# CLIMATE AND WATER:

## On the search for improved interconnections between climate models and scenarios, hydrology, and water resources management

By

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# Abstract

Water—in its many different functions—is one of the key substances in climatology and meteorology. It is the atmosphere's major energy carrier and most climatic issues as felt by humans or the nature have a water component in them.

This document summarizes the major issues and their recent developments along the functional chain from climate models to climate scenarios, through hydrology all the way to water resources management, design, and policy-making.

Although the climate models (chiefly Global Circulation Models, GCMs) continue to undergo a fairly rapid evolution, their outputs are still very crude, unreliable, and even inappropriate to watershed-scale hydrological analyses. The bridging techniques are evolving, though. Under a general concept of regionalization, many families of technologies are under progress in parallel. They can be classified under the statistical-empirical ones, dynamical ones, and the hybrids of these two. Whereas the physically-based dogmatists keep on refining their dynamic models to allow more resolution in predictions, the empiricists are using multivariate statistics, artificial neural networks and similar techniques to provide empirical and computationally fast approaches for the purpose. The underlying problem remains irrespective of the regionalization approach used—it is the questionable reliability and uncertainty of the GCMs. Perhaps the most important advances in the recent past have been recorded in the field of detecting regional weather patterns and incorporating them into the arena. These patterns include issues such as ENSO and NAO.

The gap from hydrology to water resources is considerably narrower. The traditional and contemporary practices for incorporating hydrological characteristics to design, operation, planning, management, and policy making respective to water resources are very sophisticated, and their modification and adaptation to situations in which the variability of the climate is feared to change is bound to rely upon climate scenarios and ultimately to climate models. Therefore, the bottleneck is not in the hydrology-water resources link itself but in the climatic part.

The tendency seems to be towards integrated water resources assessments, where the climatic component is only one among many changes that are expected to take place. Others may be issues such as demographic changes and redistribution, changes in land cover and land use, changes in economic structure, production systems, technologies, and so forth. In such a pragmatic setting the climate scenarios are set in a realistic light, and more often a risk-analytic interpretation of those scenarios is called for.

The above-outlined continuum from climate to water is a topic where not the physically-based modelers, nor the empiricists and nor the pragmatists should get restricted to their own way of thinking. These issues should develop hand in hand. Perhaps the greatest challenge is to incorporate and respect the pragmatic—policy-related component to the two other branches. For this purpose, it is helpful to reverse the direction of thinking from time to time to start—instead of climate models—from practical needs and think how the climate scenarios and models help really in the difficult task of designing better water structures, outline better policies and formulate better operational rules in the water field.

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# 1 Introduction

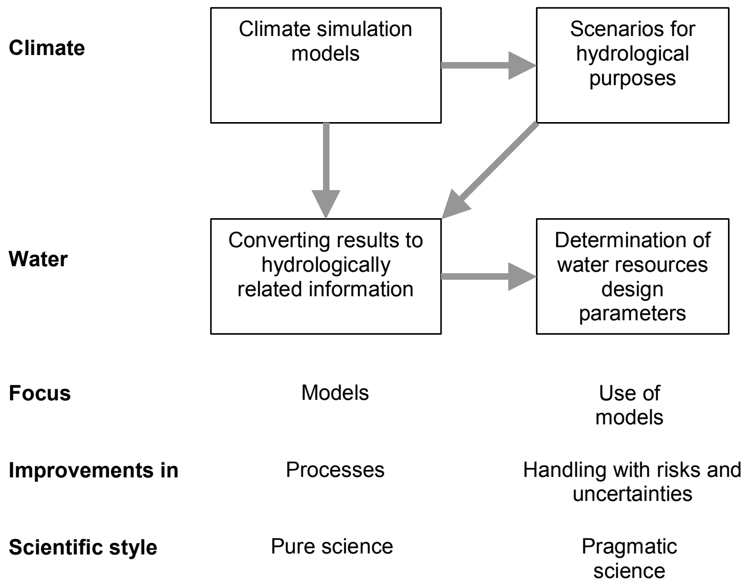
The purpose of this document is to summarize the results and findings on the recent developments in the field of climate and water. More precisely, the task was defined as follows:

a) To prepare a report concerning the experience in RA VI on activities in relation to climate and water,

- the status of existing climate simulation models,
- the development of existing climate scenarios for hydrological purposes in RA VI,
- the progress in respect to converting the results of climate models into hydrological related information, and
- new methodological tools for the determination of water resources design parameters in the light of potential climate change and in respect of climate change impacts on the water cycle on different scales, on water quality and on ecosystems; and

b) To follow up on the recommendations of recent international events.

Figure 1 structures this task. It has a dual character in two separable dimensions. First, both the climatic and hydrologic systems are included, and their links are of particular interest. Second, the science-driven process of model development by developing better and more refined process descriptions must be analyzed together with the policy-driven process of managing the uncertainties, translating them into risks for the society, and feeding policy processes.




First, the principal points from the Second International Conference on Climate and Water (CaW2) from the year 1998 are summarized. This conference was the major event in the field during the past decade. Thereafter, the summaries of the methodological topics are presented. In addition to these topics, a concise follow-up of an additional, important topic is made, namely the role of experts and expert judgment in the whole inference chain from climate models to hydrological design. This issue has received increasing notice in the field during the last few years.

At the end, some remarks on the recent initiative of an International Dialogue on Water and Climate are presented.

# 2 Key messages from CaW2

The most important milestone in the field of climate and water was the Second International Conference on Climate and Water that was held in Espoo, Finland on August, 1998[1]. It gathered 176 published papers on the following topics:

- Uncertainties of climatic change—a hydrological perspective
- Impact of climate variability and change
- Beneficial impacts and losses for water resources and water management as a result of climate change
- Research—water policy/policy options
- Education and training, adaptation of technologies, technology transfer, innovations

The objective of the Conference was to review developments in the study of the impact of climate variation and change on hydrology and water resources since the Conference on Climate and Water in Helsinki, Finland, 11-15 Sept. 1989. The main conclusions and recommendations of the conference were summarized in the final report as an input to the current debate at national and international levels on the implications for science and for society of climate variation and climate change. Annex 1 includes the full list of recommendations.

The analysis of the present situation and the background to these recommendations was summarized under three main headings of (a) data networks and trend analysis, (b) modeling of climate and water and (c) impacts and policy responses.

