A module to couple an atmospheric and a hydrologic model - description and preliminary results

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Summary: A land-surface module to couple a meteorological and a hydrologic model is described. It was implemented and tested in the Leipzig's version of GESIMA. Preliminary results of a coupling with NASMO are presented, although this article mainly focuses on the description of the module and its effect on the atmospheric water cycle. One positive impact of the module is that it allows to produce subgrid-scale evapotranspiration in more details and to heterogenize precipitation. This strongly affects soil wetness, cloudiness and the thermal regime of the atmospheric boundary layer.

Zusammenfassung: Ein Bodenmodul zur Kopplung eines meteorologischen mit einem hydrologischen Modell wird vorgestellt. Er wurde implementiert und getestet in der Leipziger Version von GESIMA. Obgleich der Schwerpunkt des Artikels auf der Beschreibung des Moduls und seiner Auswirkung auf den atmosphärischen Wasserkreislauf liegt, werden auch vorläufige Ergebnisse einer Kopplung mit NASMO präsentiert. Ein positiver Effekt des Moduls ist, daß er ermöglicht, detaillierter die subskalige Evapotranspiration zu beschreiben und den Niederschlag zu heterogenisieren. Dies wirkt sich stark auf die Bodenfeuchte, die Bewölkung und das thermische Regime der atmosphärischen Grenzschicht aus.

1. Introduction

The water cycle is a major part of the global climate system. Although at any given time rivers hold only a fraction of the world's total water, they provide the critical link for returning water from continents to the ocean (Miller et al. 1994). For individual river catchments, runoff depends on precipitation and evapotranspiration within the basin and the ability of the land to store water (Liston et al. 1994). Water storage within the river basins among others depends on soil type, depth, surface heterogeneity and vegetation cycle (Miller et al. 1994).

Since meteorological models usually neglect the transport of water by rivers as well as the re- and discharge of the groundwater storage, they do not simulate a closed water cycle (Mölders et al. 1996a). As a consequence, meteorological model predictions yield that the flat regions of river valleys are often much drier than the nearby mountainous regions, which correctly receive more precipitation than the former. This misprediction of soil wetness results from the practice that in meteorological applications soil processes are treated in the vertical direction only (Müller et al. 1995). This procedure was motivated by simple scale analysis that provides for the time scale of several days lateral soil water movements of several cm only (Mölders and Raabe 1996a).

Wrong distribution of dry and wet surfaces may significantly affect the local water supply to the atmosphere (Milly and Dunne 1994) and, hence, may significantly affect cloud and precipitation formation (Mölders and Raabe 1996b) and the quality of numerical weather prediction (Müller et al. 1995). Moreover, for long-term applications like climate modeling the neglecting of lateral soil and ground water fluxes and the assumption of a fixed ground water level may give the climate system a tug in a certain direction which would not have established if the water cycle was simulated in a closed manner. Hence, the tendency of droughts or of large precipitation events to contribute to their own persistence might be underestimated (Mölders and Raabe 1996a).

To more appropriately model the water cycle, hydrologic and meteorological concepts have to be matched. In a first step, precipitation and evapotranspiration predicted by meteorological models may serve as input for the hydrologic model (Mölders and Raabe 1996a, Maniak 1996). Obviously, the spatial scales considered in hydrologic models require much finer model grid resolutions than those regarded in meteorological models. Unfortunately, a better representation of the surface characteristics may not be achieved by a finer grid resolution of meteorological models due to parameterization limitations, the limited availability of initial data and computer resources (Mölders and Raabe 1996b). Consequently, parameterizations to downscale hydrologically relevant quantities provided by meteorological models are required to utilize those data as input to a runoff model. This article suggests a module to overcome the gap between those models and presents some preliminary results. The main focus is on the impact of the module on the atmospheric water cycle.

2. Description of the coupling

The meteorological model used is the Leipzig's version of the non-hydrostatic model GESIMA (**GE**esthacht's **SI**mulation **M**odel of the **A**tmosphere). The model is described in detail by Kapitza and Eppel (1992) and Eppel et al. (1995). The Louis-parameterization scheme has been replaced by the parametric model of Kramm et al. (1995). A five bulk-water class (*water vapor, cloud water, rainwater, ice, graupel*) cloud module was included (Mölders et al. 1996b). The horizontal grid resolution of the meteorological model is N x N = 5 x 5 km^2. The vertical resolution varies from 20 m close to the ground to 1 km at the top of the model domain in 12 km height with 8 levels below 2 km and 11 levels above that height.

For some preliminary tests the hydrologic model NASMO (**N**iederschlags**A**bfluß-**S**imulations**MO**dell, i.e., precipitation runoff model; Maniak 1996) is used, which is a precipitation-runoff model applying the curve number method. It is assumed that the total rainfall volume is allocated to (1) initial abstraction which is the amount of storage that must be satisfied before event flow can start, (2) retention of water (after the end of the initial abstraction), which does not contribute to the event flow, and (3) event flow (Maniak 1996). The horizontal resolution of NASMO varies from 50 m to about 1 km side length of the triangles.

2.1 Downscaling of precipitation, evapotranspiration and soil wetness

To downscale the hydrologically relevant quantities provided by the meteorological model an explicit subgrid-scheme, first suggested by Seth et al. (1994), is applied. Herein, a higher resolution grid (1 x 1 km^2) consisting of several subgrid cells is defined for each grid cell (Fig. 1). These subgrid cells are considered to be homogeneously covered by their individual vegetation and soil types. For each subgrid cell unique energy and hydrological budgets (Eqs. 1 to 4) are maintained using the subgrid cell forcing at the representative location, i.e., the fluxes in each subgrid cell are calculated individually with their own subgrid soil temperatures, soil wetness and near-surface meteorological forcing in the immediate vicinity of the Earth's surface (Mölders et al. 1996a). The soil wetness, soil temperature as well as the near surface air temperature and moisture are stored for each subgrid cell and serve to determine these quantities in the next time step. The fluxes for the *m*th subgrid cell of the *j*th grid cell are, therefore, written as (Mölders et al. 1996a)

$$Q_{m,j} = -S_{m,j}(1 - \alpha_{m,j}) - \varepsilon_{m,j}L_{m,j} + \varepsilon_{m,j}\sigma T_{sm,j}^{4} \quad , \qquad (1)$$

