Macroscale hydrologic models in support to climate research

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ABSTRACT For simulation experiments with atmospheric general circulation models (GCMs) more realistic information is required on certain land surface related hydrologic variables, in particular soil moisture and areal evapotranspiration. After reviewing in brief the present situation in large scale hydrologic land surface modelling a proposal is made for a grid related first level modelling which fulfills the requirements of GCMs and a subsequent second-level modelling which is used for validation of the first level and is river basin oriented. An important aspect of the proposed methodology is that it can be applied to any area of interest inside or outside gauged river basins, including also to the large GCM grid areas. The proposal takes into account existing experience in the application of grid techniques to river basin modelling as well as the important requirements to and recent developments relating to macroscale oriented hydrologic land surface modelling.

Des modèles hydrologiques de grande échelle pour les besoins de la recherche climatique

RESUME Pour l'expérimentation avec les modèles de la circulation générale atmosphérique (GCMs) il est nécessaire d'avoir une représentation plus réaliste de certains phénomènes hydrologiques manifestant sur la surface du sol et dans ce dernier, en particulier l'humidité du sol et l'évapotranspiration globales. Après une revue succincte de la situation actuelle dans la modélisation à grande échelle du cycle hydrologique au niveau est un modèle hydrologique maillé qui correspond aux besoins des GCMs. Le deuxième niveau permet une vérification du modèle de premier niveau en utilisant le débit mesuré à l'échelle d'un bassin fluvial. La caractéristique la plus importante de cette proposition prend en considération l'expérience qui existe dans la modélisation hydrologique au niveau du bassin qui utilise le procédé de maille et, en même temps, les besoins impératifs de la modélisation du cycle hydrologique au niveau de sol à grande échelle.
Introduction

The World Climate Programme (WCP) and, in particular the World Climate Research Programme (WCRP), as indicated in its implementation plan (WMO 1985) will require far-reaching co-operation of national administrations, scientific institutions and individual scientists to bring about the necessary concentration of material resources and scientific talents to bear on the complex problem of climate and climate changes. It is clear that contributions from the world community of scientists not only in the field of meteorology but also of oceanography, hydrology and glaciology will be needed to achieve the ambitious objectives of the programme. The range of interests of the WCRP reaches far beyond meteorology and atmospheric sciences and the nature of phenomena require much longer observational efforts extending over several years or even decades.

The highest priority requirement of WCRP is for consistent long time series of global data describing the components of the climate system. For the atmosphere there exist sources of such series, in particular those supplied by the World Weather Watch (WWW) of the WMO. For the oceans there exists the Integrated Global Ocean Services System (IGOSS) of the IOC/WMO. The only global data series on water runoff that has been assembled for the time being for these purposes is the set of data on runoff in selected stations in the world for water years 1978-1980. The Global Water Runoff Data Centre has until now received data from about 1100 stations, collected by the WMO Secretariat. The basic data consist of daily average discharges in m$^3$s$^{-1}$. The data centre is proceeding with quality control and transfer of the data using standard computer-compatible support. While the collection of the data continues, the requirement of the WCRP, as formulated in the First Implementation Plan (WMO, 1985, para. 5.8), is the support to the operation of a Global Water Runoff Data Centre for a ten-year period (1986-1996).

However, what do these hydrologic data represent for climate research? The discharge measured at a stream gauging station is the total surface and sub-surface runoff from a basin (catchment) of a river, integrated in space and time to the measurement point by the runoff process. The fact of having an integrated measurement of the result of three very important processes within the hydrologic cycle: precipitation, evaporation/evapotranspiration and runoff, is not often sufficiently appreciated by those who try to model these three processes not only in a vertical column (as do the majority of general atmospheric circulation models (GCMs)), but also in a three-dimensional space. Often the observational data of the integrated process are by far the most accurate; for monthly (and larger time step) averages the relative accuracy can be about five per cent for the catchment as a whole.

