Advancements in Modeling Protocols for Assessing Climate Change Impacts on Water Resources: A Review

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ABSTRACT

The scientific community has dedicated significant attention to climate change and climate variability in the past two decades, with numerous investigations focused on these topics. The Intergovernmental Panel on Climate Change's third and fourth assessment reports have provided clear evidence that the planet's climate has undergone significant changes since the pre-industrial era, resulting in a warmer phase. These changes have had severe effects on hydrological processes and the availability of water resources due to shifts in temperature and precipitation patterns. A better comprehension of climate change's impact on water resources can aid in developing sustainable strategies for their management and development. Hydrological models combined with climate models can offer a framework to comprehend and explore the interplay between climate, human activities, and water resources.

Keywords: Climate change;hydrological model;water;temperature; climate model.

1. INTRODUCTION

Climate is the long-term average of regional weather conditions. Climate change is defined as “a change in the state of the climate that can be identified by changes in mean and/or variability of its properties, and that persists for an extended period, typically decades or longer” (IPCC, 2007). It can result from natural variability or human activity, with changes in land use patterns and greenhouse gas (GHG) concentrations being the two primary drivers. Human activities, including rapid industrialization, have caused GHG concentrations like carbon dioxide (CO^2), carbon monoxide (CO), methane (CH_4), chlorofluorocarbons (CFCs), and nitrous oxide (NOX) to increase in the atmosphere, altering the radiative balance and causing global warming (Houghton et al., 1990). Concentrations of these gases are expected to continue increasing, with CO^2 rising from 280 ppm in pre-industrial times to 379 ppm in 2005 and methane rising from 715 ppb to 1732 ppb in the early 1990s and 1774 ppb in 2005. The increase in GHGs has caused three visible signals of climate change: global temperature increase, changes in precipitation patterns, and an increase in the frequency of extreme events, including sea level rise. According to the IPCC’s Fourth Assessment Report, the average global surface temperature is projected to increase by 1.1-2.9°C for low emission scenarios and 2.4-6.4°C for high emission scenarios during 2090-2099 relative to 1980-1999. Over the same period, the global mean sea level is projected to rise by 18-38 cm and 26-59 cm for low and high emission scenarios, respectively, with implications for inundation of coastal and low-lying regions.

Water is an indispensable resource for sustaining all forms of life on earth. Changes in the water cycle, driven by climate change, have significant impacts on water resources due to their sensitivity to changing climatic conditions. These impacts are manifested through three visible signals of climate change, which are translated into regional scale hydrological changes that affect water availability, agricultural water demand, river/stream flow, hydrological extremes, water quality, salinity intrusion, groundwater recharge, and related phenomena (Borgomeo, 2022). The changing climate conditions can have severe impacts on the hydrological cycle, which can potentially threaten human societies that depend on water resources for agriculture, hydropower production, and ecosystems. Hence, it is crucial to provide decision-makers with reliable information about the possible future changes in the hydrological cycle to help them formulate effective strategies for mitigation and adaptation.

In order to assess the potential impacts of climate change on water policy and infrastructure at a regional level, it is crucial to obtain reliable regional projections of temperature, precipitation, stream flow, and other relevant variables, and then use these projections in impact models to determine specific impacts (Schwarze et. Al., 2022). Hydrological models are the primary tool for simulating the effects of climate change on the water cycle and projecting future hydrological patterns. These models require accurate information on climatological variables, such as temperature, precipitation, and evapotranspiration, as well as their distribution in time and space. A strong linkage between climate models and hydrological models is needed to establish future water resource scenarios. This article aims to identify the current gaps between climate models and hydrological models, discuss recent research advances, and present the challenges for future research on the hydrological impacts of climate change.

2. MATERIALS AND METHODS

To investigate the effects of climate change on water resources, two types of models and simulations are typically required. The first type is climate models, which simulate future atmospheric variables under various climate scenarios. These variables serve as inputs, either directly or indirectly, for studies on climate change. In cases where climate models are not available, hypothetical scenarios can be created to represent changes in atmospheric variables, which can then be used as inputs for hydrological models (as shown in Figure 1).

