the model allows us to perform long-term (multi-millennial) simulations and numerous sensitivity experiments needed to facilitate understanding of the role of model uncertainties and limitations.

4.9.3 Complexity of the Study

Individual components of the Earth system are represented in CLIMBER-2 by relatively simple models, but in respect of the total number of the processes and feedbacks our model is comparable with the comprehensive models. In particular, the atmosphere module of CLIMBER-2 is a 2.5-dimensional[1] statistical-dynamical model. This model is based on the assumption that the general structure of the atmosphere can be expressed in terms of large-scale, long-term fields of the main atmospheric variables and ensembles of synoptic eddies and waves. The latter are parameterised in terms of their statistical characteristics. The atmosphere module describes atmosphere dynamics, moisture transport, precipitation and cloudiness, and radiative processes. The ocean module describes the ocean hydro- and thermodynamics, sea ice and the ocean carbon cycle. It is based on the multi-basin zonally-averaged approach. Simulations of terrestrial vegetation are based on a continuous description of plant functional types. For each continental grid cell, the vegetation module computes fractions of vegetation cover and desert. The vegetation module includes a simple carbon cycle model in which allocation of carbon to four pools (leaves, stems and roots, humus, soil) is evaluated. Vegetation adapts to climate on a time scale proportional to the turn-over time of carbon in the pool of slowly varying biomass, i.e. stems and roots. Hydrology and interaction between climate and vegetation are described using Atmosphere-Surface Interface (ASI). ASI is based on BATS (Biosphere-Atmosphere Transfer Scheme) (Dickinson et al. 1986), simplified and modified for the level of spatial

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[1] The term “2.5-dimensional” reflects the fact that unlike atmosphere GCMs the vertical profiles of main atmospheric characteristics - wind speed, temperature and humidity - are not computed using prognostic 3-D equations but rather diagnosed based on an assumption on the universal vertical structure derived from climatology. This is why our atmosphere model is placed between the simplified 2-D and comprehensive 3-D models.

and temporal aggregation and degree of complexity of CLIMBER-2. The ASI distinguishes six surface types, including two vegetation types - forest and grassland. The presence of vegetation affects interaction between land surface and atmosphere via surface albedo (especially for snow-covered conditions), evapotranspiration (different root distribution in soil and LAI) and surface roughness. In turn, the natural distribution of vegetation is controlled by temperature and precipitations.

4.9.4 Experiences (Lessons Learned)

CLIMBER-2 has been successfully tested against modern climate data, as well as for a variety of palaeoclimates (Last Glacial Maximum, Holocene Optimum, etc.). Furthermore, the model has been extensively compared with comprehensive climate models (GCMs) in respect to the sensitivity to CO_2, solar insolation and perturbations in freshwater flux. Special emphasis in our research has been given to climate-biosphere interaction on different spatial and temporal scales. These studies demonstrate the importance of realistic description of climate properties of vegetation cover-surface albedo, roughness, transpiration. Results of our experiments also indicate that interaction with the ocean (primarily via the hydrological cycle) affects considerably the climate sensitivity to changes in vegetation cover (Ganopolski et al. 2001; Claussen et al. 2001).

Using CLIMBER-2, we have studied separately the impact of deforestation/aforestation on climate via biogeophysical processes (energy and hydrology) and the combined effects of biogeophysical and biogeochemical (carbon dioxide) processes. With respect to the biogeophysical effect only, our results demonstrate the important role which the ocean plays in amplification and modification of the climate response to changes in vegetation cover. Fig. 4.9-3 shows that in the case of interactive ocean, cooling caused by deforestation is much more pronounced and wide-spread. The same is true for the reduction in precipitation. One of the prominent features of climate response to boreal deforestation is a strong reduction in summer monsoon precipitation in southern and south-eastern Asia. An important result of our study is that in the coupled climate model both boreal and tropical deforestation leads to global cooling, while the atmosphere-only version of the model predicts the opposite sign of temperature changes for boreal (cooling) and tropical (warming) deforestation. The reason for global cooling due to tropical deforestation in the coupled model is a strong reduction in downward long-wave radiation, caused by the reduction of water content in the atmosphere. The interactive ocean reacts to the decrease of water content in the atmosphere by cooling and a decrease in evaporation that amplifies the decrease in the water vapour greenhouse effect.

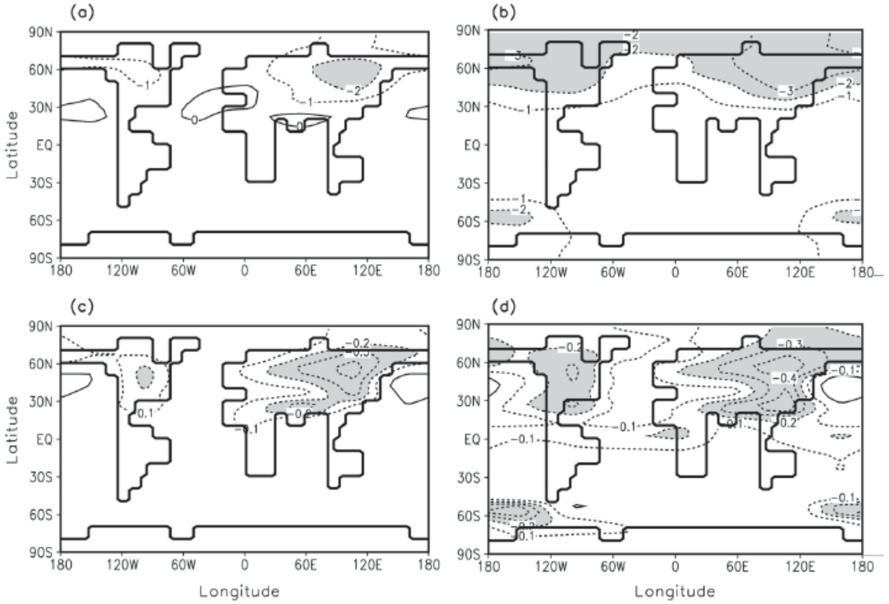

Fig. 4.9-3 Differences in **a, b** annual near surface air temperature (in ^{O} C) and **c, d** precipitation (in mm d^{1}) between "boreal deforestation" and control experiments. **a, c** correspond to experiment with fixed ocean characteristics; **b, d** to experiment with interactive ocean (from Ganopolski et al. 2001)

Release of carbon due to deforestation leads to increased greenhouse effect and, thus, works in the opposite direction to the biogeophysical effect. When both effects are taken into consideration (Claussen at al. 2001), our sensitivity studies show that in the tropics the climate impact of deforestation via changes in CO_2 outweighs the biogeophysical effects, while in boreal latitudes biogeophysical processes play a dominant role. These sensitivity studies have a practical implication: they show that afforestation in high latitudes is not an efficient way to curb global warming via uptake of CO_2, since the net effect of boreal afforestation is warming rather than cooling.

Our current analysis is focused on the large-scale patterns of climate response to different external or internal perturbations, in particular the question of stability and synergism in climate systems. As the first results are quite promising, further progress needs considerable improvements in the description of climate-biosphere interactions by increasing spatial resolution and the number of considered processes and feedbacks. It is crucially important to achieve this by preserving relatively low computational costs – otherwise the model cannot be used for the kind of studies which have been performed with the CLIMBER-2 model. This is why the new model, CLIMBER-3, currently under development at the Potsdam Institute for Climate Impact Research, is based on the combination of simplified (highly parameterised) and state-of-the-art components and is specially designed for a high-performance parallel-processor computer.

4.10 Feedbacks and Coupling between Water, Carbon and Nutrient Cycling at the Hillslope Scale

Lawrence E. Band, Christina L. Tague

4.10.1 Motivation and Objectives for the Coupling Approach

The motivation behind the coupling methods presented here is to capture mechanistically the impacts of hillslope level lateral water flow and redistribution on nutrient biogeochemical cycling and export from catchments. Much of the cycling and transport of nutrients from terrestrial to aquatic ecosystems represents a complex response to the distribution and flux of water within the length scale of a hillslope. With the exception of deep groundwater that may follow flow paths independent of surface topography, the drainage divides of the hillslope represent no flux boundaries – and a stream at the hillslope base is an absorbing boundary. The average hillslope length is the inverse of the drainage density, and will typically range between tens to at most hundreds of metres. Note that this is well under the resolution of standard regional to global simulations but contains much of the land-surface heterogeneity and process dynamics.

Within this domain, in situ organic matter decomposition, mineralisation and uptake by plant and microbial biomass are mediated by the soil water content in the upper soil horizons, which in turn are mediated by local soil and canopy structure as well as topographically driven catenary patterns. The feedbacks between water, carbon and nutrient cycling and transport occur at time scales ranging from individual storm events and interstorm periods through decadal or centennial canopy growth, biomass accumulation and succession. Spatial coupling occurs at scales ranging from within and between canopy gaps through a full topographic gradient, including hillslope wetness and topoclimatic patterns. Efforts to explain dynamics at one of the space/time scales may be subject to prescription of system state or dynamics at the other(s). Therefore, we seek to develop operational models to investigate feedbacks between dominant space/time variables within hillslope systems. An extension to the terrestrial phase of catchments is made by treating the catchment as a population of hillslopes organised around the drainage network.

