3.3 Feedbacks at the Hydrometeorological Interface

Nicole Mölders

Hydrologists and atmospheric scientists have a common interest in specific parts of the water cycle, namely the "land-surface/atmosphere interface"; this is the upper boundary for hydrological models and the lower boundary in meteorological models. Precipitation, for instance, is a source of water for hydrological models, yet is a sink for meteorological models. In the case of evapotranspiration[1], the opposite is true.

Due to the different aspects of the water cycle that are of major or minor interest to hydrologists or atmospheric scientists, only those processes are considered in detail that are relevant for the specific application while other aspects are neglected or crudely simplified. Such simplifications, however, can cause inconsistencies in the description of the water cycle, even in the case of uncoupled modelling. In hydrological modelling, for instance, neglecting the feedback of increased soil moisture on evapotranspiration, cloud- and precipitation-formation can lead to failures in predictions of flood intensity, because runoff from an individual river catchment may depend partly on precipitation and evapotranspiration originated in the basin (e.g. Liston et al. 1994). Water storage within the river basins, among others, depends on soil type, soil depth, surface heterogeneity and vegetation phenology (Miller et al. 1994). Vegetation phenology itself depends on microclimatological conditions and again affects them. Such interaction between vegetation phenology and the atmosphere is usually not included in the simulations despite models exist that describe plant growth and could provide the phenological parameters required. However, first attempts of linking the reaction of vegetation dynamics to climate changes are encouraging (e.g. Claussen 1997).

In General Circulation Models (GCM), river runoff provides the crucial link for returning water from continents to the ocean (Miller et al. 1994). River runoff is an important input for ocean models because freshwater flow affects the thermohaline circulation of the ocean. Thus, neglecting processes that are usually attributed to another scientific discipline may lead to false predictions in that part of the water cycle that one is interested in.

This example shows that in some cases, but definitely not all, Earth system modelling, climate modelling, water resource research, climate impact studies etc. require the coupling of hydrological and atmospheric

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[1] Evapotranspiration stands for the sum of transpiration and evaporation. It should be determined concurrently.

models. The aim of coupling these models is to more appropriately consider the interaction of the atmospheric and land-surface component of the water cycle. This section evaluates recent concepts on such a coupling, points out the difficulties to be solved, and addresses the advantages and disadvantages. Finally, a concept of a hydrometeorological module to specifically represent the interface of hydrological and atmospheric models is introduced.

3.3.1 Introduction

Types of models

In coupling hydrological and atmospheric models, regional climate, mesoscale[2] meteorological or NWP (Numerical Weather Prediction) models should be applied as atmospheric models. The atmospheric model may be nested into a global model to allow large-scale integration. To derive a consistent parameterisation, the hydrological model should be based on the fundamental laws of hydro- and thermodynamics, which in hydrology has been labeled as "physically based hydrological model". Concerning the spatial discretisation, the so-called "distributed hydrological" models are of special interest for the coupling with atmospheric models, in order to account for the spatial heterogeneity of hydrology and atmospheric processes.

Different Relevance of Processes

Despite the common interest of atmospheric scientists and hydrologists in land-surface modelling, both by tradition and purpose, the land-surface parameterisations applied in hydrological and atmospheric models differ strongly (e.g. Mölders and Raabe 1997; Graham and Bergström 2000). Hydrological models require a precise partitioning of precipitation into evapotranspiration, infiltration, interception, retention and runoff to determine the water fluxes within the soil and groundwater recharge, i.e. the water budget is of main interest. Atmospheric models need a precise partitioning of precipitation between the aforementioned processes to determine the partitioning of incoming radiation between soil heat flux and the turbulent fluxes of sensible and latent heat, i.e. they additionally need the energy budget.

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[2] The term mesoscale is used in the meteorological sense and addresses meteorological phenomena of 2 to 2000 km extension with time scales from several minutes to severals days (see also Sect. 1.2).

Coupling requires that the process description is compatible to both models. Thus, prior to coupling of hydrological and atmospheric models (1) it has to be defined which processes are of relevance for the hydrological or atmospheric model under consideration, and (2) the parameterisations have to be chosen that allow representation of the relevant processes in the coupled system. This means that simplifications, which are suitable for one of the models but not for the other, have to be replaced by the respective more complex description. For example, in atmospheric models, the water budget is often parameterised by using a bucket model (e.g. Manabe 1969) or a force restore method (e.g. Deardorff 1978). These parameterisations, however, are rarely suitable for the demands of hydrological models.

Spatial and Temporal Scales

Other differences between hydrological and atmospheric models are related to the typical scales of processes to be simulated (see Figs. 1.2-3 to 1.2-6). Therefore, the temporal and spatial resolutions of these models differ strongly. Atmospheric models usually apply grid cells of several square kilometres as their horizontal unit of area. Depending on the projection of the grid, they may be of rectangular, square or triangle type. Despite increasing computational power, decreasing the size of these grid cells is limited by the range of validity of the assumptions made in the parameterisations (e.g. the fetch-conditions from which the parameterisations of the surface fluxes are derived require a relationship of 1:100 for the ratio of the vertical to horizontal grid resolution), and the limited availability of initial data. Hydrological models have to represent adequately the river basin variability and its sub-basins which consequently define the model dimensions. Especially in complex terrain, the grid resolution may be very fine. Decreasing the horizontal resolution of hydrological models to match the resolution of atmospheric models makes it difficult to know how to represent the (then subgrid-scale) heterogeneity of land-surface properties, such as topography, geology and vegetation cover. These characteristics, however, play an important role in determining the water storage and runoff.