$$L_vE_{m,j} = \rho L_v C_{qm,j} u_{Rj} \left(q_{sm,j}(T_{sm,j}) - q_{Rj}\right) w_{em,j} \quad , \qquad (2)$$

$$H_{m,j} = \rho c_p C_{hm,j} u_{Rj} \left(\Theta_{sm,j} - \Theta_{Rj}\right) \quad , \qquad (3)$$

$$G_{m,j} = \begin{cases} -\lambda_{m,j}\partial T_{sm,j} / \partial z & \text{, for land} \\ Q_{m,j} + L_v E_{m,j} + H_{m,j} & \text{, for sea, lakes and rivers} \end{cases} \quad (4)$$

where Θ and q represent the potential temperature and specific humidity at the surface (index s) and the reference height (index R) located at the first half level in 10 m height above ground. Furthermore, α, ε, λ, σ, S and L stand for the albedo, the emissivity of the surface, the soil thermal conductivity, the Stephan-Boltzmann constant, the shortwave and longwave radiation, respectively. T_s is the surface temperature, and u_R is the wind speed at the reference height. The density of air is denoted as ρ, c_p and L_v are the specific heat at constant pressure and the latent heat of condensation, C_h and C_q are the transfer coefficients for heat and water vapor. For bare soil the so-called wetness factor, w_e, equals the soil surface wetness while for vegetated surfaces it considers canopy conductivity, insolation, water vapor deficit, air temperature and soil wetness. The coupling to the *j*th atmospheric grid cell is realized by arithmetically averaging the individual subgrid-cell fluxes, $F_{m,j}^k$, to provide the grid cell fluxes

$$F_j^k = \frac{1}{N^2} \sum_{m=1}^{N^2} F_{m,j}^k \quad . \quad (5)$$

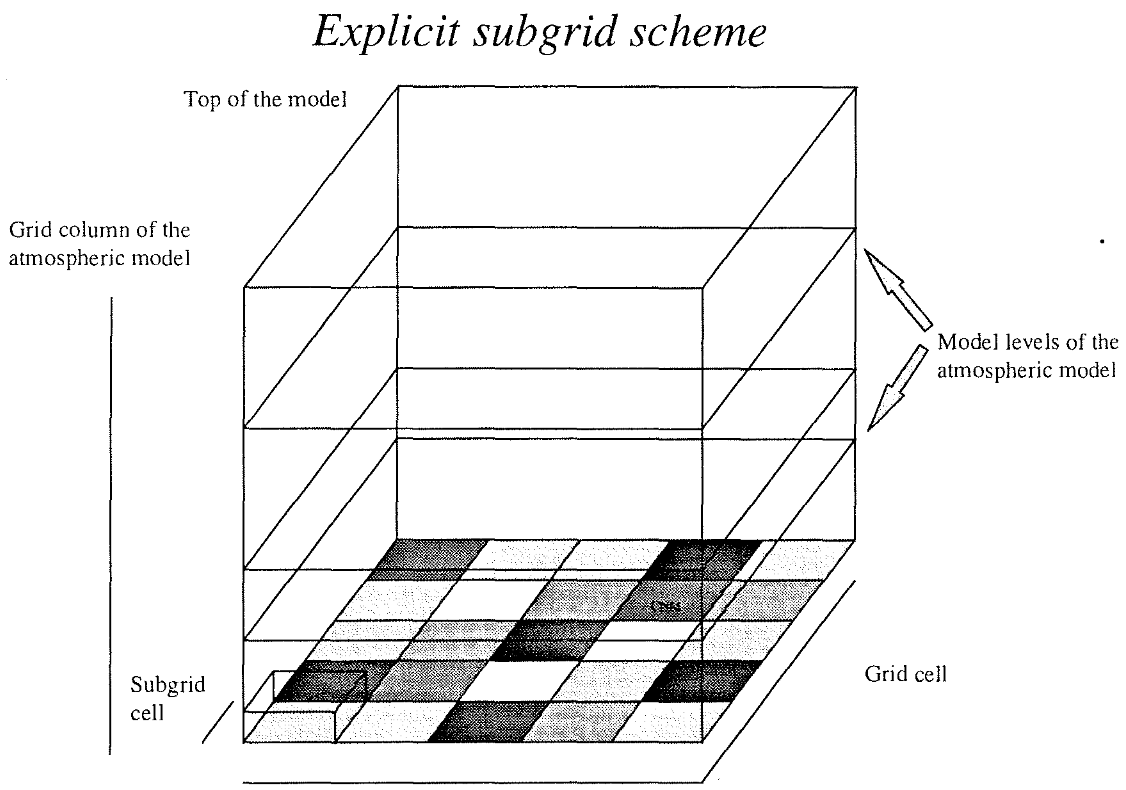

Fig. 1. Schematic view of a grid column and the subgrid cells within a grid cell of the meteorological model for N = 5 (modified after Mölders et al. 1996a).

Here, N^2 (= 25 in this study) is the number of subgrid cells occurring within that *j*th grid cell and the index k stands for the turbulent fluxes of latent, L_vE, and sensible heat, H, soil heat flux, G, and net radiation, Q. Assuming that precipitation is related to surface elevation (i.e., areas elevated higher than the mean terrain height receive more precipitation than those which are located lower than that height) heterogeneity of precipitation, $P_{m,j}$, can be written as (Mölders et al. 1996a)

$$P_{m,j} = (z_{m,j} / z_j)\, P_j \,. \qquad (6)$$

Here, z_j and $z_{m,j}$ are the mean terrain height of the *j*th grid cell and the *m*th subgrid cell and P_j is the mean precipitation predicted for the *j*th grid cell by the cloud parameterization scheme. This parameterization (Eq. 6) does not consider that there might be fractions of the grid cell which do not receive precipitation at all, i.e., it is not suitable for convective precipitation events. Obviously, the explicit subgrid strategy does not consider advective effects accompanied by occasionally observed internal boundary layers (IBL; Raabe 1983, 1991, Hupfer and Raabe 1994) and ignores subgrid-scale dynamical effects related to the surface heterogeneity, for instance, directed flows caused by topography or luv and lee effects.