As to the determination of the goals of this report, the issue (b) modeling of climate and water is the most crucial one to be summarized here. Four points were raised in this issue:

## 2.1 Role of modeling

The traditional paradigm of model development and application that stems from model calibration and validation, proceeds to climatic scenario analysis and therafter to application of hydrologic models to assess the consequences of these scenarios, and ends to the comparison of the variables of interest was questioned. The enormous uncertainties and inappropriateness to basin-scale analyses of GCMs is the major obstacle. Not even the directions of change are always correct or logical. The hydrological models as well have their large uncertainties. Within the period of prognostic simulations, not even the governing processes need to be same as today.

Given these challenges and shortcomings in the prevailing modeling paradigm, the mechanistic simulation approach, the focus should be shifted towards the systematic analysis

[1] The summary of the Second International Conference on Climate and Water was accomplished by Dooge, J.C.I. & Kuusisto, E. 1998. Climate and Water—a 1998 Perspective. Edita, Helsinki. http://www.water.hut.fi/wr/caw2/

and simulation of uncertainties in the system. This may lead to "…*bigger dividends than a number of single scenario impact studies conducted throughout the world, which may in the future prove to have been ill conceived*". A further point on the importance and poor representation of natural climate variability in the climate and water studies was made.

### 2.2 The problem of scales

A fundamental barrier between the climate models and hydrological models is due to the very different spatial and temporal scales used. This problem has perennially been approached from the both directions: by proposing downscaling procedures for the climate models and upscaling procedures for the hydrologic models. The use of regional, high-resolution climate models is one promising approach, among several other techniques. There are some major shortcomings such as the simulation of extreme precipitations. The need to first quantifying the uncertainties of these models and then reducing them was highlighted.

### 2.3 Land surface processes

The importance of the description of soil surface processes was emphasized. A particular bottleneck is soil moisture; it is poorly presented in the GCMs, yet it is crucial in the quantification of the energy balance and evaporation. In contrast to the aggregation of vegetation effects in the models—which has progressed substantially—the soil processes are not sufficiently well aggregated so far. GIS techniques have provided some improvements, but only to a small extent. The problems peak again when simulating extreme events, particularly floods. Most influential are the shortcomings in the ability to track the monsoon floods. The GCMs are weaker with them than with any other major climatic event, and the hydrological models are neither very appropriate with them.

### 2.4 Individual components of the cycle

A series of more specific comments were made on the major weaknesses of modeling individual processes of the hydrologic system. Snow, ice, groundwater, paleogroundwater and so forth attracted attention. However, the problems come back in a very essential way to the three above points, particularly to the first one, when talking about climate and water. The uncertainties of climate scenarios and models—in the catchment scale—are still superior to those of the hydrologic models.

## 3 The status of existing climate simulation models

A science-driven dominance is clear in this area. Process models such as GCMs, hydrological simulation tools, etc., along with empirical models dominate.

What comes to GCMs, a great part of their most important uncertainties are directly water related. Fernau, Makofske and South[2] have listed these key uncertainties in the following way:

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[2] Fernau, M.E., Makofske, W.J. and South, D.W. 1993. Review and impacts of climate change uncertainties. Futures, October 1993: 853-863.

- Uncertainties in greenhouse gas emissions
- Uncertainties in sinks
- Feedbacks
- Water vapor
- Clouds
- Oceans
- Sea ice and snow

This list seems to be well in place, since most of these issues have inherited themselves into the IPCC's Third Assessment Report[3] (Appendix 2) as issues of continuing interest in GCM development, albeit with more specification. IPCC's highlights are:

- **Atmospheric feedbacks** largely control climatic sensitivity. After 1996, there has been a better appreciation of the crucial mechanisms. These mechanisms are those that control water vapour distribution in the atmosphere, and they are very sensitive to warming. In the present models, the most important response of increased greenhouse gas concentrations is the growing water vapour concentration in the troposphere.

- This **water vapor** feedback approximately doubles the warming in comparison to the previous models without this feedback.

- The greatest uncertainty is now in the **cloud system** and their interaction with radiation.

- Descriptions of **ocean processes** have undergone improvements in the models. Particularly the heat fluxes between water and air, as well as large-scale circulation patterns such as ENSO (El Niño-Southern Oscillation) and NAO (North Atlantic Oscillation) are better modeled than before. Major uncertainties remain to exist in important small-scale processes such as coastal currents and flows in narrow straits, in mixing and in convection processes.

- The **thermohaline circulation** is still a major problem in present models. The great uncertainties in the interplay and feedbacks between ocean temperature and salinity profile do not allow reliable simulations of high-latitude processes in particular, such as those in the northern Atlantic. Those processes include the Gulf stream, the flows induced by the Greenland glaciers and the Arctic flows that govern much of the climate in western and northern Europe.

- **Vegetation photosynthesis and water use** are now better understood than in 1996. Accordingly, model parameterizations of land-atmosphere fluxes of carbon and water undergo improvements.

[3] Intergovernmental Panel on Climate Change, 2001. Third Assessment Report. Part I: The Scientific Basis. IPCC, Geneve.

- Also processes to simulate **snow, permafrost, and sea ice** have improved. Particularly interesting are the descriptions that allow the simulation of sub-grid scale variations in ice cover and thickness, and their impact to albedo. Similar progress is being introduced to snow processes. However, the present global climate models still ignore ice dynamics and thermodynamics entirely.

- Many of the **relevant processes for simulating regional climate variability** such as NAO and ENSO are already in the models, but much refinement in details is needed.

- Possible **threshold-type of changes** have received increased attention. Based on the experience from paleoclimatic studies, as well as observations from the recent past, abrupt climatic shifts are numerous. Possible threshold levels and their underlying mechanisms are poorly known and non-existing in the models.

The report summarizes that the understanding of processes and feedbacks in the climate system has improved considerably after the Second Assessment in 1996. Consecutively, models have improved. IPCC still ignores the structural uncertainty issues that were highlighted above, and that are the crucial uncertainties indeed. After the report, more quantification of uncertainties of GCMs is possible by comparing outcomes of different models and running them with different initial conditions. This style reveals that the uncertainty issue is still in a very infantile stage with GCMs.

