Assessing the Key Factors in Climate Change Studies

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Abstract. The complexity of assessing the impact of climate change (CC) on hydrology requires the use of reliable methods and high quality data. In this study, we provide a brief review of basis and key factors requires for assessing the hydrologic impact of climate change before using hydrologic models. Here, General Circulation Models (GCMs), greenhouse gas emission scenarios, downscaling approaches and sources of uncertainties are discussed, whereas inattention to these would result in imperfect knowledge of the future climate and its consequences. Moreover, it can be emphasized that adaptation policies should rely on applying more accurate and reliable methods with high quality and long-term data sets.

Keywords: Climate change, downscaling approaches, GCMs, hydrology, RCMs, uncertainty

1. Introduction

According to various greenhouse gas emission scenarios (GHGES), little doubt remains that the global warming is happened which affected various aspects of water resources, and this warming is expected to continue in 21st century [1]. CC affect a region's hydrology such as increasing/decreasing runoff or river flow, increasing flood/drought frequency, changing soil moisture, increasing snowmelt runoff, rising sea levels, affecting lake volumes, increasing water consumption and so forth [2]. As global CC and its consequences have become one of the most difficult challenges faced by water managers and hydrologists since the 1980s [3], it is important to investigate the relationship between CC and hydrology process and water resources. In such case, long-term assessment of CC impacts on hydrology and water resources is beneficial for sustainable management and future water resource planning [2,3,4,5].

Climatic conditions, sources of runoff, physical characteristics of the basin and the magnitude of projected climate scenarios will change the hydrological response of the basin. Hence, different impact of climatic variability will be experienced in basins located in different regions [3]. Although, it is hard to accurately predict when various effects of global warming will occur or what the magnitude of the effect will be; quite a lot of studies have assessed the effect of CC on hydrology and water resources from different viewpoints [e.g. 6,7] using various sources of data, models, catchments and methods. Three steps commonly perform to assess the effects of CC on regional water resources, i.e. *i*) using climate models (GCMs); *ii*) using downscaling techniques; and *iii*) using hydrological models. This review briefly summarizes the important base features namely GCMs and emission scenarios, downscaling approaches and uncertainties for assessing and modeling the effect of climate variability on hydrology.

2. General Circulation Models (GCMs)

CC and the response of hydrologic systems are two problems which affecting the modeling of hydrologic impacts of global CC. Over the past years three-dimensional (3D) climate models namely GCMs are being used within global coverage. Due to the complexities of land-atmosphere-ocean-cryosphere couplings, GCMs play key roles in assessment of climatic impacts of the GHGs. GCMs are based on *i*) Thermodynamic,

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ii) Navier-Stokes and *iii*) Mass Conservation equations which use finite difference or spectral techniques over an appropriate time continuum to project CCs [8]. Various institutes across the globe have developed a number of GCMs which produce different impacts on global climate from given emission scenarios. Their main variables can be summarized as air temperature, humidity, precipitation, surface atmospheric pressure and north-south and east-west components of wind velocity.

However, to assess the impact of expected CC under GHG and aerosol emissions scenarios on water resources, the GCMs should be coupled with hydrologic models [1,9]. GCMs application for studying the impact of CC on the hydrological response are limited and questionable to make reliable predictions of regional hydrologic changes [4] directly from climate models due to the coarse spatial resolution of GCM grids. At present, most GCM future climate projections are based on grid spacing (typically about 2° to 10° in latitude and longitude) [9,10]. In contrast, Regional Climate Models (RCMs) nested within GCMs are developed which finer spatial and temporal information (typically resolution of 0.5°) can be derived from these physically based models [11]. The climate characteristics of the GCM simulations are based on a set of story lines or emission scenarios created by the Intergovernmental Panel on Climate Change (IPCC). The scenarios are related to different combinations of scientific, technical, economic growth, environmental and social development [12]. The six modeling teams (SRES-Scenarios) proposed by IPCC are summarized in Table 1. These allow for different possible futures according to different world views.