The solution of the energy balance demands time steps of several minutes in atmospheric models, while a lot of hydrological models are often satisfied with daily time steps (e.g. Graham and Bergström 2000). NWP models usually neglect lateral flows of soil water and groundwater, because these processes are slow as compared to the typical simulation period (1-3 days) of these models. Furthermore, they do not account for river flow dynamics as this does not match their spatial discretisation concept.

One main task in coupling hydrological and atmospheric models is to overcome these temporal and spatial gaps. Procedures for aggregation (upscaling) and disaggregation (downscaling) serve to bridge these spatial gaps (see e.g. Mölders and Raabe 1997). These procedures have been discussed in more detail in Sect. 1.2. For further information see Mölders et al. (1997) or Giorgi and Avissar (1997).

3.3.2 Different Levels of Coupling

The task to be addressed by the coupled model system determines the degree of coupling and its realisation. We may distinguish between parameterisations, one-way coupling, two-way coupling, and integrated (sometimes denoted as integrative) modelling. If the identity of the models vanishes (i.e. there are no two models that can easily run alone) or when the coupling time shrinks to zero (because the response times in the coupled parts become equal) one speaks of integrated models. In integrated models all processes are calculated simultaneously and as such, variables of state and fluxes are updated at the same place. In the following, the advantages and disadvantages of the three ways of coupling are discussed and examples are presented. It is shown that these different types of coupling are all justifiable depending on the intent of the application, as the task to be addressed determines the degree of coupling required. This means that integrated modelling is not necessarily the better choice than one-way coupling, and one-way coupling is not necessarily less advanced or smart than two-way coupling or integrated modelling.

Simple Parameterisations of Large-scale Runoff

Being aware of the difficulties in coupling hydrological and atmospheric models caused by the different spatial and temporal scales, several authors suggested a simple scheme in which all runoff within a river basin reaches the river mouth instantaneously: Miller et al. (1994) introduced a river model that allows the excess land-surface water (over saturated soils) calculated by a GCM to run off into a river if a river is available within a grid cell. The direction and speed of flow is either constant or depends on topographical gradient. Sausen et al. (1994) proposed a one-parameter model that represented each grid cell by a linear reservoir with different retention coefficients for the flows in the east, west, north and south direction. These coefficients depend on orography and grid size. This approach allows for discharge in the horizontal direction (2D-plane) in all directly adjacent grid cells, for which the approach is addressed to as being two-dimensional. As this approach does not distinguish the different types of flow processes, Hagemann and Dümenil (1998) introduced a parameterisation that realised the cascade of overland and river flow by equal linear reservoirs, and considered base flow by a one parameter model. The corresponding retention coefficients depend on topographical gradient between two neighbouring grid cells and on the grid cell size.

This type of approach gives only a very rough estimate of the river runoff component of the hydrological cycle and is much too uncertain to be used for hydrological purposes. Additional difficulties arise due to the coarse resolution of GCMs resulting in the disappearance of some large lakes in the land-surface scheme of the atmospheric model. If the river retention process in a lake (or large wetland system) is not represented by the GCM, the calculated runoff into the oceans may be overestimated significantly. Another difficulty is that the coarseness of the GCM grid cells also may introduce errors in the river network, consequently leading again to errors in the fresh-water supply to the oceans.

Despite the temporal and spatial gaps between the resolutions of hydrological and atmospheric models, several different methods have been developed and tested recently to couple these models directly, as introduced in the following paragraphs.

One-way Coupling

One-way coupling is the simplest way to couple hydrological and atmospheric models. This way of coupling was intended to drive hydrological models by the output of atmospheric models for flood prediction or water management. The models are coupled in a cascading manner, first running the atmospheric model and then running the hydrological model. Usually, the time-steps of the precipitation (computed by the atmospheric model) prescribes the time steps to be applied for the hydrological model.

Due to the cascading nature of one-way coupling, no feedback effects of the hydrological model can influence the simulation of the atmospheric model. Obviously, if simulating the hydrological cycle of large areas, applying a one-way coupling may lead to wrong estimations of the water fluxes from the land surface to the atmosphere which may be propagated in wrong cloud and precipitation distributions (e.g. Mölders 1999). However, this aspect plays a minor role in short-term predictions (several hours).

There are several short-comings of one-way coupling. Different parameterisations might be used in the coupled models. The soil-physical and plant physiological parameters or even topography, soil- and vegetation-

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type may differ (see Mölders and Raabe 1997) resulting in different soil wetness and infiltration within the one-way coupled model system, i.e. the soil and vegetation processes look different in the respective model. Such inconsistencies may lead to model artifacts that can yield wrong results or conclusions. To avoid discrepancies in the surface characteristics of the coupled modelling system, the parameterisations of the soil and vegetation processes should be similar or, even better, the same. The latter means a complete re-coding of parts in at least one of the coupled models.

If atmospheric and hydrological models are coupled to improve forecasting for flash floods (= flood caused by short, local and high intensive rain storms), a one-way coupling may be disadvantageous, because the errors in the predicted precipitation pattern and intensity will propagate in the hydrological model (e.g. Mölders et al. 1999). A false prediction of the position of the precipitation field of only one atmospheric grid cell may already lead to significant simulation errors in the magnitude and location of the river flood.

