# Concepts for coupling hydrological and meteorological models

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**Summary:** Earth system modeling, climate modeling, water resource research as well as integrated modeling (e.g., climate impact studies) require the coupling of hydrological and meteorological models. The paper presents recent concepts on such a coupling. It points out the difficulties to be solved, and provides a brief overview on recently realized couplings. Furthermore, a concept of a hydrometeorological module to couple hydrological and meteorological models is introduced.

**Zusammenfassung:** Wasserresourcenforschung, Erdsystem- und Klimamodellierung sowie integrierte Modellierung (z.B. Klimafolgenforschung) erfordern das Koppeln von hydrologischen und meteorologischen Modellen. Dieser Artikel präsentiert Konzepte für eine solche Kopplung. Er zeigt die zu lösenden Schwierigkeiten auf und gibt einen kurzen Überblick über bisher realisierte Kopplungen. Ferner stellt er ein Konzept für einen hydrometeorologischen Moduls zur Kopplung von hydrologischen mit meteorologischen Modellen vor.

## 1. Introduction

In nowadays there are several reasons and interests to couple hydrological and meteorological models. Climate impact studies, planing of water resources or landscapes as well as ecosystem modeling require to describe the water cycle in a closed manner. Due to the different aspects of the water cycle that are of major or minor interest to hydrologists, meteorologists or climatologists only those processes are considered in detail that are relevant for the specific application of interest while other aspects are neglected or crudely simplified. As a consequence the water cycle is not simulated in a closed manner. The simplifications, however, can provide difficulties in the description of the water cycle even in fields of non-interdiciplinary modeling. In traditional numerical weather prediction (NWP) models, for example, the neglecting of lateral soil water movements and surface runoff may yield to an underestimation of soil moisture in river valleys and an overestimation of soil moisture in the nearby mountainous regions, which usually receive more precipitation, if the simulated soil moisture distribution of the previous day is used to initialize the soil moisture distribution for the next forecast (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. In weather forecasting or climate modeling, for instance, a pre-given constant water table may provide errors in the water supply to the atmosphere. In nature, namely, the water table will rise during long-lasting precipitation episodes in areas of flat water tables, while it will sink or even decouple from soil moisture during long-lasting drought episodes. Evidently, during droughts, the lowered ground water table may contribute to the duration of the drought because evapotranspiration, ET, is reduced (Fig. 1). On the contrary, long-lasting extreme precipitation events may trigger their persistence by recycling of previous precipitation because the high water table yields in enough water available for evapotranspiration (Fig. 1). In hydrological modeling, for instance, neglecting the feedback of increased soil moisture on evapotranspiration, cloud- and precipitation-formation can lead to mispredictions of flood intensity, because runoff of an individual river catchment depends on precipitation and evapotranspiration within 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 cycle (Miller et al. 1994) where the latter again depends on microclimatological conditions which are not simulated. In general circulation models (GCM), for example, river runoff provides the critical link for returning water from continents to the ocean (Miller et al. 1994). Although at any given time rivers hold only a fraction of the world's total water river runoff is an important input value for ocean models because freshwater flow affects the thermohaline circulation of the ocean.