# 4 The evolution of climate scenario techniques

The techniques for developing climate scenarios are in continuous progress. Hulme and Carter[4] have presented a typology for scenario construction, which consists of the following eight stages:

1. **Scenarios based on expert judgment.** One of the earliest climate scenarios were produced in the 1970s, by asking a panel of members to provide the upper (10 percentile), middle (median), and the lower (90 percentile) estimates for the Northern Hemisphere temperature by the year 2000. The responses were averaged and weighted and a probability distribution resulted. This approach has been criticized widely, yet Hulme and Carter conclude that this approach produces a probabilistic scenario with a clear uncertainty estimate, which has been lacking from the majority of climate change impact scenarios ever since.

2. **Equilibrium 2x$CO_2$ scenarios.** The first serious GCM experiments were done in the early 1980s. The models had a coarse resolution and the intercomparison was made at the point where atmospheric $CO_2$ was doubled. These scenarios missed the temporal evolution of the climate with feedbacks and lags, and results were unrealistic and potentially misleading. Uncertainties were assessed from the divergence of the results from different models.

3. **Time-dependent climate change.** By the late 1980s, the temporal descriptions and dynamics of these models had evolved to a stage in which simulations for specific future periods were possible.

[4] Hulme, M. & Carter, T. 1999. Representing uncertainty in climate change scenarios and impact studies. In: Carter, T., Hulme, M. & Viner, D. (Eds.), ECLAT-2 Workshop Report No. 1, Helsinki, Finland, 14-16 April, 1999.

4. **Multiple forcing scenarios.** Besides $CO_2$, increasingly other forcing factors such as surface aerosols were included in the models by early 1990s.

5. **Climate system unpredictability**. It was found out in late 1990s that the models give diverging outcomes with slightly modified climatic conditions. This type of structural issues and apparent randomness of models of very high complexity add markedly to the de facto uncertainty of the models.

6. **Natural climate variability**.

7. Scenarios combining uncertainties based on **Bayesian logic**.

8. **Sub-grid scale variability.** This topic was defined as one of the focal points of the report at hand, and therefore, the following section will concentrate solely in it.

# 5 Bridges between climate and water through regionalization

Climate change will have an effect on water resources in many regions. The temporal and spatial distribution and availability of water resources, as well as frequency of extreme events will be affected. To meet the new challenges focused on water resources management, the quantification of climate change impact on basin-scale hydrology is essential. When determining water resources design parameters such as riverflows in selected river basins, the change of the hydrological variables (e.g. precipitation) has to be predicted.

General circulation models (GCMs) are used to generate projections of future climate change on a large spatial and temporal scale (several decades). Although computational power has remarkably increased during the past years, grid size of GCMs is still limited to few hundred kilometers. Assessing of climate change impacts at watershed level requires higher resolution and thus excludes efficient utilization of GCM output. The practical need to bridge the gap between the different spatial and temporal scales has created regionalization a.k.a. the downscaling methods in which regional information is produced from data generated by GCMs. Currently regionalization is widely recognized as a very important issue concerning climate change and its impacts. Downscaling methods and their applications in regional climate change impact studies are extensively researched by different organizations. The following section shortly describes the different downscaling methods and their advantages and disadvantages. In addition some comparison between downscaling methods is represented.

## 5.1 Statistical-empirical downscaling methods

Von Storch et al.[5] have written a wall-to-wall review of empirical downscaling techniques out of which the following is mainly synthesized.

Empirical downscaling combine information about large scale climatic changes with small scale physiographic details (e.g. topography). The method is based on seeking the statistical relationships which link large scale GCM results with fine resolution regional observations. The regional climate is seen as a random process conditioned upon a driving large-scale

[5] Von Storch, H., Hewitson, B. & Mearns, L. 2000. Review of empirical downscaling techniques. In: RegClim Workshop General Technical Report No. 4, Jevnaker, Norway, 8-9 May 2000. http://www.nilu.no/regclim/rapport_4/Default.htm

climate regime. Thus the concept of downscaling consists of a predictand (a set of regional climate variables), predictor (a set of large-scale variables) and a function conditioned by the predictor. The deterministic or/and stochastic function is generally unknown and is modeled dynamically or empirically from observational data sets.

Numerous statistical downscaling applications have been developed, but can be put into three main categories which are:

1) *Weather generators.* Provide synthetic weather records (daily precipitation) by statistical models of observed sequences of weather variables. Include e.g. Markov-chain approach (e.g. WGEN-model) and spell-length approach (e.g. SPEL-model).

2) *Transfer functions.* Regression-like techniques or piecewise interpolations using a linear or nonlinear formulation. Include e.g. multiplelinear regression, canonical correlation analysis (CCA), principal components analysis and artificial neural network (ANN) approaches.

3) *Weather typing schemes.* Relationships between atmospheric circulation types and local weather are calculated. Weather typing schemes define empirically weather classes (synoptically or by constructing indices of airflow) related to regional climate variations. These include e.g. analog method and classification tree analysis

Von Storch et al. bring out the following advantages of statistical downscaling methods:

+ based on standard and accepted statistical procedures

+ computationally inexpensive

+ may flexibly be crafted for specific purposes

+ able to directly incorporate the observational record of the region

Goodess et al.[6] summarizes the common disadvantages of statistical downscaling methods as follows:

- assume that predictor/predictand relationships will be unchanged in the future

- require long/reliable observed data series

- affected by biases in the underlying GCM

Although there is a methodological similarity between the applications, a great number of different permutations is used. This makes the comparison of climate change results from separate studies very difficult. Wilby et al.[7] have carried out a comparison study of downscaling methods by using standard sets of observed and GCM-derived predictor

[6] Goodess, C., Hulme, M. & Osborn, T. 2001. The Identification and evaluation of suitable scenario development methods for the estimation of future probabilities of extreme weather events. Tyndall Centre Working Paper No. 6.
www.tyndall.ac.uk/publications/working_papers/wp6.pdf

[7] Wilby, R. L., Wigley, T. M. L., Conway, D., Jones, P. D., Hewitson, B. C., Main, J. & Wilks, D. S. 1998. Statistical downscaling of general circulation model output: A comparison of methods. Water Resources Research. Vol. 34, No. 11: 2995-3008.

variables. Additionally, the comparisons were integrated by using standard suite of diagnostic statistics. The chosen downscaling techniques included two models from each category: WGEN- and SPEL-models (weather generators), ANN1- and ANN2-models based on artificial neural network approach (transfer functions) and B-Circ and C-Circ models based on airflow indices (weather typing). According to the study the weather generation techniques yielded the smallest differences between observed and simulated daily precipitation while the transfer functions performed poorly. In an average sense, changes in diagnostics derived directly from the GCM are generally larger in magnitude than those obtained from the area-average statistical downscaling models. The circulation-based models and weather generators did not adequately simulate lower frequency variations in precipitation variability. Wilby et al. demonstrated that there are significant differences in the level of skill among the statistical downscaling methods.

