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Climate change projections for impact and adaptation studies at the urban watershed scale

By Van-Thanh-Van Nguyen and Filippo Giorgi

Introduction

Most countries in the world have significant investments in urban water infrastructures (e.g., storm drainage and flood management systems). Every day, people rely on these systems to protect lives, property, and natural water environment. These infrastructures have reduced the vulnerability of the cities, but at the same time could make them more vulnerable to climate extremes, due to the lack of consideration of what might occur when the design criteria are exceeded. Furthermore, recent assessment reports on climate change have indicated for the late 20th century a worldwide increase in the frequency of extreme weather events because of global warming, and this trend would be very likely to continue in the 21st century[3]. Consequently, research on developing innovative approaches for limiting and adapting climate change impacts on urban water infrastructures is highly critical due to the substantial investments involved. However, it has been widely recognized that the main difficulty in dealing with climate change impacts for urban areas is “how to estimate accurately the changes in the hydrologic processes at the urban basin scale projected by global/regional climate models because these models do not contain an adequate description of the hydrologic governing processes at relevant high temporal and spatial resolutions as required by the impact and adaptation studies”. This necessitates some form of downscaling of the climate model simulations from a coarse spatial resolution (20 – 250 km) down to much finer spatial grids, and even point values if changes in local hydrologic processes are to be assessed. In addition, the required time scales for assessing the climate change impacts on the urban hydrologic processes are usually less than one day.

Consequently, in the last decades, different downscaling methods have been developed, ranging from Dynamical Downscaling (DD) approaches, based on high resolution Regional Climate Models (RCMs), to Empirical/Statistical Downscaling (ESD) procedures to establish the linkage between large-scale climate variability to the historical observations of the surface parameters of interest (e.g., precipitation and temperature). If this linkage could be established, then the projected change of climate conditions given by a Global Climate Model (GCM) could be used to predict the resulting change of the urban runoff process for impact and adaptation studies. In the DD approach, RCMs today can downscale GCM output to resolutions of up to a few kilometers. In ESD, statistical models are developed to link large-scale climate predictors to historical observations of the surface parameters of interest at a given location. The overall objective of this article is to provide a critical review of the feasibility and adequacy of various existing downscaling techniques to identify the most suitable procedure for evaluating the impacts of global climate changes on the hydrologic processes at a given location or over a given urban watershed. Of particular interest is the ability of downscaling approaches for describing accurately the linkages between large-scale climate variables and the physical and statistical characteristics of temperature and precipitation processes since these two processes are the main components of the urban runoff generating mechanisms. In summary, it is expected that this review article will enhance our understanding of the reliability and uncertainty of climate change projections and their effects in the planning, design, and management of our urban water systems.

Overview of downscaling approaches

GCMs have been developed for simulating the present climate and for predicting future climatic change. In recent years, the reliability of these models has been significantly improved as compared with those in the early 1990s. Recent GCMs could describe reasonably well the climate system at the continental and hemispheric spatial scales[3]. Despite this significant progress, these models are still unable to provide reliable results at the temporal and spatial scales that are relevant for many impact studies in urban areas. One reason for this problem is that GCMs were not primarily developed for climate change impact studies and hence are not well suited for simulating regional hydrologic variability at the catchment scale or at a given location. A second reason is that the refining of GCM results for the high regional (or local) resolutions of interest would incur extremely heavy computational costs because of the high complexity in the modeling of the atmospheric processes. Moreover, results from different GCMs are not fully consistent with each other at the regional scale[9]. This inconsistency would put their reliability into question[3, 4].

To circumvent the above-mentioned issues, tools for generating the high-resolution meteorological inputs required for modelling hydrological processes are needed. “Downscaling” approaches have subsequently emerged as an efficient means of relating large-scale atmospheric predictor variables to local- or station-scale hydrologic processes. In general, downscaling methods could be grouped into three broad categories (**Figure 1**): 1 | DD methods, involving the explicit solving of the process-based physical dynamics of the system[5]; 2 | ESD procedures based on the relationships between coarse-scale predictor climate variables (e.g., atmospheric circulation indices) and at-site predictand surface parameters (e.g., precipitation)[8]; 3 | Downscaling approaches based on Machine Learning (ML) methods[7].