4.10.2 Short Description of the Study

Area

Simulations of integrated water, carbon and nutrient cycling and transport are carried out for a small catchment that is instrumented as part of the Baltimore Ecosystem Study (BES), one of the NSF-funded LTER (Long-Term Ecological Research) sites in Maryland, USA. Pond Branch is in the Oregon Ridge County Park in Baltimore County, draining 34 ha of upland Piedmont topography with a dominant oak-hickory canopy cover. The canopy has been growing for about 80 years, and last had selective cutting in the 1950s. Typical of headwater Piedmont catchments in this area, the upper portions of the drainage area are characterised by gentle slopes with broad valley bottoms, which narrow and become increasingly incised downstream (Fig. 4.10-1). Silt loam soils overlay deep saprolite on gentle interfluves,

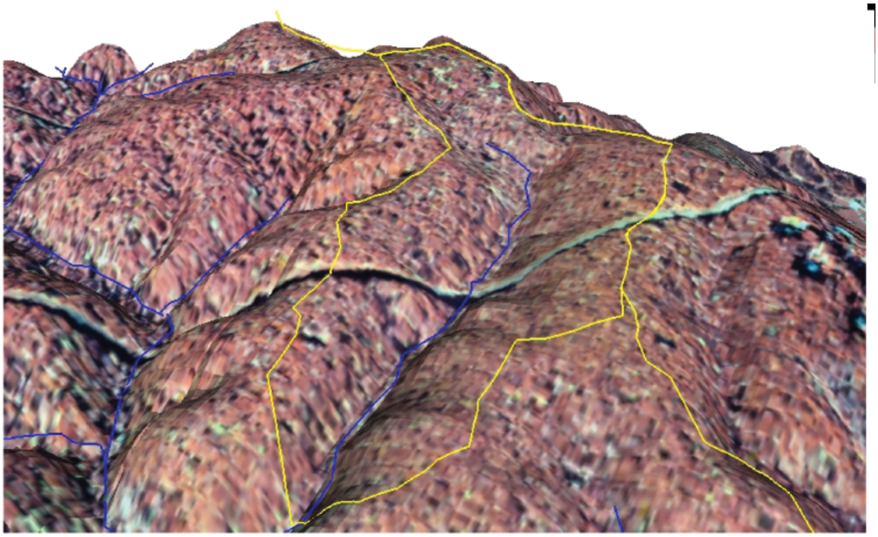

Fig. 4.10-1 Colour infrared image superimposed on the Digital Elevation Model (DEM) for the Pond Branch catchment in Baltimore County, Maryland, USA

which thin into patchy bedrock exposures of the underlying schists in parts of the lower slopes. The broad bottomland in the upper catchment is wet and organic-rich, with disorganised drainage at low flows characterised by anastomosing, discontinuous channels. Streamwater sources include a combination of diffuse seepage from the hillslopes as well as discrete spring sites. Continuous flow monitoring and weekly stream chemistry sampling at the outlet have been ongoing since the autumn of 1998. A more detailed description of the site and an earlier version of the model application to this catchment can be found in Band et al. (2001b).

Coupled processes and compartments

A key approach that we have taken is to attempt to describe a formal geomorphic framework for the spatial nesting of surface attributes and processes. We have produced this approach in successive versions of RHESSys (Regional HydroEcological Simulation System; Band et al. 2001a,b). Within this framework (Fig. 4.10-2), the primary processes of biogeochemical cycling and fluxes of water, carbon and nutrients are

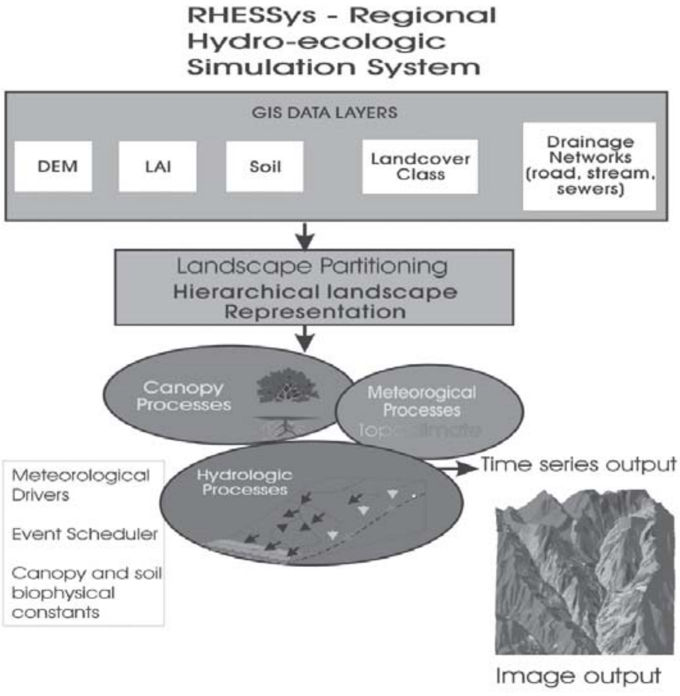

Fig. 4.10-2 RHESSys model structure showing ingestion of spatial catchment data, partitioning into hierarchical landscape representation and hydroecological process modelling driven by meteorological forcing

distributed through the canopy and soil, solving for flux divergence at the surface patch level, and building these components hierarchically into a full basin representation. Using the geomorphic framework, the catchment is partitioned successively into a containment hierarchy with component hillslopes arranged around the stream network (one hillslope draining to the left and right side of each stream link). Each hillslope in turn is partitioned into a set of contiguous patches based on topography and canopy cover, as well as the requirements of solving subsurface flow equations. Grids can serve as patches as a special case, although we often prefer to vary resolution and shape to characterise small, but essential, elements of the topography in hollows or along riparian areas. Each patch in turn is partitioned into canopy elements which can have fractional cover and multiple vertical (i.e. overstorey and understorey) layers within the patch. Canopy layers are sorted by height to resolve radiation and precipitation interception.

Water, carbon and nutrients are subject to mass conservation with respect to in situ cycling and flux divergence over the network of patches and into the stream at the base of each hillslope. All biophysical processes are associated with a specific element of the catchment representation hierarchy. Transfer between compartments occurs both within a level of the hierarchy (e.g. patch-to-patch transport of water and nutrients) and between levels of the hierarchy by aggregation or disaggregation procedures (litterfall or uptake between a patch and its component canopy strata). Table 4.10-1 lists specific processes and the compartment level with which they are associated.

Spatial and temporal scales

Time steps for different processes range from sub-daily (e.g. canopy radiation, infiltration) up through seasonal (canopy carbon allocation). However, most of the carbon, nutrient and water transport and cycling processes are run at the daily time step. The daily time step is used as the model is operated typically over temporal domains, ranging from annual to centennial in order to develop feedbacks and dynamics of the more slowly varying stores, such as the canopy and soil development.

Maintaining the dynamics of the slowest responding variables in the hillslope system places an additional burden in model initialisation as imbalanced system components may lead to very long transients. Therefore, it is necessary to be able either to prescribe realistic spatial patterns of carbon and nutrient pools or to run very long (e.g. 10^3 years) spin-up simulations to derive balanced stocks. Once model spin-up has produced a stable distribution of carbon and nitrogen stores, this initialised state can be used to run multiple scenarios at shorter time scales.

Table 4.10-1 Simulated processes for water, carbon and nutrient cycling associated with different levels of the watershed hierarchy. Note that the patch represents all soil processes and the strata are considered well mixed within the patch (share a common soil pool)

	Hydrologic Processes	**Biogeochemical Cycling**	
	Water	**Carbon**	**Nitrogen**
Basin	Stream routing		Nitrogen export
Hillslope	Lateral water flux		Nitrate transport
Patch	Soil evaporation	Decomposition	Decomposition
	Infiltration	Soil respiration	Mineralisation
	Vertical unsaturated, saturated flux	Litter accumulation	Immobilisation
		Humus formation	Nitrification
	Root uptake		Denitrification
			Root uptake
			Deposition
Strata	Interception	Photosynthesis	Uptake
	Transpiration	Respiration	Rubisco dynamics
		Allocation	Rubisco dynamics
		Litterfall	Litterfall, retranslocation

RHESSys has been operated over catchments varying by four orders of magnitude in area, with the largest application being the South Platte River Basin (Baron et al. 1998) with 63 000 km^2. However, more recent applications coupling nutrients or resolving roads in a fully distributed, explicit flow routing and cycling have been carried out on much smaller experimental catchments. These smaller scale applications have shown that the feedbacks and interactions between lateral water transport in the terrestrial phase and ecosystem water/carbon/nutrient dynamics exist within the domain of the hillslope, requiring a representation of system patterns evolved at these length scales. A current goal is to find methods that can capture the effects of flow routing on net nutrient retention, treating these as subgrid processes with much lower computational expense by using a combination of spatial distribution and explicit routing approaches.

4.10.3 Complexity of the Study

Type of feedbacks involved

The mix of rapidly and slowly varying stores produces a complex response in nutrient dynamics which, at short time scales, are controlled strongly by variations in temperature and moisture content that influence root uptake, nitrogen transformations, and soil immobilisation that vary with landscape position. At progressively longer time scales, variations in the canopy cover, maturity and carbon balance of the canopy, and the distribution of the amount and quality of soil organic matter, are important long-term controls. These latter characteristics build a long memory into the ecosystem such that previous land uses may still exert an influence on system structure and dynamics. Interactions between soil water state and in situ carbon and nutrient cycling are represented at patch and canopy strata by process modules drawn from the Biome-BGC (Biogeochemical Cycling) model (Running and Hunt 1993) and the NGAS (Nitrogen Gas) module of CENTURY (Parton et al. 1996). In terms of nitrogen cycling, denitrification rates increase non-linearly with soil water as values approach saturation, while for decomposition and mineralisation, rates follow parabolic trajectories with maximum values at intermediate moisture conditions. While a set of other factors and processes influence in-situ N cycling, including temperature, carbon substrate availability and net immobilisation, soil moisture is a dominant factor controlling space–time variation of the transformation and flux of soluble carbon and nitrogen constituents over landscape level gradients.

Soil water state is developed by solving patch and canopy level interception, infiltration, evapotranspiration, unsaturated and saturated zone dynamics, with lateral divergence computed with routing techniques drawn from modified forms of either TOPMODEL (Beven and Kirkby 1979) or the Distributed Hydrology Soils Vegetation Model, DHSVM (Wigmosta et al. 1994). Note that TOPMODEL does not actually route water, but redistributes saturation deficit by use of hydrological similarity measures, and therefore does not account for transformations of transported constituents along a flowpath. Therefore, in the examples given here, we make use of the DHSVM routing modules.

At time scales of daily to seasonal, simulated soil water patterns in Pond Branch vary between states of showing strong or weak coupling with topographic gradients. During the winter and early spring, near-saturation conditions are frequently exhibited in the broad valley bottoms, hollows and lower slopes, while growing season conditions show saturation levels declining in the interfluves with drying trends extending into the valley bottoms during the summer (Fig. 4.10-3). These space–time soil water patterns interact with nitrogen cycling by restricting nitrification and promoting denitrification during the wet period, both in the uplands and bottomlands, while shifting to a greater rate of net nitrification during the drier period. In the bottomlands, the organic-rich soils which accumulate due to a combination of fluvial/colluvial transport and low decomposition rates, may shift from acting as nitrate sinks to becoming small nitrate sources. Full field verification of this shift is still in progress. However, nitrate concentrations sampled at the weir show values below the detection limit for most of the dormant period, but show consistently higher values during the growing season, with greater concentrations corresponding to the drier summers (out of three summers sampled so far).

