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Land surface modelling in hydrology and meteorology—lessons learned from the Baltic Basin

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Abstract

By both tradition and purpose, the land parameterization schemes of hydrological and meteorological models differ greatly. Meteorologists are concerned primarily with solving the energy balance, whereas hydrologists are most interested in the water balance. Meteorological climate models typically have multi-layered soil parameterisation that solves temperature fluxes numerically with diffusive equations. The same approach is carried over to a similar treatment of water transport. Hydrological models are not usually so interested in soil temperatures, but must provide a reasonable representation of soil moisture to get runoff right. To treat the heterogeneity of the soil, many hydrological models use only one layer with a statistical representation of soil variability. Such a hydrological model can be used on large scales while taking subgrid variability into account. Hydrological models also include lateral transport of water—an imperative if river discharge is to be estimated. The concept of a complexity chain for coupled modelling systems is introduced, together with considerations for mixing model components. Under BALTEX (Baltic Sea Experiment) and SWECLIM (Swedish Regional Climate Modelling Programme), a large-scale hydrological model of runoff in the Baltic Basin is used to review atmospheric climate model simulations. This incorporates both the runoff record and hydrological modelling experience into atmospheric model development. Results from two models are shown. A conclusion is that the key to improved models may be less complexity. Perhaps the meteorological models should keep their multi-layered approach for modelling soil temperature, but add a simpler, yet physically consistent, hydrological approach for modelling snow processes and water transport in the soil.

Keywords: land surface modelling; hydrological modelling; atmospheric climate models; subgrid variability; Baltic Basin

Introduction

Hydrologists and meteorologists have a common interest in developing better land surface modelling but, both by tradition and purpose, the land parameterisation schemes of their models differ greatly. Meteorologists are concerned primarily with solving the energy balance, whereas hydrologists are most interested in the water balance. This polarization of interests contributes to the scientific "culture clash" that exists between the two disciplines, although effort has been put into integrating the approaches, e.g. within GEWEX (Global Energy and Water Cycle Experiments).

Model scale is one factor of cultural difference between meteorology and hydrology. Meteorological models have their foundation in representing the large-scale processes, covering not only whole continents but also the entire globe. Lack of adequate computing power has always limited the reduction of grid square size, their horizontal unit of area. This is becoming less of a technological hindrance and, together with the increased use of regional climate models, grid square size has recently decreased significantly. Hydrological models have their origin in operational applications where adequate representation on the basin and sub-basin scale defines model dimensions. Thus, the two modelling cultures have co-existed on two quite different spatial scales.

Time scales are also different. Solution of the energy balance, together with numerical demands, requires time scales of the order of minutes in meteorological models. Hydrological models are often satisfied with daily timesteps, reflecting the resolution of observations for input and validation, and the lack of improved model performance at higher resolution in time.

Climate modelling over the Baltic Basin is the primary goal for both BALTEX (Baltic Sea Experiment) and SWECLIM (Swedish Regional Climate Modelling Programme). Recent results from these research programs show that continental scale runoff modelling for the Baltic Basin can be solved rather pragmatically with existing conceptual hydrological models (Bergström and Graham, 1998; Graham, 1999). This is in anticipation of more sophisticated, physically-based hydrological models that are plagued by problems of both limited geophysical data and insufficient computing power for such scales. Thus, meteorological models and hydrological models can finally meet on a comparable spatial scale. This allows for direct comparison of model results from the two different scientific approaches.

Additional differences between hydrological and meteorological approaches to land surface modelling are detailed below. This is followed by results obtained when using a hydrological model over the Baltic Basin, HBV-Baltic, to review the performance of atmospheric climate models on the continental scale. The runoff signal from river flow observations is used to calibrate and validate the hydrological model, which in turn is used to review the runoff processes in climate models. How this benefits future model development is then discussed.

A difference of approach

In addition to those introduced above, there are fundamental differences between meteorological and hydrological approaches to land surface modelling. The following discussion focuses on the physically logical, yet relatively simple, hydrological models typically referred to as "conceptual." These hydrological models usually rely on empirically derived functions for water fluxes, for which the energy balance is included as a semi-empirical component. Meteorological models traditionally depend on "theoretically" derived equations for fluxes of water and energy. However, theory must often be adjusted to available data and computational constraints, whence the approach becomes a "parameterisation." Put simply, this implies adjustments to the equations to get everything in balance, with particular emphasis on solving the energy budget. This is not entirely dissimilar to the process of "conceptualisation" applied by hydrologists.

