

Uncertainty Analysis of Climate Change Impacts on Runoff

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Abstract. Warming of the atmosphere observed over several decades is associated with the changes occurring in hydrological systems. These changes include precipitation patterns and extremes; the amount and generation of river flow; the frequency and intensity of flood and drought; and, by extension, the quantity and quality of freshwater resources [1]. To study the climate changes, General Circulation Models (GCM) are repeatedly stated as the main tools to assess the changes. In water resources studies, hydrological models are mainly used to quantify the hydrological effects of climate change using GCM simulations as input [2]. However, the spatial resolution mismatch between GCMs outputs and the data requirements of hydrological models constitutes a major obstacle in impact studies [3]. Along with the uncertainties associated with GCMs, Greenhouse Gases Emissions Scenarios uncertainty has also been treated as a structural uncertainty. To date, there has been a little discussion on the influence of uncertainties related to the downscaling methods [4] and hydrological models [5] on the magnitude of driven uncertainty of impact studies. This article reviews recent advancements in the uncertainty analysis and modeling of the climate change impacts and propose a strategy for integration of all sources of uncertainty and in this regard to provide a comprehensive climate change uncertainty model.

Keywords: uncertainty, climate change impacts, GCM, emission scenario, downscaling, hydrology

1. Introduction

Climate change is a very broad term that encompasses anthropogenic changes in the atmosphere and on land. Increase in concentration of greenhouse gases [6] in the atmosphere has affected large scale atmospheric circulation patterns which in turn alter precipitation and temperature. Land development and channelization of waterways have influenced climate on a much more local scale by altering the watershed hydrology, inducing greater erosion and accelerated sedimentation, all of which generally impact local ecosystems to the worst [7]. Due to the effects of atmospheric changes on precipitation and the effects of land-based changes on routing of the precipitation, stormwater management activities are clearly influenced by climate changes and thus needs to take into cognizance key elements of climate change (e.g., precipitation, temperature, flooding) [7]. Previous studies had demonstrated that runoff trend is closely associated with precipitation and temperature trend, although the relationship between climatic variables and runoff are not always linear. Runoff variability is closely associated with multi-year or multi-decadal scale climate variability [8]. As anthropogenic climate change might shift the seasonality and magnitude of precipitation, temperature, and thus runoff [9], water resource managers are highly concerned about the sustainability of water resources since a long-term shift in runoff will undoubtedly strongly affects energy supply, water demand, and flood control plans. The following sections review the components of climate change impact studies and the uncertainties related in this discourse.

2. General Circulation Models (GCMs)

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In order to model the hydrologic impacts of climate change, simulation results of GCMs are commonly used in hydrologic models. GCMs are the most credible tools designed for the simulation of climate variables globally [10]. GCMs are numerically coupled models that various earth systems including atmosphere and land surface are incorporated in the model structure. General principles of fluid dynamics and thermodynamics are the fundamentals of GCMs [7]. A large number of researches have studied the climate impacts on runoff by coupling GCM outputs and hydrological models. Ahn et al. [11] used GCM outputs in water balance model to study runoff changes. Merritt et al. [12] utilized three GCMs and the UBC watershed model to evaluate the hydrologic response to the climate change scenarios in Okanagan basin of Britain. In a similar manner, by applying the two GCMs simulation results on SWAT hydrological model, Zhang et al. [13] estimated the effect of potential climate changes on available streamflow volume. However, the coarse resolution of GCMs is an obstacle in detailed assessment of land surface processes and investigation of climate change impacts at regional and local scales. For instance, ecosystem models, soil erosion models, and hydrological models require finer resolution climate grids [14].