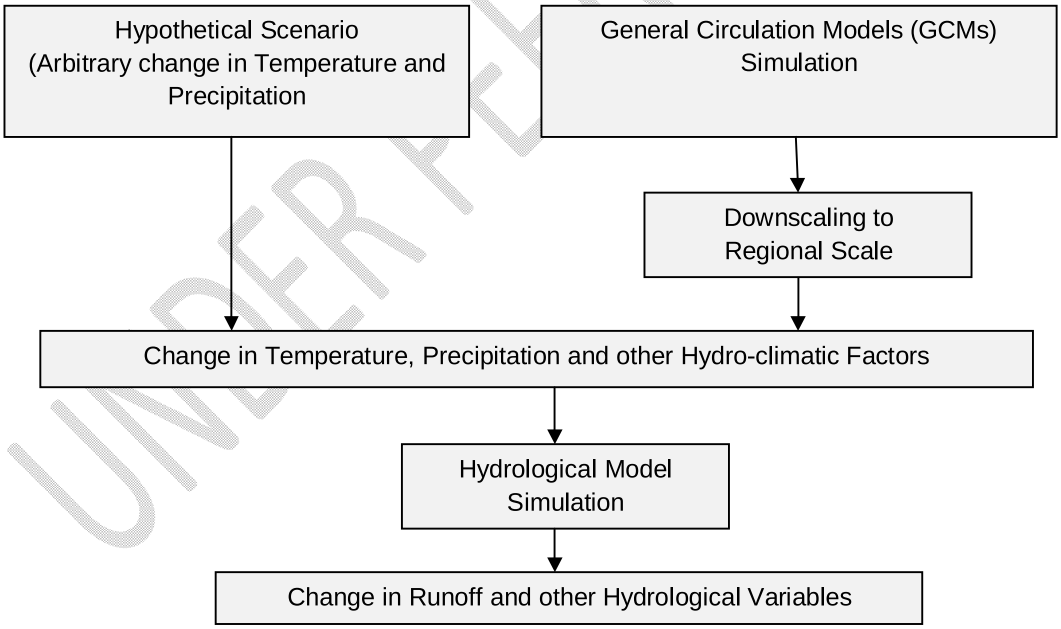

Fig. 1. Methodology for assessing climate change impact on hydrology and water resources

2.1 Hydrological modeling for climate change impacts study

Hydrological models have been used to simulate hydrological regimes since the 1960s, with the development of different types of models, including conceptual, lumped, and physically-based distributed models. With the advancements in computer technology, these models have improved significantly, allowing for the application of more complex models at higher resolutions in a shorter amount of time. Furthermore, hydrology has become more interdisciplinary, particularly with climate change science, as changes in the climate can have both direct and indirect impacts on the hydrological cycle, which in turn can affect the global and local climate. While the connection between hydrology and climate science is now widely acknowledged, coupling the two is still a relatively young discipline. However, given the increasing awareness of climate change, there is now a greater demand for simulations that can predict potential hydrological changes under future climate conditions.

Studies have explored the effects of climate change on various aspects of the hydrological cycle, such as flood frequencies (Cameron, 2006), runoff (Bergstrom et. al., 2001),soil moisture (Mavromatis, 2012), groundwater levels (Goderniaux et. al., 2009), evaporation (Kay and Davies, 2008), and water quality (Wilby et. al., 2006). However, these studies mainly focus on either large-scale climate change impacts or projections at low temporal resolutions such as seasonal or annual changes. Studies on regional impacts and extreme events such as floods and droughts are limited due to the coarse spatial and temporal scales of climate model simulations. These scales do not match the required regional scale for analyzing daily water resource variations. A fundamental problem is the lack of standardized procedures for post-processing climate model outputs for hydrological impact analyses. The resulting hydrological simulations' uncertainty has not been fully evaluated due to limited computer power, which hinders further investigations.

2.2 Modeling for Climate Study

To simulate the current climate and forecast future climate changes, global atmospheric General Circulation Models (GCMs) have been created.

2.2.1 Roles of GCMs in Climate Change Study

The first global climate models (GCMs) were introduced by Phillips (1956) to simulate average, synoptic-scale (i.e., 104–106 km^2 spatial scale), and atmospheric circulation patterns for specified external forcing conditions. Over time, various atmospheric GCMs were developed to simulate average, large-scale, atmospheric circulation (e.g., Holton, 1992). Some of the most widely used GCMs include the Canadian Climate Center (CCC) model, the Geophysical Fluid Dynamic Laboratory (GFDL) model, the Goddard Institute for Space Studies (GISS) model, the National Center for Atmospheric Research (NCAR) model, the Oregon State University (OSU) model, and the United Kingdom Meteorological Office (UKMO) model, among others.

Hydrologists are interested in regional-scale hydrologic variability, but general circulation models (GCMs), which are used for modeling future climate evolution, are not ideal for this purpose. GCMs operate on a large spatial scale and have a relatively low temporal resolution, providing limited direct usefulness for impact studies and hydrological applications. To bridge this gap, researchers have developed approaches to use GCM output in hydrological modeling at the basin scale. However, there are several limitations to using GCM data directly for hydrological modeling, i.e.,

- Decreased accuracy at finer spatial and temporal scales.
- Decreased accuracy for surface variables compared to free tropospheric variables.
- Decreased accuracy for variables such as precipitation, evapotranspiration, runoff, and soil moisture, which are crucial for hydrologic regimes.