The fact that meteorology uses grid squares as its primary unit, while hydrology uses runoff sub-basins, is not an obstacle for comparing the two approaches. Using sub-basins in hydrology allows for ease of model application and validation, but the response of the modelled system should be the same, no matter whether the area is a square or of some irregular shape. (However, dealing with the issue of deciding how to distribute runoff in grid squares that lie on a basin divide may not be trivial.) Of more practical importance is the proper definition of key variables in different models. For instance, what is typically called "runoff" in meteorological models is actually "runoff generation" in hydrological models. This is the excess water per surface unit (grid square or sub-basin) that is available for flow to the nearest streambed to eventually become "river runoff." It is simply,

$$\text{Runoff Generation} = P - EA - \Delta S$$

where, P = precipitation
EA = actual evapotranspiration
ΔS = change in storage. (snowpack, interception, soil moisture)

Runoff generation is an instantaneous value without translation or transformation for either groundwater, lake and channel storage, or transport time. In traditional hydrological terms, this is "effective precipitation," which is available for routing to the sub-basin outlet and includes snowmelt. Its dimension is millimetres per unit time. This should not be confused with "river runoff" or "river discharge," terms used synonymously for the measured streamflow in a river channel at some downstream point in the sub-basin. More specific differences between hydrological and meterological modelling approaches follow below.

HYDROLOGICAL TRADITION

Hydrological modelling is a well-proven standard tool for solving a vast number of water resources problems like flow forecasting, design of dams and reservoir operation. The scale transition has been debated since models for the GEWEX continental scale experiments have developed, and so has the meaning of the concept *distributed modelling*. The term distributed refers to modelled spatial discretization of both the terrain and its hydrological characteristics within a basin (Abbott and Refsgaard, 1996). Today, most hydrological models are distributed to some degree but it is still relevant to distinguish between *physically based* and *conceptual* models. The following focuses on the semi-distributed conceptual approach, which is the most commonly used in operational practice and, is represented here by the Swedish HBV model (Bergström, 1995; Lindström *et al.*, 1997). The important components of such a model are shown in Fig. 1, which is an illustrative schematic of the primary land surface processes represented by hydrological and meterological modelling approaches, respectively.

Hydrological models must provide a reasonable representation of soil moisture to predict runoff but they are typically less interested in soil temperatures. To treat the heterogeneity of the soil, many hydrological models use only one soil layer with a statistical representation of soil variability. The model becomes distributed through the use of elevation zones as shown by the stair step character of the schematic in Fig. 1, although it is not important to know exactly where in the basin these zones are located. Primary vegetation zones—open land, forest, lake surface—are assigned in each elevation zone. Actual evapotranspiration from each vegetation zone in each elevation zone is a function of available soil moisture in relation to field capacity (the water holding capacity of the soil) and potential

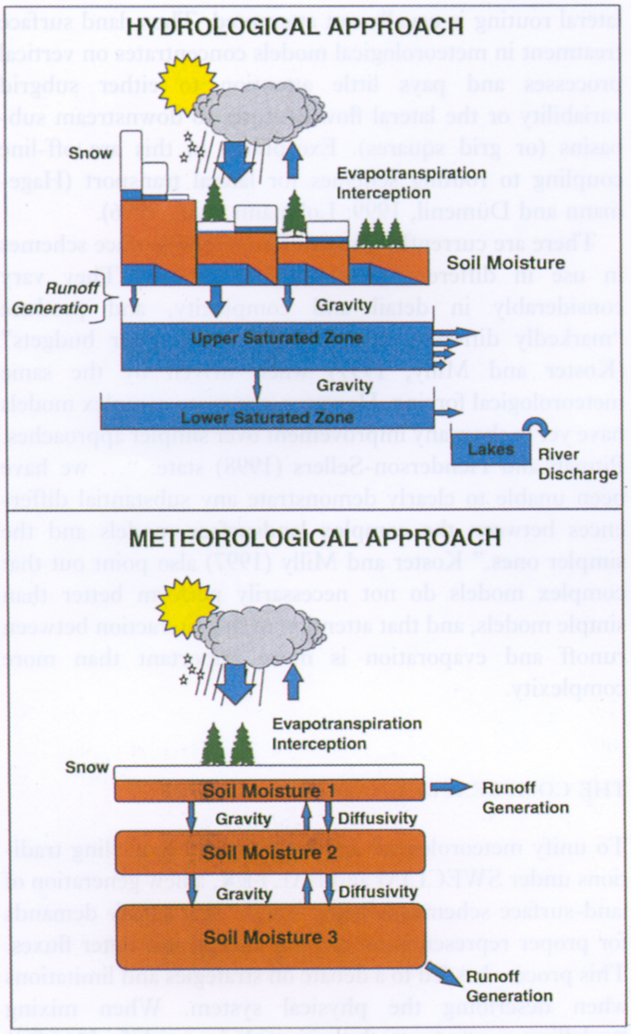

Fig. 1. *Schematic view of typical hydrological and meteorological approaches to surface parameterisation, shown for one sub-basin and one grid box, respectively. The hydrological approach is represented by the HBV Model with the following characteristics:*

- *the basin is divided into sub-basins if its complexity so requires*
- *large lakes are modelled explicitly, small lakes are integrated into the saturated zone*
- *each sub-basin is divided into elevation zones*
- *each elevation zone is divided into open land and forest*
- *snow accumulation can be distributed statistically in each elevation zone*
- *water is stored as snow, capillary water in snow, soil moisture, groundwater and lakes*
- *flow from the saturated zone is routed through lakes and rivers.*

evapotranspiration. Runoff generation in turn is also a variable function of soil moisture for each zone. Thus, the immense heterogeneity in soil conditions and area contributing to runoff is reduced to a statistical representation that can be mastered easily with limited computer power and demands for input variables.

