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Modelling Hydrological Consequences of Climate Change—Progress and Challenges

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ABSTRACT

The simulation of hydrological consequences of climate change has received increasing attention from the hydrology and land-surface modelling communities. There have been many studies of climate-change effects on hydrology and water resources which usually consist of three steps: (1) use of general circulation models (GCMs) to provide future global climate scenarios under the effect of increasing greenhouse gases, (2) use of downscaling techniques (both nested regional climate models, RCMs, and statistical methods) for "downscaling" the GCM output to the scales compatible with hydrological models, and (3) use of hydrologic models to simulate the effects of climate change on hydrological regimes at various scales. Great progress has been achieved in all three steps during the past few years, however, large uncertainties still exist in every stage of such study. This paper first reviews the present achievements in this field and then discusses the challenges for future studies of the hydrological impacts of climate change.

Key words: climate change, water-resources assessment, water balance, regional scale, hydrological models, review

1. Introduction

The effects of climate change on hydrological regimes have become a priority area, both for process research and for water and catchment management strategies. This is a three-step process basically consisting of: (1) the development and use of general circulation models (GCMs) to provide future global climate scenarios under the effect of increasing greenhouse gases, (2) the development and use of downscaling techniques (both nested regional climate models, RCMs, and statistical methods) for "downscaling" the GCM output to the scales compatible with hydrological models, and (3) the development and use of hydrological models to simulate the effects of climate change on hydrological regimes at various scales. General reviews of the methodology and progress in simulating river flow from GCM-derived climate change scenarios include, among others, Leavesley (1994) and Xu (1999a). However, since then great progress and improvement have been achieved in all three stages of the research field. It is therefore needed to review the new developments and discuss the challenges that we are now facing. For example, in most GCMs, the simple bucket models have been replaced by more physically-based SVAT models which provide better simulations of the vertical water distribution at each grid point at each time interval (e.g., Dolman et al., 2001). More and more physically-based regional climate models have been developed and tested to account for sub-GCM grid-scale forcing (e.g., complex topographical features and land-cover heterogeneity) in a physically-based way and to enhance the simulation of atmospheric circulations and climatic variables at fine spatial scales (e.g., Rummukainen et al., 2004). A variety of statistical downscaling techniques has been developed (e.g., Wilby et al., 2000; Stehlik and Bardossy, 2002; Hellström and Chen, 2003; Wetterhall et al., 2005a, b) and used in hydrological studies. Considerable effort has also been expended on developing improved hydrological models for estimating the effects of climate change with a focus on a realistic representation of the physical processes involved (e.g., Ma et al., 2000; Müller-Wohlfeil et al.,

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2000; Engeland et al., 2001; Kunkel and Wendland, 2002; Graham, 2004). Computer developments have also made it possible to increase the spatial resolution of the different models and to increase the number of scenario runs with each model. The current limit is the 10-km-resolution GCM run on the supercomputer Earth Simulator (Ohfuchi et al., 2004).

The objectives of this paper are: (1) to review the existing methods/models for assessing water resources under changing climate conditions at different spatial and temporal scales with emphasis on the new developments made after 1999, and (2) to discuss challenges that remain and the possible further developments in the field. The paper is intended to be a useful reference to those hydrologists who are working with impact studies of climate change. However, it does not intend to discuss all individual methods/models that have appeared in the literature; instead, representative methods/models are discussed.

The paper is organized as follows. Methodologies for assessing hydrological responses to global climate change are reviewed and discussed in section 2. Progress and challenges related to the impact study methods are discussed in section 3. Conclusions are presented in section 4.