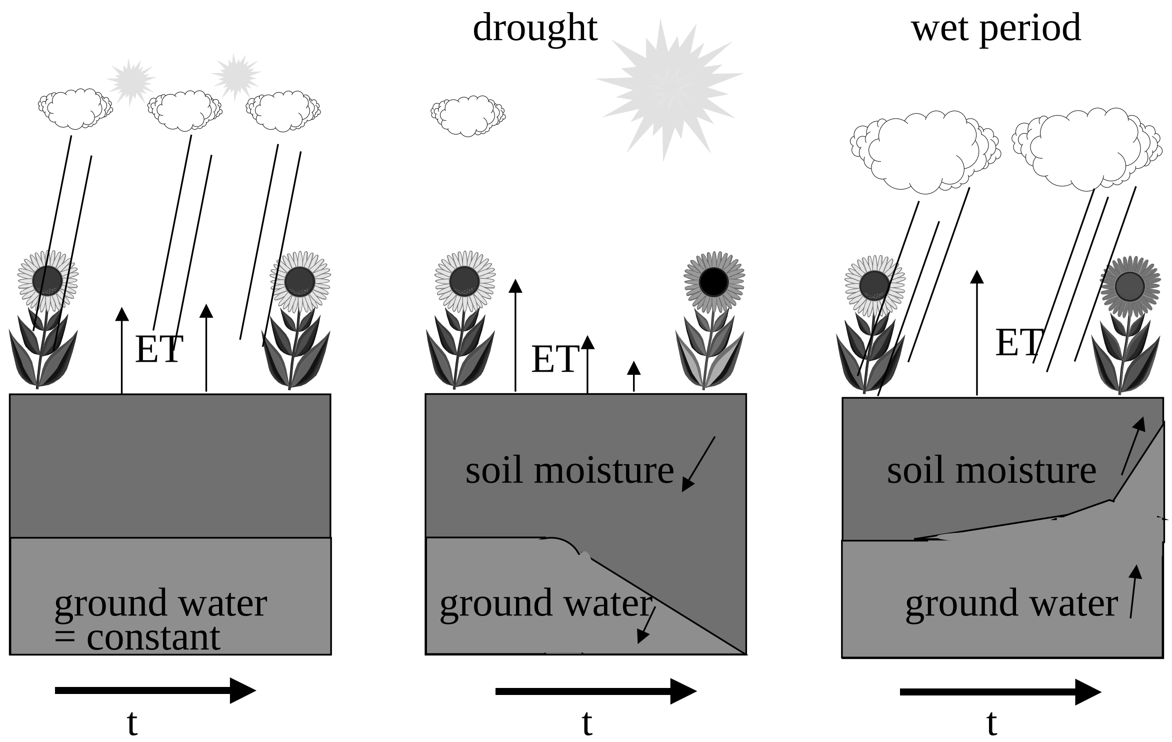


Fig. 1. Schematic illustration of the impact of a flat water table on atmospheric water fluxes.

To more appropriately consider the interaction of the atmospheric and land-based path of the water cycle a closed description of the water cycle is an urgent need. In this paper, recently published concepts to model the water cycle are evaluated and a concept to couple hydrological and atmospheric models by use of a hydrometeorological module are presented.

**2. The coupling problem**

As pointed out above, meteorologists and hydrologists have a common interest in land-surface modeling, but both by tradition and purpose, the land surface parameterizations applied in hydrological and atmospheric models differ strongly (e.g., Graham and Bergström 2000). Hydrologic models require a precise partitioning of precipitation into evapotranspiration, infiltration, interception, retention, and runoff to determine the water fluxes within the soil and ground water recharge, i.e., the water balance is of main interest. Meteorological 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 balance. The water balance is often very simplified by using a bucket model or a force restore method.

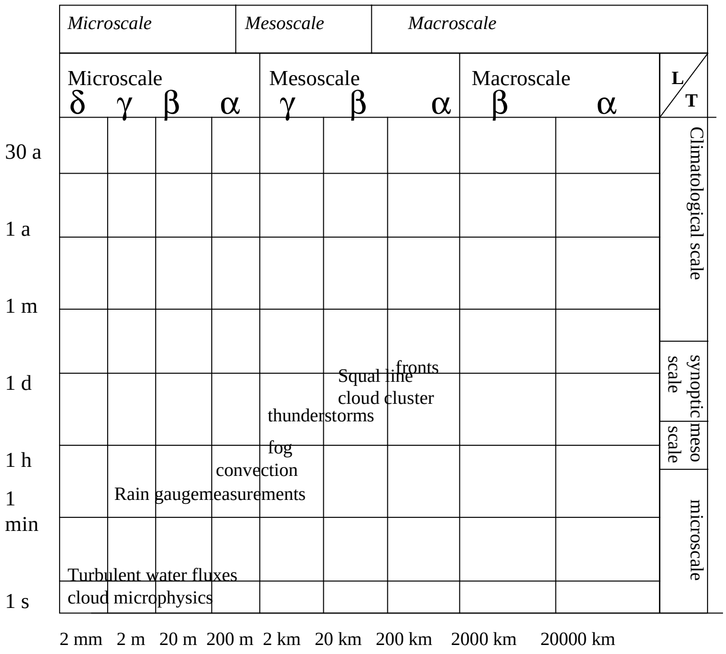


Fig. 2. Schematic view of spatial (L) and temporal (T) scales in hydrological and meteorological models. The upper and lower termin of scales address the hydrological and meteorological models, respectively. Note that hydrological models used in flood forecasting or warning systems have typical application times of several days to a week with time resolutions of one to several hours, while water balance models address the climatological scale with time resolutions of one day. Macroscale hydrological models range from synoptic to climatological scale with time resolutions of 10 to 30 minutes. See text for further discussion.

Other differences between hydrological and meteorological models are related to the typical scales of processes to be simulated (Fig. 2). Therefore, the temporal and spatial resolutions of these models differ strongly. Meteorological models usually apply square grid cells as their horizontal unit of area. Despite of increasing computational power decreasing of these grid cells is limited by the range of validity of the assumptions made in the parameterizations (e.g., the fetch-conditions from which the parameterizations of the surface fluxes are derived lead to a requirement of a relation 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 and its sub-basins which consequently define the model dimensions. Thus, especially in complex terrain, the grid resolution may be very fine. Decreasing the horizontal resolution of hydrological models, for instance to match the resolution of meteorological models, provides the difficulty how to represent the (then subgrid-scale) heterogeneity of land surface properties, such as topography, geology, and vegetation cover. As pointed out before these characteristics, among other things, determine the runoff and storage of the basin.

The solution of the energy balance, which is of essential need in meteorological models, demands time steps of several minutes, while a lot of hydrological models are often satisfied with daily time steps (e.g., Graham and Bergström 2000). Meteorological models usually neglect lateral flows of soil water, surface runoff, the transport of water by river flow as well as the re- and discharge of the groundwater storage, because these processes are slow as compared to typical simulation time scales of meteorological models. As aforementioned, these processes, however, are important in hydrological models and may be of great relevance in climate modeling as well as in weather forecasting (Mölders and Raabe 1997). Thus, one main task in coupling hydrological and meteorological models is to overcome these temporal and spatial gaps.