Snow accumulation exhibits great spatial variability, particularly in wind-blown areas where redistribution is common. This is also modelled statistically by distributing snow accumulation according to different snow classes for each elevation zone. This is particularly important for elevations above the tree line. An important detail in snow modelling is to take account of the storage of liquid water in the snow before transport into underlying soils occurs. Experience shows this to amount to some 5–10% of the volume of the snowpack (Bergström, 1975; Vehviläinen, 1992). Due to lack of data for full energy balance computations, snow accumulation and snowmelt are normally modelled by a degree-day approach based on air temperature observations.

Runoff generation from the soil moisture zone flows downward by gravity into the groundwater, or saturated zone. In the hydrological model, it flows into artificial boxes that represent the response function of a sub-basin. This is where lateral flow routing due to lake storage, channel storage and travel time occurs; runoff generation is transformed from its instantaneous value to river discharge at the outflow of the sub-basin. Major lakes are modelled explicitly, while smaller lakes are integrated into the saturated zone of the model. This lateral transport of water is imperative if estimates of river discharge at streamflow gauging stations are to be attained.

In summary, the hydrological approach is detailed in the horizontal rather than the vertical sense. Such a model can be used on large scales while taking into account subgrid variability. Consequently, the HBV model has been applied to basins ranging in size from one to several hundred

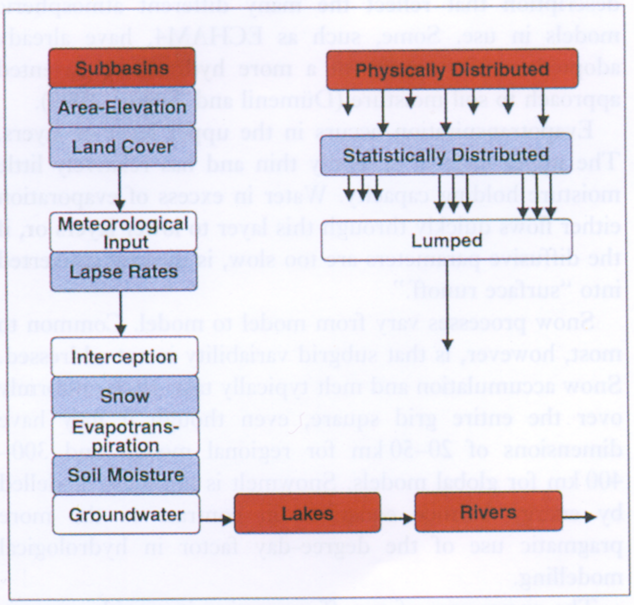

Fig. 2. *The three stages of the complexity chain and its structure in the HBV model, which is typical for many hydrological models.*

thousand square kilometres, without modification to its structure.

METEOROLOGICAL TRADITION

Meterological modelling was originally developed for short term forecasting of atmospheric variables, whereby models are updated with observations on short time scales. For this application, the land surface processes are not critical as they can never deviate far from prescribed conditions. Current use of meteorological models extends to climate modelling, not only over years, but also over tens of years. Under this extended application, the land surface processes are much more important, as they are no longer constrained. Updating with observations is no longer possible and feedback from the surface to the atmosphere influences climate results. Thus, the need for better performance from land surface modelling evolved. Recent effort has focused on assembling relevant validation data, comparing different models and assessing model deficiencies (Lohmann *et al.*, 1998; Robock *et al.*, 1998; Wood *et al.*, 1998).

Meteorological models often have multi-layered soil parameterisation that solves temperature fluxes with diffusive equations (Viterbo, 1996; Viterbo and Beljaars, 1995). Figure 1 shows three layers, but this varies from model to model. The same approach is often carried over to the treatment of water transport, with minor allowance for downward gravity flows. "Runoff" (i.e. runoff generation) typically occurs from two levels, the top surface layer and the bottom layer. Some modelling approaches have been criticized for not conserving the water balance due to relaxation to climatological deep soil conditions, but this is less common in current models. There are variations to this general description that reflect the many different atmospheric models in use. Some, such as ECHAM4, have already adopted certain aspects of a more hydrological oriented approach to soil moisture (Dümenil and Todini, 1992).

Evapotranspiration occurs in the upper layer or layers. The upper layer is generally thin and has relatively little moisture holding capacity. Water in excess of evaporation either flows quickly through this layer to lower layers or, if the diffusive parameters are too slow, is directly converted into "surface runoff."

Snow processes vary from model to model. Common to most, however, is that subgrid variability is not addressed. Snow accumulation and melt typically take place uniformly over the entire grid square, even though it may have dimensions of 20–50 km for regional models and 300–400 km for global models. Snowmelt is normally modelled by energy balance equations in contrast to the more pragmatic use of the degree-day factor in hydrological modelling.

The occurrence of runoff generation in a grid square is typically the end of the water cycle in a meteorological model. Combining flows from grid squares and further lateral routing is usually not attempted. Thus, land surface treatment in meteorological models concentrates on vertical processes and pays little attention to either subgrid variability or the lateral flow of water to downstream sub-basins (or grid squares). Exceptions to this are off-line coupling to routing schemes for lateral transport (Hagemann and Dümenil, 1999; Lohmann *et al.*, 1996).