## 5.2 Dynamical downscaling

Dynamical downscaling techniques can be classified into two categories:

1) high or variable resolution atmospheric GCM (AGCM)

2) nested limited area model (LAMs) or regional climate models (RCMs)

High resolution AGCM technique has been used just a few years and is still in its infancy. Atmospheric and land-surface conditions interpolated from the corresponding GCM fields are used to initialise the simulations. Significant underlying errors are often present in high-resolution atmospheric GCMs. Another disadvantage of this method is that it is computationally very demanding. The main advantage of high and variable resolution AGCM technique is that the resulting simulations are globally consistent.

The nested regional modelling technique essentially originated from numerical weather prediction and was for the first time applied for climate applications by Dickinson et al.[8] in 1989. The regional climate models can provide high resolution with a grid-size starting from 10 km. RCMs are able to produce multi-decadal simulations and furthermore describe climate feedback mechanisms which act at the regional scale. The nested regional climate models are driven with initial conditions, time-dependent lateral meteorological conditions and surface boundary conditions. The driving data sets are derived from GCMs.

According to Christensen and Christensen[9] the main limitations in the principles of nested RCM technique are:

- the inheritance of systematic errors in the driving fields provided by global models

- lack of two-way interactions between regional and global climate

- the algorithmic limitations of the lateral boundary interface

Since 1996 significant improvements have been achieved in the area of nested regional climate modeling[10]. RCMs ability to reproduce present day climate has substantially

[8] Dickinson, R. E., Errico, R. M., Giorgi, F. & Bates, G. T. 1989. A regional climate model for western United States. Climatic Change 15: 383-422

[9] Christensen, J. H. & Christensen, O. B. 2001. Regional Climate Simulations- a Study on Precipitation. In: Jørgensen, A., Fenger, J. & Halsnaes, K. (Eds.), Climate Change Research: Danish Contributions. Danish Climate Centre, DMI, Copenhagen. http://www.dmi.dk/f+u/publikation/dkc-publ/klimabog/klimabog.html

improved. New RCM systems have been introduced including multiple nesting and atmospheric RCMs coupled with e.g. lake and hydrology models. The effects of domain size, resolution, boundary forcing and internal model variability in regional climate modeling are now better understood. It is essential that the quality of GCM large-scale driving fields continues to improve as those operate the regional climate simulations.

## 5.3 Statistical-dynamical downscaling (SDD)

Frey-Buness, Heimann and Sausen[11] have applied the statistical-dynamical downscaling method for the first time to the output of GCMs. SDD links global and regional model simulations through statistics derived for large-scale weather types. The method consists of three steps which are:

1) *Classification of large-scale weather.* A multi-year time series of a GCM simulation are classified into large-scale weather types which are specific to the region of interest.

2) *Regional simulation.* Representative regional model simulations are performed with the initial and boundary conditions derived from the large-scale fields of the corresponding weather types.

3) *Climatological evaluation.* The regional model output is weighted with the respective frequencies of the weather types

Statistical-dynamical downscaling combines advantages from both statistical and dynamical downscaling. Fuentes and Heimann[12] state the advantages and disadvantages of SDD as follows:

+ does not depend on the availability of long-term observational time series

+ the assumption that statistical relationships derived for an observed climate are still valid in a changed climate is not needed

+ the computational effort is significantly reduced compared with dynamical downscaling

- the spatial resolution attainable is limited by the resolution of the regional model

- reduction in temporal variability

Fuentes and Heimann have introduced an improved statistical-dynamical downscaling method for the regionalization of large-scale climate analysis or simulations. They applied the downscaling to the Alpine region emphasizing the reproduction of the present-day regional precipitation climatology for the winter months. According to the study the improved SDD proved to be an efficient and relatively accurate method for reproducing regional climate estimates on the basis of a multi-annual time series of large-scale fields. The main error of the method originated from the regional model used, thus the procedure itself was relatively

[10] Intergovernmental Panel on Climate Change, 2001. Third Assessment Report. Part I: The Scientific Basis. IPCC, Geneve.
[11] Frey-Buness, A., Heimann, D. & Sausen, R. 1995. A statistical-dynamical downscaling procedure for global climate simulations. Theoretical and Applied Climatology 50: 117-131.
[12] Fuentes, U. & Heimann, D. 2000. An improved statistical-dynamical downscaling scheme and its application to the alpine precipitation climatology. Theoretical and Applied Climatology 65: 119-135.

certain. As a conclusion of the research, the improved statistical-dynamical downscaling has proved to be an efficient and economical alternative to the dynamic downscaling method.

### 5.4 Dynamical downscaling vs. statistical downscaling

To date few formal studies comparing regionalization techniques exist. Murphy[13] has assessed downscaling estimates of screen temperature and precipitation by using a statistical downscaling technique and two separate dynamical downscaling techniques. The methods are compared in terms of the correlation between the estimated and observed time series of monthly anomalies. Overall, the dynamical and statistical methods showed similar levels of skill. Mearns et al.[14] have compared regional climate change scenarios (temperature and precipitation) produced by a semiempirical statistical downscaling technique and regional climate model (RegCM2) experiments. Both methods used large scale information from the same GCM. The study demonstrated that significant differences in the regional details of climate change are produced by two different means of downscaling.

Though the regionalization techniques have developed and improved, yet specifying consistent estimates on the regional and local scale is limited. There is an obvious need for further research concerning the comparison of downscaling techniques.

## 6 New tools for determination of water resources design parameters

One of the tasks of this report was to define new methodological tools for the determination of water resources design parameters in the light of potential climate change. In addition, climate change impacts on the water cycle on different scales, on water quality and on ecosystems should be considered. The following section starts with the determination of water resources design parameters and proceeds to deal with the methodological tools.