Unfortunately these runoff data cannot be used directly in GCMs (Nemec, 1986), because they include the time lag caused by the process of flow of water through different storages in the basin. Approximate techniques exist for separating discharges, represented as a time sequence in the form of a hydrograph, into their main components, thus singling out the flow through individual storages. However, it is not possible, in particular in larger and more complex river basins to redistribute the flow measured at a gauging station.
(outflow from the basin) to different points or to hydrologically uniform unit areas of the basin from where they originated. Thus it is not possible to solve the differential water balance equations for these points or unit areas using a computational time DT and from these equations to derive and use directly in GCMs the most important hydrologic variables, namely change of soil moisture and real evapotranspiration over the time interval DT.

The GCMs of an earlier generation assumed these differential equations to be for a hydrologic balance of nearly or completely uniform land surface and soil conditions, which was not realistic and did not permit advances in general circulation modelling.

It is therefore necessary, and the climate modellers have now fully realized this need, to use more complex approaches to simulate and parameterize land surface and soil moisture processes with the help of physically based macroscale hydrologic models. These did not exist, however, until relatively recently.

Why do physically based hydrologic models satisfy climate research requirements?

The requirements on hydrologic models for simulation of land surface processes in relation to the atmospheric boundary layer have been investigated by several authors. From the hydrologic researchers it was in particular Klemes (1985) who examined the suitability of hydrologic models for investigating the sensitivity of water resources to climate processes. He formulated the following general requirements for these models:

(a) They must be geographically transferable and this has to be validated in the real world;

(b) Their structure must have a sound physical foundation and each of the structural components must permit its separate validation;

(c) The accounting of evapotranspiration must stand on its own and should not be a by-product of the runoff accounting. Precipitation and potential evapotranspiration usually form the independent input variables.

It may be said that these requirements are inherent to physically based hydrologic models, as they represent the system's components as they appear in nature. While physically based models are satisfactory as regards their structure, their use presents several problems, the first relating to the different scales of hydrological processes.

Scale in hydrology

Depending on the space and time scale of a hydrologic investigation, different models and modelling approaches may be applied. A general overview of scale ranges of meteorologic and hydrologic processes is given in Figure 1. If the fundamental differential equations of the continuum hydro- and thermo-dynamics are applied to the modelling of the hydrologic land surface processes, they can only conserve a real-world validity on a microscale, where the conditions of continuity, internal homogeneity, etc. are sufficiently fulfilled, i.e. in a "topic" dimension (point, elementary plot, hydroteope, or homogeneous
The problem of the hydrologic macroscale is extensively discussed by the GCM modellers themselves. Dickinson (1985) indicated that most GCMs used, if they introduced the land surface hydrologic processes, Budyko's "bucket model." It represents a large scale lumped soil reservoir with one single layer, that can be filled to some maximum theoretical "field water capacity" (e.g., 150 mm) from which soil water evaporates at a rate proportional to the remaining water content. This macroscale "hydrology" conserves the mass (water) and net energy balance at the land atmosphere interface, but it is oversimplified in areal integration to the extent that the results of the modelling become questionable and are in many respects not in accord with reality. Efforts were therefore directed to use physically and biologically better based models. One interesting attempt was that of Warrilow (1986) who replaced the bucket model in a GCM by an improved hydrologic model. However, this model could not be validated against observed discharges within the framework of a river basin model.

Others attempted to take care of the complex processes in the soil-plant continuum, including the stomatal processes (Sellers et al., 1985). Their use and problems were characterized by McNaughton and Jarvis (1983):

"Plant communities are complex in ways that the atmosphere is not. If we had the wit and the computing power then we might solve the
equations of atmospheric motion and thermodynamics to a very close approximation, since the equations and properties of the system are quite well known. The biosphere, on the other hand, is replete with particular adaptations and special cases to such an extent that some biologists and ecologists deny that any general quantitative predictions can be made. Such people seem unduly pessimistic, of course, but they do have a point. There are no general laws of plant response to environment. Plant form and function are both highly variable. Our basic knowledge consists of a collection of empirical examples, all different but with some common trends which can be interpreted using some unifying conservation principles. Models, if they are to claim generality, must necessarily be approximate."