There are currently many different land surface schemes in use in different meteorological models. They vary considerably in detail and complexity, and produce "markedly different surface energy and water budgets" (Koster and Milly, 1997) when driven by the same meteorological forcing. However, the more complex models have yet to show any improvement over simpler approaches. Pitman and Henderson-Sellers (1998) state: "... we have been unable to clearly demonstrate any substantial differences between the complex landsurface models and the simpler ones." Koster and Milly (1997) also point out that complex models do not necessarily perform better than simple models, and that attention to the interaction between runoff and evaporation is more important than more complexity.

THE COMPLEXITY CHAIN

To unify meteorological and hydrological modelling traditions under SWECLIM and BALTEX, a new generation of land-surface schemes is being sought that satisfy demands for proper representation of both energy and water fluxes. This process has led to a debate on strategies and limitations when describing the physical system. When mixing modelling components, there is an obvious risk for interface problems if the principles for model distribution are in disharmony.

One critical point that has been identified is the complexity chain in coupled modelling systems. Model components can normally be classified as physically distributed, statistically distributed or lumped, depending on the degree of sophistication in the description of the system. A physically distributed component models the process on its proper geographical location while statistical distribution means that only the sub-basin fraction of the characteristics is required. Examples of the latter are elevation zones, vegetation zones, or recharge and discharge areas in hydrological modelling.

While a fully physically based distributed model component can be aggregated into statistically distributed and lumped approaches, the reverse is difficult to achieve. As an analogy, it is difficult to separate different colours once paint is mixed! Figure 2 illustrates this in the HBV model. There is a tendency to go from higher to lower degrees of sophistication although some inconsistencies can be identified. Routing in lakes and rivers is based on additional local information and therefore a shift towards more physical methods can be justified.

Results from the Baltic Basin

Within both the BALTEX NEWBALTIC project (Numerical Studies of the Energy and Water Cycle of the Baltic Region) and SWECLIM, modelling the climate of the Baltic Sea Region is in focus. As with the other GEWEX continental experiments, developing coupled atmospheric, oceanographic and hydrological models is a primary objective. Validation of models is an important step towards that goal. A valuable source of validation data is the recorded runoff to the entire Baltic Sea.

Along with other climatological databases, the runoff record is used in a continental scale water balance model of total river flow to the Baltic Sea, HBV-Baltic. This comes from the HBV hydrological model and is the largest scale application of this model to date (Bergström and Graham, 1998). A map showing the extent of HBV-Baltic is shown in Fig. 3; model details are available in Graham (1999).

An effective way to use the runoff record in model development is to apply the hydrological model as a type of validation tool for review of atmospheric climate model results (Graham and Jacob, 2000). Not only can one use the hydrological model to transfer backward from river discharge to runoff generation, but other important model processes, such as snow and soil moisture, can be evaluated. Review studies consist of using climate model results as forcing for HBV-Baltic. The climate-model-forced HBV-Baltic results are then compared to corresponding results from the atmospheric models.

Although HBV-Baltic is by no means considered the absolute truth, the HBV model has been tested enough in other applications over the years to give it a measure of credibility. Previous validation studies show that HBV has to get the soil moisture and snow processes reasonably right in order to get runoff right. Further scrutiny through internal model process validation studies for snow and soil moisture routines have also been carried out (Andersson and Harding, 1991; Lindström *et al.*, 1997). As HBV-Baltic is calibrated with all available runoff data to the Baltic Sea, this logic leads to the conclusion that HBV-Baltic provides a reasonable representation of the runoff processes in the basin. Comparison with models such as this is one step that can be taken in the absence of adequate observations for validation. However, results on the HBV-Baltic scale should not be considered as absolute values at a point, but rather index-type measures of average conditions over the given basin area.

Several applications of this type of review have been made to date. In Figs. 4 through 7, results from two separate climate models are presented. The first is the Max-Planck-Institute global climate model (ECHAM4), run on a spatial resolution approximating 100 km grids (Stendel and Roeckner, 1998). The second is the first version of the Rossby Centre regional atmospheric (RCA0) model, run on a spatial resolution approximating 44 km grids (Rummukainen *et al.*, 1998). Both are 10-year integrations of the present climate, but they are not driven with the same forcing. Therefore, direct comparison of like years is not possible between the atmospheric models. The results shown here are summarized for the total Baltic Sea Drainage Basin, but more-detailed comparisons between different regions of the Baltic Basin have also been made.

Figure 4 shows daily results for snow water equivalent. Both atmospheric models show modelled snow values much lower than in HBV-Baltic with the same forcing. The snow season appears to get off to a good start early in the cold season, but the snowpack never reaches the same magnitude as in HBV-Baltic. As total precipitation (i.e. no separation into rain and snow) from the climate models was used to drive the hydrological model, this implies that snowmelt must be much higher in both of the atmospheric models.