As water resources management encompasses several sectors such as irrigation and drainage, hydropower, flood control, water supply and inland navigation, the determination of all the water resources design parameters in the context of this report is purposeless. Instead, information that may be required for impact assessments in water resource management and the design of water resources systems (determination of design parameters) can be listed and includes i.a.[15]:

- Mean river flow
- Mean groundwater recharge
- Mean seasonal (or monthly) variation in river flow
- Seasonal variation in groundwater recharge

[13] Murphy, J. 1999. An evaluation of statistical and dynamical techniques for downscaling local climate. Journal of Climate. Vol. 12, No. 8: 2256–2284.
[14] Mearns, L.O., Bogardi, I., Giorgi, F., Matayasovszky, I. & Palecki, M. 1999. Comparison of climate change scenarios generated daily temperature and precipitation from regional climate model experiments and statistical downscaling. Journal of Geophysical Research. Vol. 104, No. D6: 6603-6621.
[15] Kilsby, C. 1999. Hydrological impact modelling and the role of downscaling. In: Carter, T., Hulme, M. & Viner, D. (Eds.), ECLAT-2 Workshop Report No. 1, Helsinki, Finland, 14-16 April, 1999.

- Q95 of river flow (5 percentile flow)
- Flow-duration curves of river flow
- Run-sums (volumes available to reservoir in certain time periods)
- Snowmelt supplied river flows, requiring joint temperature/precipitation information
- Mean annual flood
- T-year flood (e.g. 100 year return period)
- T-year floods with joint probability of snowmelt and rainfall
- Reliable yields for river of groundwater resource

To determine the first four quantities, the mean GCM output variables are used as input in hydrological modeling. A minimum of downscaling is needed which means that at least a series or field of rainfall with realistic intensities at the daily level should be produced. Rest of the quantities are more problematic to determine. When considering the frequency distribution of river flow (e.g. Q95) the GCM rainfall output is insufficient. The determination of extreme events such as 100-year flood is not possible with the length of GCM output. In cases when both variables temperature and precipitation are needed (snowmelt supplied river flows) the joint probability has to be determined. Generally this is not possible with two simple independent downscaled distributions. Determination of the fore-mentioned variables needs more sophisticated downscaling methods.

Investigations of the sensitivity of hydrologic systems to climate change by using one-way coupling with landscape-scale hydrologic models and GCMs originates from the 1980s (e.g. Gleick[16]). However the direct use of GCM output results in hydrological modeling gives often inaccurate hydrological simulations due to the different temporal and spatial scales used in GCMs and hydrological models. Situations where the output of GCMs might be directly used are the estimations of runoff on the global or continental scale. When hydrological modeling takes place on a regional or local scale, downscaling of GCM output is required.

## 6.1 Climate change and water resources on the regional scale

The most important sources and driving forces of global change are located at the regional level. In addition when considering that political and technical measures to adapt on the global change takes place at regional level (river basin level) it is clear that regional-scale studies on global change are a matter of great concern.

Hostetler and Giorgi[17] have investigated the feasibility of coupling regional climate models (RCMs) with landscape-scale hydrologic models (LSHMs). They used the output from two year-round RCM (MM4) simulations to drive a lake model and a streamflow model in the western United States at a basin scale. The lake model produced reasonably good predictions of surface temperatures and evaporation. The runs of streamflow model resulted good simulations of the seasonal cycle of streamflow (monthly time series), but underestimated the

[16] Gleick, P. H. 1987. Regional hydrological consequences of increases in atmospheric $CO_2$ and other trace gases. Climatic Change 10: 137-161.
[17] Hostetler, S. W. & Giorgi, F. 1993. Use of output from high-resolution atmospheric models in landscape-scale hydrologic models: an assessment. Water Resources Research. Vol. 19, No. 6: 1685-1695.

wintertime discharge and soil moisture. This was due to the deficiencies in precipitation simulated by MM4.

The impacts of climate change to water storage and groundwater recharge has been studied by Bouraoui et al[18]. They have presented a general approach to evaluate the effect of potential climate change on groundwater resources. The method consists of a simple disaggregation scheme including three steps:

1) development of local weather generator

2) analyzing of GCM outputs corresponding to the present-day and $CO_2$-doubling scenarios to determine the impacts of these changes on the mean and standard deviation of the climate variables and

3) generation of long term series of rainfall, temperature and evapotranspiration corresponding to the modified scenario. The retreated outputs can then be used as input into a hydrological model to evaluate the impact of $CO_2$-doubling on groundwater recharge. The method is relatively simple. However the results were obtained from only one GCM and therefore must be used with caution.

The determination of extreme weather events is important in terms of water resources management and design. Climate change will have an effect on the occurrence of floods and droughts. According to the IPCC[19] flood magnitude and frequency are likely to increase in most regions, and low flows are likely to decrease in many regions. However defining of credible scenarios for changes in flooding is difficult. This is due to the inability of GCMs to simulate accurately short-duration, high-intensity and localized heavy rainfall. A few studies on flood frequencies have been carried out. These are mainly based on the assumption that monthly rainfall also apply to “flood-producing” rainfall. Defining of droughts is even more difficult due to the different definitions (rainfall deficits, soil moisture deficits, lack of flow in a river , low groundwater levels or low reservoir levels) used. Changes of hydrological drought have been studied by using different indices of low river flows. The results emphasize the high sensitivity of computed future runoff changes to GCM calculations. Even the same GCM scenario can produce fairly different changes in different catchments due to the differing geological conditions among the river basins.

## 6.2 Climate change and water resources on the global and continental scale

Even at the continental-scale the direct use of GCMs output for determining runoff can be misleading. Wolock and McCabe[20] have examined the effects of potential climate change on mean annual runoff in the conterminous U.S. by using a simple water-balance model and output from two GCMs. The results were highly controversial: the CCC (Canadian Centre for Climate Prediction and Analysis) GCM climate produced decreases in runoff while the Hadley Centre´s GCM climate produced increases in the annual runoff. The study concludes that the effects of climate change on mean annual runoff cannot be estimated reliably because of the uncertainty related to GCMs capability to estimate changes in precipitation. When evaluating climate change impacts on water resources it is essential to use as many GCM

[18] Bouraoui, F., Vachaud, L., Li, L. Z. X., Le Treut, H. & Chen, T. 1999. Evaluation of the impact of climate changes on water storage and groundwater recharge at the watershed scale. Climate Dynamics 15: 153-161.

[19] Intergovernmental Panel on Climate Change, 2001. Third Assessment Report. Part II: Impacts, Adaption and Vulnerability. IPCC, Geneve.

[20] Wolock, D. M. & McCabe, G. J. 1999. Estimates of runoff using water-balance and atmospheric general circulation models. Journal of American Water Resources Association. Vol. 35, No. 6: 1341-1350.

scenarios as possible. Conclusions concerning impact assessments based on one or two GCM scenario are very difficult or impossible to make.