2. Hydrological simulation under changing climate

The tremendous importance of water in both society and nature underscores the necessity of understanding how a change in global climate could affect the availability and variability of regional water resources. It is not surprising that the hydrological literature now abounds with regional-scale hydrological simulations under greenhouse scenarios. Despite the progress achieved in the last few years, there are still many unsolved problems. For example, the scale dilemma in applying hydrological models to impact studies as discussed by Schulze (1997) still exists. Detailed regional climate scenarios that are used as input to hydrological models must be obtained from the coarse-scale output of GCMs by using three main methods: simple interpolation, statistical downscaling, and high-resolution dynamic modelling (e.g., IPCC, 2001). Due to the difficulties involved in the modelling of hydrological response to the global climate change, various approaches have been carried out by researchers working at different institutions.

Approach 1: Direct use of GCM output. The approach is to directly use the GCM-derived hydrological output since the GCM is the only available tool for detailed modelling of a future climate. River flow has been modeled in GCMs for years. Until recently, the methods have, however, been simplistic (Varis et al., 2004). The deficiency of GCMs in providing detailed regional hydrological scenarios has been discussed in many studies including IPCC (2001), Schulze (1997), and Xu (1999a). The main problem includes the too-coarse scale of the GCMs and that the GCMs calculate precipitation with large errors. Over the past few years, tremendous advances have taken place in our ability to simulate the earth climate in general, and land-surface processes in particular. For example, the use of physically-based SVAT models in GCMs provides better simulations of the vertical water distribution at each grid point at each time interval (e.g., Dolman et al., 2001), and incorporation of flow routing has increased the ability of GCMs to simulate runoff and streamflow (Varis et al., 2004). Despite recent advances in the representation of land-surface processes in general circulation models (GCMs), large uncertainty still exists in GCM-simulated land-surface processes, which require further quantification through model intercomparisons and new model simulations. Arora (2001) has pointed out the competency of the third-generation GCM of the Canadian Centre for Climate Modelling and Analysis to simulate the global hydrological cycle and the globally averaged precipitation and runoff over land. However, the streamflow simulations for 23 major river basins were inaccurate; the mean annual runoff was within 20% of the observed estimates for only 4 river basins. Poorly simulated regional precipitation and errors associated with the land-surface scheme (partitioning of precipitation into evapotranspiration and runoff is not realistic) were the main reason for the deficiencies. Development in the representation of hydrological processes in land-surface schemes and improved regional precipitation estimates with higher GCM resolutions will produce better streamflow simulations in the future. Such research could facilitate future evaluation of impacts in a risk assessment framework (IPCC, 2001).

Approach 2: Regional climate models. As discussed above, general circulation models (GCMs) are used to generate projections of future climate change on large spatial and temporal scales (several decades). Even as GCM grid sizes tend towards one or two degrees, there is still a significant mismatch with the scale at which many hydrological and water resource studies are conducted (Varis et al., 2004). Regional climate models (RCMs) have been developed by using dynamic downscaling techniques to attain horizontal resolution on the order of tens of kilometres, over selected areas of interest. This nested regional climate modelling technique consists of using initial conditions, time-dependent lateral meteorological conditions derived from GCMs (or analyses of observations) and surface boundary conditions to drive high-resolution RCMs (e.g., Cocke and LaRow, 2000; von Storch et al., 2000). The basic strategy is, thus, to use a global model to simulate the response of the global circulation to large-scale forcings and an RCM to (1) account for sub-GCM grid-scale forcing (e.g., complex topographical features and land-cover inhomogeneity) in a physically-based way; and (2) enhance the simulation of atmospheric circulations and climatic variables at fine spatial scales (up to 10 to 20 km or less). More recently, significant improvements have been achieved in the area of nested RCMs (Christensen et al., 2001; Varis et al., 2004). The ability of RCMs to reproduce the present day climate has substantially improved. New RCM systems have been introduced including multiple nesting and atmospheric RCMs coupled with, e.g., lake and hydrology models (e.g., Rummukainen et al., 2001; Hay et al. 2002; Samuelsson et al., 2003; Rummukainen et al., 2004). The effects of domain size, resolution, boundary forcing and internal model variability in RCMs are now better understood.