In consideration of Sellers' canopy model which contains 49 tunable constants, plus a leaf angle distribution function, it is further argued:

"There is a great scope for imagination here and, although it cannot be doubted that a careful selection of 49 values will give a good fit to almost any data available, the relationship between the model and the world can become tenuous. Let us, however, suppose that the model is accurate for a given canopy and soil, and that values for the constants have been selected. A GCM grid square of about $10^5$ km$^2$ contains many such units, so we must address the problem of averaging the model over the whole range of vegetation and soil types... Then we could calculate the behaviour of each of the different canopies separately and so form an average by weighing their individual contributions according to their fractional areas. But this is of course absurd.... If these arguments be accepted, then many parts of a reasonably complete model, such as Sellers', would have conceptual value only, signifying real processes but not describing them in any interpretable fashion. But what, in the context of a GCM, is the conceptual significance of a root resistance or a stomatal response to saturation deficit? Surely something simpler is indicated."

On the same lines Dooge (1985) discusses the problem of scales in hydrology, but in a more general way. He argues that the large scale usually means that "the finer scale processes may be either ignored or may be represented by their statistical effects on the large scale description." He states that "it has been found in practice that the models based on the continuum mechanics are too complex to allow for the spatially variable nature of hydrologic systems to be taken into account and they have been simplified to such an extent that they became in effect simple conceptual models."

As indicated above, modelling in hydrologic macroscale has begun only recently. It has been examined by Nemec (1970), Dooge (1981), Eagleson (1982), Fiering (1982) and Dyck (1983). The statement of the latter applies best to the problem of hydrology in the GCM: "One of the assumptions frequently made is that our understanding of the microscale elements and processes (in the hydrologic cycle) can, with minor modifications, be extrapolated in principle to the understanding of the macroscale environment, thus enabling reliable predictions to be made by linking the solutions to form a causal chain. Unfortunately, it seldom happens that way. Sooner or later, at some scale or characteristic dimension, mechanistic explanation breaks down and is
necessarily replaced by unverified causal hypotheses or statistical representations of the processes."

The extension of differential equations of hydro- and thermodynamically forced processes of moisture movement in a vertical column of the soil covered by vegetation to a basin or eventually to the large grid surface of GCMs is an excellent example of passing from a hydrologic microscale to a hydrologic macroscale. It is of course understandable to examine the microscale hydrologic processes in order to justify the prediction which will eventually have to be made on meso or macroscale. The microscale is, however, in our opinion unable to express the feedbacks, areal variabilities and other spatial integrational features needed to be included in a macroscale hydrologic land surface process model.

From the above and from our own experience it can be concluded that models based on continuum mechanics and/or on existing knowledge of transpiration control of vegetation canopy will hardly supply better results than the simplest models, such as the Budyko "bucket." The latter is oversimplified, while for the former, in the words of McNaughton "something simpler is needed." Here the knowledge of hydrologists is to be put to use and their existing conceptual physically based models could be a starting point for the "something."

The path towards an improved macroscale hydrologic land surface process modelling

The first large scale computations in hydrology were estimations of areal evapotranspiration for larger river basins, and finally for the whole land surface part of the earth, on the basis of the water balance equation in which long-term annual averages of precipitation and runoff were inserted. This is indicated in Figure 1 in the right upper part (Dyck, 1983). Later, in particular during the last decade, efforts were initiated to adopt shorter time scales as is indicated by the arrows in Figure 1.

A methodologically important attempt in this direction was the "statistical dynamic approach" of Eagleson (1978). It unifies in a coherent system a number of complex interrelated phenomena and represents them in an appropriate and efficient manner. The use of a modified infiltration equation of Philip results in an average annual local water balance equation by which the water balance is defined in terms of only four independent system parameters (three for soil, one for vegetation). Eagleson's approach is primarily oriented towards the incorporation of the vital short-term soil moisture dynamics into long-term average water balances. Thus it solves the time integration but does not deal satisfactorily with the integration of space variability.

In conceptual hydrologic models the areal non-homogeneities are in general averaged and expressed by lumped large scale parameters (including system parameters as well as inputs, state variables, etc). Such average values are then used in microscale dynamics (processes) to obtain a "lumped" representation of the macroscale system.

