CLIMATE CHANGE AND HYDROGEOLOGIC PROCESSES

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Contents

Summary

The theory of climate change and the relationship of climate-change forcing to regional hydrologic processes are summarized in this article. The focus is on regional aquifer systems, and on the methods to link large-scale climate-change processes to groundwater recharge, and to simulate groundwater flow and solute transport in a warmer climate with twice the amount of the 1990 atmospheric carbon dioxide concentration (2 x CO_2).

There are substantial uncertainties associated with climate-change scenarios, be they transient or equilibrium 2 x CO_2 cases. Those uncertainties arise primarily from the complexity of the Earth's climate system, and from complex, nonlinear, climate feedbacks that arise in connection with a rapidly warming planet.

The best methods currently available to generate climate-change scenarios and to simulate regional aquifer systems under the ensuing scenarios are covered in this work. Detailed implementation procedures for climate-change/aquifer simulation are presented. An example illustrates a specific procedure and our current capabilities to assess the potential impacts of a warming climate on regional-scale aquifer systems.

1. Introduction

1.1. The Climate-Change Puzzle

What is climate change? The answer to this question, plus the effects that climate change might have on regional groundwater processes, constitute the subject of this article. For the purpose of current and future impacts, the term "climate change" has become synonymous with modern-age global warming.

The latter, in turn, refers to post-Industrial Revolution changes in global mean surface–air temperature, which are hypothesized to have been caused by increased atmospheric concentrations of carbon dioxide (CO_2)—an active greenhouse gas—during the eighteenth, nineteenth, and twentieth centuries. In 1765, the CO_2 atmospheric concentration was about 280 L L^{-6}, while in 1999 it was near 364 L L^{-6}.

The atmospheric concentrations of other greenhouses gases have also risen as a result of accelerated economic activity and energy use in the last two centuries. Some of the principal gases besides CO_2 are: methane (CH_4, 700 L L^{-6} circa 1765, and 1720 L L^{-6} in 1999), nitrous oxide (N_2O, 275 L L^{-6} circa 1765, and 315 L L^{-6} in 1999), and, in the post-Second World War period, chlorofluorocarbons CFC-11 (CCl_3F, from near zero concentration in 1945, to about 270 L L^{-9} in 1999) and CFC-12 (CCl_2F_2, near zero in 1945, to about 550 L L^{-9} in 1999). The mean concentration of water vapor—another key greenhouse gas—in the atmosphere has remained at a level of about 3000 L L^{-6} in the Holocene (last 10 000 years).

The rapid rise in fossil-fuel combustion as an energy source since the late eighteenth century has caused the observed increase in the atmospheric concentration of CO_2. While the post-Industrial Revolution rise in CO_2 atmospheric concentration is beyond doubt, the question of whether or not the Earth's mean surface air temperature has increased relative to the pre-Industrial Revolution level remains an elusive hypothesis. In spite of the difficulties associated with calculating a global mean surface air temperature, recent estimates indicate that it has increased between 0.3°C and 0.6°C during the last 150 years. However, that increase has not been monotonic, but, rather, irregular, with interspersed cooling periods. A cause–effect linkage between the slight, long-term, post-Industrial Revolution rise in the global mean surface–air temperature and the concomitant heightening of key greenhouse gases remains to be proved. This is so because the great variability of the Earth's climate and its interdependence with multiple terrestrial and extra-terrestrial phenomena.

1.2. Climate Change and Hydrologic Scales

To the hydrologist, the question of whether global mean surface temperature has increased or will continue to increase, say, at a rate of 0.5°C every 100 years, is largely irrelevant. The scope of work of the hydrologist is delimited by the capacity to measure hydrologic fluxes (water, substances, energy), to analyze them, and to make meaningful and useful inferences and predictions about them. In the practical realm, where most hydrologic work lies, the intersection of hydrologic relevant spatial scales and administrative/political boundaries defines a context to the study of hydrologic processes, with or without climate change.