## 3. Concepts

*3.1 Parameterizations*

Being aware of the problematic of an unclosed water cycle and the difficulties in coupling hydrological and meteorological models caused by the different spatial and temporal scales, recently, several authors (e.g., Kuhl and Miller 1992, Marengo et al. 1994, Miller et al. 1994, Sausen et al. 1994, Hagemann and Dümenil 1998) suggested parameterizations of different complexity to directly parameterize runoff in GCMs. Kuhl and Miller (1992) suggested a simple scheme wherein all runoff within a river drainage basin instantaneously reaches the river mouth. Although the global runoff agreed well with the observed runoff, great errors occurred locally. Miller et al. (1994) introduced a river model that allows the excess water at the surface calculated by a GCM to run off into the river within a continental grid cell. The direction and speed of flow is either constant or depends on topography gradient. Sausen et al. (1994) proposed a one-parameter model that represented each grid cell by a two-dimensional linear reservoir with different retention coefficients for the flows in the east, west, north, and south direction. These coefficients depend on the orography and grid size. This approach does not distinguish the different types of flow processes. Thus, in an attempt to improve this approach Hagemann and Dümenil (1998) introduced a global parameterization wherein the cascade of overland and river flow is realized by equal linear reservoirs, and baseflow is considered by a one parameter model. The corresponding retention coefficients depend on topography gradient between two neighbored grid cells and on the grid cell size.

*3.2 Direct coupling by data exchange*

Despite of the temporal and spatial gaps between the resolutions of hydrological and meteorological models, recently, several different methods have been developed and tested to couple hydrological and meteorological models directly.

*3.2.1 One-way-coupling*

The simplest version to “couple” hydrological and meteorological models is the one-way coupling wherein the hydrological model is driven by the meteorological model. There exists no feedback of the hydrological model results to the simulation of the meteorological model. It is obvious that, in the case, of large floods, applying a one-way coupling may lead to false water supply to the atmosphere which may result in a wrong cloud and precipitation distribution (e.g., Mölders 1999). From the practical point of view a one-way coupling is not advantageous for flood forecasting, because the errors in predicted precipitation pattern and intensity propagate in the hydrological model (e.g., Mölders et al. 1999a).

*3.2.2 Two-way-coupling*

In a two-way coupling, a feedback between the atmospheric and hydrological model results exists. This feedback depends on the degree of coupling. Mölders and Raabe (1997) as well as Mölders et al. (1999a) coupled a conceptual hydrological model (NASMO, precipitation runoff model) and a meteorological model (GESIMA, Geesthacht’s simulation model of the atmosphere) in a two-way mode. In doing so, the hydrologic processes of the river catchment (translation, retention, lateral discharge) are considered in the meteorological model which itself drives the hydrological model by predicted evapotranspiration and precipitation. The quantities provided by the hydrological model served to modify soil moisture in the meteorological model. The different 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 in the meteorological model, i.e., the module designed to couple the models allows to heterogenize precipitation and to consider subgrid-scale surface processes in the meteorological model. A main problem in this way of coupling was that soil wetness, vegetation- and soil-type as well as topography differ between the models because of the conceptual approaches applied in the hydrological model.

To avoid such discrepancies in the surface characteristics of the coupled modeling system, so-called distributed or the lumped integral models should be used as hydrological models (Todini 1988) and GCMs, NWP or regional-climate models should be applied for the atmospheric part. Note that NWP models belong to the group of mesoscale-meteorological models. In the coupling, the meteorological model should be nested into a global model to allow long-term simulations. In order to derive suitable parameterizations (quasi) distributed differential hydrological models should be used which are based on the fundamental laws of hydro-dynamics (e.g., MIKESHE; Abbot et al. 1986, Refsgrad et al. 1992) and that also include hydro-thermodynamic effects like soil frost.

### *3.3 A hydrometeorological module as intersection*

According to the first experiences with loosely coupled hydrological and meteorological models it seems to be necessary that coupled hydrological and meteorological models should become a hydrometeorological model, i.e., one model, to avoid that processes are differently parameterized in the hydrological and meteorological model parts (e.g., Mölders and Raabe 1997, Mölders et al. 1999a). Such a realization would save computer time and man-power, but needs interdisciplinary cooperation. It guarantees that the landscapes, soil processes, and the processes at the earth-atmosphere interface are identical in both model parts and provides a closed and such more appropriate description of the water-cycle than the single models or loosely coupled models.

Recently, some developments into the direction of a hydrometeorological module as an interesection to couple hydrological and meteorological models were carried out. TOPMODEL (Beven and Kirkby 1979) was coupled with SVAT (soil vegetation atmosphere transfer schemes), for example by Famiglietti and Wood (1991), Band et al. (1993), Stieglitz et al (1997). Walko et al. (2000) coupled TOPMODEL into a regional atmospheric modeling system (RAMS). Recent state-of-the-art land surface models (LSM) like OSULSM (Oregon State University land surface model, Chen et al. 1996), HTSVS (hydro-thermodynamic soil vegetation scheme, Kramm et al. 1996, Mölders et al. 1999b, Mölders and Rühaak 2000), SEWAB (Mengelkamp et al. 2000) that are used in mesoscale meteorological models address both hydrological and meteorological aspects. Some LSMs also include a component to consider surface runoff and channel flow by using the unit hydrograph (e.g., SEWAB) or the St.-Vernant-equation (e.g., HTSVS).