Two-way Coupling

As pointed out above, neglecting feedback processes of one part of the water cycle may cause errors in predicting the other part of the water cycle. On the typical time scales of NWP models, for instance, lateral soil moisture fluxes are negligible. Since no three-dimensional distributions of soil moisture exist, soil moisture in NWPs is initialised by the soil moisture distribution of the prediction of the previous day. Doing so, however, makes the assumption of negligible lateral soil water fluxes invalid. Thus, this kind of initialisation in combination with neglecting the lateral soil water movements and surface runoff may yield an underestimation of soil moisture in river valleys and an overestimation of soil moisture in the nearby mountainous regions, which usually receive more precipitation (e.g. Müller et al. 1995). Consequently, the local recycling of previous precipitation may be predicted incorrectly which may lead to wrong forecasts of convective clouds, showers and thunderstorms (for details see Mölders et al. 1999).

In NWP models and GCMs, for instance, a constant groundwater level may cause errors in the simulated water fluxes to the atmosphere (Fig. 3.3-1, left picture), because a fixed groundwater level neglects the water table increase during precipitation periods and the decrease during drought periods. On large-scales, during droughts, the lowered groundwater table may amplify the drought because evapotranspiration is reduced (Fig. 3.3-1, middle picture) and thus reducing soil moisture available for clouds and rainfall. On the contrary, long-lasting rainfall may trigger its persistence

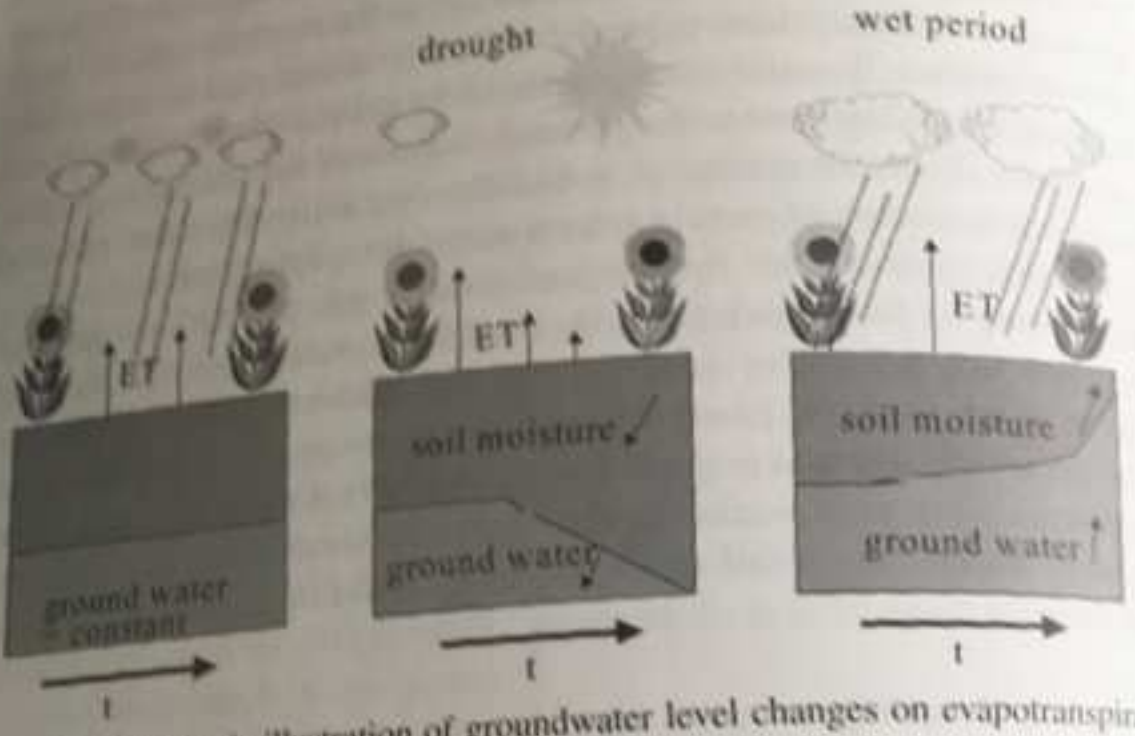

Fig. 3.3-1 Schematic illustration of groundwater level changes on evapotranspiration modelling, ET, with time, *t*

by recycling previous precipitation through enhanced evapotranspiration possible because of the high water table (Fig. 3.3-1, right picture). On local scales, the soil moisture decreases during drought, but may have little effect on the groundwater table in most cases. The groundwater is usually renewed by transverse movements in aquifers. Replenishing of the groundwater (e.g. from rivers) is not necessarily related to rain in the same area. In the case of wet periods, evaporation may be marginal or even zero on the local scale because of the increase in atmospheric humidity. Local groundwater rise may be caused by transverse movements in aquifers by rivers being connected with such aquifers. In general, on the local scale, floods can cause a temporary rise in groundwater tables downstream of areas that received huge amounts of precipitation.

Of course it is not necessary to include all processes that are, in principle, coupled. For example, in Mediterranean or maritime areas, precipitation mainly results from advection of cloud systems that formed over the oceans. The more continental an area is located, the smaller the total amount of precipitation. The fraction of the total precipitation that results from local recycling of precipitation increases with increasing distance from the oceans on the upwind side. In continental areas, soil moisture and the depth of the groundwater table play a dominant role in precipitation.