Figure 5 shows daily results for soil moisture, expressed in terms of *soil moisture deficit* (smd). This is a more relevant quantity to compare as it reflects the amplitude of change for soil moisture. Some models have absolute values for soil moisture that are disproportionately large. Although this may be physically wrong, it makes little difference if the volume is never used; it equates to a type of dead storage. Therefore, it is only the dynamic part of the soil moisture that is of interest, particularly when comparing model outputs.

There is no consensus in results between the climate models for smd. ECHAM4 shows trends of wetter soil conditions (low soil moisture deficit), whereas RCA0 shows considerably drier conditions (high soil moisture deficit). The general seasonality in both cases is reasonable; soil moisture is highest in winter and lowest in summer as should be expected.

Figure 6 shows monthly results for evapotranspiration. This variable is perhaps the most difficult to evaluate as there is so much uncertainty regarding its true value. Widespread measurements are not readily available and there is no established basis to confirm that one model does a better job than the other in simulating evapotranspiration. Common to both comparisons is that wintertime evapotranspiration is higher in the atmospheric models than in the hydrological model. These differences in winter are not surprising as wintertime evapotranspiration in the HBV model is included in a general snowfall correction factor when the ground is covered by snow. It is thus not modelled explicitly under such periods and does not show up as evapotranspiration in model results.

Figure 7 shows monthly results for runoff generation. For both comparisons, the atmospheric models show considerably lower runoff than the hydrological model. In neither case do they reach the magnitudes of runoff apparent in HBV-Baltic. This is direct evidence that the land surface routines of climate models have a long way to go before runoff processes can be directly used for further analyses, such as climate change impact studies to water resources. For the RCA0 model, this result was expected as it was known that water is not conserved in this model due

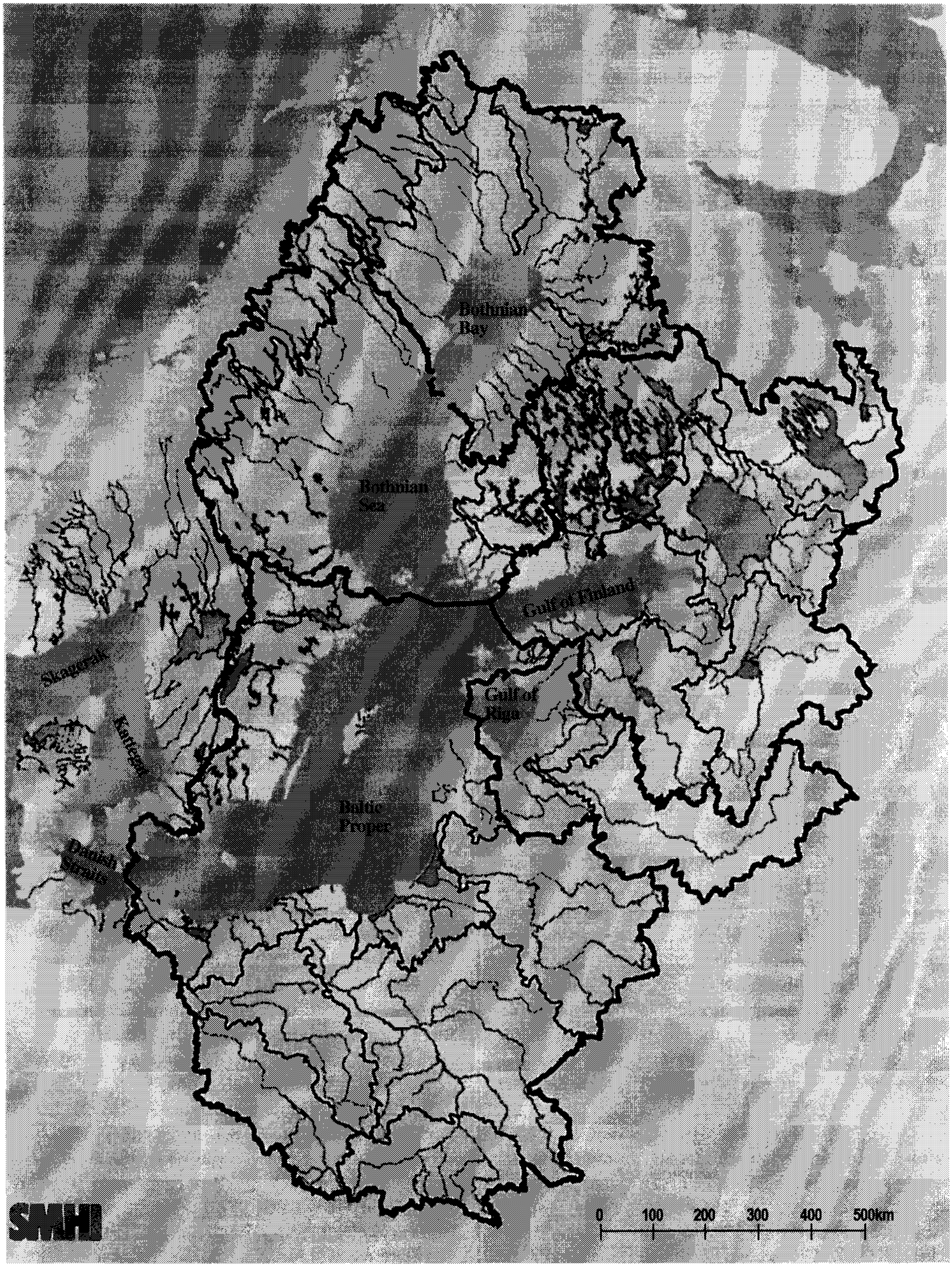

Fig. 3. *The Baltic Basin and sub-basins used in the large-scale hydrological model HBV-Baltic.*