In general, in a coupled hydrological and meteorological model system, the hydrological model should calculate the ground water, horizontal soil water fluxes, and runoff. The meteorological model should determine the fields of wind, pressure, air temperature, humidity, radiation, cloudiness, and precipitation. In realizing the coupling, the soil-vegetation module of the hydrological or meteorological model should be the common part of data exchange and use. It serves as the upper boundary condition for the hydrological model and the lower boundary condition of the meteorological models. The hydrometeorological module has to fulfill the requests of both the hydrological and meteorological models in the highest degree of accuracy and physical process details required by one of the models. In the following, the special needs of atmospheric and hydrological models to simulate the boundary conditions are discussed to elucidate which physical processes are to be considered in the hydrometeorological module with which accuracy.

The hydrometeorological module has to be called with the time step of the meteorological model. The hydrological model can be called at coarser time steps than the meteorological model. It has to be examined whether the usual time step of the hydrological model is sufficient or whether a shorter time step delivers better results for the coupled system.

*3.3.1 Representation of finescale variations in surface characteristics and conditions*

As pointed out above, the heterogeneity of surface characteristics is of great importance in hydrological modeling. It also plays an important role in meteorological modeling. Friedrich et al. (2000) examined the influence of surface heterogeneity on spatial distribution, temporal development, and on the domain-average of the ratio between sensible and latent heat-flux (Bowen-ratio) for synthetic landscapes of differing degrees of surface heterogeneity 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 an area of a grid-cell, the margin of error in the Bowen-ratio depends on the horizontal resolution of the model (or on available data).

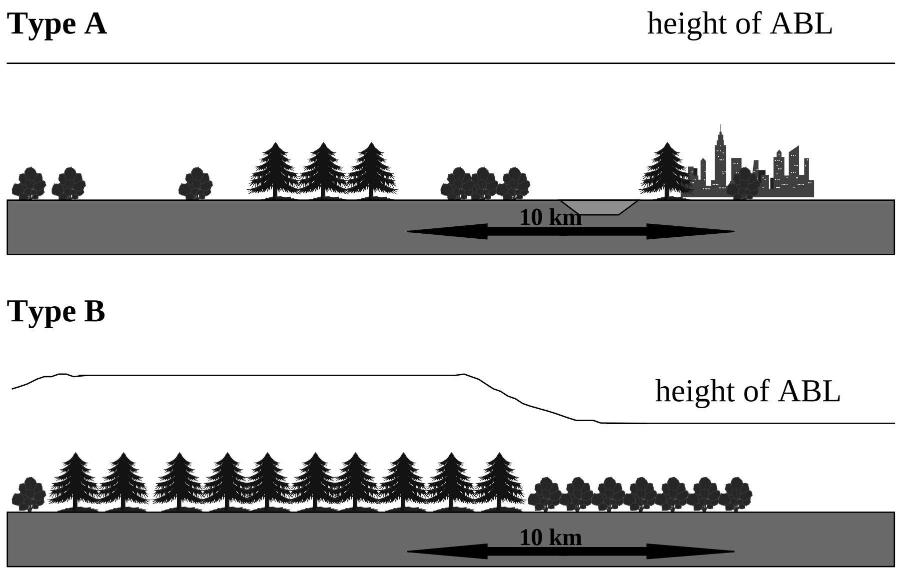


Fig. 3. Schematic view of the affect of mesoscale surface heterogeneity on the height of the ABL (modified after Shuttleworth 1988). Type A and B refer to the classification of heterogeneity type introduced by Shuttleworth (1988).

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 affect the height of the atmospheric boundary layer (ABL; Fig. 3), vertical mixing, and possible cloud location, should be taken into account. For the reasons discussed above, a special feature of the hydrometeorological module should be its ability to represent finescale 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., Fig. 5).