To include such prominent feedback processes, the idea of a two-way coupling was developed. The coupling is achieved through the exchange of simulated fluxes (e.g. evapotranspiration, precipitation, soil moisture fluxes, lateral soil water fluxes, groundwater recharge/discharge, etc.). The design of the models to be coupled determines the degree to which a coupling is possible.

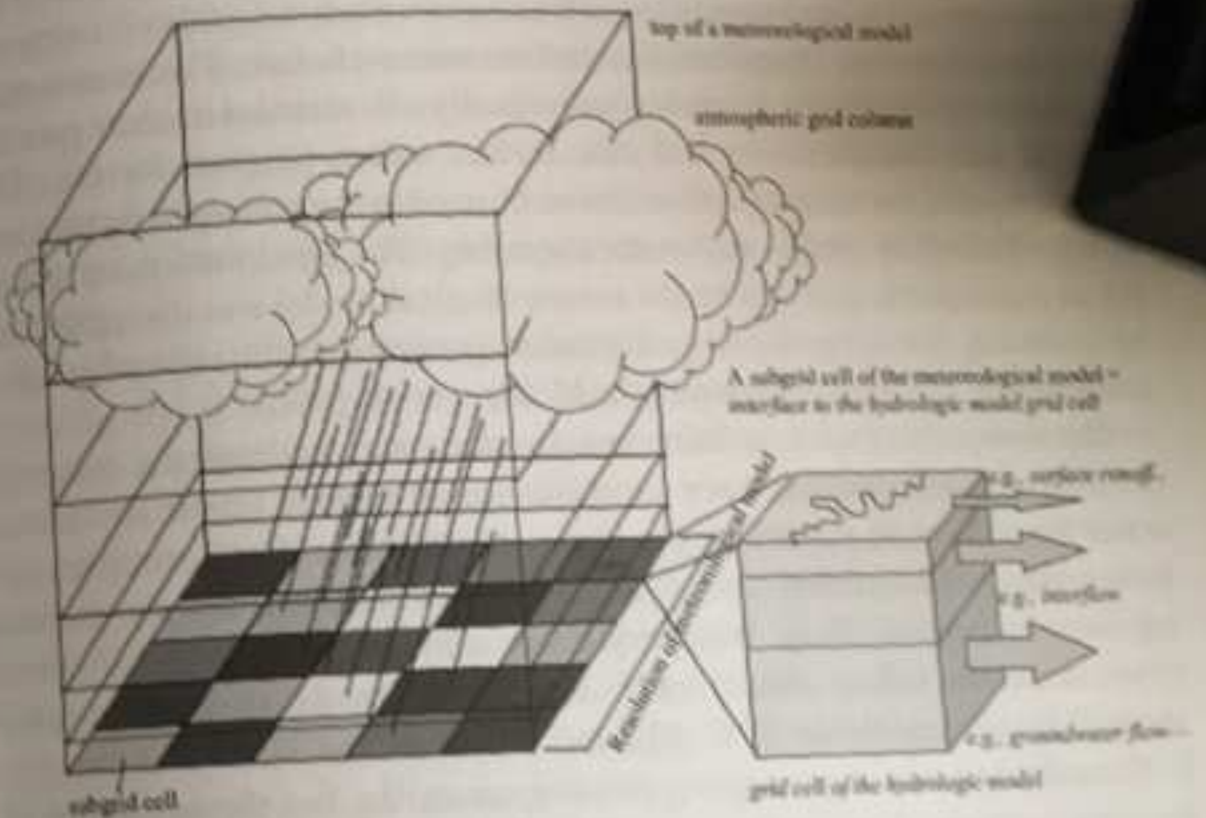

Fig. 3.3-2 Schematic view of the downscaling applied in the atmospheric model. The different grey levels represent different types of land use (after Mölders et al. 1999)

Mölders et al. (1999) coupled a conceptual hydrological model (NASMO, precipitation runoff model, Maniak 1996) and an atmospheric model (GESIMA, Geesthacht's simulation model of the atmosphere, Eppel et al. 1995) in a two-way mode. In doing so, the hydrological processes of the river catchment (translation, retention, and surface and subsurface lateral fluxes) are introduced into the atmospheric model. The atmospheric model drives the hydrological model by providing evapotranspiration and precipitation rates. The results provided by the hydrological model are used to modify soil moisture in the atmospheric model. The different spatial scales of the models were bridged by aggregation of lateral flow and runoff determined by the hydrological model and disaggregation of evapotranspiration, precipitation as well as soil wetness simulated by the atmospheric model. The module designed to couple the models was based on the explicit subgrid scheme (see discussion of disaggregation in Sect. 1.2), adapted for the mesoscale to downscale the hydrologically relevant quantities (e.g. Mölders et al. 1996). At the land-atmosphere interface, a high resolution grid is defined, i.e. several subgrid cells within one cell of the atmospheric model, to enable the exchange of the simulated fluxes of the two models (see Fig. 3.3-2). These subgrid cells may be covered by at least one vegetation- and/or soil-type. The energy and water budgets are calculated for each subgrid cell using the subgrid cell surface characteristics and the micro-climate. This means that, in each subgrid cell, the fluxes are individually calculated with their specific subgrid soil characteristics and near-surface meteorological forcing. The aggregation of the subgrid-cell results to be used in the atmospheric grid cell was performed by simple arithmetic averaging. The precipitation simulated for an atmospheric grid cell by the meteorological model was disaggregated by assuming that subgrid-cell precipitation is related to the ratio of subgrid cell and grid cell mean elevation (see Mölders et al. 1996).