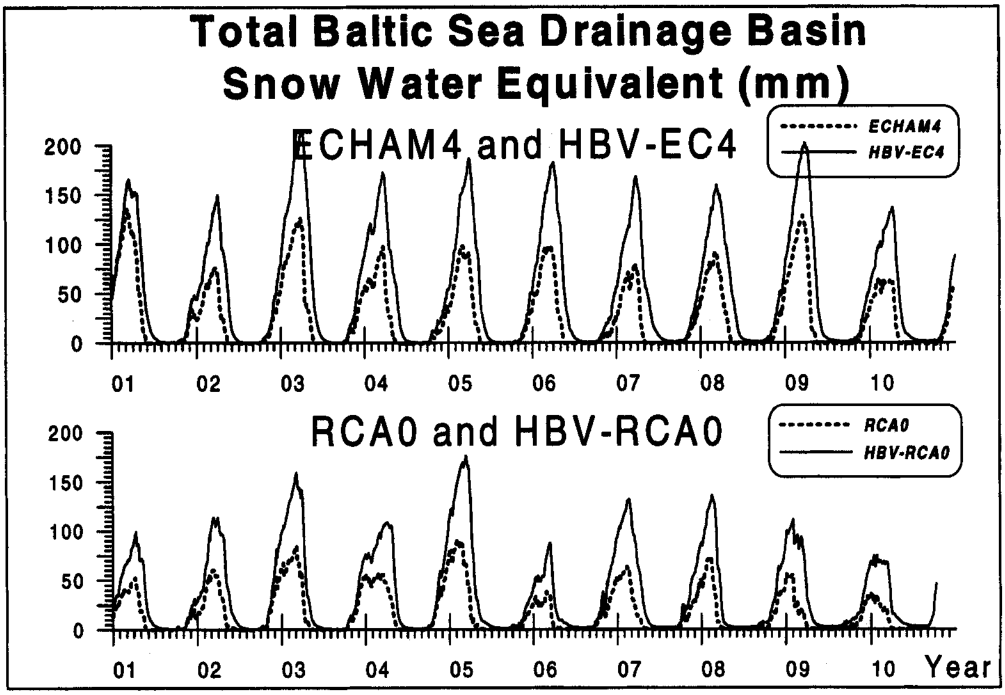

Fig. 4. *Modelled snow water equivalent (mm) over the total Baltic Sea Drainage Basin, where direct climate model output (ECHAM4 and RCA0) is compared to output from HBV-Baltic with climate model forcing (HBV-EC4 and HBV-RCA0).*

to relaxation to climatological deep soil conditions (this has been corrected in the next version of the model).

Of particular interest for this type of comparison between models is to see how changes to model parameterisations affect results. If one takes the results presented above as the first iteration in continued model development, similar