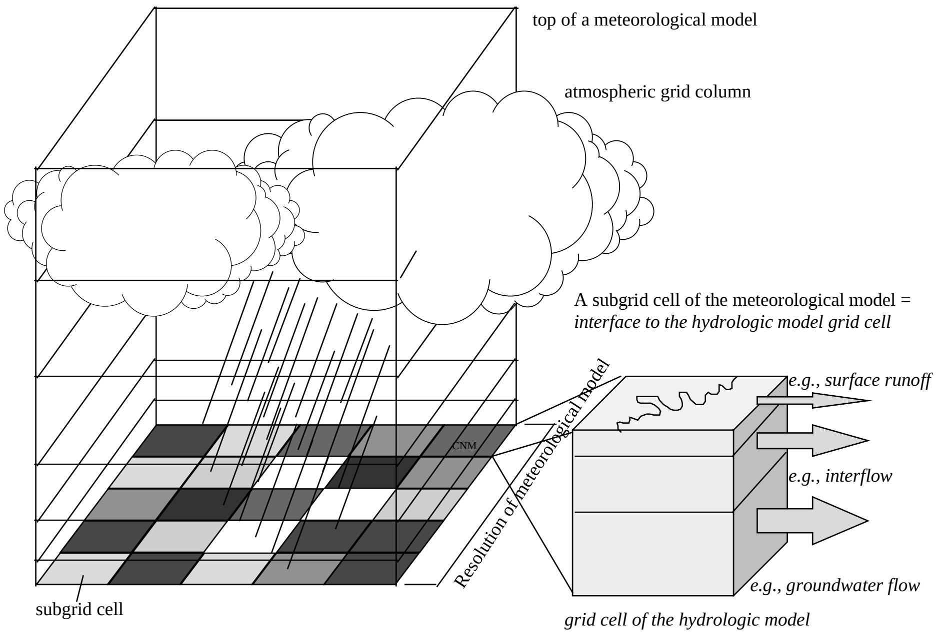


Fig. 4 Schematic view of the downscaling applied in the meteorological model. The different grey levels represent different types of landuse (after Mölders et al. 1999a).

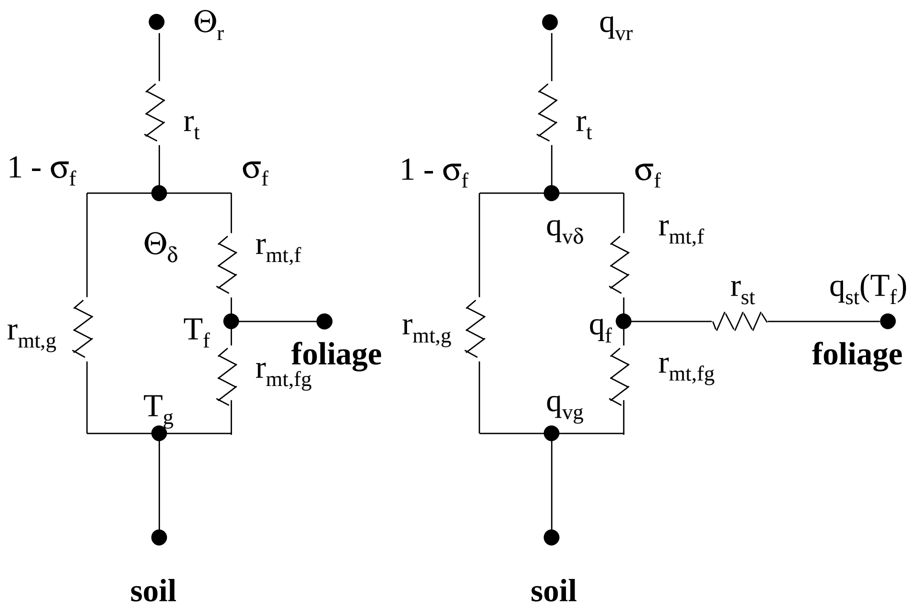


Fig. 5. Schematic view of a resistance network for the mixture approach assuming a dry vegetation shielding the ground by $\sigma$ percent given in values between 0 and 1 (modified after Kramm et al. 1996). Here, $r_{mt}$, $r_t$, $r_{st}$, T, $q_{st}$, $q_v$, and $\Theta$ stand for the molecular turbulent resistance, the turbulent resistance, the stomatal resistance, temperature, specific humidity in the stomata, specific humidity, and the potentail temperature where the subscripts f, $\delta$, and g stand for the foliage, the reference height and ground, respectively.

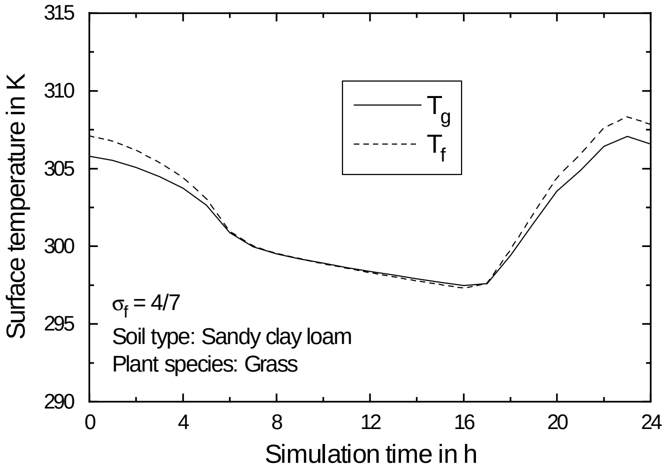


Fig. 6. Temporal development of foliage and ground temperature.

The heterogeneity on the microscale should be included by a mixture approach (e.g., Fig. 5) to consider simultaneously at least bare soil and/or vegetation within one grid-cell (e.g., Deardorff 1978). The surface temperatures of the foliage and the soil as well as their diurnal course, namely, may differ strongly (Fig. 6).

The heterogeneity on the mesoscale can be considered by some type of mosaic approach (e.g., Avissar and Pielke 1989, Seth et al. 1994, Mölders et al. 1996).