In addition to the uncertainty aspect of the GCMs another fundamental problem arises when trying to estimate water resources parameters with a hydrological model driven by GCM output. Due to the different physics in the representation of land surface – atmosphere exchanges of heat and water vapour between the models, inconsistent use of GCM output occurs. The use of `offline´-hydrological model does not take into account the feedback of water from soil to the atmosphere which for one's part 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 macro-scale.

River flow has been modeled in GCMs for several years. Until recently the methods have however been simplistic including i.a. distribution of land surface runoff over all ocean cells in some predetermined manner or moving runoff from land cells to their respective target ocean cells with no time delay. The ability of GCMs to simulate runoff and streamflow has lately improved due to the incorporation of flow routing. This has enabled the direct use of GCMs for studies concerning the impacts of climate change on water resources and hydrology of major river basins. Arora[21] 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. The weak river discharge simulations were mainly due to the deficiencies in simulation of regional precipitation. Errors associated with the land-surface scheme (partitioning of precipitation into evapotranspiration and runoff is not realistic) were another factor affecting negatively the accuracy of the results. 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.

The Global Energy and Water Cycle Experiment (GEWEX)[22] is an extensive research program whose aim is to model the global hydrological cycle and its impact on the atmosphere, oceans and land surfaces. One of its objectives is to develop the ability to predict the variations of global and regional hydrological processes and water resources, and their response to environmental change. GEWEX has five continental scale experiments interacting with each other. These studies will provide improved observations and coupled land-atmosphere models. Construction of a global model of the full hydrological cycle with two-way linking of atmospheric, oceanic and hydrological models is under way.

## 6.3 Global change impact studies proceed towards integrated modeling systems

Climate change is just one factor, which will affect hydrological systems and water resources. Changes in e.g. land-use and -cover, ecosystems, water demand and human activities have their own implications for the quantity and quality of water resources and vice versa. Sosio-economic development as well has an effect on water demand and supply especially in the developing world. All of these factors should be considered when constructing water related scenarios.

[21] Arora, V. K. 2001. Streamflow simulations for continental-scale river basins in a global atmospheric general circulation model. Advances in Water Resources 24: 775-791.
[22] See www.gewex.com

Transdisciplinary approaches in climate change impact studies on hydrological characteristics are taking place in several research programs. Global Change in the Hydrological Cycle (GLOWA)[23] is developing integrated strategies for sustainable and far-sighted water resources management, which take into account ecosystem contexts and the socio-economic framework. GLOWA consists of four river basin studies, which investigate the various levels of complexity relating to the availability, quality and distribution of water resources. The core themes of the project include e.g. natural variability of precipitation levels and variations caused by human activity and their effect on the hydrological cycle and interactions between the hydrological cycle, the biosphere and land use.

Potsdam Institute for Climate Impact Research (PIK) has also several transdisciplinary studies concerning water resources and global change. RAGTIME (Regional Assessment of Global Change Impacts Through Integrated Modelling in European River Basins) investigates the impacts of climate change, of land-use and land-cover change and of other human activities on hydrological and ecological characteristics[24]. The study has developed modeling frameworks (including i.a. the GIS-based hydrological model ARC/EGMO and the integrated hydrological/vegetation/water quality model SWIM) allowing inter alia the simulation of evapotranspiration, runoff, groundwater recharge and storage, river discharge and water quality in the light of climate and land-use change. WAVES (Water Availability, Vulnerability of Ecosystems and Society in the Northeast of Brazil) is estimating the possible consequences of climate change in semi-arid regions. To reach its goal the study is considering the interactions between natural, social and economic systems. Combining the results of all the disciplines in an overlying level integration is pursued through the representation of dynamic processes in modeling, analysis of spatial data in landscape ecology, and construction of scenarios of regional development[25].

# 7 Uncertainties and expert judgment gain increasingly notice

A probabilistic approach has gained more dominance than before. This development has been driven by the practical need to provide advice for policy processes, hydrological design, and similar questions, which often benefit from the translation of scenarios into risk levels. Pure scientists still feel uncomfortable with the presentation of "unknowns", "surprises", "consensus views" and so forth by the probabilistic, typically Bayesian language.

The existing tension between the science-driven approach to refinement of model descriptions and the policy-driven quest to grasp the uncertainties and risks of the model outputs has become into daylight perhaps more strongly than before. The tension along this axis is understandable, and the discussion we have seen in the scientific forums is an extremely valuable and inevitable component when bringing these paradigmatic tensions down. This detention process is mandatory in order to gain respect over this gap from both directions and closing this paradigmatic gap.

Two examples of this debate are given here. One on a very general level on the issue what is good climate change science and what is not good science. The other has been chosen to be a

[23] See www.glowa.org

[24] Becker, A. 2000. Transdisciplinary Regional Studies: RAGTIME Regional Assessment of Global Change Impacts Through Integrated Modelling in European River Basins. In: Boysen, M. (Ed.), Biennal Report 1998&1999. PIK, Potsdam.

[25] Gerstengarbe, F. 2000. WAVES Water Availability, Vulnerability of Ecosystems and Society in the Northeast of Brazil. In: Boysen, M. (Ed.), Biennal Report 1998&1999. PIK, Potsdam.

very technical one. It deals with the subjective (pragmatic allowing the use of expert judgment) and objective (restricted to empirical approaches).

## 7.1 The debate between policy and science driven analysis: A macro case

GCM development is one of the major scientific attempts in the field what comes to costs and manpower needs. These models continue to grow in complexity, the paradigm being in the continuous refinement of the process descriptions of global-scale atmospheric models that have evolved also to include increasingly sophisticated descriptions for the terrestrial and oceanic processes. Whereas the models have shown unambiguous evolution in many ways during the past three decades, there are many arguments of criticism with regards to their dominance in the exercise to derive climate change scenarios[26].

Although being principally a science-driven community, the GCM developers have been criticized among other things of the following features, which in turn raise the hair of the GCM experts:

- modelers are unaware of uncertainties (of models and policy)
- pluralism is avoided by modelers,
- modelers are ignorant of the social and policy dimensions of climatic science

A pluralistic approach, the critics continue, that allows the use of a spectrum of models to satisfy different objectives would be far more efficient and scientifically just as a source of scientific input to policy-making exercises.