3. Greenhouse Gas Emission Scenarios

Climate change assessment basically requires a global perspective and a very long time horizon of at least a century. However, prediction of future Green House Gas (GHG) emissions is virtually impossible; thus, the alternative GHG emissions scenarios have become the main tool for the analysis of potential long-term developments of the socio-economic system and corresponding emission sources. GHG emission scenarios provide only an image of the future, or alternative futures. They are neither predictions nor forecasts and they only surmise about how the future may unfold. In fact, GHG emission scenarios are a linkage between qualitative stories about future and quantitative formulations like formal modelling of future. In scientific assessments, scenarios are usually based on an internally consistent and reproducible set of assumptions, which are derived from our understanding of both history and the current situation [15]. Future global GHG emission scenarios are the resultant of a very complex, ill-understood dynamic system, driven by forces such as population growth, socio-economic development, and technological progress and a host of others that may have yet to crop up. Therefore, accurate prediction of emissions is relatively impossible and this is a source for uncertainty. Policy makers need a comprehensive view of the knowledge of possible future GHG emissions, given the uncertainties in both emissions models and our understanding of key driving forces. Thus, scenarios are an appropriate tool for summarizing both current understanding and current uncertainties [15].

4. Downscaling

As was discussed earlier, GCMs provide reasonable outputs of weather variables at global scales, but their resolution is not sufficient to produce accurate local data to study the climate change impacts at the drainage basin scale. Establishment of downscaling methods have been a useful tool to link GCM outputs at coarse resolutions with surface weather variables at finer resolutions [16]. Basically, two fundamental techniques were developed for downscaling of coarse GCM simulations to finer resolutions; dynamical and statistical downscaling. Statistical methods build a statistical relationship between large-scale GCM outputs and local weather variables, whereas, dynamic methods utilize the high-resolution Regional Climate Models (RCMs) embedded in GCMs to obtain local weather variables. Both statistical and dynamical downscaling methods have their own advantages and practical usage, although statistical downscaling has been more widely employed in hydrological studies because of its less computational demand [16].

As dynamical downscaling refers to the use of RCMs, this method uses the large-scale and lateral boundary conditions from GCMs to produce finer resolution outputs. Dynamical downscaling is a suitable method to realistically simulate regional climate features because they can be fixed at the nearly 0.5° latitude and longitude scale. Orographic precipitation, extreme climate events and regional scale climate anomalies, or non-linear effects, such as those associated with the El Niño Southern Oscillation can be studied using dynamical downscaling method [17]. On the other hand, among the several statistical downscaling methods developed, the simplest method is to apply GCM outputs in the form of Change Factors (CFs). This method works based on the differences between the control and future GCM simulations. The differences between

the control and future GCM-scale outputs are applied to baseline observations by simply adding or scaling the mean climatic CF to each day. Accordingly, it can be simply applied to several GCMs to produce a range of climate scenarios. More sophisticated statistical downscaling methods are generally classified into three groups namely, regression models, weather typing schemes, and weather generators. A fundamental concept of these methods is that the regional climates are largely a function of the large-scale atmospheric state. This relationship can be expressed as a stochastic and/or deterministic function between large-scale atmospheric variables (predictors) and local or regional climate variables (predictands) [18].

5. Hydrological Models

Hydrologic models are the major tool for flow estimations at the watershed scale by accounting for various parameters such as elevation, soil type, and land use etc. Hydrologic models can generally fall into two broad categories named lumped and distributed models. Grid-based or distributed models account for spatial variability in sub-catchment hydrologic response and can make use of gridded, spatially-distributed climate data obtained from climate models [19]. Uncertainty of hydrological models relates to the model structure and model parameters sets. Therefore, utilization of GCM outputs can increase the uncertainty of the final result of the climate change impact studies done at the regional scale. Hydrological models uncertainty has not been given enough attention in the climate impact studies and its uncertainty has been reported relatively small. However, this can be a large source of uncertainty when only one hydrologic model is employed at the study [20].