The main theoretical limitations of this technique that remain to be improved include (Hay et al., 2002; Varis et al., 2004): (1) the inheritance of systematic errors in the driving fields provided by global models. For example, boundary conditions from a GCM might themselves be so biased that they impact on the quality of the regional simulation, complicating the evaluation of the regional model itself (e.g., Hay et al., 2002). (2) Lack of two-way interactions between regional and global climate, and (3) the algorithmic limitations of the lateral boundary interface. Other limitations are: (1) depending on the domain size and resolution, RCM simulations can be computationally demanding, which has limited the length of many experiments to date, and (2) there will remain the need to downscale the results from such models to individual sites or localities for impact studies (Wilby and Wigley, 1997; Xu, 1999a). It is essential that the quality of GCM large-scale driving fields continues to improve as these operate the regional climate simulations (Varis et al., 2004).

Approach 3: Global water-balance models. Global water-balance models calculate the water balance of each grid cell globally and route the runoff to the oceans or to an inland sink. The routing could be with or without time delay. The three main global water-balance models, MacPDM, WBM and WGHM/WaterGAP, have all been used in the climate studies by Arnell (1999a, 2004), Vörösmarty et al. (2000) and Alcamo and Henrichs (2002), respectively. Global water-balance models normally work with a spatial resolution of $0.5^\circ \times 0.5^\circ$ latitude and longitude and with a daily or monthly time step. They must be simple since data are not available globally for setting parameter values in complicated models. An important task is the regionalisation of parameter values to ungauged areas, which account for an important fraction of the global land-surface area. Uncertainties in global hydrological modelling arise from model uncertainties and data uncertainties, including input, calibration (model tuning) and validation data. Precipitation is the major part of the input-data uncertainties, independent of whether it is based on measurements (Fekete et al., 2004) or simulated by a GCM (Arora, 2001). River runoff is used for parameter-value estimation and validation. One problem to tackle is the fact that almost all the large rivers of the world are regulated, while hydrological models usually model natural flow. The global water-balance models are run "off-line" (without feedback) with the climate forcing from GCMs in climate studies.

Pure global routing models exist in addition to the global water-balance models. These models only compute lateral water flows and need gridded runoff as input. They are often coupled to GCMs or land-surface models, either online or off-line. Examples of such models are the model by Miller et al. (1994), the HD model (Hagemann and Dümenil, 1998), TRIP (Oki et al., 1999) and the model by Arora and Boer (1999). Global-scale models also include detailed dynamic global vegetation models that simulate the carbon cycle and thus can model evaporation changes without changes in the climate forcing (Gerten et al., 2004). Such models include land-surface models and can be coupled to GCMs (Kuchareik et al., 2000).

Global water-balance models provide an opportunity for hydrologists to look at hydrological properties and variability consistently over large geographical domains, at a detail finer than normally can be provided by real hydrological data and GCM output. The previous studies have shown that the quality of the simulated flow is very constrained by the quality of the input data followed by the estimated model parameters (or at least some of them), with model form being least significant (Arnell, 1999b).

Approach 4: Macroscale (continental-scale) hydrological models. Simulation of water resource response has been carried out on the world's largest river basins with macroscale hydrological models driven by hydroclimatic data from GCMs or RCMs. We distinguish macroscale models from global water-balance models in such a way that the macroscale (continental-scale) models focus on the water-balance computation of particular large catchments (e.g., Liang et al., 1994; Ma et al., 2000; Kunkel and Wendland, 2002; Graham, 2004), while global models attempt to simulate water balance globally (Arnell, 1999a, 2004; Vörösmarty et al., 2000; Döll and Seibert, 2001; Döll et al., 2003; Alcamo and Henrichs, 2002). In the literature, global models are also called macroscale models (e.g., Arnell, 1999a, 2004). The key characteristics of a macroscale model include: (1) The model should be transferable from one geographical location to another. Model parameters should therefore be physically relevant. (2) The model should be applied either to every sub-basin in the spatial domain or on a regular grid. (3) Runoff must be routed from the point of generation (the fundamental unit) through the spatial domain along the river network.