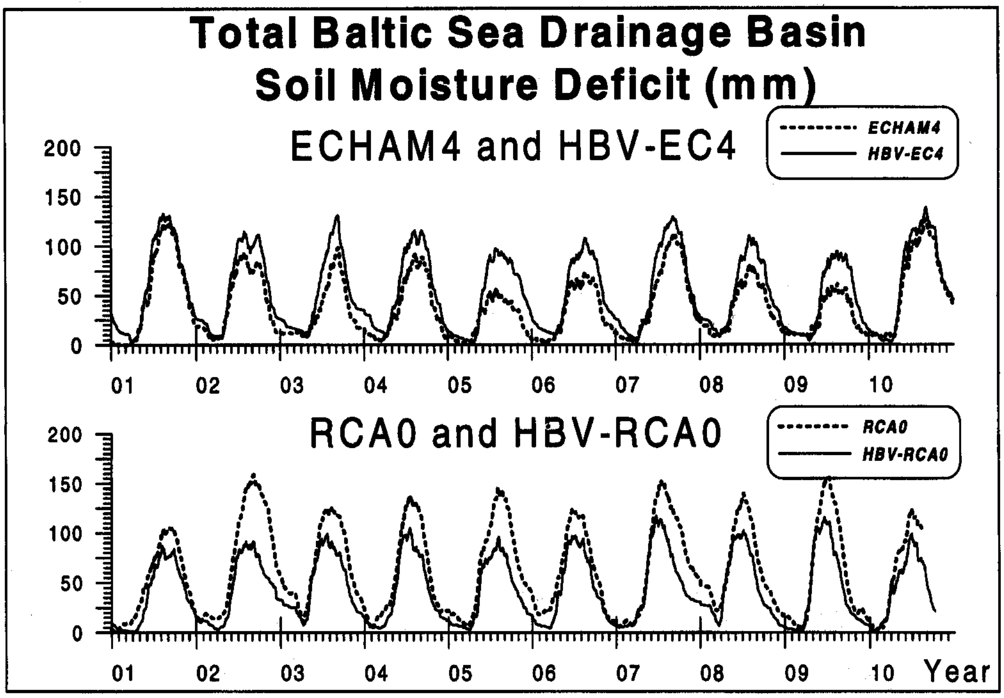

Fig. 5. *Modelled soil moisture deficit (mm) over the total Baltic Sea Drainage Basin, where direct climate model output (ECHAM4 and RCA0) is compared to output from HBV-Baltic with climate model forcing (HBV-EC4 and HBV-RCA0).*

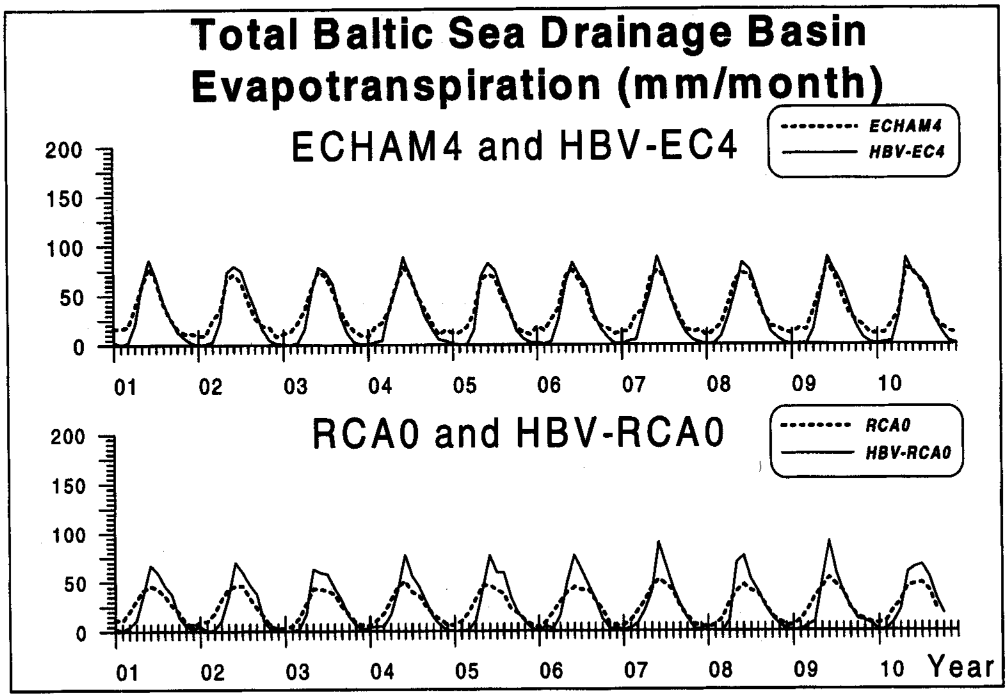

Fig. 6. *Modelled evapotranspiration (mm/month) over the total Baltic Sea Drainage Basin, where direct climate model output (ECHAM4 and RCA0) is compared to output from HBV-Baltic with climate model forcing (HBV-EC4 and HBV-RCA0).*

analyses should be made after changes are made in the atmospheric models. Keeping the HBV-Baltic calibrations constant, forcing from modified versions of either ECHAM or RCA should be used for additional hydrological model runs. For instance, changes to the atmospheric snow routine should show up in the hydrological review. If the two