A very early attempt to improve this approach was the introduction of statistical distribution functions for most important parameters,
e.g. a linear distribution of the soil capacity for infiltration and evaporation within a river basin (so-called "source-area" method used by Crawford and Linsley (1966)). This method makes it possible to assess "statistically" the areal variability within a river basin of important system parameters.

Later the same principle was applied to the tension water storage capacity WSM of the rooted soil zone as is shown in Figure 2 (Becker, 1975). As a result, an improved macroscale soil moisture accounting model with three parameters (WSMAX, WSC, WSGR according to Figure 2) was obtained as a separate component for river basin models. This accounting procedure appears to be advantageous in three respects:

(a) It takes into consideration, at least to a first approximation, the areal variability of the storage capacity for tension water of the rooted soil layer (in contrast to other models, such as the "Sacramento Model," where this is considered a lumped parameter (Burnash, Ferral, 1980));

(b) It relates this storage capacity to soil and vegetation parameters which are observable in the basin, in particular field capacity, wilting point and root depth;

(c) It is capable of working with different computation time steps (Δt) without losing its physical relevance (in contrast to most infiltration excess models).

Thus, the model can be considered as physically based. In comparison with the simple Budyko bucket model, it introduces in the surface hydrologic cycle an areal distribution function and is applicable without the need for local calibration from observed rainfall and runoff series (as is usually necessary in conceptual catchment modelling). The final model equations derived by Becker (1985) may be used as a component of any large scale model (for a large grided surface or river basin area).

Figure 2 Real distribution (dashed line) and generalized distribution (solid line) of the soil storage capacity for tension water (WSM) within a river basin subarea AF (permeable soils, deep groundwater). AFC = fraction of AF.
That the model fulfills the expectations has been demonstrated by different operational applications of it as a sub-component within the framework of the river basin model system EGMO (Becker, 1985; Becker and Pfützner, 1986, 1987). It should be noted that these applications were for those subareas of the modelled river basins where the groundwater table is so far below the surface that plant roots cannot reach it (deep groundwater block in Figure 3). For the other parts of the basins (shallow groundwater areas, impervious areas, etc., see Table 1 and Figure 3), other specific submodels were applied. That for the shallow groundwater areas AN is described in the above-mentioned paper by Becker and Pfützner (1986).

Table 1 Subareas in a river basin with significantly different hydrological regime

<table>
<thead>
<tr>
<th>SUBAREA TYPE</th>
<th>SYMBOL</th>
<th>EVAPOTRANSPIRATION</th>
<th>DIRECT RUNOFF GENERATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open water surface</td>
<td>AW</td>
<td>potential</td>
<td>100% of precip.</td>
</tr>
<tr>
<td>Impervious area</td>
<td>AIMP</td>
<td>nearly zero</td>
<td>nearly 100%</td>
</tr>
<tr>
<td>Shallow groundwater</td>
<td>AN</td>
<td>potential</td>
<td>from saturated parts</td>
</tr>
<tr>
<td>Deep groundwater</td>
<td>AF</td>
<td>soil moisture dependent</td>
<td>nearly zero</td>
</tr>
<tr>
<td>Slopes with shallow permeable soils</td>
<td>AH</td>
<td>soil moisture dependent</td>
<td>interflow and infiltration</td>
</tr>
</tbody>
</table>

Two-level modelling approach

The approach of EGMO can be used as a basis for a two-level concept of hydrologic modelling. Furthermore, it is an intermediate between the coarse large scale approach of lumping all parameters over the river basin or other larger areas and the fine square grid based approaches as indicated below. It assumes the following modelling steps:

(a) Subdivision of the basin into hydrologically nearly homogeneous uniform subareas (with regard to evapotranspiration and runoff formation) in accordance with Table 1 and Figure 3;

(b) Modelling of moisture variations, evapotranspiration and "runoff production" in each subareas type by separate specific submodels (as mentioned in the last section) which take into account in a generalized form (statistically) the areal variability of important land surface characteristics within the subarea, but not the geographical position of each contributing elementary unit;

(c) Establishing of models for each of the existing flow systems in the river basin (surface flow and subsurface flow, possibly in different levels) by taking into account the water divides and the interlinks (inflows, outflows, extractions, feedbacks, etc.) between the different subsystems.
It may be noted that this approach implies on one hand a large scale oriented approximate solution of the areal integration problem, and on the other hand a step towards "two-level modelling." The first-level model is principally related to the vertical processes as indicated under (b):
- the moisture exchange with the atmosphere,
- the runoff production in each flow level of interest,
- the local or subarea type related water balance.
Accordingly the first-level model can provide all information which is required for coupling hydrologic land surface models and climate models.