Whereas these arguments might be an exaggeration at least to some level, they highlight the danger of approaching complex and far-reaching real-life issues through too narrow scientific paradigms. It is important that this debate goes on and wider acceptance and co-operation of experts with different scientific background will result. There is an obvious danger of falling in the classical problem of the Law of the Hammer[27]: "If the only tool available is a hammer, every object starts to look as a nail". On the other hand, a hammer is useful for nails.

## 7.2 The debate between policy and science driven analysis: A micro case

The methodological hub of the discussion on uncertainties is the interpretation of a probability distribution. Despite the various alternative approaches to deal computationally

[26] As a 'macro-level' illustration on the ongoing debate between the advocates of the process-based, scientifically-driven models, particularly GCMs and the practically-oriented modelers that emphasize methodological pluralism in reaching the goal of gaining practically-usable results with realistic uncertainty bounds, see

- Shackley, S., Young, P., Parkinson, S. & Wynne, B. 1998. Uncertainty, complexity, and concepts of good science in climate change modelling: Are GCMs the best tools? Climatic Change 38: 159-205.
- Henderson-Sellers, A. and McGuffie, K. Concepts of good science in climate change modeling. Comments on S. Shackley et al., Climatic Change 38, 1998. Climatic Change 42: 597-610.
- Shackley, S., Young, P. & Parkinson, S. 1999. Response to A. Henderson-Sellers and K. McGuffie. Climatic Change 42: 611-617.

[27] See, e.g., Hopple, G.W. 1986. Decision aiding dangers: the law of the hammer and other maxims. *IEEE Transactions on Systems, Man and Cybernetics* **16**: 948-963.

with uncertainties such as fuzzy sets and Dempster-Shafer Theory, the probabilistic approach has remained as the absolutely dominant approach, and it seems to reinforce this position.

The discussion and disagreement is not so much any more whether a probabilistic approach is appropriate, but what to understand with a probability distribution[28]. Many pragmatically-oriented scientists feel comfortable with the statement of Daniel Katz: "...anything less than a fully probabilistic approach to uncertainty analysis is inadequate". This means that the various uncertainties in the process of measuring the processes and phenomena in the nature and the society, in representing their variability, in the structures of the models used, and so forth must be systematically analyzed using probabilities. Such probabilities include not only classical "objective" frequency distributions (since only a small part of the uncertainties and the information in general comes directly from measurements) but more crucially from prior knowledge on the issues under study.

This approach of "subjective" probability raises over and over again deeply negative feelings among the representatives of the opposing school, who are cautious and concerned about the empirically exact form and parameterization of the distributions used. Quoting Antonio Navarra: "…There must be no mistake, the probability can be determined only by increasing the ensemble size, improving resolution and making models more complex in processes. At present this is the major obstructing factor on the road towards improvement. We need more people working with models, better and bigger computers".

This discussion should perhaps be set in comparison with the perennial debate among empirical modelers and process modelers in hydrology. The former ones base their analyses on statistical methods, whereas the latter ones rely on prior, theoretical knowledge on the structure of the system, and only calibrate and validate these structures with some data, which typically is far from adequate in strictly statistical criteria.

This debate among process modelers and empirical modelers seems to have cooled down quite remarkably in emotional terms during the past decade, but the one between empirical probabilistic and pragmatic ones (often using Bayesian techniques, Monte-Carlo analysis and so forth) seems to be heating up. Clearly, both directions have their justification, and the demarcation lines on the applicability of these approaches needs obviously a heated discussion.

## 7.3 The gap is ancient but more bridges are necessary

The paradigms of classical statistics and sciences that rely on "objective" science contrast with the pragmatic schools of applied science, that focus on problem solving, and see the added value of successful science in the form of better policies, better products, improved procedures, and other issues of similar character. This gap does not only exist in climatic and hydrologic sciences, but is as old as the basic concepts of western science. The disagreement

[28] As a 'micro-level' illustration on the above issue, see

- Katz, D. 1999. Techniques for estimating uncertainty in climate change scenarios and impact studies. In: Carter, T., Hulme, M. & Viner, D. (Eds.), ECLAT-2 Workshop Report No. 1, Helsinki, Finland, 14-16 April, 1999.
- Grübler, A. 1999. Uncertainties in social and economic projections. In: Carter, T., Hulme, M. & Viner, D. (Eds.), ECLAT-2 Workshop Report No. 1, Helsinki, Finland, 14-16 April, 1999.
- Gyalistras, D. 1999. Techniques for estimating uncertainty in climate change scenarios and impact studies—Quantitative techniques. In: Carter, T., Hulme, M. & Viner, D. (Eds.), ECLAT-2 Workshop Report No. 1, Helsinki Finland, 14-16 April, 1999.
- Navarra, A. 1999. Predictability and surprise. In: Carter, T., Hulme, M. & Viner, D. (Eds.), ECLAT-2 Workshop Report No. 1, Helsinki, Finland, 14-16 April, 1999.

of Plato and Aristotle went along the same divide. Plato argued for practical and social value of knowledge, Aristotle for the theoretical merits. Given this historical setting, this debate is likely to continue in the domain under discussion, yet bridges over this gap are necessary.

# 8 Conclusion

The climate change impact studies on water resources are needed for long-term water resources design. Impact studies carried out by hydrological modeling are mainly based on direct or downscaled GCM output. The reliability of results of global climate models plays thus a crucial role in water resources applications concerning climate change. Although the GCMs simulate reasonably logically various atmospheric variables, hydrological information such as precipitation is frequently controversial among different models. Better climate change scenarios add the value of impact studies on water resources and thus facilitate policy-making in the sector of water resources management.

When determining water resources scenarios multidisciplinary approaches should be favored. Climate change is just one factor affecting the hydrology and water resources in the future. Other non-climatic factors such as socio-economy, landscape, ecology and water demand have to be considered to produce realistic water resources/availability scenarios.

Representative data sets are often unavailable which limit the development of hydrological models. Furthermore the use of statistical downscaling as a regionalization technique is incompetent if long and reliable observed data series are not available.

Although many problems exist in the use of expert judgment in the probabilistic scheme it is an important path forward. The merits of the probabilistic approach are far larger than the problems at this very modest stage of development in the management of uncertainty.

Risk assessment and management is crucial to adaptation and reducing vulnerability. It is important to be able to deal with risks of highly uncertain phenomena since the extremes are so poorly known.