The main objective of DD is to extract the local information from the large-scale GCM data using RCMs. In general, three

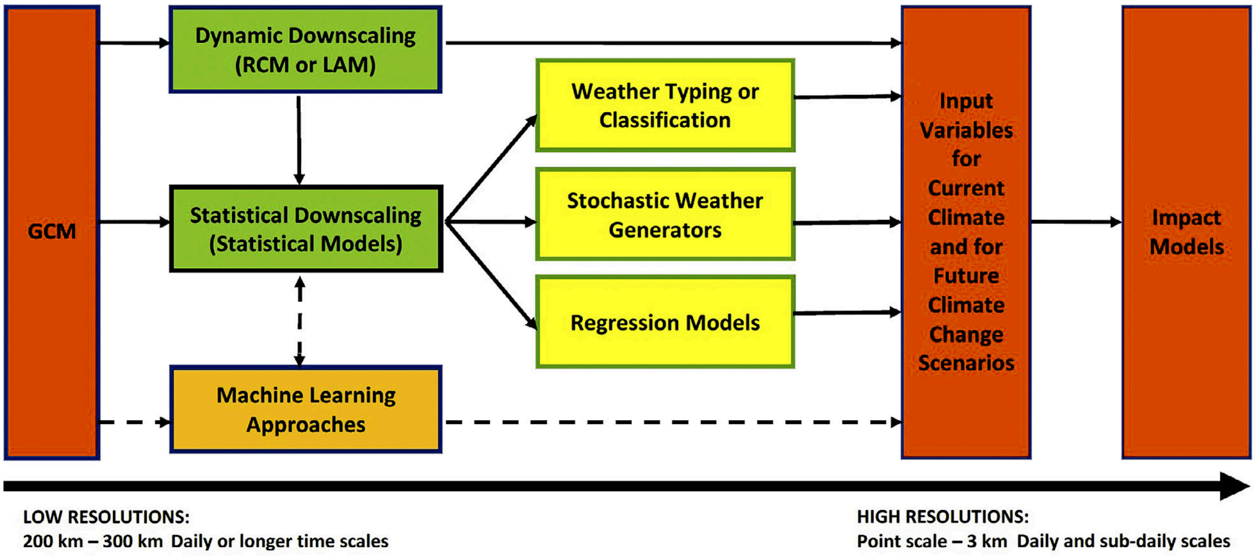

Figure 1 | Downscalling methods

different DD approaches have been used for climate change impact studies^5: 1 | running a regional-scale limited-area model with the coarse GCM data as boundary conditions (the so-called "one-way nesting" method); 2 | performing global-scale experiments with high resolution atmosphere GCMs using coarse GCM data as initial (and partially as boundary) conditions; and 3 | using a variable-resolution global model with the highest resolution over the area of interest. Of these three methods, the most popular procedure could be the nesting of a higher resolution RCM with the coarse GCM data as boundary conditions.

Compared with GCMs, RCMs could model the physical dynamics of the atmosphere using horizontal resolution in the order of 20-50km. The resolution of these RCMs is thus more suitable for coupling RCMs and hydrologic models for evaluating the impacts of climate change on hydrologic regime. Hence, the main advantage of RCMs is that they can describe the smaller-scale atmospheric features (e.g., orographic precipitation better than the host GCM). In addition, RCMs could be used to evaluate the relative significance of different external forcings such as terrestrial-ecosystem or atmospheric chemistry changes. However, there are several acknowledged limitations of the DD using RCMs^5. The main limitation is that RCMs require considerable computing resources as GCMs (which restricted the number of experiments and the duration of climate simulations). Furthermore, the climate scenarios produced by RCMs are sensitive to the choice of boundary conditions used to initiate the experiments. DD methods cannot correct the large-scale GCM model inaccuracies. Finally, for many hydrologic applications, it is still necessary to downscale the spatially average results from RCMs to smaller spatial scales or individual sites for local hydrological impact studies.

Empirical/Statistical Downscaling (ESD) methodologies can be classified into three categories according to the computational techniques used^8: weather typing approaches; stochastic weather generators; and regression methods. In general, these ESD methods require three common assumptions: 1 | the surface local-scale parameters are a function of synoptic forcing; 2 | the GCM used for deriving downscaled relationships is valid at the scale considered; and 3 | the derived relationships remain valid under changing climate conditions.