Table 1: The main characteristics of the six SRES modeling teams reported by IPCC (12)

SRES / Development	A1F1	A1B	A1T	A2	B1	B2
Gross Domestic Product Growth	Very High	Very High	Very High	Medium	High	Medium
Energy Use	Very High	Very High	High	High	Low	Medium
Technological Change	Rapid	Rapid	Rapid	Slow	Medium	Medium
Oil/Gas Resource Availability	High	Medium	Medium	Low	Low	Medium
Population Growth	Low	Low	Low	High	Low	Medium
Land Use Change	Low-Medium	Low	Low	Medium-High	High	Medium

Although all GCMs describe basically the same physical processes, CCs simulated by different GCMs forced by various climate scenarios can be potentially useful for assessing the implications of CC to water resources [13,14]. However, it is clear that within the group of GCMs used, models may be considered more or less adequate for the study region. Due to the simulation of non-linear physical processes, different model experiments (GCMs) yields differing results. Hence, various models should be examined to see which ones performed the best in simulating the region's climate [5]. Table 2 shows comparison of studies results which different GCMs and scenarios were used. In summary, it can be concluded that *i*) although the GCMs are not a reliable source of information for local and small temporal decisions [15], but the information provided by the models can be used to predict future trends from the current climate knowledge; *ii*) exploring several alternative climate scenarios would be useful for effective management of water resource systems [10] and to make informative decisions about resource by policy makers.

Table 2: Results of studies using GCMs and scenarios

GCM	Scenario	Results	Ref.	Remarks
CGCM2, HadCM3, CSIROMk2	A2, B2	Increase in temperature and precipitation over future (2080s) for all GCMs. e.g. The CSIROMk2 predicts an increase in the average precipitation of 31% from the base scenario under the A2 scenario, compared with 16% for the B2 scenario.	16	All GCMs predicted an increase in temperature and precipitation. The magnitudes of future changes by GCMs were different. Scenarios showed different results.
HadCM3	A2a, B2a, GGa1,	Increment in mean annual temperature for future (2080s) by 5.7, 4.0 and 4.7°C for A2a, B2a, and GGa1, respectively. Decrement in mean annual precipitation (future) by 13.6%, 7.2% and 6.2% for A2a, B2a, and GGa1, respectively.	17	Climate model with various scenarios projected an increase in temperature and decrease in precipitation. Future changes by scenarios were different in gradients.

3. Downscaling techniques

Raw outputs from GCMs due to their large resolution are inadequate, often biased and not suitable for assessing the impacts of CC on hydrological responses at regional scales. To address such concerns, the coarse scale outputs of GCMs must be downscaled by using simple interpolation, statistical downscaling (SD) or high-resolution dynamical modeling [3,4,18,19,20,21] to convert GCM results into regional and local meteorological variables required for reliable hydrological modeling [3,5,16,20,22,23]. Wang et al. [24] used a single GCM for their study. They reported that however the uncertainties cannot be completely qualified, but using a single future scenario from selected GCM can provide a basic information set. Since the past decades, downscaling techniques are widely used and developed for GCMs [e.g. 4,23]. However, it is found that generally the results of these approaches have similar levels of skill [e.g. 18,21].

The simplest downscaling method is achieved by perturbing historical time series data by the change in the long-term monthly or seasonal variables under the CC scenario which referred to as change factor method [3,16,25]. SD uses the empirical/statistical relationships as a key step between atmospheric variables simulated by GCM and regional climate observations [6,7,20,26]. Various methods have been developed which generally lies in one of the three major categories namely, regression methods, stochastic weather generator and weather typing scheme. Another alternative methodology is dynamical downscaling in which physically based RCMs uses GCM outputs as initial and boundary conditions to produce finer scale outputs [4,19]. However, this resolution is not enough for most hydrological models, thus further downscaling methods are needed to produce finer and adequate resolution (<10 km) [18]. Dynamical downscaling methods are not completely satisfactory [20] and cause significant errors due to the accumulation of GCM and RCM biases [4,18]. Table 3 shows the pros and cons of change factor, statistical and dynamical downscaling techniques.

Table 3: Description of the relative advantages and disadvantages of downscaling techniques (modified from 14,22,23)

Downscaling Techniques	Advantages	Disadvantages
Change Factor	Can provide Point-scale scenarios Computationally simple, straightforward and quick to apply Local climate change scenario is directly related to changes in the regional climate model output Use changes rather than absolute values	Depends on quality of the climate model providing the change factors Unchanged temporal structure for future climate scenarios Step changes in scaling at the monthly interface Limited to time-slice scenarios
Statistical	Easy access, cheap and computationally efficient Can provide station-scale climatic variables from GCM-scale output Usable to obtain variables not available from RCMs Can be easily transferred to other regions Can directly incorporate observations into method Delivers transient climate change scenarios at daily time-scale	Require high quality observed historical data series (for calibration) and climate model output (affected by biases in underlying GCM) Depends on the choice of predictors Predictor-predictand relationships are not always stationary Exclude climate system feedbacks Predictor variables and transfer function (e.g. domain size, climatic region and season) affects downscaling skill and results
Dynamical	Produces responses based on physically consistent processes Can produce finer scale information from GCM-scale output	Usually expensive and computationally intensive Available in a limited number of scenarios Depends on GCM boundary forcing