Recently, several different strategies have been developed to parameterize subgrid-scale surface heterogeneity, for instance, by averaging surface properties (e.g., Lhomme 1992, Dolman 1992), or by statistical-dynamic approaches (e.g., Wetzel and Chang 1988, Entekhabi and Eagleson 1989). Computationally more expensive procedures to consider patchy surface properties are the mosaic approach (Avissar and Pielke 1989), the explicit subgrid strategy (Seth et al. 1994), or the mixture strategy, wherein for the different surface types tightly coupled energy balances are determined (e.g., Sellers et al. 1986, Dickinson et al. 1986, Kramm et al. 1994). Several authors comparing the results provided by simulations with and without consideration of subgrid-scale surface heterogeneity found that for very patchy surfaces large differences in the predicted fluxes can occur (e.g., Avissar and Pielke 1989, Seth et al. 1994, Mölders and Raabe 1997). A review on methods to treat heterogeneity is given by Giorgi and Avissar (1997).

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 on the mesoscale. First, parameterizations to downscale hydrologically relevant quantities provided by the meteorological model are required to utilize evapotranspiration and precipitation in the hydrological model. The quantities delivered by the hydrologic model have to be up-scaled for use in the meteorological model.

To downscale the hydrologically relevant quantities an explicit subgrid-scheme, firstly suggested by Seth et al. (1994) for the global scale, should be adapted for the mesoscale to downscale the hydrologically relevant quantities (e.g., Mölders et al. 1996, 1999, Mölders and Raabe 1997). Herein, a higher resolution grid is defined at the interface earth-atmosphere and within the soil. This higher resolved grid consists of several subgrid cells per grid cell (e.g., Fig. 4). According to the mixture approach suggested before, these subgrid cells may be covered by at least one vegetation- and/or soil-type. Thus, coupled energy (for soil and vegetation) and hydrological budgets are maintained for each subgrid cell using the subgrid cell surface characteristics and the micro-climate at the representative location. This means that, in each subgrid cell, the fluxes are individually calculated with their own subgrid soil forcing and near-surface meteorological forcing in the immediate vicinity of the earth's surface. Soil water content, soil-temperature, near-surface air-temperature and humidity have to be stored for each subgrid cell. They have to be used to determine these quantities in the next time step. The coupling of the subgrid cells to the atmospheric grid cell may be realized by the arithmetic average of individual subgrid cell fluxes to provide the grid cell fluxes (e.g., Avissar and Pielke 1989, Mölders and Raabe 1996, Mölders et al. 1996).

The explicit subgrid scheme belongs to the class of mosaic approaches. The main advantages of the subgrid scheme as compared to a simple mosaic approach are that by explicitly breaking down the grid cells of the atmospheric model (1) the spatial location of each subgrid flux is known (Fig. 4), (2) precipitation can easily be heterogenized, (3) the coupling can be realized on the subgrid cells, i.e., the hydrological and meteorological model have the same surface characteristics. The disadvantage of the explicit subgrid scheme is that it can be much more computationally expensive than a simple mosaic approach, especially, when the surface conditions are relatively homogeneous (see Mölders et al. 1996).

The precipitation provided by a state-of-the art cloud module by the atmospheric model has to be downscaled (e.g., von Storch et al. 1993, Leung and Ghan 1995) to the resolution of the hydrological model. In most regions of the world, long-lasting precipitation increases with elevation (orographic effect) because horizontally moving air encounters a topographic barrier and, hence, aquires vertical motion when passing the barrier. The related cooling leads to precipitation. Assuming that precipitation increases with elevation and taking into account the direction of wind, stratiform precipitation can be heterogenized (e.g., Leung and Ghan 1995, Leung et al. 1996, Mölders et al. 1996). For convective cases, heterogenization of precipitation should be related to surface characteristics (e.g., large patches of sand) and wind speed and wind direction. Note that, in the meteorological model used for the coupling, a bulk-parameterization (e.g., Mölders et al. 1997) considering at least five water classes (water vapor, cloud water, rainwater, ice, graupel) should be applied to predict the mean precipitation within a meteorological grid cell, because such a parameterization is more physical and closer to the processes than a cumulus-parameterization, for instance (e.g., Mölders et al. 1994).

Short vegetation should be considered by at least one layer. In the case of high vegetation, multi-layer canopy models (e.g., Ziemann 1998) should be applied within the subgrid cells partly or totally covered by high vegetation. Note that, up to now, there exist no NWP models or GCMs which consider high vegetation by some kind of multiple layer canopy model.

Interception loss should be included at least for high vegetation. Herein, it should be allowed that only parts of the vegetation are wetted. In such a case, three energy and two hydrological budget equations have to be solved within a subgrid cell simultaneously. Here, again the mixture approach can be applied to allow partly wetted canopies.

### *3.3.2 Soil physics*

In the hydrometeorological module, all soil processes are calculated on the subgrid that ought have the same resolution as the hydrological model. The treatment of the soil physics should be based on the thermodynamics of irreversible processes (e.g., Philip and de Vries 1957, Philip 1957, de Vries 1958). Among other things Darcy's law and the Richards equation should be included. The effect of the horizontal soil water fluxes should be calculated by the hydrological model and can be determined with a coarser time step than that used by the hydrometeorological module and the atmospheric model. The heat- and moisture transport within the soil should be solved by balance equations for soil-temperature and volumetric water content (e.g., Zdunkowski 1983, Kramm et al. 1996). These equations are a coupled system of partial differential equations and have to be solved iteratively (e.g., Kramm et al. 1996). Solving the 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. An approximation that decouples moisture and heat processes within the soil should be avoided if long-term simulations were to be carried out that are often the aim of coupled model simulations (e.g., investigations on the impact of land-use changes on climate and water resources). Within the soil, different soil types should be allowed in the vertical soil column. The soil-module should reach into the level of ground water to be able to examine impacts and changes of ground water recharge on soil moisture, evapotranspiration, and runoff.