A fundamental assumption of this strategy is that the subgrid-scale near-surface meteorological forcing, which is experienced by the surface, is important in determining the net exchange of heat, moisture and momentum at the interface Earth-atmosphere. However, no interaction between the different landuse types exists.

2.2 Upscaling of runoff

Since the hydrologic model NASMO uses triangular grid elements of irregular size, following the slopes of the Earth's surface, a projection from the subgrid cells of the meteorological model to the grid elements of NASMO - and in the case of a two-way-coupling vice versa - is required. This is achieved by aggregating the NASMO grid cells to 1 x 1 km^2 areas (Maniak 1996; Fig. 2). When a 1 x 1 km^2 area consists of more than one landuse/soil type, an area-weighted average curve number is computed (Maniak 1996). This aggregating procedure is only required for hydrologic models with irregular grids and can be avoided if gridded hydrologic models like MIKE SHE (e.g., Refsgaard 1993) are utilized. Note that the latter models are computationally burdensome as compared to hydrologic models like NASMO.

2.3 Two-way-coupling

In nature the coupling of the atmospheric and the land phase of the water cycle occurs through mass (precipitation and evapotranspiration) and energy exchanges. In the coupling of GESIMA and NASMO the influence of soil temperature on soil wetness is neglected and the coupling is realized by a flux correction basing on mass conservation only. Herein, a balance between the sources of water by precipitation, groundwater discharge and lateral inflow, the sinks by lateral outflow, groundwater recharge, and evapotranspiration are conceptionally balanced with the change in soil wetness (Eq. 7). Runoff is calculated by NASMO for each grid cell. Differences of lateral in- and ouflow serve as input for GESIMA to correct the soil wetness. Hence, the change in soil wetness is given by

$$\frac{\partial f}{\partial t} = -\frac{E - P}{w_k \rho_w} + \frac{\alpha_c}{\rho_w}(1 - f) + \beta \frac{RO}{w_k \rho_w} \quad , \quad \beta = \begin{cases} 1 & \text{catchment area} \\ 0 & \text{elsewhere} \end{cases} \quad , \qquad (7)$$

where f is the soil wetness factor, t is the time, RO is the difference between the lateral in- and outflow of the 1 x 1 km^2 subgrid cell, E and P stand for the evapotranspiration and precipitation within the subgrid cell, respectively. Further, ρ_w is the density of water, α_c is the capillarity and w_k represents the amount of water that a soil layer may uptake before saturation occurs. The first term on the right hand side of Eq. 7 represents the external forcing by evapotranspiration and precipitation and the second term the transport of water from the ground water to the surface. The parameter β serves to apply the original formulation of the soil module of GESIMA in those regions where NASMO and GESIMA do not overlap, i.e., the change of soil moisture due to lateral effects can only be performed in those areas common to both models. In the determination of the change in soil moisture due to lateral effects it is assumed that the lateral in- and outflow can be considered as constant for one hour duration.

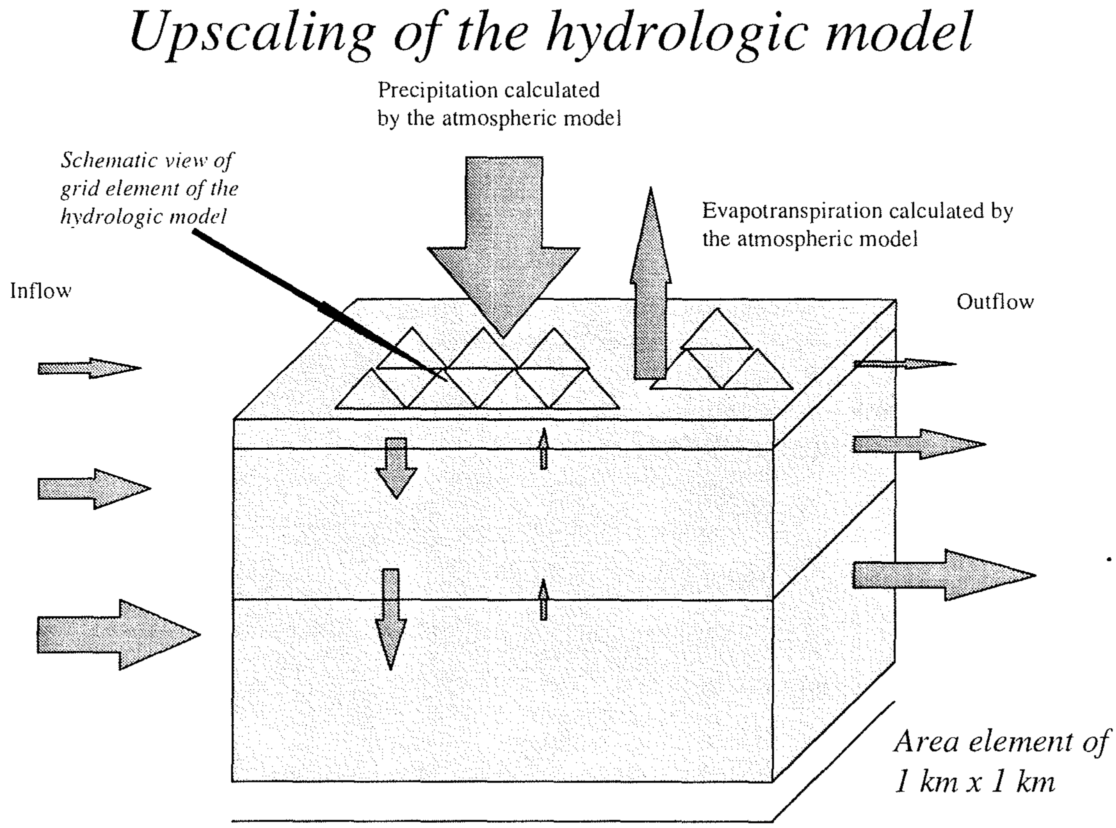

Fig. 2. Schematic view of the upscaling procedure applied in NASMO (modified after Maniak 1996).

3. Preliminary results

If land evapotranspiration partially feeds precipitating clouds, then the land hydrology may influence its own forcing. Several sensitivity studies were carried out to investigate this impact.