Guo et al. [26] compared the monthly temperature and precipitation series of statistically downscaled GCM output, raw GCM output (HadCM2) and regional observation data in the San Juan River basin. All outputs indicated an increase in temperature with significant differences in monthly amount and their magnitudes. They stated that the GCM outputs (downscaled and raw) yielded generally higher temperatures and large seasonal differences in precipitation in comparison to regional observation data. Main factors which should be considered to select the predictor variables in downscaling techniques are *i*) variables should be reliably simulated by the selected GCM, *ii*) they should be available from archives of GCM output and *iii*) should be strongly correlated with the surface variables of interest.

4. Uncertainties

Many studies have reported that the GHGES and the GCM are the main sources of climatic uncertainty [e.g. 27,28,29] which represent an imperfect climate processes e.g. runoff and evapotranspiration processes [9] and topography [27] in large parts due to computational limitations. Main sources of uncertainties in the impact of climate change on hydrology studies can be classified as GCM outputs, climate change scenarios (SRES), downscaling techniques, non-climate data and hydrology models. Jyrkama and Sykes [30] mentioned that it is very difficult to predict the actual change in climate variables using GCMs in the future which involves high uncertainty. It is pointed out that using a large number of GCM and GHGES as possible [16] and a large number of catchments [14] would be resulted in better encompass the uncertainty originated with climate projections for assessing the implications of CC to water resources. In GCMs, some climate data is well represented while some outputs (e.g. precipitation) are often not well produced in both magnitude and timing [31]. Hence, bias correction approaches [25] are useful to remove bias between model and observations over the study region.

In addition, due to the coarse resolution of GCMs and RCMs, downscaling the predicted results from these models to the fine scale of hydrologic models, add more uncertainty into the climate data and analysis [27,31] because of the limitations that are inherent in each technique. Semadeni-Davies et al. [13] for instance, noted that using RCMs add another layer of uncertainty as climate variability becomes more pronounced at the regional scale. Jones et al. [14] also recommended that the application of only one or two scenarios allows the use of more realistic methods while using a larger number of scenarios requires simpler, less resource-intensive methods of downscaling. Moreover, data sensors recording climate data, precipitation, streamflow, snow, soil temperature, moisture, and so forth at high temporal and spatial resolution are subjected to noise and errors due to extreme weather conditions which could affect instruments.

Thus, careful quality checks and corrections in the input data are necessary before their use in hydrologic studies and modeling. Other uncertainties would be originated in the non-climate inputs to the model such as vegetation, changes in land use and soil moisture [16]. For example, the uncertainties associated with changes in land use could be reduced by integrating data from a variety of disciplines in order to gain a clearer picture of past variability, and hence better isolate the climate component of future vulnerability in nature-society systems [32]. The vegetation feedback loop is also of concern to hydrologic models [33]. Thus, considering how the vegetation will respond to changes in weather and how that response will in turn affect and modify the response of the hydrological processes is significant. Relative to the errors from GCM simulations and downscaling methodologies, errors from hydrologic modeling can be expected to be modest [16]. Hydrologic uncertainty results from *i*) the transferability of hydrological models to a future climate [27], *ii*) model structure which caused by the model assumptions and equation simplification, and could be identified by comparison to other models [14,34] and *iii*) input data which may be caused by the limitation of measurements, or the quality of the observations, output data from GCMs, RCMs or downscaled approaches [34] and non-climatic data. The validation of hydrological models under CC is also reported to be problematic because there are no observed results against to compare [35]. Overall, enhancements in spatial resolution, high-quality and long-term data sets, combined with improved process-level quantifying and understanding of complex feedbacks and all sources of variability (environmental change) involving water, should be taken into account to reduce levels of uncertainty.

5. Conclusions

According to the brief information provided in this paper, it can be concluded that *i*) the outputs of GCMs can be extremely useful in projecting and understanding future global climatic changes; *ii*) it is not yet possible to make reliable predictions of regional hydrologic changes directly from climate models due to the coarse resolution of GCMs; *iii*) using dynamically downscaled data directly as inputs for hydrologic simulations is not recommended because of the accumulation of GCM and RCM biases; *iv*) GCMs and downscaling methods may yield different regional CC outputs, however assessment of the relative merits of different GCM and downscaling methods should be helpful in CC studies; *v*) the sources of uncertainties should be evaluated in hydrologic impacts of CC studies; for example, high quality and long-term data could be helpful to deplete input data uncertainties.

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