6. Discussion on Uncertainty Modelling

The coarse resolution of GCM data necessitate using downscaling and analytical studies to determine the most appropriate GCM for assessing climate change impacts at the watershed scale. The lack of knowledge behind the selection of the right number and type of GCMs is argued recently by Xu et al. [21]. They have highlighted that the uncertainty would increase had a very large number of GCMs been employed in impact studies, but however there is no recommendation for the number of GCMs to be used while it differs on a case by case basis. On the other hand, it was discussed that based on the current state of the art of climate change impact studies it is not possible to recommend a specific downscaling method for a given application, or even to use multiple downscaling methods to produce an ensemble of forcings for hydrological models [3]. Therefore, a remarkable source of uncertainty is attributed to this aspect of climate studies that is in urgent need of development. Downscaling methods are not created equal and the choice of one or more approach should be evaluated on a (climate region) case by case basis with respect to the objectives of the climate change impact study [3]. It is reported that downscaling uncertainty is more critical when only one GCM is employed in the study, thus cases where the downscaling uncertainty envelope is contained within other sources of uncertainties should not be treated with the same attention as those cases where downscaling is the main source of uncertainty. It is stressed by Quintana Segui et al. [4] that if all the uncertainties cannot be explored, the results of the study should be taken with caution, without overselling them, and the result would be more scattered at extremes. In addition, according to the importance of extreme flows (e.g. Q05, Q95) as a representative of the hydrology change under the climate change impacts, and considering the research gap on extreme values analysis in impact studies [3, 21], more focus and study on extreme values is strongly recommended. Furthermore, the need of a research to analysis and quantify the effect of all possible uncertainties in climate models is recently highlighted in the literature and a research question raised is, if downscaling uncertainty substantially increases the ensemble of climate models uncertainty when all possible uncertainties of emissions scenario, GCM, RCM, downscaling, hydrological model are taken into account [3], what then is the lump sum uncertainty?

During the last decade, research on uncertainty modelling of climate change impacts has advanced from several fronts. From probabilistic modelling of the uncertainty related to the GCMs that assign equal probability ratings within an ensemble of opportunities of GCMs to define the uncertainty of each GCM [22]; to development of Reliability Ensemble Averaging (REA) approach [23] that assignment of weights to GCMs is based on model evaluation; and further advancements in REA approach [24, 25, 26]. A review of the studies done on the developed methodology, REA, in uncertainty modelling revealed that it is still

lacking from several aspects such as, not considering uncertainty caused by parameterization and the structure of the impact model itself, uncertainty caused by starting conditions used in GCM simulations, and more importantly the downscaling techniques uncertainty. Even in the newest improvements of the REA approach [27], it is found that the model is highly variable and unstable because of not encumbering the downscaling method uncertainty. According to the aforesaid research gap and more recent researches in uncertainty modelling of the climate change impacts, a novel research area is proposed on modelling downscaling uncertainty along with GCM uncertainty [3, 4, 27, 28].

7. Conclusion - Significance of a new research

Studies of the impact of climate change on water resources usually follow a top to bottom approach: a scenario of greenhouse gas emissions is used to run a GCM simulation, which is downscaled and bias-corrected. Then, this data is used to force a hydrological model [4]. Seldom, impact studies take into account all relevant uncertainties. In fact, many published studies only use one climate model and one downscaling technique. Authors according to the review of the advancements in climate change impact studies in water resources context aim to establish a new research project that may integrate diverse developments at every aspect of climate change studies and provide a framework for climate change study. It is also aimed to establish an uncertainty model that encompasses every uncertainty sources in climate change impacts studies. This study that is currently being conducted considers the effects of three different GCMs and emissions scenarios (high from the IPSL GCM's A2 scenario, middle from the ECHAM5 GCM's A2 scenario, and low from the GISS GCM's B1 scenario) using daily downscaled precipitation and temperature data over the Klang River basin, Malaysia, and the Zayanderud River basin, Iran. Outputs of GCMs will be downscaled and bias-corrected using three different techniques: a statistical method based on weather regimes, a quantile-mapping method and the method of the anomaly. The study employs Soil and Water Assessment Tool (SWAT) software as a distributed hydrologic model to predict the daily flows in the basins. For uncertainty analysis and modelling, GCM outputs of large-scale climate variables will be first downscaled using the three downscaling methods and the underlying uncertainty is modelled with Reliability Ensemble Averaging (REA) technique [27]. In this method, weights are assigned to GCMs on the basis of model performance and model convergence, computed with the deviation of simulated Cumulative Distribution Functions (CDF) from that of target (for observed period) and weighted mean CDF (for future). The challenge of this research is the entrance of downscaling uncertainties to the REA method to be combined with GCMs uncertainty and be modelled using imprecise modelling method, which is based on probability density function and general statistical uncertainty analysis methods.

8. References

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