3.1. Effect of the explicit subgrid scheme on the prediction of the atmospheric water cycle

Figs. 3, 4 show the 24 h accumulated precipitation provided by simulations with and without consideration of subgrid-scale heterogeneity by the explicit subgrid scheme for the southern part of the Aller catchment which belongs to the Weser basin. The results substantiate that the precipitation pattern and intensity are obviously affected by the heterogeneity of the underlying surface. The simulated changes in cloud structures, precipitation pattern and intensity, evapotranspiration and soil wetness can be related to the subgrid-scale heterogeneity. Less precipitation was predicted in the simulations without the explicit subgrid scheme but the horizontal extension of the precipitation fields was larger. Note that this was found in a stronger form for the lower stretches of the river Elbe under low flow synoptic conditions in spring time (e.g., Mölders et al. 1996a).

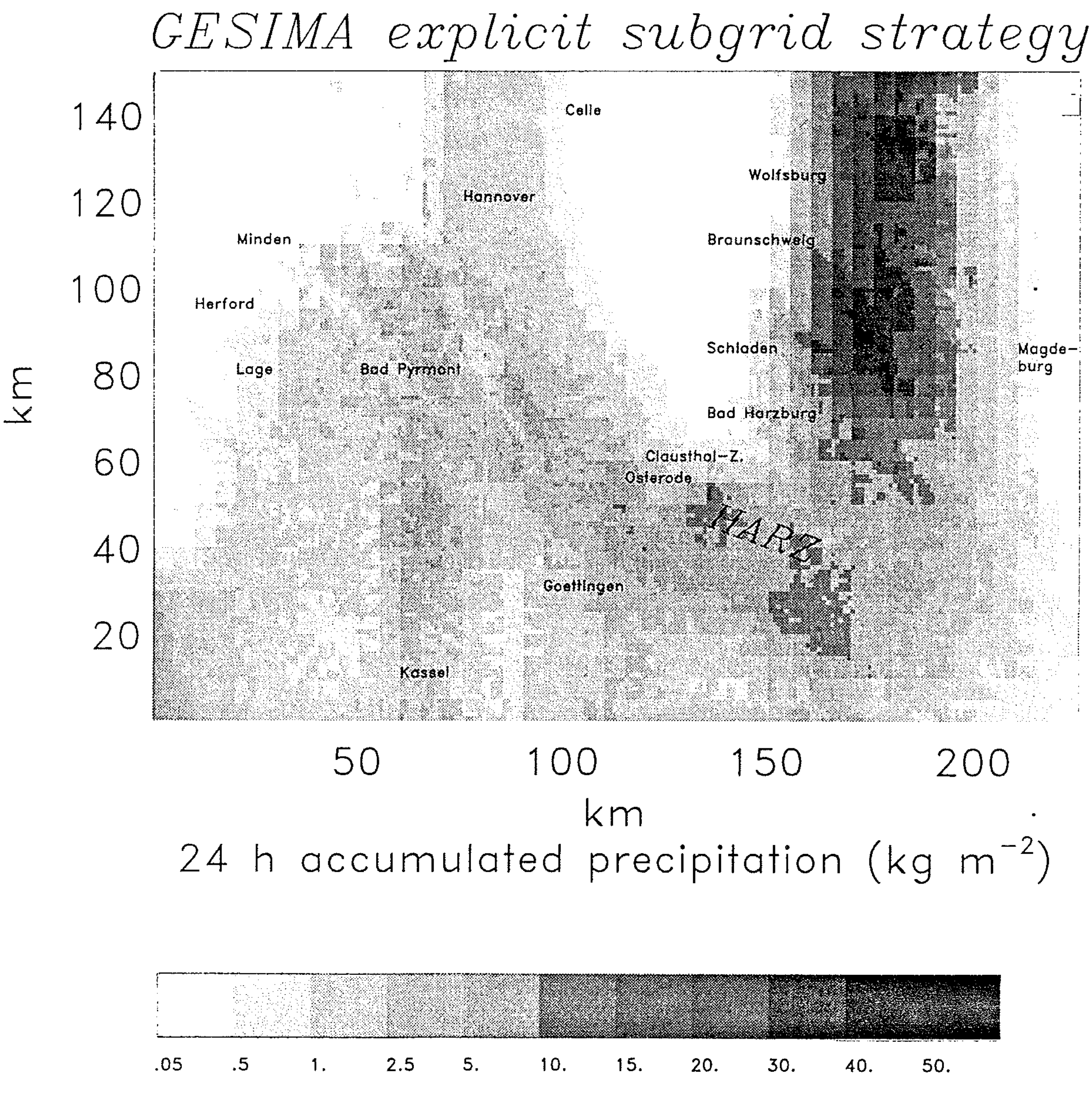

Fig. 3. 24 h accumulated rainfall (kg m^{-2}) of April 13, 1994 as predicted by the simulation of GESIMA including the explicit subgrid scheme.

Physical heterogeneity within a grid cell, i.e., that of the surface temperatures and soil wetness, which results from the subgrid-scale heterogeneity of the landscape, enhances the differences, especially, if precipitation occurs. Evidently, the local recycling of water to the atmosphere decreases with increasing subgrid-scale heterogeneity. Consequently, a more structured cloudiness and a more variable precipitation distribution establishes in the run with consideration of subgrid-scale heterogeneity as compared to that using the strategy of dominant landuse types (Note that strategy of dominant landuse types means that the landuse type prevailing in a grid cell area is assumed to be the representative one for that grid cell area and serves to determine the energy and water fluxes at the boundary Earth-atmosphere. The strategy of dominant landuse types is usually applied in meteorological modeling.). Hence, the patchiness of surface quantities (surface temperature, soil wetness) going along with the heterogeneity seems to enhance the persistence of the physical heterogeneity within the grid cells and the model domain. On the contrary, large areas covered by the same landuse type tend to continuously provide water to the atmosphere yielding to homogeneously stratiform cloud and precipitation and less physical heterogeneity. Note that these effects are stronger for low flow synoptic conditions than for situations for which the large scale forcing is great.