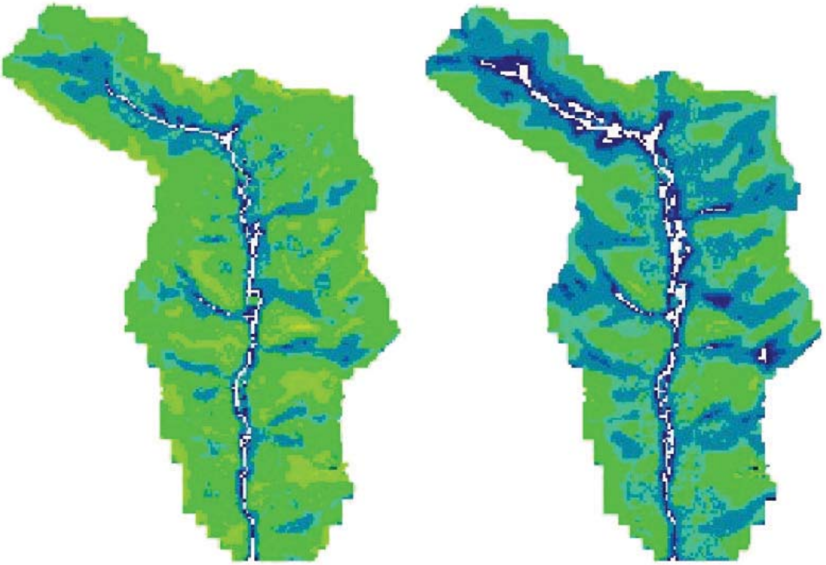

Fig. 4.10-3 Mean monthly saturation deficits in a catchment for August 1998 (left) and January 1998 (right), showing expansion of saturated areas in bottomland and hillslope hollows during the winter. Blue represents saturated conditions, ranging through greens and yellows (driest). Saturated and near saturated areas are restricted to the bottomland and hollows in August and expand during the winter, on right)

The results we show here are qualitatively similar to results presented in Band et al. (2001b) in terms of the temporal patterns of predicted streamwater nitrate concentrations, but are closer to the observed trends (Fig. 4.10-4).

This results from a few improvements in model structure as well as an improved, higher resolution Digital Elevation Model (DEM) that allows us to resolve the topography and particularly the critical riparian areas within the bottomland. In addition, we have used a 5 m grid for this simulation as opposed to the larger, irregular polygons used previously. Even with these improvements, we are still over-predicting NO_3-N concentrations, but would point out that we are not currently modelling within-stream sinks and transformations.

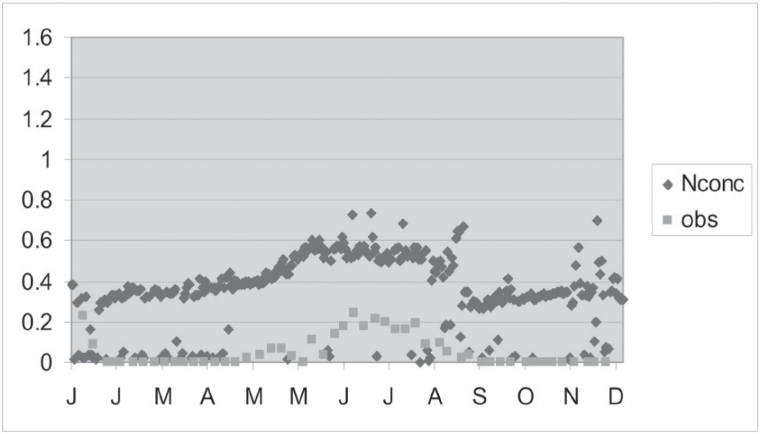

Fig. 4.10-4 Observed and simulated nitrate concentrations (mg $NO_3 - N\ l^{-1}$)at the catchment weir. Note the consistent overprediction of concentrations as in-stream processing is not incorporated, but the consistency with elevated export during the active growing season

Simplifications

Among a number of simplifications in our model approach, an important one is the parsimonious representation of unsaturated/saturated zone dynamics which includes a litter layer, unsaturated and saturated zone, following the approaches in TOPMODEL and DHSVM. The mass balance for nitrate is carried out for the full soil column, with the nitrate profile represented as an exponential distribution with depth. This produces the observed flushing effect as lateral flow in the saturated phase rises towards the surface. While a number of recent observations in both forest and agricultural sites appear to support the flushing concept, we are currently evaluating this assumption with more detailed simulations of unsaturated zone dynamics and field measurements.

We also maintain a simplified treatment of dissolved organic nitrogen loss which may lead to an underestimate of total N export from the basin and may be contributing to our overestimates of inorganic N export by maintaining higher N soil content. We are currently implementing a more mechanistic approach to dissolved organic matter evolution and export.

Internal processes and external factors

Currently, we operate spatially distributed water, nutrient and carbon mass balances with prescribed meteorological forcing, atmospheric CO_2 concentrations (no vertical gradients through the canopy) and N deposition. The nearest National Atmospheric Deposition Program (NADP) sites are some tens of kilometres away so we are using regional estimates of wet and dry deposition. Atmospheric nitrogen deposition is an important source in this region, and while retention in the ecosystem is very high (>90%), long-term growth of the canopy is enhanced by the moderate to high values. To spin-up the simulations to the last decade, we have run the model for a period of 400 years to gain stable spatial distributions of soil C and N, canopy above and below ground biomass and leaf area index (LAI). As patterns are internally generated, this provides additional information to compare with field measurements to check the consistency of model performance. Soil depth and hydraulic conductivity profiles are highly uncertain and are estimated from knowledge of the geomorphology of the area, limited pit data (four sites) with measured conductivity profiles (to a depth of two metres) and calibration to hydrographs. At present, the model operates its carbon, water and nutrient flux as a function of species-specific physiological parameters, to which the model can be very sensitive. Species composition is prescribed in the model as we do not treat succession.

Coupled natural cycles

The spatially distributed cycles of nutrient cycling (in this case nitrogen), carbon and water are coupled directly at subhillslope scales. Over long periods, water and nutrients control biomass accumulation, carbon allocation within the canopy which determines changes in canopy structure, canopy LAI and soil organic matter. These variables, in turn, are important short-term controls on water, carbon and nitrogen flux through the full system.

Treatment of uncertainty

A shortcoming of integrative process models such as that presented here is the proliferation of model parameters that can be known only with limited certainty (or high uncertainty). This is especially true of subsurface parameters, as soil biogeochemical and hydraulic characteristics are well known to be highly variable in lateral and vertical extent. This is one motivation to attempt to keep the model to as simple a representation of the key processes as is feasible, while attempting to retain the major non-linearities and feedbacks. As model complexity increases, it becomes less feasible to create adequate samples of model realisations with variable parameter sets. However, a potential advantage of an integrated model is the availability of a larger set of simulated model state and flux variables, a set of which can be observed for comparison. In our model, in addition to hydrographs, we develop patterns of soil water content, C/N content, standing biomass and LAI. The Pond Branch site has a set of terrestrial ecosystem plots in which these variables are estimated and used to develop pattern indices to describe the topographic zonation of these slowly and more rapidly developing variables with landscape position which can be compared with model output.

In addition to parameter uncertainty, the physics and chemistry controlling water and nutrient movement through hillslopes may still be poorly known. A major uncertainty in hydrology at present is whether treatment of soil water flux by Darcy matrix flow is correct, given recent demonstration of the effectiveness of preferential flow.

4.10.4 Experiences

Difficulties

The processes we describe in this paper are typically sensitive to conditions near the stream as well as channel conditions. Several researchers have shown that stream chemistry can be largely reset in the riparian zone, such that connectivity of the hillslope water to the stream, as mediated by the riparian buffer, is a critical control. However, topographic and soil information are typically poor in these areas, and standard methods of terrain interpolation tend to smooth out bottomland topography substantially. The uncertainty attached to soil information in the near stream environment, of course, can be extended to soil information through the full catchment.

Additional difficulties arise out of the problem of equifinality in complex simulations, as discussed by Beven and Freer (2001) and others. In this case, a number of different model structures and parameterisations may lead to similarly good fits of simulated to observed flow and quality data. Therefore, it is important to maximise the number of independent observational data available to assess the consistency of model behaviour.

Conclusions

Conceptual and model coupling of space-time variations in water storage and flux with biogeochemical cycling and export allows us to consider a richer set of dynamics and feedbacks to catchment behaviour. In particular, the short and long term interactions of catchment hydrological cycling with ecosystem pattern and process embedded within our modelling framework provides a set of spatial and temporal signals that can form more comprehensive testing with field observation. As examples, we can use space–time distributions of leaf area, standing biomass, streamflow and water quality to test model behaviour with observations. The hierarchical representation of the landscape also allows us to investigate system behaviour at scales commensurate with ecosystem field plots, as well as aggregate this information to resolutions commensurate with medium to coarse resolution satellite observations (Band 2000). The feedbacks of short-term flux of water, carbon and nutrients with canopy growth in mixed topographic settings also allows consideration of long-term effects of forest harvest and road development on hydrological and ecosystem behaviour (Tague and Band 2001). In short, this coupling allows us to move beyond the need to prescribe canopy and ecosystem conditions independent of hydrological regime.

Further applications

While we have concentrated our application of this modelling approach to forested catchment, we are currently extending the model approach to incorporate the set of features and processes typical of urbanising catchments. This includes the patchy nature of the surface with detailed mixtures of pervious and impervious surfaces, drainage infrastructure, and localised water and nutrient applications. These applications are being tested and supported by distributed monitoring in more urbanised catchments monitored in the Baltimore Ecosystem Study.

Acknowledgements

The Baltimore Ecosystem Study project is supported by the National Science Foundation grant GRS 0095796 to L. Band and C. Tague, and NSF Long-Term Ecological Research program, grant number DEB 9714835. We thank the USDA Forest Service Northeastern Research Station for site management, and in-kind services to the BES. In addition we thank the University of Maryland, Baltimore County for their contribution to office and laboratory space at the Research Technology Center on their campus.