As a result of these constraints, hydrologic studies are largely circumscribed to the watershed and the regional aquifer system. Typically, this entails working with regions of less than 10^6 km^2, and in the great majority of cases, the typical perimeter of the watershed or groundwater basin encloses areas well under 10^5 km^2. (These relevant spatial scales are referred to in this article as "regional scales"). Therefore, to the hydrologist, climate change must be resolved in terms of precipitation, surface–air temperature, evapotranspiration, sediment, water quality, and runoff changes at the relevant spatial scales.

As for the temporal resolution of climate change, hydrologic processes encompass a wide spectrum of meaningful time scales. In the case of flood studies, the relevant temporal scales of precipitation changes are on the order of minutes to days, while for drought-impacts studies, the precipitation and temperature temporal scales of interest can vary from days to years, depending on the inter- and intra-seasonal disposition of water in the natural and human-occupied environment.

As we shall see, the inability to resolve accurately the consequences of climate change on hydrologic fluxes constitutes the main source of uncertainty in any study of climate-change/hydrologic interactions. The remainder of this article provides a critical analysis of the state of the art in the analysis of climate change and its hydrologic consequences, and highlights the associated limitations. The discussion is focused on the groundwater component of the hydrologic cycle. One example is presented to illustrate the principles laid out in this article.

2. The Status of Climate-Change Predictions and Associated Hydrologic Consequences

2.1. Climate-Change Scenarios and Simulation Models

Early studies (many were produced between 1970 and 1985) of the regional-scale hydrologic consequences of climate change were mostly based on simple scenarios for precipitation and temperature under a warmer climate. Precipitation was increased or decreased by a certain percentage relative to historical values (the ± 20% range was commonly used).

Historical temperature was increased a few degrees (typically between 1 °C and 5 °C, which now seems somewhat high in light of the most current estimates of long-term surface-air temperature change). With these two forcing variables, calibrated hydrologic models were then implemented to carry out hydrologic simulations in the region of interest. It was assumed that the calibrated model under the historical climate remained valid under a modified climate.

The results so obtained for important fluxes such as sediment output, groundwater recharge, and stream flow or other variables and water-resources systems of interest (for example, groundwater levels, water-quality characteristics, reservoir storage and releases, irrigation scheduling, and so on) were then compared with those corresponding to the historical-climate simulations. The differences between the two sets of results were then attributed to climate change, all other things being equal (for example, population, water use, cropping patterns, water technology).

A second wave of studies started to appear in the refereed literature with increased frequency after 1985. They were based on the linkage between climate predictions from general circulation models (GCMs) and regional climate models (RCMs). GCMs, which made their early appearance in the global-scale climatic modeling community in the late 1960s, have been steadily improved in their physically based structure and numerical solution algorithms.

They also have evolved by incorporating refined spatial resolution of their numerical grids. RCMs have basically the same physical basis as GCMs but a much greater spatial resolution and are confined to synoptic-scale simulation regions rather than planet-wide simulations.

At present, a GCM—and there are several leading ones—may have a spatial grid with cells on the order of 200 km × 200 km, while the RCMs have achieved resolutions on the order of 20 km × 20 km. The RCMs rely on the coarser output from GCMs, which they use as initial and boundary conditions to drive their spatially refined simulations of climate change.

The great majority of GCM and RCM climate change simulations are based on the so-called "2 x CO_2 scenario," whereby the 1990 CO_2 atmospheric concentration (about 355 L L^{-6}, a base level adopted by the climate-change community) is doubled and that value is used in the GCMs and RCMs to simulate the 2 x CO_2-warmer climate.

The climate models simulate various relevant climate-forcing variables of hydrologic interest at the land–atmosphere interface: precipitation, air temperature, radiant-energy fluxes, wind speed, atmospheric pressure, absolute humidity, latent-heat flux, and runoff averaged over the models' surface grid cells. The RCM key output variables, such as precipitation, surface air temperature, ground-level radiant-energy fluxes, water-vapor pressure, and wind speed, become the forcing input variables to hydrologic models which then calculate in a classical fashion the dependent hydrologic variables of greatest interest, of which stream flow and groundwater levels are examples.