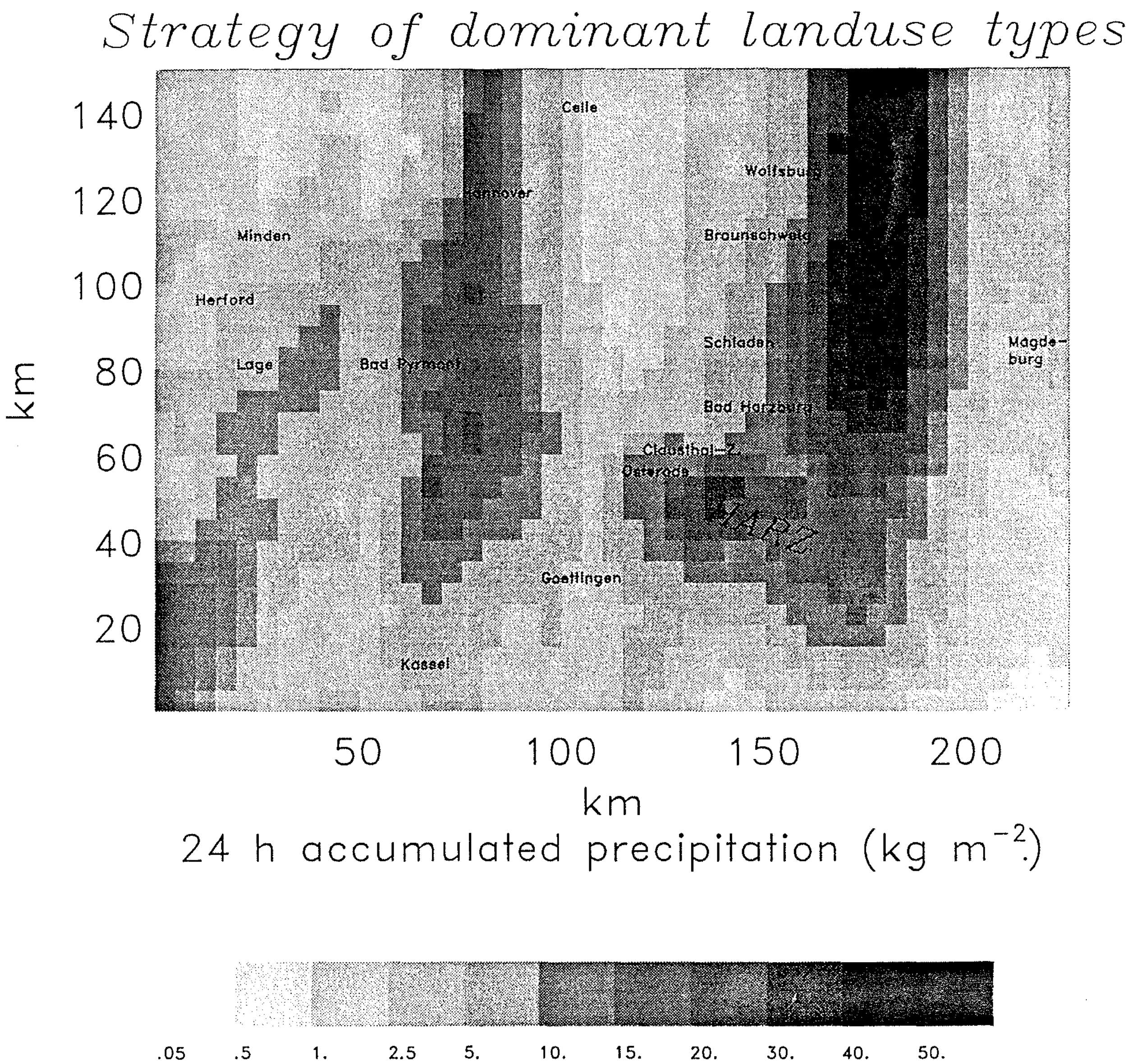

Fig. 4. As Fig. 3 but without the explicit subgrid scheme, i.e., the strategy of dominant landuse within a 5 x 5 km^2 grid cell is applied.

3.2. One-way coupling
Fig. 5 illustrates the runoff as determined by NASMO for a 1 x 1 km^2 grid structure (Maniak 1996) for the southern part of the Aller using the precipitation and evapotranspiration data generated by GESIMA applying the explicit subgrid scheme with a horizontal resolution of the subgrid cells of 1 x 1 km^2 and a horizontal resolution of the atmospheric grid cells of 5 x 5 km^2.