Two types of macroscale hydrological models are currently developed. The first ones are macroscale water-balance models, MWB, (e.g., Engeland et al., 2001; Graham, 2004) which focus on the catchment water balance and provide no coupling with GCMs or RCMs and run "off-line". The second type is macroscale land-surface hydrological models, MHM, (e.g., Liang et al., 1994; Chen and Dudhia, 2001) which have a primary purpose of improving the land-surface hydrological characteristics of global climate models, regional climate models and meso-scale meteorological models. Compared with the first type of model, the MHM uses the energy balance as its primary concept and it could be coupled with GCMs/RCMs, and therefore it could run with smaller time steps. A discussion of the critical issues involved in MHMs can be found in Dolman et al. (2001) and Singh and Frevert (2002).

Two approaches have been used in developing an MHM: The first is improving the energy-balance process within an existing hydrological model and enabling it to couple with an atmospheric model (e.g., Liang et al., 1994; Wood et al., 1997) and the second is improving the hydrological processes in land-surface models developed for atmospheric models (e.g., Kim et al., 2001; Chen and Dudhia, 2001; Ledoux et al., 2002). The water-balance and energy-balance equations at the land surface are connected through the rate of evaporation that appears in both equations (Fig. 1), and the energy-balance and radiation-budget equations at the earth surface that are linked through the net radiation (Fig. 1). This gives yet another method to estimate evaporation, i.e., considering it as the residual in the energy-balance equation. The results of these studies (e.g., Chen and Dudhia, 2001; Ledoux et al., 2002) show that coupling the hydrological model with GCMs/RCMs results in a better representation of the recorded flow regime than GCM-based predictions of runoff for large river basins.

Coupled modelling of the atmospheric and hydrological processes is proved to be a powerful tool to study the spatial and temporal evolution of the water and energy budgets of a basin. Moreover, the coupled model can make good use of largely-existing hydrological measurements and greatly improve the simulation accuracy. Interests in such modelling exist for both the atmospheric and hydrological communities (Ledoux et al., 2002): (1) the accurate surface description of the basin and a better understanding of the physical processes are expected to improve the atmospheric forecasts; (2) water cycle climatology and surveys can be used to manage the water resources. Moreover, the impact of climatic changes on the basin can be studied. The main problem in using such models is that the large amount of hydroclimatic and topographic data needed for model calibration may not available everywhere.

Approach 5: Hypothesized scenarios. The fifth approach, namely the use of hypothesized scenarios as input to catchment-scale hydrological models, is also widely used (e.g., Nemec and Schaake, 1982; Xu, 2000; Graham and Jacob, 2000; Engeland et al., 2001; Arnell and Reynard, 1996; Leavesley, 1994; Boorman and Sefton, 1997). This is because today's GCM-calculated precipitation is still very uncertain, and hence does not provide a reliable estimate that can be used as a deterministic forecast for hydrological planning. Accordingly, methods of simple alteration of the present conditions are widely used by hydrologists. This approach consists of the following stages (e.g., Loaiciga et al., 1996; Xu, 1999a): (1) Determination of parameter values of a hydrological model in the study catchment using current climatic inputs and observed river flows for model validation. (2) Perturbation of historical time series of climatic data according to some climate change scenarios. (3) Simulation of hydrological characteristics of the catchment under the perturbed climate using the calibrated hydrological model. (4) Comparison of the model simulations of the current and possible future hydrological characteristics.

Various hypothetical climate-change scenarios have been adopted and the techniques for developing climate scenarios are in continuous progress. Hulme and Carter (1999) as cited by Varis et al. (2004) have presented a typology for scenario construction, which consists of the following eight stages: Scenarios based on expert judgment; Equilibrium 2 $\times CO_2$ scenarios; Time-dependent climate change; Multiple forcing scenarios; Climate system unpredictability; Natural climate variability; Scenarios combining uncertainties based on Bayesian logic; Sub-grid scale variability.