# 9 Epilogue: Climate and water vs. water and climate

The WMO's Regional Association has been working under the title Climate and Water over many years when the issue of combining meteorology with hydrology and water management have been under concern. The two international conferences with the same title—the first one in Helsinki, Finland in September 1989 and the second one in Espoo, Finland in August 1998 have been the culminations of this activity, as was stated at the beginning of this report.

The Bonn Feshwater Conference in December, 2001[29] saw the launching of an initiative of an International Dialogue on Water and Climate[30]. The dialogue defines its mission and goal with the following words:

[29] International Freshwater Conference in Bonn, December 3-7, 2001, was the main activity on freshwater issues in the preparation of the Johannesburg 2002 summit. www.water-2001.de

[30] The International Dialogue on Water and Climate (www.waterandclimate.org) is a joint initiative of GWP, WMO, IPCC, IUCN, IWMI, IRI, WWC, Secretariat World Water Forum 3, Netherlands Water Partnership, Programme Partners for Water (the Netherlands), and UNESCO.

"The International Dialogue on Water and Climate is a platform that bridges the information gaps between the water management and climate sectors in order to improve our capacity to cope with the impacts of increasing climate variability and change."

"The goal of the dialogue is to develop a knowledge base, generate widespread awareness, and identify policy and management options that build such capacities, and make this knowledge available to the most affected communities"

The political and institutional dimension is said to be the most critical element in coping with climate variability and change in the inauguration material of the Dialogue.

The Climate and Water has traditionally been far more science driven, although policy issues have been included at some level. The direction of thinking is also reverse. Precisely as the order of the two keywords of the two titles are reverse.

**Climate and Water**—being science-dominated—follows more or less the physical movement of water from the atmosphere to rainfall, to soil and ground and surface waters, to water users, to the ocean and back to the atmosphere. Equally as can be seen at this very report. Thereby, the policy issues have not been at the center. Instead, the hydrological cycle and its drivers have been the governing domain of interest.

**Water and Climate** seems to start from the risks, problems, vulnerabilities, and other impacts that the climatic irregularities and changes cause to human societies. The "South", i.e. the developing world, is focused in particular due to the fact that societies that are lacking the sufficient capacity to cope with climate-related problems are most vulnerable anyway.

This new Dialogue is very much welcomed. As a policy-centered platform it hopefully will feed the more science-driven activities in the field such as Climate and Water with novel links to the policy level, particularly in the developing world. At the same time, the sound scientific background of the Climate and Water and other such activities should be taken to the policy processes more rigorously than before.

## Annex 1

**Recommendations of the second International Conference on Climate and Water, 17-20 August 1998, Espoo, Finland.**

In regard to research priorities, which are crucial in this context, the following two recommendations arose:

1. Increased efforts should be made in the establishment and maintenance of data networks and the development and application of reliable methods of trend analysis and their application to existing data sets including historical records.
2. High priority should be given in modelling studies to further research on the scaling problem (both upscaling and disaggregation), to improved methods of modelling extreme events and to the integration into model studies of factors such as biological effects and land use effects.

In regard to research management, the following recommendations were made:

3. Research scientists dealing with climate and water should recognise the importance of communication between natural scientists of different disciplines (both physical and biological), between natural scientists and social scientists, between scientists and policy makers and between scientists and the general public. Provision should be made in the planning of research programmes for the communication of the results of research in an appropriate form to policy makers and to the general public.
4. Continued support should be given to large-scale land surface experiments in order to provide verification data for hydrologic models and climate models used for predicting the effects of climate variation and change.
5. Advance planning is needed to ensure the availability of accommodation on all programmes of remote sensing for instruments of significance in hydrologic data accumulation and hydrologic research.

In regard to project design and management, the following points were emphasised:

6. It should be recognised by all concerned that climate variation and change is an important factor in water resources management along with such key factors as population growth, changes in land use and economic development.
7. Dialogue is necessary between hydrologists on the one hand and water project planners and managers on the other hand and this dialogue will be most useful if focused on actual problems arising in practice.
8. There is growing need for the study of conflict resolution in relation to water at all levels in view of the ever increasing pressure on water resources.

The following recommendations were suggested in the general area of policy formulation:

9. National water planning and legislation should be based on the most up-to-date information available and should be adequately implemented in all sectors of society.
10. All such administrative actions should take due account of local culture and customs and of the level of economic development.
11. Governments and administrators should involve all stake-holders at an early stage of water resource development.
12. Special attention should be paid to making known to school children the basic facts about water and its use.

**Annex 2**

## Climate Change, Hydrology and Water Resources Development needs according to the 3rd assessment report of the IPCC

*1. Creation of credible climate change scenarios*
Improvements to GCMs capability to simulate present climate and its multi-decadal variability. Development of conceptually sound downscaling techniques. Characterization of potential changes in variability at temporal scales from daily to decadal.

*2. Characterization of natural climatic and hydrological variability*
Potential future anthropogenic climate changes need to be placed in context by appreciation of natural climatic and hydrological variability. More grasp about linkages between different components of the climate system in different parts of the world is needed. This requires joint use of observational data (including remotely sensed data), palaeoclimatic data, and model simulations. Very useful information on the variability in natural hydrological systems and insights into nonlinear relationships between climate forcing and hydrological response can be obtained by palaeoclimatic and palaeohydrological reconstructions.

*3. Improved hydrological models*
Development and application of process-based models of hydrological processess including realistic representations of processes that generate streamflow and recharge and determine water quality. Development of models that do not need catchment calibration (but may require remotely sensed inputs) to assess the effects of climate change in areas with limited hydrological data. Development of coupled climate-hydrology models.

*4. Characterization of uncertainty*
There has been little systematic analysis of the relative importance of different sources (emissions, global climate response, regional climate change) of uncertainty.

*5. Impacts on real-world water systems*
Few published studies exist on the impacts of climate change on real-world water resources systems. Conclusions about impacts have generally been made from estimates of changes in streamflow alone. This may give a significantly misleading impression of the actual impacts of change since the characteristics of the water management system are a very important buffer between hydrological effect and impact on users and the environment. More studies into real-world systems are needed.

*6. Effects of adaption*
Most impact studies have ignored adaption by water managers and assume that water managers are able to adapt. Studies are needed to investigate e.g. how will managers make adaption decisions in practice on the basis of incomplete information and what would be the effects of inefficient adaption on the impacts of climate change.