Among the three ESD procedures, the regression and stochastic weather generator methods are the most popular because the weather classification schemes are somewhat subjective. Furthermore, several features distinguish DD and ESD methods. DD methods contain more complete physics than ESD techniques. However, the more complete physics significantly increases computational cost, which limits the simulation of a climate by these models to typically a single realization. On the other hand, ESD approaches are relatively fast and less expensive than computationally intensive DD methods. These convenient features of the ESD allow the users to develop many different climate realizations and thus to be able to quantify the confidence interval of simulated climate variables. In addition, ESD methods can directly account for the observed climate and weather data available at the local study site. The results are thus consistent with the local climate conditions as described by observations. Finally, many downscaling approaches are based on the mixture of more than one of the above-mentioned downscaling methods^6.

These more recent downscaling approaches are based on machine learning (ML) methods such as Artificial Neural Network (ANN) and Support Vector Machine (SVM). So far it has been found that the direct application of these state-of-the-art ML methods to statistical downscaling did not provide a direct significant improvement over the traditional regression-based ESD procedures^7. The key challenge remains in this statistical downscaling work is how to be able to identify the climate predictors given by climate models that could significantly affect the temperature and precipitation characteristics at a given local site. The use of ML methods could provide hence a more efficient and more robust procedure for selecting these significant climate predictors.

Overview of changes in extreme hydrologic processes

Global warming can substantially affect the global hydrologic cycle, by modifying the Earth's water and energy budget and, as a result, by affecting the dynamical and thermodynamical characteristics of the general atmospheric circulation. Hydrological impacts can also be modulated at regional to local scales by forcings such as complex topography, coastlines, or inland bodies of water. Here we present a brief discussion of changes in the hydrologic cycle emerging from both, observations from the past, and model projections for the 21st century. In general, the GCMs provide historical simulations and projections of future climate change based on a range of future forcing scenarios incorporating greenhouse gases (GHGs), aerosols, and land-use change. For instance, the fifth phase of the Coupled Model Intercomparison Project (CMIP5) was an internationally coordinated effort that produced a multi-model ensemble of climate projections. Results from this ensemble specific to Canada have been generated using output from 29 CMIP5 GCMs, based on three scenarios: a low emission scenario (RCP2.6), a medium emission scenario (RCP4.5), and a high emission scenario (RCP8.5).

Observed and projected changes in temperature extremes

Temperature extremes can change by shifts and/or changes in the temperature distributions at daily to seasonal scales. Therefore, a change in mean temperature is already expected to lead to an increase in temperature extremes. According to the latest IPCC report, the Earth's global temperature has risen by about 1.07°C since the late 19th century. Consequently, observations show that hot extremes and heat waves have become more frequent and more intense, while cold extremes have decreased. This has been observed over most continental areas of the planet.

Climate projections show that this trend will continue in the future with continuing global warming, with the extent of the increase in extremes depending on the warming. In some scenarios, temperature conditions will increase well beyond current extremes. For example, some studies show that in the most extreme scenario (RCP8.5) the summer of 2003 over Europe, which in some areas was 4 standard deviations away from the current mean, may become the norm, and even hotter summers would be likely to occur. Marine heatwaves are also projected to increase with increased warming.

Model projections also show that the warming would not be uniform across the continental surfaces, but that there are some areas, called "hot-spots", that warm much more than the global average. The most prominent hot-spot is the Arctic, which is warming at more than double pace than the global average due to the ice-albedo feedback mechanism. Other prominent hotspots, mostly associated with reduced precipitation and cloudiness, and thus increased solar insolation and reduced evaporative cooling, are the Mediterranean basin, a portion of the Amazon Basin, Southern Africa, central America, and the southwestern United States.