The comparison of simulation results with and without the two-way coupling showed that even on a short time-scale surface runoff and lateral water flows have an impact on the spatial distribution of soil wetness, soil temperature, and therefore a feedback effect on cloudiness and the thermal regime of the atmospheric boundary layer within the catchment. A trend towards moister valleys and drier hills is predicted by the two-way coupled mode (Mölders and Raabe 1997, Mölders et al. 1999).

Compared to one-way coupling two-way coupling has the advantage of the consideration of the feedback between the land and atmospheric part of the water cycle. As for the one-way coupling, shortcomings of the two-way coupling are that (1) the parameterisations and surface characteristics can be inconsistent, and that (2) false predictions may propagate.

A technical disadvantage of the two-way coupling is that the data exchange requires that both models have to be run simultaneously and the data exchange requires a lot of storage capacity. In many cases, hydrological and atmospheric models apply different simulation time steps, so the exchange of simulation results has to be carefully adapted to the corresponding time step, i.e. an adequate time sequence for the data exchange has to be defined. If the time step for data exchange is large, information may be lost due to the aggregation procedure performed.

An Integrated Hydrometeorological Module

To avoid the before-mentioned shortcomings of a two-way coupling by exchanging simulation results of two rather independent hydrological and atmospheric models, the development of a two-way coupling by a fully integrated model (one single code) is presented. Such a realisation saves computer time and manpower, but needs interdisciplinary cooperation. It guarantees that the hydrological, soil and the atmospheric processes are represented in a consistent manner.

Recently, some developments in the direction of a fully integrated hydrometeorological module were carried out, for example – starting from the hydrological modelling perspective – by Famiglietti and Wood (1991), Band et al. (1993), Stieglitz et al. (1997). On the other hand, atmospheric scientists have included the most relevant hydrological processes into their existing surface modules of atmospheric models, such as OSULSM (Oregon State University land-surface model, Chen et al. 1996), HTSVS (hydro-thermodynamic soil vegetation scheme, Kramm et al. 1994, 1996; Mölders and Rühaak 2002), SEWAB (Mengelkamp et al. 1999), RAMS (Walko et al. 2000).

In general, if coupling hydrological and atmospheric models, the hydrologists should provide the modelling expertise for groundwater dynamics, lateral soil water fluxes and surface runoff. The atmospheric modellers should determine the fields of wind, pressure, air temperature, humidity, radiation, cloudiness and precipitation. The soil-vegetation module should be a common part (hydrometeorological module) that serves as the upper boundary condition for the hydrological and the lower boundary condition of the atmospheric processes. This soil-vegetation module has to fulfill the requests of both scientific disciplines to the highest degree of accuracy. In the next section, the special needs of atmospheric and hydrological models to simulate the boundary conditions are discussed to elucidate which physical processes have to be considered in the hydrometeorological module to which accuracy (for more details see Mölders 2001).

3.3.3 Specific Requirements for Modelling Water and Energy Fluxes at the Hydrometeorological Interface

Representation of Small-scale Variations in Surface Characteristics and Conditions

The heterogeneity of surface characteristics is of great importance in both hydrological and atmospheric modelling. Friedrich et al. (2000) examined the influence of surface heterogeneity on spatial distribution, temporal development and the domain-average of the ratio between sensible and latent heat flux (Bowen-ratio) for synthetic landscapes of differing degrees of surface heterogeneity by applying a mesoscale meteorological model. Their results substantiate that land-surface distributions will non-linearly influence the Bowen-ratio if patches of equal type exceed a certain size and that the surface type dominating a landscape does not necessarily determine the mean Bowen-ratio representative for this area. Thus, when applying the dominant surface type as the representative one for a grid cell, the margin of error in the Bowen-ratio depends on the horizontal resolution of the model (or of available data).

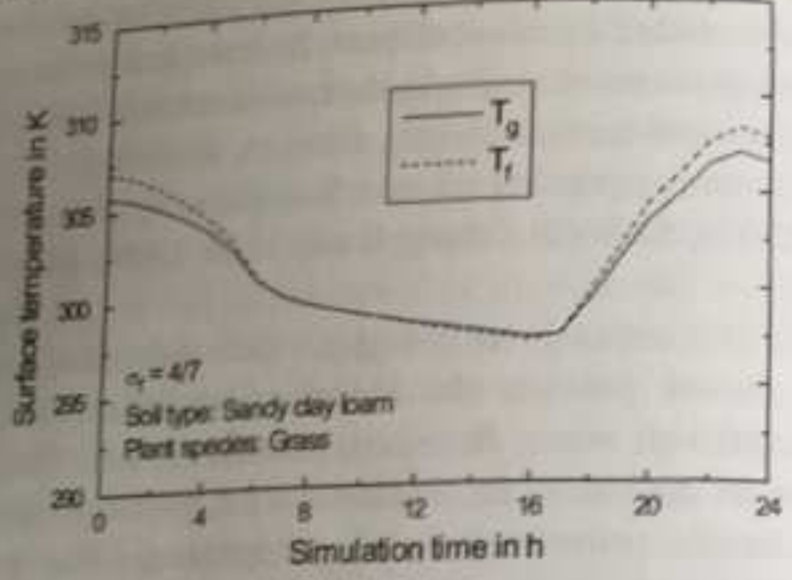

Fig. 3.3-3 Temporal development of leaf surface and ground temperature (T_g: Temperature of the ground; T_f: Temperature of the foliage)

Therefore, the heterogeneity on the microscale, which is of relevance for the near-surface stratification of the atmosphere (stability) and the atmospheric fluxes of sensible and latent heat, as well as the heterogeneity on the mesoscale, which affects the height of the atmospheric boundary layer, vertical mixing, and possibly cloud location, should be taken into account. A special feature of the hydrometeorological intersection module should be its ability to represent fine scale variations in surface characteristics, such as terrain slope, vegetation type, soil type and moisture or water bodies, which often vary considerably over short distances (e.g. Avissar and Pielke 1989).