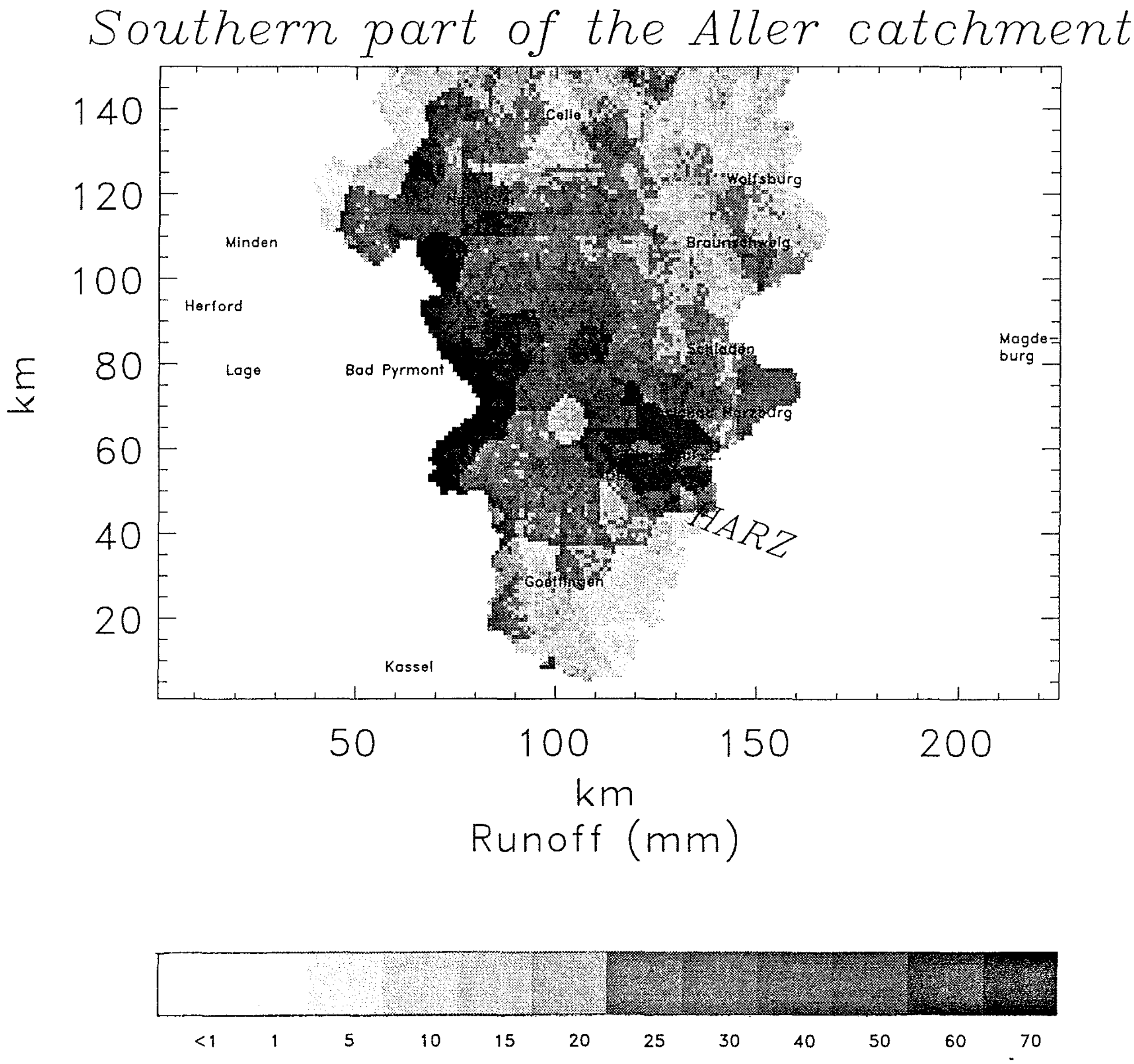

Fig. 5. Runoff as modeled by NASMO for April 13, 1994 using the data provided by GESIMA (one-way-coupling).

Two problems are obvious. Hydrologic models are committed at the areas of the drainage basins. At the moment no data could be obtained by NASMO for the other parts of the GESIMA domain. Moreover, the coarse model grid cell resolution (1 x 1 km^2) of the meteorological model is strongly reflected in the runoff data (Fig. 5). This means that especially for small basins offsets in the prediction of the meteorological fields (wind, temperature and moisture, precipitation) may locally yield to large differences in runoff. Consequently, for small basins on a small time scale the runoff calculated using predicted precipitation may be completely wrong, but the long-term runoff predicted at the mouth of the larger catchment including the smaller one may deviate less from the observations.

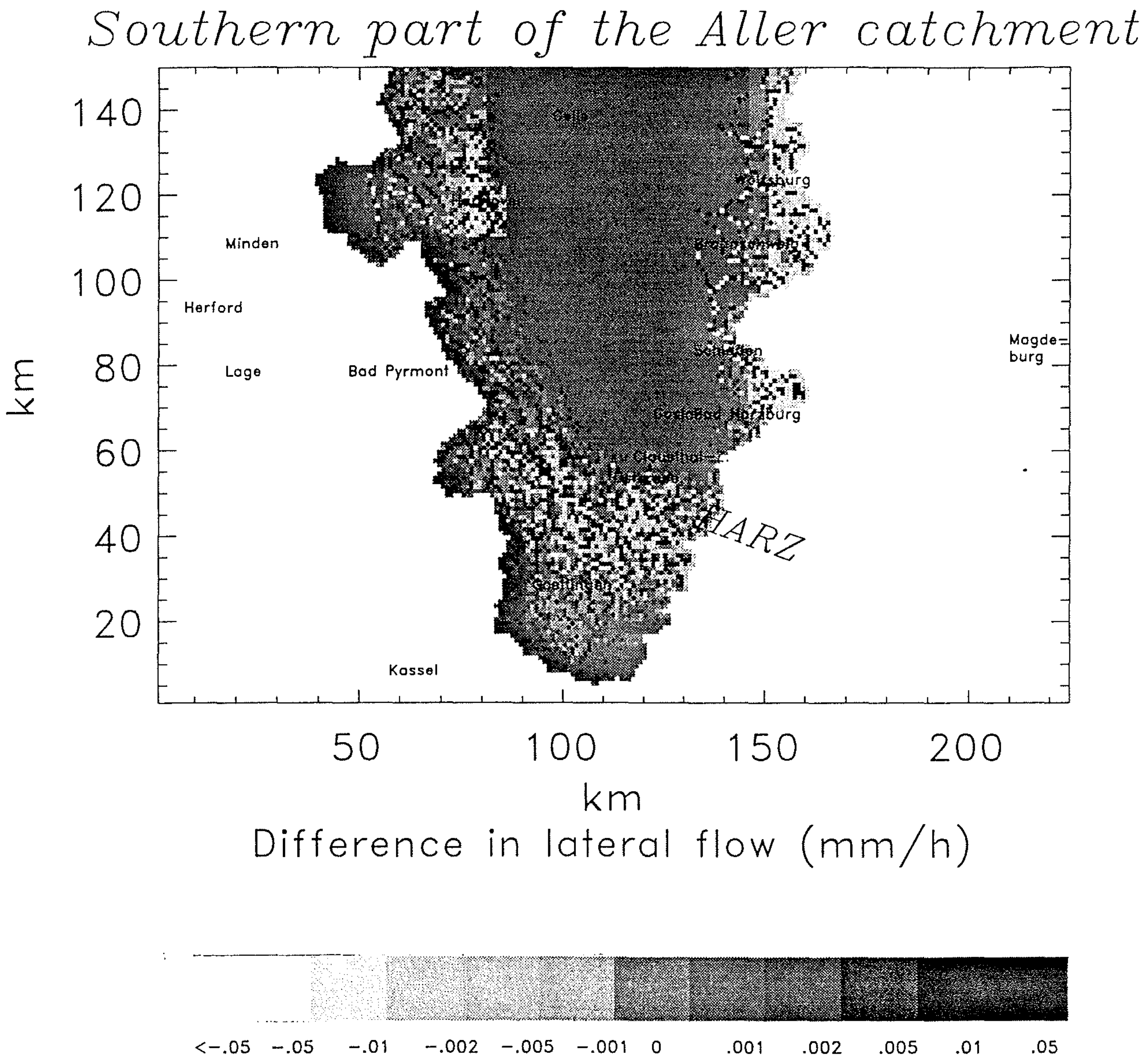

Fig. 6. Lateral in- and outflow as determined by NASMO for April 13, 1994 for the 11th hour.