4.11 The Boreal Ecosystem-Atmosphere Experiment (BOREAS)

Forrest G. Hall

4.11.1 Motivation and Objectives for the Coupling Approach

The boreal ecosystem encircles the Earth above about 48° N, covering Alaska, Canada and Eurasia. It is second in areal extent only to the world‘s tropical forests and occupies about 21% of the Earth’s forested land surface. Nutrient cycling rates are relatively low in the cold wet boreal soils, resulting in relatively high long-term boreal carbon storage rates. These rates average roughly 30 to 50 g C m^{-2} y^{-1}, a result of relatively high root turnover from trees, shrubs and mosses with relatively low decomposition rates. Over the past few thousand years, these below-ground storage processes have created a large and potentially mobile reservoir of carbon in the peats and permafrost of the boreal ecosystem. Currently the boreal ecosystem is estimated to contain approximately 13% of the Earth’s carbon, stored in the form of above-ground biomass, and 43% of the Earth’s carbon stored below-ground in its soils. Meridional gradients in atmospheric CO_2 concentrations suggest that forests above 40° N sequester as much as 1 to 2 gigatons of carbon annually, or nearly 15 to 30% of that injected into the atmosphere each year through fossil fuel combustion and deforestation. Given the enormous areal extent of the ecosystem, roughly 20 million km^2, shifts in carbon flux of as little as 50 g C m^{-2} y^{-1} can contribute or remove one gigaton of carbon annually from the atmosphere. If the strong high-latitude warming trend continues, leading to warmer soils and a reduction in the extent of the boreal permafrost zone, the resultant increases in soil organic matter decomposition could switch the boreal ecosystem from a long-term carbon sink to a significant carbon source, accelerating global warming.

The boreal ecosystem also strongly influences short-term climate: (1) Its nutrient-limited conifers growing on cold, moisture-saturated peats, strongly limit evapotranspiration, creating a deep, dry atmospheric boundary layer more characteristic of an arid ecosystem, essentially “a green desert”. (2) Both long- and short-term changes in its high-albedo snow and ice extent are linked to global climate variations and coupled to climate through the albedo feedback. Since 1970, climate change has had a significant impact on snow cover, which may have enhanced spring warming through feedbacks from the subsequent decrease in surface albedo. (3) Smoke aerosols produced by extensive lightning-induced forest fires modify regional climate by reducing surface insolation and influencing cloud formation and precipitation tendencies.

4.11.2 Short Description of the Study

BOREAS was an interdisciplinary, multi-scale field experiment to study the role of the boreal ecosystem in global change (Sellers and Hall 1997). 85 science teams, including atmospheric physicists, micrometeorologists, ecologists, hydrologists, biogeochemists, and remote sensing specialists were involved. During 1993 through 1996 the BOREAS science team consisted of over 300 scientists. BOREAS was originally planned to last three years, with field campaigns in the first year and disciplinary data analysis occurring in the second and third years. However, analyses performed in the second year of BOREAS showed that there were a number of gaps in the first year's data; thus a third year of data collection was proposed and funded, along with an additional fourth year to analyse the data. During the first four years of BOREAS, scientists focussed on acquiring, quality assuring, and analysing their own data. Process model work focussed mainly on analysing tower site data for model development and validation.

An additional call for proposals was issued in the fourth year of BOREAS to permit more integrative, interdisciplinary, regional-scale analyses focussed on broader scientific questions. The call resulted in the selection of thirteen guest investigations. These investigations focussed generally on modelling and analysis, extending and building on the BOREAS scientific results and database.

A major emphasis within the Guest Investigator Program was to link carbon modelling efforts closely to those of the energy, water, and hydrology modelling teams. The BOREAS nested resolution modelling approach, of tower > study area > transect > region was a cross-cutting theme for all simulation efforts. Nine ecosystem process models and seven hydrometeorological models were evaluated in three phases. Of the ecosystem process models, three ran at hourly time steps, five at daily time steps and one at a monthly time step. Model outputs such as net primary production (NPP) and net ecosystem production (NEP) as well as plant and soil respiration were cross-compared. In addition, model outputs were compared to tower-observed values for radiation, CO_2, water vapour, and heat flux. The hydrometeorological model output was also evaluated by comparison with values of runoff in gauged catchments.

4.11.3 Complexity of the Study

The objectives of BOREAS relate to two spatial scales that had to be reconciled within the experiment design: the local scale, a few centimetres to a kilometre, and the regional scale from a few kilometres to the 1000 km x 1000 km BOREAS study region in central Canada. The primary focus of local-scale experiments was to improve and characterise the performance of the process models that describe the exchanges of radiative energy, water, heat, carbon and trace constituents between the boreal forest and the atmosphere. The regional-scale experiments were concerned with applying and validating the process models over large spatial scales using remote sensing. In BOREAS, as in previous field experiments, the science team adopted a nested multi-scale measurement strategy to integrate observations and process models over the scale range.

Because BOREAS was a multi-scale, multidisciplinary experiment, BOREAS investigators were able to measure, model and validate models for a number of coupled land-atmosphere exchanges of mass, heat and energy.

For example, in the boreal ecosystem, the land surface and atmospheric boundary layer are strongly coupled through the ecophysiological control on surface evapotranspiration. Boundary layer drying feeds back to stomatal conductance through the Ball-Berry-Collatz-expression for stomatal conductance $g_c = Ah/c$, (A is the canopy photosynthetic assimilation rate, h is relative humidity and c is carbon dioxide concentration near the canopy), as humidity h drops from boundary layer warming (mentioned in Fig. 4.11-1 caption). The average seasonal diurnal effects of this are illustrated in Fig. 4.11-1. The bottom row of Fig. 4.11-1 shows the early-morning increase in stomatal conductance with increase in solar radiation (third row). The top row of Fig. 4.11-1 shows the decrease in relative humidity with increasing R_n as surface heating expands the atmospheric boundary layer. Decreasing boundary layer humidity and increasing air temperature begin to exert physiological effects on leaf stomata conductance around 0200 to 0300 UTC (8 to 9 local time), reducing stomatal conductance even though photosynthetically active radiation continues to increase. Stomatal reduction of surface evapotranspiration is rapid as indicated by the rapid drop in evaporative fraction in the second row. Restriction of surface evaporation further dries the atmospheric boundary layer, which in turn couples back to stomatal conductance throughout the day. On many days during the BOREAS observing period, high surface sensible heat flux drove boundary layer depths to a height of 3 km, more typical of a desert than a forested ecosystem.

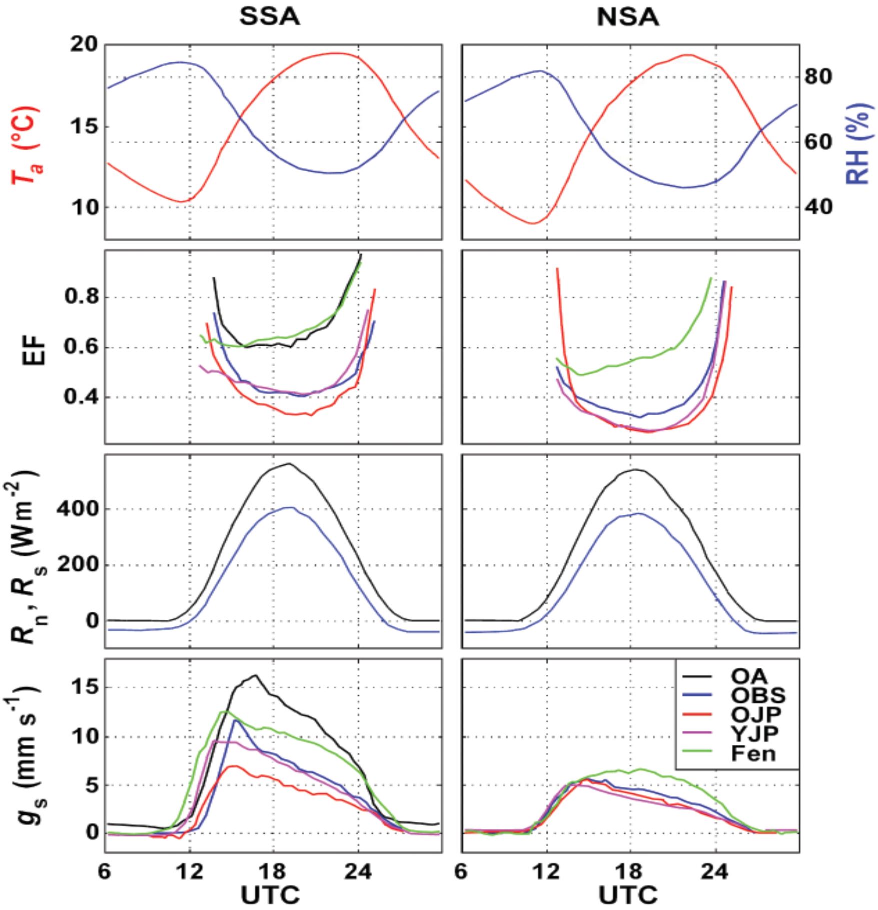

Fig. 4.11-1 Diurnal variation in air temperature, T_a (red lines), relative humidity, RH (blue lines), evaporative fraction, EF, solar radiation, R_s (black lines), net radiation, R_n (blue lines) and conductance to water vapour, g_s from BOREAS tower flux sites in the SSA (southern study area) and NSA (northern study area), averaged between 24 May and 19 Sept 1994. We first averaged the fluxes by time of day before calculating EF. The mean surface conductance was calculated from measured data only (e.g. with no gap filling) after excluding values below the 10th and above the 90th percentiles. The line style is the same for each land-cover type. Local time in the SSA and NSA is 6 hours less than UTC. (OA: old aspen; OBS: old black spruce; OJP: old jack-pine; YJP: young jack-pine)

This diurnal boundary-layer/surface feedback also couples into the seasonal atmosphere-surface exchange of carbon through temperature elevation (1) increasing canopy and soil respiration and (2) restricting photosynthetic uptake of carbon dioxide. BOREAS respiration measurements show that for wetland boreal conifer stands, below-ground respiration was ~50-70% of total ecosystem respiration. All respiration rates showed temperature dependence with Q10 values (i.e. rate increases for a 10° C temperature increase) of ~1.5 for wood, ~1.9 for roots, ~2.0 for foliage and 2.6 for soil. Chamber measurements in BOREAS peatlands showed Q10 values of 3.0 to 4.1.

Currently, respiration loss and photosynthetic uptake of carbon in the boreal wetlands are almost balanced, with a net uptake over the past few thousand years averaging about 50 g C m^{-2} y^{-1}. This sensitivity of the boreal ecosystem carbon exchange to temperature may couple strongly in the long-term with the observed and predicted warming at higher latitude continental interiors to accelerate high-latitude warming through increases in CO_2 input to the atmosphere.