The difficulty to bridge the spatial scales by aggregation/disaggregation can be addressed within the framework of considering subgrid-scale heterogeneity, i.e. the heterogeneity at the mesoscale (see discussion of disaggregation and aggregation issues in Sect. 1.2). Disaggregation of hydrologically relevant quantities provided by the atmospheric calculations are to be used as evapotranspiration and precipitation rates in the hydrological model part. The calculated hydrological processes have to be upscaled for use in the calculation of the atmospheric processes.

The heterogeneity at the microscale should be included by a mixture approach to consider simultaneously at least bare soil and/or vegetation within one grid cell (e.g. Deardorff 1978; Kramm et al. 1994, 1996). The surface temperatures of the leaf surface (foliage) and ground may differ strongly during the diurnal course (Fig. 3.3-3).

In the atmospheric model part used in the integrated model, a bulk-parameterisation (e.g. Cotton et al. 1982, Mölders et al. 1997) considering at least five water classes (water vapour, cloud water, rainwater, ice, graupel) should be applied to predict the mean precipitation within an atmospheric grid cell, because such a parameterisation is more physical and closer to the real processes than using only a cumulus-parameterisation (e.g. Mölders et al. 1994). The precipitation provided by a state-of-the art cloud module by the atmospheric model part has to be downscaled to the resolution of the hydrological model part. Recently, various downscaling procedures of different degrees of complexity and concept were developed to heterogenise precipitation (e.g., von Storch et al. 1993, Leung and Ghan 1995, Leung et al. 1996, Mölders et al. 1996).

Short vegetation should be considered by at least one layer. In the case of tall vegetation, multi-layer canopy models (e.g. Ziemann 1998) should be applied within the subgrid cells partly or totally covered by tall vegetation. Up til now, there exist no NWP models or GCMs that consider tall vegetation by some kind of multiple layer canopy model. Recently, Pyles (2000) coupled a multi-layer canopy model with a mesoscale meteorological model.

Interception loss should be included, at least for tall vegetation. It should be allowed that only parts of the vegetation are wet. The energy and hydrological budget equations have to be solved within a subgrid cell simultaneously.

Soil Physics

In the hydrometeorological module, all soil processes are calculated on the subgrid-scale, i.e. the same resolution as the hydrological model part. The treatment of the soil physics should be based on the fundamental principles of thermodynamics of irreversible processes, energy and mass conservation. An appropriate approach for the vertical water dynamics in the unsaturated zone should be applied, accounting for gravity and soil water tension, i.e. the unsaturated Darcy equation or a similar simplified approach should be applied. The hydrological model part should also account for the lateral soil water fluxes. The heat and moisture transport within the soil are to be solved by balance equations for soil temperature and volumetric water content. Solving the fully coupled equations means that the Ludwig-Soret effect (i.e. a temperature gradient can change soil volumetric water content) and Dufor effect (i.e. a moisture gradient may alter soil temperature) are taken into account, which may be especially important if high differences in temperature of rainfall and soil water exist. Within one cell, vertical varying soil types should be taken into account. The soil-module should include groundwater table dynamics to account for the impacts of changes in groundwater recharge and varying groundwater level on soil moisture, evapotranspiration and runoff. The impact of surface soil moisture on the atmosphere was discussed earlier in Sect. 3.2.1 as an example of feedback mechanisms that can require coupled models

Moreover, the soil-water uptake by roots has to be considered to ensure that evapotranspiration is related to the water content of different soil layers (not only the uppermost soil layer as often realised in atmospheric models). It should be ensured that the root density may vary with depth and time.

The parameterisation of infiltration has to be consistent with the calculation of the soil water dynamics. It may account for variable infiltration capacity, including macropore effects, and for differences in subgrid infiltration characteristics.

For coupling of a hydrological model part with an atmospheric model part, soil frost processes have to be considered because large parts of the continents are regularly frozen during winter in high and mid-latitudes or mountainous regions. From the hydrological point of view, soil frost leads to the freezing of soil-water, virtually totally restricting its mobility and capillarity, such that infiltration as well as percolation are almost ineffective. Since soil frost hinders infiltration of water into the soil, rain falling onto frozen soil or the melting of a snow layer over frozen soil will contribute strongly to runoff. Aspects of soil frost that affect the atmosphere are more indirect than those in hydrology. The thermal stability and low air temperatures, and the consequent low saturation pressure of water vapour, lead to low evaporation. The moisture will be stored in frozen ground and may increase spring peak flood events. In addition, transpiration plays a minor role because deciduous forests have lost their leaves and the stomatal conductivity of coniferous forests is also lower. If the freezing processes of soils are neglected, excessive water vapour fluxes into the atmosphere will be predicted as there is seemingly still "liquid" water available that, moreover, requires less energy for evaporation than ice (e.g., Mölders and Walsh 2004).