Under climate change, a warming climate is expected to lead to increases in atmospheric moisture, and consequently increases in extreme precipitations, with the result that infrastructure designed with historical extreme values may be at greater risk from damage or failure. It has been argued that the increase in mean precipitation in a climate warmed by rising GHGs is energetically constrained to 2% per °C, while, in the absence of other influences (e.g., changes in large-scale circulation, local storm dynamics, etc.) extreme precipitation could be free to intensify closer to the theoretical Clausius-Clapeyron (CC) rate (7% per °C). Expressing the relative change in precipitation extremes as a function of warming is commonly referred to as "temperature scaling". Given that projections of temperature change are felt to be more reliable than those for extreme precipitation, temperature scaling is used as the basis for providing guidance to engineers on future changes in rainfall extremes in Australia[1] and in Canada[2].

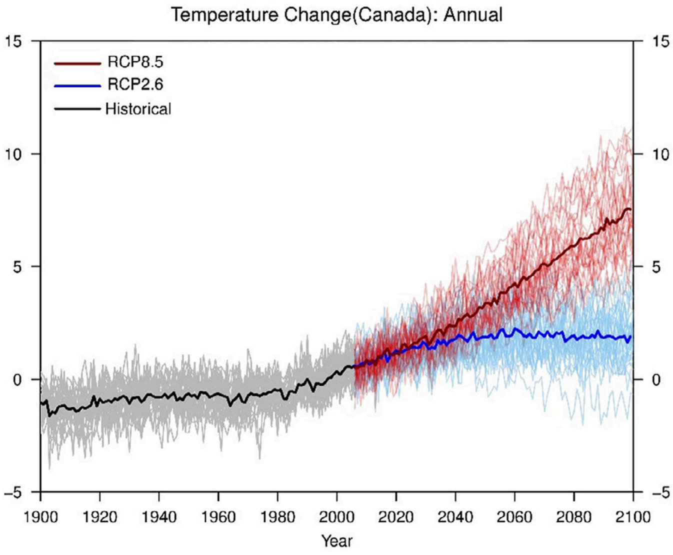

Figure 2 | Historical and projected annual temperature changes (°C) in Canada (CSA, 2019)

Figure 2 shows the evolution of historical and projected annual mean temperature changes averaged for the Canadian land area and over the 1900 - 2100 period. The thin lines show results from the individual CMIP5 models, and the heavy line is the multi-model mean. The spread among models is quantified by the box and whisker plots to the right of each panel. They show, for the 2081-2100 period, the 5th, 25th, 50th (median), 75th, and 95th percentile values[2].

Observed and projected changes in precipitation extremes

Global warming can profoundly affect the characteristics of precipitation in a multiplicity of ways. First, changes in the global circulation can modify the trajectories of storms and thus the spatial patterns of precipitation. For example, one of the circulation responses to warming is an expansion of the Hadley cell, which in turn induces a poleward shift of the mid-latitude jet streams with a consequence increase in precipitation at mid to high latitudes, e.g., in the central and northern portions of Europe, North America and Asia, and a decrease in subtropical areas, e.g., in the Mediterranean and central America, southern

Africa, and southern Australia. This precipitation change pattern is evident both in model projections and, albeit to a lesser extent, in observations.

A second response of the hydrologic cycle to global warming is the so-called "intensification of the hydrologic cycle". A warmer atmosphere contains more energy and, because of the Clausius-Clapeyron law, more water vapor (about 7% per degree of warming). Therefore, when precipitation is triggered, the precipitation intensity tends to grow with higher temperatures. A ubiquitous increase in the intensity of precipitation and associated frequency and intensity of extremes is consistently shown in model projections for all scenarios, also with the future occurrence of events of unprecedented intensity. Observed increases in heavy precipitation since 1950 has been identified in extended regions of Asia, Northern Europe, North America, North Australia, and Southern Africa (and to a lesser extent South America).

At the same time model experiments show that global warming induces a decrease in the frequency of precipitation events and an increase in the length of dry periods. This, along with the increasing temperatures, leads to an increased risk of drought. Such response is widespread in future model projections and has been found also in observations for the past decades in areas of Western and Southern Europe, West and East Asia, Southern Australia, Western North America and North-Eastern South America. Occurrence of compound extremes, e.g., drought and heat waves, can further increase the impacts of such events.

Global warming can also influence the characteristics of regional circulations, such as the monsoons. Monsoon precipitation tends to increase in projections due to the greater moisture amounts in the atmosphere, but trends in observations are unclear due to the competing regional effects of aerosols and greenhouse gases.