Another important atmosphere-surface feedback that was not investigated extensively in the boreal zone is precipitation-driven. Increased storage of water in the boreal wetlands could alter carbon storage rates in these wetlands, through reduced decomposition rates below ground. Wetland spruce/tamarack communities have high root turnover, resulting in carbon storage rates ranging from 30 to 160 g C m^{-2} y^{-1}. Depending on the degree of soil saturation, anaerobic decomposition of organic materials in the boreal wetlands can generate methane and reduce rates of CO_2. On the other hand, drying and warming of the boreal ecosystem could switch peatlands from a net sink of carbon to a net source in exceptionally dry periods due to increased aerobic respiration.

4.11.4 Experiences

Boreal ecosystem-atmosphere exchange of carbon, water and energy from remote sensing

BOREAS thoroughly tested all aspects of computing the surface-atmosphere exchange of carbon, water and energy using a combination of surface-vegetation-atmosphere transfer models and satellite remote sensing to provide inputs to those models. These results are reported in detail in an 85-paper volume of the JGR - Atmospheres BOREAS special issue (Sellers and Hall 1997), and two subsequent issues, a 27-paper BOREAS special issue volume of JGR - Atmospheres (Hall 1999), and a 12-paper BOREAS special issue (Hall 2001). In addition there was an 11-paper volume of the BOREAS special issue of "Tree Physiology" (Margolis and Ryan 1997), a

9-paper volume of the Canadian Journal of Remote Sensing (O'Neill and Ranson 1997), and an 8-paper volume of Remote Sensing of Environment (Gamon et al. 2004).

This body of research led to a better definition and careful evaluation of the technology and analysis framework required to locate, understand the dynamics of and predict the future strengths of sources and sinks of land carbon. The analysis framework concept evolved from the BOREAS experience includes (1) inverse models, (2) coupled physical and biogeochemical process models, and (3) space-based and conventional observations. Inverse models predict the location and strength of terrestrial and ocean surface CO_2 sources and sinks, and rely on precise observations of spatial and temporal variations in atmospheric CO_2 concentrations. Process models predict carbon storage and the exchange rates of CO_2 at the atmosphere-land-ocean interfaces. Both the inverse and process modelling approaches are designed to infer regional magnitudes of net CO_2 exchange, and provide a means for cross validation. Inverse models can be used to provide a detailed analysis of what has happened to the CO_2 that has already been emitted by human activities. Physical and biogeochemical process models will provide a picture of the effects of land management and land use, terrestrial ecosystem and ocean dynamics, and other environmental factors on carbon sources and sinks over time. Importantly, these models will show how future atmospheric CO_2 concentrations might change as a result of natural occurrences, human actions, and past and future emissions. It is the synergy and interplay among advances in modelling, new observations of key Earth surface and atmospheric carbon properties, and improvements in the computational capacity that supports modelling and satellite data analysis that will enable major advances in our understanding and ability to predict climate change.

To implement this framework the major challenges for land remote sensing are (1) remote sensing of the spatial and temporal distributions of atmospheric CO_2 concentration to constrain model-based estimates of regional, continental, and global variations of land-ocean-atmosphere carbon exchange; (2) remote sensing of land biomass and biomass change resulting from land-use change, logging, fire, and changes in rates of growth resulting from climate change, CO_2 fertilisation, and nitrogen deposition; (3) more direct measurements of vegetation productivity using remote sensing to observe rates of vegetation photosynthetic activity; and (4) global satellite observations of soil moisture fields.

To accomplish these goals, an integrated and coordinated set of activities will be required. These include (1) technology development to support the new observations, (2) algorithm and model development to infer regional and global variations in atmosphere-surface carbon exchange, (3) additional coordinated field experiments of the type mounted in BOREAS for algorithm and model development and validation, and (4) data synthesis activities to provide the regional and global data sets needed to drive the carbon analysis framework.

Experiment design, coordination, data sharing and archive

To observe and quantify the many complex feedbacks regulating surface-atmosphere interactions in the boreal ecosystem, or any ecosystem for that matter, requires multi-scale, multidisciplinary research to produce the required integrated and multi-scale data sets to support research and validate models. These requirements in turn define the framework and organisation of the experiment. BOREAS involved the classic elements of any scientific study: formulation of the science questions to be addressed; definition of an analysis framework to address the questions; identification of the data required by the analysis framework; design of an approach and experiment to acquire the data; experiment execution including procurement, installation and operation of the necessary infrastructure; collection, processing and quality assurance of the data; utilisation of the analysis infrastructure and data to address the science questions; writing, review and publication of results; and finally, documenting and archiving the data. BOREAS included 85 teams involving over 300 scientists. To reduce redundancy of effort among the teams, a core staff at the Goddard Space Flight Center was formed. This staff handled many of the BOREAS-enabling tasks such as procurement, installation and operation of the experiments' core facilities (e.g. aircraft). In addition, the staff integrated the BOREAS data stream providing quality assurance, integration, documentation and archiving of the nearly 500 gigabytes of satellite imagery, aircraft imagery, and numeric data - 266 documented datasets in all.

Considering the costs involved in the planning and execution of large-scale field studies, it is advantageous to expend a bit more to create a finalised data archive that can be the legacy of the project for years to come. For a minimal additional cost (over the long-term) a centralised staff can help create a better-run project. An information system can help to publish a data product that will be useful in Earth systems science for decades. Too many projects neglect the data publication phase and in the end have no coherent data archive, limiting their usefulness to Earth systems science research. The value of these final data archives to future scientists cannot be overestimated, but is often underestimated, or worse, not even considered by project planners and sponsors. In the end, a scientific field study is not just about publishing scientific papers by the investigators, but is about creating a data archive that can be of use to scientists for decades, spawning new work and new publications far into the future.

4.12 Integrated Modelling of Water Availability and Vulnerability of Ecosystems and Society in the Semi-arid Northeast Brazil

Maarten S. Krol, Axel Bronstert, Annekathrin Jaeger

4.12.1 Motivation and Objectives for the Coupling Approach

Northeast Brazil is seriously influenced by the insufficiency and unreliability of precipitation in the semi-arid environment. The adverse natural conditions and the underdevelopment of the region means that the rural population cannot support itself in drought years.

The central objective of the project WAVES (Water Availability, Vulnerability of Ecosystems and Society, see Gaiser et al. 2003) was to improve the integrated understanding of the relationships between water availability, agro-ecosystems and society in the context of global environmental change. This understanding should assist in the assessment of climate change impacts, of the sustainability of long-term regional development and of the efficiency of various policy options.

An integrated model has been constructed covering the multidisciplinary themes involved. It has been termed “SIM” (semi-arid integrated model) and summarised by Krol et al. (2003) and documented comprehensively by Jaeger (2004).

4.12.2 Short Description of the Study

The study area shown in Fig.4.12-1 comprises the Brazilian Federal States of Ceará and Piauí, together covering 400 000 km^2. Most of this area has a semi-arid climate, with precipitation ranging from 500 to 900 mm y^{-1} and potential evapotranspiration exceeding 2000 mm y^{-1}. The climate exhibits an annual cycle with a dry period of six months (July - December); inter-annual variability is high, partly related to El Niño, with irregular severe droughts. Few rivers are naturally perennial. Dam construction, aiming at maintaining

Fig. 4.12-1 The "drought polygon" with a semi-arid climate in northeastern Brazil. The study area consists of the States of Ceará and Piauí. The border between Piauí and Maranhão is formed by the river Parnaíba

river flow and urban water supply, has a tradition of over a century. In rural areas an immense number of small reservoirs succeed in storing water to overcome shortage in normal dry periods but they fail in drought years. Groundwater availability in the interior, consisting of crystalline rock, is sparse and waters are often saline; aquifer systems exist in the coastal region and the downstream area of the Jaguaribe, the main river of Ceará. Apart from alluvial soils in the riverbed, soils are generally shallow and poor. Land use consists largely of extensive cattle holding and subsistence farming. The main crops are maize, beans, dry rice, cassava and cashew. Distribution of land property and income is very uneven, making small subsistence farmers highly vulnerable. The current population is about 10 million, increasing at a rate of 1.4 % per year. A steady rural–urban migration compensates for the rural birth excess, with migration strongly elevated in drought years. Migration to urban centres in the south of Brazil or to land-reclamation areas in the Amazon area is also an important demographic factor.

The processes described by the developed integrated model (Bronstert et al. 2000; Krol et al. 2003) cover the complete causal chain, from climate forcing to selected societal impacts.

- Climate variables are input to the model, shown in Fig. 4.12-2.
- A hydrological sub-model (Güntner and Bronstert 2003) describes runoff generation, evapotranspiration, soil humidity and deep percolation in a vertical water balance with a multi-layer soil model. Lateral flows and river flow are routed, and small water storage facilities in the landscape are accounted for. Large reservoirs in the main river network are described explicitly within the water balances.
- Water extraction is quantified for sectoral use in households, husbandry, irrigation, industry and tourism. Here, the physical availability of water is a restricting factor.
- Agricultural yields for regionally common crops are evaluated, depending on the relative sufficiency of evapotranspiration in phenological periods, regional soil characteristics and the agricultural management applied.
- Agricultural land use is represented by an agro-economic model, optimising economic returns given simulated yields, under restrictions in the availability of natural and economic resources,
- Population development is simulated, accounting for regional fertility and mortality, and for migration described by a push-pull model basing on income gradients.

Simulations are performed for the area of Ceará and Piauí (400 000 km^2) for periods of many decades (historic simulations 1921–1998 and scenarios 2000–2050). The common resolution factor in all calculations is the municipality (in average about 1000 km^2) and the year, but finer resolutions are used for various model components.

Calculations of hydrology and crop yield resolve daily time steps for terrain units within municipalities, which are homogeneous in their topographic characteristics, soils and vegetation, and average 75 km^2. Water extraction is computed at daily resolution. Model compartments are coupled directly at their finest common resolution.