Moreover, the soil-water uptake by roots should be considered to assure that evapotranspiration is related to the volumetric water content of different soil layers (not only the uppermost soil layer as often realized in meteorological models). Parameterizations using the Cowan (1965) model could be applied (e.g., Martin 1990, Dickinson 1993). It should be ensured that the root amount can vary with depth (e.g., Wilson et al. 1987) and time (e.g., Mölders et al. 1999b).

The parameterization of infiltration should be consistent with Richards equation. It should allow that only parts of the atmospheric grid cell experience infiltration. This may be realized within the frame-work of an explicit subgrid scheme wherein, among others, soil type, land-use type, and precipitation may be heterogenized (e.g., Mölders 1996).

For coupling of a hydrological model with a NWP or GCM, soil frost processes have to be considered, because large parts of the continents are regularly frozen during winter in high and mid-latitudes or in mountainous regions. From the hydrological point of view soil frost leads to the freezing of soil-water for which its mobility is nearly totally restricted and capillarity, infiltration as well as percolation are only slightly effective. Since soil frost hinders infiltration of water into the soil (e.g., Cherkauer and Lettenmaier 1999), rain falling onto frozen soil or melting of a snow package laying over frozen soil will contribute to runoff. Aspects of soil frost that affect the atmosphere are more indirect than those in hydrology. The thermic stability and low air temperatures, and the consequently low saturation pressure of water vapor lead to low evaporation. Thus, the moisture will be stored in frozen soil and may increase spring peak flood events (e.g., Cherkauer and Lettenmaier 1999). In addition, transpiration plays a minor role because deciduous forests have already lost their leaves and even the stomatal conductivity of coniferous forests is low then. Obviously, if the freezing processes of soils are not considered, too high water vapor fluxes into the atmosphere will be predicted as there is seemingly still „liquid“ water available that, moreover, requires less energy for evaporation than ice.

The boundary between an unfrozen upper soil layer and a frozen deeper soil layer, for instance, may vary within the diurnal course. The determination of the surface water and energy fluxes is extremely difficult when the exact depth of the freezing line is unknown. The reduced hydraulic conductivity of frozen soil increases the potential for high snowmelt runoff losses.

For the reasons discussed above, the inclusion of soil frost processes when coupling hydrological and meteorological models is an urgent need for an adequate calculation of runoff and water supply to the atmosphere in winter. The terms of soil frost and thawing should be included in the coupled equations of heat and moisture transport within the soil and should be based on the thermodynamics of irreversible processes. Thus, it has to be run at the same time step than the soil model part of the hydrometeorological model (e.g., Fuchs et al. 1978, Flerchinger and Hanson 1989, Cherkauer and Lettenmaier 1999).

*3.3.3 Snow*

Another important process to be considered in the hydrometeorological module is the treatment of snowmelt and previous snow accumulation. Snow is commonly treated differently in the hydrological and meteorological models because of the different relevance of the various aspects of snow for meteorological and hydrological processes. In hydrological modeling, namely, the retarded entering 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. Besides the retarded entering of water in the land-phase of the water cycle, in meteorological models, the insulating effect of snow that prevents the underlying soil from cooling as well as 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 albedo below 0.15 when wet. Since the albedo associated with snow cover typically ranges between 0.35 and 0.9, the coupling between the surface and atmosphere is generally weaker than in summer.

Disappearance of snow leads to runoff and removes a critical constraint on both water vapor 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 should proceed with more vigor after the melting of snow (Baker et al. 1999). 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 budget 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, in coupling a hydrological and a meteorological model, 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) if snow events were frequent and snow accumulation is high. In the case, that the coupled model is mainly applied in regions of seldom snowfall and usually not long-lasting snow coverage it has to be examined whether a single layer model can be sufficient.

## 4. Conclusions

During the last decade, several attempts to consider the interaction between the land and atmospheric part of the water cycle were undertaken in both long-term climate modeling and short-term weather forecast applications. There are three different concepts of how to treat the complexity of the physical system “water cycle”:

- parameterization of subsurface and surface hydrological processes in the atmospheric model,
- one-way or two-way coupling of hydrological and atmospheric models by data exchange, and
- direct coupling of hydrological and atmospheric models by use of a common intersection, here denoted as hydrometeorological module.

The latter seems to be the most advantageous way is to realize the coupling between hydrological and meteorological models, because such a realization would save computer capacities as well as man-power and provides an optimized physical consistency between the models.