2.2.2 Gaps between Climate Modeling and Hydrologic Modeling

The atmospheric components of GCMs are highly advanced, utilizing many layers to simulate atmospheric conditions. However, despite identical atmospheric forcing, parameterizations in current

GCMs often fail to provide accurate predictions for many hydrological variables. As a result, gaps exist between hydrologic and climate modeling due to limitations in GCM simulations. These gaps can be attributed to several factors, including:

1. Mismatches in spatial and temporal scales between GCMs and hydrology needs,
2. Vertical level mismatches,
3. Discrepancies in the accuracy of GCMs compared to the importance of certain variables inhydrological regimes.

2.2.3 Recent Research Developments and Achievements

The challenge of mismatches between GCMs and hydrological models is a difficult one for both the meteorological and hydrological modeling communities. In order to address these gaps and reduce the differences between GCMs and hydrology needs, various methodologies have been developed in the last two decades. These include:

- Dynamic downscaling (nesting) approaches for generating high-resolution meteorological inputs to narrow gap 1.
- Statistical downscaling approaches that use large-scale free tropospheric variables and/or surface patterns to simulate local-scale surface variables, and narrow gaps 1 and 2.
- Macro-scale hydrological modeling approaches for correcting perceived weaknesses in the representation of hydrological processes in GCMs, and narrowing gap 3.
- Hypothetical scenarios used as input to hydrological models to show the sensitivity to climate change within a reasonable interval.

2.2.4 Dynamic Downscaling (DD)

The process of dynamical downscaling, also known as nested RCM approach, involves utilizing regional climate models (RCMs) for specific regions with boundary conditions derived from GCM simulations. This approach was first applied by Dickinson et al. (1989) in the late 1980s for climate change studies. RCMs, also called Limited-Area Models (LAMs), produce highly resolved spatial and temporal climate information, with a grid resolution of approximately 0.22-0.44° (~25-50 km) and a time step size of six hours (Mearns et al., 2003). The coarse-grid GCM simulation output is used for initial and lateral boundary conditions, which is called a "one-way nesting approach." While most RCM studies implement the one-way mode without feedback from RCM to GCM, two-way nesting with feedback from RCM simulations back to the GCM is an alternative (Lorenz and Jacob, 2005; Foley, 2010; Bowden et al., 2011; Chan et al., 2012).

The DD method is capable of resolving atmospheric processes and producing internally consistent output variables while ensuring consistency with the GCM that is driving it. However, this method requires powerful computing resources and is heavily dependent on initial and boundary conditions. Although some RCM simulations include hydrological components such as surface and subsurface runoff, they often disagree with stream flow observations, making RCM-simulated hydrological variables less useful for hydrological impact studies. Therefore, other RCM-simulated variables such as temperature and precipitation are more commonly used in offline mode as inputs to hydrological models. Nevertheless, even RCM simulations of temperature and precipitation can be significantly biased and must be handled with care. As RCM models cannot satisfy the needs of spatially explicit models of ecosystems or hydrological systems, it is still necessary to downscale the results from such models to individual sites or localities for impact studies.

2.2.5 Statistical Downscaling

In statistical downscaling, the relationships between large-scale atmospheric predictor variables and local meteorological series are established (Kim et al., 1984; von Storch et al., 1993). The classification of statistical downscaling methods can be based on the techniques used or the predictor variables selected (Wilby and Wigley, 1997; Rummukainen, 1997). Commonly used predictors include free atmospheric variables such as geopotential heights (Bardossy and Plate, 1992; Wilby, 1995) and surface patterns such as sea level pressure (Karl et al., 1990).

The statistical downscaling approach has been criticized for assuming the invariance of stochastic parameters in response to changes in climate. However, despite this limitation, the approach has started to produce regional algorithms that are useful for hydrological applications. Statistical downscaling plays a crucial role in translating global climate change scenarios into regional impact assessments, as demonstrated in studies by von Storch et al. (1993) and Wilby and Wigley (1997).

3Development of Macroscale Hydrologic Models (MHM)

Macroscale hydrological modeling (MHM) involves applying hydrological models over a large spatial domain, ranging from a ‘large’ basin (over 104 km2), through a continent, to the entire land surface of the globe (Arnell, 1993). Hydrologists have become interested in MHM for two basic reasons:

- to correct perceived weaknesses in the representation of hydrological processes in regional and global atmospheric models, and
- to simulate river flows in large river basins for operational and planning purposes, such as water availability for agriculture, flood hazard, hydroelectric potential, and sediment transport.