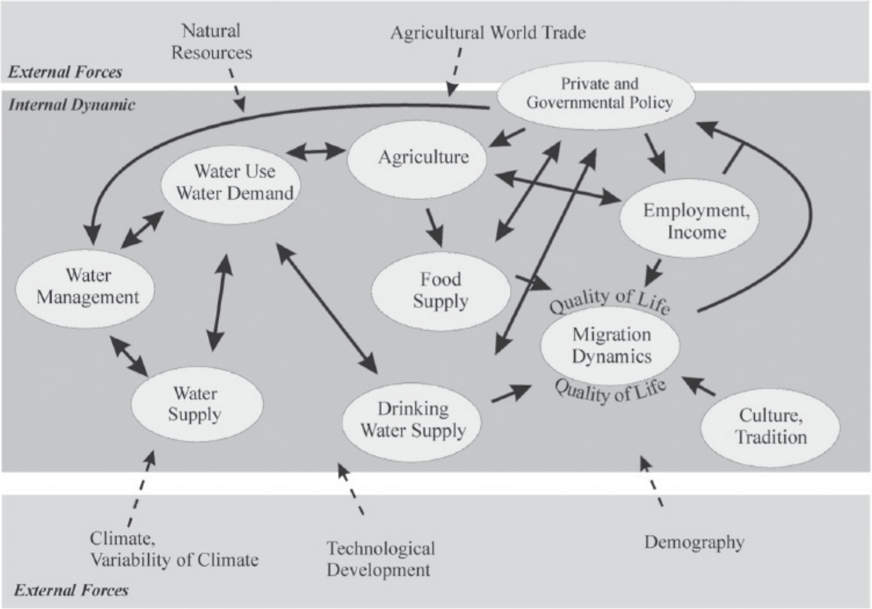

Fig. 4.12-2 Conceptual model, sketched as box-and-arrow diagram, of dynamic relationships between water availability, agriculture and migration in northeastern Brazil, as influenced by global change

4.12.3 Complexity of the Study

Feedbacks play an important role in the study. They necessitate a coupled integrated modelling, as opposed to an off-line (segmented) chain of models with one-way data transfer only. Important feedbacks in the model are, for example, the effect of water extraction for municipal water supply or irrigation on physical water availability, and the effects of land use and population development on water use.

The importance of the water extraction feedback is stressed by the fact that they become especially relevant during droughts. The land use and population feedback is especially relevant for long-term developments. Both couplings concern anthropogenic feedbacks on the natural water cycle.

Geographic couplings are of dominant relevance as well. The relative scarceness of water stresses the relevance of upstream-downstream relationships and the spatial distributions of water availability and water demands.

This aspect relates both to the level of model descriptions, which require an adequate spatial resolution, and to the level of policies. Large water storages are meant to guarantee urban water supply and small dam construction in the hinterland is presently being suppressed as the large number of small reservoirs appears to be reducing the effectiveness of large reservoirs.

The SIM Model is a concrete implementation of the result of the systems analysis shown in Fig. 4.12-2. The model is built up in a modular way, roughly representing the disciplinary contributions from different research groups, see Table 4.12-1.

Table 4.12-1 Structure of SIM: modules, content, methods applied, and scientific institutions responsible for the modules (PIK: Potsdam Institute for Climate Impact Research; FUNCEME: Fundação Cearense de Meteorologia e Recursos Hídricos (Fortaleza, Brazil); UFC: Universidade Federal do Ceará Hídricos (Fortaleza, Brazil); Uni KS: University of Kassel; FAO: Food and Agriculture Organisation; Uni HO: University of Hohenheim; FH K: University of Applied Sciences Cologne)

Module	Scientific disciplines covered by each module	methods applied	institution
climate	- historic reconstruction and scenarios of daily time series	- statistical/empirical downscaling	- PIK / FUNCEME
water	- large-scale water balance - water use and management	- process-based / deterministic - data driven budgeting	- PIK/UFC - Uni KS / UFC
land use	- crop yield - soil description - agro-economy	- empirical - distributed soil data base - mathematical optimisation	- FAO - Uni HO/ UFC/PIK - FH K
socio-economy	- quality of life - migration and demography	- empirical, data driven	- Uni KS / UFC / PIK

Many simplifications were made in constructing the different modules of the whole integrated model. The simplifications originated from lack of knowledge, lack of trustworthy data and from the focus on specific topics in the research.

Water quality issues were not addressed in the modelling, although salinisation is a serious problem for water use. The abundant small water reservoirs and reservoir operation were represented in general in a simplified, schematic way. Developments in water use and water use efficiency are only coarsely understood. Both in the agricultural economy and migration modules, only some of the well-understood processes are represented, omitting many other processes that are known only qualitatively.

The model is driven by external and internal factors, such as climate trends, market prices (external) and trends in economic growth and demographic parameters (internal).

Handling of uncertainty in an interdisciplinary integrated model poses a major challenge. In this project, only sensitivity studies were performed, estimating uncertainty effects due to uncertainties in base data and model parameters.

4.12.4 Experiences

The problems encountered in the project can be divided in those of a disciplinary and an interdisciplinary nature. Working in an underdeveloped region, reliable data over longer timescales and with reasonable spatial coverage are rarely available, posing problems for all disciplines. For interdisciplinary work, data should preferably be available with combined characteristics (e.g. water extraction both per sector and per water source) but are not found in this way; here mostly coarse assumptions have to be used. This may pose a serious problem for integrated modelling but on the other hand it illustrates the relevance of integrated studies in identifying the concrete gaps in available data and knowledge. In studying socio-economic impacts, the understanding of human behaviour in water use and strategies of adaptation to drought are only partly understood and hardly quantified. This is a problem for integrated studies connected with the state of the art in the contributing disciplines rather than of the integration itself.

Another category of problems concerns the involvement of disciplinary scientists and policy makers in integrated assessments. Both groups generally recognise the relevance of integrated studies but are not very eager to participate in modelling studies. Here, participative scenario studies and stationary integration of geographic data (in GIS) were found to have an initial attractiveness and to show the relevance of integrated modelling as a tool to support the assessments quantitatively in a way to best safeguard the consistency of scenarios.

Model applications focussed mainly on analysing regional sensitivity to climate change, on scoping pathways of regional development and assessing policy interventions related to dam construction and agricultural alternatives, see Jaeger (2004).

The integrated modelling in SIM successfully integrates the state-of-the-art understanding of regional processes. This understanding is incomplete, but consistent implications of interconnections on the systems dynamics can be shown and the most relevant knowledge gaps identified.

The integrated model proved very useful in improving the awareness of regional policy makers to the relevance of climate change for the region.

Acknowledgements

This case study concerns the project WAVES, studying the semi-arid north-eastern Brazil. German and Brazilian research institutions participated in the project. The authors thank the German Federal Ministry of Education and Research (BMBF) and the Brazilian National Council of Science and Technology Development (CNPq) and the Potsdam Institute for Climate Impact Research (PIK), Germany, for supporting this research.

4.13 Integrated Global-change Modelling with IMAGE-2

Bas Eickhout, Rik Leemans

4.13.1 Motivation and Objectives

IMAGE-2 (Integrated Model to Assess the Global Environment; Alcamo et al. 1998) is an integrated assessment model that calculates the environmental consequences of human activities worldwide. IMAGE-2 represents interactions between society, the biosphere and the climate system, to assess environmental issues like climate change, biodiversity decline and human well-being. The objective of the IMAGE-2 model is to explore the long-term dynamics of global environmental change, which requires a representation of how the world system could evolve. Future greenhouse gas emissions, for example, are the result of complex interacting demographic, technological, economical, social, cultural and political forces. The model is designed to compare business-as-usual scenarios with specific mitigation and adaptation scenarios and thus compare the effectiveness of such measures. Scenarios are “what if” representations of how the unknown future might unfold. They form an accepted and valuable tool in analysing how different comprehensive sets of driving forces may influence future emissions, concentrations, climate change and impacts. No specific likelihood can be specified to any scenario due to major uncertainties involved in the society-biosphere-climate system.

The socio-economic and energy-use calculations are performed for 17 world regions (see Fig. 4.13-1). The atmospheric and ocean components are based on globally aggregated approaches. The land-use and terrestrial-carbon calculations are performed on a high-resolution grid of 0.5 × 0.5 degrees. The innovative aspects in IMAGE-2 consisted in bringing together in a comprehensive framework these highly different resolutions and dimensions. The IMAGE-2 simulations are carefully calibrated with observed data for the period 1970–1995. Future trends in socio-economic scenario variables (e.g. demography, wealth and technology) have to be defined for each simulation. IMAGE-2 represents major global dynamic processes, including several natural interactions and feedbacks, such as CO_2 fertilisation and land-use change induced by changed climate.

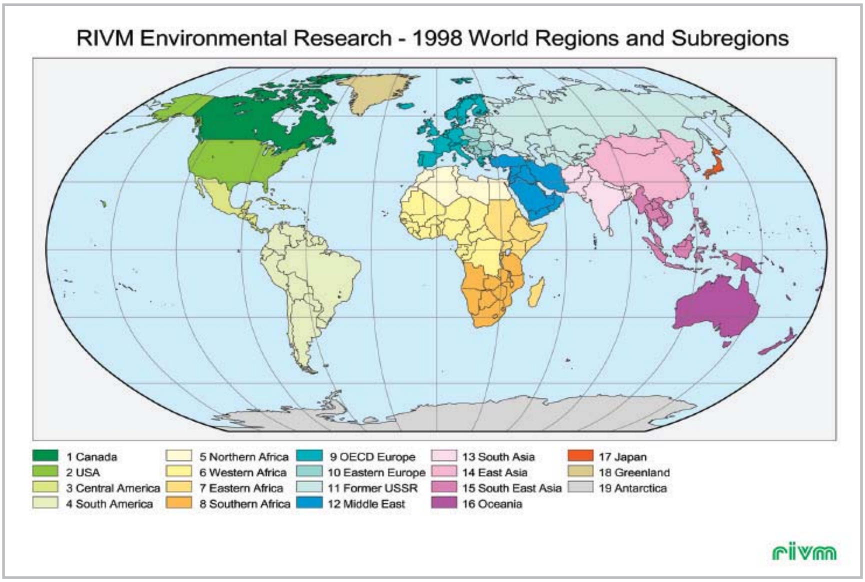

Fig. 4.13-1 The 17 world regions plus Greenland and Antarctica in IMAGE-2

4.13.2 Short Description of the Study

Recently, the Intergovernmental Panel on Climate Change (IPCC) published a set of standardised reference emission scenarios (SRES; Nakicenovic et al. 2000). A thorough review of the literature led to the development of different narrative "storylines"[1]. The quantification of these storylines was based on six different integrated models. These storylines were constructed on two axes, i.e. the degree of globalisation versus rationalisation, and the degree of orientation on material values versus social and ecological values. The resulting clusters were given neutral names: A1, A2, B1 and B2 (Fig. 4.13-2). The original SRES implementation focused mainly on the emissions from energy use and was only implemented for four regions (OECD, countries in transition, Asia and rest of the world). This aggregation concealed important regional differences in development as well as in socio-economic and environmental conditions. Also, SRES estimates emissions only: atmospheric, climatic and environmental processes that could alter emissions are neglected.