The depth of the interface between an unfrozen upper soil and a frozen deeper soil, for instance, may vary within the diurnal course. The determination of the surface water and energy fluxes is extremely uncertain when the exact freezing depth is unknown.

For the reasons discussed above, the inclusion of soil frost processes when coupling hydrological and atmospheric models is important for adequate calculation of runoff and water supply to the atmosphere in winter. The terms for soil freezing and thawing should be included in the coupled equations of heat and moisture transport within the soil and should be based on thermodynamics.

Snow

Another important process to be considered in the proposed hydrometeorological module is the treatment of snowmelt and previous snow accumulation. Snow is treated differently in hydrological and atmospheric models because of the different relevance of the various aspects of snow for atmospheric and hydrological processes. In hydrological modelling, namely, the retarded entry of precipitation into the land phase of the water cycle is the most prominent aspect of snow. Thus, a simple day-degree method is sufficient in most hydrological applications. In atmospheric models, besides the delayed water entry into the land phase of the water cycle, the insulating effect of snow that prevents the underlying soil from cooling and the high albedo of snow that affects the energy budget (e.g., Plüss and Ohmura 1997; Abdalati and Steffen 1997; Cline 1997; Baker et al. 1999; Robinson et al. 1992) are the most important aspects of snow to be considered. Albedo, for instance, dramatically changes when snow falls and rests on the ground, especially where the underlying ground has an albedo below 0.15 when wet. Since the albedo associated with snow cover typically ranges between 0.35 and 0.9, the energy exchange between the soil surface and atmosphere is therefore in winter generally weaker than in summer.

Disappearance of snow leads to runoff and removes a critical constraint on both water vapour pressure and surface temperature. As long as the snowpack exists, these quantities cannot rise above 610 Pa and 273.15 K. Therefore, the surface-atmosphere coupling becomes more relevant after the melting of snow. Exposed soil surfaces within a partly broken snow coverage lead to substantial sensible heat fluxes, convection and increased vertical mixing in the surface layer. If sufficient moisture is available, clouds may form. The cloud shadows may feed back to a reduced melt process. The strong spatial contrast in the energy budgets of snow-covered and snow-free areas may lead to significant advective flow similar to a sea breeze (Baker et al. 1999).

As a consequence of the aspects discussed above, when coupling hydrological and atmospheric model parts, the snow accumulation and melt processes should be considered by a multiple layer snow model (e.g. Anderson 1976; Foster et al. 1996; Cayan 1996; Fröhlich and Mölders 2002) if snow events were frequent and snow accumulation is high. In the case when the coupled model is applied mainly in regions of little snowfall and usually ephemeral snow coverage, it has to be examined whether a single layer snow model could be sufficient.

3.3.4 Conclusions

During the last decade, several attempts were made to consider the interaction between the land and atmospheric part of the water cycle in both long-term climate modelling and short-term numerical weather predictions. There are three different concepts of how to treat the complexity of the physical system "water cycle":

- Parameterisation of subsurface and surface hydrological processes in the atmospheric model;
- One-way or two-way coupling of hydrological and atmospheric models by data exchange between independent hydrological and atmospheric models; and
- Direct coupling of hydrological and atmospheric model parts by use of a common intersection module, here denoted as the hydrometeorological module within a fully integrated model.

In the latter, the hydrological and atmospheric model loose their stand-alone identity and become one hydrometeorological model. Such an integrated concept seems to be the most sophisticated and detailed way to realise the coupling between hydrological and atmospheric models, because it provides optimised technical and physical consistency within one model system.

Irrespective of the large amount of scientific effort in recent years, the current state of complex modelling is far from being satisfactory from the point of view of operational applications, e.g. for flood prediction, water resource management, or climate change assessment (see also IPCC 2001). The choice of the type and degree of coupling (parameterisation, one-way, two-way, or fully integrated) should depend on the task to be addressed. The requirements for the design of integrated coupling between an atmospheric and hydrological model was introduced earlier, Sect. 3.3.3. This hydrometeorological module may serve as the lower boundary condition

for an atmospheric model. A schematic view for the data to be provided and exchanged by the hydrometeorological module is given in Figure 3.3-4. The hydrometeorological module is to be called up for each surface grid cell of the atmospheric model and should include subgrid-cell representation of prognostic snow-cover, prognostic equations for soil volumetric water content and soil temperatures (in z-direction only) considering the Ludwig-Soret- and Dufor-effect, treatment of soil freezing and thawing, water uptake by roots, local runoff of heavy precipitation and snowmelt, as well as energy and moisture budgets for soil, vegetation, canopy air, temporary surface water, respectively (e.g. intercepted water, flood, snow-cover). The subgrid cells should match the resolution of the hydrological model. Soil and snow-cover have to be divided into multiple vertical levels. Vegetation and canopy have to be represented by at least a single layer.

The hydrometeorological module provides the water and energy fluxes, surface temperature, and moisture, surface albedo and emissivity to the atmospheric model, while it provides the vertical soil water fluxes, soil volumetric water content, groundwater recharge, infiltration, melt water, and ponded water to the hydrological part. The ponded water can produce runoff. The atmospheric model delivers to the hydrometeorological module surface pressure, specific humidity, air temperature, wind and short- and long-wave downward radiation. The hydrological model provides to the hydrometeorological module the lateral soil water fluxes, surface and channel runoff (Fig. 3.3-4).