This approach provides a useful sensitivity study of hydrological regimes to global climate change. The

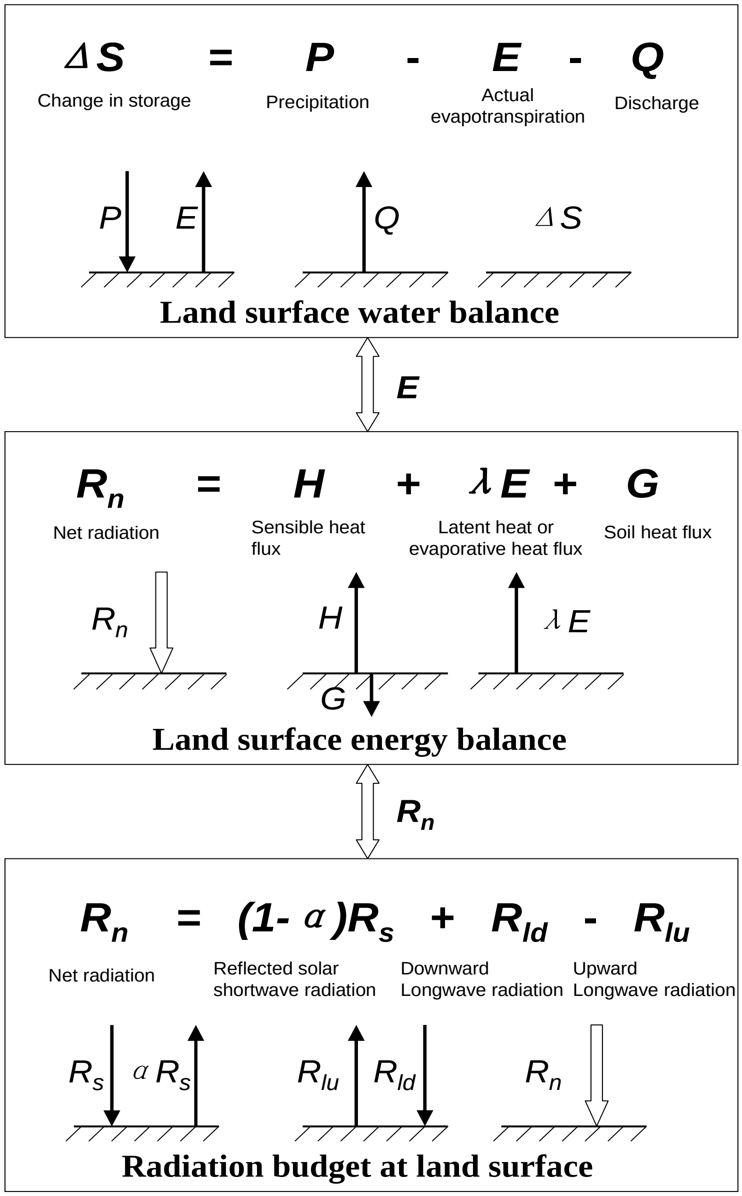

Fig. 1. Linking the land-surface energy and water balances through E (evaporation) and energy balance with radiation budget through R_n (net radiation).

drawbacks when using modified observed records as driving forces for model-based impact studies are discussed in detail by Kilsby et al. (1998). For example, the temporal patterns of wet and dry spells may be altered with climatic change. The simple methods do not allow changes in temporal variability. It is difficult to quantify the imposed changes if the projected hydrological quantities are not linked to the GCM scenarios.