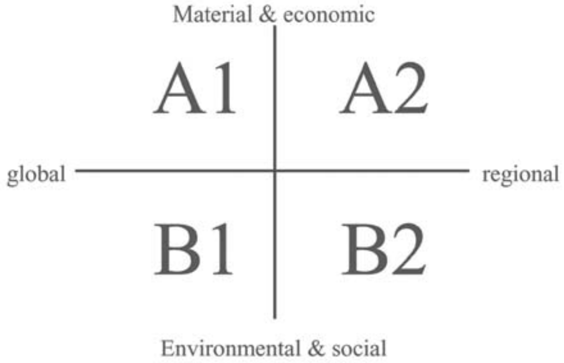

Fig. 4.13-2 The dimensions of the four SRES storylines, which define the storylines. In a globalised world, free trade and rapid conversion of technology define socio-economic developments, while in a regionalised world there is less exchange between and more diversity among regions. In a world that focuses on material and economic growth, resource use rapidly increases, while in a world with an environmental and social focus resources are used much more efficiently.

We have implemented these SRES storylines in IMAGE 2.2 on a more detailed level, taking several impacts and feedbacks into account (IMAGE team 2001). Basic demographic and economic information is derived from the original SRES data and disaggregated for 17 world regions. The data were checked for consistency by using the Phoenix model (population) and the WorldScan model (World economy) into the three linked subsystems of IMAGE-2 (Fig. 4.13-3):

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[1] The innovative aspect of using narratives in the SRES storylines lies in the consistency of future trends in population, wealth, technology, equity and energy use within each scenario. The earlier IS92 emission scenarios were based on expert judgment or literature surveys for every scenario assumption independently, returning a high, middle and low scenario. In the SRES approach each narrative defines characteristic, consistent trends in the input assumptions, recognising explicitly the correlations between the different assumptions.

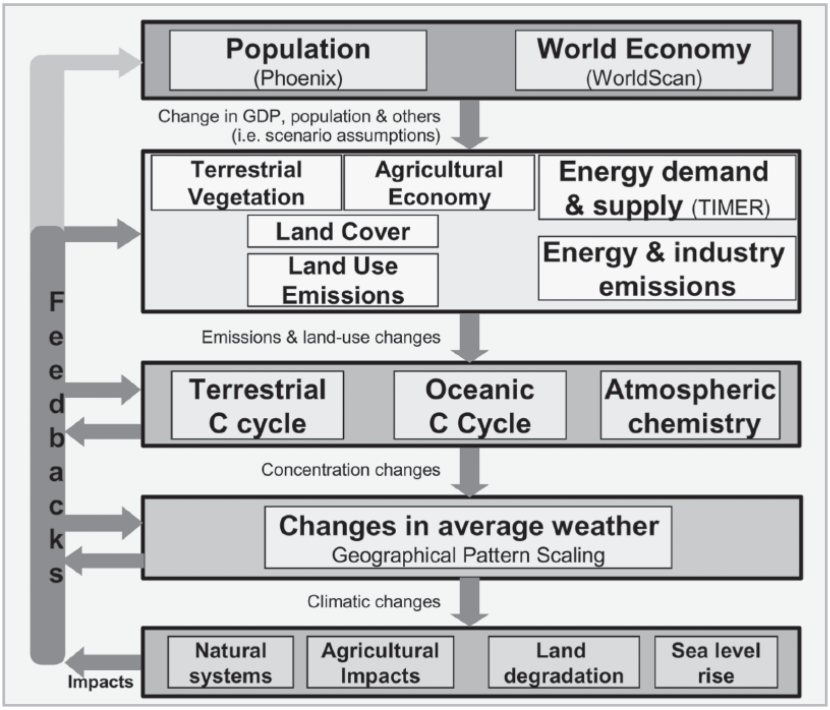

Fig. 4.13-3 The structure of the IMAGE-2 model

- The Energy-Industry System (EIS), which calculates regional energy consumption, energy efficiency improvements, fuel substitution, supply and trade of fossil fuels and renewable energy technologies. On the basis of energy use and industrial production, EIS computes emissions of greenhouse gases (GHG), ozone precursors and acidifying compounds.

- The Terrestrial Environment System (TES), which computes land-use changes on the basis of regional consumption, production and trading of food, animal feed, fodder, grass and timber with consideration of local climatic and terrain properties. TES computes emissions from land-use changes, natural ecosystems and agricultural production systems, and the exchange of CO_2 between terrestrial ecosystems and the atmosphere.

- The Atmosphere-Ocean System (AOS) calculates changes in atmospheric composition using the emissions and other factors in the EIS and TES, and by taking oceanic CO_2 uptake and atmospheric chemistry into consideration. Subsequently, AOS computes changes in climatic properties by resolving the changes in radiative forcing caused by greenhouse gases, aerosols and oceanic heat transport.

4.13.3 Complexity of the Study

The goal of simulating the complete cause-effect chain of global change requires a model with global coverage, but the multitude of components in the society-biosphere-climate system constrains the possibility to use detailed process-based models for each component. We have used simpler well-accepted models and focused on the interactions. Therefore, a more complete coverage of many feedbacks could be included in IMAGE-2 (Alcamo et al. 1998). For example, climate change induces shifts in global vegetation patterns; this changes the yield of crops and, hence, changes land-use patterns and thus influences the carbon uptake by biosphere and oceans. In other words: the strength of the IMAGE-2 model is found in the comprehensive coupling of the anthropogenic influences, the biosphere, ocean and atmosphere (c.f. Fig. 4.13-3) and not in the complexity of the different submodels.

IMAGE-2 is calibrated on historical data from 1970 to 1995. This calibration is performed on a number of data sources, concerning energy use, land use and national emission inventories. The global carbon cycle model required a longer calibration period, which is based on data for the atmospheric increase and energy and industry emissions of CO_2 for the period from 1765 to 1995.

In implementing the IMAGE-2 SRES storylines, much attention has been paid to identifying major sources of uncertainties. The different storylines result in largely different sets of energy use and energy carriers, land-use and land-cover patterns, emission trends and levels, concentrations and climate change (Table 4.13-1). Consequently, sea-level rise and other impacts also differ.

Additionally, we have run these storylines with different climate sensitivities and with or without specific feedback processes. The results of this sensitivity analysis indicate a possible global mean temperature increase, ranging from 1.6 to 5.5° C at the end of the 21st century, which is considerably larger than the range listed in Table 4.13-1. Another uncertainty stems from the pattern scaling of global-mean temperature changes to geographically explicit temperature and precipitation change by a given climate-change pattern obtained from state-of-the art climate models (GCMs). To assess such uncertainty, the pattern scaling has been carried out with different GCM climate-change patterns. In Fig. 4.13-4, the consequences of two different climate patterns for the yield of tropical cereals are depicted. These sensitivity experiments provide some insights in the uncertainty of quantification of these storylines.

Table 4.13-1 Results from the IMAGE-2 implementation of the SRES storylines after 100 simulated years (IMAGE team 2001)

	A1	A2	B1	B2
Global forest area (in Mha)	4980	3420	5750	4800
Global crop area (in Mha)	1480	2600	1260	1660
Global CO_2 emissions (in Pg C y^{-1})	13.6	29.0	2.7	10.1
Global CH_4 emissions (in Tg CH_4 y^{-1})	667	1102	491	696
Global N_2O emissions (in Tg N y^{-1})	20.7	27.4	17.5	20.8
Global CO_2 concentration (ppmv)	755	870	515	605
Global CO_2-equivalent concentration (ppmv)	1030	1315	640	820
Global mean temperature increase since pre-industrial times (in ° C)	3.4	3.7	2.3	2.9

4.13.4 Experiences

This IMAGE-2 case study provides detailed results from the SRES storylines for scientists interested in the causes and consequences of global change. Moreover, the results give a good perception on the important role of people and society in determining energy use, land use, emissions and changes in climate and biosphere. The storylines show that regionally largely different development patterns can emerge, depending on the assumptions that describe the specific SRES narrative. Especially, land-use dynamics, driven by shifts in population, diets and trade, are very important but are often neglected by the very detailed models restricted to the physical environment. IMAGE-2 gives good insight in how the terrestrial biosphere may evolve in different futures.

Uncertainty analyses with changed climate sensitivity parameters and different climate patterns show the relative importance of these factors. Especially, different climate patterns can change local and regional conclusions, as shown in Fig.4.13-4.

In the future, IMAGE-2 will pay more attention to biodiversity and adaptation of terrestrial ecosystems. For these issues, IMAGE-2 should be extended with a climate model that takes climate variability into account because ecosystems do not only respond to global-mean changes in the climate but are sensitive to local extremes. Moreover, to assess the vulnerability of ecosystems, more detailed ecosystem models will be

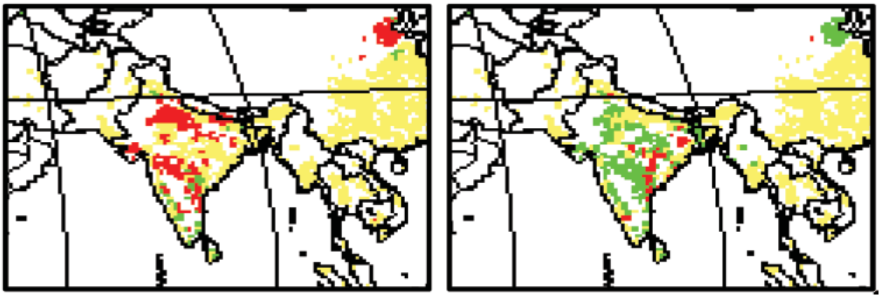

Fig. 4.13-4 Change in yield of rice in the current rice area of southern Asian, due to different climate patterns from HADCM2 and ECHAM4. Green indicates a yield increase, while red a yield decline

applied which means that the impact side of the causal chain especially has to be improved. This is policy relevant because now that climate change is accepted as a real issue, the possible impacts and adaptation have to be assessed more realistically.