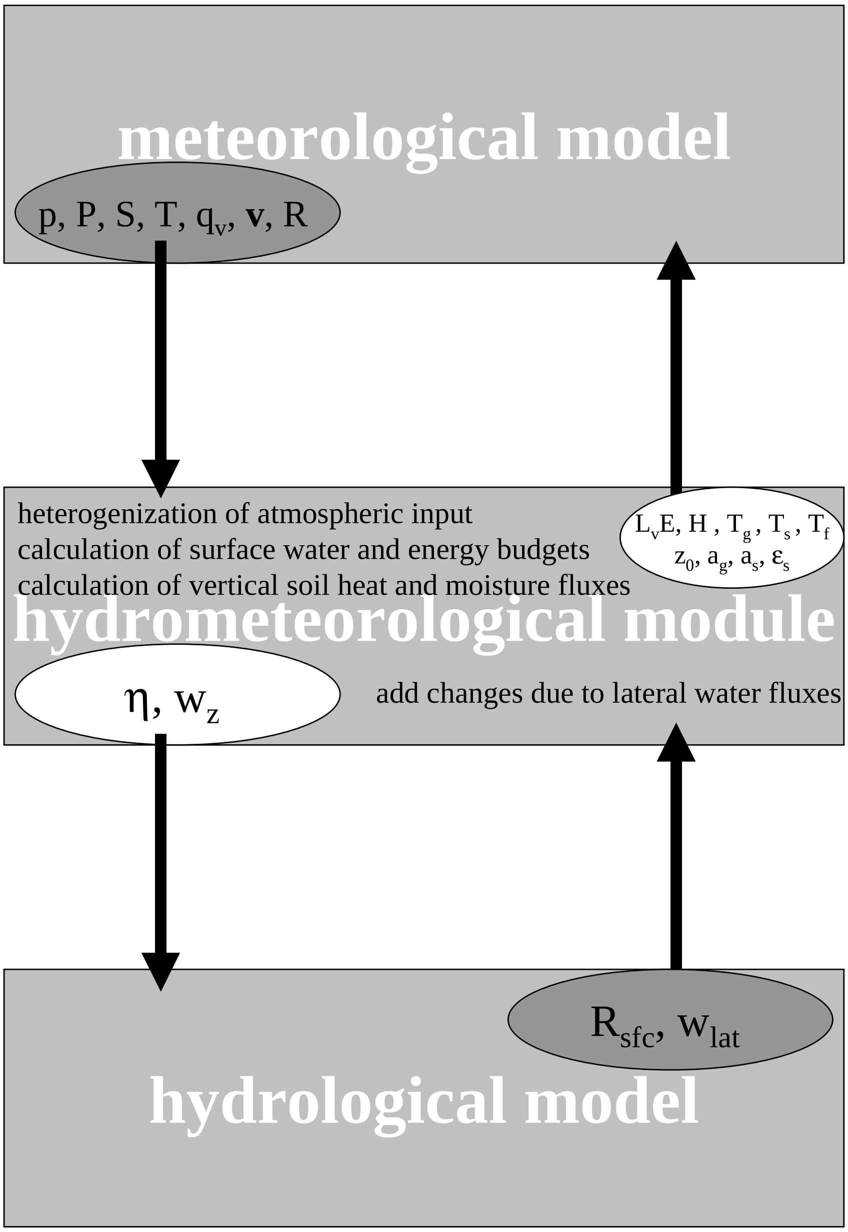


Fig. 7. Flow chart of calculated data exchange in a hydrometeorological module used as intersection for coupling a hydrological and meteorological model. Here, p, S, T, $T_g$, $T_s$, $T_f$, $q_v$, **v**, R, $\varepsilon_s$, $a_g$, $a_s$, $\eta$, $w_{lat}$, $w_z$, $R_{sfc}$, $L_vE$, H, $T_g$, $T_s$, $T_f$, $z_0$, $\alpha_g$, $\alpha_s$, and $\varepsilon_s$ stand for pressure, precipitation (rain and/or snow), the temperatures of the air, ground, snow and foliage, specific humidity of air, wind vector, short-wave and counter radiation radiation, emissivity of snow, albedo of ground and snow, volumetric water content, horizontal and vertical moisture and water fluxes in the soil, (channel and/or surface) run-off, latent and sensible heat flux densities, ground temperature, snow temperature foliage temperature, roughness length, albedo of the ground and snow as well as emissivity of snow, respectively.

A concept of the design of a hydrometeorological module was introduced. Such a hydrometeorological module is to serve as the lower boundary condition for the atmospheric model and as upper boundary condition for the hydrological model. The hydrometeorological module is to be called for each surface grid cell of the atmospheric model and should include subgrid cell representation of prognostic snow-cover, prognostic equation for soil volumetric water content and soil temperatures (in z-direction only) under consideration of the Ludwig-Soret- and Dufor-effect, treatment of soil freezing and thawing, water uptake by roots, local runoff of heavy precipitation and snowmelt, and of energy and moisture budgets for soil, vegetation, canopy air, temporary surface water (e.g., intercepted water, flood, snow-cover). These subgrid cells should match the resolution of the hydrological model. Soil and snow-cover are to be divided into multiple vertical levels. Vegetation and canopy are 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, ground water recharge, infiltration, melt water, and ponded water to the hydrological (Fig. 7). Note that 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 (Fig. 7). The hydrological model provides to the hydrometeorological module the lateral soil water fluxes, surface and channel runoff (Fig. 7).

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