The second-level model is concerned with the flow processes: surface flow, interflow and groundwater flow. Whereas the first-level model can be related to any land surface unit (river basins, small or larger uniform subareas, or grid areas), the second-level model has to take into account existing water divides and is therefore more closely related to river basins, aquifer systems, etc.

This two-level modelling approach is particularly suitable for the coupling procedure because it makes it possible to construct that part of the hydrologic model which will be coupled (the first-level model) in such a manner that it is already adapted to the requirements of climate models (e.g., grid structure). The other part (the second-level model) can then be related to river basins, aquifer systems, etc., as is usually done in hydrology. It is important here...
to clearly define the interface between these two modelling levels, and in particular the water exchanges between them (outputs in form of infiltration excess, soil percolation, exfiltrations, water extractions, feedbacks between different subsystems, grids, etc.). The first-level model must be able to supply the required inputs for climate models on one hand and river basin or aquifer system models on the other, independently of the space scale applied in the modelling approach.

The use of flexible grids

The atmospheric models assume a computation in grid points. The upper range of GCM grids is 250 to 500 km. For some purposes, however, finer grids are used (subgrids or different mesoscales according to Figure 1) with a lower limit of 10 km.

Hydrologic models start with much smaller grids (1 km or less). Except for large scale homogeneous land surfaces (for instance the Sahara) a 10 km grid is considered as a reasonable upper limit in any hydrologic modelling. Therefore such a grid could be a meeting point acceptable for hydrologic and climatic models. To make a step forward a flexible grid technique is however required so as to satisfy smaller or larger scales.

The present state of grid technique application in larger scale river basin modelling is represented by the work initiated by Girard (1970) and Solomon et al. (1968). The rationale behind the models of Girard et al. and Solomon et al. is different but the actual applications are similar. In the work of Solomon et al. the "study area" is covered with a square grid and then considered as a matrix of squares. The system is thus adapted for computer processing and is used first to store, process and retrieve information on each grid square and then to estimate, by multiple regression, precipitation, temperature and runoff distribution on a larger scale. It presumes a hydrologic regionalization of the larger "study area" so that the squares are hydrologically homogeneous. The method has been further developed and lately used as a model for information transfer and network design in the Amazon basin in Brazil (UNDP/WMO, 1983) and for similar purposes in Canada (Ambler, 1986). A similar recent application of grid techniques was recently undertaken in Sweden (Johansson, Jutman, 1986).

The approach of Girard (1970) was later developed by Girard et al. (1972) and in his work at INRS-CEQUEAU in Quebec transformed into the so-called CEQUEAU model by his co-authors. It was finally modified by Girard et al. (1981) into the so-called "modèle couplé." The model uses a conceptualization of the moisture regime and runoff production process in the soil in each grid square. A simple routing model and a distributed groundwater model based on the Darcy equation are used for the surface and for the groundwater flow respectively. Due to the use of the grid, the system is readily usable for input from remote sensing devices, in particular satellite pictures. As is obvious, this feature makes the model particularly suitable for linking with GCMs, because the remote sensed information will, in some cases, be the only directly observed data to be used in the land surface processes model. This was clearly demonstrated in practice.
during the HAPEX-1 experiment in France.

 Proposed approach for macroscale modelling

It is felt that the required progress in macroscale hydrologic land surface modelling can most efficiently be achieved by further development and application of the two-level modelling approach described earlier, in combination with square-griding for the first-level model. General principles of the first-level model and its application could be the following:

(a) The land surface area of interest, e.g. a grid area of a GCM or a large river basin, is subdivided into square subgrid units as shown in Figure 4. The size of these subgrid units is dependent on the areal variability of the hydrologic and climate conditions. In relatively homogeneous conditions the subgrid units can be 50 X 50 km, in some cases, 100 X 100 km or even greater (e.g. in the Sahara, in large flatlands, prairies, pampas, tundra, etc.). In other areas, e.g. in mountainous regions and in the case of river basin modelling for testing or other purposes, it will be necessary to consider smaller subgrid units, e.g. 10 X 10 km.