Approach 6: Statistical downscaling. The sixth approach links the GCMs with catchment-scale hydrological models through statistical downscaling techniques (e.g., Wilby et al., 2000; Müller-Wohlfeil et al., 2000). The poor spatial resolution is a limiting factor when hydrological models are linked to GCMs. One of the intentions in the studies by Wilby et al. (2000) and Müller-Wohlfeil et al. (2000) was to bridge the gap between (1) the simple use of GCM output to generate hypothetical scenarios and (2) coarse-resolution macroscale applications with direct coupling to GCMs or RCMs. Although IPCC (1996) stresses the importance of this statistical downscaling step for hydrological impact assessments, compared with numerous studies using hypothetical climate change scenarios as input to hydrological models, there are few studies that focus on the direct applicability of statistical downscaling methods that enable the preservation of the day-to-day variability of rainfall and runoff (Wilby and Wigley, 1997). Wilby et al. (2000) and Müller-Wohlfeil et al. (2000) provide integrated modelling systems that can link climate models (GCM/RCM) with hydrological models through statistical downscaling. Compared with dynamic downscaling, statistical downscaling methods have the following advantages (von Storch et al., 2000): they are (1) based on standard and accepted statistical procedures, (2) computationally inexpensive, (3) may be flexibly crafted for specific purposes, (4) able to directly incorporate the observational record of the region. However, the following disadvantages have also been summarized by Goodess et al. (2001): they (1) assume that predictor/predictand relationships will be unchanged in the future, (2) require long/reliable observed data series, (3) are affected by biases in the underlying GCM. The last point also exists in dynamic downscaling methods. Furthermore, the skill of statistical downscaling depends on the climatic region and season (Wetterhall et al., 2005a, b).

3. Problems and challenges

Different approaches have been used in studying hydrological consequences of climate change. There is no doubt that great progress has been achieved in the research field during recent decades. Consistency of results among different types of models has also been demonstrated in some applications. For example, a shift to earlier and increased winter runoff and decreased spring and summer runoff was simulated by a range of water-balance models (e.g., Xu, 2000; Graham, 2004) for different snowmelt basins of the globe. However, it is necessary to make clear that the approach in the above studies will not lead to definitive quantitative answers. These studies primarily show the hydrological sensitivity to climate change within a reasonable interval. This is because great uncertainties exist in every stage of the study. From the discussion above, the following uncertainties and challenges can be identified.

(1) The uncertainties of climate scenarios and GCM outputs are large. Although the GCMs' ability to reproduce the current climate has increased, direct outputs from GCM simulations are inadequate for assessing hydrological impacts of climate change at regional and local scales. It is true that different hydrological models can give different values of streamflow for a given input (e.g. Boorman and Sefton, 1997), but the greatest uncertainties in the effects of climate on streamflow arise from uncertainties in climate change scenarios, as long as a conceptually sound hydrological model is used (Dooge et al., 1998; Graham and Bergström, 2001). In order to deal with GCM inadequacies, the "delta-change" method, i.e., the computation of differences between current and future GCM simulations and addition of these changes to observed time-series, is widely used (approach 6). This assumes that GCMs more reliably simulate relative changes rather than absolute values. However, the use of an "offline"-hydrological model does not take into account the feedback of water from soil to the atmosphere, which for one affects the output of GCMs. Therefore, the development of hydrological or land-surface parameterizations coupled with GCMs is recognized as one of the most promising approaches to determine the water cycle and its components at the macro scale (Varis et al., 2004).

(2) The uncertainties of nested high-resolution regional climate models (RCMs) are also large. It is true that difficulties with direct use of GCM scenarios in hydrological studies because of scale mismatch may be alleviated by techniques of dynamic downscaling. Regional climate models are good at simulating some variables, but extreme precipitation cannot be adequately simulated (Dooge et al., 1998; Graham and Bergström, 2001). Conceptual hydrological models play an important role in the realm of continental scale hydrological modeling and will continue to be used until more detailed models can be successfully applied at this scale. The final quality of results from nested RCMs depends in part on the realism of the large-scale forcing provided by GCMs, so the reduction of errors and improvement in parameterisation of subgrid-scale processes in both GCMs and RCMs remain a priority for the climate-modelling community.