In some instances, GCMs and RCMs have undergone "sub-grid" parameterizations, which introduce approximate numerical representations of hydrologic processes at the land-surface interface, allowing them to make calculations of hydrologic fluxes at fine spatial resolution or at selected locations (for instance, at stream gages, or zones of influence of a water well).

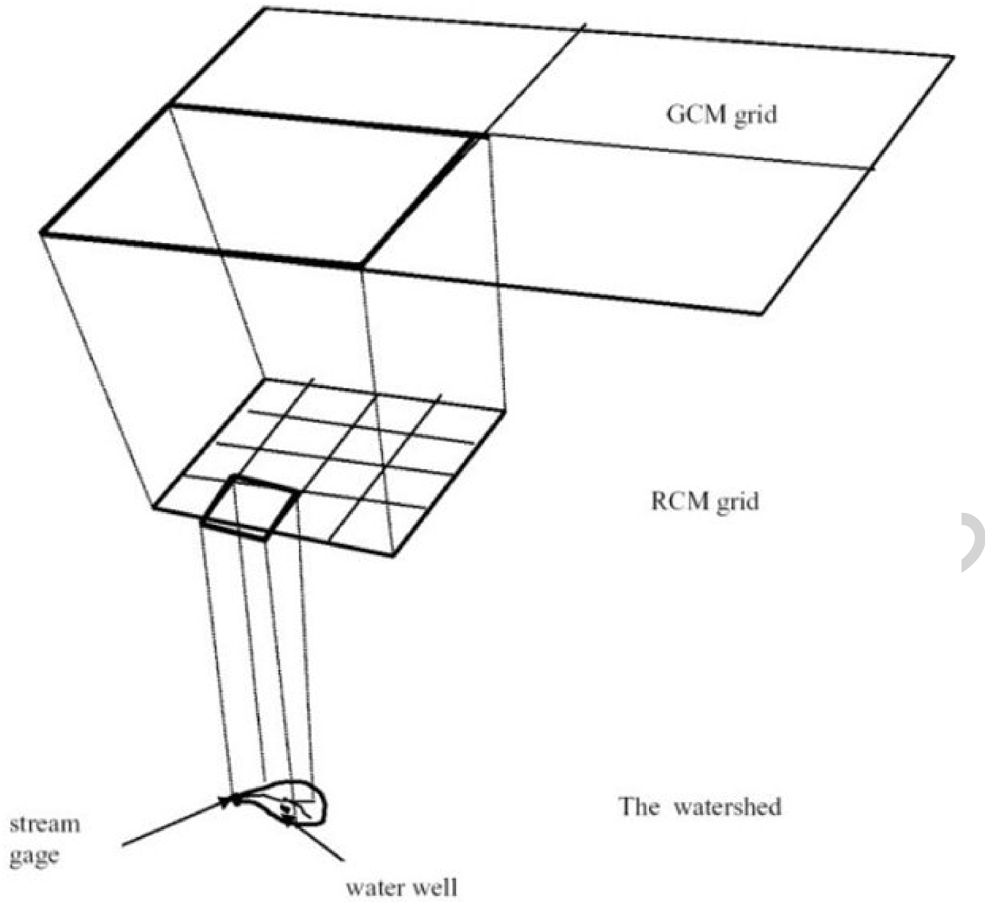

Figure 1. The nesting approach to simulate watershed-scale hydrologic fluxes in a warmer climate

However, watershed-scale hydrologic models are better suited to carry out fine-resolution hydrologic simulations (for example, of stream flows at selected gages, spring flows, groundwater levels) because of their more realistic physically based structure and internal parameterization. This is particularly true when attempting to simulate groundwater response to climate change, since groundwater flow, transport, and geochemical processes are poorly represented (if at all, as is the case with water-quality characteristics) by the sub-grid parameterizations proposed thus far. Therefore, the GCM–RCM–hydrologic model linkage is the one pursued in this article. Figure 1 shows graphically the "nesting" of hydrologic models within RCMs, and of the latter within GCMs.

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Biographical Sketch

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