The practical aspects of the difficulties in coupling hydrological and atmospheric models are not only in identifying the feedback and bridging the spatial gaps of the models, but also setting up the coupled model packages in such a way that computational efforts, data exchange and required data are kept manageable in a time reasonable for forecasts and applications. A general challenge is to initialise the coupled model and provide the soil physical and plant physiological data needed. While for the atmospheric part the initial data can be obtained from radiosonde observations, there are no routine networks measuring soil moisture, soil ice, and soil temperature. Measurements of the level of groundwater tables exist only for selected catchments and not for large areas. Data sets of vertical profiles of soil types are not available in a spatial resolution and completeness as required, for instance, for NWP or GCMs.

One big challenge is not to couple what can be coupled all into one integrated model, but rather to couple only what makes sense to answer a question that could not be addressed without coupling.

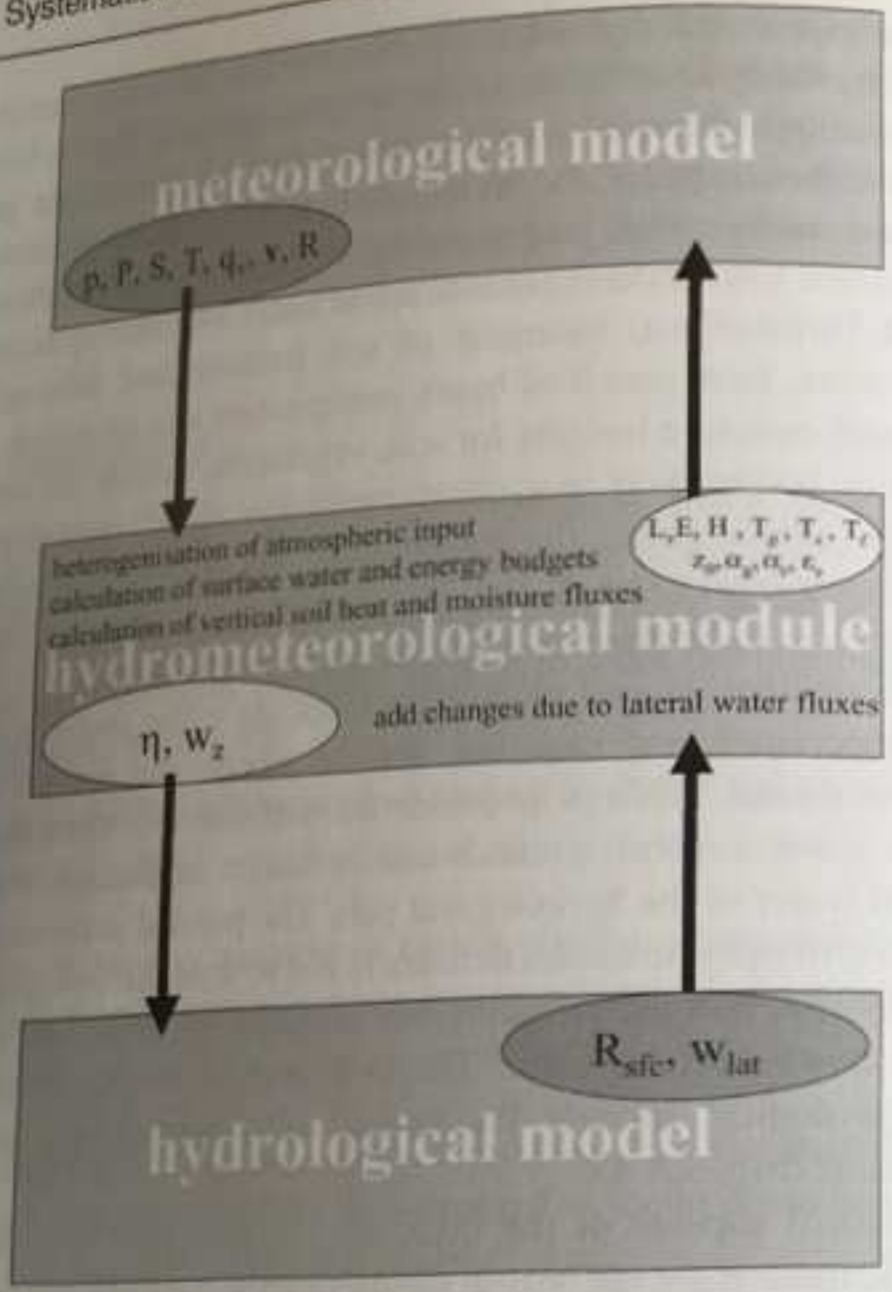

Fig. 3.3-4 Flow chart of calculated data exchange in a hydrometeorological module used as intersection in a fully coupled hydrological-atmospheric model (after Mölders and Rühaak 2002). Here, p is pressure, P stands for precipitation, S for snow, T, T_g, T_S, T_f denote to the temperatures of air, ground, snow and foliage, q_v and **v** are the specific humidity of air and the wind vector, respectively. The letter R represents the short-wave and long-wave downward radiation. Furthermore, η, w_{lat}, w_z, and R_{sfc} are the volumetric water content, lateral and vertical water fluxes in the soil as well as (channel and/or surface) runoff. The latent and sensible heat flux densities are denoted as L_VE, and H, respectively. Finally, z_0, α_g, α_S, and ε_S represent the roughness length, albedo of the ground and snow as well as the emissivity of snow

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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.