The interannual variability of precipitation is expected to increase with warming conditions, as well as the proportion of intense tropical cyclones (categories 4 and 5) and the peak wind speeds of the most intense cyclones. These cyclone trends have been already seen in the historical record.

Strengths, limitations, and uncertainties associated with different approaches for climate change projections

GCMs are the main tools we have today to produce projections of climate change and associated hydroclimatic regimes and extremes. Present day GCMs used for climate projections include different components of the climate system, such as the oceans and cryosphere, and reach horizontal grid spacings of the order of 80-100 km. While GCMs can reproduce fairly well the general characteristics of the global circulation and its main modes of internal variability, e.g., the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), they have problems in simulating regional and local climates due to their coarse spatial resolution. Both dynamical (e.g., RCMs) and empirical/statistical downscaling techniques can then be used to downscale the GCM information and achieve finer scale climate information.

GHG concentration scenarios, which is usually dealt with by performing projections with a range of such scenarios developed by the IPCC. Once the GHG scenarios are input into the GCMs, different models generally produce different climate responses as measured for example by the Equilibrium Climate Sensitivity (ECS), i.e., the global temperature response to doubling of carbon dioxide concentration.

Current GCMs exhibit an ECS ranging from 2.0 to 4.5°C, a range that has remained relatively stable throughout several generations of models. The climate sensitivity of a model is determined by the fact that each model has different numerical representations of dynamical and physical processes, and among these one that greatly contributes to the ECS is the representation of clouds and precipitation processes, and in particular tropical convection. The representation of cryosphere processes is another important factor. The presence of a range of ECS implies that climate change information cannot be based on a single model but needs to employ an ensemble that covers the ECS range of GCMs. Some techniques have been developed to reduce this intermodel uncertainty by weighting GCMs according to their performance in reproducing different climate characteristics or by constraining climate projections with observations.

In addition, GCMs are characterized by long term internal variability associated with the slow component of the system (e.g., the oceans), and this can be explored by carrying out projections using different initial ocean conditions (or different "realizations" of the same scenario).

Similar considerations are valid when using RCMs to downscale the GCM information. It is not sufficient to downscale a single GCM projection, but the need is there to downscale a range of GCM simulations covering to the extent possible the full GCM ECS range and the GCM internal variability. This is a formidable task from the computing viewpoint, so that only a sub-set of available GCMs can be downscaled, and the choice of these GCMs must be done very carefully. In addition, different RCMs have themselves different representations of dynamical and physical processes, so that they provide different simulations even for the same GCM boundary condition forcing. For this reason, a suitable matrix of GCM/RCM pairs need to be considered to properly interpret uncertainties in projections.

The use of large ensembles is especially important when looking at extreme events, which are by definition rare. In addition, simulated meteoclimatic events need to be properly interpreted in view of systematic biases in the models (e.g., over- or underestimation of intensities).

Often, bias correction techniques are applied to the model output before use in impact studies. In these techniques, the model output is corrected to remove biases compared to given observation datasets, assuming that the model bias in reproducing present day climate is carried over to the simulation of future climates.

Concluding comments

Urban infrastructures must be designed and operated to be safe for people and the environment, and economically viable. This requires the prediction of urban hydrologic processes during the lifetime of these infrastructures in the context of a changing climate. The large uncertainty in climate change projections and increasing climate variability makes this task challenging.

In summary, the present review has indicated that, while significant advances have been made regarding the accuracy and reliability of global/regional climate modeling, outputs from these GCMs/RCMs are still not appropriate for the assessment of climate change impacts on hydrologic regime at small spatial and short time scales. To circumvent this difficulty, several downscaling methods have been proposed in the scientific and technical literature. Despite some shortcomings, these methodologies have been found to be able to provide some useful tools for the assessment of the potential impacts of climate change in practice. However, downscaling methods are still relied on the accurate and reliable outputs of GCMs/RCMs to be able to develop realistic scenarios for describing possible changes of hydrologic processes under changing climate conditions. Furthermore, due to their different nature and different associated skills, it is recommended that the best approach for developing physically plausible climate scenarios for impact and adaptation studies at a local site or over an urban watershed should be based on the combination of these three DD, ESD, and ML methods.

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