4.14 The Virtual Watershed Laboratory

George Leavesley, Everett P. Springer

4.14.1 Motivation and Objectives

Hydrological simulation models have evolved from stand-alone, conceptual models that treat the entire watershed or basin as a single unit, to complex, spatially-distributed, physics-based process models. This development was driven by an improved understanding of the elements of the regional hydrological cycle, the availability of cheaper and more powerful computers, and increased societal demands for environmental decision-making tools. The National Academy of Sciences (1997), in their report "Preparing for the 21st Century", stresses the need for a scientific basis for risk assessment and the use of science to strengthen environmental policies and policymaking.

Increasingly, decision makers must balance competing demands for water and are relying on the results of strongly coupled and complex systems, for instance, by weighing the needs of riparian communities and endangered species against those of irrigated agriculture and municipal water supply, by managing the conjunctive use of surface and groundwater, or by considering the effects of climate variability on the integrated management of water. All these concerns require models in which system components are fully integrated and dynamically coupled through feedback mechanisms.

The current state of the art combines separate models of system components, operating independently and exchanging information in essentially one direction only. This does not reflect the actual dynamics of basin-scale systems whose components interact through complicated feedback mechanisms occurring on many time and space scales. Unfortunately, the development of fully integrated models is costly and time consuming. In application, the model specifics depend on the geographical location, the appropriate processes, and relevant time and space scales, all of which change from application to application. A single integrated model has limited utility.

To address these issues, we propose the development of the Virtual Watershed Laboratory (VWL), an extensible, object-oriented, parallelised, plug-and-play modelling environment with dynamic coupling of physics-based process models operating on different temporal and spatial scales. The modelling environment will consist of a data model, physics-based process models, coupling algorithms and a user interface that will facilitate both model development and analysis of model input and output. The VWL will provide a platform for the development of new, integrated models to study watershed and basin dynamics, as well as a test bed for new physical process models.

By employing information technology – developing the user interface, analytical tools, and "coupling modules" that link one physical process to another – we can advance the state of the art of basin-scale modelling without prescribing any particular computer model. Users will be free, for instance, to select a specific groundwater code from the process library or to insert one of their own choices, so long as it meets well-defined input/output conventions and software engineering requirements. The VWL project will focus initially on interactive modelling of the water and energy balance below, at, and above the land surface. However, the VWL will be a modelling environment rather than a specific model and will be designed to allow the incorporation of process models describing, for example, chemical and nutrient balances, and plant physiological and biogeochemical processes.

The VWL is a platform that will allow and encourage the development of models to simulate and predict the complex interactions taking place in the Earth system, using the latest computer tools produced by the IT community, and making them available to the scientific community, decision makers and even the public.

Specifically, the VWL will:

- Advance software engineering of coupled processes operating in distributed memory, message-passing environments;

- Develop scalable and portable tools for analysing, managing and visualising large data sets;
- Develop a graphical user environment that hides parallel programming details from users;
- Extend existing tools that support parallel workspace management and object orientation to Earth science applications;
- Implement a basic library of parallel models for groundwater, surface water, and atmospheric fluxes of mass and energy. In particular, the VWL will address the issue of parallel solvers for unstructured grids;
- Define a new generation of physics-based coupling models for linking process models operating on different time and space scales.

4.14.2 Short Description of the Study

The VWL integrates process models – the atmosphere, land-surface hydrology, subsurface hydrology, the river network, and riparian plant communities – and represents feedbacks among them in a plug-and-play user environment. We envision that the VWL will be applied to systems as small as a local watershed in eastern Massachusetts, and as large as a major river basin, such as the Rio Grande basin, with an emphasis on the basin scale. Although it is not intended to be applied at the continental scale, it could be, albeit with some modifications.

4.14.3 Complexity of the Study

Our basic goal is to apply and advance the physical science and information technology needed to model coupled processes that operate at different space and time scales, and to provide the software tools that will allow this. Although hydrological science and applications will be the direct beneficiary, the approach and many of the software tools will be transferable to other geophysical and environmental sciences, especially Earth systems science.

The plug-and-play exchangeability of software components is a widely used technique in commercial software applications, but it has not found widespread application in Earth system science. Until now, researchers have focused largely on the development and improvement of process models that simulate the water and energy fluxes within individual system components (e.g. the atmosphere, the vadose zone, the river channel). Because of the multiplicity of data formats, computer languages and software design strategies (or lack thereof), integration of these components is currently no easy task. This not only hinders the development of fully integrated models but also limits the opportunities for the developers of process models to test their models in an integrated environment and distribute their findings to a wider audience.

Experimental sciences like hydrology build on hypothesis testing and interpretation, which is based on earlier, published hypotheses and results (e.g. Reynolds and Acock 1997). However, modellers prefer to build new models from the ground up, typically because existing models are not well designed for incremental improvement by others. A plug-and-play approach to model development facilitates model process comparisons by enabling detailed analysis of individual processes and their interactions. It provides a framework in which to conduct hypothesis testing and analysis and to make incremental model improvements.

Efforts at process model integration are currently underway in a number of areas. Polcher et al. (1998) have proposed a general interface to allow coupling of land-surface schemes and general circulation models. The backdrop for their proposal is formed by the Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS; Henderson-Sellers et al. 1996), which will ultimately compare different land-surface schemes coupled to the same atmospheric model, and the Atmospheric Model Intercomparison Project (AMIP; Gates 1992). Within hydrology, the only modelling environment that allows the exchange of model components to build watershed and problem-specific hydrologic models conveniently, is the U.S. Geological Survey's Modular Modeling System (MMS; Leavesley et al. 1996, 2002). MMS consists of three components: (1) The pre-processor aids in data analysis and preparation; (2) The model component consists of a process module library with modules written in C or Fortran, an interactive, graphical model-builder tool and an execution environment; (3) Finally, the post-process component provides tools to display and analyse results. Communication between the process modules is managed through a common database, accessible by all models. The USGS is porting part of the MMS into a parallel environment. The MMS is a paradigm for development of the VWL, although MMS includes a smaller set of processes and cannot handle massive data sets. VWL will be a much more powerful, flexible and evolved approach, both in terms of both information technology and Earth system science. To take advantage of the "lessons learned" by the developers of MMS, they are collaborators in the proposed project.

As an extensible, object-oriented, parallelised, plug-and-play modelling environment, the VWL will consist of the following components:

- Parallelised data management;
- Model building environment;
- Parallelised model execution environment;
- Parellelised data analysis and visualisation environment;
- A code library that will contain a hierarchy of object-oriented process models and coupling algorithms.

The VWL will be comprehensively documented. Documentation will consists of a set of web-accessible source codes, user guides and tutorials that describe and explain the VWL and its application programmer's interface.

4.14.4 Experiences

Initial experience with the VWL has been a coupling of the RAMS (Regional Atmospheric Model) (Pielke et al. 1992) with a hydrology model LADHS (Los Alamos Distributed Hydrology System) and applying this to Water Year 1993 on the upper Rio Grande Basin. This modelling approach was pursued to answer questions concerning the relative effects of climate variability versus land-use change within the upper Rio Grande. Coupling for this system is currently one-way, with meteorological variables passed from RAMS to LADHS every 20 minutes. The rapidly varying topography and shifting land use within the upper Rio Grande make it necessary to use fine grid spacing for both model components. A 5 km grid was used for RAMS and LADHS uses a 100 m grid cell size. Both codes were implemented on a parallel processor, and PAWS (Beckman et al. 1998) is used to facilitate the data transfer between components.

The one-year simulation is basically a proof of concept and also designed to answer computer science questions relative to coupling and machine performance. Fig. 4.14-1 presents soil moisture and snowpack from November 5, 1992 as an example of the data that can be produced. A key problem was the bias (over-prediction) in precipitation estimates from RAMS, especially for the higher elevation areas. Both are on a 100 m scale as the precipitation is downscaled to 100 metres from RAMS. Although this is not necessarily a problem with coupling, the precipitation bias does

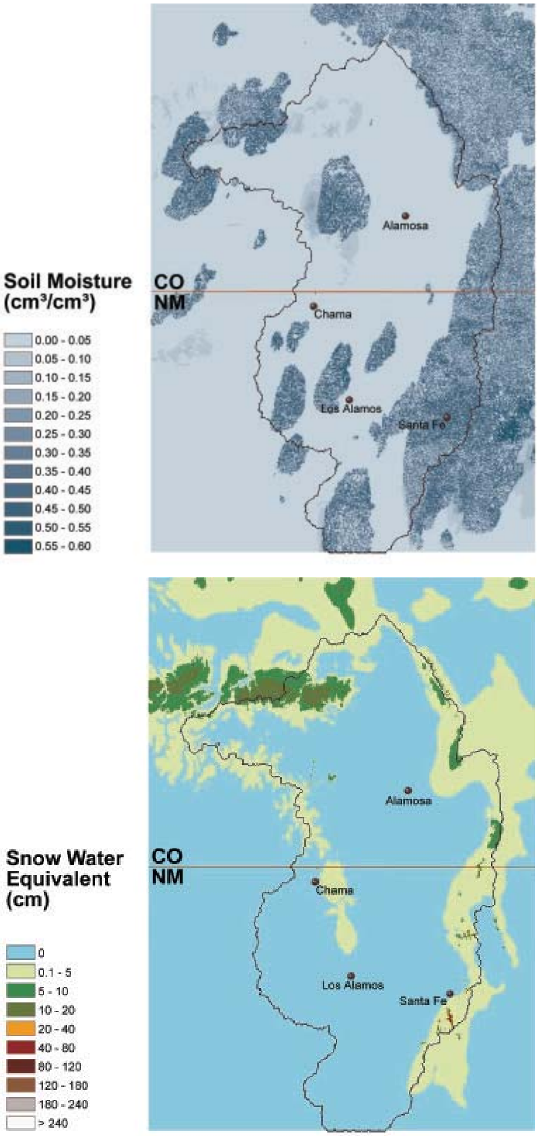

Fig. 4.14-1 Soil moisture and snow water equivalent distribution for upper Rio Grande Basin for November 5, 1992 at 00:00 UTC

represent an issue when using regional atmospheric models to address water resources scenarios for future change issues. Future modifications include developing the two-way coupling between LADHS and RAMS, which will require an energy balance to be added to LADHS. To develop the VWL further, the modular capability will need to be executed on parallel architecture using a MMS type approach. PAWS has demonstrated potential in this regard and further efforts will use the approach applied in this case study.

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