A macromodel should be transferable from one geographical location to another, applied either to every sub-basin or on a regular grid, and route runoff from the point of generation through the spatial domain along the river network (Vorosmarty et. al., 1989). Two approaches have been used in the development of a macro-model: 'top-down' and 'bottom-up'. The former treats each fundamental unit as a single lumped catchment, and applies a simple conceptual hydrological model to each of them, while the latter identifies representative hydrological areas and applies highly-detailed physically-based hydrological models, then aggregates upwards to all catchments or fundamental units in a large area (Arnell, 1993; Kite et. al., 1994; Liston et. al., 1994; Sausen et. al., 1994).

4Use of Hypothetical Scenarios

The simulations from GCMs are highly valuable for understanding the impacts of climate change on hydrologic systems and water resources. However, using GCM simulations to directly drive hydrologic models is challenging due to the mismatch in space and time scales between the two modeling approaches. This issue was discussed earlier and highlights the need for downscaling techniques to bridge the gap between the different scales.

As a result of the challenges in using GCMs to drive hydrologic models, hydrologists have resorted to using simple methods to modify present conditions. To estimate the impacts of hypothetical climate change on hydrological behavior, various climate change scenarios have been developed and widely adopted. For instance, predictions for "double CO^2" conditions have become a standard approach in the field (Loaiciga et al., 1996).

The procedure for estimating the impacts of hypothetical climate change on hydrological behavior typically involves several stages. First, hydrologists determine the parameters of a hydrological model in the study catchment using current climatic inputs and observed river flows for model validation. Second, the historical time series of climatic data is perturbed according to some climate change scenarios, such as adding $\Delta T = +1, +2, +4$ for temperature or multiplying precipitation values by $(1 + \Delta P /100)$. Third, the hydrological characteristics of the catchment under the perturbed climate are simulated using the calibrated hydrological model. Finally, the model simulations of the current and possible future hydrological characteristics are compared. This general procedure has been widely adopted by hydrologists to estimate the impacts of hypothetical climate change on hydrological behavior (e.g., Loaiciga et. al., 1996).

5Uncertainties in the Modeling Chain

Utilizing climate model simulations for hydrological studies presents a significant challenge due to the diversity of projections that can be produced. The reason for this diversity is that each projection depends on several factors such as the chosen GCM and its conceptualization, initial and boundary conditions, the GHG emission scenario, and the chosen downscaling method. The modeling chain for future hydrological projections comprises three models: GCMs, downscaling models (SD or DD), and hydrological models. Consequently, uncertainties are introduced due to the choice of future GHG emission scenarios, climate models and their parameterization, downscaling/post-processing techniques, and hydrological models and their parameterization. In addition, errors in observed data used for calibration and validation should also be considered. As a result, it is still challenging to quantify and reduce individual uncertainties in climate simulations and the subsequent modeling procedure, as they are often propagated through the entire modeling chain and ultimately lead to large errors in the final simulation. (Kay et al., 2009; Teutschbein et al., 2011; Beven, 2002; Teutschbein and Seibert, 2010).

To overcome the challenge of producing a variety of different projections when using climate model simulations for hydrological studies, a possible solution is to apply several model simulations together, referred to as "ensemble simulations" (Giorgi, 2006; Teutschbein and Seibert, 2010; Ehret et al., 2012). This method involves the use of multi-model approaches, which have two key advantages: first, the spread of individual ensemble members covers a more realistic range of uncertainty, and second, the ensemble median may fit observations better (Teutschbein and Seibert, 2010). By combining multiple simulations, it is possible to generate a more comprehensive and accurate representation of the projected hydrological changes, reducing the influence of uncertainties introduced by individual models and improving the reliability of the final simulations.

6. SUMMARY AND CONCLUSIONS

The hydrological literature contains numerous regional-scale hydrological simulations that consider greenhouse scenarios. However, these studies have also highlighted several problem areas related to the current capacity of GCMs, limitations of downscaling techniques, and hydrological modeling tools. The significant difference in spatial and temporal scales between GCMs and hydrological models is a fundamental problem. These issues provide an opportunity for collaborative research between hydrologists and climate modellers that could be both intellectually stimulating and potentially beneficial.

The challenges faced by both communities are clear.

- Firstly, improved methodologies are needed to develop climate change scenarios, which requires improvements in both GCMs and downscaling techniques. These scenarios must provide the spatial and temporal resolution necessary for assessment models and must incorporate changes in the mean and variability of climate variables.
- Secondly, the development of hydrological macroscale models based on a better understanding of hydrological processes and their interactions is necessary.
- Thirdly, simulation capacities have generally surpassed available data. Therefore, collecting reliable data at various spatial and temporal scales is essential to enhance our understanding of hydrological processes and to test and validate the downscaling techniques and hydrological models that are being developed.

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