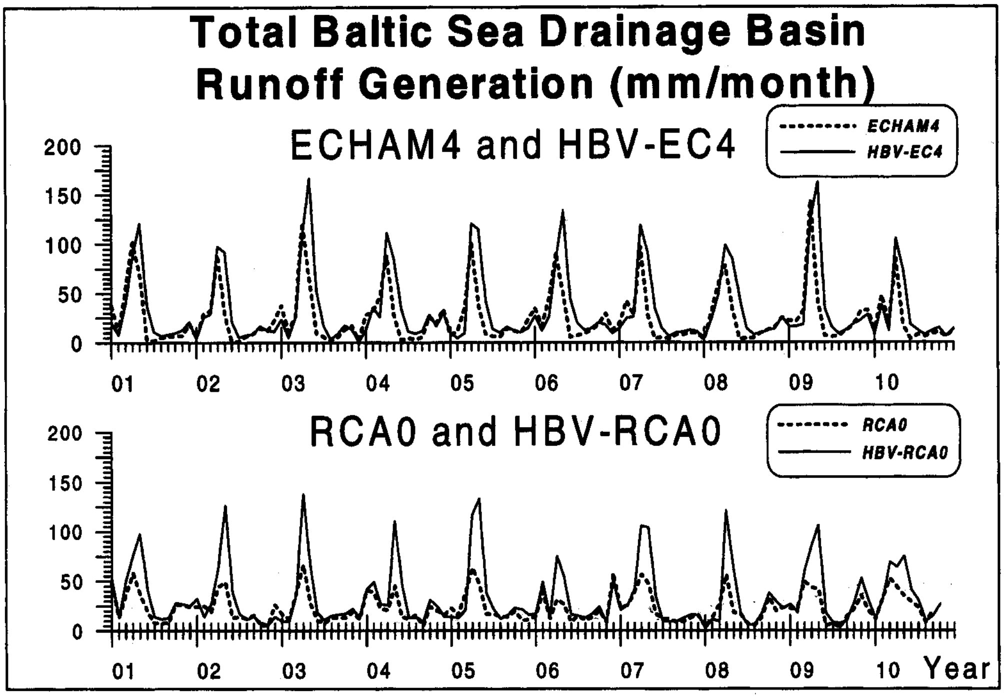

Fig. 7. *Modelled runoff generation (mm/month) over the total Baltic Sea Drainage Basin, where direct climate model output (ECHAM4 and RCA0) is compared to output from HBV-Baltic with climate model forcing (HBV-EC4 and HBV-RCA0).*

curves—climate model and HBV-Baltic with climate model forcing—come closer to one another, positive improvements have likely been made.

Thus far, the iterative step of reviewing results from modified climate model parameterizations has not been taken. This is the logical next step and is under way within SWECLIM as discussed below.

The future

More advanced models are needed to bridge the scientific gap between meteorology and hydrology. However, this need not mean more complexity! Perhaps the meteorological models should keep their multi-layered approach for modelling soil temperature, but add a simpler, yet physically consistent, hydrological approach for modelling water transport in the soil. They could thus address subgrid or sub-basin variabilities in a heterogeneous landscape in a realistic, but still practical manner. Some aspects of this are already included in the ECHAM4 model (Dümenil and Todini, 1992). Further development requires an intensified use of both field data and re-analysis data for the internal validation of the individual components of land parameterisation schemes to overcome problems, such as those related to compensating errors.

Hydrological modelling experience can also be used to better parameterise the subgrid variability of snow processes in climate models. In mountainous areas in particular, there can coexist three separate seasons in a single grid square—winter, spring and summer! Hydrological snow models, with their degree-day tradition, are often described as simple in comparison to the more sophisticated physically-based schemes of meteorological models, but they can describe snow processes in much more detail. As illustrated in Fig. 1, they include elevation zoning and lapse rates, variable vegetation cover, statistical snow distribution for drifting, and water-holding capacity of snow. This comprehensive treatment is difficult to incorporate directly into atmospheric models. However, with compromise, this experience can be used to improve the areal discretisation of snow processes.

Modelling evapotranspiration is one place where improvement is needed for both meteorological and hydrological approaches. There is much uncertainty involved and little validation data available. The various flux measurement campaigns taking place in the Baltic Basin and surrounding areas may play a key role in improvements. Questions such as the degree of variation with different land cover and the importance of wintertime evapotranspiration need to be addressed. A high bias in wintertime evapotranspiration for both ECHAM4 and RCA0 offers a possible explanation for some of the underestimation of snow, and hence runoff, in these models. Unfortunately, it is not currently possible to estimate accurately how much winter evapotranspiration contributes to the HBV snowfall correction factor for comparison. This must be investigated in future studies.

The question of time scales still needs to be addressed. How relevant are short time scales really, when land surface modelling is mostly focused on long-term simulations? Aside from numerical and some diurnal considerations, are daily results not sufficient for most land surface variables? And if so, why not apply appropriate time scales to appropriate parameters, instead of forcing all parameters to the same timestep?

Within SWECLIM, cooperation between hydrological and meteorological modellers is well established. Changes reflecting the hydrological approach have already been introduced into the second version of RCA and plans for further development are under way for the third version. For each new development, HBV-Baltic will be used to review results as described above. Thus, changes to the land surface scheme can be evaluated systematically. In turn, aspects of the meteorological approach will be incorporated into improved evapotranspiration modelling for HBV-Baltic. This is a prerequisite for more detailed modelling of future climate water resource scenarios.

Conclusions

Spoken and written communication between disciplines deserves more attention. The use of technical jargon is commonplace in all sciences, allowing each group to create their own special language. Unfortunately, this leads mainly to confusion. Even fundamental concepts can be misunderstood. For instance, it may seem trivial to spend time defining such basic terms as runoff, but experience has shown that meteorologists and hydrologists have different perceptions of what this is; the same can be said about soil moisture and water pathways. Interdisciplinary discussions should always devote some time to defining basic concepts and jargon so that everyone involved knows what is being discussed. Moreover, an effort should be made to reduce the *abuse* of technical jargon.

One common problem in all modelling is compensating errors. This might block further development, as improvement in one process description may be interpreted falsely as a failure if a compensating error is not simultaneously analysed. More attention must be paid to internal process validation in future models. The application of a hydrological model to a continental scale basin has great potential as it offers opportunities to review how the physical processes are modelled and behave.

Finally the concept of a complexity chain helps to avoid inconsistency traps in unified modelling. This means that the degree of discretization should be logical and normally follow a declining scale through the modelling process. This helps to develop consistent, robust models and avoids systems of insurmountable complexity.

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