3.3. Preliminary results of a two-way coupling

The difference of lateral in- and outflow as determined by NASMO (Fig. 6) serves as input for the third term of Eq. 7. Since in the hours before strong precipitation occurred only at the boundaries of the domain area of NASMO, the lateral flow only slightly affects soil moisture (Figs. 7, 8). Nevertheless, a slight drying effect in the (mountainous) areas of the precipitation and a slight shift towards a wetting in the valleys can be detected. The contribution of lateral in- and outflow to the change of soil wetness is only about some percent within an hour for the episode simulated here. Note that the change of soil moisture (Figs. 7, 8) also partly results from a change in precipiation and evapotranspiration caused by the different soil mositure.

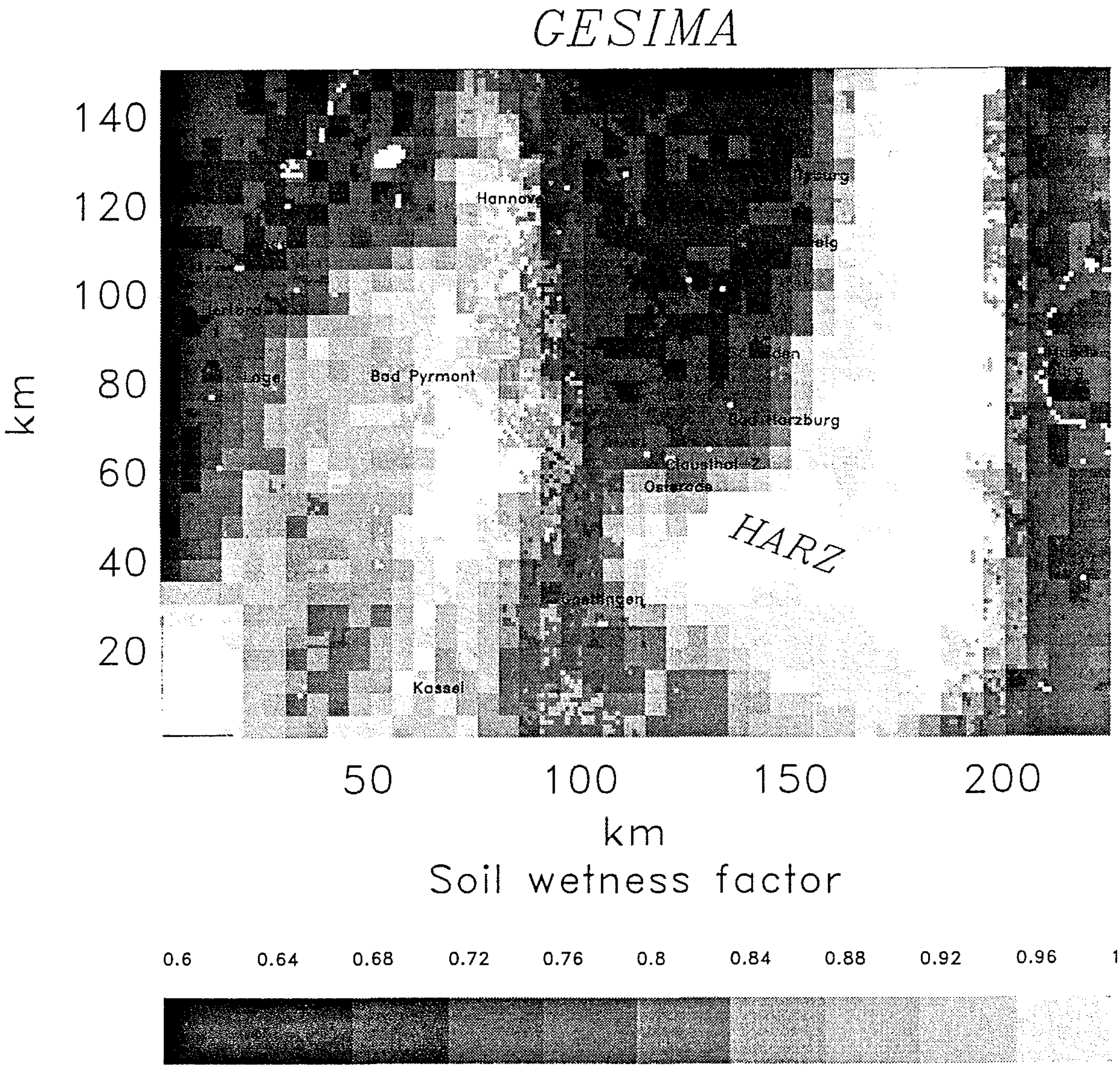

Fig. 7. Soil wetness as predicted by GESIMA for 1200 LT using the explicit subgrid scheme (without coupling of the hydrologic and meteorological models).

3.4 Evaluation

The predicted precipitation was evaluated by station data on a point by point basis, by determination of measures of skills and by comparison of the precipitation pattern. It has to be admitted that an evaluation of the precipitation prediction is complicated due to errors in measurements, low spatial and temporal resolution of the data as well as due to model technical reasons. Precipitation data of 508 stations are available in a daily frequency. A shift in the positions of the predicted and the observed precipitation pattern was found. Since the data have no temporal resolution it will be indistinguishable if this offset is due to the time required for cloud and precipitation formation, i.e., due to the initial conditions (The mixing ratios of the liquid and solid water substances are set equal to zero at the begin of the simulation.) or due to the boundary conditions. The locally appreciable differences may partly be attributed to site specific differences between the simulation and nature (e.g., differences in landuse type, elevation, roughness, directed flows), the initialization procedure (1D-simulation of GESIMA using the radiosonde data of Hannover), boundary conditions, and parameterization of cloud microphysics. Alternatively applying two different bulk-parameterizations of cloud microphysics Mölders et al. (1996b) found that predicted precipitation characteristics may be sensitive to the saturation adjustment scheme, the parameterization of the processes, and parameters applied.