(3) Statistical downscaling techniques provide regional and local climate scenarios, but the accuracy in current scenarios provided by such downscaling must still be improved to better simulate observed changes in the mean and variance of climate variables (Wetterhall et al., 2005a, b). Given the range of downscaling techniques and the fact that each approach has its own advantages and shortcomings, no universal method exists that works for all situations. In fact, all the downscaling methods are still very much in the development and testing stages. It is possible that testing and comparison of statistical downscaling approaches with, e.g., meteorological limited-area models could improve this.

(4) The uncertainties of hydrological model predictions are also large. The problems related to hydrological models in climate change studies include: (a) Different hydrological models can give different stream-

flow values for a given input (Boorman and Sefton, 1997). Instead of the mechanical running of climate change scenarios through hydrological models, more effort should be given to determine the magnitude of the uncertainty of the hydrological response to climate change. (b) Hydrological models are normally designed for stationary conditions, but they are used under changing or changed conditions in climate-change studies. The traditional split-sample-test method may not be sufficiently useful for models used in predicting effects of climate changes where the data on the changed system are not (and cannot be) available for comparison with the model predictions. Model validation is theoretically impossible, as a result of this problem, the credibility of the models is often questioned. But some better testing methods can be used such that the model validation/testing demonstrates "fitness for the said purpose" (Xu, 1999b). A hierarchical scheme for the systematic testing of hydrological simulation models was proposed by Klemes (1986), which consists of four model testing methods according to the purposes for which the model is used. (c) Model parameterisation techniques must be improved. Since all models (including the physically-based models) have parameters that are not directly measurable, numerous studies have been directed at developing improved a priori parameter-estimation procedures (Xu and Singh, 2004). These include: (i) Proxy-basin method; (ii) Linear-interpolation methods; (iii) Kriging-interpolation methods; (iv) Multiple regression; (v) Multivariate regression; (vi) One-step regression – regional calibration; and (vii) Bayesian method. All the methods assume that similar catchment characteristics lead to similar hydrological behaviour and most common methods follow a strategy to calibrate a selected model on gauged catchments and look for possible relationships between model parameter values and land-surface data. However, the transferability of parameterisation schemes across scales, regions and models is still an unsolved problem. The relationship between model parameter values and catchment characteristics can normally only be obtained at a sub-basin scale, while future model applications will most likely be done on grid cells of different sizes in different regions. The uncertainties in transferring regionalisation schemes and parameter values obtained at sub-basin scale to rectangular grid units of various sizes must be studied. Moreover, the main assumption in such models, that the hydrological model parameter values are the same today and in a different future climate, might be far from true.

(5) Considerable advances have been made in developing sophisticated distributed models for the description of heterogeneities, but we do not have sufficient field data at all scales to decide unambiguously between several possible descriptions. Simulation capacities have generally exceeded available input data. On the one hand, many regions in the world lack observed data of sufficient detail and quality. On the other hand, the global scale of human activities and the historically unprecedented magnitude of human-induced land-use and climatic changes mean that past data may not be a reliable guide to predictions in the future. Collection and testing of reliable data in a range of spatial and temporal scales are critical to improve our understanding of hydrological processes.

4. Conclusion

A review of current studies shows that considerable progress has been made in simulating the hydrological consequences of climate change. It is now well accepted that modelling seems to be the only resort to address complex environmental and water-resource problems. More and more people use models, and models will continue to find increasing use in the entire gamut of water-resource planning, development, assessment, and management (Maidment, 1996). The study also indicates a number of problem areas. These relate to the current capacity of GCMs, to limitations of downscaling techniques, and to hydrological modelling tools. It is a fundamental problem that the spatial and temporal scales of GCMs and hydrological models are different. These problems offer opportunities for cooperative research between hydrologists and climate modellers that can be both intellectually stimulating and potentially useful. It is important to foster a dialogue between climatologists and hydrologists through hybrid modelling approaches. It is anticipated that, in the near future, studies where both modelling groups address the same problem at the same time will lead to significantly improved hydrological predictions.

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