(b) The subgrid units are modelled separately without taking account of water divides between river basins (gauged or ungauged).

(c) The heat and moisture fluxes at the land surface, in particular precipitation and evapotranspiration, are estimated for each subgrid unit. Precipitation and all meteorologic mesoscale parameters which control potential evapotranspiration (air temperature, humidity, etc.) are considered as lumped inputs (or as uniformly distributed within the subgrid area, e.g. according to the long-term average areal distribution).

(d) Subareas of a significantly different hydrologic regime, in particular for evapotranspiration and runoff formation as indicated in Table 1, may be determined and separately treated within each subgrid unit (Figure 3).

(e) Physically based large scale oriented submodels are then used. Their parameters can be estimated for each subarea in all

![Figure 4 Schematic representation of a river basin and of a hydrologic subgrid within a GCM grid area.](image-url)
subgrid units from "real world" characteristics (soil, land use, vegetation, geology, geomorphology, etc.) by making use of generally available information such as maps, air photographs, satellite pictures, etc.

(f) Continuous computations of soil moisture variations, evapotranspiration and runoff formation are performed for each subarea in all subgrid units (for simplicity, subareas for which the meteorologic inputs and the model parameters are within a certain range can be grouped together in these computations).

(g) The computed subarea outputs are superimposed in each subgrid unit, to give lumped outputs (actual evapotranspiration, runoff formation from the subgrid in its main components: overland flow, interflow, percolation, see Figure 3).

(h) These outputs are then taken as inputs to GCMs and to second-level models related to river basins.

The second-level model is developed for selected test river basins where a comparison of simulated with observed river discharges is intended. The model simulates the dynamics of the most important flow systems:
- land surface and channel system;
- interflow system
- base flow system (short period and delayed component).

Submodels for the different systems may be either conceptual or distributed (hydraulics-based), grid related or not, according to the available information. The inputs into the model are outputs of the first-level model, which can be aggregated, in the presence of data as a macroscale distributed model input and in the absence of data as macroscale "statistically" lumped model input. The output of the second level model permits a validation of the whole modelling system using measured outflows from corresponding river basins, provided such measurements are at hand. In this way the global runoff data set can be used for the validation of the GCMs and their hydrologic components.

One additional interlink between both levels is the extraction of water from the above-mentioned flow systems by evapotranspiration (from open water surfaces and shallow groundwater areas, see Figure 3). A simplified solution of this problem on a larger scale has been presented in a recent publication by Becker and Pfutzner (1986).

Conclusions

After reviewing in brief the present situation in large scale hydrologic land surface modelling a proposal is made for a grid related first-level modelling which fulfills the requirements of climate models (GCMs) and a subsequent second-level modelling which is used for validation of the first-level and is river basin oriented. An important aspect of the proposed methodology is that it can be applied to any area of interest inside or outside of gauged river basins, i.e. also to the large GCM grid areas.

The critical problem in the practical application of the methodology is the requirement that the first-level models be physically based and their parameters be derived from generally available characteristics (soil, geological, geomorphological, land
use and others). Performance tests of the grid related first-level land surface models are possible by routing their outputs through the flow subsystems of existing gauged river basins in the investigated region. When a sufficiently good fit of computed and measured river basin discharges is at hand, this can be considered as an indication of the reliability and correctness of the results of the first-level model. This permits their extrapolation to other areas in the region (GCM grid areas, etc.) where no directly measured discharge data exist. It is considered that this is the only way of using measured discharge records for the benefit of climate models.

Indeed, it would be a waste to leave aside this important data source, which the GCMs cannot afford to do without at the present state of ground truth availability. The proposed model is readily usable for remote sensed data input, as demonstrated by the referenced literature, which however does not take into consideration the use of the measured discharge data for the validation of the parameters.

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