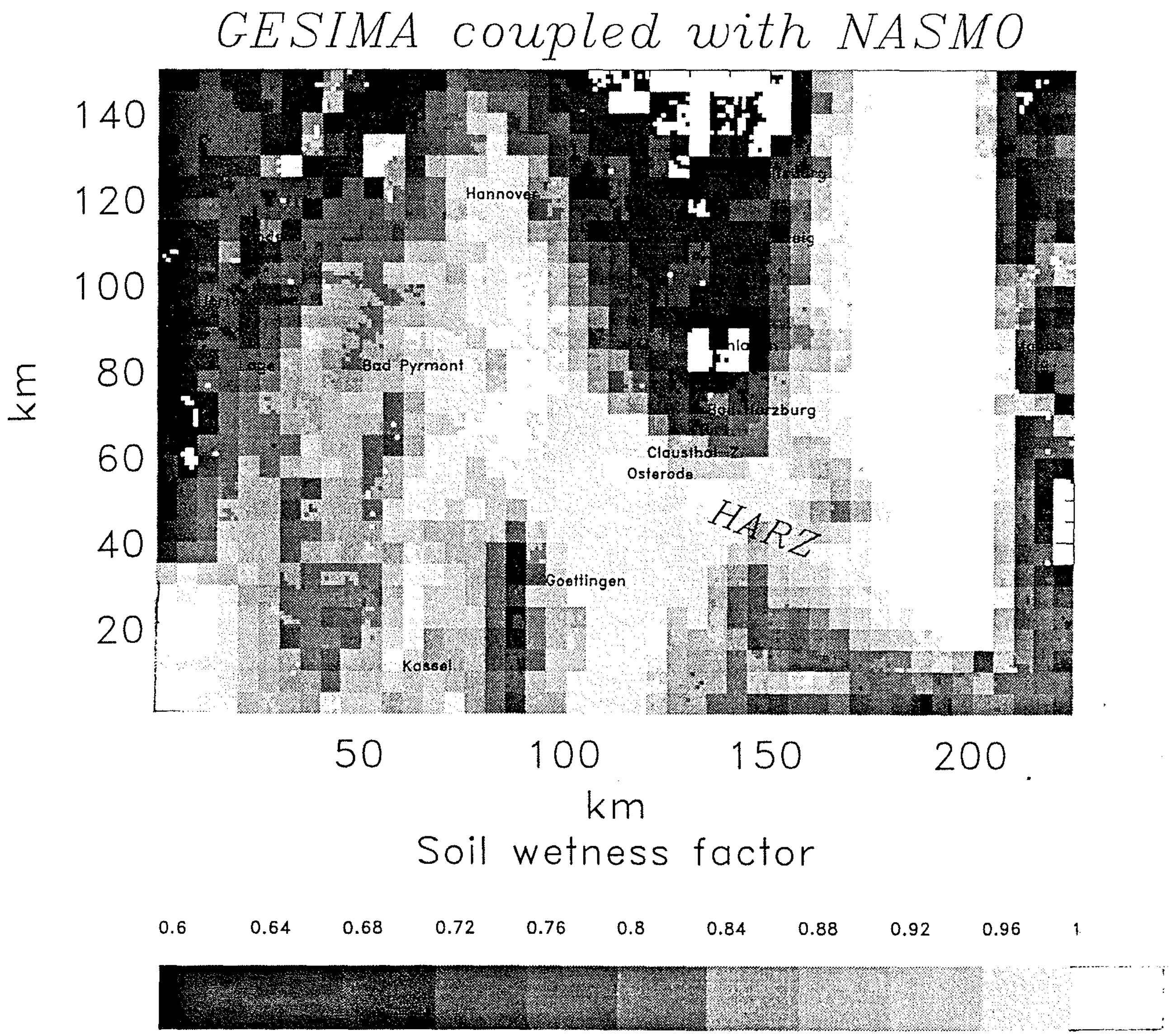

Fig. 8. As Fig. 7 but for the simulation using the explicit subgrid scheme with the two-way-coupling.

Moreover, the weather situation to be simulated is at the limit of that for which GESIMA was designed. Therefore, no good forecast can be expected. In Mid-Europe during the time of the Harz flooding the meteorological situation was governed by intensifying low pressure activity at the edge of an anticyclone located over the Atlantic. The under-estimation of precipitation relates to the under-prediction of the temperature and of the rising of the air masses.

4. Summary

A module to couple a meteorological and a runoff model was presented. By explicitly breaking down the grid cells of the atmospheric model the spatial location of each subgrid flux is known (Fig. 1) and evapotranspiration, precipitation and soil wetness can be provided for gridded hydrologic models in a much finer resolution (e.g., Figs. 3, 7, 8) than that of the atmospheric model (e.g., Fig. 4). In addition, the module includes the ability to account for subgrid-scale surface heterogeneity in meteorological models that affects the water (and energy) fluxes and, hence, the supply of water to the atmosphere. Implementation of the module in meteorological models requires landuse, soil and topographical data in the resolution of the desired subgrid.

5. Outlook

There are still a lot of inconsistencies between NASMO and GESIMA which have to be removed. For instance, it has to be realized that the two models use the same landuse/soil types. This can be achieved by applying a mosaic approach for the subgrid cells in the meteorological model. Such a mosaic approach has already been developed and tested (Mölders and Raabe 1996b) as well as compared to the explicit subgrid scheme (Mölders et al. 1996a).

At this point, it can not be expected that the calculations of the hydrologic model will be improved when being driven by precipitation and evapotranspiration data of a meteorological model. Nevertheless, it has been shown that there is an impact of the surface hydrology on cloud and precipitation formation. Therefore, further affords are required on a better parameterization of the land phase of the hydrologic cycle in meteorological as well as in climate modeling.

At the moment the procedure to run GESIMA and NASMO in a two-way-coupling mode requires still a lot of man-power because up to now the models run at Leipzig and Braunschweig, respectively, and the data still have to be updated hourly via ftp and transformed to the respective model grids. Here, still a lot of work is to be done to automatically run the model package GESIMA-NASMO. At the moment 2 days of work are required to realize one hour of two-way-coupling.

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